MCSC | MIT Climate & Sustainability Consortium

Alternative Fuels and Powertrains to Decarbonize Heavy Duty Trucking

Contributors

Danika MacDonell
MCSC Impact Fellow

Sayandeep Biswas
Graduate Student, MIT Green Group

Kariana Moreno Sader
Graduate Student, MIT Green Group

Table of Contents

Executive Summary

Amid mounting urgency to rapidly decarbonize the global economy in the coming decades, the trucking industry sits on the cusp of a dramatic transition to low-carbon alternative fuels and powertrains. Technological trends suggest that multiple solutions will emerge in the near term to fill different niches of the trucking market. Faced with a diverse and continually evolving space of alternatives, each with its own set of up-front costs and risks, industry stakeholders report decision paralysis when it comes to navigating the transition.

In the coming years, a *valley of death* period is anticipated during which up-front costs of purchasing alternative vehicles and installing refueling infrastructure will be high, and availability of public infrastructure will be limited. Governments have a crucial role to play in providing the regulation and incentives needed to ensure that companies and customers are able and willing to pay higher costs and take on financial risk to bridge the valley of death. In addition, owing to their geographical flexibility and capacity to take on up-front costs and risk, there is an opportunity for large fleets to leverage first mover advantages in the space and take the lead in piloting and adopting alternative fuels and powertrains.

Informed by perspectives from industry members of the MIT Climate & Sustainability Consortium (MCSC), and insights shared by invited experts from academia and industry during a study panel hosted by the MCSC, we identify near-term priorities to support industry stakeholders in overcoming decision paralysis, navigating the valley of death, and positioning trucking fleets to thrive as the industry transitions to alternative fuels and powertrains.

Start with the low-hanging fruit. We compile a set of characteristic features that can make a given trucking operation or corridor particularly amenable to near-term transition. Identified features include 1) the presence of pre-existing charging or refueling infrastructure, 2) short distances between hubs or refueling stations, 3) well-defined routes and schedules, 4) light payloads, and 5) the presence of supportive policy and incentives.

Leverage available incentives and support. Many governments, utilities and other organizations offer a range of supportive policy and incentives to facilitate adoption of alternative fuels and powertrains. Fleets can significantly lower transition barriers by identifying and applying for incentives and funding sources available to them.

Provide comprehensive tools to support fleet owners. Fleet owners need access to comprehensive and user-friendly tools to support their decision-making process. The tools should enable fleet owners to perform targeted assessments of transition costs and potential CO_2 reductions to determine the right solution for their fleet.

Take advantage of resource pooling opportunities. There is an opportunity for industry stakeholders to work collaboratively by pooling demand and resources to collectively lower the barriers to transition.

Be prepared to adapt as the technology evolves. Alternative fuel and powertrain technologies differ notably from conventional diesel and are evolving rapidly. Companies should seize low-hanging opportunities to start deploying alternative fleets within today's trucking networks. But it's also important to closely monitor the evolution of these technologies, and be prepared to adapt in the future to optimize their adoption.

Study Panel Overview

In Spring 2023, the MIT Climate & Sustainability Consortium (MCSC) hosted a study panel attended by representatives of MCSC member companies to discuss opportunities and barriers faced by trucking fleets in navigating the transition to alternative fuels and powertrains. MIT researchers, Prof. Green and Mr. Biswas, MCSC member company expert Joel van Rensburg from Vontier, and STEPS program director Dr. Fulton from UC Davis shared insights on tools and strategies that stakeholders can leverage to overcome decision paralysis and position fleets to adapt and thrive as the industry transitions.

Expert Panelists

			
William H. Green Hoyt C. Hottel Professor in Chemical Engineering, MIT	**Sayandeep Biswas** Ph.D. Candidate in Chemical Engineering, MIT	**Joel van Rensburg** President of Alternative Fuels ANGI/Gasboy, Vontier	**Lewis M. Fulton** Director of STEPS (Sustainable Transportation Energy Pathways), UC Davis

Background

Medium- and heavy-duty trucks produce an estimated 23% of transportation-related greenhouse gas (GHG) emissions, representing 6% of all GHG emissions in the U.S. (EPA, 2023). Additionally, particulate emissions from diesel exhaust produced by trucks are responsible for significant adverse health impacts in local communities (CARB, 2023). Yet, the trucking industry plays a fundamental role in enriching modern life through the distribution of goods (FWHA, 2020). A range of alternative fuels and powertrains have emerged in recent years with potential to help decarbonize the trucking industry.

A Complex Solution Space

The space of alternative fuels and powertrains is diverse and continually evolving (Figure 1). Despite their inherent CO_2 emissions, hydrocarbons, including natural gas will be necessary to bridge a transition to non-hydrocarbon sources.

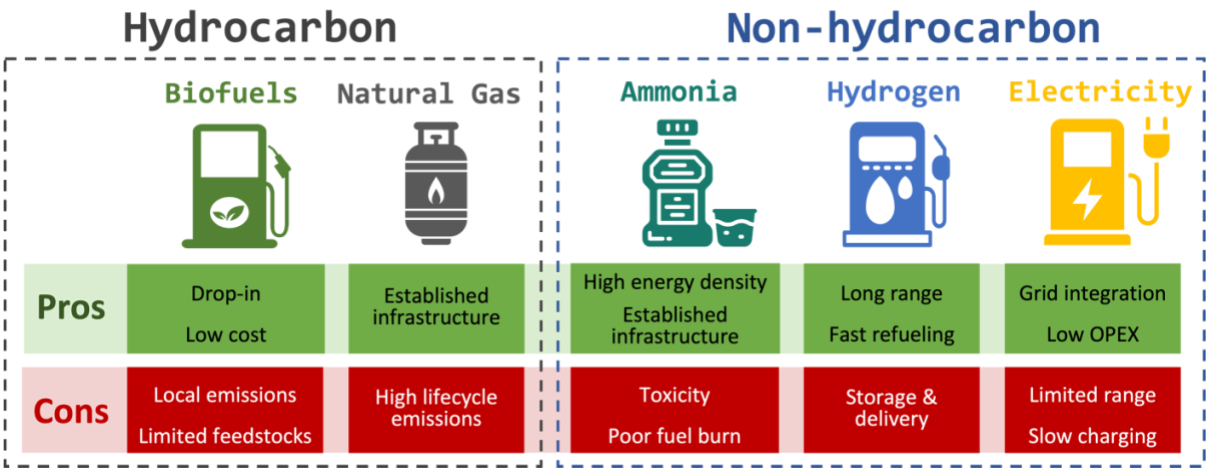

Figure 1: Summary of alternative energy carriers emerging to decarbonize heavy duty trucking

If produced with sustainable feedstocks, **biodiesel and renewable diesel** can offer very low CO_2 emissions on a lifecycle basis, thanks to the uptake of atmospheric CO_2 during feedstock growth (Xu et al., 2022). Challenges persist in terms of land use implications and overall availability.

Shifting to non-hydrocarbon sources**, battery electric powertrains** are garnering significant interest as advances in battery technology continue to extend vehicle range (IEA, 2023) and reduce electric vehicle battery costs (EERE, 2023). Lifecycle emissions of BEV trucks are expected to drop drastically in the coming years as more clean power sources are integrated into the grid (Iyer et al., 2023).

Hydrogen is also gaining attention as an alternative trucking fuel, thanks in part to its long range and quick refueling times. Its carbon intensity is also expected to drop rapidly in the coming years as more “green hydrogen”, produced using electrolysis powered by renewable resources, becomes available (Iyer et al., 2023). Because of its low volumetric density at room temperature, advanced storage methods are needed to safely distribute pure hydrogen to refueling stations, and expensive compression is needed prior to refueling (EERE, 2023).

Liquid organic hydrogen carriers (LOHCs) are room-temperature liquids that can be reversibly hydrogenated or dehydrogenated to capture and release hydrogen (Modisha et al., 2019; Biswas et al., 2023). LOHCs represent a promising solution to store and deliver hydrogen using well-established infrastructure. They offer efficient synthesis, low toxicity, and relatively straightforward hydrogen release compared with alternative liquid hydrogen carriers such as ammonia (Abdin et al., 2021).

Ammonia is also being considered as an alternative fuel, in addition to a liquid hydrogen

carrier. It offers high volumetric and gravimetric energy density relative to many other hydrogen carriers, and there is already substantial infrastructure in place for its production and distribution. Significant obstacles with regards to its toxicity (Dolan et al., 2021) and fuel combustion characteristics (Li et al., 2021) will need to be overcome, however, before it can be considered for wide scale deployment in this capacity.

Decision Paralysis

As discussed in a recent Greenbiz article, many fleet managers in the industry report decision paralysis when faced with the range of options emerging to decarbonize trucking fleets. With rapid technological advancements and changes to the regulatory environment, the challenge is compounded by the ever-changing nature of the landscape.

> From the point of view of research, small fleets are a bit lost in terms of what life will be like with different technologies. Big fleets can afford to try different things.
>
> ***Lew Fulton, UC Davis***

On top of the up-front costs of purchasing alternative trucks, fleet owners need to consider the availability of charging and refueling infrastructure. If they need to install their own infrastructure, how much will that cost? Will they need to worry about permitting delays (Nelder & Rogers, 2019), or potential shortages of fuel or electricity?

Most trucking fleets in the U.S. have fewer than 20 trucks (FMCSA, 2022). Given the tight profit margins in the industry (Biery, 2018), the consequences of a wrong decision can be steep, especially for small fleets. It can be challenging for small fleets to afford the risk and up-front costs associated with transitioning to alternatives.

Large fleets may be better placed to afford these up-front costs and risks. As a result, there is an opportunity for large fleet owners to lead in piloting and adopting alternative fuels and powertrains. In addition, larger fleets are likely to have a wider geographical coverage and range of operations, which offers them the flexibility to select regions and operations that are particularly amenable to initial adoption.

A Multi-fuel Future

Current technological trends point towards the likelihood of a multi-fuel future for trucking. This reflects the fact that there is currently no one-size-fits-all solution that optimally replaces diesel in all fleets and operations. Rather, different payloads and operating regimes will present different constraints that impact the optimal choice of alternative for a given fleet (Mauler et al., 2022).

Can Hydrocarbons Decarbonize Trucking?

Cleaner hydrocarbon alternatives including biofuels and natural gas have the advantage that they can be used as 'drop-in fuels', so-called because they require minimal or no modification to diesel-burning engines and associated infrastructure. But because of their inherent CO_2 emissions, it's unlikely that hydrocarbon fuels can support significant decarbonization of the trucking industry. While biofuels can reduce emissions on a lifecycle basis thanks to CO_2 uptake of biomass feedstocks during growth (Xu et al., 2022), future availability of sustainable feedstocks will be limited by land use constraints and competition from other sectors (Kalt et al., 2020).

Deep decarbonization of the trucking industry will likely require widespread adoption of non-hydrocarbon energy carriers, the current forerunners of which are batteries and hydrogen (Cunanan et al., 2021). In parallel, the power grid will need to continue to shift aggressively away from fossil fuel power sources and towards low-carbon renewables. Hydrogen production, which is presently dominated by the carbon-intensive steam methane reforming (SMR) process will need to shift to electrolysis powered by renewables ("green" hydrogen) (Megia et al., 2021).

It's worth acknowledging that synthetic electro-fuels (Lehtveer et al., 2019), produced by synthesizing hydrogen and CO_2 through an electrically powered chemical process, could in principle offer a pathway to trucking decarbonization using drop-in hydrocarbon fuels, provided that the hydrogen is green and the carbon is produced from direct air capture (DAC). However, the power requirements and subsequent efficiency losses involved in producing carbon from DAC and performing hydrocarbon synthesis will likely render it more cost-effective for trucks to adopt alternative powertrains that utilize electricity and hydrogen directly (Gray et al., 2022).

What Does a Non-hydrocarbon Future Look Like for Trucking?

While technological advancement and societal preference may shift the market towards a single fuel choice in the long term, the near-term expectation is that the optimal choice for a given fleet will depend on a variety of factors. Between hydrogen and battery electric, a transition to battery electric is expected to be most immediately suitable for fleets that operate on well-defined short-haul routes and carry relatively light payload that can accommodate the extra battery weight (Mauler et al., 2022), and in areas of the world with a well-developed electrical grid.

For intercity transport, electric has an advantage. The real question for heavy-duty trucking is the tradeoff distance. We don't know the cutoff point yet, but for long-haul (600 miles daily range) the energy density of H_2 makes a lot more sense.

Sayandeep Biswas, MIT

In general, a transition point with respect to various axes is expected, beyond which hydrogen becomes the more suitable alternative relative to battery electric thanks to some combination of its higher gravimetric energy density, faster refueling times, and transportability. However, the exact transition point will depend on a range of future conditions, including the availability of suitable infrastructure. For example, a recent cost optimization study by Mauler et al. (2022)

found that the exact transition point varies dramatically depending on future system costs, electricity and hydrogen prices.

> At Vontier, we strongly believe in a multi-energy future. The question is, how do fleet owners arrive at the right decision when considering when, how or even which vehicles to transition to battery electric vs. hydrogen vs. renewable natural gas? The tools needed to inform those decisions are lacking today.
>
> ***Joel van Rensburg, Vontier***

Navigating the Valley of Death

The trucking industry today sits at the cusp of a transformative sea change. In recent years, alternative fuels and powertrains needed to realize meaningful decarbonization have either already reached or are imminently approaching technological maturity. But the pathway to net zero is anything but straightforward. A widespread shift away from fossil fuels will require massive buildout of recharging and refueling infrastructure, both at trucking hubs and along highway corridors. In some areas, upgrades to the power grid will be needed to support the increased power load (Borlaug et al., 2021). In the coming years, a *valley of death* period is anticipated during which up-front costs of purchasing alternative vehicles and installing refueling infrastructure will be high, and availability of public infrastructure will be limited.

But to climb out of the valley of death, continued adoption of alternative fuels and powertrains is needed in the industry to ensure that the costs of alternative fuels, vehicles, and infrastructure can benefit from learning curves and economies of scale. Even in cases where a transition to battery electric or hydrogen would pay off financially today over the lifetime of the vehicle, it can be challenging for fleet owners to bear the up-front investment costs of purchasing alternative fuel trucks and installing the requisite infrastructure.

> We need the cost of fueling and infrastructure and trucks all to go down. BEV and hydrogen fuel-cell heavy duty trucks are currently selling for two times the cost of equivalent diesel trucks because volumes are low and production companies are seeing what the market will bear. I'm hopeful that as we get to scale and learn about building out the hydrogen system we can get all those costs down to competitive levels, maybe within 5-8 years.
>
> ***Lewis M. Fulton, UC Davis***

The Role of Government

Governments have a crucial role to play in providing the regulation and incentives needed to ensure that companies and customers are able and willing to pay higher costs and take on financial risk during the valley of death period. Many governments, utilities, and other organizations are already stepping up at both national and regional levels by offering a range of

supportive policy and incentives to facilitate the transition (DOE, 2021; EPA, 2023; CARB, 2023; ICCT, 2019).

We have to make sure customers are willing to pay more to improve the environment. It might not cost much more, and if so, many customers may be willing to pay the premium, or perhaps a government policy will put a thumb on the scale. But if the customers' choice is to always accept the lowest bid, it may be hard to introduce some environment-friendly technologies.

William H. Green, MIT

First-mover Advantage

While initiating a shift to alternative fuels and powertrains comes with risk and uncertainty, it also comes with compelling opportunities for first mover advantage. Alternative charging and refueling infrastructure can take years to build, often slowed by permitting delays (Nelder & Rogers, 2019). Companies and fleets that take a forward-looking approach by anticipating their future needs and beginning to transition their infrastructure, networks, and operations today have an opportunity to position their operations to adapt and thrive as the wider market shifts to these alternatives in the coming years.

There are heavy-vehicle incentive programs in California, but currently not with enough funding for those programs to cover the necessary number of vehicles. But with sufficient funding they may help in bridging the valley of death.

Lewis M. Fulton, UC Davis

To support fleets in taking the first-mover role, many governments at both local and federal levels are implementing a diverse range of incentives and policies to support fleets in bridging the valley of death period (AFDC, 2023). It is likely that these supportive measures will not cover the full trucking fleet, however, and will gradually diminish as alternative fueling and charging infrastructure becomes more ubiquitous and up-front costs become competitive in the free market.

Where Do We Begin?

So how can fleet owners overcome decision paralysis, navigate the valley of death, and position their fleets to thrive as the industry transitions to alternative fuels and powertrains?

1. Identify available incentives and support

We need to figure out where the money is flowing from the government in order to accelerate progress. Can we build consortia to pool expertise and resources? Let's get big partnerships moving, so that there's enough capital investment on the backend to ensure success.

Joel van Rensburg, Vontier

In the U.S. alone, the DOE's Alternative Fuels and Data Center (AFDC, 2023) lists over 100 incentives, regulations, and programs at the federal level to support fleets in transitioning to alternative fuels and powertrains. In addition, most states offer dozens of state-level incentives. Fleet owners can start by identifying and applying for incentives and funding sources available to them.

2. Provide comprehensive tools to support fleet owners

It's important to consider many companies have ESG goals and metrics. And then provide the tools that can help them to calculate their potential CO_2 emissions reductions from alternative fuels, against the costs of refueling today and in the future. In other words, for a fleet: how do you understand where your costs are, and where the biggest opportunities are for making improvements on the ESG front? There needs to be some financial model to determine what the right solution is for them.

Joel van Rensburg, Vontier

Fleet owners need access to comprehensive and user-friendly tools to support their decision-making process. Tools should enable targeted analysis of each fleet to optimize where and how best to transition their fleets based on details of their typical operations, payloads, and operating regions.

3. Start with the low-hanging fruit

The easy lower-hanging fruit is the short-haul deliveries. Real long-haul in the US needs infrastructure in lots of states all across the country. It needs government support or some consortium of a lot of customers who are going to pay a lot to put it all in.

William H. Green, MIT

It may not be necessary or even desirable in many cases to transition an entire fleet simultaneously. Fleet owners can instead start by identifying the "low-hanging fruit" - i.e., which routes and operations serviced by their fleets can be readily transitioned at minimal up-front cost and risk. While the details of which alternative to transition to and where may be highly contextual, Table 1 summarizes some common features that can make a given route or

operation particularly amenable to transitioning to alternative fuels and powertrains in the short term.

Table 1: Common features of trucking routes and operations that are amenable to transitioning to alternative fuels and powertrains in the near future

Feature	What makes this feature favorable
Pre-existing infrastructure to support recharging or refueling	Minimizes up-front costs and risks associated with procuring infrastructure and a reliable supply of alternative fuel or power.
Short distances between hubs or refueling stations	Alleviates the risk of fuel/power shortages and associated range anxiety among truck drivers.
Well-defined routes and schedules	Operations with well-defined routes and schedules make it easy to plan and deploy charging and refueling infrastructure needed by the fleets.
Light payloads (by mass or volume)	Trucks that consistently carry payloads well below either their maximum gross vehicle weight or volume capacity are well suited to accommodate the added weight or volume associated with some alternative fuels and powertrains.
Supportive policy and incentives	Many regional governments and utilities have developed strong policy and generous incentives to support the purchase and operation of alternative vehicles and infrastructure. Targeting areas where fleet owners can take advantage of these policies and subsidies can help keep up-front costs and financial risks manageable.

4. Take advantage of resource pooling opportunities

There is an opportunity for industry stakeholders to work collaboratively by pooling demand and resources to collectively lower the barriers to transition. In areas that lack public charging or refueling stations, freight providers can partner to identify shared corridors and operations and either share infrastructure installation costs, or advocate for increased public infrastructure spending along these high-traffic routes.

For companies that contract freight transport to third-party providers, a first step could involve partnering with other companies that use the same providers. Together, they can support these shared providers through collective investments in alternative vehicles and infrastructure.

5. Be prepared to adapt as the technology evolves

Battery and fuel cell technologies are continuing to evolve, and the transition is evolving with them. Are there any breakthroughs that really are going to flip the equation? Looking ahead to the extent we can, can we see how that technology is going to evolve? There's no blueprint here; it's exciting but unchartered territory, and we need to be prepared to adapt where we can.

Nate Valaik, Vontier *(study panel participant)*

The technology involved in virtually every aspect of the transition to alternative fuels and powertrains is evolving rapidly. Companies should capitalize on first-mover advantage as much as possible and start deploying alternative fleets and infrastructure where feasible. But at the same time, it's important to closely monitor how the technology and its wider deployment are evolving.

Lastly, it's important to bear in mind that today's trucking networks, including locations of hubs, truck stops and trucking schedules, were built around and optimized for diesel combustion. While there are opportunities to deploy alternative fuels and powertrains within the existing networks, ultimately the networks will themselves need to evolve in the future to optimally accommodate the new technologies. For example, overnight charging will likely be an important component of operating electrified trucking fleets (Whitehead et al., 2020), potentially requiring upgrades to local power grid infrastructure. It may also be beneficial to move towards more closely-spaced truck stops and refueling stations to reduce the sizes of batteries and hydrogen tanks that trucks need to carry.

Tools and Databases to Support Trucking Fleets

The above discussion highlights an urgent need for tools to support trucking fleet owners in navigating the transition to alternative fuels and powertrains. While continued development is needed to this end, Table 2 summarizes the tools that are currently available to support fleet owners in their decision making.

Table 2: Summary of tools and databases currently available to support trucking fleet owners in navigating the transition to alternative fuels and powertrains.

Resource	Database	Tool	Summary
Fleet Procurement Analysis Tool	No	Yes	Spreadsheet tool to compare a variety of makes and models between ICE, BEV and PHEV engines, including heavy-duty trucks. Maintained by ATLAS Public Policy.
Summary of U.S. federal laws and incentives	Yes	No	Summary of U.S. federal incentives, laws and regulations related to alternative fuels, vehicles and powertrains. Produced by the U.S. DOE

			Office of Energy Efficiency and Renewable Energy.
Summary of U.S. state-level laws and incentives	Yes	No	Summary of U.S. state-level incentives, laws and regulations related to alternative fuels, vehicles and powertrains. Produced by the U.S. DOE Office of Energy Efficiency and Renewable Energy.
Alternative fueling station locator	Yes	Yes	Geospatial data and visualization tool to locate alternative fueling stations along U.S. corridors. Produced by the U.S. DOE Office of Energy Efficiency and Renewable Energy.
Electric Vehicle Infrastructure Projection Tool (EV-Pro) Lite	Yes	Yes	Regional electric charging load profile estimator. Produced by the U.S. National Renewable Energy Laboratory.
Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool	No	Yes	Estimates emissions and costs associated with transitioning diesel-powered heavy duty vehicle fleets to EV or natural gas. Produced by Argonne National Laboratory.
JOBS models	No	Yes	Estimates the economic impacts of the development, construction, and operations of charging and alternative refueling stations. Produced by Argonne National Laboratory.
Geospatial decision support tool for heavy-duty vehicle fleets	No	Yes	Geospatial mapping tool to support fleet owners in assessing where and how to transition their fleets to alternative fuels and powertrains. In development within the MIT Climate & Sustainability Consortium - contact: Danika MacDonell (danikam@mit.edu).

Summary of MIT Climate & Sustainability Consortium Research Related to Decarbonizing Heavy Duty Trucking

Electrified trucking logistics

Summary: Developing an electrified logistics and optimization model for commercial trucking, including both vehicle routing and charging infrastructure placement.

Team: Professor Alexandre Jacquillat, Sean Lo, Andrea Zanon

Contact: Professor Alexandre Jacquillat (alexjacq@mit.edu)

Liquid organic hydrogen carriers for hydrogen trucking

Summary: Advancing the concept of distributing and storing hydrogen in the form of room-temperature liquid organic hydrogen carriers (LOHCs) by developing and a heat-integrated on-board LOHC dehydrogenation unit.

Team: Professor William H. Green, Professor Wai Cheng, Sayandeep Biswas, Kariana Andrea Moreno Sader

Contact: Professor William H. Green (whgreen@mit.edu)

Hydrogen storage solutions for long-haul trucking

Summary: Studying onboard hydrogen storage solutions for long-haul trucks. This work explores alternative storage configurations to maximize storage capacity, considering practicalities such as driver comfort and sleeping space.

Team: Professor Amos Winter, ZhiYi Liang

Contact: Professor Amos Winter (awinter@mit.edu)

Geospatial decision support tool for trucking fleet decarbonization

Summary: Geospatial decision support tool help trucking fleets assess how best to decarbonize their fleets by transitioning to alternative fuels and powertrains, accounting for regionality.

Team: Danika MacDonell, Florian Allroggen, Micah Borerro

Contact: Danika MacDonell (danikam@mit.edu)

References

Abdin, Z. *et al.* Large-Scale Stationary Hydrogen Storage via Liquid Organic Hydrogen Carriers. *iScience*, **24**, 9, 102966 (2021). https://doi.org/10.1016/j.isci.2021.102966

Biery, M. E. Trucking Companies Hauling in Higher Sales. *Forbes* (4 Mar. 2018). www.forbes.com/sites/sageworks/2018/03/04/trucking-companies-hauling-in-higher-sales/?sh=21a076aa3f27

Biswas, S. et al. Perspective on Decarbonizing Long-Haul Trucks Using Onboard Dehydrogenation of Liquid Organic Hydrogen Carriers. *Energy & Fuels* (2023). https://doi.org/10.1021/acs.energyfuels.3c01919

Borlaug, B. *et al.* Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems. *Nature Energy* **6**, 673–682 (2021). https://doi.org/10.1038/s41560-021-00855-0

California Air Resources Board. California approves groundbreaking regulation that accelerates the deployment of heavy-duty ZEVs to protect public health. (2023, April 28). https://ww2.arb.ca.gov/news/california-approves-groundbreaking-regulation-accelerates-deployment-heavy-duty-zevs-protect

Cunanan, C. *et al.* A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. *Clean Technologies* **3**, 474–489 (2021). https://doi.org/10.3390/cleantechnol3020028

Dolan, R. *et al*. A Outlook for ammonia as a sustainable transportation fuel. *Sustainable Energy & Fuels* **5**, 4830-4841 (2021). https://doi.org/10.1039/D1SE00979F

Gray, N. *et al.* Batteries, fuel cells, or engines? A probabilistic economic and environmental assessment of electricity and electrofuels for heavy goods vehicles. *Advances in Applied Energy*, **8**, 100110 (2022). https://doi.org/10.1016/j.adapen.2022.100110

International Council on Clean Transportation. CO2 Standards for Heavy-Duty Vehicles in the European Union. *Policy Update* (Apr. 2019). https://theicct.org/sites/default/files/publications/CO2%20HDV%20EU%20Policy%20Update%202019_04_17.pdf

International Energy Agency. Global final energy demand for trucks and buses by fuel, 2000-2021, and 2030 in the Net Zero Scenario (22 Sep. 2022). https://www.iea.org/data-and-statistics/charts/global-final-energy-demand-for-trucks-and-buses-by-fuel-2000-2021-and-2030-in-the-net-zero-scenario

International Energy Agency. Global EV Outlook 2023: Catching up with Climate Ambitions (2023). https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf

Iyer, R. K. *et al*. Vehicle-cycle and life-cycle analysis of medium-duty and heavy-duty trucks in the United States. *Science of the Total Environment*, **891**, 164093 (2023).

https://doi.org/10.1016/j.scitotenv.2023.164093

Kalt, G. *et al.* Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different food-system pathways. *Environmental Research Letters,* **15** 034066 (2020). https://doi.org/10.1088/1748-9326/ab6c2e

Lehtveer, M. *et al*. What Future for Electrofuels in Transport? Analysis of Cost Competitiveness in Global Climate Mitigation. *Environmental Science & Technology,* **53**, 3, 1690–1697 (2019). https://doi.org/10.1021/acs.est.8b05243

Li, J. *et al*. A Review on Combustion Characteristics of Ammonia as a Carbon-Free Fuel. *Frontiers in Energy Research.* **9** (2021). https://doi.org/10.3389/fenrg.2021.760356

Mauler *et al*. Cost-effective technology choice in a decarbonized and diversified long-haul truck transportation sector: A U.S. case study. *Journal of Energy Storage* **46**, 103891 (2022). https://doi.org/10.1016/j.est.2021.103891

Megia *et al*. Hydrogen Production Technologies: From Fossil Fuels toward Renewable Sources. A Mini Review. *Energy Fuels*, **35**, 20, 16403–16415 (2021). https://doi.org/10.1021/acs.energyfuels.1c02501

Modisha et al. The Prospect of Hydrogen Storage Using Liquid Organic Hydrogen Carriers. *Energy Fuels*, **33**, 4, 2778–2796 (2019). https://doi.org/10.1021/acs.energyfuels.9b00296

Nelder, C. and Rogers, E. Reducing EV Charging Infrastructure Costs. *Rocky Mountain Institute* (2019). https://rmi.org/insight/reducing-ev-charging-infrastructure-costs/

U.S. DOE. DOE Announces $162 Million to Decarbonize Cars and Trucks. (2021, April 15). https://www.energy.gov/articles/doe-announces-162-million-decarbonize-cars-and-trucks

U.S. DOT Federal Highway Administration. The Freight Story: Freight Transportation Today (23 Mar. 2020). https://ops.fhwa.dot.gov/freight/publications/fhwaop03004/today.htm

U.S. DOT Federal Motor Carrier Safety Administration. Pocket Guide to Large Truck and Bus Statistics (Dec. 2022). https://www.fmcsa.dot.gov/safety/data-and-statistics/commercial-motor-vehicle-facts

U.S. DOE Office of Energy Efficiency & Renewable Energy. FOTW #1272, January 9, 2023: Electric Vehicle Battery Pack Costs in 2022 Are Nearly 90% Lower than in 2008, according to DOE Estimates. (Jan. 9, 2023). https://www.energy.gov/eere/vehicles/articles/fotw-1272-january-9-2023-electric-vehicle-battery-pack-costs-2022-are-nearly

U.S. DOE Office of Energy Efficiency & Renewable Energy. Alternative Fuels Data Center: Federal and State Laws and Incentives. (Accessed August 18, 2023). https://afdc.energy.gov/laws

U.S. EPA Office of Transportation and Air Quality. Proposed Standards to Reduce Greenhouse Gas Emissions from Heavy-Duty Vehicles for Model Year 2027 and Beyond Regulatory Announcement (Apr. 2023). https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P101762L.pdf

Whitehead, J. *et al*. Exploring public charging infrastructure requirements for short-haul electric trucks, *International Journal of Sustainable Transportation*, **16**, 9, 775-791 (2022). https://doi.org/10.1080/15568318.2021.1921888

Xu, H. *et al*. Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. *Environmental Science & Technology,* **56**, 7512−7521 (2022). https://doi.org/10.1021/acs.est.2c00289