CALIFORNIA AIR RESOURCES BOARD

2022 TECHNOLOGY ASSESSMENT: NON-TRUCK TRANSPORT REFRIGERATION UNITS (TRU)

Trailer TRUs, Domestic Shipping Container TRUs, Railcar TRUs, and TRU Generator Sets

October 2022

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Acronyms

2022 Amendments	2022 Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU), TRU Generator Sets, and Facilities where TRUs Operate
AB	Assembly Bill
AC	Alternating Current
CARB or Board	California Air Resources Board
CORE	Clean Off-Road Equipment Voucher Inventive Program
DC	Direct Current
GHG	Greenhouse Gas
hp	Horsepower
hr	Hour
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-Hour
lb.	Pound
LCO2	Liquid Carbon Dioxide
LN2	Liquid Nitrogen
MJk	Megajoule per Kilogram
Non-Truck TRUs	Trailer TRUs, Domestic Shipping Container TRUs, Railcar TRUs, and TRU Generator Sets
NOx	Oxides of Nitrogen
OOS	Out-of-state
PEM	Polymer Electrolyte Membrane or Proton Exchange Membrane (Hydrogen Fuel Cell)
PM	Particulate Matter
PM2.5	Fine Particulate Matter (<2.5 Microns)
SB	Senate Bill
TRU	Transport Refrigeration Unit

TRU ATCM	2004 Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
V	Volt
yr	Year
ZEV	Zero-Emission Vehicle

Introduction

This document was prepared by California Air Resources Board (CARB or Board) staff to assess available and developing zero-emission technologies for trailer transport refrigeration units (TRU), domestic shipping container TRUs, railcar TRUs, and TRU generator sets (collectively referred to as non-truck TRUs).

Background for the 2022 Technology Assessment

This chapter provides background information on the purpose of the 2022 Technology Assessment: Non-Truck Transport Refrigeration Units (TRU) – Trailer TRUs, Domestic Shipping Containers TRUs, Railcar TRUs, and TRU Generator Sets (2022 Technology Assessment) and the process used to develop the assessment. It also provides a brief description of the elements CARB staff evaluated for each zero-emission technology for non-truck TRUs.

TRUs

TRUs are refrigeration systems powered by integral (inside the TRU housing) diesel engines. The refrigeration systems are used to control the environment of temperature-sensitive products transported in insulated trucks, trailers, shipping containers, or railcars. TRU generator sets are internal combustion engine-powered generators designed to provide power to electrically driven refrigeration units. TRUs emit diesel particulate matter (PM), fine particulate matter (PM2.5), oxides of nitrogen (NOx), and greenhouse gases (GHG) while in transit and during stationary operation at refrigerated warehouses or distribution centers, grocery stores, seaport facilities, intermodal railyards, and other locations of operation. These locations are often near sensitive receptors, such as schools, hospitals, elder care facilities, and residential neighborhoods.

California Regulations and Policy Related to TRUs

To help meet the State's air quality and climate change goals, the Board adopted the existing *Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU), TRU Generator Sets, and Facilities where TRUs Operate* (TRU ATCM) in 2004 (amended in 2010, 2011, and 2022) to reduce diesel PM emissions.[1,2] In 2015, CARB staff developed the Technology Assessment: Transport Refrigerators that focused on assessing

[1] Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate, 13 CCR § 2477 (2022). *https://govt.westlaw.com/calregs/Document/I95479DD0181211EDB2198818E412AA21?originationContext=document&transitionType=StatuteNavigator&needToInjectTerms=False&viewType=FullText&ppcid=24a439acc68445eaa22ebeab1cace0a8&t_T1=13&t_T2=2477&t_S1=CA%20ADC%20s&bhcp=1&contextData=%28sc.Default%29*

[2] For more information on the TRU regulation, please visit: *https://ww2.arb.ca.gov/rulemaking/2021/tru2021*

conventional and advanced technologies available to meet the State's long-term objective to transform TRUs to zero-emission and near-zero emission technologies.[3]

Despite the progress made, TRU emissions still contribute to health risks and must be further reduced to protect nearby communities. In September 2020, Governor Newsom issued Executive Order N-79-20, which directs CARB, in coordination with other State agencies, United States Environmental Protection Agency (U.S. EPA), and local air districts, to develop and propose technologically feasible and cost-effective strategies to achieve 100 percent zero-emission operation for off-road vehicles and equipment in the State by 2035. The State also passed Assembly Bill (AB) 617 in 2017.[4] AB 617 is a significant piece of air quality legislation that highlights the need for further emission reductions in communities with high exposure burdens.

To meet the goals of Governor's Executive Order (EO) N-79-20, the Board adopted amendments to the TRU ATCM (2022 Amendments) in February 2022 to start transitioning TRUs to zero-emission. The 2022 Amendments require a lower global warming potential for refrigerant, set a more stringent PM emission standard, and mandate the transition of truck TRUs to zero-emission.[5,6]

Purpose of the 2022 Technology Assessment

The 2022 Technology Assessment evaluates the current and projected state of zero-emission technologies for non-truck TRUs. CARB staff are developing the 2022 Technology Assessment to assess new TRU technologies that can eliminate emissions, and to inform and support CARB planning and regulatory actions, including:

- California Sustainable Freight Action Plan[7]
- 2020 Mobile Source Strategy[8]
- State Implementation Plan development[9]

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[3] California Air Resources Board. (2015). *Technology Assessment: Transport Refrigerators*. CARB. *https://ww2.arb.ca.gov/sites/default/files/2020-06/TRU%20Tech%20Assessment%20Report%20ada.pdf*

[4] Assembly Bill 617, Cristina Garcia. Nonvehicular air pollution: criteria air pollutants and toxic air contaminants. (CA. 2017). *https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB617*

[5] Beginning December 31, 2022, newly-manufactured truck TRUs, trailer TRUs, and domestic shipping container TRUs shall use refrigerant with a global warming potential (GWP) less than or equal to 2,200, or no refrigerant at all.

[6] Beginning December 31, 2022, model year 2023 and newer trailer TRU, domestic shipping container TRU, railcar TRU, and TRU generator set engines shall meet a PM emission standard of 0.02 grams per brake horsepower hour or lower (aligns with U.S. EPA's Tier 4 final off-road PM emission standard for 25-50 horsepower engines).

[7] California Department of Transportation, et al. (2016 July). *California Sustainable Freight Action Plan*. DOT. *https://ww2.arb.ca.gov/sites/default/files/2019-10/CSFAP_FINAL_07272016.pdf*

[8] California Air Resources Board. (2021, April 23). *Revised Draft 2020 Mobile Source Strategy*. CARB. *https://ww2.arb.ca.gov/sites/default/files/2021-04/Revised_Draft_2020_Mobile_Source_Strategy.pdf*

[9] California Air Resources Board. (n.d.). *California State Implementation Plans*. CARB. *https://ww2.arb.ca.gov/our-work/programs/california-state-implementation-plans*

- California's Climate Change Scoping Plan[10]
- California Zero-Emission Vehicle (ZEV) Market Development Strategy and CARB ZEV Action Plans (2013, 2016, 2018)[11]
- The California Energy Commission's AB 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support ZEVs in 2030[12]
- Funding Plans including AB 617 Community Air Protection Incentives, Low Carbon Transportation Investments, and Proposition 1B: Goods Movement Emissions Reduction Program[13,14,15]
- Senate Bill (SB) 100 Joint Agency (California Energy Commission, California Public Utilities Commission, and CARB) Report – "The 100 Percent Clean Energy Act of 2018"[16] which sets the goal of zero-carbon electricity sales to customers by 2045
- California's coordinated goals to reduce greenhouse gases and to meet the statewide goal to achieve carbon neutrality no later than 2045 and maintain net negative emissions thereafter[17]

The 2022 Technology Assessment focuses on zero-emission technologies applicable to non-truck TRUs because CARB adopted amendments in February 2022 that require truck TRUs to transition to zero-emission. Some of the technologies are commercially available while others are still in development. The zero-emission technologies assessed include:

- Batteries (lithium-ion)
- Hydrogen fuel cells
- Cryogenics
- Cold plates

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[10] California Air Resources Board. (2017, November). *California's 2017 Climate Change Scoping Plan. CARB.* *https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/scoping_plan_2017.pdf*

[11] Governor's Office of Business and Economic Development. (2021). *ZEV Action Plan History*. Go-Biz. *https://business.ca.gov/industries/zero-emission-vehicles/zev-action-plan*

[12] California Energy Commission (2021, July). *Electric Vehicle Charging Infrastructure Assessment – AB 2127*. CEC. *https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127*

[13] California Air Resources Board. (2021). *Community Air Protection Incentives*. CARB. *https://ww2.arb.ca.gov/our-work/programs/community-air-protection-incentives*

[14] California Air Resources Board. (2021). *Low Carbon Fuel Standard*. CARB. *https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard*

[15] California Air Resources Board. (2021). *Proposition 1B: Goods Movement Emissions Reduction Program*. CARB. *https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard*

[16] California Energy Commission (2021, March). *SB 100 Joint Agency Report*. CEC. *https://www.energy.ca.gov/sb100*

[17] Executive Department State of California. (2018, September 18). *Executive Order B-55-18, State of California Executive Order signed by Governor Edmund G. (Jerry) Brown Jr*. Executive Department State of California. *https://www.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf*

The 2022 Technology Assessment also assesses supporting technologies that include:

- Regenerative braking systems and solar assist
- Telematics

Process for Developing the 2022 Technology Assessment

Staff conducted a literature search for each prospective technology. Staff also interviewed people with knowledge and expertise in advanced technologies from various institutions, such as national laboratories, university researchers, technology experts, original equipment manufacturers, dealers, zero-emission fuel suppliers, electric power companies, and engineering consultants. The 2022 Technology Assessment incorporates public input.

During development of the draft Technology Assessment, staff hosted a technology-focused, virtual workshop on May 17, 2022 where CARB staff solicited comments, data, and feedback to help inform development of the 2022 Technology Assessment. CARB staff requested additional input and information from operators and original equipment manufacturers on zero-emission technology demonstration projects and costs, as well as other related technical information.

The draft Technology Assessment also included call-out boxes specifying the data that CARB staff were seeking.

CARB staff received some comments that were considered for this document. Staff will continue to gather information on zero-emission technology demonstration projects and costs, as well as other related technical information to further assess the state of zero-emission technology. **If you have information on these topics to share, please submit to *freight@arb.ca.gov*.**

2022 Technology Assessment Elements

The 2022 Technology Assessment discusses each of the zero-emission TRU technologies independently. As outlined in the 2022 Technology Assessment Elements section, a set of elements is commonly discussed within each zero-emission technology section of this document. For each technology, the 2022 Technology Assessment includes and addresses the elements listed below.

1. Technology Description – A description of the technology and how it works.
2. Technology Readiness – A description of the stage of technology development (e.g., research and development, prototype/pilot demonstration, pre-commercial demonstration, or commercially available), a discussion of the scope of commercial introduction (number in use) and how widely available it is (where; what classes of fleets/applications), and a complete list of demonstration projects is included in Appendix A).
3. Emissions Benefits – A discussion of the emissions benefits for criteria air pollutants and GHGs that can be achieved from the operation of the technology.

4. Infrastructure Requirements – A description of the supporting infrastructure, how it supports the technology, and an assessment of the current landscape.
5. Economics – A discussion of costs (e.g., capital, operational, maintenance, infrastructure), if known, at current production levels and a comparison to diesel costs, and a discussion of potential returns on investment or payback period. Programs that may offer funding for zero-emission engines, equipment, or infrastructure are included in Appendix B.
6. Technology Outlook – A description of the advantages and challenges of the technology and any issues that may impact the technology's deployment or become a barrier to commercialization.

I. Overview of Transport Refrigeration Units

This chapter provides an overview of different classes of non-truck TRUs, the population and emissions of non-truck TRUs operating in California, and non-truck TRU operational characteristics.

Non-Truck TRU Classes

Table 1 summarizes general operations for the four classes of non-truck TRUs, including trailer TRUs, domestic shipping container TRUs, railcar TRUs, and TRU generator sets.

Table 1: Summary of General Operations for Non-Truck TRUs, by Class

Non-Truck TRU Class	Mode of Transportation	Operational Route	Horsepower (hp)[18]	Container Size (length)[19]
Trailer TRU	On-road or rail	Short-haul, long-haul, regional	23-35 hp	28 to 53 feet
Domestic Shipping Container TRU	On-road or rail	Long-haul	23-35 hp	20 to 40 feet
Railcar TRU	Rail	Long-haul	23-35 hp	64 to 72 feet[20]
TRU Generator Set	On-road or rail for temperature-controlled ocean containers	Short-haul, long-haul, regional	23-35 hp	20 feet or 40 feet

Trailer TRUs

Trailer TRUs (Figure 1) are used to control the environment of temperature-sensitive freight transported in semi-trailers that have integrated wheels and detach from the truck cab (tractor). Trailer TRUs are mainly transported by a tractor but can also be transported by rail on a flatbed railcar. They often have longer loading times due to larger cargo capacity. Trailer TRUs can be used for short-haul, long-haul, or regional operations.

Short-haul operations occur most commonly within an urban area or region and can be completed in a day. A short-haul operation can have frequent stops and door openings. After completing a short-haul route, the driver generally returns to base to refuel. Long-haul trips generally occur from one pick-up point, normally a warehouse, to one or multiple delivery points. A long-haul route can take up to several days and can consist of interstate travel.

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[18] California Air Resources Board. (2019, October). *Draft 2019 Update to Emissions Inventory for Transport Refrigeration Units*. CARB. https://ww2.arb.ca.gov/sites/default/files/classic/cc/cold-storage/documents/hra_emissioninventory2019.pdf

[19] Container size impacts the horsepower needed for the non-truck TRU.

[20] Union Pacific (2021, September 7). *What is a Boxcar Rail Car?* UP. https://www.up.com/customers/track-record/tr081721-what-is-a-boxcar-rail-car.htm

While en route, trailer TRUs can refuel at truck stops, gas stations, or are refueled using a fuel delivery service. Regional routes can be either short-haul or long-haul, can consist of an overnight stay, and the term is defined differently from fleet to fleet.

Trailer TRUs generally operate at refrigerated warehouses or distribution centers, grocery stores, seaport facilities, intermodal railyards, truck stops, and other locations. Time spent at each location varies depending on how long it takes to dock, unload, and load if needed.

Some fleets have multiple temperature-controlled trailers (trailers) per tractor, which means the TRU might operate without the tractor in proximity, such as in "drop and hook" logistical operations.[21]

Figure 1: Trailer TRU

Domestic Shipping Container TRUs

Domestic shipping container TRUs (Figure 2) are used to control the environment of temperature-sensitive products transported in domestic shipping containers that do not have integrated wheels. Domestic shipping containers travel on container chassis pulled by trucks or by rail on flatcars. In general, when transported by truck, domestic shipping containers are refueled by the truck driver at truck stops, gas stations, or are refueled using a fuel delivery service. When transported by rail, the cargo owner usually hires a third-party contractor to ensure the TRU has adequate fuel.

[21] One tractor-pulled fleet may drop off a trailer at the unloading site, disconnect, and then connect to a different trailer, referred to as "drop and hook." A new tractor or tractor belonging to a different fleet may later hook up to the trailer to haul it away. Drop and hook operations are a consideration for zero-emission technologies that potentially rely on the tractor to assist the TRU in some manner (e.g., provide electric power to the TRU).

Domestic shipping container TRUs are used in long-haul operations, visit other states to deliver or bring in loads, and generally do not return to a home base each night. Domestic shipping container TRUs generally operate at refrigerated warehouses or distribution centers, intermodal railyards, truck stops, and other locations.

Figure 2: Domestic Shipping Container TRU

Railcar TRUs

Railcar TRUs (Figure 3) are used to refrigerate railcars, a railway vehicle used for transportation. Temperature-controlled railcars (railcar) are similar to trailers in that the container is permanently integrated with the wheels, unlike domestic shipping containers, or temperature-controlled ocean containers (ocean container) that are loaded onto a mode of transportation with wheels.

Distribution routes are generally long-haul and may exceed a week. When in transit, railcar TRUs are generally unattended. Railcar TRUs operate at seaport facilities and intermodal railyards. The major railroads in California, BNSF Railway and Union Pacific, have railcar TRU operations at intermodal railyards throughout California. When railcar TRUs are parked at an intermodal railyard, cold chain suppliers who own or lease the railcars will often hire third parties to maintain, operate, and refuel their TRUs using fuel trucks.

Figure 3: Railcar TRU

TRU Generator Sets

TRU generator sets (generator sets) are designed and used to provide electric power to temperature-controlled ocean containers when they are not plugged into ocean-going vessel electric power or the electric grid at seaport facilities. Generator sets have three configurations: pin-on, under-slung, or powerpack.

1. Pin-on generator sets (Figure 4) are attached to the rear of the ocean container above the electrically-driven TRU to provide power. This configuration is convenient when changing from one mode of transportation to another since the power source does not change.
2. Under-slung generator sets (Figure 5) are clamped to the frame rails of a trailer chassis that is designed for the sole purpose of transporting domestic shipping containers on the roadway.
3. Powerpack generator sets (Figure 6) can be used to power multiple TRUs. Powerpack containers are loaded onto railcars and connected to multiple temperature-controlled shipping containers on adjacent railcars.

Generator sets are generally owned by the shipping companies and ocean carriers. Once off-loaded from the ocean-going vessel, owners work with a third-party or broker to move the ocean containers powered by the generator set to delivery locations either by truck or rail transport. On long truck routes, the driver refuels the generator set as needed.

Figure 4: Pin-on TRU Generator Set

Figure 5: Under-slung TRU Generator Set

Figure 6: Powerpack TRU Generator Set

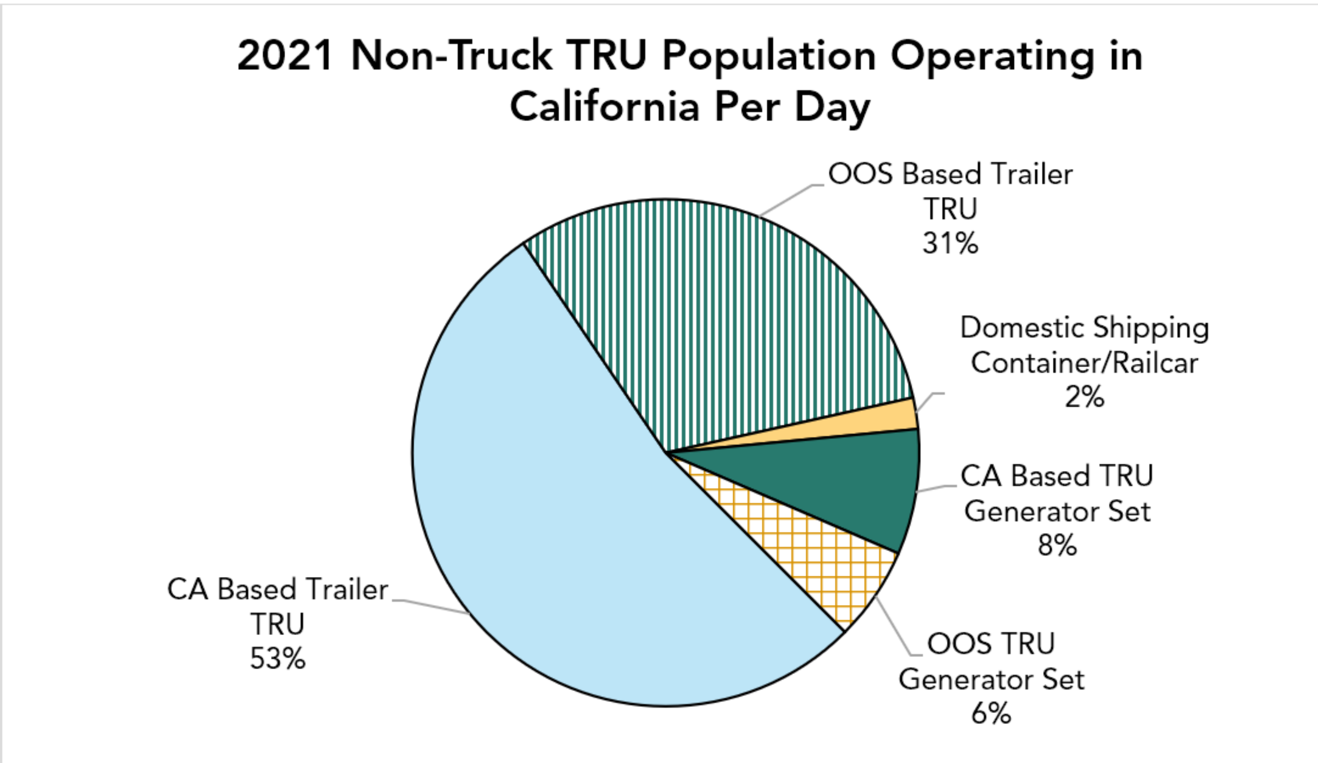
Population and Emissions Summary

Non-truck TRUs are conventionally powered by diesel engines which emit PM2.5, NOx, and GHGs. Communities near facilities where TRUs operate bear a disproportionate health burden due to their proximity to the emissions from non-truck TRUs.

PM2.5 pollution contributes to more fatalities than other air pollutants and can lodge deep in the lungs or pass through the lungs to enter the blood stream and affect the heart, brain, and other organs. Adverse health effects from long-term exposure to PM2.5 pollution include increased risk of heart attacks and heart disease, impaired lung development in children, the development and exacerbation of asthma, and premature death. NOx is a precursor to ozone, which can cause irritation and damage lung tissue, worsen asthma and chronic illnesses including obstructive pulmonary disease and reduce lung function. GHGs contribute towards climate change.

California's statewide emissions inventory includes emissions from truck and non-truck TRUs operating in California regardless of where the equipment is based.[22] Figure 7 provides a summary of the non-truck TRU population operating in California per day for 2021. The non-truck TRU population data presented are scaled up to account for TRUs which fail to report per TRU ATCM reporting requirements. The out-of-state (OOS) TRU population data are estimated by scaling up in-state TRU population data using CARB's on-road mobile source emissions inventory in-state versus out-of-state data. Figures 8 through 10 provide a summary of the emissions from non-truck TRUs operating in California for 2021.

Figure 7: Summary of California's Non-Truck TRU Population Operating in California Per Day for 2021[23,24]

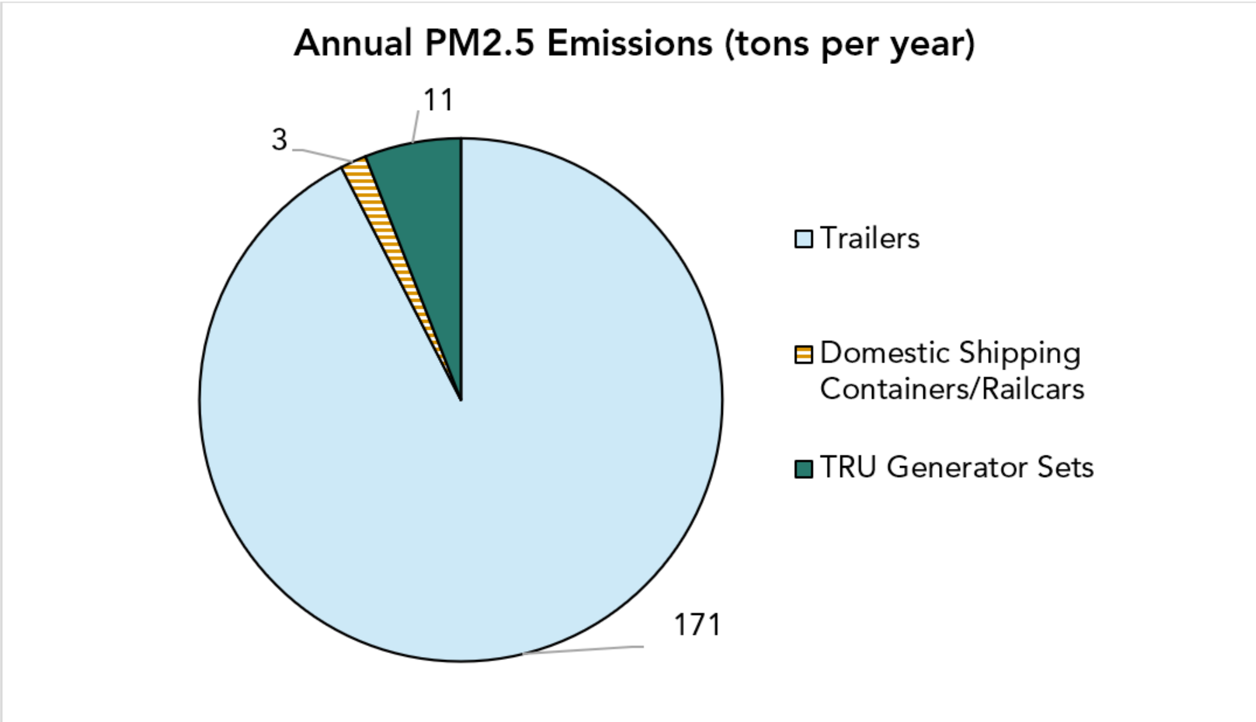


[22] Due to this document's focus on non-truck TRUs, the truck TRU population and emissions are not shown.

[23] California Air Resources Board. (2021, July 27). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: Data - Emission Inventory Programming and Inputs.* (Microsoft Access Database). https://ww3.arb.ca.gov/board/rulemaking/tru2021/apphdata.accdb

[24] California Air Resources Board. (2021, July). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: 2021 Update to Emissions Inventory for Transport Refrigeration Units.* CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/apph.pdf

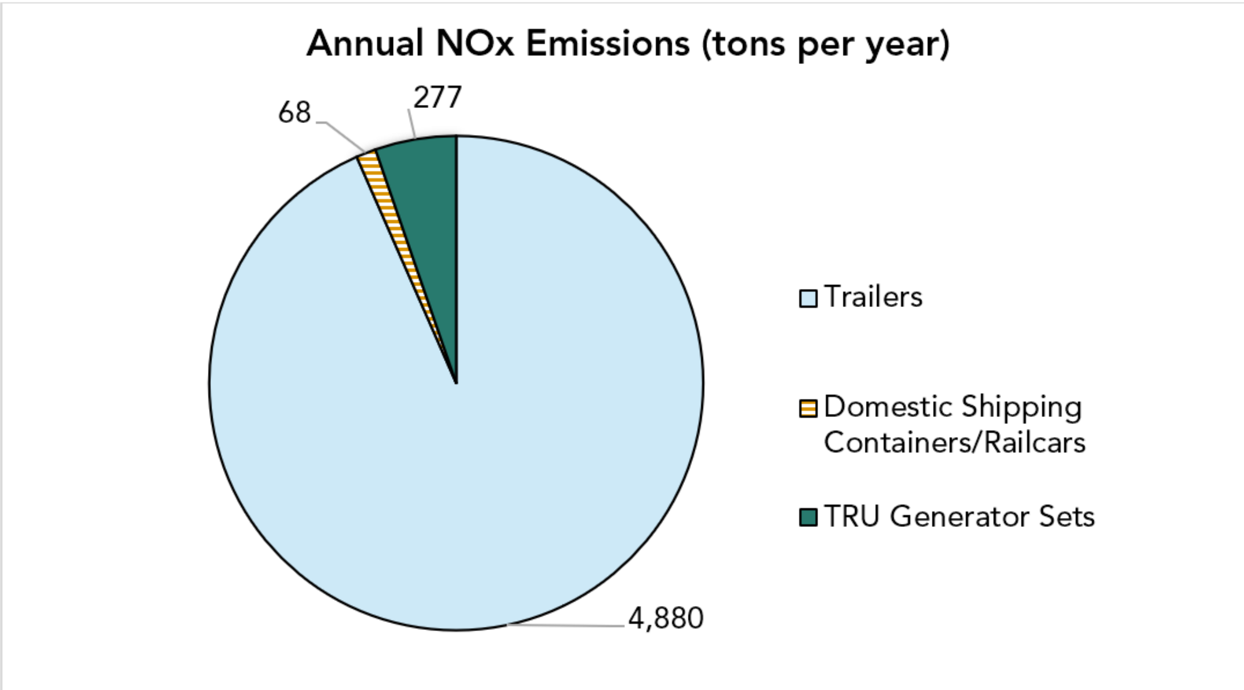
Figure 8: Summary of California Non-Truck TRU PM2.5 Emissions for 2021[25,26]



[25] California Air Resources Board. (2021, July 27). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: Data - Emission Inventory Programming and Inputs.* (Microsoft Access Database). *https://ww3.arb.ca.gov/board/rulemaking/tru2021/apphdata.accdb*

[26] California Air Resources Board. (2021, July). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: 2021 Update to Emissions Inventory for Transport Refrigeration Units.* CARB. *https://ww3.arb.ca.gov/board/rulemaking/tru2021/apph.pdf*

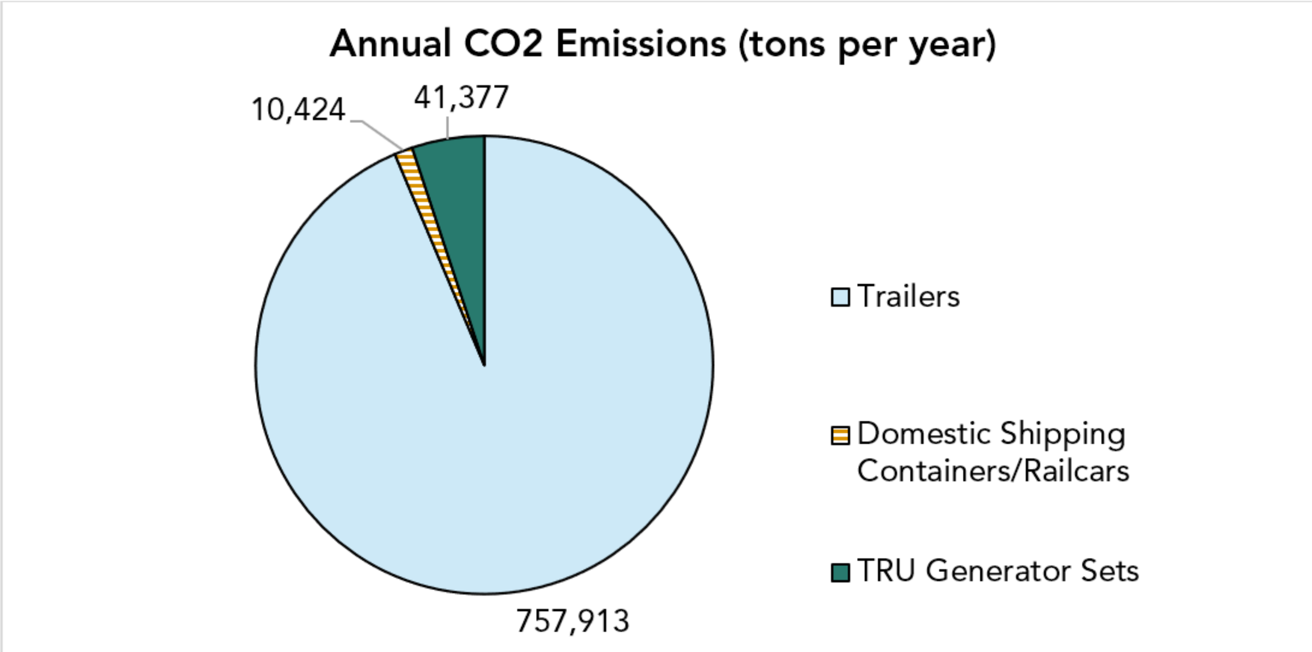
Figure 9: Summary of California Non-Truck TRU NOx Emissions for 2021[27,28]



[27] California Air Resources Board. (2021, July 27). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: Data - Emission Inventory Programming and Inputs.* (Microsoft Access Database). https://ww3.arb.ca.gov/board/rulemaking/tru2021/apphdata.accdb

[28] California Air Resources Board. (2021, July). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: 2021 Update to Emissions Inventory for Transport Refrigeration Units.* CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/apph.pdf

Figure 10: Summary of California Non-Truck TRU CO2 Emissions for 2021[29,30]



TRU Operational Characterization and Considerations

Various industries, including food (frozen and chilled), pharmaceuticals, florists, and more, utilize temperature-controlled transport to move their freight. TRUs may need to maintain temperatures while traveling through various environments and climates. Below is a summary of the capabilities and operational parameters TRUs need to meet to ensure the safe transportation of temperature-sensitive freight.

TRU Capabilities

Freight Temperature Control

TRUs are capable of being programmed to maintain an optimum set-point temperature for the product being hauled. In addition to cooling, TRUs can provide heat to defrost the evaporator or warm the cargo space to protect products from cold weather. TRUs can also

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[29] California Air Resources Board. (2021, July 27). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: Data - Emission Inventory Programming and Inputs.* (Microsoft Access Database). *https://ww3.arb.ca.gov/board/rulemaking/tru2021/apphdata.accdb*

[30] California Air Resources Board. (2021, July). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate: Staff Report: Initial Statement of Reasons, Appendix H: 2021 Update to Emissions Inventory for Transport Refrigeration Units.* CARB. *https://ww3.arb.ca.gov/board/rulemaking/tru2021/apph.pdf*

be programmed to shut off when the set-point temperature is reached, similar to a home refrigerator. Alternatively, they can maintain the set-point temperature while providing continuous air flow across the cargo space. Air flow disperses the heat of respiration generated by certain food products and ethylene gas emitted by many types of produce. Lack of air flow accelerates ripening and reduces shelf-life.

Fleet Management Technology

To ensure that TRU operations are as efficient as possible, there are advanced technological solutions available that enable fleet owners and operators of temperature-controlled trailers, shipping containers, and railcars to monitor their shipments. They also provide real-time updates that allow tracking of freight.

Fleet management technology is discussed further in Chapter II, *Complementary Technology*.

Key Operational Parameters

Ability to Perform Duty Cycle

TRUs must be capable of maintaining the optimum set point temperature to ensure product integrity, provide fast pull-down (pre-cool) to prepare the cargo space for loading, and recover quickly from door openings that occur on route.

Most transport refrigeration applications demand high performance cooling capacity and airflow. Delivery routes can require trailer doors to be opened frequently. Rapid cool-down after each stop is required and the additional fan and evaporator load for multiple cooling zones in a trailer also adds to the power demand on the engine. Original equipment manufacturers of TRUs regularly redesign most of their product lines to be more efficient and equipped with more sophisticated control systems.

Operating Range

For TRUs, range is the number of hours between refueling. Short-haul and regional operations, such as grocery and foodservice distribution, may require a minimum of 8 to 10 hours on average between refueling, for either continuous or start-stop engine operation. Some delivery routes involve numerous door openings for deliveries. Door openings allow temperatures inside the trailer, railcar, or shipping container to increase. Rising temperatures require the TRU to increase its operations to maintain the set temperature.

The standard size TRU diesel fuel tank is 50 gallons, which allows for approximately two-to-four days of TRU operation between refueling. However, a truck driver may only drive a maximum of 11 hours after 10 consecutive hours off duty per standards set by the Federal Motor Carrier Safety Administration.[31] For long-haul operations, a driver may use their break

[31] Federal Motor Carrier Safety Administration. (2020, September 28). *Summary of Hours-of-Service Regulations.* FMCSA. https://www.fmcsa.dot.gov/regulations/hours-service/summary-hours-service-regulations

to refuel. Long-haul operations generally have few if any door openings while en route which helps conserve fuel.

Payload Impacts

Maximizing the payload carrying capacity of a truck can improve the economics of moving freight. This applies to both available space and maximum weight.[32] Cargo space is the limiting factor for light, less dense freight. Freight weight is the limiting factor for heavier, dense freight.

Energy efficiency measures, such as extra insulation, may impact the available cargo space of the trailer while the weight of a battery-electric TRU may decrease the available payload capacity of the trailer.[33] AB 2061 (2018) partially addressed weight issues for zero-emission equipment by increasing the gross vehicle weight allowance by up to 2,000 pounds.[34] However, this extra weight allowance was for a zero-emission or near zero-emission powered vehicle and did not address the extra weight that may be associated with a zero-emission trailer TRU.

Fuel Infrastructure Availability

Infrastructure throughout California is needed to support zero-emission technologies for all non-truck TRU classes and route types. Availability may influence a TRU owner's choice of zero-emission technology or how the fleet operates. The California Energy Commission has dashboards that provide locational information on chargers and hydrogen stations.[35]

Infrastructure for each zero-emission technology is discussed further in Chapter II, *Zero-Emission Technologies*.

Costs

Profit margins are generally slim in the food transport industry.[36] It is generally more expensive to transport temperature-sensitive products compared to dry goods. For the same size transport container of 40 feet, it can cost up to $25,000 more to transport temperature-sensitive goods compared to dry goods.[37] Capital costs of zero-emission TRUs

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[32] Truck weight laws are an additional consideration. California's max gross weight for truck operations is 80,000 pounds (lb.).

[33] Electric Power Research Institute. (2017). *Pacific Gas and Electric Company (PG&E) Electrification Case Study Report*. EPRI.

[34] Assembly Bill 2061, Fraizer. Near-zero-emission and zero-emission vehicles. (CA. 2018). *https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180AB2061*

[35] California Energy Commission. (2022). *Dashboards include Hydrogen Refueling Stations in California*. CEC. *https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/hydrogen-refueling* and Electric Vehicle Chargers in California*https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/electric-vehicle*

[36] California Air Resources Board. (2015). *Technology Assessment: Transport Refrigerators*. CARB. *https://ww2.arb.ca.gov/sites/default/files/2020-06/TRU%20Tech%20Assessment%20Report%20ada.pdf*

[37] Winnesota. (2017, November 28). *What Is Refrigerated Transportation And How Is It Changing The World Around Us?* Winnesota. *https://www.winnesota.com/news/refrigeratedtransportation*

must be reasonable to stay within budget, provide a short time for return of investment, and avoid creating a financial obstacle.

Diesel fuel cost increases and volatility can create uncertainty in the long-term planning process.

Operation and maintenance costs are also important considerations which may influence a TRU owner's choice in zero-emission technology or influence fleet operations. The estimated overall maintenance cost for a diesel-powered TRU is $0.95 per hour of operation, or $1,900 per year if operating for 2,000 hours per year although the cost is dependent on the engine run time.[38] This maintenance cost estimate reflects the costs of routine maintenance, preventative maintenance, and repair of broken parts. Additional cost considerations for each technology are discussed in Chapter II, *Zero-Emission Technologies*.

General cost information for zero-emission technologies is also included in each technology section, where available. Additional detailed cost information was requested from industry, and CARB staff will continue to research cost information for the development of concepts for transitioning to zero-emission non-truck TRUs.

Reliability

TRUs have specialized diesel engines that meet more robust specifications than a general use off-road diesel engine. The TRU engine needs to withstand potential vibration impacts caused by roadway travel or potential long service intervals. Reliability is important because loads of perishable goods can be worth high value.

Safety

There may be potential safety risks associated with zero-emission technologies that should be evaluated and managed. Some zero-emission technologies can pose risk of electric shock, fire, or asphyxiation if handled incorrectly. Special training to ensure safe use of new technologies would be an additional expense, if needed. Another consideration is the analysis of current or development of future codes and standards related to zero-emission technologies such as electric batteries, hydrogen fuel cells, cryogenic fuels, or other zero-emission technologies. Establishment of codes and standards are important to help ensure uniformity of safe operation, handling, transport, and use. Another consideration is the ability of zero-emission technologies to allow compliance with Food Safety Modernization Act.

Noise Pollution

TRU operations produce noise that can be problematic when deliveries that often occur late evening or early morning are near residential neighborhoods, hotels, hospitals, and elder care facilities. Some noise ordinances can effectively ban TRUs from operating in diesel mode

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[38] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

during late evening or early morning hours.[39] One study conducted by LSA Associates found that a diesel-powered TRU operating at high idle produces an A-weighted decibel (dBA) noise rating of 104 dBA, while a diesel truck at idle produces a noise rating of 96 dBA.[40] Zero-emission technologies generally produce little to no noise.

Emission Pollution

Diesel-powered TRUs produce PM2.5, NOx, and GHG emissions, which contribute to community health risk, regional air pollution, and global climate change. These pollutants are emitted while in-transit and during stationary operation. Stationary TRU operations at facilities are often near sensitive receptors such as schools, hospitals, elder care facilities, and residential neighborhoods. CARB has rules that limit diesel truck and bus idling to five minutes and idling is not allowed at all within 100 feet of the property line of restricted areas such as schools, homes, hospitals, and senior and childcare facilities.[41] However, these anti-idling rules do not apply to the TRU. Addressing idling for TRUs is a challenge because the TRU must run to maintain temperatures.

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[39] Refrigerated Transporter (2008, October 1). *Engineers working to limit noise from trucks and trailers.* Refrigerated Transporter. *https://www.refrigeratedtransporter.com/fleet-equipment/components/article/21720140/engineers-working-to-limit-noise-from-trucks-and-trailers*

[40] LSA Associates, Inc. (2013 June). "Noise Impact Analysis". Bloomington Truck Terminal, LSA Project No. PAC1301. *http://www.sbcounty.gov/Uploads/lus/Valley/Pacific_Industrial/Noise.pdf*

[41] California Air Resources Board. (2020, July 23). Breathe easier, California! Turn off your engine [PDF]. AQMD. *https://www.aqmd.gov/docs/default-source/ab-617-ab-134/steering-committees/southeast-los-angeles/carb-factsheet-idling-july23-2020.pdf?sfvrsn=8#:~:text=CARB%20has%20rules%20that%20limit,to%20idle%20in%20restricted%20areas.*

II. Zero-Emission Technologies

eTRUs

Technology Description

An eTRU is a TRU that has an internal refrigeration system (e.g., compressor, condenser fans, evaporator-blower, etc.) that is electrically driven. Many TRUs today use an electrically-driven internal refrigeration system but rely on a full-time diesel generator to produce power. In contrast, eTRUs can be used with an electric power source instead of the diesel generator. There are generally three categories of eTRUs.

- An all-electric eTRU has no diesel engine and is a full-time zero-emission device.
- A hybrid-electric eTRU has an integrated diesel generator, which drives an electric motor that drives the refrigerator. The internal electric motor can either receive power from the internal diesel generator or can receive power by plugging into an external power source such as grid power electricity to drive the electric motor thus operating as a zero-emission device. The compressor of a hybrid-electric eTRU is always driven by an electric motor.[42]
- A standby-electric eTRU has integral refrigeration equipment that can be powered either directly by the integrated diesel engine, or an integrated electric motor. Unlike the hybrid-electric eTRU, the compressor can be driven by either the diesel internal combustion engine or the electric motor, depending on if it is plugged into an external power source such as grid power electricity. The standby-electric eTRU is similar to the hybrid-electric eTRU in that it also can be plugged into a zero-emission external power source to operate as a zero-emission device.

Hybrid-electric and standby-electric eTRUs contain a diesel internal combustion engine, so they are only considered to be zero-emission devices when operating without use of that engine. "eTRU-" for the 2022 Technology Assessment means zero-emission operation unless otherwise stated.

All-Electric eTRUs

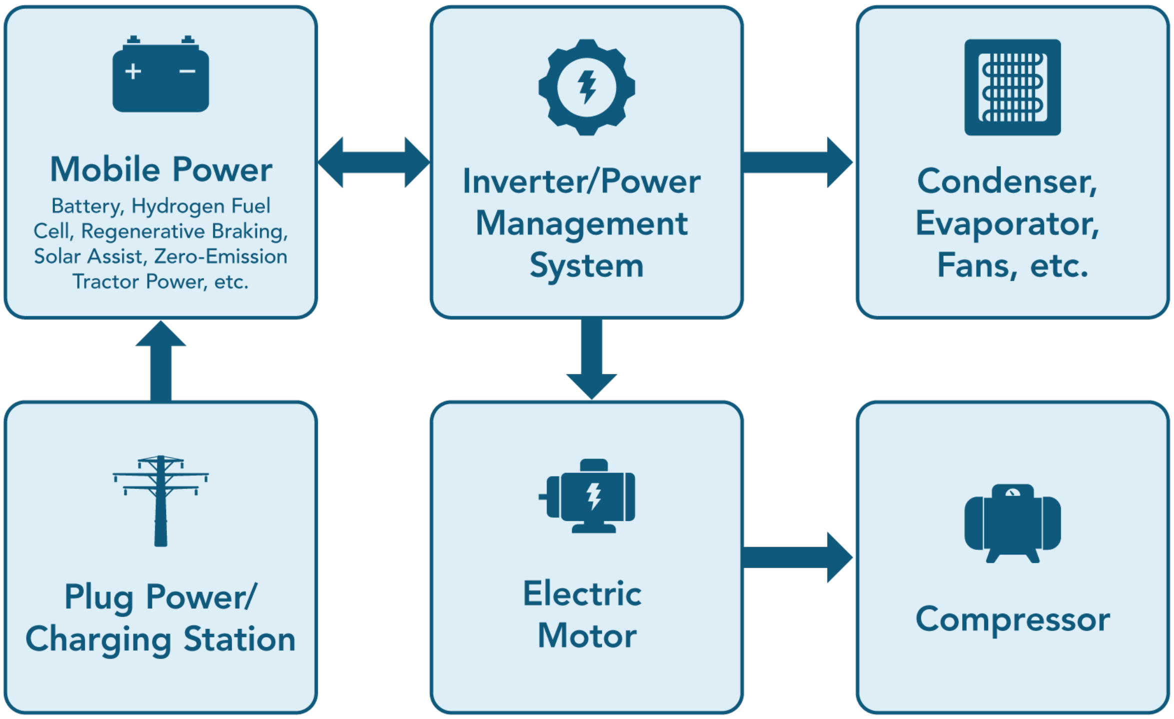
An all-electric eTRU is a TRU which has no diesel engine. All components are electrically-driven. An electric motor runs the compressor that drives the refrigeration system to maintain the required temperature without generating any emissions (e.g., PM2.5, NOx, GHGs).

Most all-electric eTRUs for trailers sold in the United States (U.S.) are only for stationary applications while plugged into grid power electricity. However, all-electric eTRUs can be configured to receive power through multiple energy sources including batteries, hydrogen

[42] United States Environmental Protection Agency. (2019, December). *2020 Diesel Emissions Reduction Act (DERA) National Grants Transport Refrigeration Unit (TRU) Factsheet*. U.S. EPA. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100Y6MX.PDF?Dockey=P100Y6MX.PDF

fuel cells, range extending technologies (e.g., regenerative braking, solar assist) or power from the leading zero-emission tractor (Figure 11).

Figure 11: All-Electric eTRU Diagram



Note: This diagram may not be reflective of all all-electric eTRUs and is only intended to show the concept that eTRUs may receive power from multiple sources.

Zero-emission trailer TRUs that are powered by battery packs are commercially available and in use by fleets. The architecture for trailers is similar to the architecture for domestic shipping containers and railcars and many components can be shared between platforms. Therefore, producing eTRUs for domestic shipping containers or railcars should not be a technological challenge for original equipment manufacturers. The refrigeration systems used for ocean containers are electrically-driven but are integrated into the ocean container and not sold as stand-alone units. Ocean containers are full-time zero-emission devices that must always be plugged in to an external power source to operate. Power sources are the onboard power system of the ocean vessel, grid power electricity on shore, or a mobile power source such as a TRU generator set during transport.

There are currently no zero-emission TRU generator sets operating in California. However, one company, LogiXpower, produces two models of battery-electric TRU generator sets (40 kilowatt-hours [kWh] or 80kWh) that can be used to power an eTRU or an ocean container equipped with 460 volts of alternating current (AC) input. These products are designed to mount to a flatbed trailer used for transporting ocean containers. There have been no sales of these products as of 2021.

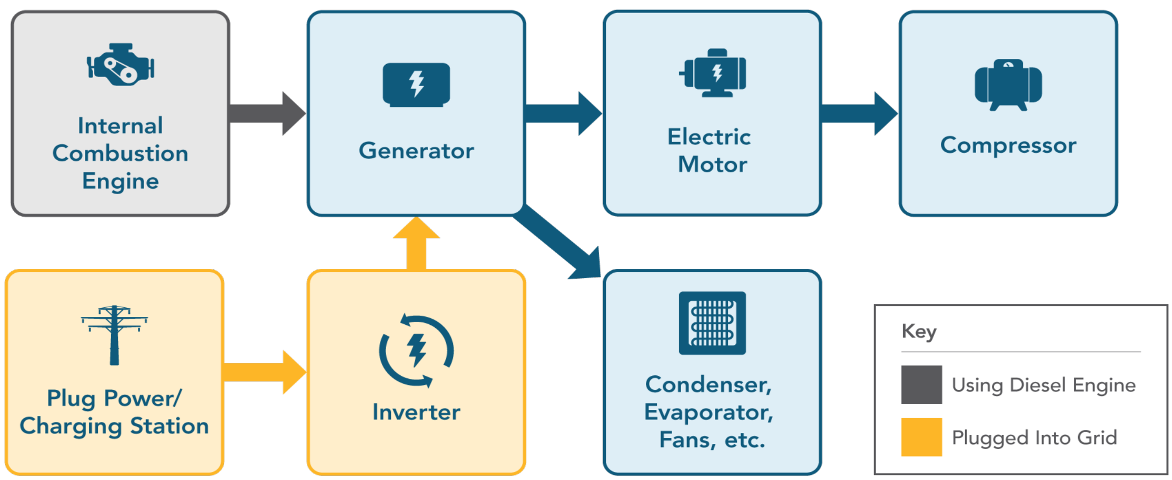
Zero-emission hydrogen fuel cells for eTRUs and ocean containers are discussed separately in Chapter II, *Hydrogen Fuel Cells*.

Hybrid-Electric and Standby-Electric eTRUs

The terms hybrid, standby, and plug-in are often used interchangeably for eTRUs. In 2022, these terms indicate that these eTRUs provide plug-in capability when stationary. When the system is unplugged, these eTRUs revert to using the diesel internal combustion engine to power the heating or cooling systems.[43] Hybrid-electric and standby-electric eTRUs have different approaches to switching between diesel power and grid power electricity.

Figure 12 shows zero-emission power options and a general schematic of a hybrid-electric TRU and Figure 13 shows zero-emission power options and a general schematic of a standby-electric TRU.

Figure 12: Hybrid-Electric eTRU Diagram



Note: This diagram is not specific to any product and is intended to show the general concept behind a hybrid-electric eTRU configuration and how it manages power from both grid power electricity and a diesel internal combustion engine.

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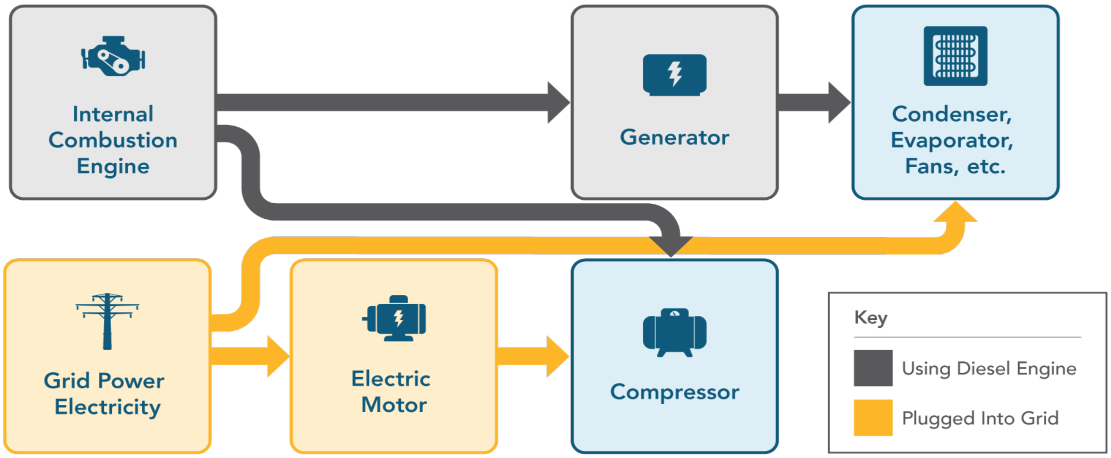
[43] United States Environmental Protection Agency. (2019, December). *Diesel Emissions Reduction Act (DERA) National Grants Transport Refrigeration Unit (TRU) Factsheet.* U.S. EPA. *https://nepis.epa.gov/Exe/ZyPDF.cgi/P100Y6MX.PDF?Dockey=P100Y6MX.PDF*

Figure 13: Standby Electric eTRU Diagram



Note: This diagram is not specific to any product and is intended to show the general concept behind a standby-electric eTRU configuration and how it manages power from both grid power electricity and a diesel internal combustion engine.

As of 2022, currently available hybrid-electric and standby-electric eTRUs can only operate without the use of the diesel internal combustion engine while stationary and plugged in to grid power electricity. However, these two categories of eTRUs have the potential to operate with power from an onboard zero-emission power source such as a battery or a hydrogen fuel cell while mobile. This built-in zero-emission capability makes these two categories of eTRUs unique because they can achieve zero-emission and potential cost savings by plugging into grid power electricity while stationary and can be configured to operate with zero-emission while mobile.

Zero-Emission Tractor as a Power Source for eTRUs

A zero-emission tractor, a vehicle designed to pull a semi-trailer, can be used as a power source for eTRUs. A zero-emission tractor can be used to power an eTRU directly using a power cable between the eTRU power system and the zero-emission tractor. Not all trailer pick-up and drop-off locations have plug-in charging capability for an eTRU, so trailers being powered by zero-emission tractors may require their own separate battery pack onboard the trailer so that the tractor can disconnect from the trailer and the tractor can continue on its route. This battery pack onboard the trailer would be charged by the zero-emission tractor while the tractor is pulling the trailer, and this would power the trailer's eTRU while stationary until it is either re-connected to the tractor or plugged into grid power electricity. While stationary, the trailer can plug in at various operating locations such as warehouses or distribution centers, or freight facilities.

Zero-Emission Trailer as a Power Source for eTRUs

A trailer chassis could include a battery pack and necessary power cable to provide a power source for an eTRU. The trailer chassis with a battery pack could be charged by connecting to a charging station while in storage and be ready to provide power to a domestic shipping container or ocean container with an eTRU. This configuration would be considered a battery-electric TRU, which is discussed in Chapter II, *Battery-Electric TRUs*.

Technology Readiness

All-Electric eTRUs

All-electric eTRUs for trailers are used in commercial applications but make up a small percent of the total mobile TRU population in the U.S.[44] All-electric eTRUs have been used since the late 1960s in the form of ocean containers.[45,46] However, as a solution for mobile trailers, all-electric eTRUs have had virtually no presence in the U.S. until the late 2010s.

There are several manufacturers that offer all-electric eTRUs for trailers that are either currently available or soon to be available in the U.S. Some of the companies that offer all-electric eTRUs include Advanced Energy Machines, Carrier (a North American TRU original equipment manufacturer), Daiken, Electric Reefer Solutions, and Kingtec (another TRU original equipment manufacturer).

Advanced Energy Machines has deployed nearly 100 all-electric eTRUs into service and is processing orders to deploy even more.[47] Carrier manufacturers the Vector™ 8100 all-electric eTRU which is designed for a stationary temperature-controlled trailer but is being used for multiple successful demonstrations for mobile zero-emission trailer solutions. As of 2021, eTRUs for domestic shipping containers or railcars are not yet offered.

CARB staff seeking additional information on the population of TRUs that operate as eTRUs in California.

[44] Robert Koelsch, Advanced Energy Machines. (July 20, 2021). *Meeting with CARB staff and Advanced Energy Machines.*

[45] Escola Europea. (2019, March 19). *#DidYouKnow – A short story of the refrigerated container.* Escola Europea. *https://escolaeuropea.eu/did-you-know/didyouknow/*

[46] Carrier Transicold. (2018). Celebrating 50 Years of Container Refrigeration Innovation. Carrier. *https://www.carrier.com/container-refrigeration/en/worldwide/media-center/ContainerLINE/celebrating-50-years-of-container-refrigeration-innovation/*

[47] Robert Koelsch, Advanced Energy Machines. (July 20, 2021). *Meeting with CARB staff and Advanced Energy Machines.*

Hybrid-Electric and Standby-Electric eTRUs

Hybrid-electric and standby-electric eTRUs have been available since the early 2000s. More than 70 percent of TRUs in Europe have plug-in capability, however estimates show only 15 percent of TRUs in operation in the U.S. can plug-in.[48,49] Combining these classes of eTRUs with mobile power sources (e.g., batteries, hydrogen fuel cells, regenerative braking, solar assist, or zero-emission tractor power) to operate in zero-emission mode while mobile is not yet offered and has not been demonstrated.

Zero-Emission Tractor as a Power Source for eTRUs

There are no known demonstration projects of zero-emission tractors providing a direct power connection for eTRUs and there are no plans known by CARB staff of any development or demonstration projects in the U.S. or Europe. Coordination between original equipment manufacturers of zero-emission tractors and eTRUs would be needed since this application has not been developed. Power management could be especially challenging due to the different electrical power requirements for zero-emission tractors and eTRUs. For example, an eTRU requires up to 19 kW (25 horsepower) of power, whereas a typical battery-electric tractor could have a power requirement of up to 350 kW (450 hp). In addition to the large difference in magnitude, the type of electricity required may differ between alternating current or direct current among the various eTRU manufacturers. In addition, the impact from the eTRU on the zero-emission tractor's range capabilities is unknown at this time.

Zero-Emission Trailer as a Power Source for eTRUs

Trailers can be fitted with zero-emission power sources, such as a battery pack or hydrogen fuel cell to power an eTRU. There are two companies in the U.S. offering a trailer TRU solution powered with an onboard battery pack and these are discussed further in Chapter II, *Battery-Electric TRUs*.

Emissions Benefits

eTRUs operating in electric-only mode are inherently zero-emission devices. When evaluating the emissions benefits associated with eTRUs, the power source of the eTRU is the primary consideration.

Emissions benefits associated with eTRU power sources are discussed in their respective sections. For emission benefits of batteries for eTRUs, see Chapter II, *Battery-Electric TRUs*. For the emissions benefits of hydrogen fuel cells for eTRUs, see Chapter II, *Hydrogen Fuel Cells*.

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[48] Boxwheel Trailer Leasing. (2019, May 14). *The Many Benefits of Electric Standby Reefers*. Boxwheel. https://boxwheel.com/the-many-benefits-of-electric-standby-reefers

[49] Claimed confidential data obtained from industry sources that requested non-attribution.

Infrastructure Requirements

Existing eTRUs may be configured to be powered by electricity from the grid while stationary using special power cords with multipronged plugs. For more information regarding plug-in operation of eTRUs refer to CARB's 2015 *Technology Assessment: Transport Refrigerators*.[50]

An increasing number of refrigerated warehouses and distribution centers are equipping their facilities with infrastructure to support electricity grid operation of hybrid-electric or standby-electric eTRUs- because of its environmental and economic advantages. For example, 25 cords and multipronged plugs were installed at an Albertson's grocery distribution center in Tracy, California funded by a Pacific Gas and Electric grant.[51] In Livingston, California, Foster Farms utilized Proposition 1B: Goods Movement Emission Reduction Program funds to install plugs at their loading docks and parking spots. Plugging into the electrical grid allows fleet operators to eliminate all diesel engine emissions while the unit is stationary at a facility. There are a variety of operating voltages and electrical connectors that standby-electric and hybrid-electric fleets can utilize. Cost savings may result if the plug-in operation occurs during favorable off-peak times when electricity rates are lower. Fleets would need to understand their specific time-of-use electricity rates to minimize charging costs.

Power sources for zero-emission operation of mobile eTRUs discussed in the 2022 Technology Assessment include batteries in Chapter II, *Battery-Electric TRUs* and hydrogen fuel cells in Chapter II, *Hydrogen Fuel Cells*. The infrastructure requirements for eTRUs which receive their primary power from batteries or hydrogen fuel cells are discussed in their respective chapters. Infrastructure needs for each zero-emission technology depend on the power draw of the eTRU, the operating range between refueling, and the specific operations of each TRU fleet. The power draw and operating range of eTRUs are discussed further in Chapter II, *Zero-Emission Technologies*.

Economics

Costs include several categories: capital, operation, maintenance, fuel, and infrastructure costs. Capital costs for all-electric eTRUs include the cost of the zero-emission power generating equipment, associated power conversion equipment, and any required cooling equipment. These capital costs would need to be factored in when comparing the cost of an all-electric eTRU with the costs associated with a diesel-powered TRU. The cost of an all-electric eTRU is approximately the same as its hybrid-electric or -standby-electric

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[50] California Air Resources Board. (2015). *Technology Assessment: Transport Refrigerators*. CARB. *https://ww2.arb.ca.gov/sites/default/files/2020-06/TRU%20Tech%20Assessment%20Report%20ada.pdf*

[51] Pacific Gas and Electric. (2021, May 20). *National Grocer Reduces Costs and Emissions with eTRUs*. PG&E. *https://www.pge.com/pge_global/common/pdfs/solar-and-vehicles/your-options/clean-vehicles/charging-stations/ev-fleet-program/albertsons-case-study.pdf*

counterpart, between $25,300 and $32,500.[52] The average capital cost in 2021 for a hybrid-electric or standby-electric eTRU is greater than a diesel-powered TRU but these eTRUs are generally estimated to have greater operational and maintenance savings. Infrastructure costs vary by numerous factors including possible volume discounts on the equipment, site conditions, and the number of chargers being installed. Table 2 provides the cost comparison for an eTRU using plug in capability when stationary and diesel when mobile and a diesel TRU.

[52] California Air Resources Board. (2020, August 8). *Preliminary Cost Document for the Transport Refrigeration Unit Regulation*. CARB. *https://ww2.arb.ca.gov/sites/default/files/2020-08/Preliminary%20TRU%20Cost%20Doc%2008202020.pdf*

Table 2: Cost Comparison for Trailer Ownership – eTRU vs Diesel-Powered TRU (Single Temperature Unit)

Cost Component	All-electric eTRU	Hybrid-electric/stationary eTRU Using Plug-In when Stationary Costs	Hybrid-electric eTRU when Mobile Costs[53]	Mobile Diesel-Powered TRU Costs
Capital Cost of Equipment (manufacturer's suggested retail price)	*[CARB Staff Seeking Info]*	$33,500 to $36,000 (<25 hp with new standards)[54]	$33,500 to $36,000 (<25 hp with new standards)[55]	$29,400[56]
Annual Fuel Costs	$1.52 per hour on electricity[57] $3,040 per year electricity	$1.52 per hour on electricity[58] $760 per year electricity $4660 per year[59] total (diesel and electric)	$2.60 per hour on diesel $3,900 per year diesel $4,660 per year total (diesel and electric)	$2.60 per hour[60] $5,200 per year

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[53] Operates on diesel while mobile.

[54] California Air Resources Board. (2020, August 8). *Preliminary Cost Document for the Transport Refrigeration Unit Regulation*. CARB. https://ww2.arb.ca.gov/sites/default/files/2020-08/Preliminary%20TRU%20Cost%20Doc%2008202020.pdf

[55] California Air Resources Board. (2020, August 8). *Preliminary Cost Document for the Transport Refrigeration Unit Regulation*. CARB. https://ww2.arb.ca.gov/sites/default/files/2020-08/Preliminary%20TRU%20Cost%20Doc%2008202020.pdf

[56] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

[57] Calculation for hourly operation cost of an eTRU: 8 kWh/hr X $0.19/kWh (2021 California Energy Commission Integrated Energy Policy Report) = $ 1.52/hr. Annual fuel costs based on 2000 hours per year. Time-of-use and peak demand charges not included.

[58] Calculation for hourly operation cost of an eTRU: 8 kWh/hr X $0.19/kWh (2021 California Energy Commission Integrated Energy Policy Report) = $ 1.52/hr. Time-of-use and peak demand charges not included.

[59] Calculation for cost of an eTRU operating 25 percent of the time on grid power: 2,000 hr/yr (total average operation time for a TRU) X 25 percent (time plugged into grid power) = 500 hr/yr operation on grid power. 500 hr/yr X $1.52/hr = $760/yr annual cost for electricity for an eTRU. Calculation for cost of fuel for an eTRU operating 75 percent of the time on diesel: 2,000 hr/yr X 75 percent operation on diesel = 1,500 hr/yr. 1,500 hr/year X $2.60/hr = $3,900/yr. $760 electricity cost + $3,900 diesel cost = $4,660/yr total energy cost. 2021$.

[60] Calculation for hourly operation cost of a diesel-powered TRU: 0.8 gallon/hr X $3.25/gal = $2.60/hr. 2021$.

Table 2: Cost Comparison for Trailer Ownership – eTRU vs Diesel-Powered TRU (Single Temperature Unit)(cont.)

Cost Component	All-electric eTRU	Hybrid-electric/stationary eTRU Using Plug-In when Stationary Costs	Hybrid-electric eTRU when Mobile Costs[61]	Mobile Diesel-Powered TRU Costs
Operation and Maintenance – Maintenance	$0.50 per hour[62] $1,000 per year	$0.50 per hour[63] $1,000 per year	$0.50 per hour[64] $1,000 per year	$0.95 per hour[65] $1,900 per year[66]
Infrastructure Capital	$4,300-$5,700[67] (one-time)	$3,200[68]	No additional cost	No additional cost

The costs associated with using these categories of eTRUs while mobile and without the use of the diesel internal combustion engine has not been investigated and the costs would vary depending on how often the eTRU used alternative power instead of diesel. However, there are case studies for costs associated with plugging-in at facilities.

[61] Operates on diesel while mobile.

[62] California Air Resources Board. (2020, August 8). *Preliminary Cost Document for the Transport Refrigeration Unit Regulation*. CARB. https://ww2.arb.ca.gov/sites/default/files/2020-08/Preliminary%20TRU%20Cost%20Doc%2008202020.pdf

[63] California Air Resources Board. (2020, August 8). *Preliminary Cost Document for the Transport Refrigeration Unit Regulation*. CARB. https://ww2.arb.ca.gov/sites/default/files/2020-08/Preliminary%20TRU%20Cost%20Doc%2008202020.pdf

[64] California Air Resources Board. (2020, August 8). *Preliminary Cost Document for the Transport Refrigeration Unit Regulation*. CARB. https://ww2.arb.ca.gov/sites/default/files/2020-08/Preliminary%20TRU%20Cost%20Doc%2008202020.pdf

[65] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

[66] Diesel-powered TRU maintenance costs: $0.95/hr for 2,000 hr/yr. 2021$.

[67] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

[68] Claimed confidential data obtained from an industry source that requested non-attribution. 2017$.

One case study in Troy, Missouri involved the conversion of a fleet of 280 diesel-powered TRUs to hybrid-electric eTRUs. The conversion of the fleet resulted in an estimated fuel savings of approximately $10,000 to $17,000 per week, assuming diesel at $3 per gallon and fuel consumption at a rate of 0.6 to 1.0 gallon per hour.[69]

Another case study in Tracy, California involved Albertsons equipping 280 of their temperature-controlled trailers with hybrid-electric eTRUs and installing 25 cords and multipronged plugs at their distribution center. Albertsons reduced maintenance costs resulting in an annual savings of approximately $62,000 per year, compared to using the diesel-powered TRUs, when charging at the $0.16 per kWh utility rate. They also achieved a 98 percent reduction of NOx emissions and a 77 percent reduction of GHG emissions per hour of usage at the Tracy facility.[70]

These two case studies demonstrate that the use of standby-electric (plugging into grid power electricity) can reduce operating costs. Manufacturers of standby-electric TRUs claim the cost savings of plugging in while stationary reduces operating costs between 40 percent and 70 percent depending on diesel costs and power costs.[71]

CARB staff seeking additional information on capital, operation, maintenance, and infrastructure cost for eTRUs.

Technology Outlook

Advantages

As of 2022, hybrid-electric and standby-electric eTRUs are readily available and are competitively priced with their diesel-only counterparts. They are in operation throughout the U.S. and California. This existing eTRU population can be leveraged to accelerate the implementation of zero-emission TRU equipment.

In-use hybrid-electric and standby-electric eTRUs can be plugged in at many California facilities to operate as a zero-emission device while stationary for extended time periods to realize immediate cost savings and emissions reductions. The technologies (e.g., battery packs, hydrogen fuel cells, range-extending devices, and zero-emission tractors) used to power zero-emission mobile operation for hybrid-electric and standby-electric eTRUs are already available. For example, the LogiXpower battery-powered TRU generator set powers

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69 Electric Power Research Institute. (2018, November). *EPRI Case Study for Truck Refrigeration Electric is Better*. EPRI. https://energyconversionhub.com/sites/default/files/attachments/truck_refridg.pdf

70 Pacific Gas and Electric. (2021, May 20). *National Grocer Reduces Costs and Emissions with eTRUs*. PG&E. https://www.pge.com/pge_global/common/pdfs/solar-and-vehicles/your-options/clean-vehicles/charging-stations/ev-fleet-program/albertsons-case-study.pdf

71 Transport Topics. (2019, May 24). *Electric-Powered Reefer Units Gaining Momentum*. Transport Topics. https://www.ttnews.com/articles/electric-powered-reefer-units-gaining-momentum

a hybrid-electric eTRU and in France, a hydrogen fuel cell is being used to power a hybrid-electric eTRU.[72,73] See Appendix A for a complete list of demonstration projects.

There is also a commercially available all-electric eTRU for mobile operation that is offered as a fully integrated battery-electric TRU solution in the U.S. See Chapter II, *Battery-electric TRUs* for more information. eTRUs can be powered directly by the battery pack or fuel tank used by a zero-emission tractor. This can eliminate the need for a separate energy or fuel storage system dedicated to the eTRU, reducing costs, and saving space on the vehicle.

Many incentive programs are available at the local, State, and federal level to encourage fleets to implement eTRUs. Incentives can help fleets to realize immediate cost and emissions reductions and assist with charging infrastructure to power eTRUs. See Appendix B for a list of incentive programs.

Challenges

Operating eTRUs as zero-emission devices when mobile is a technological challenge although all three categories of eTRUs are commercially available.

The technology challenge for widespread deployment of zero-emission eTRUs does not lie with the development of eTRUs, but with the integration of mobile power technologies (e.g., batteries, hydrogen fuel cells, range-extending technologies, and zero-emission tractors) that can accommodate the operational requirements of trailers.

A key challenge for direct power connections with a zero-emission tractor is that the tractor must be equipped with a compatible power supply and connectors for the eTRU. Operators can use multiple trailers for a given tractor. For direct power connections to work, both the tractor and the trailer need to have compatible systems.

Using a direct power connection system with a zero-emission locomotive as a solution for zero-emission temperature-controlled freight transport via rail would be challenging as there are no zero-emission locomotives in commercial operation.

CARB staff seeking additional information on any additional implementation challenges or technologies that can power an eTRU.

[72] FuelCellWorks. (2021, September 14). *FresH2 Hydrogen Fuel Cell Refrigerated Transport Project Enters Road Testing Phase*. FuelCellWorks. https://fuelcellsworks.com/news/fresh2-hydrogen-fuel-cell-refrigerated-transport-project-enters-road-testing-phase/

[73] LogiXpower. (2020, March 26). *EGENset Carrier Vector 8500 Presentation.* [Video]. YouTube video. https://youtu.be/HFE_dOKDm3s

Battery-Electric TRUs

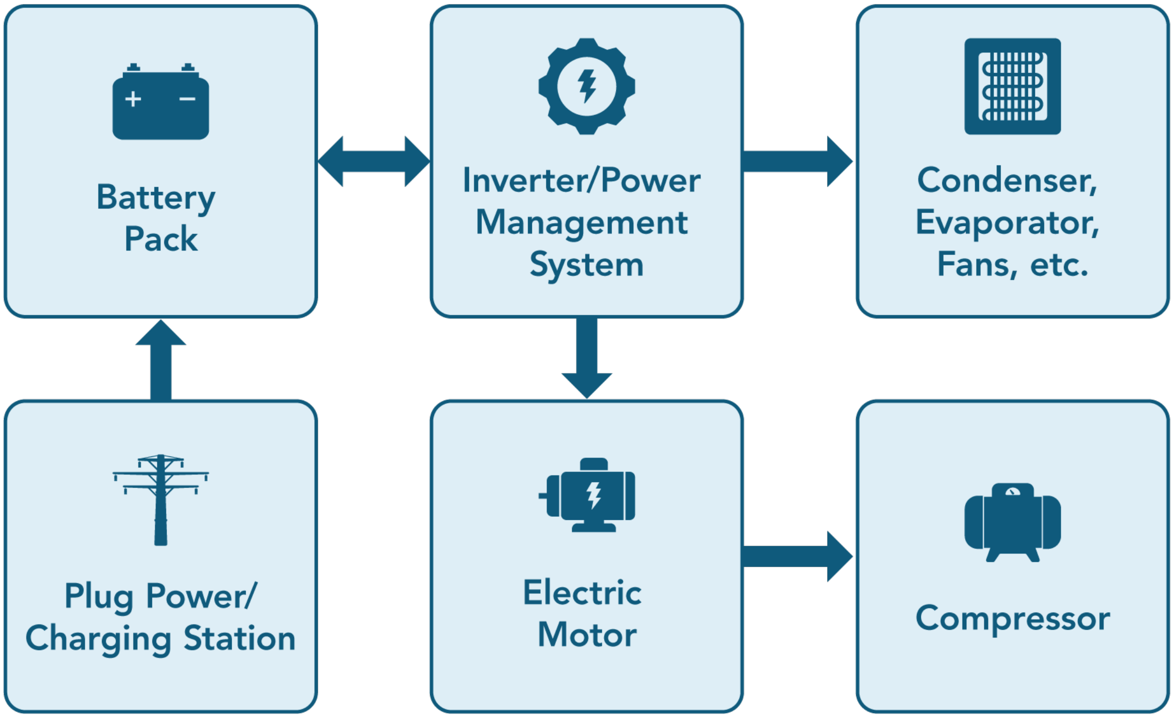
Technology Description

A battery-electric TRU is an eTRU that has electric motors that is powered by a rechargeable battery pack. During battery-powered operation, the battery pack is the power source and provides electricity to the eTRU power management system. The power management system uses the supplied electricity to power the compressor motor, evaporator fan, and condenser fan, as needed. When the TRU is plugged into a charger, the electricity can be used to power the TRU or to charge the battery pack.

The main component of a battery-electric TRU is the battery pack, which can come in multiple different chemistries. The lithium-ion battery has many positive attributes that make it useful for TRU application. Compared to traditional lead-acid batteries, lithium-ion batteries have higher energy density, are lighter, take up less space, and do not lose memory even if they are repeatedly only partially recharged. Lithium-ion batteries can also have long lives and are capable of high charge/discharge rates.

Another necessary component of the battery-electric TRU is the power management system, which manages the provision and utilization of electrical power for the components in the system. Power management systems are necessary for all eTRUs, even when equipped with a diesel engine. However, a battery-electric TRU requires a more complex system to handle the numerous electricity inputs and outputs. The electricity inputs and outputs include grid power supplied through a charger to charge the battery pack, electricity from the battery pack to power the TRU, and any other electricity inputs such as power supplied through range extending technologies (i.e., solar panels, regenerative braking systems). Depending on the system design, the power management system may also include inverters to convert power to the required current (alternating or direct) needed to charge the battery pack and/or operate the eTRU. Figure 14 shows the power inputs and outputs and direction of electricity flow for a battery-electric TRU. Battery-electric TRUs also contain refrigeration system components, such as the compressor, condenser, evaporator, and fans, all which are standard among both diesel-powered and battery-electric TRUs.

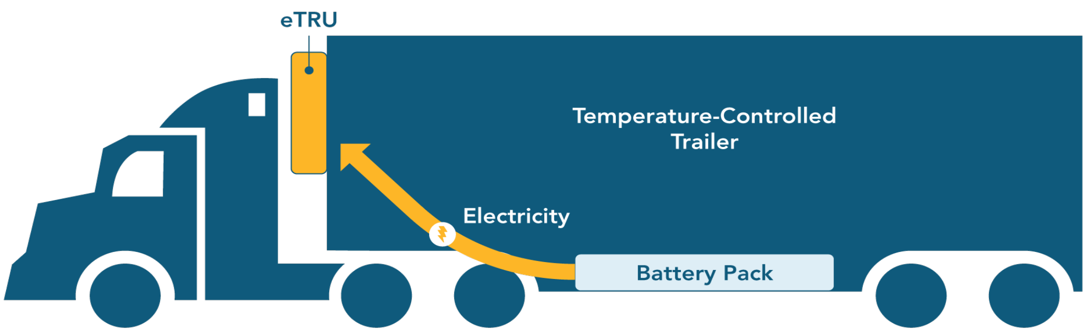
Figure 14: Battery-Electric TRU Diagram



Battery-electric technology allows the TRU to operate without the need of a diesel engine, which requires frequent maintenance. Removing the diesel engine eliminates the need for a diesel tank and diesel engine maintenance. Battery-electric technology also enables the TRU to operate quietly and more reliably.[74] Battery-electric technology is most applicable to trailer TRU applications (Figure 15). Utilizing battery-electric TRUs for domestic shipping containers and railcars has yet to be demonstrated.

[74] The New York State Energy Research and Development Authority. (2005, June 24). *Electric-Powered Trailer Refrigeration Unit Market Study and Technology Assessment.* Shurepower LLC.

Figure 15: Battery-Electric Trailer TRU



The power draw, which is the amount of electricity needed to operate a battery-electric TRU, can vary, depending on the specific operating conditions of the TRU. For example, maintaining the temperature of a trailer that has been pre-cooled would require much less power draw than lowering the temperature of a trailer just loaded with warm goods. Operating conditions, such as the temperature setpoint, ambient temperature, insulation of the trailer, and number of times the doors are opened, can impact the power draw of the TRU.

Operating conditions and the power draw of the battery-electric TRU also directly impact operating range of the battery-electric TRU. Both operating conditions and power draw can be situation specific, so it is challenging to state expected ranges for a battery-electric TRU.

Technology Readiness

Hybrid TRUs that can be plugged in while stationary have long been commercially available and contain many of the same electrical components found in diesel-powered TRUs. By the early 2000s, all-electric stationary TRUs became commercially available. In recent years, improvements in battery technology have allowed manufacturers to offer mobile TRU applications that depend in part or wholly on batteries.

As of September 2021, eNow offers battery-electric trailer TRUs in both 48-foot and 53-foot trailer lengths with a battery pack capacity up to 107 kWh.[75] Advanced Energy Machines offers battery-electric TRUs for trailers ranging from 28 feet to 53 feet with battery pack sizes

[75] eNow. (n.d.). *eNow Rayfridgeration Trailer Systems: Zero-Emission All-Electric Reefers*. eNow. https://www.enowenergy.com/copy-1-intro-to-enow-rayfrigeration-trailer-systems/

up to 96 kWh.[76,77] These battery packs are similar in size to the battery packs inside light-duty battery-electric vehicles. Both eNow and Advanced Energy Machines include trailer roof top solar panels that can extend the operating range of the trailer TRU. See Chapter II, *Range Extending Technologies* for more information.

Currently, many battery-electric TRUs have been purchased by leasing companies such as Personalized Lifecycle Management Trailer Leasing and are leased to various food distributors. One of these food distributors, United Natural Foods, Inc. (UNFI), plans to remove 53 diesel-powered TRUs from their Riverside, California distribution center fleet and replace them with 53 leased battery-electric TRUs.[78]UNFI will be working to integrate this battery-electric fleet in their temperature-controlled distribution network in California.

Maxwell and Spark produce a battery-electric trailer TRU solution. In September 2021, Maxwell and Spark began a pilot project to operate four battery-electric trailer TRUs in partnership with Unilever, TIP Trailer Services, and Daily Logistics Group transporting frozen foods in the Netherlands.[79] The expected completion is May 2022. Other manufacturers such as Carrier and Thermo King are also working to test and develop battery-electric TRUs. See Appendix A for a complete list of demonstration projects.

CARB staff seeking additional information on any additional battery-electric TRU manufacturers.

Emission Benefits

Operations of all-electric TRUs eliminate PM2.5, NOx, and GHG emissions with the removal of the diesel engine that powers the TRU's compressor and fans. As a result, they are 100 percent cleaner from a direct emissions standpoint than TRUs with diesel engines.

Infrastructure Requirements

Electricity as an energy source to power battery-electric TRUs requires supporting infrastructure. Like diesel refueling, fleets may rely on private and public refueling infrastructure. Electricity may be generated on site or supplied by the electrical grid.

Electric vehicle supply equipment and special power cords with multipronged plugs will provide electricity to charge the battery packs or to provide real-time power to

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[76] Advanced Energy Machines: Electric Refrigeration Units. (n.d.). *Innovative Solutions*. Advanced Energy Machines. https://www.aem.green/

[77] California Clean Off-Road Equipment Voucher Incentive Program (CORE). (n.d.). *Transportation Refrigeration Units (TRUs).* California Core. https://californiacore.org/equipment-category/transport-refrigeration-units-tru/

[78] Goldschmidt, B. (2021, May 6). *UNFI Deploys Emerging Transportation Tech to Lower Emissions* Progressive Grocer. https://progressivegrocer.com/unfi-deploys-emerging-transportation-tech-lower-emissions

[79] Maxwell and Spark. (2021, September 29). *Business pilot breakthrough innovation in temperature-controlled transport.* Maxwell and Spark. https://www.maxwellandspark.com/ice-cold-but-without-the-co2-100-electric-reefer-trailers-released-for-a-pilot-with-unilever/

battery-electric TRUs. Electric charging infrastructure at a facility is typically connected to the electric power grid through power conditioning equipment to provide compatible electric power for the TRU. Several types of electric power can be utilized for operation of the TRU including, 40 volts (V) direct current (DC); or single phase or three-phase alternating current at various voltages.

Battery-electric trailer TRUs must be able to connect to an electrical energy source that is compatible with both the battery system and the operation of the TRU. This allows for the unit to operate while simultaneously charging the onboard batteries. Depending on the type of charger used and power available, it can take anywhere from 20 minutes to 12 hours to recharge a 100-kWh battery pack.[80]

Seaport facilities currently provide electricity to power generator sets on international shipping containers. Intermodal railyards may consider supplying electricity to recharge battery packs or eTRU (grid power) type connectors. When selecting zero-emission equipment, fleets need to select the infrastructure best suited for their needs. Considerations include the size of the battery packs, charging speed, to include the power converter on the TRU or on the charger, compatibility with other battery-electric vehicles and equipment in their fleet, use of smart charging, electrical rates, available space, cost of the equipment and infrastructure, and future growth.

CARB staff seeking additional information on how much space is needed, power requirements, and other zero-emission infrastructure requirements at seaport facilities and intermodal railyards.

Economics

Battery-electric trailer TRUs have several costs to consider (Table 3). The battery cost is the largest contributing factor associated with the price of a battery-electric TRU, although costs are projected to fall in the coming years because with economies of scale and further manufacturing cost reductions.[81] The required size of the battery is dependent on the size of the trailer, as well as other factors specific to each operation, including the length of the route, product being transported, temperature of the load, number of door openings on the route, and outdoor temperature. Battery pack replacements every ten or more years also need to be considered. Battery life is impacted by battery pack temperatures, maintaining the proper amount of charge in the battery, and the number and speed of charging events.[82]

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[80] Thermo King. (2021, October). *Trailer Electrification Position Paper*. Thermo King. *https://www.thermoking.com/content/dam/thermoking/documents/marketing/Trailer-electrification-position-paper-Thermo-King.pdf*

[81] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. *https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf*

[82] Green Cars. (2021). *Definitive Guide to Electric Car Batteries*. Green Cars. *https://www.greencars.com/guides/definitive-guide-to-electric-car-batteries-range*

Besides the cost of batteries, battery-electric TRUs also have power management system, operation, maintenance, and infrastructure costs. The infrastructure to support battery-electric TRUs has several costs including the charging equipment, the infrastructure supporting the charging equipment, the cost to install the chargers, and the cost of electricity. Installation costs can vary due to site-specific factors, such as the existing electric panel capacity, installation location, and regional labor costs. However, the International Council on Clean Transportation reports that per-charger costs decline as more chargers are installed.[83] In addition to installation, the total cost for infrastructure and electricity will vary fleet to fleet depending on their operations.

Table 3: Cost Comparison Between a Battery-Electric TRU and a Diesel-Powered TRU

Cost Component	Battery-Electric	Diesel-Cost
Capital	$80,000[84]	$29,400)[85,]
Lithium-Battery Pack	$450 to$500 per kWh[86,87]	Not Applicable
Battery/Diesel Engine Replacement	$9,000 to $50,000[88]	$7,795[89]
Annual-Fuel	$3,950[90]	$5,750[91]

[83] The International Council on Clean Transportation. (2019, August). *Estimating Electric Vehicle Charging Infrastructure Costs Across Major U.S. Metropolitan Areas*. ICCT. *https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf*

[84] Claimed confidential data obtained from an industry source that requested non-attribution. 2021$.

[85] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. *https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf*

[86] Claimed confidential data obtained from an industry source that requested non-attribution. 2021$.

[87] Battery pack costs are included in the capital cost of the battery-electric TRU.

[88] Battery replacement costs vary with battery size. Replacement costs assume battery sizes from 20 kWh to 100 kWh and a 10-year battery life.

[89] My Little Salseman. (n.d.). *Yanmar 3TNV76-CSA Industrial Engine - 25 HP*. mylittlesalesman. *https://www.mylittlesalesman.com/yanmar-3tnv76-csa-industrial-engine-10902471*

[90] Cost = 80 kWh/day x 260 days/year x $0.19/kWh = $3,950/year. Assume 80 kWh battery is depleted and fully charged daily. 2021$.

[91] Cost = 8 hours/day x 5 days/week x 52 weeks/year x 0.85 gallons/hour x $3.25/gallon = $5,750/year. 2021$.

Table 3: Cost Comparison Between a Battery-Electric TRU and a Diesel-Powered TRU (cont.)

Cost Component	Battery-Electric	Diesel-Cost
TRU Maintenance	$0.50 per hour of operation[92]	$0.95 per hour[93]
Infrastructure Capital	$4,300 to $5,700[94]	$0

CARB staff seeking additional information on capital, operation, maintenance, and infrastructure cost for battery-electric TRUs.

Technology Outlook

Advantages

Battery-electric TRUs can support most intrastate, local, and regional routes and other duty cycles that allow the fleet to return to base and recharge. Additionally, battery-electric TRU operations are quieter, cleaner, require less maintenance, and produce less hazardous waste (e.g., lube oil, worn belts, filters) than diesel-powered TRUs. Battery-electric TRUs have fewer moving parts than a diesel-powered TRU and batteries are more efficient than the diesel engine.

Despite larger upfront costs, battery-electric TRUs are also economical for certain routes and operations. They generally have lower maintenance costs in part due to fewer moving components. CARB staff estimate maintenance costs of $0.50 per hour of operation for a battery-electric TRU and $0.95 per hour of operation for a diesel-powered truck TRU.[95]

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[92] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

[93] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

[94] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

[95] California Air Resources Board. (2021, July 27). *Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate. Staff Report: Initial Statement of Reasons, Section X(A)(2)(d)(i)*. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/isor.pdf

CARB staff assume these maintenance and cost benefits will translate to the operation of battery-electric trailer TRUs, although the exact costs per hour may differ. Some operators of battery-electric trailer TRUs claim a lower total cost of ownership compared to diesel-powered trailer TRUs.[96]

Challenges

Batteries are heavy and can limit available payload capacity. However, the extra weight is partially offset by the elimination of the diesel engine and fuel tank used on trailer TRUs.

For example, a 102.4-kWh lithium-ion Tesla battery pack weighs approximately 630 kilograms (kg)(1,389 lbs.)[97] A trailer TRU is typically equipped with a 50-gallon diesel tank which weighs approximately 190 kg (428 lbs.), 160 kg (250 lbs.) of diesel fuel, 30 kg (76 lbs.) for the tank, and a diesel engine that weighs about 110 kg (250 lbs.) for a total of approximately 300 kg (676 lbs.)[98,99] This shows there is a difference of 330 kg (728 lbs.) in system weight that could impact the available payload of a battery-electric trailer TRU. See Table 6 for a comparison of weight between a battery-electric TRU and a diesel-powered TRU.

Table 4: Weight Comparison of a Battery-Electric TRU and a Diesel-Powered TRU

Fuel	Tank Weight	Fuel Weight	Diesel Engine	Battery Pack Weight	Total Weight
Diesel	30 kg	160 kg	110 kg	Not applicable	300 kg
Battery-Electric	Not applicable	Not applicable	Not applicable[100]	630 kg	630 kg

Another consideration is that battery-electric TRUs have additional costs compared to diesel-powered TRUs such as adding battery charging infrastructure. The initial cost to purchase and install charging infrastructure may pose a challenge however, the initial costs can be offset with the lower total cost of ownership. Since infrastructure costs will vary fleet-to-fleet based on their operations and needs, CARB staff plan to develop a fleet survey to better understand the various fleet operations and develop estimations of infrastructure costs.

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[96] Business Wire. (2021, July 21). *XL Fleet and eNow Announce Partnership to Electrify Refrigerated Trailers*. Business Wire. https://www.businesswire.com/news/home/20210721005903/en/

[97] Lima, P. (2021, September 7). *Comparison of Different EV Batteries in 2020 (update).* Push Electric Vehicles. http://pushevs.com/2020/04/04/comparison-of-different-ev-batteries-in-2020/

[98] Thermo King. (2020). *Specification Sheet Precedent-S-700 Specification Sheet*. Thermo King. https://thermokingedmonton.com/wp-content/uploads/2020/10/2020-55871_New-Precedent-S-700-Spec-Sheet.pdf

[99] Carroll Stream Motor Company. (n.d.) *Kohler 22 HP Diesel Engine With Electric Start KD6252-1001*. Carroll Stream. www.carrollstream.com/Kohler-KD625-2-25HP-Diesel-Engine-Electric-Start-p/kd625-2.htm

[100] The weight of an electric motor is not included since a diesel-powered TRU (hybrid-electric or standby-electric) and battery-electric TRU contain an electric motor.

Fleets will need to consider operation limits if using battery-electric TRUs. However, with increasing power density in batteries and more efficient solar panels, long-haul fleets could enable battery-electric TRU to meet or exceed the requirements of these duty-cycles. Solutions can also be found with improved thermal efficiency of the insulated trailer, the mechanical efficiency of the refrigeration system, and the efficiency of the electric motor which can effectively reduce the battery storage capacity needed for adequate operating range.

Battery safety is an important consideration as more vehicles and equipment on the road will be utilizing this technology. The two primary risks are shock and flammability. Risks to the operator when connecting and disconnecting a charger are minimized when using properly installed equipment and following manufacturers' protocols.[101] While there have been incidences of vehicle battery fires, a recent study of recalls and on-road incidents demonstrated that combustion vehicles have much higher fire-related incidence rates than battery-electric vehicles.[102] Measures taken to reduce vehicle battery fires may be applied to TRUs.

[101] Forbes. (2021, July 27) *Considering An Electric Car? Review The Risks And Learn How To Stay Safe*. *http://www.forbes.com/sites/forbestechcouncil/2021/07/27/considering-an-electric-car-review-the-risks-and-learn-how-to-stay-safe/?sh=75ad6f1e5578*

[102] Bodine, Rachel. (2022). AutoInsuranceEZ.com: Gas vs. Electric Car Fires [2021 Findings]. January 21. Accessed February 17, 2022. *https://www.autoinsuranceez.com/gas-vs-electric-car-fires/*

Hydrogen Fuel Cells

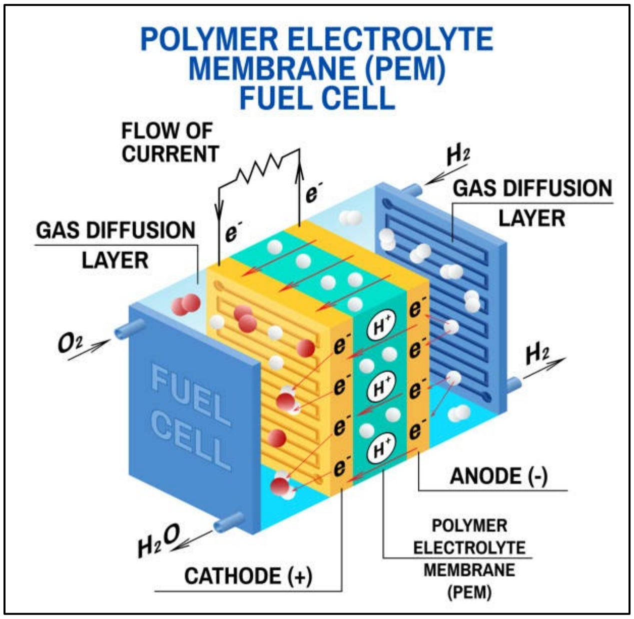
Technology Description

A fuel cell is a device that generates electricity by inducing an electrochemical reaction involving a fuel and an oxidizing agent with the most common type of fuel cell being a PEM fuel cell, a type of hydrogen fuel cell. PEM stands for either polymer electrolyte membrane or proton exchange membrane and is the most practical solution for transportation applications due to its relatively low operating temperature, shorter time to start producing power upon startup, and ease in using atmospheric air as an oxidizing agent.[103]

A PEM fuel cell, referred to in this section as a hydrogen fuel cell (Figure 16), uses hydrogen as the fuel and the oxygen found in air as the oxidizing agent. Similar to a battery, a hydrogen fuel cell has an anode and a cathode. However, unlike a battery, the hydrogen fuel cell requires a continuous supply of the fuel and oxidizing agent which can in turn provide a continuous supply of electricity as the reaction occurs. The byproducts of the electrical chemical reaction between the hydrogen and the oxygen are heat and water. The heat and water produced are released to the atmosphere as water vapor and warm air through the hydrogen fuel cell exhaust system. There are no harmful tailpipe emissions, thus hydrogen fuel cells can convert a zero-emission source of power (i.e., hydrogen) which can be used to power an electrically-driven TRU.

[103] Deloitte & Ballard Power Systems. (2020). *Fueling the Future of Mobility Hydrogen and fuel cell solutions for transportation*. Deloitte. *https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf*

Figure 16: PEM (Hydrogen) Fuel Cell Diagram[104]



Multiple hydrogen fuel cells can be stacked together to form a hydrogen fuel cell stack; the primary power-generation system. The power capacity of the stack increases as more stacks are added.

Additional “balance of plant” components are required for a hydrogen fuel cell to be integrated into products and provide consistent reliable power, such as a hydrogen fuel cell TRU or TRU generator set.[105] The complete solution of a hydrogen fuel cell, balance of plant components, and electric motor is sometimes referred to as a hydrogen fuel cell engine.[106]

Hydrogen fuel cell and hydrogen fuel cell engine manufacturers must consider many factors (e.g., performance, cost, reliability) to deliver their products at the highest performance (kW output) at the lowest price, while increasing longevity and reliability. Efforts are under way to optimize the component material including studies focused on anode and cathode bipolar plates. Graphite plates show promise to reduce cost and improve longevity over metal.[107] Improvements are being explored to reduce the brittleness inherent to graphite plates and

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[104] Airbus. (2021, January 29). *Bjorn’s Corner: The challenges of hydrogen. Part 22. Hydrogen fuel cells.* Leeham News. *https://leehamnews.com/2021/01/29/bjorns-corner-the-challenges-of-hydrogen-part-22-hydrogen-fuel-cells/*

[105] Balance of point components include energy storage (battery packs may be used to provide power in excess of nominal power during peak loads), filters, flow meters, air compressor, air humidifier, DC-to-AC inverter, cooling system for the stack, battery packs, DC-to-DC converter (e.g., coolant pump, intercooler, radiators, fans), protective devices, sensors, electronic control unit, system controller, cables, and connectors.

[106] As an example, Plug Power’s website refers to their ProGen product line as a “fuel cell engine suite.” *https://www.plugpower.com/fuel-cell-power/progen/*

[107] Ballard. (2019). *PEM Fuel Cell Bipolar Plate Material.* Ballard. *https://www.ballard.com/docs/default-source/web-pdf's/technical-note-_-2019-metal-vs-graphite-bipolar-plates-update.pdf*

to address the shock and vibration imparted to the equipment during transportation.[108] Additional improvements in the material science and manufacturing processes for the bipolar hydrogen fuel cell plates have also decreased plate thickness. Thinner material means more layers of cells can be stacked together resulting in higher power density. Hydrogen fuel cells are expected to increase in power density output over 2021 values by 25 percent by 2025.[109,110]

Regardless of the power density, hydrogen fuel cells powering an eTRU need to be designed to provide the maximum power required by the TRU during operation. Sizing the hydrogen fuel cell correctly will ensure there is adequate power available for all operating conditions. However, the size and pressure capacity of the on-board hydrogen tank would impact the operating range of the TRU, so they would need to be factored into the design to meet the specific operational requirements of the fleet.

Three configurations for using hydrogen fuel cells to power TRUs have been demonstrated since the 2010s: a hydrogen fuel cell TRU, a hydrogen fuel cell-powered eTRU, and a hydrogen fuel cell TRU generator set.

Hydrogen Fuel Cell TRUs

A hydrogen fuel cell TRU is a TRU in which a hydrogen fuel cell engine is integrated into the TRU housing, similar to how the diesel engine or generator is housed inside a diesel-powered TRU enclosure. This configuration is essentially the same as a hybrid-electric eTRU in which the diesel generator would be replaced by the hydrogen fuel cell engine (Figure 17). See Chapter II, *eTRUs* for a description of the hybrid-electric eTRU configuration. This configuration is desirable as it would be similar to the form factor of current diesel-powered TRUs and could potentially be a drop-in replacement in addition to a similar appearance to diesel-powered TRU products.[111] Like the diesel-powered TRU arrangement, the larger the hydrogen tank, the further the operating range. Range-extending technologies such as battery packs, regenerative braking, or solar panels could be added to further extend the operating range for hydrogen fuel cell TRUs.

For a trailer, just as the diesel tank is located on the underside of the trailer with the diesel being routed to the TRU, the hydrogen tanks would be mounted under the trailer and routed to the hydrogen fuel cell TRU.

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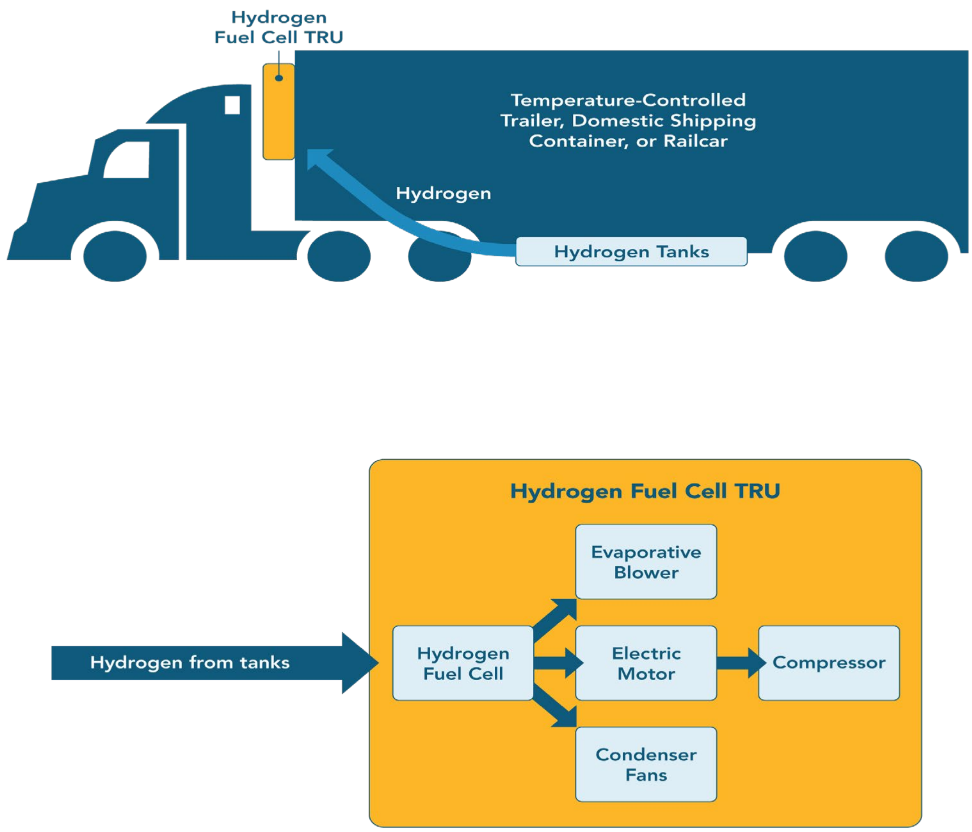
108 Van den Broeck, H. (n.d.). *Fuel Cells for Transportation*. Science Direct. *https://www.sciencedirect.com/topics/engineering/fuel-cells-for-transportation*

109 Ballard. (2019). *PEM Fuel Cell Bipolar Plate Material*. Ballard. *https://www.ballard.com/docs/default-source/web-pdf's/technical-note-_-2019-metal-vs-graphite-bipolar-plates-update.pdf*

110 Gus Block, Nuvera. (Personal communication with CARB staff, March 29, 2021).

111 Nuvera Fuel Cells. (2013, August 30). *Demonstration of Fuel Cell-Based Auxiliary Power Unit for Refrigerated Trucks*. pp. 17-18.

Figure 17: Hydrogen Fuel Cell TRU Configuration

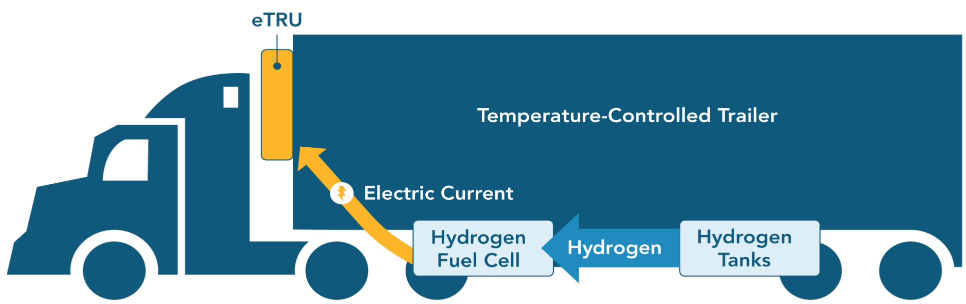


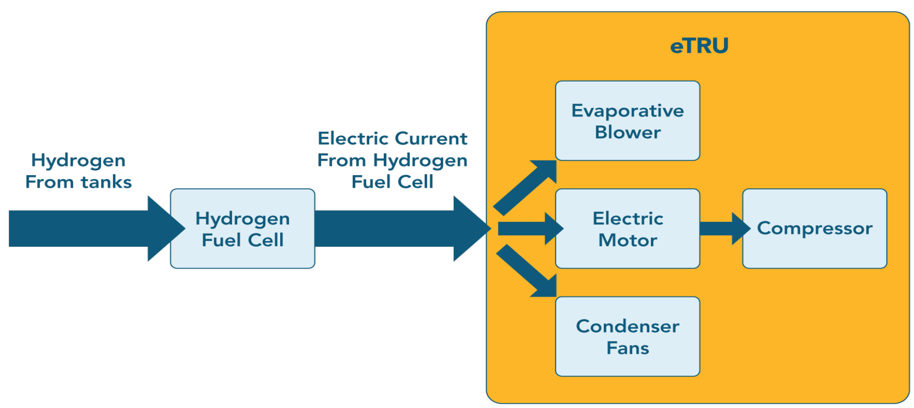
Hydrogen fuel cell TRUs could also be used for domestic shipping containers and railcars. In each of these configurations, the TRUs would be replaced with hydrogen fuel cell TRUs and the diesel tanks would be replaced with hydrogen tanks. However, the equivalent volume of the hydrogen tank may not provide enough hydrogen fuel for an equivalent range to the diesel. The range would likely not be sufficient for the long-haul requirements of rail applications. Additional hydrogen tanks may be required which may change the form factor of the current standard configurations for domestic shipping containers and railcars.

Hydrogen Fuel Cell-Powered eTRU

A hydrogen fuel cell-powered eTRU configuration consists of a hydrogen fuel cell that is external to, and provides power for, an eTRU. The hydrogen fuel cell stack and balance of plant is integrated semi-permanently onto the temperature-controlled trailer as a complete trailer solution; most likely mounted under the trailer along with the hydrogen tanks (Figure 18). In this configuration, a standard eTRU is used to heat or refrigerate the trailer. The power for the eTRU would be supplied by a hydrogen fuel cell that would likely be mounted on the underside of the trailer.

Figure 18: Configuration of an External Hydrogen Fuel Cell-Powered eTRU





There are currently no eTRUs on the market for domestic shipping containers or railcars. Should they become available, it is unclear of what technologies will be utilized for these applications.

Hydrogen Fuel Cell TRU Generator Sets

Hydrogen fuel cells can be used as stand-alone power units for eTRUs on trailers or domestic shipping containers (Figure 19). They can also be used as a stand-alone power source for ocean containers on flatbed trailers (e.g., at a seaport facility) as a replacement for the diesel-powered TRU generator set (Figure 20).[112] Three form factors are produced for TRU generator sets: the pin-on, the underslung, and the powerpack. Hydrogen fuel cells could be configured into each of these form factors to replace the diesel-powered TRU generator set.

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[112] Nuvera Fuel Cells. (2013, August 30). *Demonstration of Fuel Cell-Based Auxiliary Power Unit for Refrigerated Trucks.* pp. 17-18.

Figure 19: Configuration of a Hydrogen Fuel Cell TRU Generator Set Powering an eTRU

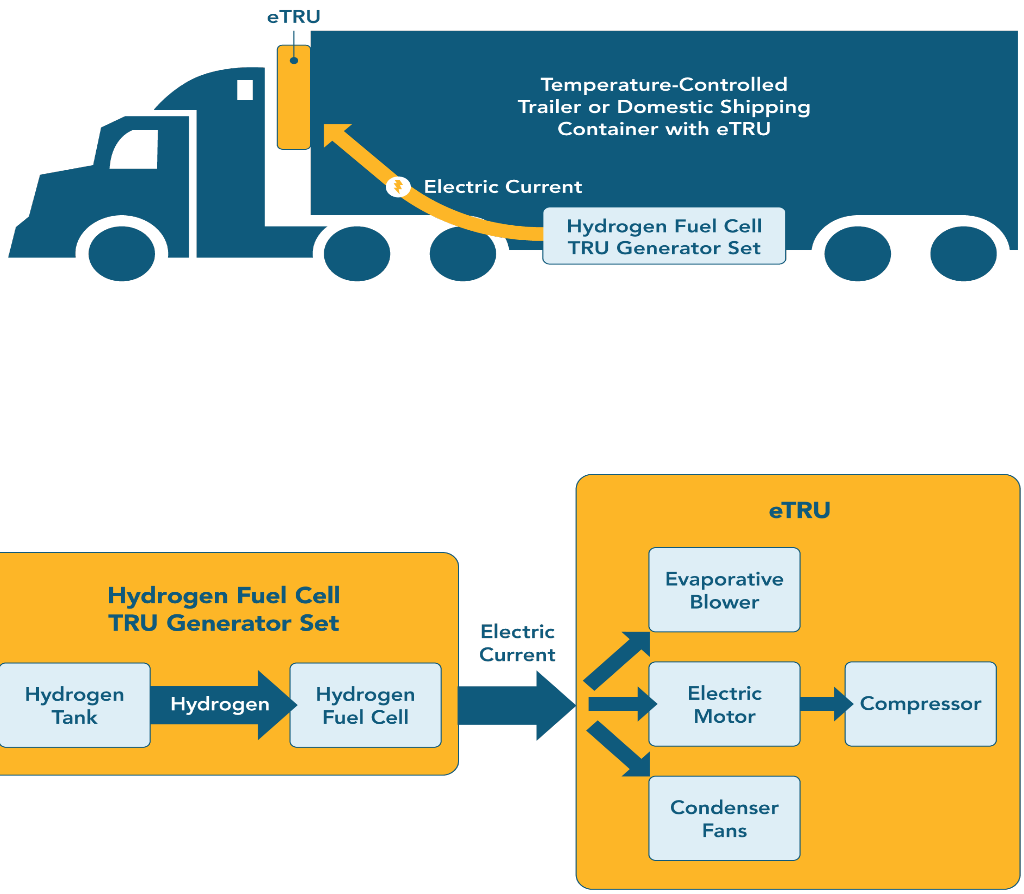
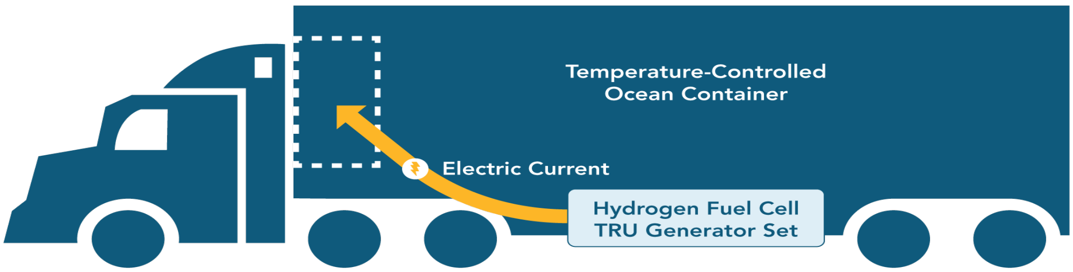
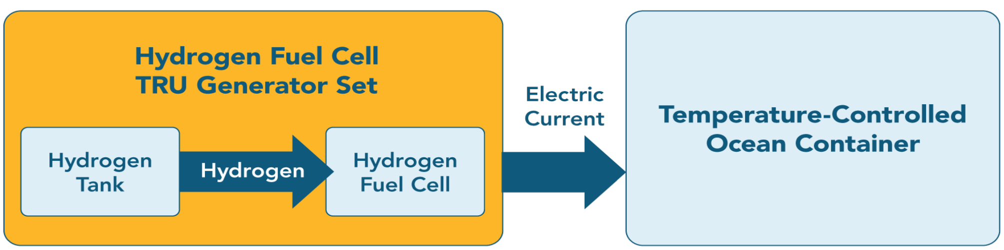


Figure 20: Configuration of a Hydrogen Fuel Cell TRU Generator Set Powering an Ocean Container





Technology Readiness

PEM fuel cells are a mature technology already used in forklift and heavy-duty vehicle applications, however there are no hydrogen fuel cell TRUs being manufactured for sale. There was a demonstration project that started in 2013 funded by the U.S. Department of Energy and carried out by the Pacific Northwest National Laboratory to demonstrate and evaluate a hydrogen fuel cell TRU for temperature-controlled trailers.

The Pacific Northwest National Laboratory study indicated that a 6 kg (13 lbs.) hydrogen tank would provide sufficient range for a typical return-to-base operation for trailers.[113]

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[113] Nuvera Fuel Cells. (2013, August 30). *Demonstration of Fuel Cell-Based Auxiliary Power Unit for Refrigerated Trucks*. p. 16.

Fuel cell-powered trailers with eTRUs are being demonstrated in France by Chereau's ROAD project as well as a collaborative project between Bosch, Carrier, Lamberet, and STEF called FresH2.[114,115,116]

Another Pacific Northwest National Laboratory demonstration used Thermo King's SGSM 3000 generator set as the volumetric and form factor envelope to develop the design for Stage III of a demonstration. Sandia National Laboratories and Hydrogenics have a portable containerized hydrogen fuel cell demonstration.[117] However more research and development are needed to produce a reliable powerpack solution.

See Appendix A for a complete list of demonstration projects.

Emissions Benefits

The byproducts of the electricity-producing reaction within the hydrogen fuel cell are water and heat. Using fuel cells instead of diesel engines for powering TRUs eliminates PM2.5, NOx, and GHG emissions.

Though there are multiple hydrogen production methods, as of December 2021, 95 percent of hydrogen in the U.S. is produced from steam methane reformation.[118] Steam methane reformation requires the production of natural gas (methane; a fossil fuel) and then it releases carbon dioxide into the atmosphere. Another common hydrogen production method is electrolysis, where water is electrochemically split into hydrogen and oxygen. There are no direct emissions associated with the electrolysis itself, however the process is very electricity-intensive.

For transportation uses, hydrogen can generate credits in the Low Carbon Fuels Standard based upon the carbon intensity of the fuel for different applications.[119] Many entities who participate in the Low Carbon Fuels Standard and generate credits from hydrogen utilize pathways with carbon intensities which are lower than the conventional fossil natural gas steam methane reformation pathways. The most common method for lowering emissions is by matching renewable natural gas attributes to steam methane reformation produced hydrogen, however there are also multiple electrolytic hydrogen pathways.

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114 Chereau. (2021, April 9). *ROAD Project Presentation* [Video]. YouTube. *https://youtu.be/uruNPpOKCJE*

115 Fuel Cells Works. (2019, July 8). *Chereau's the ROAD Hydrogen Refrigerated Semi-Trailer Hits the Road*. Fuel Cell Works. *https://fuelcellsworks.com/news/chereaus-the-road-hydrogen-refrigerated-semi-trailer-hits-the-road/*

116 Carrier Transicold. (2021, September 14). *FresH2 Hydrogen Fuel Cell Refrigerated Transport Project Enters Road Testing Phase*. Carrier. *https://www.carrier.com/carrier/en/worldwide/news/news-article/fresh2-hydrogen-fuel-cell-refrigerated-transport-project--enters-road-testing-phase.html*

117 California Air Resources Board. (2015, August). CARB. *Technology Assessment: Transport Refrigerators*. *https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/tru_07292015.pdf*

118 Office of Energy Efficiency & Renewable Energy. (n.d.). *Hydrogen Resources*. U.S. DOE. *https://www.energy.gov/eere/fuelcells/hydrogen-resources*

119 California Air Resources Board. (n.d.). *Low Carbon Fuel Standard*. *https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard*

Infrastructure Requirements

The use of hydrogen fuel cells to power TRUs requires hydrogen refueling infrastructure. Each refueling infrastructure station (station) has the same functional components that include hydrogen storage vessel(s), high-pressure compressor(s), chiller(s), and dispenser(s). Hydrogen may be created on-site or delivered to the site. Each station will be unique due to the layout of the site, equipment and vehicles being refueled, and the dispensing capacity.

Stations receiving deliveries will receive gaseous or liquid hydrogen. High-pressure gaseous hydrogen delivery is transferred by hose from a specialized delivery trailer into the hydrogen storage vessels, or a station could swap out bulk hydrogen storage containers. Liquid hydrogen is delivered by a tanker truck by hose like the high-pressure gaseous delivery except the liquid is at cryogenic temperature and a vent stack system must be used.

Like diesel refueling, temperature-controlled trailers will rely on private and public refueling stations. As the transportation sector electrifies, trailer TRUs will need to be refueled at a heavy-duty hydrogen or charging refueling stations. Manufacturers of fuel cell TRUs may design their units to be refueled at heavy-duty hydrogen stations or to tap into existing hydrogen infrastructure.

Seaport facilities and intermodal railyards may consider constructing new or expanding existing heavy-duty refueling stations to serve multi-modal uses that could include TRUs. TRUs on railcars are refueled using specialized vehicles. These vehicles could transport hydrogen instead of diesel in the future or the intermodal railyard could install a hydrogen hydrant system to refuel the TRUs.

CARB staff seeking additional information on fill rate and connection standards and how operators of hydrogen fuel cell TRUs will refill.

Economics

There are several costs for hydrogen fuel cell TRUs including fuel cell production, fuel cell integration, capital, maintenance, operating, and infrastructure costs. The costs associated with the purchase and operation of various options for hydrogen fuel cells as power sources for TRUs, as compared to those of diesel-powered TRUs, are shown in Table 5.

Hydrogen fuel cell production costs include the hydrogen fuel cell and balance of plant, but not the costs associated with integration into the TRU. The cost for the full hydrogen fuel cell TRU system (not including the hydrogen tanks and additional mounting structure on the bottom of the trailer due to the additional weight of the hydrogen tanks) is roughly twice the current cost of a diesel-powered TRU.

Maintenance costs for hydrogen fuel cell TRUs are expected to be less than diesel-powered TRUs because they have fewer moving parts. However, any required replacement parts for the hydrogen fuel cell stack or balance of plant may be expensive when hydrogen fuel cell TRU products are still new to the market. Higher cost of parts may offset operating cost savings over internal combustion engines. However, some of the balance of plant components are becoming more commonly shared with the auto industry which is expected to drive prices down. Furthermore, as the volume of balance of plant components and hydrogen fuel cell suppliers increase, maintenance costs will likely still be lower when compared to internal combustion engines.

Hydrogen fuel cell TRU operating costs become more cost-effective as the price of diesel increases and the price of hydrogen decreases. The cost of hydrogen infrastructure is included in the hydrogen fuel price. The price of hydrogen fuel currently fluctuates depending on several factors such as location, supply, and method of generation due to a developing supply network with currently low throughput. It is expected hydrogen fuel prices will lower as the supply chain matures. Once costs drop, they will offer more competitive value with fossil fuels. Hydrogen costs for fleets that build their own stations will depend on the quantity of hydrogen used.

Table 5: Cost Comparison Between Hydrogen Fuel Cell TRU Options and a Diesel Powered TRU

Cost Component	Hydrogen Fuel Cell Costs	Diesel Costs
Hydrogen Fuel Cell TRU		
Capital: Fuel Cell TRU (TRU with integrated fuel cell)	$60,000	$29,400
Capital: Tanks	[CARB staff seeking information]	[CARB staff seeking information]
Annual Fuel		
Maintenance		
Hydrogen Fuel Cell-Powered eTRU		
Capital: eTRU	[CARB staff seeking information]	$29,400
Capital: Fuel Cell		Not applicable
Capital: Tanks		[CARB staff seeking information]
Annual Fuel		
Maintenance		

Table 5: Cost Comparison Between Hydrogen Fuel Cell TRU Options and a Diesel-Powered TRU (cont.)

Cost Component	Hydrogen Fuel Cell Costs	Diesel Costs
Hydrogen Fuel Cell TRU Generator Set: Pin-On Class		
Capital	[CARB staff seeking information]	$17,940[120]
Annual Fuel		[CARB staff seeking information]
Maintenance		
Hydrogen Fuel Cell TRU Generator Set: Underslung Class		
Capital	[CARB staff seeking information]	$17,250[121]
Annual Fuel		[CARB staff seeking information]
Maintenance		
Hydrogen Fuel Cell TRU Generator Set: Powerpack		
Capital	[CARB staff seeking information]	[CARB staff seeking information]
Annual Fuel		
Maintenance		

CARB staff seeking additional information on capital, operation, maintenance, and infrastructure cost for hydrogen fuel cell TRUs, hydrogen fuel cell-powered eTRUs, and the three types of hydrogen fuel cell generator set configurations.

Technology Outlook

Advantages

California has the most available hydrogen light-duty refueling stations in the U.S. Efforts began in the late 2010s to expand the hydrogen station network for heavy-duty vehicles and multi-modal equipment. Once developed, this network could also support hydrogen fuel cell TRUs. Some distribution centers already have hydrogen infrastructure in place for their warehouse material movers.

[120] GeneratorJoe. (n.d.). *Thermo King Model SGCO 4000 Clip-On*. generatorjoe. *https://www.generatorjoe.net/container-reefer-clipon-diesel-generators/containner-cllipon-thermoking/1007/*

[121] GeneratorJoe. (n.d.). *Thermo King Model SGUM 4000 Under Mount*. generatorjoe. *https://www.generatorjoe.net/container-reefer-clipon-diesel-generators/containner-cllipon-thermoking/1009/*

Return-to-base fleets and their use of hydrogen fuel cells may help reduce barriers, such as operating range, for long-haul fleets. Safety features, such as flame and hydrogen detectors have been incorporated into these systems in accordance with national standards. The experience fleets have with hydrogen fuel cell forklifts and their interest in hydrogen fuel cell TRUs indicates they have gained some level of comfort with safety issues related to handling hydrogen. Two potential safety issues with hydrogen fuel cells are danger of electrical shock and, as with diesel, flammability of the fuel.[122]

Hydrogen fuel cells are more efficient than diesel engines.[123] They also perform better at partial trailer loads.[124] How much more efficient depends on the size of diesel engine being compared and its application. For the size used in trailer TRUs, hydrogen fuel cells are at least twice as efficient.[125] Another operational characteristic that makes hydrogen a viable fuel source for TRUs is its high energy density (approximately 120 megajoules per kilogram [MJk]), which is more than twice that of diesel (approximately 45.5 MJk). The higher the energy density, the further or longer the power source will perform given the same weight of the source. Although the energy density of hydrogen is high, the weight of the hydrogen tank and required hardware needs to be considered for TRU applications.

In addition, hydrogen fuel cells can be filled in comparable or faster times than diesel. Hydrogen fuel cell-powered TRUs likely will be designed to tap into the existing retail hydrogen network for on-road vehicle (current standards at either 35 megapascal or 70 megapascal or tap into the site's existing hydrogen refueling infrastructure system for forklift equipment that fills at 35 megapascal. The refueling standard is in development for heavy-duty trucks. Hydrogen fuel cell TRUs could be manufactured to unify with the existing vehicle standards, new heavy-duty truck standard being developed, or with the forklift standard.

Range extending technologies (e.g., battery packs, regenerative braking, solar panels) can also be used in conjunction with a hydrogen fuel cell-powered TRU to reduce the amount of hydrogen required over long distances. Additionally, refueling a hydrogen tank to provide energy for a hydrogen fuel cell draws less power from the electrical grid than a battery pack would (using electrical charging infrastructure).

In comparisons to a diesel-powered TRU, hydrogen fuel cell-powered TRUs have fewer moving parts, which can result in reduced repair, maintenance, and downtime costs. They are also quieter and eliminate PM2.5, NOx, and GHG emissions.

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[122] The International Consortium for Fire Safety, Health, and the Environment. (n.d.) *safety issues regarding fuel cell vehicles and hydrogen fuel vehicles.* [white paper]. *https://dps.mn.gov/divisions/sfm/programs-services/Documents/Responder%20Safety/Alternative%20Fuels/FuelCellHydrogenFuelVehicleSafety.pdf*

[123] Molloy, Patrick. (2019, October 2). *Run on Less with Hydrogen Fuel Cells.* RMI. *https://rmi.org/run-on-less-with-hydrogen-fuel-cells/*

[124] J. Pratt, Sandia National Laboratories, Combustion Research Facility. (Personal communication with Rod Hill, CARB, September 8, 2014).

[125] Nuvera. (2013, August 30). *Demonstration of fuel Cell-Based Auxiliary Power Unit for Refrigerated Trucks, Phase I Business Case Report.* Nuvera Fuel Cells.

Challenges

The weight and size of the hydrogen tank(s) are a challenge for hydrogen fuel cell TRU applications. As shown in Table 6, a 50-gallon tank of diesel fuel weighs approximately 195 kg (430 lbs.) and can operate up to two days in mild weather conditions without any door openings. A hydrogen fuel cell TRU or TRU generator set achieving equal operating range would require multiple hydrogen tanks weighing approximately 1,243 kg (2,740 lbs.) each. For long-haul operations, the weight of the additional hydrogen tanks could be prohibitive. Short-haul, local, and return-to-base operations could opt for smaller hydrogen tanks to reduce weight, but they would require more frequent refueling. This option could work once more hydrogen filling stations become available.

Another challenge for operating range is the pressure rating for a hydrogen storage tank. Hydrogen storage tanks need to be rated for high pressure, 350 bars (about 5,000 pounds per square inch) or 700 bars (about 10,000 pounds per square inch). These high pressures require that the hydrogen tanks be made of specialized carbon fiber composite cylinders which are more costly compared to diesel fuel tanks.

The higher cost of a hydrogen fuel cell TRU and hydrogen fuel cell-powered eTRU may slow the adoption of these technologies. However, some costs can be offset because there are fewer moving parts than with diesel engines, thus reducing maintenance costs. The cost of hydrogen is currently much higher than diesel for equivalent TRU operation time, but the cost of hydrogen is expected to drop as the cost of diesel increases and hydrogen fuel cell passenger cars and heavy-duty trucks become more available.

Another challenge with the implementation of hydrogen fuel cell TRUs and hydrogen fuel cell-powered trailers is the lack of infrastructure. Implementation of hydrogen fuel cells for TRUs will depend on the proliferation of hydrogen infrastructure for heavy-duty trucks because many of the advantages for hydrogen fuel cell TRUs also apply to heavy-duty trucks. Hydrogen infrastructure developed for heavy-duty trucks will help propagate infrastructure that can be leveraged for hydrogen fuel cell TRUs and the adoption of hydrogen fuel cell-powered TRUs because operators can use one fuel source for the truck and trailer.

Safety could also be a challenge, as limited tests or studies related to the safety of hydrogen fuel cell use in TRU generator set applications exist. The Hydrogen Safety Panel, one of many existing hydrogen safety groups, continues to evaluate the safety of hydrogen fuel cell use in unique applications[126]. Continued testing and trials should further assess any potential safety issues associated with using hydrogen fuel cells and hydrogen tanks in a seaport facility or intermodal railyard environment.

[126] H2 Tools. (n.d.). *Hydrogen Safety Panel*. https://h2tools.org/hsp

Table 6: Comparison of Tank Size, Weight, Cost, and Operating Time[127]

Fuel Type	Tank Size	Operating Time (hours)	Tank Cost	Fuel Cost	Tank Weight (lb.)[128]	Mounting Equipment Weight (lb.)	Fuel Weight	Total Weight (lb.)
Diesel	50 gallons	62.5[129]	$540[130]	$163[131]	32[132]	44[133]	350 lbs.[134]	430
Hydrogen	10 kg	10[135]	[CARB staff seeking information]		350[136,137,138]	42[139]	22 lbs. (10 kg tank)	416

[127] All values are rounded to the nearest whole number.

[128] Pound (lb.)

[129] 50 gallons X (1 hr/0.8 gallon of diesel) = 62.5 hr. Typical diesel consumption for a diesel-powered TRU is 0.8 gallons per hour per California Air Resources Board. (August 2015). *Technology Assessment: Transport Refrigeration.*

[130] Diesel tank cost is an average of three new 50-gallon tanks for diesel-powered TRUs as of December 14: *www.finditparts.com* product American Mobile Power AR2250 ($670.21), *www.4statetrucks.com* product SKU 19-06006001 ($509.99), *www.otherstock.com* product stock number 12-0650 ($450.00).

[131] 50 gallons X $3.25/gallon = $163.

[132] Diesel tank and mounting equipment weight taken from American Mobile Power, product AR8550, 50-gallon aluminum. *https://www.americanmobilepower.com/products/reefer-tanks/24-diameter-reefer-tanks/aluminum-reefer-tank-50-gallon/172*

[133] Diesel tank and mounting equipment weight from American Mobile Power, product AR8550, 50-gallon aluminum reefer tank. *https://www.americanmobilepower.com/products/reefer-tanks/24-diameter-reefer-tanks/aluminum-reefer-tank-50-gallon/172*

[134] Density of diesel fuel is approx. 7 lb./gallon. 7 lb/gallon X 50 gallon = 350 lb.

[135] Hydrogen consumption for fuel cell TRU is about 1.0 kg/hr. Pacific Northwest National Laboratory. (June 13 ,2018). *Demonstration of Fuel Cell Auxiliary Power Unit (APU) to Power Truck Refrigeration Units (TRUs) in Refrigerated Trucks.* *https://www.hydrogen.energy.gov/pdfs/review18/mt014_brooks_2018_p.pdf*

[136] Quantum. (2019, June). *Hydrogen Cylinder General Specifications.* *http://www.qtww.com/wp-content/uploads/2019/06/H2-Tank-Specifications-June-2019-All-Tanks-1.pdf.* A Quantum Fuel Systems brand hydrogen tank that can contain 10.7 kg of hydrogen at 35 megapascal or 70 megapascal weighs 310 lbs. without a valve.

[137] Hexagon Purus. (n.d.). *Hydrogen Type 4 Cylinder Information*. Hexagon Purus. https*://s3.eu-central-1.amazonaws.com/hexagonpurus-website/Type4_Datasheet.pdf.* A Hexagon Purus brand hydrogen tank that can contain 10.4 kg of hydrogen at 25 megapascal weighs 424 lbs.

[138] Average of Quantum 10.7 kg product and Hexagon Purus 10.4 kg product weight extrapolated for 10 kg = 346 lbs.

[139] Assume 44 lbs. of support structure is required for full (50 gallon) diesel tank weighing 386 lbs. This produces a ratio of 0.113 lbs. of support structure per lb. A 10 kg tank full of hydrogen weighs 372 lbs. 372 lbs. X 0.113 = 42 lbs.

Table 6: Comparison of Tank Size, Weight, Cost, and Operating Time[140] (cont.)

Fuel Type	Tank Size	Operating Time (hours)	Tank Cost	Fuel Cost	Tank Weight (lb.)[141]	Mounting Equipment Weight (lb.)	Fuel Weight	Total Weight (lb.)
Hydrogen	30 kg	30[142]			1,040[143,144]	130[145,146]	70 lbs. (30 kg tank)	1,240
Hydrogen	60 kg	60[147]			2,100[148]	280[149,150]	360 lbs. (60 kg tank)	2,740

140 All values are rounded to the nearest whole number.

141 Pound (lb.)

142 Hydrogen consumption for fuel cell TRU is about 1.0 kg/hr. Pacific Northwest National Laboratory. (June 13, 2018). *Demonstration of Fuel Cell Auxiliary Power Unit (APU) to Power Truck Refrigeration Units (TRUs) in Refrigerated Trucks.* *https://www.hydrogen.energy.gov/pdfs/review18/mt014_brooks_2018_p.pdf*

143 Hexagon Purus. (n.d.). *Hydrogen Type 4 Cylinder Information*. Hexagon Purus. h*ttps: https://s3.eu-central-1.amazonaws.com/hexagonpurus-website/Type4_Datasheet.pdf.* A Hexagon Purus brand hydrogen tank that can contain 10.4 kg of hydrogen at 25 megapascal weighs 424 lbs.

144 3 X 10kg tanks at 346 lbs. each = 1,038 lbs.

145 Average of Quantum 10.7 kg product and Hexagon Purus 10.4 kg product weight extrapolated for 10 kg = 346 lbs.

146 1,116 lbs. (fuel + tank) X 0.113 = 126 lbs.

147 Hydrogen consumption for fuel cell TRU is about 1.0 kg/hr. Pacific Northwest National Laboratory. (June 13,2018). *Demonstration of Fuel Cell Auxiliary Power Unit (APU) to Power Truck Refrigeration Units (TRUs) in Refrigerated Trucks.* *https://www.hydrogen.energy.gov/pdfs/review18/mt014_brooks_2018_p.pdf*

148 6 X 10kg tanks at 346 lbs. each = 2,076 lbs.

149 Average of Quantum 10.7 kg product and Hexagon Purus 10.4 kg product weight extrapolated for 10 kg = 346 lbs.

150 2,460 (fuel + tank) X 0.113 = 278 lbs.

Cryogenic TRU Systems

Technology Description

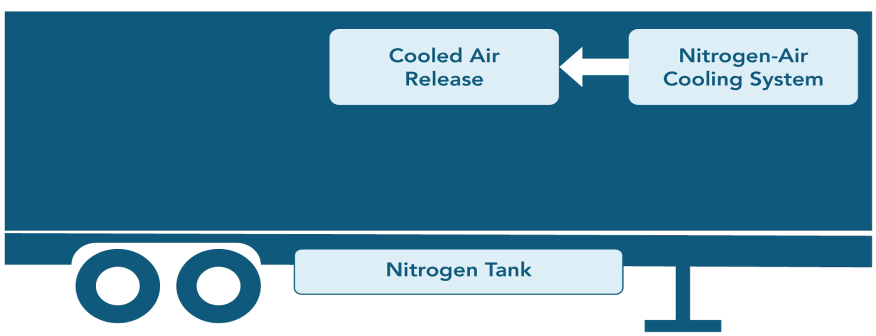
Cryogenics is the use of gases that are cooled to a liquid state and can be used for multiple applications, including transport refrigeration. A cryogenic TRU system uses either liquid nitrogen (LN2) or liquid carbon dioxide (LCO2) to cool the contents of the cargo space. These gases in their liquid state are referred to as cryogens. Use of cryogenics for transport refrigeration dates to the 1960's when LN2 was used for rail transportation.[151] However, as of 2021, there are no implementations of cryogenics for temperature-controlled transport via rail and few deployments for trailers in the U.S.

There are two types of cryogenic TRU systems: standard cryogenic TRU systems and the Dearman Engine™ cryogenic TRU system. There are also two different methods of deploying the cryogen for cooling the temperature-controlled cargo space, direct-injection and indirect-injection. With direct-injection cryogenic TRU systems (Figure 21), the cryogen is dispersed from a refillable storage tank under the trailer directly into the cargo space replacing the nitrogen-oxygen mixture of breathable air. Safety processes must be in place to prevent entry when there is an oxygen deficient atmosphere. Safety systems can include oxygen sensors to indicate if the cargo space has sufficient oxygen to enter, alarms and lights to notify the operator when the doors are open, and a rapid exhaust system to evacuate the nitrogen and replace it with breathable air. With indirect cooling cryogenic TRU systems (Figure 22), the cryogen is routed through heat exchangers which transfer the heat from the cargo space to the cryogen without the cryogen physically entering the cargo space. The warmed cryogen changes state from liquid to gas as it heats up and is then expelled from the system into the atmosphere. Both direct and indirect cryogenic TRU systems can be used in a multi-zone temperature-controlled trailer (Figure 23).

[151] Voss, J. (2015, August 26). *Cryogenics 101: An Introduction to a Cleaner, Quieter Alternative*. Refrigerated Transporter. *https://www.refrigeratedtransporter.com/refrigeration/article/21720389/cryogenics-101-an-introduction-to-a-cleaner-quieter-alternative*

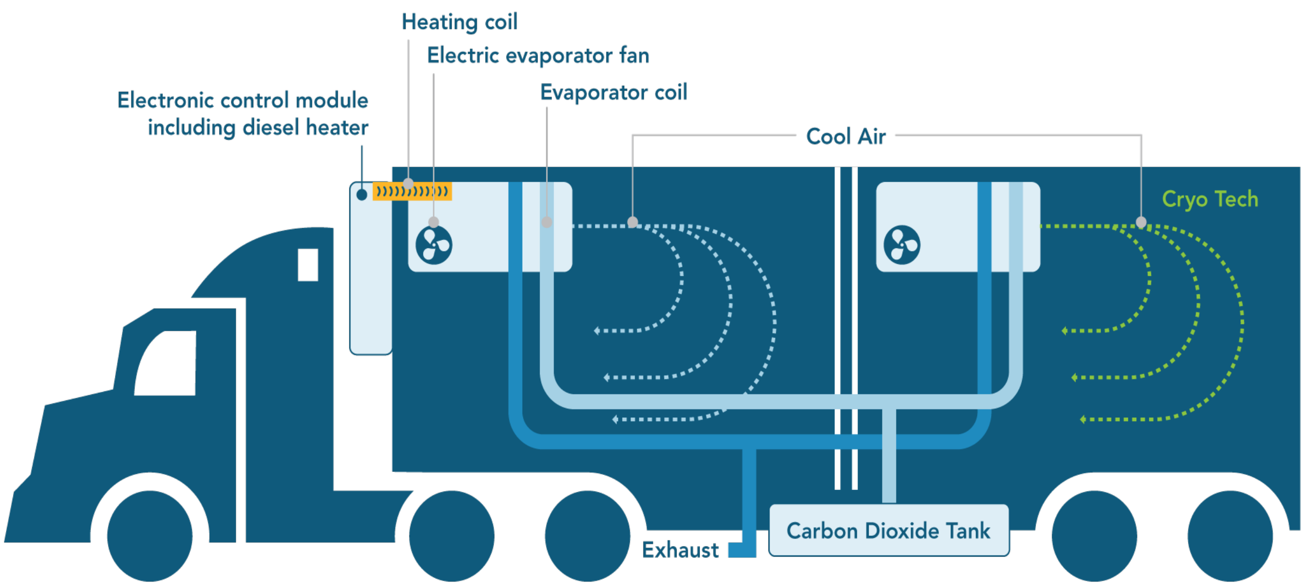
Figure 21: Example of Direct Injection Cooled LN2 Cryogenic TRU System

Figure 22: Example of Indirect Cooling LN2 Cryogenic TRU System[152]



[152] Pedolsky, H., & La Bau, R. (2010). *Reintroduction of Cryogenic Refrigeration for Cold Transport*. International Refrigeration and Air Conditioning Conference. *http://docs.lib.purdue.edu/iracc/1021*

Figure 23: Indirect LCO2 Cooling System – Multi-Temp Temperature-controlled Trailer[153]



The primary components of a cryogenic TRU system are the cryogenic storage tank; a means to dispense the cryogen and transfer cooling, by either sprayer in direct-injection systems, or heat exchangers in indirect cooling systems; and fans to circulate air. The storage tanks for cryogens are sized to provide adequate cryogenic TRU system operating range. Operating range is dependent on door openings, trailer thermal efficiency, and outside climate but is usually less than 24 hours.

Controllers and flow regulators are also needed to meter the dispensing of the cryogen to properly control the desired temperature. Redundant electronic sensors and controllers are often used to ensure desired temperatures are maintained and safety systems are robust. Standard cryogenic TRU systems have fewer moving parts than a diesel-powered TRU as it does not require an engine or compressor. Some of the equipment directly contacts the cryogen, which can be as cold as -320 degrees Fahrenheit (-196 degrees Celsius) so equipment materials must be compatible with cold very temperatures.[154]

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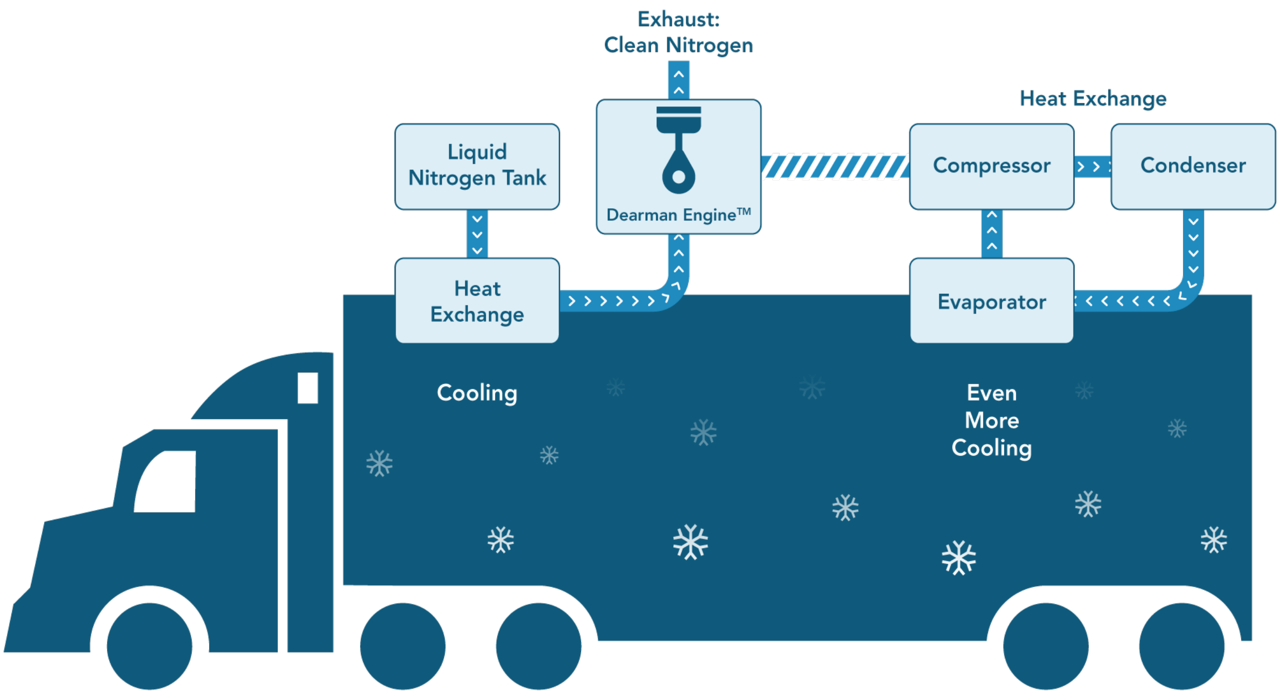
[153] Thermo King. (2020). *CryoTech Brochure*. Thermo King. *https://europe.thermoking.com/wp-content/uploads/2019/07/TK80.22_CryoTech-08-2020-EN_V1.0.pdf*

[154]Health and Environmental Safety of Nanomaterials. (2014). *Liquid Nitrogen*. Science Direct. *https://www.sciencedirect.com/topics/chemical-engineering/liquid-nitrogen*

Clean Cold Power's Dearman Engine™ cryogenic TRU system (Figure 24) uses LN2 for two cooling cycles. The first cycle is the standard indirect cooling process described previously in which the LN2 is pumped through heat exchangers to pull heat from the cargo space. This provides about two-thirds of the total cooling for the system.[155] As the LN2 absorbs heat from the cargo space, it changes to a gaseous state and is injected into the Dearman Engine™ along with a warm heat exchange fluid. The heat exchange fluid causes a rapid expansion of the gas which drives pistons which then power both a conventional vapor compression refrigeration system for further cooling to the cargo space and an electric generator to power ancillaries such as fans, defrosters, and a downsized refrigerator for additional cooling.

Figure 24: Clean Cold Power Dearman Engine™ Cryogenic TRU System Cycle[156]



[155] Dearman. (2018, April 19). *ACT Expo – Dearman/Hubbard Transport Refrigeration Unit* [Video]. YouTube. *https://youtu.be/BnvZuOK1McU*

[156] Clean Cold Power. (2021). *Clean Cold Power*.. *https://cleancoldpower.com/cool-technology/*

Similar to the cooling mechanisms of a standard cryogenic TRU system, CryoLogistics' SnowSHIP technology uses LCO2 to control the temperature within a single pallet-sized insulated container without the use of a traditional TRU equipped to the trailer. This technology allows for the transport of both temperature-controlled goods and dry goods within a trailer, and it also allows for the transport of mixed temperature-controlled goods if using multiple SnowSHIP products within a trailer[157].

Technology Readiness

Cryogenic TRU systems for trailers have been commercially available in Europe since at least 2002.[158,159] Cryogenic TRU systems were historically used for temperature-controlled trucks (truck) because trucks have a smaller volume to cool than trailers and cooling capacity is limited by the size of the cryogenic storage tanks. Tanks for trucks can be smaller, lighter, and more economical than the larger tanks required for trailers. Cryogenic TRU systems are used where the cryogen is readily available, as demonstrated by the commercial implementation of 43 trailers using the Boreas direct-injection cryogenic TRU system in Tracy, California since 2011. No new commercial deployments of cryogenic TRU systems for trailers exist in the U.S. Other manufacturers with commercially available cryogenic TRU systems offer their products only in Europe. These companies include Cryotherm, Thermo King, and Valeo-Transfrig.[160,161,162] See Appendix A for a complete list of demonstration projects.

Emission Benefits

During operation, LN2 cryogenic TRU systems use cryogen to collect the heat from the cargo space and emit the heated gaseous nitrogen into the atmosphere. Unlike LN2 cryogenic TRU systems, LCO2 systems release gaseous carbon dioxide, a GHG, during operation. However, the gaseous carbon dioxide used to produce the LCO2 in these cryogenic systems is often a byproduct of other industrial processes. The gaseous carbon dioxide which would have been expelled into the atmosphere directly as a byproduct of other industrial processes is instead

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[157] CryoLogistics (n.d.). *Reinventing the Cold Chain*. Retrieved June 23, 2022, from https://cryologistics.ca/

[158] Tassou, S. A., Hadawey, A., Ge, Y.T., & Lagroy de Groutte, B. (2008). *Carbon Dioxide Cryogenic Transport Refrigeration Systems*. The Centre for Energy and Built Environment Research. Grimsby Institute. https://www.grimsby.ac.uk/documents/defra/trns-casestudy.pdf

[159] Trailer-Body Builders. (2002, May 1). *Thermo King Introduces New Truck Units.* Trailer-Body Builders. https://www.trailer-bodybuilders.com/archive/article/21729209/thermo-king-introduces-new-truck-units

[160] Cryotherm. (n.d.). *Our cryogenic product groups*. Cryotherm. https://www.cryotherminc.com/cryogenic-products-from-the-market-leader-at-a-glance-cryotherm

[161] Bates, Scott., Thermo King. (2021, September 7). Meeting with CARB staff and Thermo King.

[162] Valeo Transport Refrigeration. (n.d.). *CryoFridge*. https://www.valeo-transportrefrigeration.com/global_en/Products/Cryogenic-Systems/CryoFridge

captured and diverted for commercial and industrial applications like soda carbonization, cement production, dry ice production, and cryogenic TRU system operation.[163,164]

Infrastructure Requirements

Companies that provide LCO2 and nitrogen gas delivery options that may include on-site generation, bulk truck delivery, or pipeline.[165,166,167] Costs vary depending on the quantity and purity of the LN2 purchased and proximity to the source producing the cryogens.

Refilling infrastructure for LN2 and LCO2 cryogenic TRU systems consists of a bulk storage tank and a dispenser with a liquid gas fill pipe. Dispensers can be gravity or pump fill. The gravity dispensers can be slow to fill depending on the temperature and pressure differentials between the dispensing tank and the receiving tank. In the U.S., many fleets prefer a quick fill system which takes about the same time as a diesel refueling. Dispensers can be configured to fill a single tank or multiple tanks as needed. Cryogen suppliers can lease tanks and dispensers, offer on-site generation packages, and provide pipeline delivery support.

Cryogenic liquid fueling infrastructure is not common in the U.S. and additional infrastructure is needed to facilitate market growth.

CARB staff seeking additional information on how operators will refill cryogen tanks for TRUs.

Economics

The economics associated with cryogenic TRU systems consist of one-time costs which include equipment and capitalized infrastructure costs. They also include recurring costs associated with the operation and maintenance of the cryogenic TRU system equipment and any leased supply infrastructure. Operating costs are comparable to a diesel-powered TRU, but maintenance costs for cryogenic TRU systems are lower due to fewer moving parts.

Table 7 displays estimated one-time equipment costs and estimated recurring costs for a trailer cryogenic TRU system compared to a diesel-powered TRU.

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[163] CO2 Cooling Marketplace. (2021, November 30). *New Refrigerated Transport System Runs on Liquid CO2 Evaporation.* R744. https://r744.com/new-refrigerated-transport-system-runs-on-liquid-co2-evaporation-compressor-free/

[164] Roberts, David. (2019, November 27). *These uses of CO2 could cut emissions — and make trillions of dollars: From concrete to fuels, CO2 from the air can replace CO2 from the ground.* Vox. https://www.vox.com/energy-and-environment/2019/11/13/20839531/climate-change-industry-co2-carbon-capture-utilization-storage-ccu

[165] Airgas an Air Liquide Company. (2021). *Airgas.* Airgas. https://www.airgas.com/

[166] Praxair. (2021). *Praxair*. Praxair. https://www.praxairusa.com

[167] Linde. (2021). *Linde*. Lindeus. https://www.lindeus.com/

Table 7: Comparison of Estimated Costs for Operation of a Cryogenic TRU System vs. a Diesel-Powered TRU

Frequency	Cost Component	Cryogenic TRU System Costs	Diesel Costs
One-Time Costs	Capital	$35,000-$50,000[168]	$29,400[169]
	Dispensing System	$10,000[170]	Not applicable
Recurring Costs	LN2 Gravity Feed System	$1,500 per month[171]	Not applicable
	LN2 Quick Fill System	$3,000 per month	Not applicable
	Tank Lease	$270 per month (13-ton)[172]	Not applicable
	Operation[173]	Cost varies	Cost varies
	Maintenance	$900 per year[174,175]	$1,900 per year[176,177]

CARB staff seeking additional updated capital, operation (including tank certification), maintenance, and infrastructure costs for a cryogenic TRU system.

[168] Claimed confidential data obtained from industry sources that requested non-attribution. $2021

[169] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA).* CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

[170] Arthur D. Little, Inc. (2001, April 23). *Demonstration of Cryogenic Refrigeration Technology in Truck Trailers.* Final Report to South Coast Air Quality Management District Contract No. 97141; ADL Case Numbers 70371-70374.

[171] California Air Resources Board. (2015, August). *Technology Assessment: Transport Refrigerators.* CARB. https://ww2.arb.ca.gov/sites/default/files/2020-06/TRU%20Tech%20Assessment%20Report%20ada.pdf

[172] Arthur D. Little, Inc. (2001, April 23). *Demonstration of Cryogenic Refrigeration Technology in Truck Trailers.* Final Report to South Coast Air Quality Management District Contract No. 97141; ADL Case Numbers 70371-70374.

[173] Cryogenic system operation costs include annual fuel costs and costs for certification of the fuel storage tank.

[174] Cryogenic TRU system equipment maintenance costs. 2020$

[175] California Air Resources Board. (2021, July 27). Public Hearing to Consider the Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate. Staff Report: Initial Statement of Reasons. CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/isor.pdf

[176] Diesel-powered TRU maintenance costs: $0.95/hr for 2,000 hr. 2021$

[177] California Air Resources Board. (2021, July 27). *Proposed Amendments to the Airborne Toxic Control Measure for In-Use Diesel-Fueled Transport Refrigeration Units (TRU) and TRU Generator Sets, and Facilities Where TRUs Operate Staff Standardized Regulatory Impact Assessment (SRIA).* CARB. https://ww3.arb.ca.gov/board/rulemaking/tru2021/appb.pdf

Technology Outlook

Advantages

Cryogenic TRU systems provide 70 percent faster initial chill-down times and better temperature maintenance after a delivery door is opened, compared to diesel-powered TRUs.[178]

Cryogenic TRU systems are quiet compared to diesel-powered TRUs due to the absence of the diesel engine and associated equipment. For example, the Boreas direct-inject cryogenic refrigeration system operates at approximately 20 decibels as compared to diesel-powered TRUs which typically operate between 75 and 85 decibels.[179,180] Quiet operations make cryogenic TRU systems ideal for operating in areas with noise restrictions.

In addition, maintenance is reduced due to the lack of a diesel engine and other associated moving parts. Cryogenic TRU systems have also been reported to cause less product dehydration compared to diesel-powered TRUs.[181] Cryogenic TRU systems do not use refrigerants, which require periodic recharging and emit GHGs.[182] The use of cryogens eliminates both the use of high global warming potential refrigerants and emissions associated with the use of diesel.[183]

Challenges

Key performance parameters issues include range, capital costs and operating costs, availability of cryogens, and safety issues around potentially oxygen-deficient atmospheres in the case of direct-injection cryogenic TRU systems.

Operating range is limited to the size of the on-board tank and the rate of release for the cryogen. Rate of release for the cryogen is affected by a temperature differential between atmospheric and product temperature, door openings, and thermal efficiency of the trailer. Minimizing door opening frequency and duration will minimize need for temperature recovery.

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[178] EcoFridge Production Company, LTD. (2014). natureFridge brochure.

[179] Boreas. (n.d.). *Boreas Nitrogen Cooling Systems* [Brochure]. Boreas. *https://www.boreassystems.com/wp-content/uploads/2018/02/Boreas-Spec-Sheet.pdf*

[180] WJV Acoustics, Inc. (2017, January 25). *Acoustical Analysis, Producers Dairy Parking Lot 450 East Belmont Avenue, Fresno, California*. Fresno. *https://www.fresno.gov/darm/wp-content/uploads/sites/10/2017/03/Appendix-G-Acoustic-Study.pdf*

[181] Konstantin Gavrilov, ecoFridge Production Company LTD, Ukraine. (personal communication with Carolyn Craig of CARB's Transportation and Toxics Division, June 24, 2014).

[182] Voss, J. (2015, August 26). *Cryogenics 101: An introduction to a cleaner, quieter alternative*. Refrigerated Transporter. Retrieved September 20, 2021, from *https://www.refrigeratedtransporter.com/refrigeration/article/21720389/cryogenics-101-an-introduction-to-a-cleaner-quieter-alternative*

[183] California Air Resources Board. (2015, August). *Technology Assessment: Transport Refrigerators.* CARB. *https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/tru_07292015.pdf*

Initial capital costs of cryogenic TRU systems are higher than diesel-powered TRUs. In addition, cryogen storage and dispensing infrastructure adds to the cost due to lack of availability of public cryogenic dispensing facilities. Some facilities may choose to capitalize storage and dispensing infrastructure, but others may choose to lease the equipment from the cryogen supplier, making it an operating expense. Cryogenic TRU systems are durable as there are fewer mechanical parts, but parts which contact the cryogen must be fabricated with materials that can withstand the low temperatures associated with cryogenic compounds. In addition, cryogenic storage tanks have periodic certification requirements that can include criteria on system design, facility siting and equipment installation, quality assurance, and safety review.[184]

Operating costs for cryogen vary based on contracts and manufacturing issues. In addition, cryogen distribution costs can vary dependent on the distance from the generation point.

Another consideration is that handling of cryogens requires training and implementation of safety protocols that are necessary to prevent personal injury.

CARB staff seeking additional information on how various operating conditions can impact operating range for cryogenic TRU systems.

CARB staff are also seeking additional information on cryogenic TRU system operational viability in California.

[184] U.S. Department of Energy. (1989, April 6). *DOE O 6430.1A Div 8-16, General Design Criteria*. U.S. DOE. *https://www.directives.doe.gov/directives-documents/6400-series/6430.1-BOrder-adiv8-16/@@images/file*

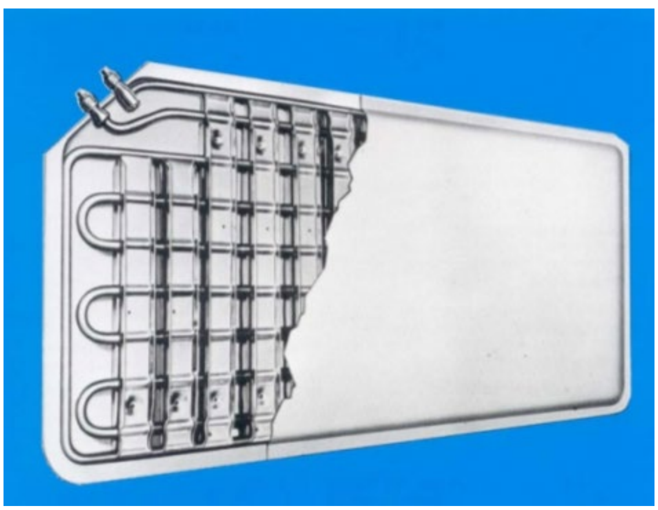
Potential Technology

Cold Plates

A cold plate (cold plate; shown in Figure 25) consists of a sheet metal enclosure with internal evaporator coils which are surrounded by fluid. The fluid used in cold plates is a mixture of water and salts (e.g., sodium and potassium salts) that form a "eutectic" solution with the lowest possible melting or freezing point.

Cold plates are mounted on the ceiling or walls of the cargo area or inside compartment partitions. The cold plate TRU system can offer single- or multi-temp applications. An electrically-driven refrigeration unit, which is mounted to the outside of the temperature-controlled container, must be plugged into shore power to pump refrigerant through the evaporator coils until the eutectic solution is frozen. Once frozen, perishable goods can be loaded. Freezing cold plates usually requires six to eight hours and is most often done overnight.[185] Cold plates can support cooling for up to 12 hours by absorbing the heat from the cargo space causing the frozen eutectic solution to phase change back to a liquid state.[186] Once thawed, cold plates need to be refrozen by plugging into a single-phase or three-phase electric power source.

Figure 25: Cold Plate



[185] Refrigerated Transporter. (2005, November 1). *Power to the plates.* Refrigerated Transporter. https://www.refrigeratedtransporter.com/archive/article/21712541/power-to-the-plates

[186] Refrigerated Transporter. (2005, November 1). *Power to the plates.* Refrigerated Transporter. https://www.refrigeratedtransporter.com/archive/article/21712541/power-to-the-plates

As of 2022, cold plate technology is used only in truck applications as there is no industry demand for non-trucks. Cold plate technology does not yet align with the economic and operational requirements associated with long-haul trailers due to their size and weight impacts on payload capacity and the short cooling times that generally limit use to short-haul applications.

As the industry shifts to zero-emission heavy-duty trucks and zero-emission TRUs, the application of cold plates may be explored further by industry as a viable zero-emission TRU alternative for trailers, domestic shipping containers, or railcars. When combined with other zero-emission technologies such as batteries, solar panels, or direct power from a zero-emission tractor, cold plates could be adapted for specific trailers including long-haul operations.

Cold plate technology for trailers is not in development. Therefore, a discussion on the following technology elements for cold plates is not included in this section: emission benefits, infrastructure requirements, economics, and technology outlook.

CARB staff seeking additional information on development of cold plate technology for non-truck applications.

Range Extending Technologies

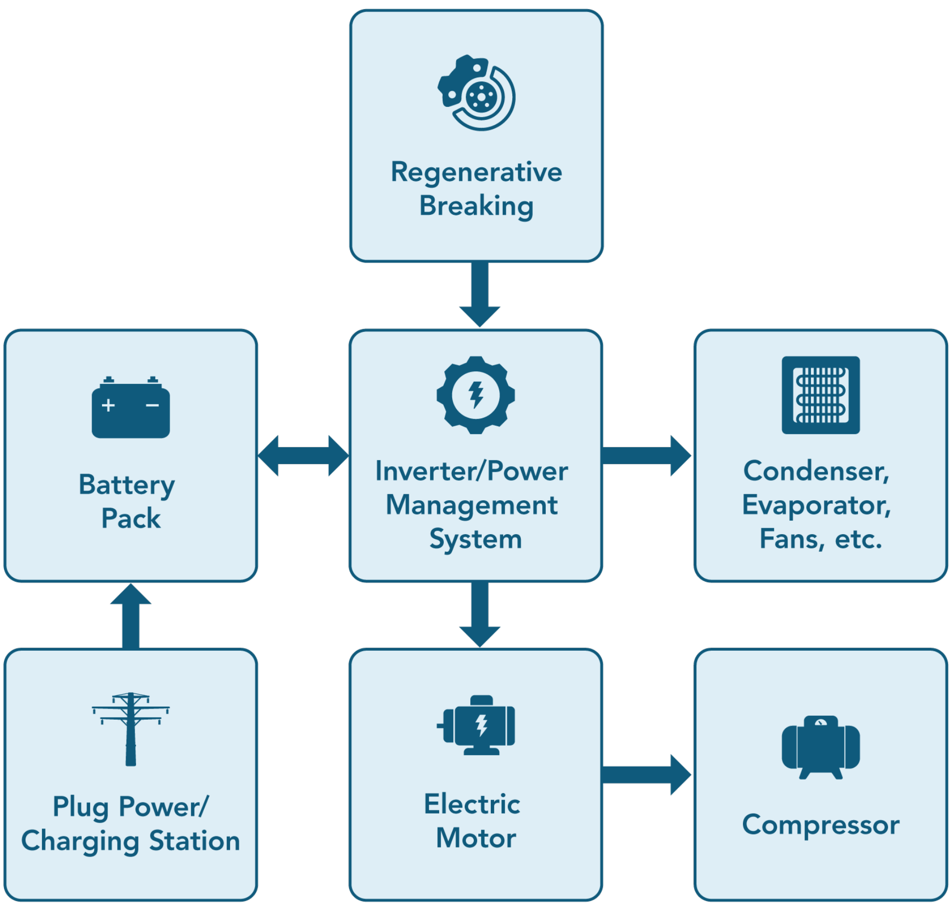
Technologies, such as regenerative braking and solar assist (photovoltaic cells) can extend the operating range of a battery-electric TRU and can reduce the frequency and duration of charging events. The Range Extending Technologies section includes a description of the technology, readiness for commercial deployment, discussion of emission impacts and infrastructure, and the future outlook of these technologies.

The additional capital costs of these range extending technologies are incorporated into the total cost of a zero-emission TRU solution when regenerative braking and/or solar assist are included. There will be additional maintenance costs for both a regenerative braking and solar assist system; however, these costs are not known at this time.

Regenerative Braking

In a traditional friction braking system (shown in Figure 26), the kinetic energy of a spinning wheel is converted into thermal energy and released as heat. A regenerative braking system converts a portion of the kinetic energy that would be lost during braking events into electrical energy that can be used immediately or stored in onboard batteries.

Figure 26: Regenerative Braking Electricity Flow Diagram



A regenerative braking system generates electricity by slowing the spinning wheel using magnetic fields or mechanical torque,[187] which is the reverse of depressing the accelerator pedal of an electric vehicle and using electricity to spin the wheel. When the vehicle operator engages the brake pedal, the onboard computer engages the generator that is connected to the rotating wheel or axle of the trailer and the process of converting motion into electro-magnetic power begins to slow the trailer. The resultant power is routed to the battery pack or used to power auxiliary equipment, such as an eTRU, depending on state of charge of the battery pack and power needs of the eTRU.

Zero-emission tractor power can also be used indirectly to drive a generator that is integrated with the wheel or the axle of a trailer or railcar. Indirect power transfer uses the kinetic energy (i.e., the momentum) of a trailer or railcar to provide power for the eTRU. The power from the generator is routed to a battery pack onboard the trailer which can then be used to power the eTRU or temperature-controlled cargo space. As with regenerative braking systems, the trailer is equipped with generators that are integrated into the wheels or axle of the trailer or railcar. The difference with indirect tractor power is that the generator is engaged as needed while the tractor or railcar is in motion to convert a small portion of the kinetic energy into electrical energy, which is then used to keep the trailer operating and the battery pack charged.

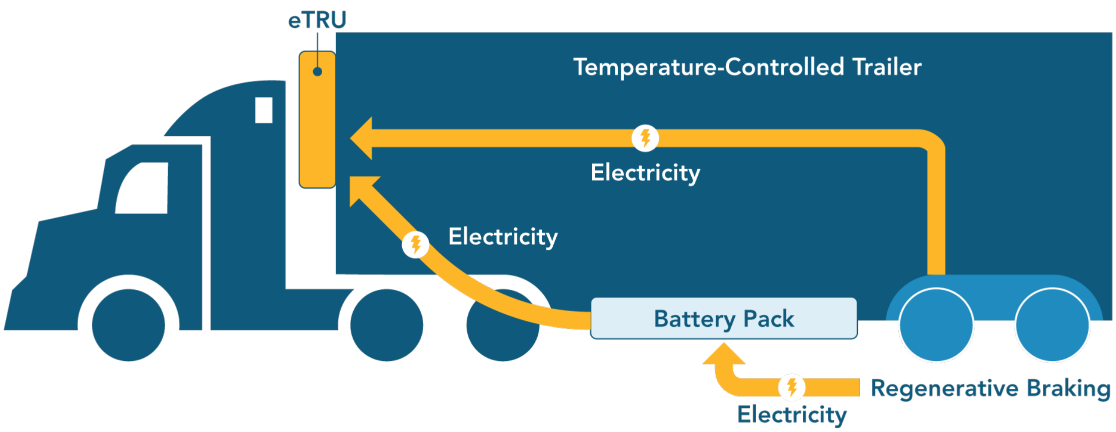
Regenerative braking systems for a trailer TRU application will be located on the trailer, however, zero-emission trucks could also have their own separate regenerative braking system. Regenerative braking systems help to decelerate the trailer, so there is less wear on brake pads, resulting in less maintenance and less particulate emissions from brake pad wear.

For zero-emission tractor power applications, the power transfer from the wheel or axle generator is represented by power flow direction 1 in Figure 27. The tractor is shown in gray in the figure to show that all the power for the eTRU is generated within the trailer without a physical connection to the zero-emission tractor. Using indirect power for the eTRU is possible with any class of zero-emission tractor or zero-emission freight locomotive.

CARB staff seeking additional information how much brake pad wear reduction is achieved with regenerative braking.

187. Afework, B., (2018, June 4.). *Regenerative Braking.* Energy Education. https://energyeducation.ca/encyclopedia/Regenerative_braking

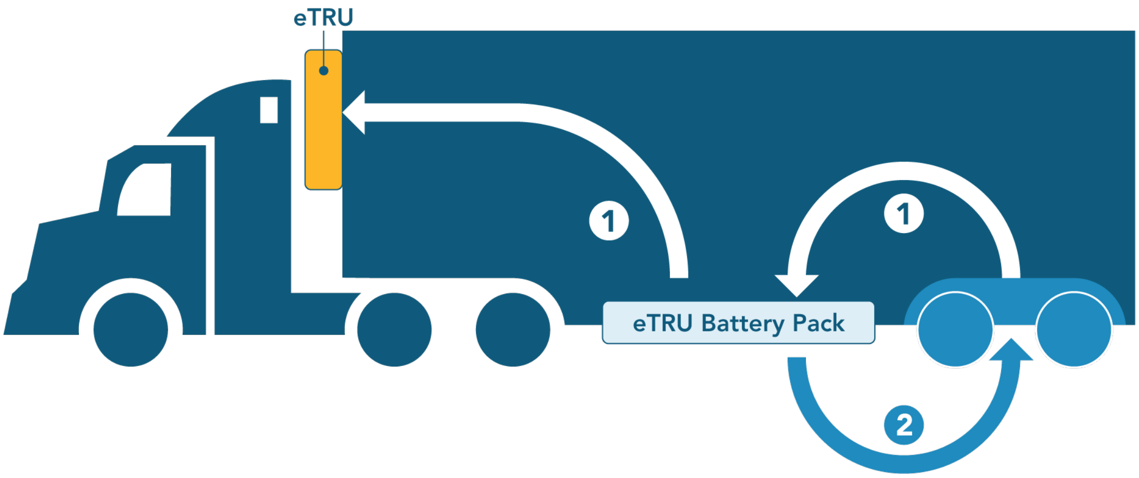
Figure 27: Battery-Electric TRU with Regenerative Braking



Inverters and other power electronics are required to provide a steady flow of current to the battery pack and the temperature-controlled trailer due to the constantly changing wheel velocity and the power requirement differences between the eTRU and the generator. There is drag placed on the tractor or locomotive because there are resistive forces at the trailer hub/axle when energy is being collected from the motion of the trailer.

Some axles or wheel generators used to provide power for the eTRU are configured to reverse the energy conversion process and also act as a motor. In this mode, the electrical energy that has been collected and stored in the battery pack is converted back into kinetic energy providing motive power to the trailer, as represented by power flow direction 2 in Figure 28.

Figure 28: Indirect Power for an eTRU Using Axle or Wheel Power Generation from the Trailer



Regenerative braking is most beneficial on routes that have many stops or routes with numerous elevation changes. The deceleration needed for frequent stops and descents allow the regenerative braking system to generate electricity and charge the onboard batteries.

Using zero-emission tractor power indirectly to power trailers has many advantages. Kinetic energy collection reduces the need to charge the eTRU battery pack when stationary. During transit, the trailer can potentially operate without any need for charging, as long as the tractor has sufficient charge to keep pulling the trailer. With sufficient battery pack capacity, the eTRU can operate independent of the tractor during any required breaks or sleepovers. Another advantage is that the trailer and tractor do not need to utilize the same fuel source.

Regenerative braking has limitations in slowing or stopping the trailer, which means that friction brakes will still be required to help slow or stop the trailer in some instances. In addition, regenerative braking relies on deceleration events to generate electricity, so routes requiring a trailer TRU to travel long distances at highway speeds without braking will not generate power for the eTRU during these constant speed portions of the trip.

There will not be an increase in emissions from the TRU or from pulling the trailer TRU with the use of regenerative braking if the tractor is already zero-emission and no additional infrastructure will be required for this technology. There are additional mechanical and electrical components needed for a regenerative braking system, but these components are not expected to impact the available payload of the trailer. Likewise, there will be no increases in emissions when a zero-emission tractor is providing indirect power to the eTRU.

Regenerative braking systems are included in all battery-electric and hybrid vehicles sold in the U.S.[188] Some heavy-duty commercial electric trucks in production also include regenerative braking. For example, the Volvo VNR Electric is a zero-emission Class 8 truck that utilizes regenerative braking to extend operating range by up to 15 percent.[189]

In addition to vehicles, companies are developing systems that can be installed on trailers that utilize either the wheel hub or axle to supply power. The manufacturers who are developing, sell, or already include regenerative braking systems in their trailer product include but are not limited to Advanced Energy Machines, Carrier, Conmet, Ecolution kWh, Emerald Technologies, Schmitz Cargobull, Nidec, and SAF-Holland. The added range due to regenerative braking on a trailer TRU or using a zero-emission tractor is not known at this time because these systems are still in development.

CARB staff seeking additional information on how much energy is generated and how much additional range is gained from regenerative braking for various route types and elevations (downhill and flat).

CARB staff are also seeking additional information on the capital and installation cost of a regenerative braking system.

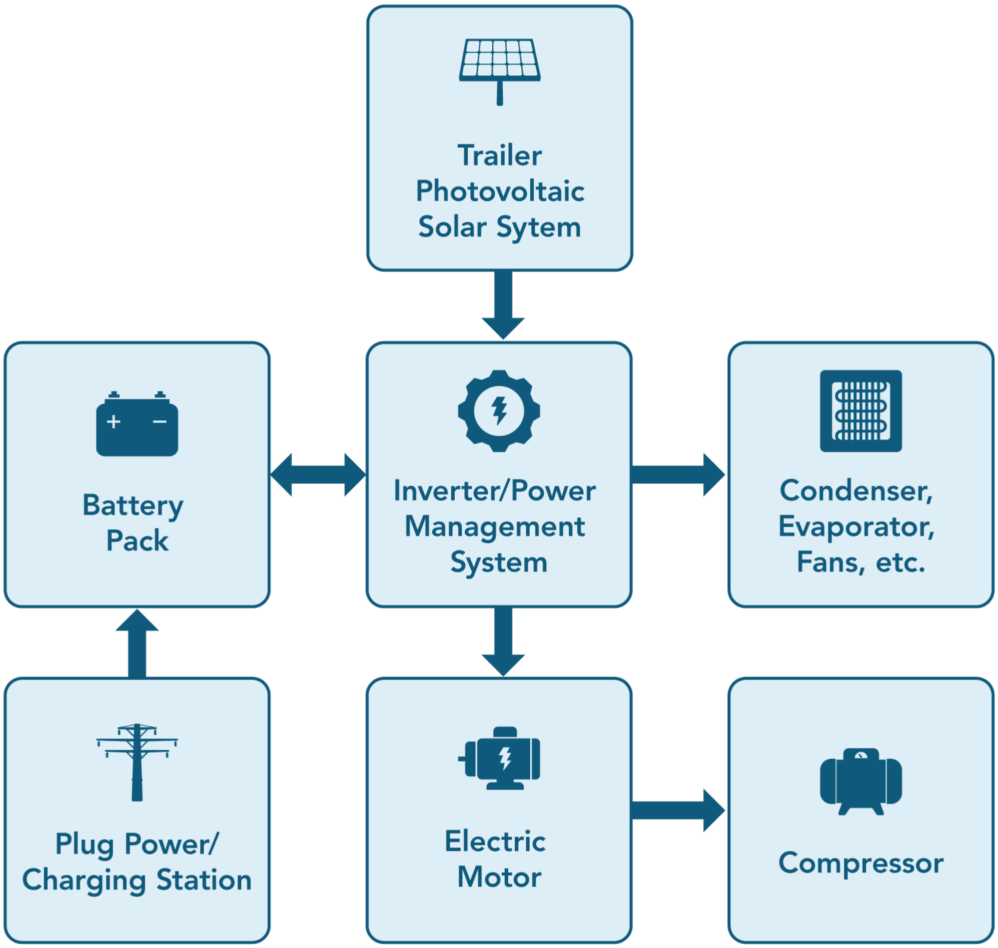
Solar Assist (Photovoltaic Cells)

Solar involves high-efficiency monocrystalline silicone solar photovoltaic cells mounted on a flexible support foundation in modules able to withstand road vibration and shock. These photovoltaic modules are mounted on top of the trailer roof to capture solar irradiation and collect the energy as DC electricity using the photovoltaic effect. The application of solar assist technology is specific to trailer TRUs as other classes of TRU applications such as railcars and domestic shipping containers are often stacked, prohibiting the installation of solar panels. A solar charge controller is used to optimize the power coming from the photovoltaic cells and manage the electric power delivery to the onboard battery pack or TRU. Figure 29 displays a diagram of the solar assist system.

[188] Vincent, J. M. (2017, March 20). *What is Regenerative Braking?* U.S. News. Retrieved October 1, 2021, from *https://cars.usnews.com/cars-trucks/what-is-regenerative-braking*

[189] Volvo. (2021, March 18). *Volvo VNR Electric Now Eligible for Vehicle Funding and Incentives Across America*. Volvo. Retrieved October 1, 2021, from *https://www.volvogroup.com/en/news-and-media/news/2021/mar/volvo-vnr-electric.html*

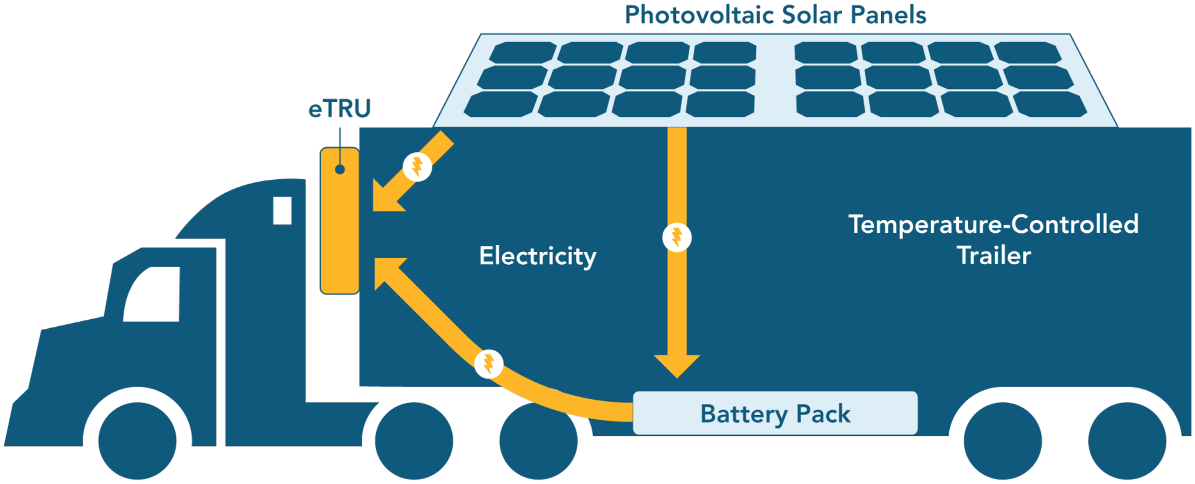
Figure 29: Solar Assist Electricity Flow Diagram



A DC-to-AC inverter is part of the power management system to convert DC power from the solar array and batteries to AC power for the refrigeration compressor, electronic controls, and condenser and evaporator fans.

The two most important factors impacting range extension are the power draw of the TRU and the overall capacity of the installed solar panels. The power draw of the TRU can vary from 2 kW to 18 kW depending on the specific cooling or heating needs of the trailer and the loaded freight. A 53-foot trailer has a rooftop surface area of about 450 square feet, which can accommodate a maximum solar capacity of about 5 kW, depending on the specific power density of the installed solar panels. The actual amount of power produced from the solar panels will depend on the available sunlight each day. When the solar panels are producing more power than needed by the TRU, the extra power charges the onboard battery pack. When the solar panels produce less power than required by the TRU, the TRU draws power from the battery pack. The solar system capacity and battery pack capacity will need to be optimized for maximum operating range. Fleets will need to consider that the power generated from the solar assist system (Figure 30) will fluctuate with the seasons due to the available sunlight and this can also change on an hour-to-hour basis.

Figure 30: Battery-Electric TRU with Solar Assist



Adding solar panels to a trailer (Figure 31) will not impact emissions from the TRU or from the truck pulling the trailer TRU and no additional infrastructure will be required. Solar panels do add weight to the trailer, but the additional weight is minimal. For example, a 5-kW solar system weighs around 125 kg (275 lbs.) compared to the overall empty trailer weight of 5443 kg (12,000 lbs.).[190,191] The extended range from the solar assist system could decrease the frequency and duration of charging events.

Manufacturers eNow and Advanced Energy Machines both have solar assist battery-electric TRUs commercially available.

CARB staff seeking additional information on how much energy is generated and how much additional range is gained from solar assist under various operating conditions

CARB staff are also seeking additional information on the capital and installation cost of a solar assist system.

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[190] PowerFilm Solar. (n.d.). *Trucking*. Power Film Solar. www.powerfilmsolar.com/markets/transportation/trucking/

[191] Great Dane. (n.d.). *Everest Refrigerated Trailer*. Great Dane. greatdane.com/refrigerated/everest/

Figure 31: Trailer with Solar Assist[192]

[192] University of Southampton. Energy and Climate Change. *Keeping Food Chilled – By Solar Power*. University of South Hampton. *https://energy.soton.ac.uk/keeping-food-chilled-by-solar-power/*

Complementary Technology

Telematics

A telematics system is hardware that provides real-time information about the operation and status of the TRU, including operating mode, operating time, temperature setpoints, fuel levels, service alerts, global positioning system location, door openings, and sensor temperatures.

The telematics system hardware consists of a small electronic device mounted within the TRU housing. The device contains a global positioning system receiver, interface with the TRU operation, accelerometer, and a subscriber identity module card and modem that allow the device to send and receive communication through a cellular network.[193] Telematics data on TRU operations can be wirelessly downloaded and used by fleets to monitor TRU performance and maximize operational efficiency.

For zero-emission TRUs, telematics systems can provide fleets a better understanding of the operational characteristics of each zero-emission technology and allow fleets to make informed decisions when incorporating these technologies into their operations. Telematics systems for battery-electric TRUs could report the state of battery charge and remaining operating hours, which would be informative for battery-electric TRU operations. Using telematics data would also allow fleets to match each specific route with the most applicable zero-emission TRU technology and plan out infrastructure needs for each facility.

A telematics system, combined with on-board control systems, can trigger different TRU system operation modes based on predetermined parameters such as location, velocity, length of time in use, time of day, ambient temperature, internal temperature, and other factors.

Telematics systems are available for all TRUs in the U.S. and European market, either factory installed by original equipment manufacturers or installed as retrofits to existing ones. Thermo King offers the ConnectedSuite telematics solution, Carrier Transicold offers the eSolutions telematics solution, and other third-party companies offer their own custom telematics solutions.[194]

[193] Geotab. (2021, March 25). *What is telematics?* Geotab. www.geotab.com/blog/what-is-telematics/

[194] Roberts, J. (2021, September 29). *How Telematics are Changing the Cold Chain*. Trucking Info. www.truckinginfo.com/10153005/how-telematics-are-changing-the-cold-chain

III. Conclusion

The 2022 Technology Assessment was developed to support the directives of Governor's EO N-79-20 to help transition off-road equipment to zero-emission by 2035. The discussion focuses on non-truck TRUs because truck TRUs are already transitioning to zero-emission operation and will complete transitioning to zero-emission by 2029. Assessing zero-emission technologies for non-truck TRUs is the first step to achieve the additional emission reductions necessary to help California achieve its emissions reduction and climate goals, improve air quality, and protect public health.

Overall, the 2022 Technology Assessment illustrates that zero-emission technologies are available (or are in development) that may be able to move non-truck TRUs toward the goal of zero-emission operations by 2035. A mix of retail and private zero-emission infrastructure will be needed to help ensure successful deployment of these zero-emission technologies.

Throughout the document, call-out boxes are included to request specific information to fill in gaps in data for the different zero-emission technologies that can be used to support the transition of non-truck TRUs to zero-emission operation. CARB staff will continue to seek this information and will continue to assess the state of technology as the development of the concepts for the next TRU regulation progresses.

IV. Appendices

Appendix A. Zero-Emission Demonstration Projects for Non-Truck Transport Refrigeration Units (Trailer TRUs, Domestic Shipping Container TRUs, Railcar TRUs, and TRU Generator Sets) and Supporting Infrastructure (2015-2021)

CARB staff seeking additional information on the demonstration projects in this table.

CARB staff also seeking additional information on any other demonstration projects for zero-emission technologies for non-truck TRUs which are not listed in this table.

Table A-1: Zero-Emission Non-Truck TRU Demonstration Projects (2015-2022)

This table is intended to represent demonstration projects of zero-emission technologies for non-truck TRUs. This table contains information for demonstration projects for zero-emission trailer TRUs, TRU generator sets, and TRU infrastructure. Information has not been verified by California Air Resources Board (CARB or Board) staff. Demonstration projects for zero-emission domestic shipping container TRUs and railcar TRUs are unknown at this time.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
Zero-Emission Trailer TRU Demonstrations							
1	**Battery-electric TRU** (Advanced Energy Machines brand eTRU with range-extending technologies)	*Advanced Energy Machines*/ "SolarTech 48k-16"	1. Riverside, CA, United States (U.S.) 2. Commercialized 3. United Natural Foods Incorporated	May 2021	23 of 53, as of Nov 2021	Deploying 53 48-foot multi-zone temperature-controlled trailers with battery-electric TRUs with range-extending technologies at -10 degrees Fahrenheit for the frozen zone and 34 degrees Fahrenheit for the refrigerated zone. The project uses the *Clean Off-Road Equipment voucher incentive program (CORE)*. (*UNFI Riverside all-electric TRU fleet deployment*)	All units operated successfully. A 32-hour battery life was confirmed (with no door openings). 90 pounds (lb.) of fine particulate matter (PM2.5) was eliminated in 2021 as compared to operating diesel-powered TRUs. 125 megawatt-hours (MWh) of grid power was used for charging in 2021.

[195] Demonstrations are categorized into zero-emission trailer TRUs, zero-emission TRU generator sets, or infrastructure for zero-emission TRUs, then alphabetically by technology, then alphabetically by company name.

[196] Deployment phases include prototype, demonstration, pilot, and commercialized. Prototype means that one or two units are built in a lab environment for proof of concept. Demonstration means the development of one or two working units to prove out the technology or application. Demonstration units are not used for revenue service but are installed on the trailer and tested with actual temperature-controlled products and delivery routes. Pilot means that small numbers (usually one or two) of non-production units are being tested in real-world, commercial applications. These are often the demonstration units. Commercialized means that units are production level and are used by end customers for revenue service.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
2	**Battery-electric TRU** (Advanced Energy Machines brand eTRU with range-extending technologies)	*Advanced Energy Machines*/ "SolarTech 48k-16"	1. Irvine, CA, U.S. 2. Commercialized 3. Albertsons	Nov 2020	9	Deployed nine single-zone, 50-foot freezer trailers with battery-electric TRUs that operate daily at -20 degrees Fahrenheit and charge wirelessly. The project uses *CORE*.	Over 15,000 total hours of operating time successfully maintaining the -20-degree Fahrenheit temperature requirement. Over 18,000 successful wireless charges. A total of 80 lbs. of PM2.5 was eliminated in 2021 as compared to operating diesel-powered TRUs. Additionally, Albertsons combined two of these trailers using this battery-electric TRU with Volvo battery-electric tractors to demonstrate a 100 percent zero-emission commercial grocery delivery. (*Albertsons' deployment of AEM eTRUs*)

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
3	**Battery-electric TRU** (Advanced Energy Machines brand eTRU with range-extending technologies)	*Advanced Energy Machines*/ "SolarTech 48k-16"	1. Gilroy, CA, U.S. 2. Commercialized 3. Performance Food Group/ Freightliner	May 2021	10	Deployed 10 36-foot multi zone trailers with the frozen zone set to -10 degrees Fahrenheit and the refrigerated zone set to 35 degrees Fahrenheit. These battery-electric units operate six days per week with 14 stops per day. The project uses the *CORE*.	A 32-hour battery life was confirmed (with no door openings). Consistent temperature control and continuous operation with no downtime was confirmed with telematics system. 18 lbs. of PM2.5 was eliminated in 2021 as compared to operating diesel-powered TRUs. 34 MWh of grid power was used for charging in 2021.
4	**Battery-electric TRU** (Advanced Energy Machines brand eTRU with range-extending technologies)	*Advanced Energy Machines*/ "SolarTech 48k-16"	1. Rancho Cucamonga, CA, U.S. 2. Commercialized 3. Evolution Fresh/ Starbucks	Dec 2020	4	Four stationary 53-foot temperature-controlled trailers with battery-electric TRUs containing frozen goods operate continuously using both grid and solar power. The project uses the *CORE*.	22 lbs. of PM2.5 was eliminated in 2021 as compared to operating diesel-powered TRUs. 38 MWh of grid power was used for charging in 2021 using an average of 2.3 kilowatts (kW) per hour per battery-electric TRU when direct sunlight is not available for the solar system.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
5	**Battery-electric TRU** (Advanced Energy Machines brand eTRU with range-extending technologies)	*Advanced Energy Machines*/ "SolarTech 48k-16"	1. Multiple locations 2. Commercialized 3. Multiple companies	2021	3	These three temperature-controlled trailers with battery-electric TRUs and range-extending technologies are being evaluated by multiple companies before they move forward purchasing more units. The project uses the *CORE*. (*PLM Fleet's collaboration with AEM*)	There have been 23 demonstrations with these three units as of December 2021 logging 6,320 hours of successful operation in 2021 resulting in the elimination of 22 lbs. of PM2.5 as compared to operating diesel-powered TRUs.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
6	**Battery-electric TRU** (Advanced Energy Machines brand eTRU with range-extending technologies)	*Advanced Energy Machines*/ "SolarTech Generation 1"	1. Multiple locations 2. Commercialized 3. Multiple companies	2014	68	Various companies purchased these temperature-controlled trailers with battery-electric TRUs and range-extending technologies between 2014 and 2019 for commercial food service and grocery deliveries. The projects were self-funded demonstrations by the various companies.	These battery-electric TRUs logged 642,332 operational hours over 7 million road miles, predominantly in California, with the electric motor operating 48 percent of the time. A total of 1,800 lbs. of PM2.5 was eliminated by using these zero-emission battery-electric TRUs instead of diesel-powered TRUs. The total grid power consumption for all units was a combined three gigawatts.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
7	**Battery-electric TRU** (Carrier brand eTRU with range-extending technologies)	*Carrier*/ "Vector® eCool™"	1. United Kingdom (UK) 2. Demonstration 3. Not applicable	Oct 2020	1	A temperature-controlled 47-foot trailer with a battery-electric TRU and range-extending technologies was constructed in the UK to be used for demonstration purposes. This unit is not being pulled by zero-emission tractors but can be to produce a full zero-emission solution. (*Carrier's Vector eCool*)	[CARB staff seeking input]
8	**Battery-electric TRU** (Carrier brand eTRU with range-extending technologies)	*ConMet*/ "Preset Plus eHub™"	1. U.S. 2. Demonstration 3. Not applicable	2021	2	Two temperature-controlled trailers with battery-electric TRUs are being tested. ConMet is seeking partners for full commercialization. (*ConMet's zero-emission trailer*)	[CARB staff seeking input]

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
9	**Battery-electric TRU** (Carrier brand eTRU with range-extending technologies)	*eNow, XL Fleet*/ "Rayfrigeration™"	1. CA, U.S. 2. Demonstration 3. Not applicable	Mar 2020	1	A 53-foot temperature-controlled trailer with a battery-electric TRU and range extending technologies was unveiled at the Work Truck Show in Indianapolis, IN. (*eNow unveils solar eTRUs on trailers*)	[CARB staff seeking input]
10	**Battery-electric TRU** (Brand-agnostic eTRU with range-extending technologies)	*Emerald Technologies*/ "KECS"	1. Tampa Bay, FL, U.S. 2. Demonstration 3. Caspers Company	2013 to 2015	1	A single temperature-controlled trailer with a battery-electric TRU and range extending technologies was deployed to deliver food to McDonald's. (*Emerald Technologies' Wedway refrigeration system*) (*Caspers-Emerald Technologies collaborative pilot*)	The demonstration showed that the kinetic energy generation system generated enough power to run the eTRU and simultaneously charge a battery to be used when the temperature-controlled trailer was not in motion. The demonstration was a success in that no diesel fuel was used for the duration of the demonstration.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
11	**Battery-electric TRU** (Thermo King brand eTRU with range-extending technologies)	*Maxwell and Spark*/ "Advantage.li"	1. Netherlands 2. Pilot 3. TIP Trailer Services, Unilever, and Daily Logistics Group	Sep 2021 to May 2022	4	Demonstration involves a nine-month pilot in which diesel refrigeration TRUs in temperature-controlled trailers will be replaced by zero-emission battery-electric TRUs. (*Maxwell and Spark's collaborative pilot*)	[CARB staff seeking input]
12	**Battery-electric TRU** (Carrier brand eTRU)	*Conmet* "Preset Plus eHub™"	1. Riverside, CA, U.S. 2. Pilot 3. Sysco	Early 2022	[CARB staff seeking input]	[CARB staff seeking input]	[CARB staff seeking input]
13	**Battery-electric TRU** (Carrier brand eTRU with range-extending technologies	*Sunswap*/ "Endurance"	1. Chesterfield, UK 2. Demonstration 3. Gist	April 2022	1	Sunswap's proprietary battery-electric trailer TRU, equipped with their rooftop solar-assist technology, is being tested.	[CARB staff seeking input]
14	**Battery-electric TRU** (Thermo King brand eTRU)	*Thermo King*/ "evolve™"	1. Shafter, CA 2. Pilot 3. Walmart	Late 2021	1	A hybrid battery-electric trailer TRU was used in a two-month trial to run 18 routes transporting groceries from a Walmart distribution center in Shafter, CA to surrounding stores. Diesel was used as a backup power source.	When the batteries depleted mid-haul, the trailer TRU switched to diesel power to complete routes. The TRU operated on battery electricity 83% of the operation time.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
15	**Battery-electric TRU** (Carrier brand eTRU with range-extending technologies	*Westhill Innovation*/ "SunShifter™"	1. Hamilton, Ontario, Canada 2. Pilot 3. Loblaw	[CARB staff seeking input]	1	A solar-assist technology was retrofitted to the rooftop of a battery-electric trailer and tested by Canadian grocer Loblaw.	[CARB staff seeking input]
16	**Cryogenic TRU system**	*Clean Cold Power*/ "Dearman Engine™"	1. Waltham Abbey, UK 2. Pilot 3. Sainsbury's	Jun 2016 to Oct 2016	1	A liquid nitrogen-powered engine is being used for a three-month trial. (*Sainsbury's pilots liquid nitrogen Deaman engine*)	The trial demonstrated the operational benefits of the TRU including cool-down rates 50 percent faster to frozen state over diesel systems and noise levels at 60 decibels as compared to diesel-powered TRUs which operate between 75 and 85 decibels.[197] The trial also demonstrated that it was cost-comparable to existing diesel systems.

[197] WJV Acoustics, Inc. (2017, January 25). Acoustical Analysis, Producers Dairy Parking Lot 450 East Belmont Avenue, Fresno, California. *https://www.fresno.gov/darm/wp-content/uploads/sites/10/2017/03/Appendix-G-Acoustic-Study.pdf*

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
17	**Cryogenic TRU system**	*Clean Cold Power*/ "Dearman Engine™"	1. Netherlands 2. Pilot 3. Unilever	Jun 2017 to Dec 2017	1	A cryogenic TRU system was used in a six-month deployment of frozen produce deliveries across the Netherlands. (*Unilever-Dearman trial*)	The trial demonstrated the operational benefits of the TRU including cool down rates 50 percent faster to frozen state over diesel systems. The trial demonstrated that it was cost-comparable to existing diesel systems. (*Unilever-Dearman trial*)
18	**Cryogenic TRU system**	*Clean Cold Power*/ "Dearman Engine™"	1. Italy 2. Pilot 3. Unilever	Sep 2019	1	A cryogenic TRU system was used in a one-month deployment of frozen produce deliveries from south to north Italy.	Four tests were conducted, each involved 90 hours of frozen produce storage including operation of the TRU system over a weekend followed by a 410-mile trip for final delivery of the cargo. The trial demonstrated cool down rates 50 percent faster to frozen state over diesel systems and four successful duty cycles of 90 hours. After the demonstrations, the customer requested a vertical, front-mounted system instead of the existing under-mounted system.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
19	**Cryogenic TRU system**	*Clean Cold Power*/ "Dearman Engine™"	1. Hemel Hempstead, UK 2. Pilot 3. Marks & Spencer	May 2018	1	A dual-compartment cryogenic TRU system was used on a temperature-controlled trailer. (*Marks & Spencer lease Dearman TRU*)	The trial involved approximately 1,500 hours of operation and demonstrated benefits of the cryogenic TRU system including cool down rates 50 percent faster to frozen state over diesel systems, noise levels at 60 decibels as compared to diesel-powered TRUs which operate between 75 and 85 decibels, overall ease of use, and that the cryogenic TRU system is cost-comparable to existing diesel systems.[198]

[198] WJV Acoustics, Inc. (2017, January 25). Acoustical Analysis, Producers Dairy Parking Lot 450 East Belmont Avenue, Fresno, California. *https://www.fresno.gov/darm/wp-content/uploads/sites/10/2017/03/Appendix-G-Acoustic-Study.pdf*

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
20	**Cryogenic TRU system**	*Hyundai Translead*/ "HT Nitro Thermo-Tech®"	1. CA, U.S. 2. Demonstration 3. Not applicable	Nov 2019	1	A full-size temperature-controlled trailer with a cryogenic nitrogen refrigeration technology system was developed to demonstrate the cryogenic TRU system concept. (*Hyundai Translead cryogenic trailer TRU*)	[CARB staff seeking input]
21	**Cryogenic TRU system**	*Boreas*/ *"Nitrogen Cooling System"*	1. Austin, TX, U.S. 2. Pilot 3. Ruan	Sep 2017	1	A temperature-controlled trailer with a nitrogen-based cryogenic TRU system traveled on repeated routes from Austin to the Dallas metropolitan area for three days, transporting grocery cargo set at 35 degrees Fahrenheit with up to four stops per route with outdoor temperatures reaching 96 degrees Fahrenheit. (*Boreas-Ruan trailer demonstration*)	The demonstration illustrated consistent temperature control within the trailer along with fuel cost savings.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
22	**Cryogenic TRU system**	*Boreas*/ *"Nitrogen Cooling System"*	1. Tracy, CA, U.S. 2. Commercialized 3. Customer not disclosed	2011	42	The largest fleet deployment of cryogenic TRU systems in the U.S. (42 units) has been operating for 10 years.	Shows successful commercialization for at least 10 years of operations.
23	**Hydrogen fuel cell powering an eTRU** (Carrier brand eTRU)	*Bosch, Carrier Transicold, Lamberet, and STEF*/ "FresH2"	1. France 2. Demonstration 3. STEF Chambéry	Sep 2021	1	A hydrogen fuel cell is powering an eTRU installed on a temperature-controlled trailer. Development of this zero-emission solution is taking place at the Bosch site in Rodez, France. (*Bosch FresH2 project*)	[CARB staff seeking input]

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
24	**Hydrogen fuel cell powering an eTRU** (Carrier brand eTRU)	Chereau/ "ROAD"	1. France 2. Demonstration 3. Not applicable	Jul 2019	1	A hydrogen fuel cell is powering an eTRU on a temperature-controlled trailer. The trailer range was increased, payload capacity was increased by 430 kilograms, aerodynamics was improved, and safety features were enhanced. (*Chereau Hydrogen Power H2 trailer*)	Successfully operated with zero-emissions during a one-day localized distribution test and a 2.5-day long-distance refrigerated freight transport test. Both tests used 14 kilograms of hydrogen. Due to the use of vacuum insulated panel technology, energy consumption was reduced by 25 percent. Aerodynamic improvements resulted in 6 percent reduction of fuel used by the tractor during demonstrations.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
25	**Hydrogen fuel cell powering an eTRU**[199]	*Pacific Northwest National Laboratory*, *Carrier*, *Thermo King*, *Nuvera*, *Ballard*/ "Fuel Cell Auxiliary Power Unit (APU) to Power Truck Refrigeration Units (TRU) in Refrigerated Trucks"[200]	1. U.S. 2. Prototype 3. Business case analysis done by Walmart	Apr 2013 to Jun 2018	1 lab prototype	A 24-month multi-phase project was funded by Pacific Northwest National Laboratory that was to involve a business case analysis, prototype development, and ultimately a demonstration of two hydrogen fuel cell TRU systems for temperature-controlled trailers. (*PNNL demonstration of fuel cell APU to power TRUs*)	A business case analysis was conducted, and a lab prototype was developed but the project terminated before the demonstration phase. The project showed that hydrogen fuel cell technology is feasible for TRUs. The project addressed barriers including inadequate user experience and infrastructure. (*PNNL demonstration of fuel cell APU to power TRUs*)
Zero-Emission TRU Generator Set Demonstrations							

[199] Lutkaauskas, T. & Block, G. (2013, August 30). *Demonstration of Fuel Cell-Based Auxiliary Power Unit for Refrigerated Trucks: Phase I Business Case Report* (pp. 16-17).

[200] Pacific Northwest National Laboratory uses the acronym TRU for truck refrigeration unit. CARB uses the acronym TRU for transport refrigeration unit. TRUs are used for temperature-controlled trucks, trailers, domestic shipping containers, and railcars. TRU generator sets are used for temperature-controlled ocean containers. This project involved the development of hydrogen fuel cells for use with trailer TRUs.

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
26	**Hydrogen fuel cell powering a containerized TRU powerpack generator set for temperature-controlled ocean containers**	United States Department of Energy (U.S DOE), *Sandia National Labs*, *Young Brothers*/ "Maritime Fuel Cell Generator Project"	1. HI, U.S. 2. Prototype 3. Not applicable	*Aug 2015* to Jun 2016	1	A 20-foot containerized hydrogen fuel cell generator powered temperature-controlled ocean containers at the Port of Honolulu. (*Young Brothers deploy hydrogen fuel cell generator*)	The commissioning process identified several technical issues with the hydrogen fuel cell generator that were corrected. The hydrogen fuel cell generator was used by Young Brothers on 52 different days for a total of 278 hours. It averaged 29.4 kW (gross) during this period for a total energy generation output of 7,285 kW-hours. (*Sandia final report - fuel cell generator project*)

ID	Technology or Technology Configuration[195]	Company or Organization/Product or Project Name	1. Deployment Location 2. Deployment Phase[196] 3. Customer	Start Date to End Date (if available)	Units Deployed	Project Description	Results (if available)
Infrastructure Demonstrations for Zero-Emission TRUs							
27	Electric grid plug-in infrastructure	*Foster Farms*/ "Foster Farms Livingston Electrification Project"	1. CA, U.S. 2. Commercialized 3. Foster Farms	2019	62 plugs	A project to install transformers, gantry system, and electric power plugs to supply power to the temperature-controlled trailers. Project enables a switch from diesel-powered TRUs to electrically-powered TRUs. *Proposition 1B: Goods Movement Emissions Reduction Program funding* was granted for two projects. Phase 1 project is complete; 62 plugs were installed at the facility. Phase 2 is on hold.	Phase 1 completed.

Appendix B. 2021-2022 Federal, State, and Local Funding Opportunities for Non-Truck Transport Refrigeration Units (TRU) (Trailer TRUs, Domestic Shipping Container TRUs, Railcar TRUs, and TRU Generator Sets) and Supporting Infrastructure

CARB staff seeking information on any other funding sources for zero-emission technologies for non-truck TRUs which are not listed in these tables.

Table B-1: 2021-2022 Federal, State, and Local Funding Opportunities for Non-Truck TRUs

Program Name[201]	Program Administrator	What the Program Targets	More Information
Assembly Bill 617 Community Air Protection Incentives	Local Air District	Projects that result in immediate air quality benefits to the most impacted communities across the State Engine / Motor Equipment Infrastructure	*https://ww2.arb.ca.gov/our-work/programs/community-air-protection-incentives*
Carl Moyer Memorial Air Quality Attainment Standards Program	Local Air District	Cleaner-than-required by law engines, equipment, and other sources of air pollution Engine / Motor Equipment Infrastructure	*https://ww2.arb.ca.gov/our-work/programs/carl-moyer-program-transport-refrigeration-unit*

[201] Funding opportunities for non-truck TRUs are organized alphabetically, by program name.

Program Name[201]	Program Administrator	What the Program Targets	More Information
Clean Diesel and Diesel Emissions Reduction Act Programs	United States Environmental Protection Agency (U.S. EPA)	Projects that protect human health and improve air quality by reducing harmful emissions from diesel engines Engine / Motor Equipment	*https://www.epa.gov/dera*
Clean Off-Road Equipment Voucher Incentive Program	California Air Resources Board (CARB or Board)	Zero-emission off-road equipment in early stages of commercial development Equipment Infrastructure	*https://ww2.arb.ca.gov/our-work/programs/clean-off-road-equipment-voucher-incentive-project* *https://californiacore.org/equipment/single-temp-zero-emission-trailer-refrigeration-system-k55540-2/*
Funding Agricultural Replacement Measures for Emission Reductions	Local Air District	Emissions from the agricultural sector Equipment Infrastructure	*https://ww2.arb.ca.gov/our-work/programs/farmer-program*
Low Carbon Fuel Standard	CARB	Low-carbon and renewable alternatives Low Carbon Fuels	*https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard*
Proposition 1B: Goods Movement Emissions Reduction Program	Select Local Air Districts	Projects that achieve early or extra emissions reductions not otherwise required by law Equipment Infrastructure	*https://ww2.arb.ca.gov/prop-1b-local-agency-contact-and-solicitation-information*

Program Name[201]	Program Administrator	What the Program Targets	More Information
Targeted Airshed Grants Program	U.S. EPA	Air pollution in the nation's areas with the highest levels of ozone and fine particulate matter (PM2.5) ambient air concentrations Equipment Infrastructure	*https://www.epa.gov/air-quality-implementation-plans/targeted-airshed-grants-program*

Table B-2: Other Funding Opportunities for Non-Truck TRUs – Infrastructure

Additional agencies that may offer funding opportunities for zero-emission infrastructure. For specifics on funding assistance for zero-emission infrastructure, please contact the Governor's Office of Business and Economic Development (Go-Biz) at *https://business.ca.gov/industries/zero-emission-vehicles/*.

State Agency	Program
California Energy Commission *https://www.energy.ca.gov/funding-opportunities/funding-resources* Sign up at *https://www.energy.ca.gov/funding-opportunities/solicitations* to receive solicitations	California Electric Vehicle Infrastructure Project *https://calevip.org/* Incentives for the purchase and installation of electric vehicle charging infrastructure at publicly accessible sites throughout California
	EnergIIZE Commercial Vehicles Project *https://energiize.org/* Funds that can be used to purchase charging and hydrogen fueling infrastructure
California Infrastructure and Economic Development Bank *https://www.ibank.ca.gov/*	Exempt Facility Bonds *https://www.ibank.ca.gov/bonds/exempt-facility-bonds/* Bonds for facility improvement
California Public Utilities Commission[202] *https://www.cpuc.ca.gov/sb350te/*	See local utility programs[203] Incentives and rebates for zero-emission charger infrastructure. Please see local utility program sites for specifics

[202] The California Public Utilities Commission funds are administered through local utility programs.

[203] Los Angeles Water and Power: *https://www.ladwp.com/ladwp/faces/ladwp/residential/r-gogreen?_adf.ctrl-state=guz5t1j27_4&_afrLoop=846044054721137*

State Agency	Program
California State Treasurer's Office *https://www.treasurer.ca.gov/index.asp*	Electric Vehicle Charging Station Financing Program *https://www.treasurer.ca.gov/cpcfa/calcap/evcs/summary.asp* Loans that can be used for the design, development, purchase, and installation of electric vehicle charging stations at small business locations in California

Pacific Gas and Electric: *https://www.pge.com/en_US/large-business/solar-and-vehicles/clean-vehicles/ev-fleet-program/ev-fleet-program.page?*

Sacramento Municipality Utility District: *https://www.smud.org/en/Going-Green/Electric-Vehicles/Business*

San Diego Gas and Electric: *https://www.sdge.com/business/electric-vehicles/lovelectric*

Southern California Edison: *https://www.sce.com/evbusiness/overview*

Appendix C. List of Reviewed Studies

CARB staff seeking information on additional studies related to zero-emission non-truck TRU technologies not listed in this table.

Table C-1 presents the studies related to non-truck transport refrigeration unit technologies which California Air Resources Board staff reviewed for the 2022 Technology Assessment.

Table C-1: Reviewed Studies Related to Non-Truck TRU Technologies

	Study	Author(s)/Publisher(s)	More Information
1	Acoustical Analysis - Producers Dairy Parking Lot 450 East Belmont Avenue (2017)	WJV Acoustics, Inc	*https://www.fresno.gov/darm/wp-content/uploads/sites/10/2017/03/Appendix-G-Acoustic-Study.pdf*
2	Annual Energy Outlook 2018 (2018)	Energy Information Administration	*https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2018&cases=ref2018&sourcekey=0*
3	Carbon Dioxide Cryogenic Transport Refrigeration Systems (2008)	The Centre for Energy and Built Environment Research, Grimsby Institute	*https://www.grimsby.ac.uk/documents/defra/trns-casestudy.pdf*
4	Demonstration of Fuel Cell-Based Auxiliary Power Unit for Refrigerated Trucks (2013)	Nuvera Fuel Cells	*https://www.hydrogen.energy.gov/pdfs/review18/mt014_brooks_2018_p.pdf*
5	Electric-Powered Trailer Registration Unit Market Study and Technology Assessment (2005)	Shurepower, LLC	Prepared for the New York State Energy Research and Development Authority (NYSERDA)
6	EPRI Case Study for Truck Refrigeration Electric is Better (2018)	Electric Power Research Institute	*https://energyconversionhub.com/sites/default/files/attachments/truck_refridg.pdf*
7	Estimating Electric Vehicle Charging Infrastructure Costs Across Major U.S. Metropolitan Areas (2019)	The International Council on Clean Transportation	*https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf*

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8	Fueling the Future of Mobility Hydrogen and Fuel Cell Solutions for Transportation (2020)	Deloitte & Ballard Power Systems	*https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf*
9	National Grocer Reduces Costs and Emissions with eTRUs (2021)	Pacific Gas and Electric	*https://www.pge.com/pge_global/common/pdfs/solar-and-vehicles/your-options/clean-vehicles/charging-stations/ev-fleet-program/albertsons-case-study.pdf*
10	Noise Impact Analysis (2013)	LSA Associates, Inc.	*http://www.sbcounty.gov/Uploads/lus/Valley/Pacific_Industrial/Noise.pdf*
11	Pacific Gas and Electric Company (PG&E) Electrification Case Study Report (2017)	Electric Power Research Institute	Not available
12	PEM Fuel Cell Bipolar Plate Material (2019)	Ballard	*https://www.ballard.com/docs/default-source/web-pdf's/technical-note-_-2019-metal-vs-graphite-bipolar-plates-update.pdf*
13	Revised Transportation Energy Demand Forecast 2018-2030 (2018)	California Energy Commission	*https://efiling.energy.ca.gov/getdocument.aspx?tn=223241*
14	Safety Issues Regarding Fuel Cell Vehicles and Hydrogen Fuel Vehicles	The International Consortium for Fire Safety, Health, and the Environment	*https://dps.mn.gov/divisions/sfm/programs-services/Documents/Responder%20Safety/Alternative%20Fuels/FuelCellHydrogenFuelVehicleSafety.pdf*
15	Trailer Electrification Position Paper (2021)	Thermo King	*https://www.thermoking.com/content/dam/thermoking/documents/marketing/Trailer-electrification-position-paper-Thermo-King.pdf*