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# Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks

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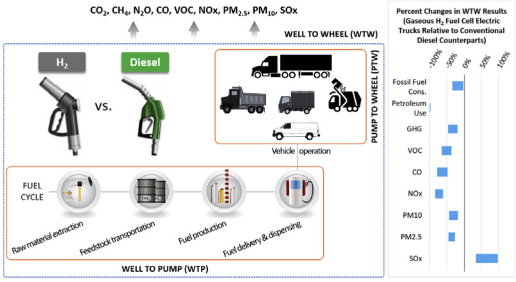
## HIGHLIGHTS

- $H_2$ fuel cell electric trucks provide life-cycle petroleum use and air emission reductions.
- For urban and local operation, life-cycle benefits of fuel cell electric trucks are significant.
- Electricity consumption is influential for $H_2$ compression and liquefaction.
- Regional electricity energy sources affect the life-cycle emissions of fuel cell trucks.
- Renewable hydrogen technology further decreases life-cycle energy use and emissions.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

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## ABSTRACT

This study provides a comprehensive and up-to-date life-cycle comparison of hydrogen fuel cell electric trucks (FCETs) and their conventional diesel counterparts in terms of energy use and air emissions, based on the ensemble of well-established methods, high-fidelity vehicle dynamic simulations, and real-world vehicle test data. For the centralized steam methane reforming (SMR) pathway, hydrogen FCETs reduce life-cycle or well-to-wheel (WTW) petroleum energy use by more than 98% compared to their diesel counterparts. The reduction in WTW air emissions for gaseous hydrogen (G.H2) FCETs ranges from 20 to 45% for greenhouse gases, 37–65% for VOC, 49–77% for CO, 62–83% for NOx, 19–43% for PM10, and 27–44% for PM2.5, depending on vehicle weight classes and truck types. With the current U.S. average electricity generation mix, FCETs tend to create more WTW SOx emissions than their diesel counterparts, mainly because of the upstream emissions related to electricity use for hydrogen compression/liquefaction. Compared to G.H2, liquid hydrogen (L.H2) FCETs generally provide smaller WTW emissions reductions. For both G.H2 and L.H2 pathways for FCETs, because of electricity consumption for compression and liquefaction, spatio-temporal variations of electricity generation can affect the WTW results. FCETs retain the WTW emission reduction benefits, even when considering aggressive diesel engine efficiency improvement.

## 1. Medium- and heavy-duty truck electrification

Medium- and heavy-duty (MHD) vehicles account for a significant portion (20–25%) of energy consumption and air emissions in the U.S. transportation sector. MHD vehicles, around 11 million trucks and fewer than 1 million buses, represent only 4.5% of the 260 million

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vehicles on the road nationally [1]. Although they compose only a small share of the national vehicle population, MHD vehicles are the second-largest energy consumers and greenhouse gas (GHG) emitters, behind only light-duty vehicles that include passenger cars, sports-utility vehicles, and pickup trucks [1–3]. Furthermore, MHD vehicles' energy use is growing faster than any other on- or off-road vehicle segment or transportation mode. Although the transit bus market has reduced its petroleum consumption to just over half of the total fuel consumed by transit buses [4], the majority of MHD trucks still run on petroleum diesel fuel [5–7].

Diesel-powered MHD trucks have a tremendous impact on national and local air pollution. Nationally, MHD diesel trucks account for approximately 30% of total NOx, PM2.5, and PM10 emissions from mobile sources [6]. In terms of local air quality, the impact of MHD trucks can be even more significant. For example, on the southern coast of California where smog (ground-level ozone) is a serious public health concern, MHD diesel trucks contribute 33% of area-wide NOx (a precursor of smog formation) emissions from all stationary and mobile sources [8]. Further, low-income and/or minority communities can be more adversely affected than other population groups by the air pollutants from diesel trucks/buses [9]. Therefore, reducing energy consumption and air emissions of MHD diesel trucks is crucial to achieving sustainable transportation, protecting public health, and improving environmental justice at the local, regional, and national levels.

To improve MHD trucks' energy efficiency and reduce their air emissions, electric vehicle technologies (e.g., battery electric or hydrogen fuel cell electric) are emerging as viable options. In general, electric trucks have two major advantages over conventional diesel trucks. First, the energy efficiency of an electric powertrain is much higher than that of its diesel counterpart, mostly due to the large heat loss (about 60% of fuel input) of internal combustion engines [10,11]. Second, electric trucks create no direct on-road emissions, other than those related to evaporation (e.g., paint) and wear (e.g., tires and brakes). It is true that today's diesel trucks create far less emissions than their predecessors, owing to the ever more stringent national standards for heavy-duty engine emissions and advances in diesel engine and after-treatment technology. That said, aside from powertrain electrification, there is a potential for further reduction of diesel trucks' tail-pipe emissions – for instance, by narrowing the gap between certified and real-world emissions, or by introducing next-generation standards [12]. Nonetheless, vehicle electrification, with the advantage of zero tail-pipe emissions, can provide a deep reduction in on-road air emissions from MHD trucks and significantly improve air quality.

## 2. Hydrogen fuel cell electric trucks (FCETs)

Battery electric and hydrogen fuel cell electric vehicles are the two leading MHD truck electrification technologies. Like battery electric trucks, hydrogen fuel cell electric trucks (FCETs) create zero tail-pipe emissions and are solely driven by electric motors. However, a FCET powertrain is typically less efficient than that of a battery electric truck, and hydrogen (around \$0.45/kWh [\$15/kg H2], for early light-duty fuel cell vehicle markets) is currently more expensive than electricity (around \$0.1/kWh, national average without demand charges) [13]. Nevertheless, hydrogen cost is expected to decrease with economies of scale and improved utilization of hydrogen refueling stations. Moreover, compared to battery electric trucks, FCETs generally have a longer driving range and refuel much more rapidly (only several minutes to fill up empty tanks, similar to the 10–12 min for conventional diesel).

MHD hydrogen FCETs can largely be categorized by vehicle energy system configuration (fuel cell– or battery–dominant) and vehicle weight classifications. Battery-dominant FCETs rely on a relatively large-capacity battery charged with electricity drawn from the power grid, for which onboard hydrogen energy system serves as a range extender. In contrast, fuel cell–dominant FCETs carry a smaller battery and are primarily powered by electricity from the hydrogen fuel cells. However, the distinction between battery–dominant and fuel cell–dominant FCETs is not always clear. Regardless of fuel (e.g., diesel or hydrogen) or propulsion technologies (e.g., fuel cell– or battery–dominant), on-road MHD vehicles are subdivided into eight different gross vehicle weight rating (GVWR) classes, spanning Classes 2b through 8b [14]. GVWR is a measure of load-carrying capability, which includes the weight of the vehicle itself (or curb weight) and the maximum payload the vehicle can carry. Class 2b includes vehicles with a GVWR between 8501 and 10,000 lbs, mostly larger pickup trucks and vans. Class 8b vehicles with a GVWR above 60,000 lbs are predominantly combination tractor-trailers ("18-wheelers"), which are the heaviest vehicles on the road.

Most of the hydrogen FCETs on the road today, with driving ranges of 150–200 miles for urban, local, and short-haul operation, are based on gaseous hydrogen compressed at 350 bar for onboard energy storage (mostly Type III tanks with metal liner and composite overwrap). The same onboard hydrogen storage pressure (350 bar) may also be adopted for FCETs that are used for regional or long-haul operation [15], although it would require more space for larger onboard storage capacity. The onboard hydrogen compression pressure (350 bar) for FCETs is lower than 700 bar for light-duty vehicles (mostly Type IV tanks with polymer liner and composite overwrap) with over 300 miles of driving range. The lower onboard hydrogen compression pressure (350 bar) and metal liner tanks for FCETs eliminate the pre-cooling requirement for fast re-fueling [16].

In the United States, nearly half of MHD trucks are used for urban, local, and short-haul operation, with a daily travel distance less than 200 miles [6]. Switching all those diesel trucks to FCETs (hypothetically) is equivalent to eliminating approximately 30% of all on-road NOx emissions from the entire MHD truck sector [17]. Although FCETs can remove tail-pipe or on-road direct emissions as such, the point or origin of emissions and corresponding environmental burden may shift from tail-pipe or the road network to upstream fuel production plants. Therefore, when comparing conventional diesel and fuel cell electric trucks, it is important to incorporate the indirect (upstream) emissions from fuel production beyond vehicle operation. To this end, life-cycle analysis (LCA) is a useful framework that incorporates and compares all direct and indirect environmental impacts over the entire well-to-wheel (WTW) chain.

When it comes to LCA of medium- and heavy-duty hydrogen FCETs, despite the growing interest in FCET technology, life-cycle energy use and emissions estimates for FCETs are scarce. Even the National Petroleum Council (NPC) report [18], one of the most comprehensive analyses of transportation fuel and vehicle technologies in recent years, lacks information about the life-cycle energy efficiency and environmental impacts of hydrogen FCETs. Some piecewise WTW analyses [9,19] exist, but those studies focus on urban transit buses. There is a relatively large number of life-cycle studies for battery electric medium- and heavy-duty trucks [20–22], which touch on an array of life cycle metrics: energy efficiency, water consumption, air emissions, and cost. However, comparable life-cycle studies are virtually nonexistent for hydrogen FCETs. To fill this knowledge gap, there is a research need to quantify and evaluate life-cycle energy and the environmental benefits and trade-offs for FCETs in comparison with other fuel-vehicle technologies, particularly in the United States. This study is a first-of-its-kind attempt to develop representative and reliable estimates of life-cycle fuel consumption and air emissions for a comprehensive set of FCETs based on a coherent set of assumptions, methods, and models. This study focuses on the life cycle of the fuel (also as known as a WTW analysis). The impact of vehicle manufacturing or end-of-life, and infrastructure construction, maintenance, operation, or end-of-life are outside of scope for this analysis and are left for future work.

The main objective of this study is to compare a variety of hydrogen FCETs (Classes 2b through 8b) and conventional diesel counterparts in terms of WTW energy use and air emissions (GHGs and criteria air pollutant [CAP] emissions). In doing so, this study proposes