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Hydrogen at Scale

for Fuel Cell Electric Buses

A California Case Study

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INTRODUCTION

Air pollution is one of the major health and environmental concerns of our time. Despite strict environmental laws, eight of the country's ten most air-polluted cities are in California (Rice, 2018). In this state alone, air pollution causes about 21,000 early deaths annually (Chu, 2013). Children, the elderly, and those with compromised immune systems are most vulnerable to vehicular air pollution. Frequent exposure to these harmful emissions is known to increase school absences, hospital admissions, and emergency room visits. In addition, the state is seeing impacts from a warming world, including prolonged drought and intense wildfires. Climate scientists forecast hotter and drier conditions for California as the climate crisis continues.

In the face of the repercussions of this global problem, each industry must act to accelerate change. Shifting away from fossil fuels in the transportation sector will be especially impactful. Heavy duty vehicles such as transit buses and delivery trucks comprise just seven percent of all vehicles in California but are responsible for about 40 percent of GHG emissions, 80 percent of NOx emissions, and 90 percent of diesel particulate matter emissions ("Innovative Clean Transit," 2019).

As longtime partners for clean air in California, public transit agencies play a pivotal role in transitioning vehicle fleets away from fossil fuel-powered technologies to zero-emission alternatives. The Innovative Clean Transit (ICT) regulation is a critical first step in accelerating this transition. The ICT regulation was adopted by the California Air Resources Board (CARB) in December 2018 and requires all public transit agencies to gradually transition to a 100 percent zero-emission bus (ZEB) fleet. Beginning in 2029, 100% of new purchases by transit agencies must be ZEBs, with a goal for a full transition by 2040.

A ZEB Rollout Plan is required from each transit agency to show how it is planning to achieve a full transition to zero-emission technologies. Large transit agencies have to submit their Rollout Plan by July 1, 2020, and small transit agencies by July 1, 2023. Transit agencies must act now to select a ZEB solution that will carry them into the future—and secure funding for their chosen technology.

Fuel Cell Electric Buses

Across California, the zero-emission transition is already underway. Eight of the ten largest transit agencies in the state are already operating zero-emission buses, including battery electric and hydrogen fuel cell vehicles ("California Transitioning," 2018).

As transit agencies evaluate the best option to transition their fleets to zero-emissions without affecting service levels, there are different electric technologies to consider. The central decision is the choice of zero-emission bus propulsion: fuel cell electric buses (FCEBs) or battery electric buses (BEBs)—or a combination of both. In most cases, the decision will be based on the routes served (how long, how flat or hilly); service constraints (hours of operation per day), the existing infrastructure (electrical capacity or CNG refueling facilities in place); and the bus depot space constraints.

The principal difference in the technologies is in how the electricity is delivered to the electric motor: from a BEB powertrain powered only by what batteries can provide in a single charge, or from an FCEB powertrain powered by batteries plus a hydrogen fuel cell power generator.

Fuel cell electric buses combine the best of battery electric bus technology with an onboard power generator. The fuel cell system onboard the bus efficiently generates electric energy from hydrogen fuel through an electro-chemical reaction, leaving only water and heat as by-products. There is no combustion. The fuel cell provides electricity to the electric drive, hotel load (heating and cooling systems) and maintains the bus battery charge.

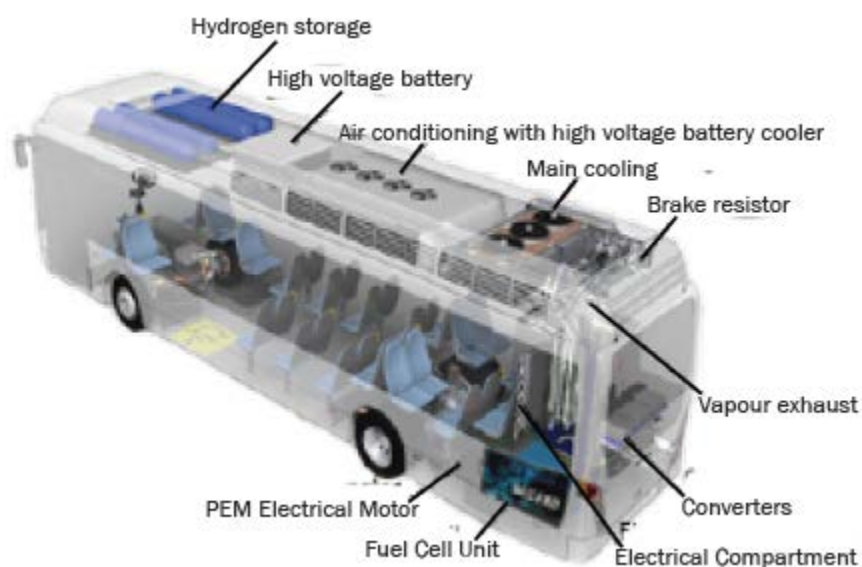


Figure 1: Fuel cell bus component layout

Today, the highest selling electric bus option is the 100% battery bus with the batteries being recharged using either roadside fast chargers or overnight depot chargers. However, challenges have arisen as these systems are implemented at larger scale. Battery electric bus range could be insufficient for some routes and duty cycles:

- Adding more batteries (weight) to the bus to increase range will reduce operational efficiency and passenger capacity.
- As battery performance is affected by climate, route conditions, and aging, it will also impact range and bus performance.

What this means: some existing public transit routes and schedules cannot be served with current or predicted BEB technology. In many cases, battery technology cannot replace diesel and compressed natural gas (CNG) buses on a 1-to-1 basis.



Figure 2: Fuel cell bus deployed by the Orange County Transportation Authority, California

Fuel cell electric buses can directly replace conventional buses in range, power, and passenger capacity. They provide zero-emission performance with no compromise in service or operation:

- Similar range (over 300 miles) to diesel and CNG buses, requiring no changes to existing routes or schedules
- Continuous power while the bus is in operation, for consistent performance throughout a shift
- Strong climbing and load-bearing performance, even in extreme temperatures
- Lightweight fuel cell system and hydrogen storage for maximum passenger capacity
- Compact depot gas refueling (like CNG), eliminating the need for a roadside charging infrastructure
- Fast refueling (less than 10 minutes of refueling delivers 18 hours of continuous service)

Fuel cell electric buses are field-proven, with a track record of millions of miles in revenue service for the past 20 years. Fuel cell electric buses have also demonstrated consistent performances throughout long daily drive cycles during all seasons in challenging geographies.

California is among the world-leaders in the deployment of hydrogen and fuel cell technologies. In California today, three transit agencies and one university together are operating 51 fuel cell electric buses. This is more than any other state.

Hydrogen Fuel

Hydrogen as a Decarbonized Fuel

Hydrogen for transportation has an essential role to play in California's energy diversification strategy. Several studies have shown that it is not possible to electrify the entire transportation sector using only the electric grid. Achieving California's zero emissions goals through grid charging alone will require adding at least as much generation, transmission and distribution as exists today, but in new load centers—which are likely to be in highly congested areas such as ports, transit agencies, and urban industrial areas.

As a means of storing and transporting cleanfuel, hydrogen is an effective alternative to the electric grid. Hydrogen enables greater energy resource diversification, utilizing not only wind and sun but waste streams such as landfill gas and wastewater biogas. Hydrogen as a fuel provides the energy supply stability that we have enjoyed for decades from liquid fuels, allowing for multiple parallel transport pathways through trucking, pipelines and on-site generation, while buffering supply interruptions through gaseous and liquid storage.

Renewable hydrogen is essential to a best-case scenario for clean energy storage and zero-emission transportation on a large scale. When produced from renewable energy, hydrogen is a true zero-emission fuel that also enables grid-balancing and large-scale, long-term energy storage.



Figure 3: Hydrogen refueling station at AC Transit, California

Similarities with Compressed Natural Gas

Fuel cell electric buses allow transit agencies that are currently operating CNG buses to gradually transition to a zero emission fleet mix using a common fuel feedstock (methane) and leveraging the existing infrastructure. Hydrogen is produced onsite using a steam methane reformer and natural gas delivered via an existing pipeline.

Hydrogen and CNG share many of the same characteristics, making implementation easier:

- Similar codes and standards for the safe handling of Class 2 flammable gases
- Common distribution equipment, along with similar piping, compression, gas storage and dispensing systems
- Similar refueling procedures
- Similar leak detection and other safety systems

When sourcing hydrogen fuel, transit operators can put out a tender for companies to supply the hydrogen and even operate and maintain the hydrogen station. There are a variety of companies that will compete for the opportunity, which keeps the price of the fuel down. The price of fuel is fixed over a period of time, and the transit operator pays in dollars per kilogram. Knowing that a bus typically needs 20 to 30 kilograms of hydrogen per day facilitates accurate budgeting.

Hydrogen filling stations at transit depots are built to be scalable. A station can simply and cost-effectively increase its capacity from 10 to 100 or more buses by upgrading the compression and storage equipment and adding dispensers. Operating a combination of low-emission CNG buses with zero-emission fuel cell electric buses out of a single transit depot is a model that is both economical and scalable to hundreds of buses.

Low Carbon Fuel Standard Program

The California Air Resources Board's low-carbon fuel standard (LCFS) program is designed to reduce carbon intensity associated with the lifecycle of transportation fuels used in California. The LCFS is helping to make fuel cell electric buses more affordable for fleet operators. Hydrogen for fuel cell electric buses generates credits under the LCFS that can be sold to reduce operating costs for transit fleets

In California, 33% of hydrogen for transportation must be produced with renewable sources (i.e. green hydrogen). Renewable hydrogen is any hydrogen produced using electricity derived from renewable sources including wind, solar, biomass and others. Renewable hydrogen supplied for vehicle fueling is eligible for a LCFS credits that can be sold or traded to offset carbon-intensive petroleum fuel usage.

The LCFS is proving to be a significant incentive for transit agencies. Incentive values can range from \$0.50 per kilogram for hydrogen produced from natural gas to \$5.40 per kilogram for hydrogen produced using renewable sources. As sources of hydrogen in California become cleaner, the hydrogen supplier will capture higher LCFS credits, further reducing the cost of hydrogen for transit agencies.

CASE STUDY

Nel Hydrogen has developed a novel approach to developing hydrogen production and distribution in a coordinated way that can support clusters of transit depot fueling sites. The concept revolves around low cost production of green hydrogen in areas rich in renewable energy resources and strategically located with respect to several transit agencies. The hydrogen is then transported relatively short distances in high pressure trailers to multiple fueling locations, and full trailers are simply swapped with empty trailers. At the production site, multiple trailers can be filled simultaneously, and likewise at the fueling sites multiple trailers can be positioned in trailer bays to provide flexibility in the logistics. The details of each segment of the operation are described further below.

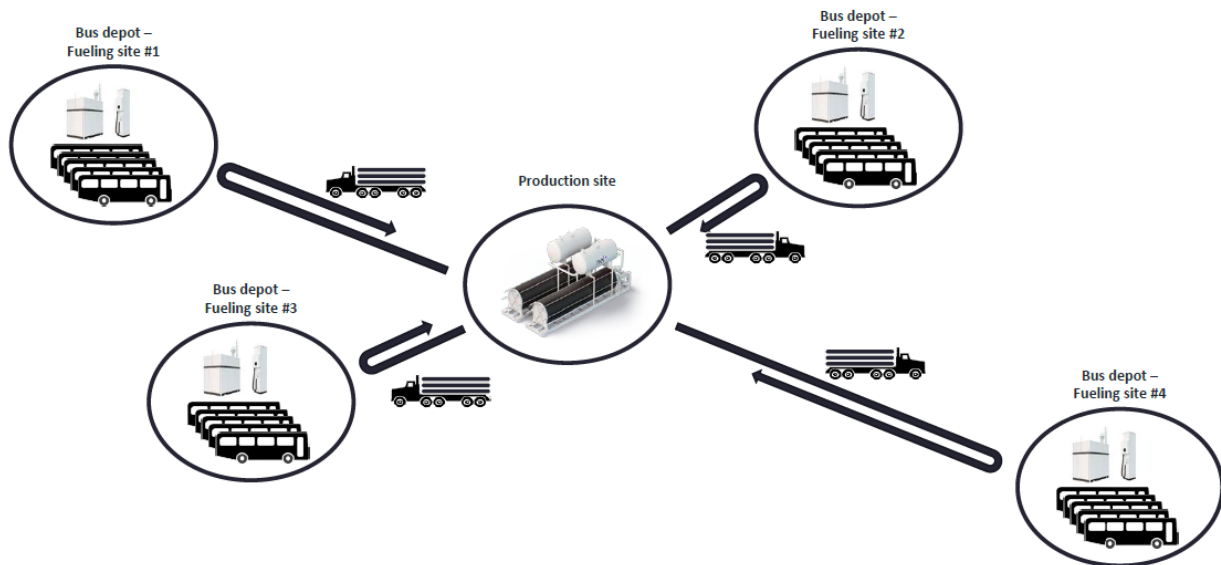


Figure 4: Nel's approach to centralized production and "drop and swap" distribution

Hydrogen Production

For the purposes of this case study, we will illustrate a scenario where the production system is supporting four bus depots, each operating 60 buses. Assuming a maximum hydrogen demand of 2,000 kg/day at each site, we would then be installing an electrolyzer system with a net capacity of 8,000 kg/day. The electrolyzer is located in an area where a low-cost renewable energy PPA can be secured, within 120 miles of the metro LA area. The map below shows the general target area for the energy supply needed for our production plant. The electrolyzer can produce low cost green hydrogen if electricity pricing is low and equipment utilization is high. In addition, by using renewable power to produce the hydrogen, the finished fuel will garner a maximum value for LCFS credits by virtue of its extremely low carbon intensity. These high value credits can help assure a viable business case for the project by offsetting distribution costs and other fixed O&M costs.

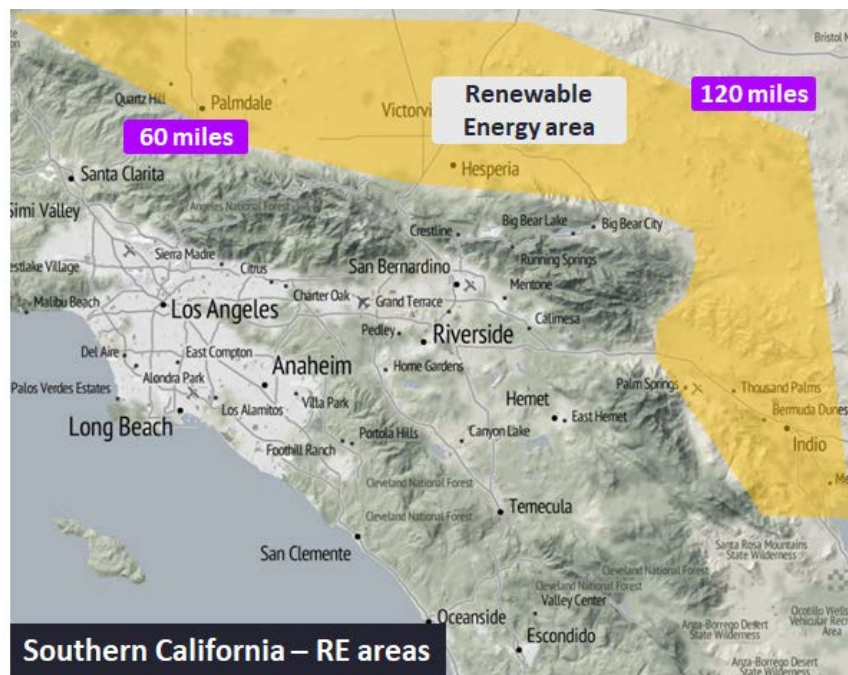


Figure 5: Southern California renewable energy areas

A trailer filling depot will be co-located with the hydrogen production plant. The capacity of the plant is such that multiple trailers can be filled at the same time. A high-level schematic of the system concept is shown below. In general, more trailer filling bays at the production site offers more flexibility in terms of coordinating deliveries with individual transit agencies. It also provides for buffer capacity, as the trailers become the primary storage for the finished fuel product.

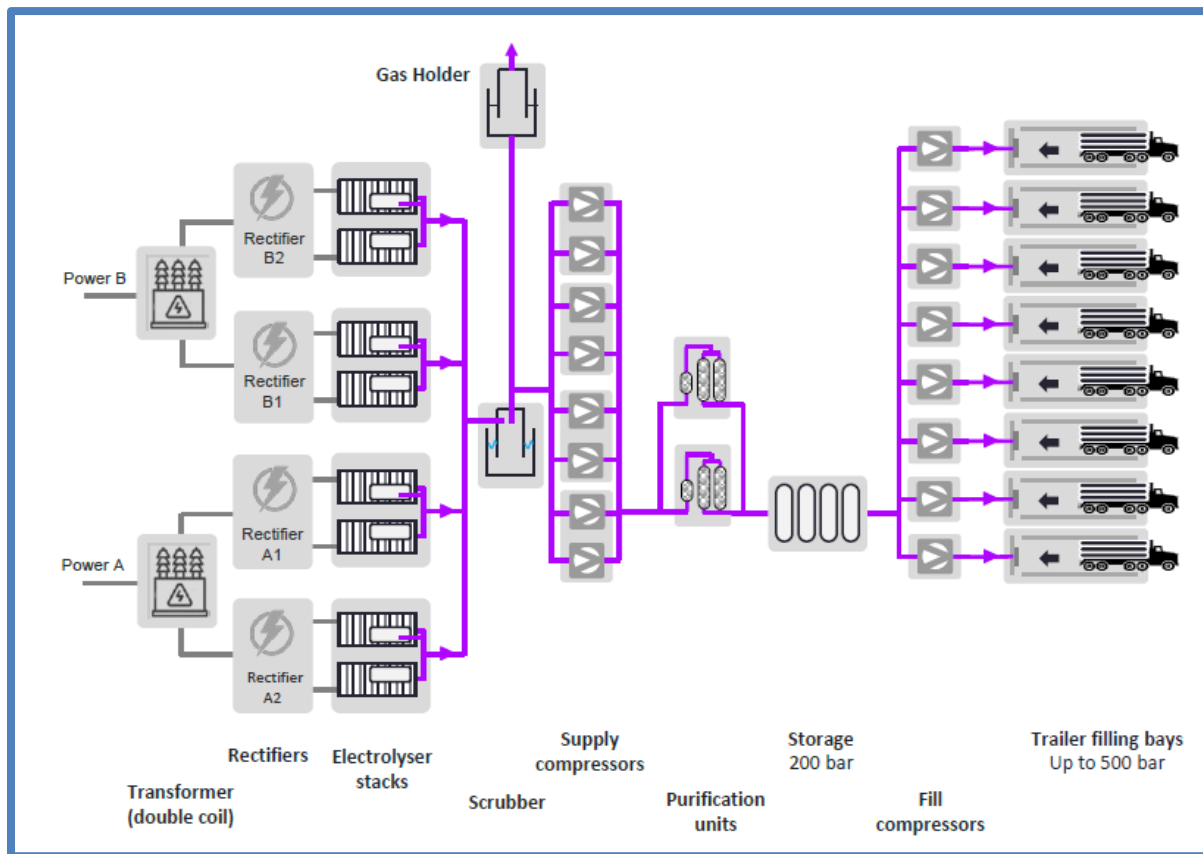


Figure 6: Nel's trailer filling system concept, integrated with a large scale electrolyzer plant



Figure 7: Representative trailer filling bay

Hydrogen Distribution

At a 500 bar filling pressure, new transport trailers can achieve more than 1,000 kg of net capacity ("Linde Raises the Bar," 2013). This is the key to cost effective drop and swap transport. A 60 bus fleet would then need a maximum of two truck deliveries per day, and they would simply replace depleted trucks already on site.



Figure 8: Linde 500 bar trailer with 1,100 kg of hydrogen capacity

In general, we would recommend at least three trailer parking bays at the transit agency.

In the three-bay scenario, one trailer is full, one is partially depleted, and one is empty, waiting for pickup. This redundancy assures that daily fueling capacity can be achieved at any time, regardless of when the empty trailer is swapped. The footprint of the trailer bays is relatively modest, only about 45 feet by 42 feet for the three-trailer configuration shown below.



Figure 9: Trailer parking bays

Hydrogen Dispensing

The hydrogen dispensing is accomplished by integrating the trailers into a distribution system that ties in a modest amount of ground storage and several H2Station® modules, each with a dedicated 350 bar dispenser. The system concept is shown below. The four dispensers will comfortably service 60 buses, all fueling back-to-back in a window of only 6 hours. Only 100 kilograms of “fueling storage” provides the peak flow capacity that allows for 5 to 10 minute fast fills on each bus.

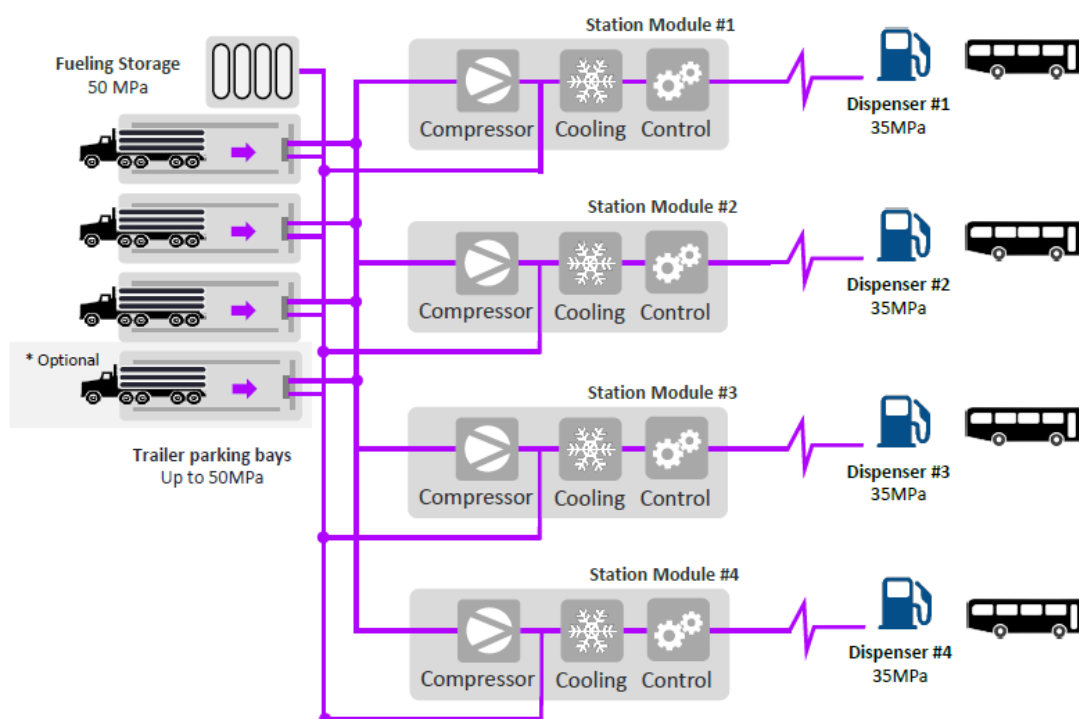


Figure 9: Hydrogen distribution system concept

The overall footprint of the trailer bays and fueling equipment is very efficient relative to the capacity provided. See the relative scale below for a typical depot installation, with the relevant equipment occupying a total space of about 55 feet by 45 feet.

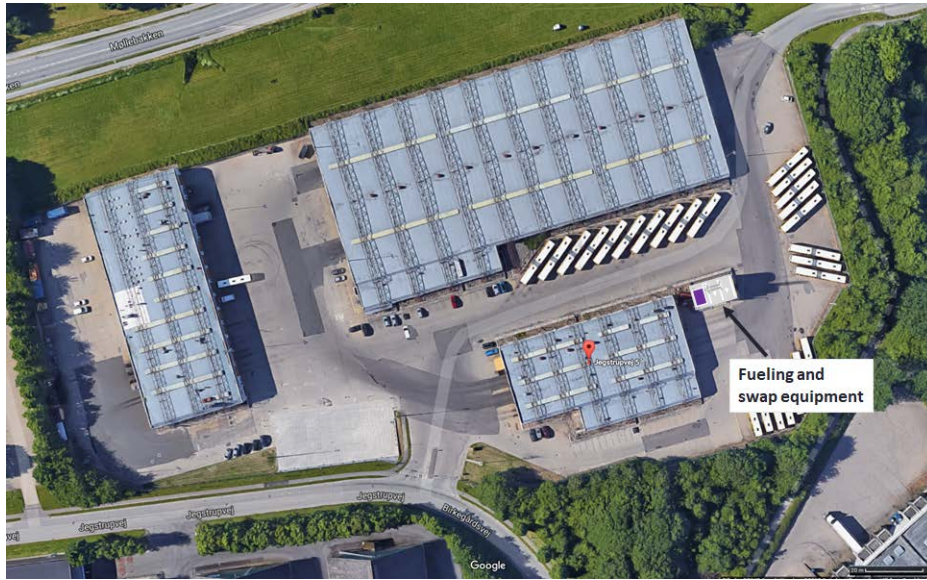


Figure 10: Sample hydrogen fueling installation at transit depot

Cost Analysis

The biggest cost driver in the production cost of hydrogen from an electrolysis plant is the cost of electricity. Getting a long-term power purchase agreement (PPA) from the local electricity utility for the electrolyzer plant is key to the economics of this solution. The table below shows a representative calculation for an 18 MW electrolyzer plant (8,000 kg/day capacity) operating at 40% capacity factor (not unreasonable for a good wind resource) and amortized over 10 years at 6%. The production cost with \$0.03/kWh power is very attractive, even at the relatively low capacity factor. The sensitivity to CAPEX becomes more pronounced as capacity factor decreases. For example, a good solar resource might offer 25% capacity factor, and with \$0.03/kWh, the production cost jumps to \$3.06/kg just because the cost recovery on the CAPEX is slower.

HYDROGEN PRODUCTION COST CALCULATOR	
Off Grid Wind 20 Year PPA	
CAPEX Electrolyzer	\$12,000,000
MW Nameplate	18 MW
Electricity	\$0.03 per kWh
Project Term	20 years
Purchase Amortization	10 years
Discount Rate	6%
Capacity Factor	40%
CAPEX	\$0.66 per kg
OPEX	\$1.63 per kg
Operation & Maintenance	\$0.24 per kg
TOTAL PRODUCTION COST	\$2.53 per kg

Overall, the economics of large scale production from electrolysis is rather good considering the present PPA pricing available for both solar and wind. When combined with the local “drop-and-swap” distribution described above (expected to add less than \$2/kg cost), the price to the end customer can be competitive on a dollar per mile basis with diesel buses and eventually even CNG buses at \$5 to \$8/kg.

Capital equipment costs at the transit agency will include the hydrogen compression, high-pressure storage and dispensers to deliver fuel to the fuel cell electric bus. The cost of this equipment for our example of a 60 bus fleet is estimated at \$150,000 per bus or less.

COST MODEL – RENEWABLE HYDROGEN DELIVERY AT SCALE	
Capital Equipment Cost	
Infrastructure cost	\$150,000 per bus
Operating Cost	
Hydrogen fuel (delivered price)	\$8/kg
LCFS incentive (ZEV truck or pipeline delivery)	(\$5.40/kg)
Fuel cost	\$2.60/kg
Fuel Cost per Mile	\$0.31/mile

Assumptions

- Fuel economy = 8.33 mi/kg
- LCFS credit \$180 per metric ton of CO₂ equivalent reduced

The transit agency has the option of purchasing this equipment outright and taking advantage of available purchase incentives. Or, as an alternative, the infrastructure provider can install, maintain and operate the equipment, retaining ownership of the fuel storage and dispensing equipment, and providing this service for a monthly fee. This creates an operating expense for the transit agency, rather than a capital expense, however incentives are not as widely available for this financial model.

The other operating cost is the price of fuel. In this example, with centralized production of green hydrogen, we estimate the delivered price of hydrogen to be \$8/kg. Transit agencies can take advantage of the LCFS incentive to reduce the cost to \$2.60/kg, resulting in a fuel cost per mile of \$0.31.

SUMMARY

Transit agencies are among the first transportation service providers to be challenged with zero emissions targets. Agencies must make plans now to meet Innovative Clean Transit (ICT) regulation and to migrate fleets to 100% zero-emission buses.

As hydrogen infrastructure technology continues to mature, improvements are being made in solutions available to transit agencies. Hydrogen produced from renewable sources, such as solar, wind or biomass are becoming more prevalent and economical.

Hydrogen as a clean fuel for transit offers:

- Fully scalable solution without off-property infrastructures
- Easy to budget operating cost (similar to CNG)
- Existing mature and competitive supply chain
- Lower implementation and operation risks at scale

As the case study in this paper shows, this option is a path to competitive and affordable 100% zero-emissions well-to-wheel operation for transit fleets at scale.

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