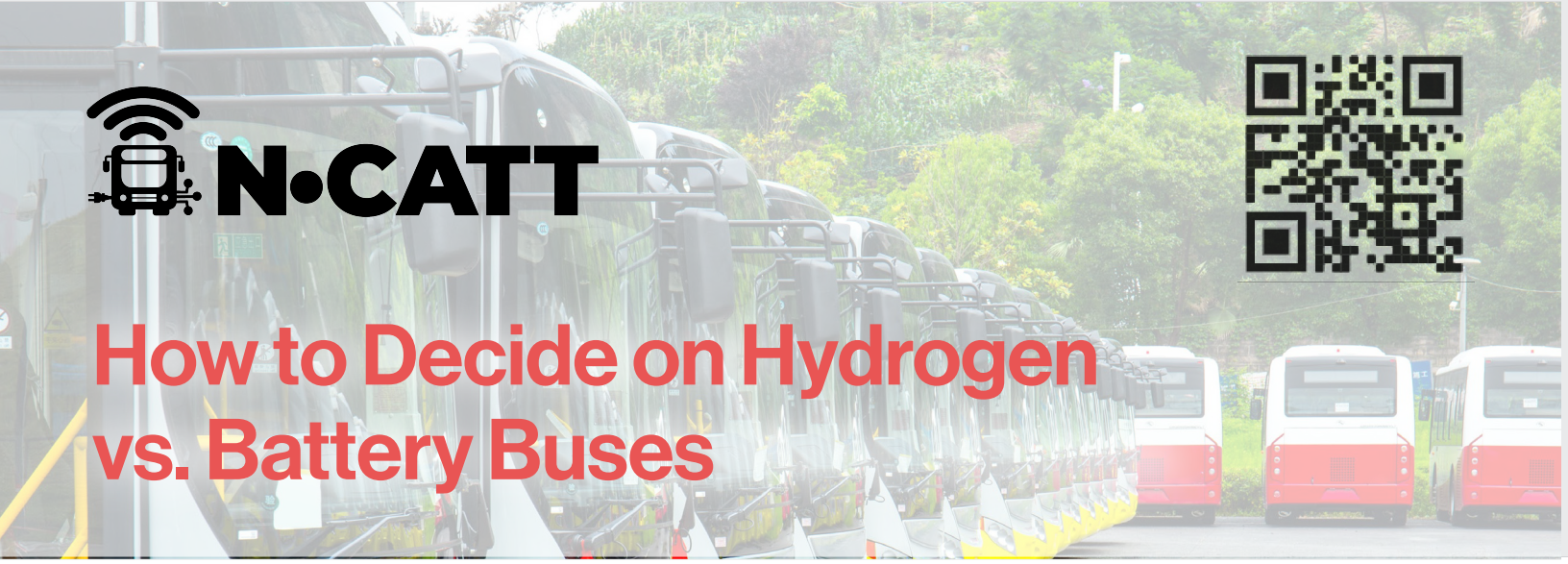
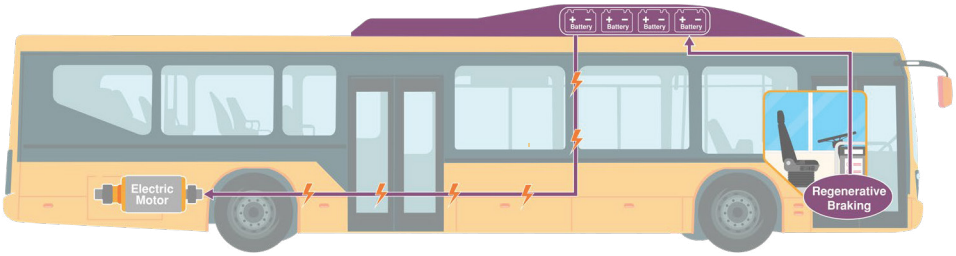


How to Decide on Hydrogen vs. Battery Buses

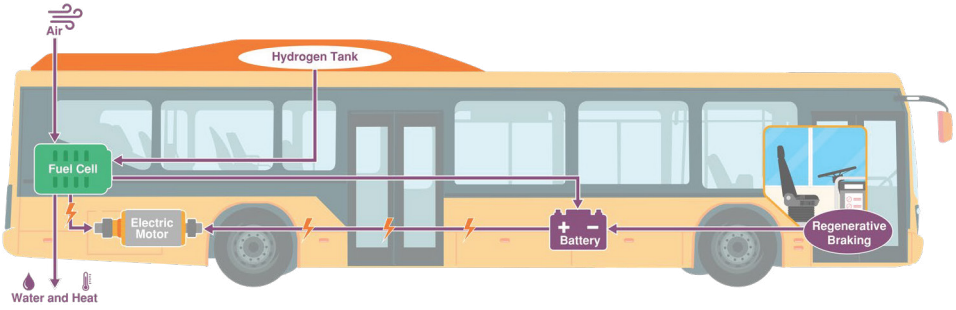
Zero-emissions buses (ZEB) produce no tailpipe emissions and are primarily powered by hydrogen fuel cells or a series of batteries. This guidebook provides an overview of how battery-electric and hydrogen fuel cell buses work and a comparison of various operational aspects, capital needs, costs, concerns, and safety considerations that will aid agencies in deciding which ZEB technology may work best for them.

Battery-Electric Buses



Battery-electric buses (BEB) are propelled by an electric motor fueled by energy stored in a battery located on the vehicle. BEB charging technology can be plug-in, overhead, or wireless inductive. Plug-in chargers are typically only used at the depot, while overhead and wireless inductive are used both on-route and at the depot. A charging station typically requires a transformer (often supplied by the utility company), switchgear, charger, and dispenser to transfer the electricity from the charger to the vehicle. The type of charging infrastructure to select depends on how many miles a bus goes per day, terrain, how often a bus stops, ambient temperatures, available garage space and power, layover locations, and utility rate costs and schedules.

Hydrogen Fuel Cell Buses



A fuel cell vehicle uses hydrogen fuel cells as its power source by converting energy produced from the reaction between hydrogen in tanks stored on the vehicle's roof and oxygen from the air into usable energy. That energy powers the electric motor and a battery that supports auxiliary functions but can also power the motor. Additionally, energy is recovered from braking (regenerative braking) and is also used to provide power to the battery. The only exhaust/waste products produced are water and heat, the latter of which can be recaptured to heat/cool the bus. Vehicles are fueled at a hydrogen fueling station with a dispensing system that delivers fuel to a vehicle (similar to a diesel/CNG fueling station). Hydrogen is either delivered or produced on-site and stored in hydrogen tanks in compressed liquid form.

COMPARISON OF BATTERY-ELECTRIC AND HYDROGEN FUEL CELL BUSES

Element	Battery-Electric Bus	Hydrogen Fuel Cell Bus
Range	» Less than 150 miles on a single charge for long/extended-range. In-route charging could allow near unlimited range based on charge time and route profile.	» Between 277-357 miles.
Capital Costs[1]	» Vehicle cost range: $750K -$1M[1] » Plug-in depot charger: ~75K-$125K » Facility electrical upgrades: $50K-$75K per charger » On-route charger design, build, and electrical upgrades: $400k- $600k per charger	» Vehicle cost range: $1.01M -$1.36M » Hydrogen fueling station: $5M » Maintenance Facility upgrades: $1M
Maintenance Cost	» $0.18 to $1.47 per mile for scheduled and unscheduled maintenance[2].	» $0.56 to $1.25 per mile for scheduled and unscheduled maintenance[3].
Fueling Technology	» Depot or on-route charging using plug-in, overhead conductive, or wireless inductive charging.	» Hydrogen fueling station required; hydrogen can either be delivered (liquid or gas) or produced on-site through electrolysis or natural gas reformation.As an alternative to large-scale fueling stations, trailer-mounted hydrogen storage and dispensing solutions have become an alternative to support pilot projects or small fleets of hydrogen fuel cell buses. The fuel can be stored in liquid or gaseous states[4].
Fueling Infrastructure	» Significant power and space to place charging technology and equipment are needed. It may require redesigning the garage or bus yard. A single charger may charge multiple vehicles.	» Fueling stations are much like existing diesel ones, with similar footprints. One station can fuel the entire depot.
Scalability	» Smaller deployments require less initial infrastructure, but additional fueling infrastructure is needed as it scales.	» More scalable than BEB because existing FCEB fueling infrastructure can be used.
Fueling Time and Considerations	» Charging at the depot may take hours to recharge fully. » Electricity rates heavily impact costs.	» Less than 10 minutes and only needs to be fueled once a day. » Potential for high electric costs if producing fuel on-site.
Facility Needs	» Fire suppression and power upgrades often required.	» Ventilation system upgrades along with fuel sensor and alarm installations.
Safety Considerations	» Lithium-Ion battery fires can last for hours and cannot be extinguished until all material is burned up due to an event known as "thermal runaway," a point at which temperatures continue to rise and a fire may reignite after being extinguished.	» Hydrogen gas is invisible and odorless but is not toxic to humans. Pressurized release valves can dissipate stored gas into the air in a matter of minutes should there be a fire.
Weather Concerns	» Electric HVAC systems require more power to keep vehicles comfortable during hot or cold days resulting in range loss of over a third during cold weather.	» Electric HVAC systems require more power to keep vehicles comfortable during hot or cold days resulting in range loss of nearly a quarter during cold weather.

1. https://nap.nationalacademies.org/download/25842
2. https://afdc.energy.gov/files/u/publication/financial_analysis_be_transit_buses.pdf
3. https://www.nrel.gov/docs/fy18osti/70075.pdf
4. https://www.powermag.com/press-releases/plug-power-showcases-portable-hydrogen-refueler-solution/ https://www.airproducts.com/services/portable-hydrogen-fueler