Hydrogen Is the New Diesel:
Electrifying Heavy-Duty Vehicles
with Nuvera Fuel Cells
Shipping ports are drivers of the global economy. They create jobs, provide entry points for goods and enable the export of products around the world.

But ports are also the source of air pollution and CO₂, compounded by emissions from vehicles and vessels that enter and leave the port.
ABOUT 90% of world trade flows through ports on container ships.
More Than

900 MILLION TONS

A major port emits over 110,000 metric tons per year of carbon dioxide
Dangerous Levels of Air Pollution
Why Hydrogen?

Hydrogen is abundant, simple, clean.

Hydrogen stores energy

Hydrogen is electricity...
...with the convenience of fuel

HYDROGEN IS PORTABLE ELECTRICITY

You can refuel a fuel cell electric vehicle in about the same amount of time as a diesel vehicle.

Advanced Fast Charger

Battery Charging is 5-15 times slower

Hydrogen Fast Fueling
WORLD ENERGY MIX TODAY

Multiple Feedstocks for Electricity
- Solar
- Nuclear
- Hydro
- Wind
- Geothermal
- Biomass
- Natural Gas
- Coal
- Petroleum

“RAW” Electricity (Energy Carrier)

Mobility is over ⅓ of global energy mix — and is almost entirely carbon-based

Energy Use
- Residential 13%
- Commercial 7%
- Industrial 54%
- Transportation 26%

Mobility vs. Stationary

Source: Table F1, International Energy Outlook, 2016, United States Department of Energy.
HYDROGEN AT PORTS

- Improve AIR QUALITY
- Reduce CO₂ EMISSIONS
- Increase ENERGY EFFICIENCY
- Reduce AMBIENT NOISE
Nuvera Fuel Cell Systems
Fast-fueled drop-in battery replacements for electric lift trucks
## Engine Specifications

### Nuvera® E-Series HD Fuel Cell Engines

<table>
<thead>
<tr>
<th>Model</th>
<th>E-45-HD</th>
<th>E-60-HD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Power Output</td>
<td>45 kW</td>
<td>59 kW</td>
</tr>
<tr>
<td>Mass</td>
<td>187 kg</td>
<td>190 kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1000 x 600 x 500 mm</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td>58%</td>
</tr>
</tbody>
</table>

### Compact, Easily Integrated Fuel Cell

Primary Power or Range Extension for Medium- and Heavy-Duty Electric Vehicles
## Definition: Fuel Cell Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
</table>
| L0:   | FC Stack  | - End-plate to end-plate  
          - Nuvera maintains all IP rights and manufacturing |
| L1:   | FC Module | - Hydrogen management  
          - Process manifold  
          - Sensors and CVM connections  
          - Covers |
| L2:   | FC Engine | - Air compressor / motor / control  
          - Coolant pump / motor / control  
          - Cooling thermostat / sensors  
          - Stack control / water balance software  
          - Hydrogen valve  
          - Electronic control unit (ECU)  
          - Air sensors (pressure, temp., relative humidity) |
| L3:   | FC Hybrid Vehicle, Power System, or Battery Box Replacement (BBR) | - Air filtration  
          - Fuel tanks / regulators  
          - DC power modules / auxiliary BOP  
          - Energy storage (battery)  
          - Thermal management (radiator)  
          - Exhaust system  
          - Vehicle hybrid control unit  
          - Enclosure with ventilation |
Example Vehicle Functions

Traditional IC Engine Vehicle
- Fuel Tank
- Transmission
- Air Filter
- Radiator
- IC Engine

Fuel Cell Engine Vehicle
- Fuel Tank
- DC/DC
- Air Filter
- Radiator
- FC Engine

Nuvera FC Engine
System Integration

Clean Air
Power
Cooling
Clean Fuel
FUEL CELLS have emerged as a clear path forward to REDUCE EMISSIONS.
How does this work?
FUEL CELL

H₂ → HEAT → -e → anode

O₂ → HEAT → -e → cathode

H₂O
Zero-Emission Infrastructure Comparison

**HYDROGEN**

- **Station Capacity**: 150 forklifts, 50 yard hustlers, and 90 delivery vans
- **Dispenser / Charger Times**: 3-10 minutes
- **Real Estate**: 1,500 kg/day, 30' x 50', 3.75 MW
- **Cost**: $, 5 Dispensers

**ELECTRICITY**

- **Station Capacity**: 348.75 MWh/day
- **Dispenser / Charger Times**: 1-2+ hours
- **Real Estate**: 20-30X, 150 MW
- **Cost**: $$$, 30-40 Charging Stations

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Fuel Cell and Battery Options

Like electricity, hydrogen can be produced renewably

+ Fuel cell vehicles have greater range than pure battery vehicles
+ Unaffected performance in cold temperatures/environments
+ Payload capacity comparable to gasoline and diesel vehicles
How does MathWorks come in?
Why Model-Based Design?

+ Fuel cell engines are still in early development (vs. 150 years for ICE)
  + Want to avoid damaging prototype engines
+ Before working on hardware, beneficial to work on a virtual system
  + Rapid design iterations
  + Identify and fix errors
  + Simulate scenarios without putting a real engine at risk
+ Save time by automatically generating code from model
Model-Based Design approach using Simulink

Model-in-the-Loop (MIL)
Controller and Plant models are simulated

Hardware-in-the-Loop (HIL)
Controller implemented on engine’s ECU
Plant model implemented on real-time computer
E.g. of problems to solve
- Maintain proper hydration
- Test fault management

Physical system modeling with Simulink
- Electrochemical reaction
- Fluids flow, temperature, pressure (H2, air, coolant)

Control system modeling with Simulink/Stateflow
- Power management, Hydration management, Fault management
- Control algorithms to optimally operate the fuel cell engine

Simulations
- Test startup, shutdown sequences
- Simulate effects of failure
- Simulate low and high ambient temperatures
- Simulate low and high humidity environments

How Model-in-the-Loop helped develop and refine features/functions
How Hardware-in-the-Loop helped test features/functions on target ECU

+ Plant → Speedgoat’s Performance real-time target machine
  + Simulink Real-Time

+ Controller → Engine ECU
  + c code autogenerated by MathWorks’ Embedded Coder
  + Autogeneration avoids introduction of manually programmed bugs

+ ECU verification
  + Firmware, impact of analog input accuracy, impact of latency in CAN communication on control logic

+ Adds rigor without putting a real engine at risk
  + Simulation of hardware failures like cooling pump, compressor, valves
Benefits of Model-Based Design to Nuvera

+ Speed up design iterations (days vs. weeks pre-MBD)
  + Simulations catch bugs early and permit assessment of
    - performance in a variety of environmental conditions
    - effects of hardware failures
  + Autogeneration eliminates hand-coding errors

+ Design reuse for derivative systems
  + Nuvera E-60-HD software developed in weeks thanks to reuse of
    E-45-HD models
Fuel Cell Engines
Enable Zero Emission Mobility

Growing global demand for clean, convenient power makes fuel cell transformation inevitable.

Fuel cells provide:

+ Zero emissions
+ Fast refueling
+ High efficiency
+ Driving range
+ Comparable payload
+ Reduced EV infrastructure requirements
Enabling the Pathway to Zero Emissions at Ports

Nuvera’s fuel cell engines are ready for:

+ Container Handlers
+ Yard Tractors
+ Drayage Trucks
+ Rubber Tire Gantries
+ Forklifts
+ Buses

We are poised to work with port authorities, terminal operators, truckers, and community groups to meet the goals for emission-free transportation.
ZERO EMISSIONS
LIMITLESS POSSIBILITIES