Battery-Electric Buses 101

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Battery Electric Buses 101

APTA 2017 Sustainability Workshop

Minneapolis, MN

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Senior Project Manager

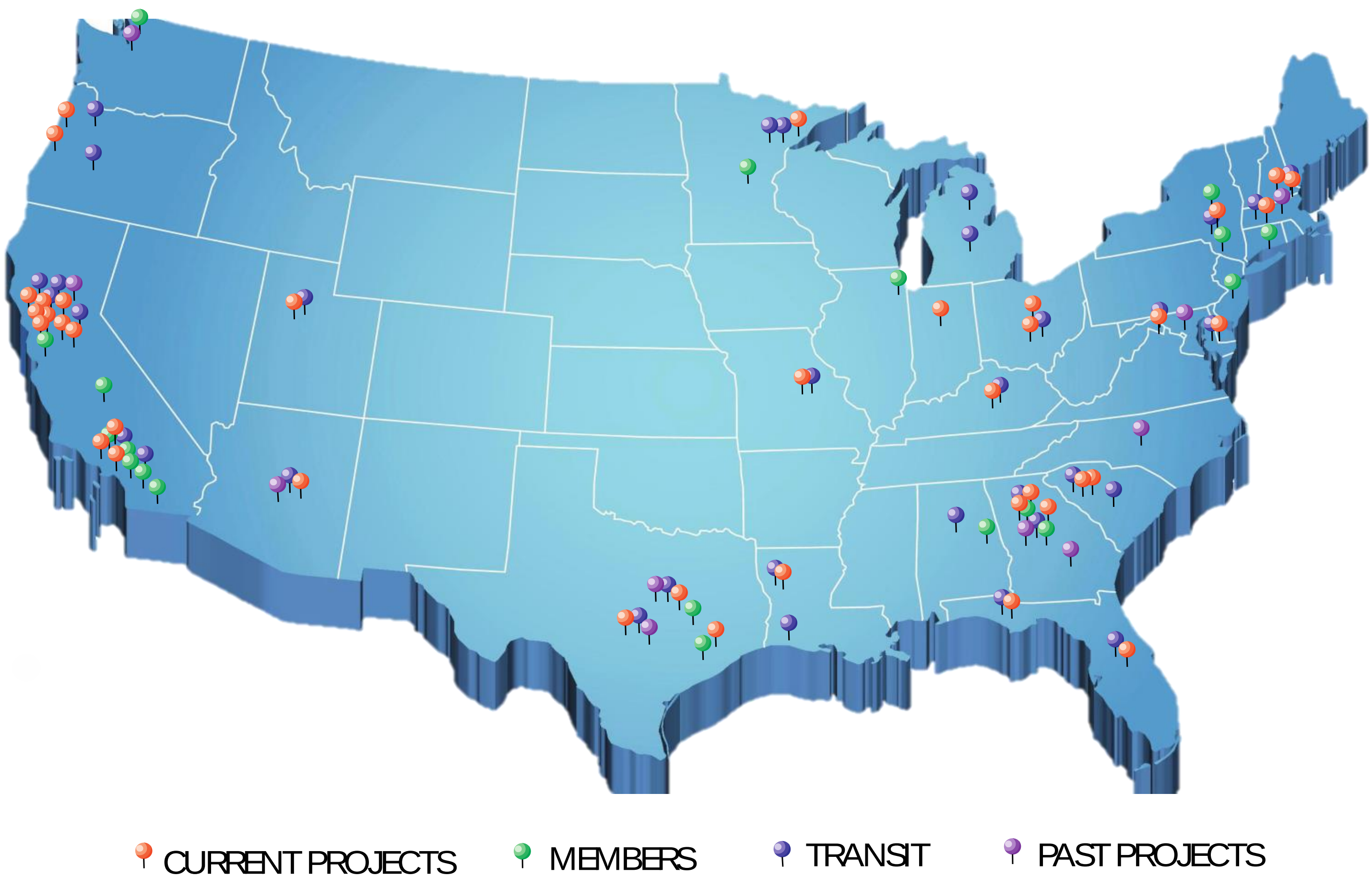
Center for Transportation and the Environment

About CTE

- Mission: To advance clean, sustainable, innovative transportation and energy technologies
- 501(3)(c) non-profit
- Portfolio - $400+ million
  - Research, demonstration, deployment
  - Alt. fuel and advanced vehicle technologies
- National presence

  Atlanta, Berkeley, Los Angeles, St. Paul

CTE Activity Roadmap



Over $217 million active project portfolio

CTE Zero Emission Bus Projects

More than 140 ZEB's with over 30 Transit Agencies

Overview & Agenda

- Why switch to electric buses?
- Battery electric bus history
- Understanding batteries
- Charging overview
- Driving range
- Electric rates and fuel cost
- Planning for your fleet

Warming Up the Batteries

- Where are you from?

- What is your experience with zero emission buses so far?

Electric Bus Fleet Trivia

- Where is the current largest US Zero Emission Fleet?
- Where is the longest (in years) running battery electric bus operation?

What do you want to hear about?

- Key concerns?
- Open questions?
- Getting started?

Key Terms

- ZEB – Zero Emission Bus
- BEB – Battery Electric Bus

Why Electrify Buses Now?

Why Electrify Buses Now?

- Currently a global movement to electrify transportation underway

Volvo

"Every Volvo from 2019 on will have an electric motor"

Toyota

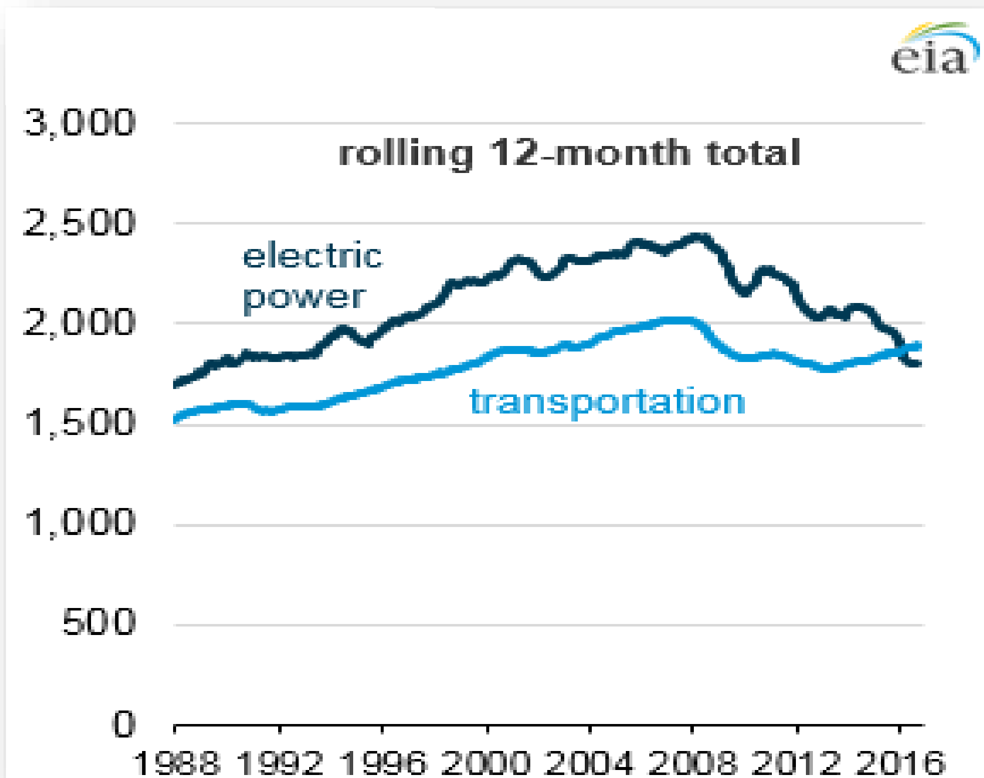
"All cars will be only battery electric or fuel cell by 2050"

France & UK

Planning to ban sales of combustion engines by 2040

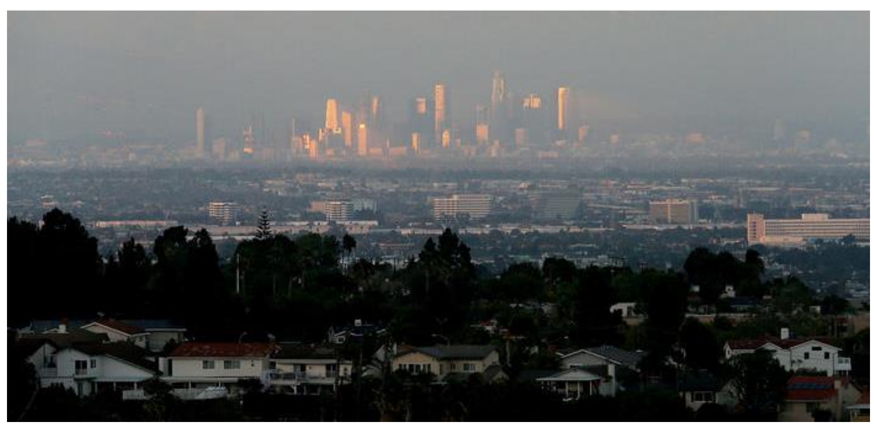
Why Electrify Buses Now?

- Transportation GHG is now above power generation for the first time



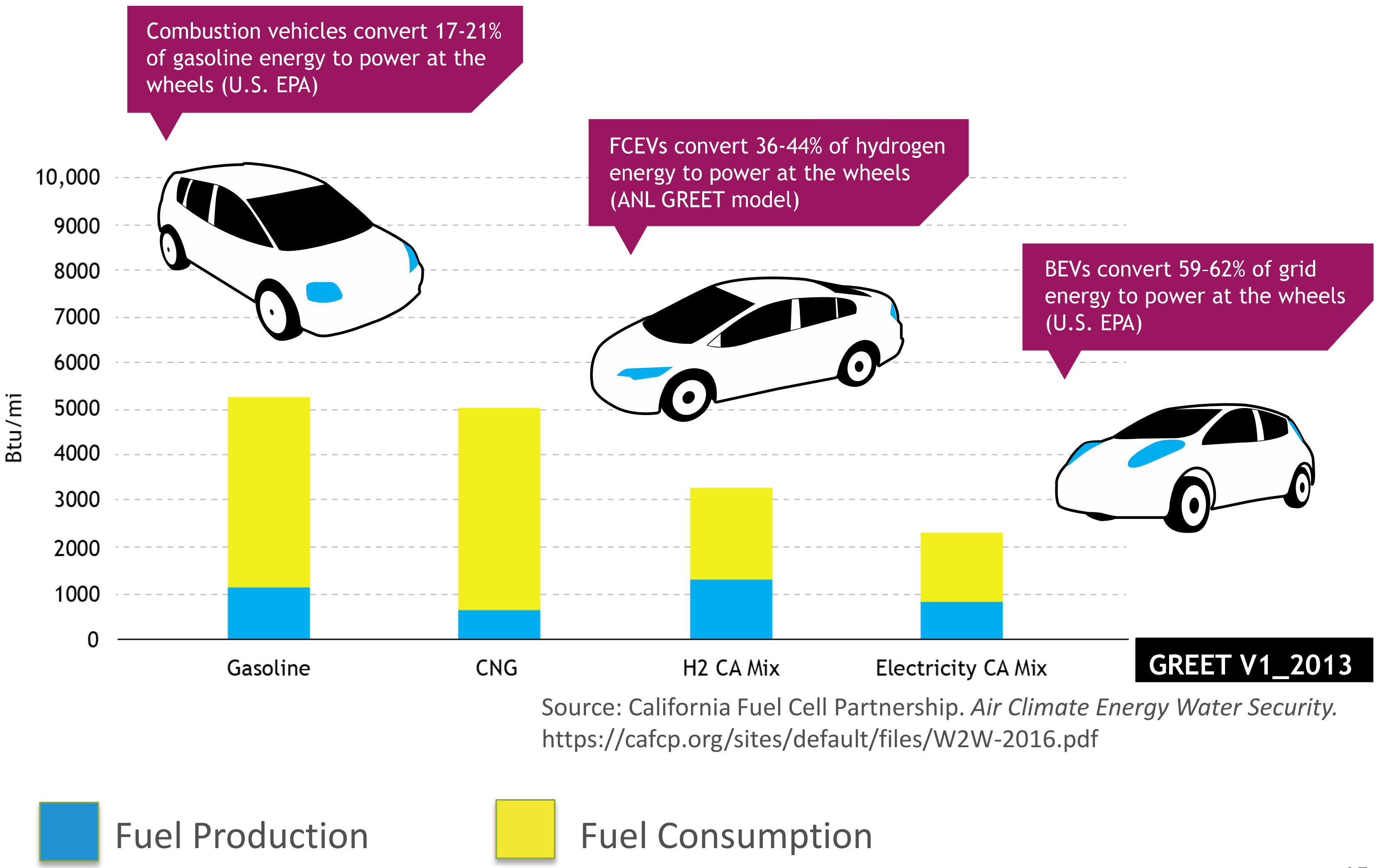
Local Pollution Control

- Most bus emissions are concentrated where people are most concentrated
- Shifting energy production to centers outside of cities, or to zero emission, reduces impacts on population



LA, Nov 2015 - from LA Times

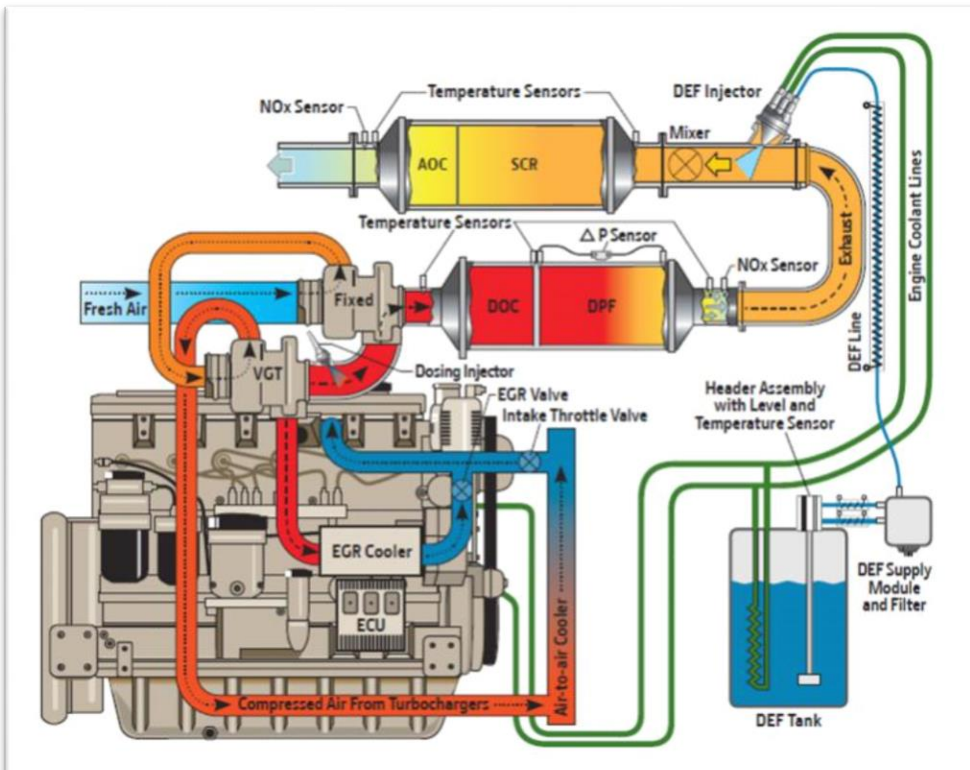
Overall Energy Efficiency – "Well to Wheels"



Source: California Fuel Cell Partnership. *Air Climate Energy Water Security.* https://cafcp.org/sites/default/files/W2W-2016.pdf

Regulatory Environment

- Increasing complexity of Emissions Controls
- Zero Emission Bus Mandates



Modern diesel emissions control Technology

- DOC
- DPF
- DEF
- SCR
- AOC
- EGR

Zero emission buses are quiet

- Quieter interiors are more comfortable
- Quieting city centers makes transit more desirable

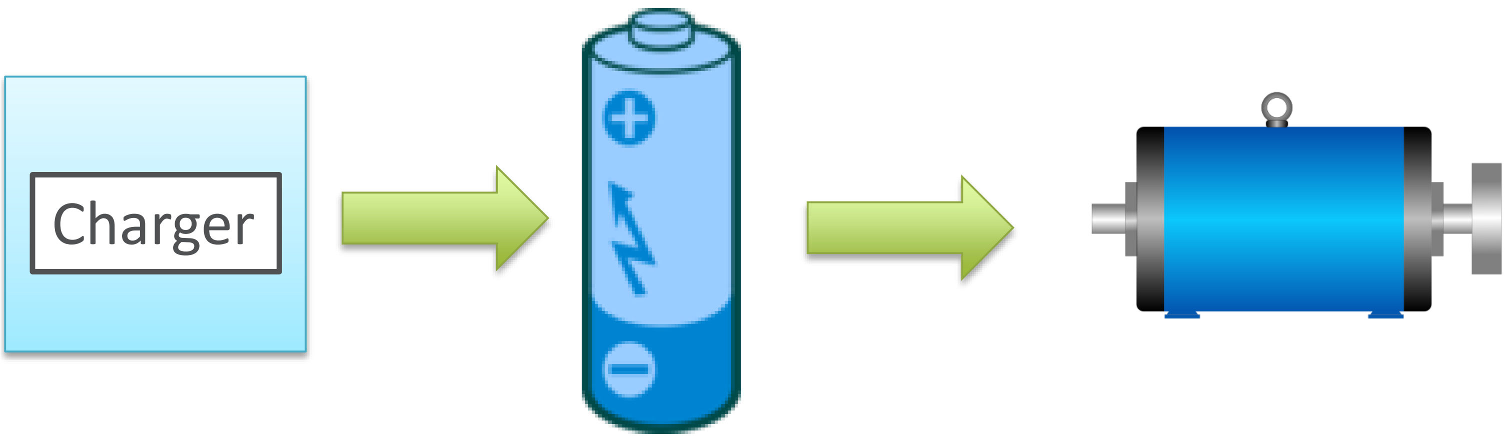
Key Current Challenges

1. Initial Capital Cost
2. New Operational Requirements
3. Procurement Hurdles
4. Charging Interfaces/Standards
5. Long Term Energy Needs

Adapted from UITP eBus Training Program, June 2017

Hydrogen Fuel Cell vs. Battery Electric

- Both are all-electric drivetrains
- Both are zero point source emission



Battery Electric Vehicle

Hydrogen Fuel Cell vs. Battery Electric

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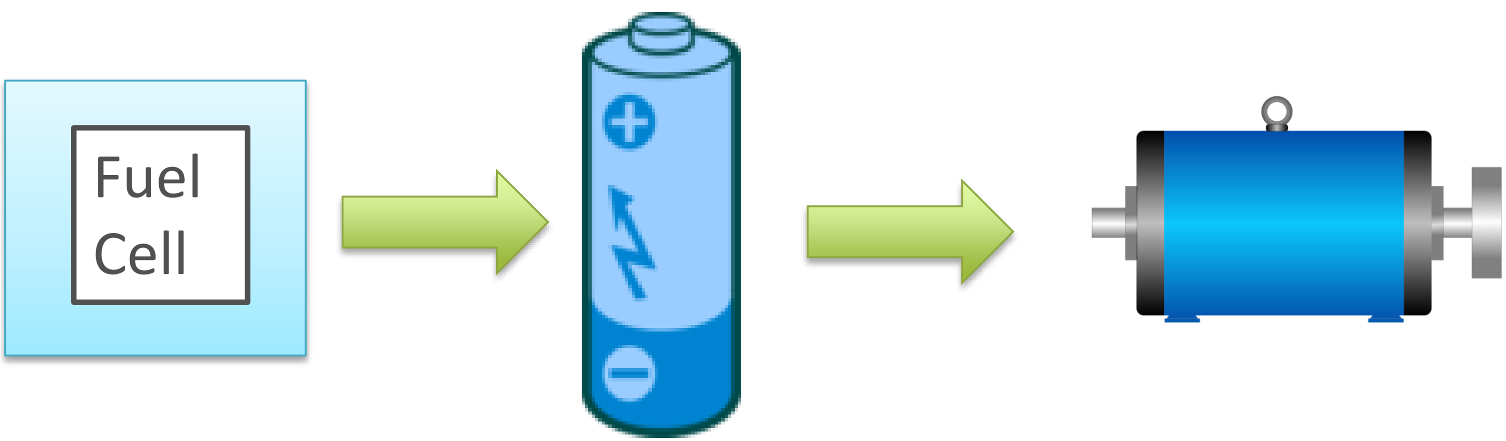


Fuel Cell Electric Vehicle

Hydrogen Refueling

- Vehicle fueling is similar to CNG
- Station fuels buses in ~15 minutes, which are then ready for the next pull out
- Sufficient range for most transit service

Hydrogen Fuel Cell Buses

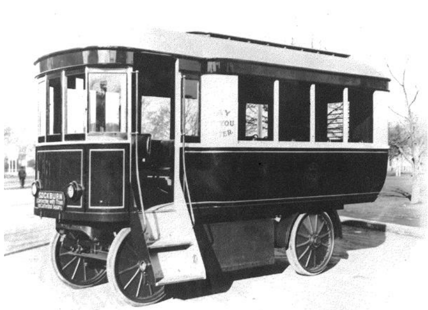
- Pro: Simpler logistics and fueling
- Con: Higher capital and operating cost
- Costs are coming down rapidly

Calendar Year	Price
2008	$3.2 mm
2010	$2.2 mm
2016	$1.1 mm
2019	Under $1 mm

40’ Fuel Cell Transit Bus Price History

Battery Electric Bus History

- Similar history to light duty vehicles
  - Technology has been generally available for decades, but the right combination of affordability and capability are here
- Earliest electric buses were before gasoline vehicles were reliable



1915

1974

1992

Understanding Batteries

High capacity batteries are the key enabler of modern electric buses

Key Topics to Discuss

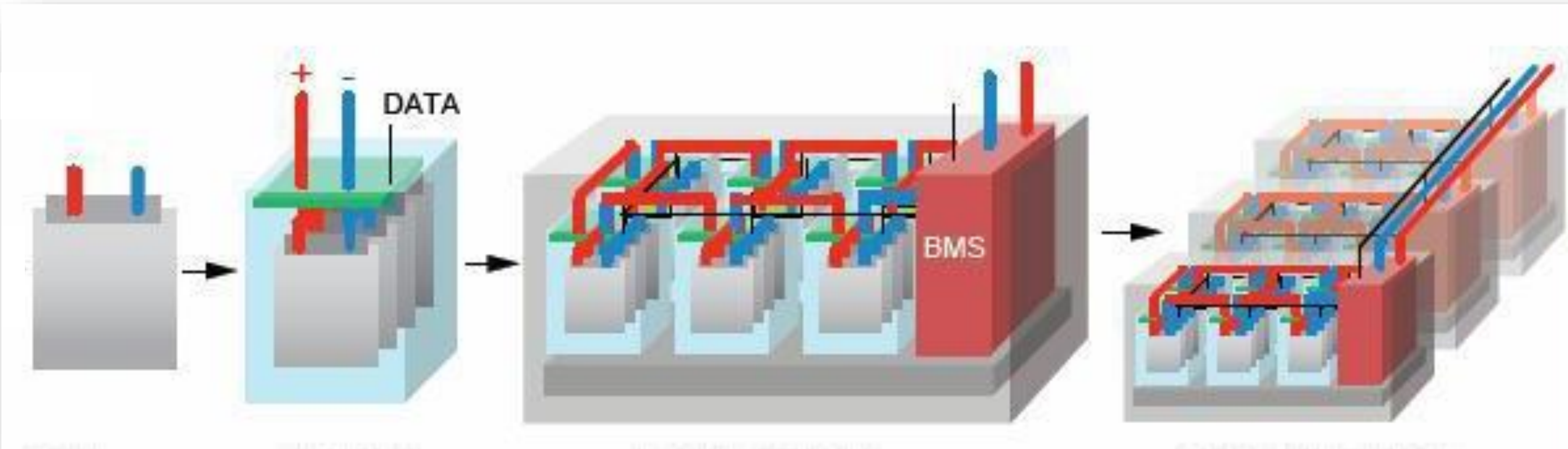
- Battery Chemistries
- System Architecture
- Safety
- Units of Measure

Battery Chemistries

- All batteries in new buses today are variations of Lithium Ion batteries
- Different battery chemistries offer different strengths and benefits

- Typical Chemistries:
  – NMC - Nickel Manganese Cobalt
  – LiFe – Lithium Iron Phosphate
  – LiTo – Lithium Titanate

Energy Storage Architecture



Source: Alexander Otto, “Battery Management Network for Fully Electrical Vehicles Featuring Smart Systems at Cell and Pack Level.”

Cell –> Module –> String -> Pack

$3V_{DC}$ $30V_{DC}$ $400\text{-}600V_{DC}$

Note: manufacturers may use different terms

Energy Storage Architecture

- A battery energy storage system is comprised of components:
  - Battery cells
  - Packaging – mechanical, thermal management
  - Safety – fusing, ground fault detection
  - Battery Management System

Battery Capacity Terminology

- State of Charge (SOC)
  - Percent of total energy currently in batteries
- State of Health (SOH)
  - Measure of degradation from BOL
- Beginning of Life (BOL) Capacity
  - Energy storage capacity when new
- End of Life (EOL) Capacity
  - Energy storage capacity when useful limit, or warranty condition, is reached

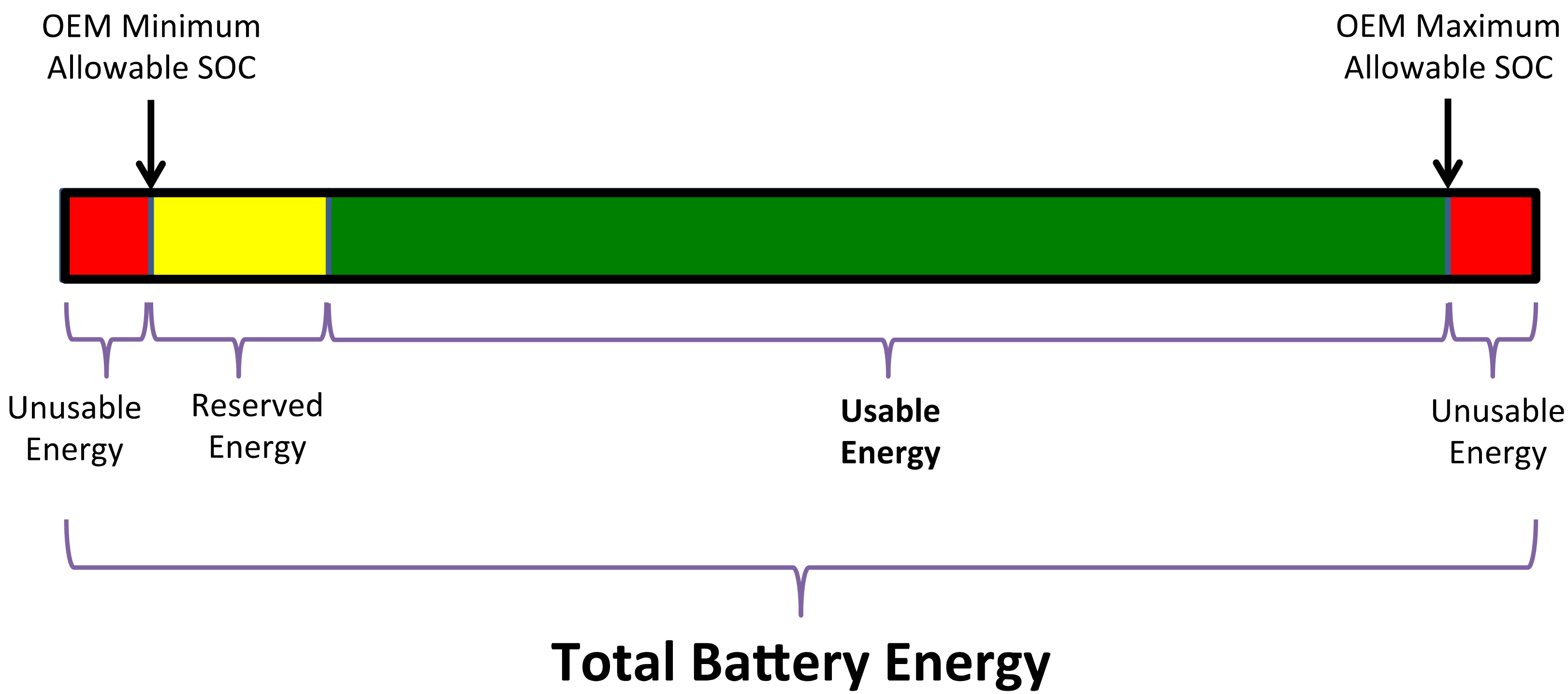
Batteries Units of Measure

- kW and kWh measure very different things

Unit	Describes what?	Conventional Equivalent	Example
kW	Power	Horsepower (hp)	This battery pack can provide 230 kW (308 hp)
kWh	Energy	Gallons of diesel	This bus stores 300 kWh (7.9 gallons diesel)

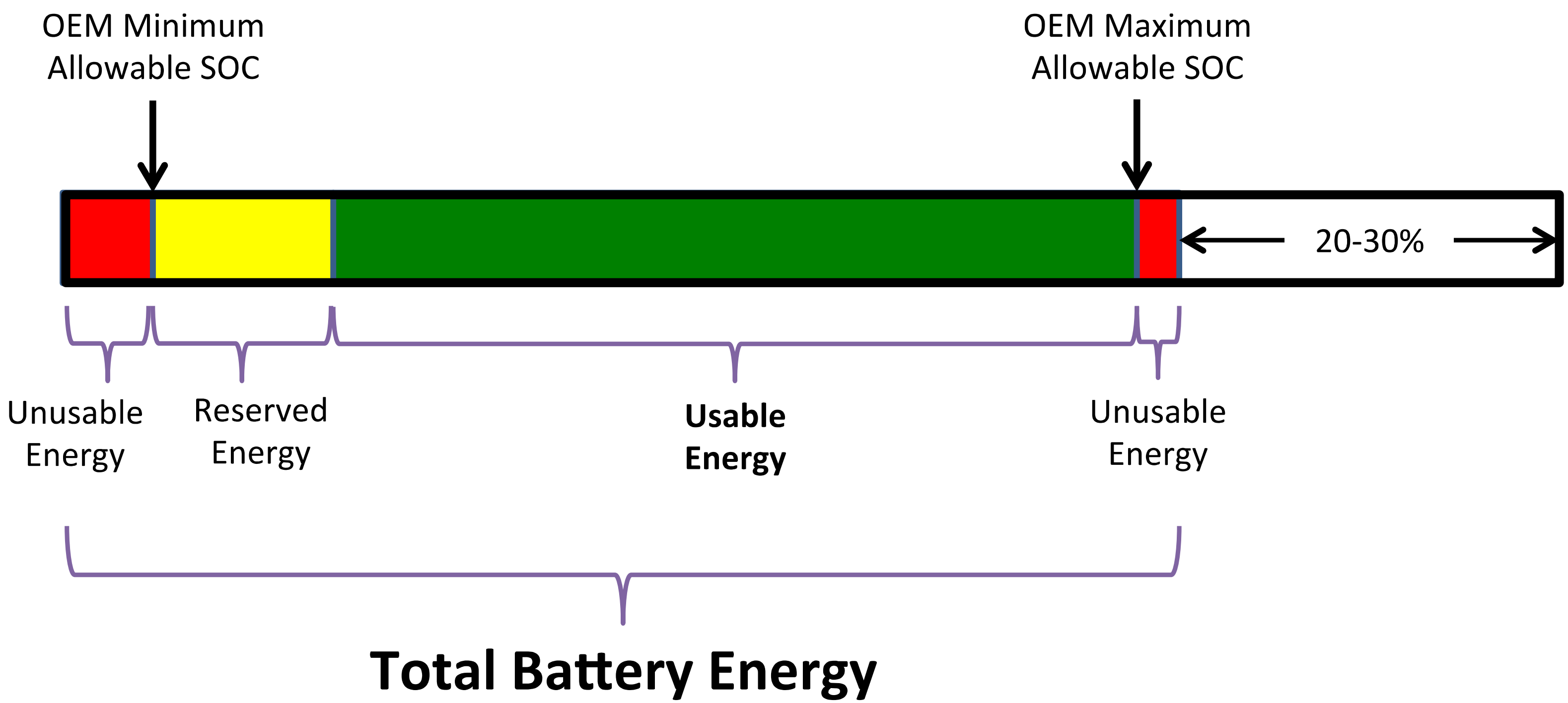
Battery Capacity Terminology

Beginning-of-Life Batteries



Battery Capacity Terminology

End-of-Life Batteries



Note: Batteries all lose capacity through use and aging

Safety

- Different batteries have different safety related characteristics, **effective cell management is the most critical**

***Any** energy storage that can move a bus (diesel, CNG, or battery) can lead to a hazard in the wrong conditions*

New vs. Similar Bus Systems

- Many onboard systems will be identical to diesel counterparts
- New Systems
  - Electric Heating and Air Conditioning
  - Electric Accessories: Power Steering, Air Compressor
  - Electric drivetrain: Batteries, Motor, Controls
- Vehicle Charging Interface

Charging Infrastructure Installation

- Installation can be a significant infrastructure project
- We typically budget around 1 year for the entire process for on-route infrastructure
- Identify how this fits in to longer range plans if possible

Charging Option Overview

Depot Charge

- Conductive

On Route Charge

- Conductive
  - Static
  - Dynamic – trolley style
- Inductive
  - Static
  - Dynamic – early research

Zero Emission Buses & Infrastructure

Depot Charge – Conductive

- Large battery pack
- 70 – 300 mile range
- 50 – 120 kW charger
- Recharge in 3-7 hours

- Fast chargers may be an option in the future

Zero Emission Buses & Infrastructure

Depot Charge – Conductive

- Pros
  - On site infrastructure (chargers at depot)
  - Takes advantage of lower off-peak electricity rate
  - Flexibility for route selection and route changes
- Cons
  - Must be taken out of service to recharge
  - Larger, heavier battery packs
  - Scalability at the depot can be a challenge

Zero Emission Buses & Infrastructure

On-Route Charge – Conductive Stationary

- Smaller battery pack
- 20 – 50 miles range
- 300 – 500 kW charger
- Full charge in 5 - 15 mins.

Zero Emission Buses & Infrastructure

On-Route Charge – Stationary Conductive

- Pros
  - Charging while on-route, 24/7 operation possible
  - Smaller Battery Pack
  - Distributed demand may minimize grid impacts
- Cons
  - Higher cost of charging infrastructure
  - Overhead systems may require dedicated/restricted pull-off
  - May require change to service schedule to charge
  - Costly to modify routes in the future

Zero Emission Buses & Infrastructure

On-Route Charge – Inductive Stationary

- Profile:
  - 50 kW charger
    - 200-250 kW in development
  - Can be primary charger with 250 kW version

Zero Emission Buses & Infrastructure

On-Route Charge – Inductive Stationary

- Pros
  - Can remain in service while charging on-route
  - Extends range of depot-charged BEB
  - Smaller on-route infrastructure footprint
- Cons
  - At current power level, cannot be used as sole source
  - Infrastructure and cost for on-route charging system
  - Costly to modify routes in the future

Range – Onboard Energy Capacity

- It depends!
- Different bus models will have different installed energy capacity
  - All else being equal, usable range depends directly on capacity
- Larger battery packs are heavier
  - Causes slight efficiency penalty
- Headlights are not a big draw

Range – HVAC Impacts

- Heating and cooling will cause the single largest impact on useable range
- In most of the US, heating on the coldest days will have a larger impact than AC on the hottest days
- Vehicle planning needs to include varied HVAC impact
- Diesel fired heaters are typically available for cold climates

Range Impacts – How is the Bus Used

- The next largest impact to efficiency is sitting in the driver's seat
- Regenerative breaking recovers significant energy
- Hard braking will increase overall energy use

Range Impacts – How is the Bus Used

kWh/mile consumption

	OEM Brochure	CTE Model
Route A (summer, no passengers)	1.7 – 2.0	1.72
Route A (summer, avg. passengers)	1.7 – 2.0	2.11
Route A (summer, max passengers)	1.7 – 2.0	2.46
Route A (winter, no passengers)	1.7 – 2.0	1.91
Route A (winter, avg. passengers)	1.7 – 2.0	2.64
Route A (winter, max passengers)	1.7 – 2.0	3.10
Route B (fall, no passengers)	1.7 – 2.0	1.68
Route B (fall, avg. passengers)	1.7 – 2.0	2.06
Route B (fall, max passengers)	1.7 – 2.0	2.20

Worst Route, Worst Case	6.17

Understanding Electric Fuel Cost

Electric rates are typically a combination of:

1. Consumption charges
   – Varies with amount of energy used

2. Demand charges
   – Based on the highest power draw that month

3. Fees
   – Fixed and variable

Understanding Electric Fuel Cost

Actual electric fuel cost can be **higher or lower** than existing fuel costs based on:

- **Baseline** - Existing conventional fuel price
- **New Fuel Cost -** Electric rate structure
- **Usage -** Bus use and recharging pattern

Time of Use Rates (TOU)

- Time of Use Rates have a varied cost structure depending on the time of day to match grid supply and demand
- Consumption and demand charges can vary significantly over the day
- Highest costs during highest demand

Charging Standards

- Charging system standards will allow common hardware between different manufacturers
- Standards are currently in development

How Do You Add Electric Buses?

- Electric buses are operationally different than conventional buses – how do you get started?

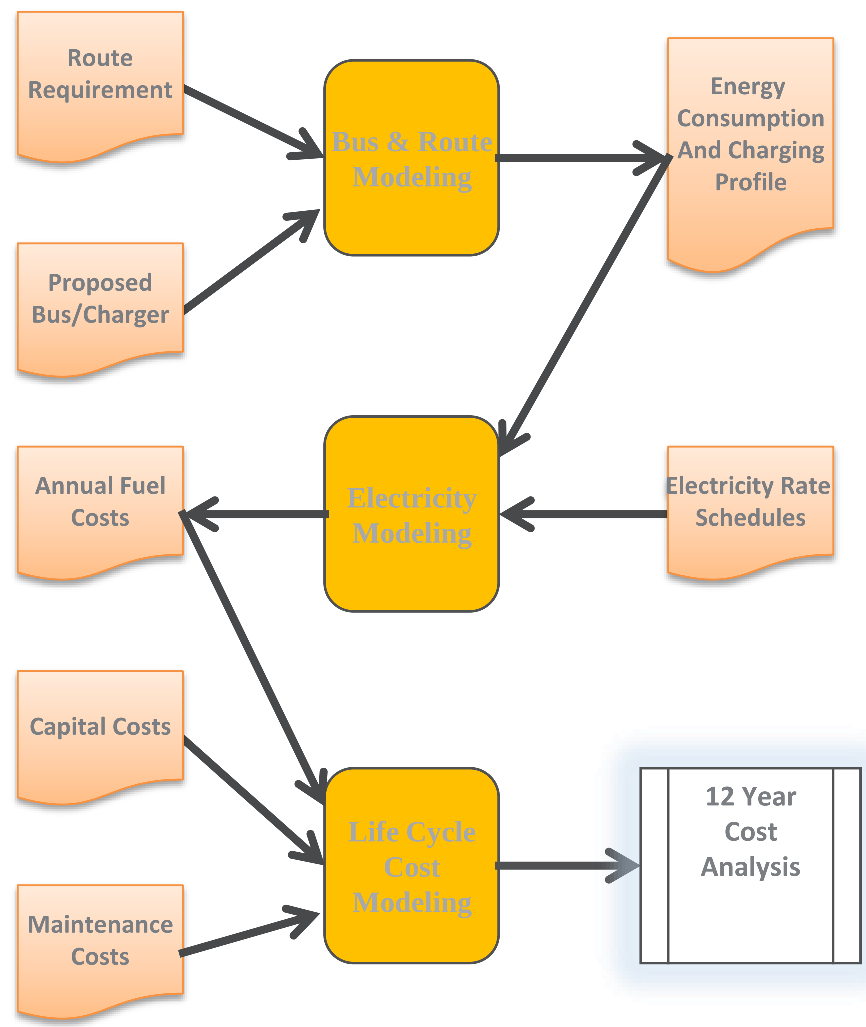
Go for it!

Go for it, conservatively!

Strategy, Planning, Implementation

Key Elements for ZEB Deployment

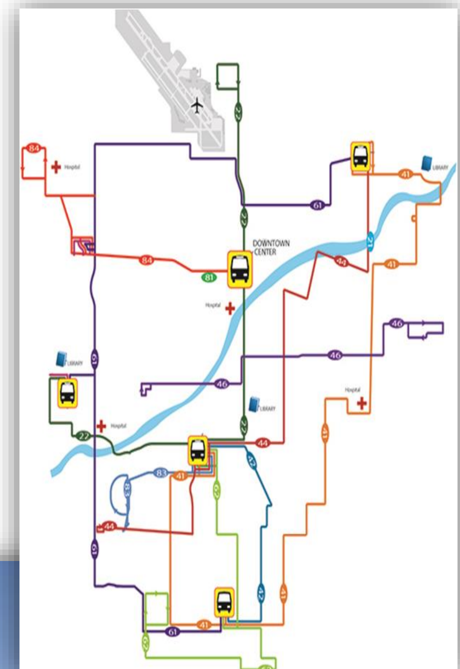
- Determine which technology is right for your routes
  - Bus Modeling & Route Simulation
- Estimate Operating Costs
  - Rate Modeling & Fuel Cost Analysis
- Establish the Business Case
  - Life Cycle Cost Analysis
  - Risk Assessment



Bus Modeling and Route Simulation

Service Requirement

- Route Logistics
  - Length
  - Duration
  - Schedule
  - Frequency
- Duty Cycle
  - Speed
  - Accel/Decel
  - Grades
  - Passenger Load
  - Auxiliary Load
  - Deadhead
- Operating Environment
  - Traffic Congestion
  - Climate



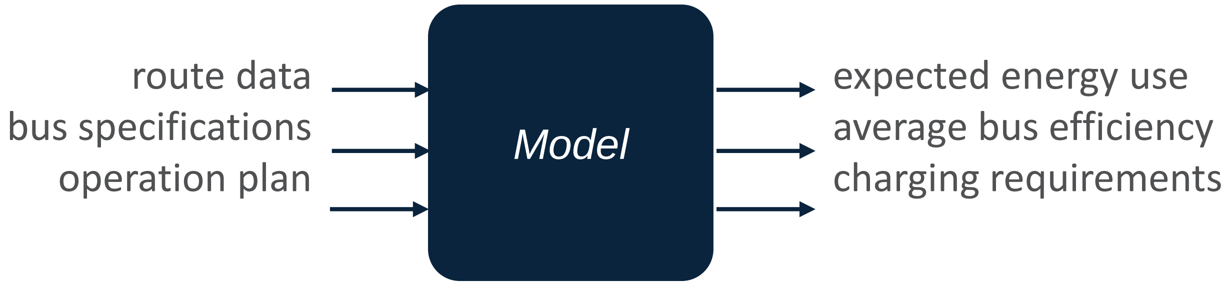
ZEB Modeling Methodology

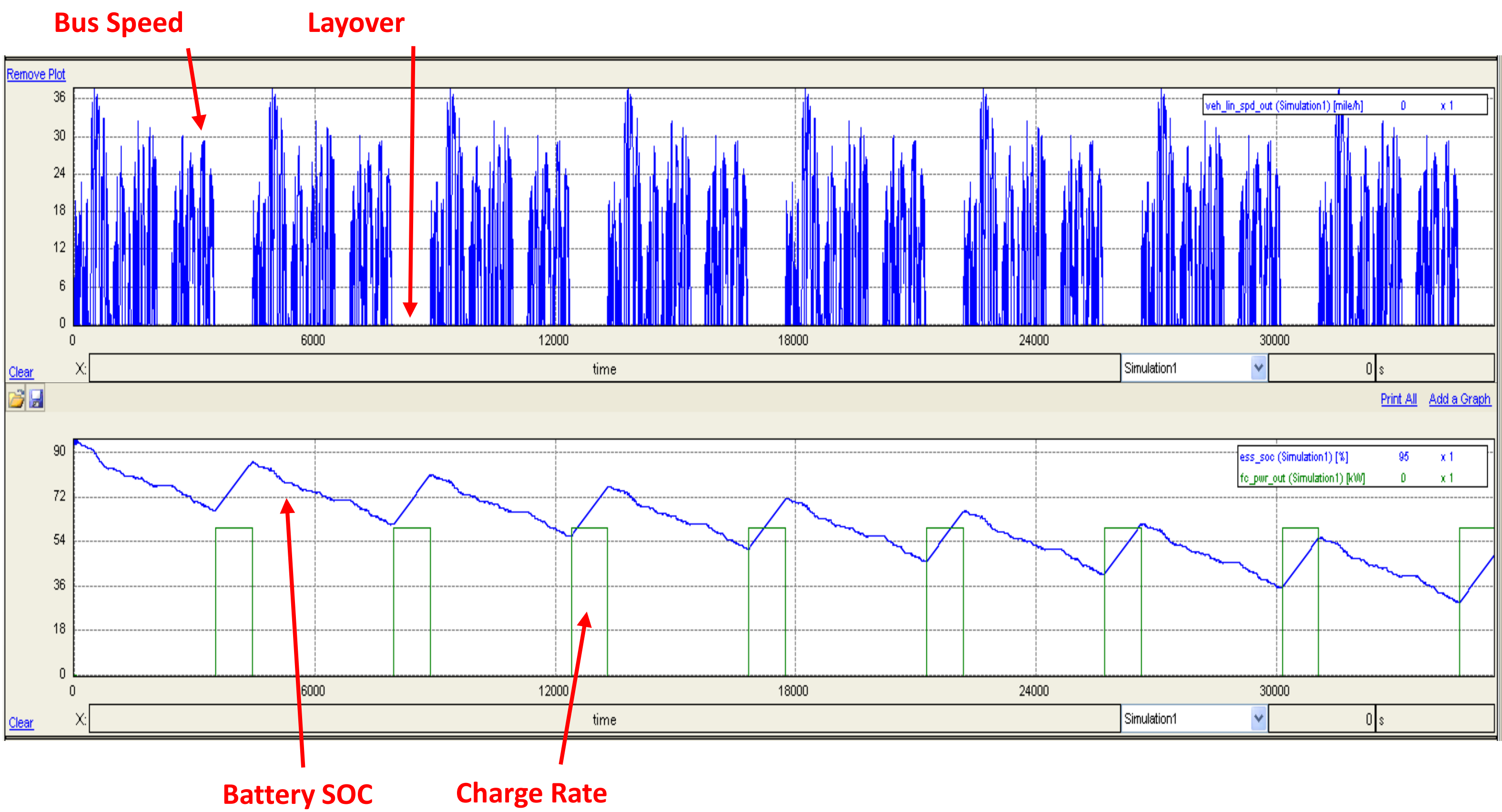
- Autonomie™ Simulation Software (developed by Argonne National Lab.)

- GUI utilizing MATLAB & Simulink software package

- Quick assembly of complex ZEB specifications:
  - Vehicle weight
  - Battery chemistry and energy capacity
  - Motor power output and energy requirements
  - Rolling resistance

Typical Route Model Results



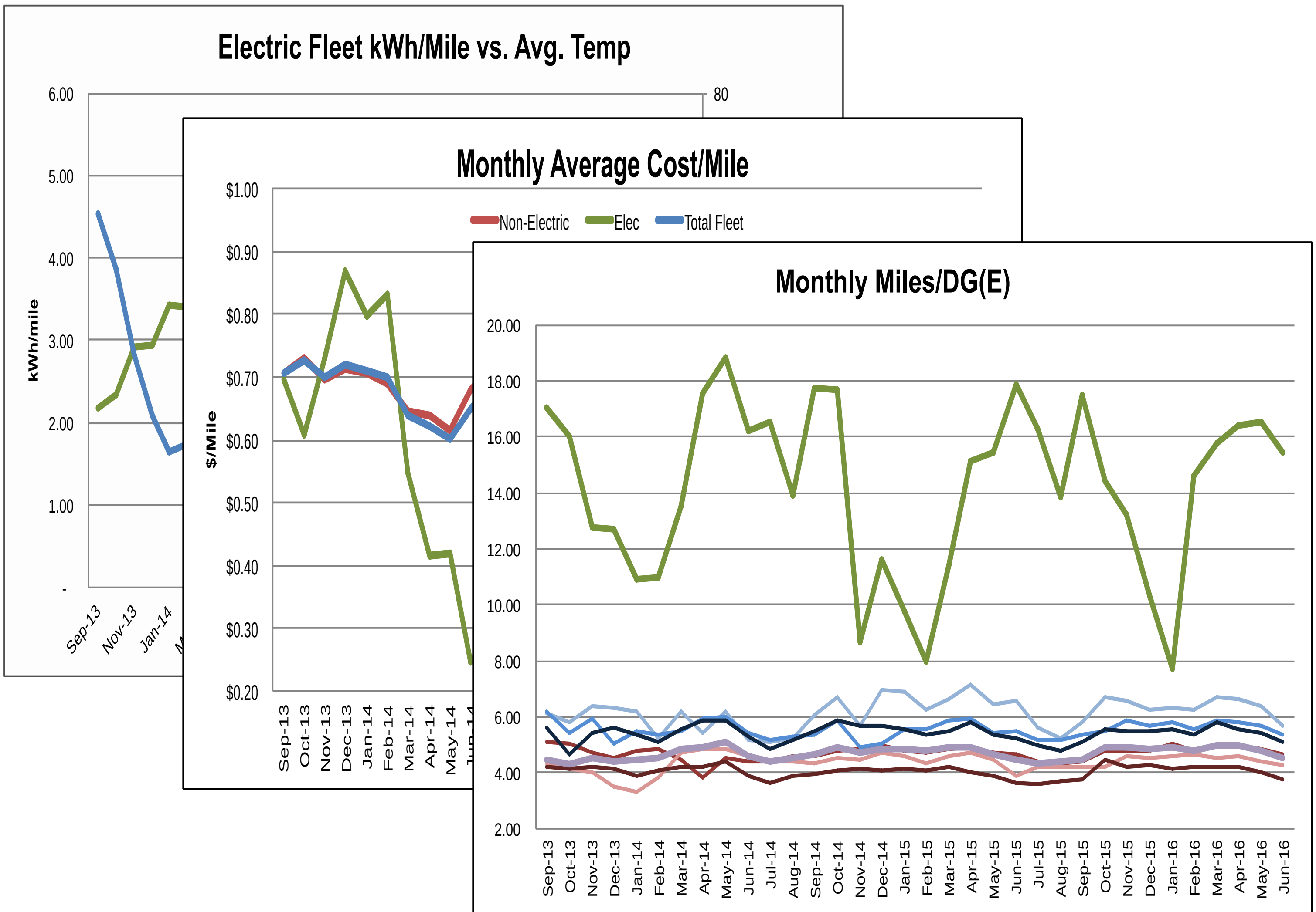


Rate Modeling & Fuel Cost Analysis

- Battery Electric Charging
  - Energy Consumption estimate from Route Modeling
  - Charger Specifications
  - Charging Profile
    - Charge Rate, Duration, Time of Day
  - Utility Rate Schedules

Key Performance Indicators

Track & Analyze Performance - Take Corrective Action - Realize Benefits - Repeat



Fleet Introduction Planning

- Training
  - Maintenance
    - New technologies and diagnostics
    - Safe handling
  - Operators
    - OEMs aim for seamless experience, some familiarization is needed
    - Charge docking, if on-route charging

Fleet Introduction Planning

- Schedule Adjustment, if needed
- Safety Planning
  - BEB: Similar training requirements as diesel electric hybrids for high voltage
  - Hydrogen Fuel Cell: Combination of requirements similar to CNG and hybrid safety

What's next for your fleet?

Zero Emission Buses work!

- Define your agency goals
- Create deployment strategy
- Start operating Zero Emission Buses

Questions?

Erik Bigelow

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