Eletra Bus
March 2004

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Mr. Thomas Balon
Topics for Discussion

- Hybrid vs. Conventional Diesel, CNG
- WVU Test Methods and Equipment
- Efficiency, GHG emissions, Fuel Economy
- Criteria Pollutant Emissions
- Emission Control Devices, Interactions
- Drive Cycles, Routes, In-Use Evaluations, Idle
  - Repeatability vs. Accuracy
- Hybrid Design Choices
  - Engine, Battery and System Efficiency
  - Modeling for Design
  - Regenerative Braking
Hybrid vs. Conventional Diesel, CNG
What is a hybrid bus?

**Definition**
- A hybrid electric bus carries at least two sources of motive energy on board and uses electric drive to provide partial or complete drive power to the vehicle’s wheels.

**Components**
- Electric Drive Motor
- Controller/Inverter
- Energy Storage/Load Leveling Device
- Auxiliary Power Unit (APU)
- Auxiliary Systems
Hybrid Configurations

Parallel

Series

Courtesy: EVTI
Hybrid Manufacturers in USA

- **BAE Systems** Series Hybrid (formerly LMCS)
  - Cummins ISB, Orion Chassis
- **Allison Transmission** Ep Hybrid Automatic Transmission, (Ev system with VM642 discontinued)
  - Cummins ISC, New Flyer Chassis
- **Neoplan** Dual Mode Articulated, MBTA
  - DDC Series 60, Neoplan USA Chassis, Skoda Drive
- **ISE Research** Series Hybrid
  - Ford V10 Gasoline Engine
- **AVS** Capstone Hybrid appears Discontinued
  - Capstone Turbine, Solectria or Siemens Drive
- **Several Others Building Hybrid Trucks**
  - International, Eaton, Dana, Permadrive
The Propulsion Control System (PCS) control unit directs the energy flow, indicated by the yellow arrows, using data from driver interfaces and all HybriDrive system components.

The Engine is controlled by the PCS to run at near constant RPM, driving the Generator.

The HybriDrive Generator provides electricity to the Batteries and the Electric Motor via the HybriDrive PCS.

The HybriDrive Battery Pack stores Generator power as well as captured energy recovered during vehicle braking. This reserve power is available to the Electric Motor on demand for acceleration or climbing.

The HybriDrive AC Induction Motor uses electrical power to drive the differential and propel the vehicle. During braking, this motor acts as a generator to return deceleration energy to the system by recharging the batteries.
# HD Hybrid APU Specs

<table>
<thead>
<tr>
<th>Bus Drive</th>
<th>Mechanical</th>
<th>Hybrid</th>
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<tbody>
<tr>
<td>Make &amp; Model</td>
<td>DDC S-50</td>
<td>DDC S-30</td>
<td>Cummins ISB</td>
<td>DDC 642</td>
<td>GM V-8</td>
<td>Capstone</td>
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<tr>
<td>Type</td>
<td>CI engine</td>
<td>CI engine</td>
<td>CI engine</td>
<td>DI engine</td>
<td>SI engine</td>
<td>Gas turbine</td>
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<tr>
<td>Peak Power (hp)</td>
<td>320</td>
<td>230</td>
<td>250</td>
<td>160</td>
<td>n/a</td>
<td>43</td>
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<tr>
<td>Displacement (L)</td>
<td>8.5</td>
<td>7.3</td>
<td>n/a</td>
<td>4.2</td>
<td>5.7</td>
<td>n/a</td>
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<tr>
<td>Weight (lbs)</td>
<td>2,230</td>
<td>662</td>
<td>962</td>
<td>662</td>
<td>n/a</td>
<td>163 w/generator</td>
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<tr>
<td>PM Emissions (g/bhp-hr)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.10</td>
<td>0.10</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>Meets EPA Urban Bus Stds</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>exempt</td>
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</table>
# HD Electric Motor Specs

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Lockheed Martin</th>
<th>Delphi</th>
<th>Siemens (dual motors)</th>
<th>Solectria</th>
<th>Unique Mobility</th>
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<tbody>
<tr>
<td>Type</td>
<td>AC</td>
<td>AC</td>
<td>AC</td>
<td>AC</td>
<td>PM</td>
</tr>
<tr>
<td>Peak Output (kW)</td>
<td>190</td>
<td>155</td>
<td>280</td>
<td>150</td>
<td>100</td>
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<tr>
<td>Continuous Output (kW)</td>
<td>190</td>
<td>140</td>
<td>170</td>
<td>136</td>
<td>N/A</td>
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<tr>
<td>Max. Torque (lbf-ft)</td>
<td>485</td>
<td>N/A</td>
<td>454</td>
<td>424</td>
<td>405</td>
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<tr>
<td>Max. Speed (rpm)</td>
<td>1,500</td>
<td>N/A</td>
<td>2,200</td>
<td>N/A</td>
<td>4,400</td>
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<tr>
<td>Cooling</td>
<td>oil</td>
<td>oil</td>
<td>water/glycol</td>
<td>air</td>
<td>oil</td>
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<tr>
<td>Dimension (in.)</td>
<td>16x25</td>
<td>N/A</td>
<td>32x20x16</td>
<td>N/A</td>
<td>15x16</td>
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<tr>
<td>Weight (lbs)</td>
<td>250</td>
<td>N/A</td>
<td>705</td>
<td>496</td>
<td>190</td>
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<tr>
<td>Power Density (kw/lb)</td>
<td>.76</td>
<td>N/A</td>
<td>.40</td>
<td>.30</td>
<td>.53</td>
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<tr>
<td>Efficiency (%)</td>
<td>90</td>
<td>N/A</td>
<td>90</td>
<td>90</td>
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## Bus Energy Storage Devices

<table>
<thead>
<tr>
<th>Supplier/Developer</th>
<th>Type</th>
<th>Affiliated Projects</th>
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<tbody>
<tr>
<td>Fulmen</td>
<td>Flooded Lead Acid</td>
<td>AVS/Capstone</td>
</tr>
<tr>
<td>Electrosource Horizon</td>
<td>Lead Acid</td>
<td>Orion IV, VI; Gillig Phantom; Georgetown University NovaBUS Fuel Cell</td>
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<tr>
<td>Saft</td>
<td>Nickel-Cadmium</td>
<td>APS/Calstart, DUETS, New York State Consortium</td>
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<tr>
<td>Hawker</td>
<td>Starved Electrolyte</td>
<td>NovaBUS/Lockheed</td>
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<tr>
<td>Tavrima</td>
<td>Super capacitors</td>
<td>NASA-Glenn</td>
</tr>
<tr>
<td>Sonnenschein</td>
<td>Sealed Lead-Acid</td>
<td>Solectria/New Flyer</td>
</tr>
<tr>
<td>Ovonic</td>
<td>NiMH</td>
<td>Allison Transmission</td>
</tr>
</tbody>
</table>
WVU Test Methods and Equipment
This configuration typically used when the exhaust is at the rear of the test vehicle

Laboratory #1

Area needed during set up: approx. 120 ft x 120 ft
Area needed for duration of testing: approx. 65 ft x 80 ft
WVU Transportable Dynamometer

Flywheels
Torque/Speed Sensor
Differential

Power Absorber
Vehicle Preparation
Dynamometer and PM Measuring Equipment in the NASA/Langley Wind Tunnel
Vehicle Being Lifted Up to Tunnel’s Test Platform
Test Vehicle on Chassis Dynamometer in the Wind Tunnel Prepared for Testing
Fuel Economy
Criteria Pollutant Emissions
GHG emissions
Monitored Emissions and Relevant Parameters

- Carbon Monoxide (CO)
- Carbon Dioxide (CO$_2$)
- Nitrogen Oxides (NO$_x$)
- Particulate Matter ($PM_{10/2.5}$)
- Volatile Organic Compounds (VOC)
  - methane/non-methane
- Fuel Economy
- APU Utilization/Output
- LLD Input/Output
- LLD State of Charge
- Controller Current to Drive Motors
- Auxiliary DC/DC Converter Input/Output
- Regenerative Braking Utilization
Testing in Boston, Massachusetts

RTS 6V92

Neoplan CNG, Cummins L10

TPI Composite CNG Hybrid
Testing in New York City

Orion CNG, Series 50G

Nova Diesel Series 50

New Flyer CNG, Series 50G
Testing in New York City

Lockheed Orion Hybrid

Allison Nova Hybrid
Dynamometer Test Cycles

- Central Business District (CBD)
- The New York Bus Cycle
- New York Composite Cycle
- Logan Massport Route 22
- Logan Massport Route 77
- Manhattan Cycle
Quantifying Fuel Economy
J2711 Correction Procedure

State of Charge Correction for Fuel Economy
Estimated Fuel Economy

Estimated Fuel Economy, Conventional Bus

Average Speed (mph)

Fuel Economy (mpg)

- NY Bus Cycle
- Manhattan Cycle
- NY Composite Cycle
- CBD Cycle
- Massport Route 22
- Massport Route 77

40 mph
Dynamometer Fuel Economy

WVU Dynamometer Fuel Economy Data

- NovaBus RTS Biodiesel
- Neoplan AN440T CNG
- NovaBus RTS Diesel
- Orion V CNG
- New Flyer C40LF CNG
- Orion LMCS VI Hybrid
- Nova Allison RTS Hybrid

Graph showing fuel economy data for different bus models across various cycles (NY Bus Cycle, Manhattan Cycle, CBD Cycle) with average speed on the x-axis and fuel economy in mpg on the y-axis.
GHG Comparison

CBD Cycle GHG Emissions

- Orion-LMCS VI Hybrid MossGas
- Orion-LMCS VI Hybrid Diesel
- Nova-Allison RTS Hybrid LS Diesel
- Neoplan AN440T CNG L10 280G
- NovaBUS RTS MossGas Series 50
- NovaBUS RTS Diesel Series 50
- Orion V CNG Series 50G
- New Flyer C40LF CNG Series 50G

Legend:
- CO2
- CH4 x 21
- NOx x 7
- NMOC x 11
- CO x 3
- N2O x 310
Historical NOx

NOx Emissions (g/mi) for CNG Fueled Buses
CBD Cycle

NOx Emissions (g/mi) for Diesel Fueled Buses
CBD Cycle
Historical PM

PM Emissions (g/mi) for CNG Fueled Buses
CBD Cycle

PM Emissions (g/mi) for Diesel Fueled Buses
CBD Cycle
Historical CO

CO Emissions (g/mi) for CNG Fueled Buses
CBD Cycle

CO Emissions (g/mi) for Diesel Fueled Buses
CBD Cycle
Historical THC

THC Emissions (g/mi) for CNG Fueled Buses
CBD Cycle

THC Emissions (g/mi) for Diesel Fueled Buses
CBD Cycle
Time Series NOx

NY Bus Cycle, Nova Diesel, NOx

NY Bus Cycle, Orion CNG, NOx

NY Bus Cycle, Orion-LMCS, NOx

NY Bus Cycle, Nova Allison, NOx
Time Series CO

NY Bus Cycle, Nova Diesel, CO

NY Bus Cycle, Orion CNG, CO

NY Bus Cycle, Orion-LMCS, CO

NY Bus Cycle, Nova Allison, CO
Time Series HC

NY Bus Cycle, Nova Diesel, NMOC

NY Bus Cycle, Orion CNG, THC

NY Bus Cycle, Orion-LMCS, NMOC

NY Bus Cycle, Nova Allison, NMOC
Emission Control Devices, Interactions
## EPA Emission Standards for Heavy-Duty Diesel Engines, g/bhp-hr

<table>
<thead>
<tr>
<th>Year</th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
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<tbody>
<tr>
<td>1988</td>
<td>1.3</td>
<td>15.5</td>
<td>10.7</td>
<td>0.6</td>
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<tr>
<td>1990</td>
<td>1.3</td>
<td>15.5</td>
<td>6</td>
<td>0.6</td>
</tr>
<tr>
<td>1994</td>
<td>1.3</td>
<td>15.5</td>
<td>5</td>
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<td>1998</td>
<td>1.3</td>
<td>15.5</td>
<td>4</td>
<td>0.1</td>
</tr>
<tr>
<td>2000</td>
<td>1.3</td>
<td>15.5</td>
<td>4</td>
<td>0.1</td>
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<tr>
<td>2002-04</td>
<td>0.5</td>
<td>15.5</td>
<td>2.5</td>
<td>0.1</td>
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<td>2007-10</td>
<td>0.14</td>
<td>15.5</td>
<td>0.2</td>
<td>0.01</td>
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</tbody>
</table>
• Mobile Source NOx Emission Controls
  • Exhaust Gas Recirculation
    – Similar to Utility option, lubrication oil impact issues
  • Conventional Three-way Catalyst
    – Only for Stoichiometric Engines (Gasoline)
  • Lean NOx Catalyst
    – Limited performance, efficiency impacts
  • Selective Catalytic Reduction
    – Requires Urea reagent injection, European Diesel Control Choice
  • NOx Adsorber (Trap)
    – Requires use of Ultra Low Sulfur Fuel, Complex Management
Mobile SCR Technology:

*Mobile Source SCR Installed on a Class 8 Diesel Refuse Collection Truck, One Possible Option*
# Staten Island Ferry System

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Class</th>
<th>Commission Date</th>
<th>Passenger Capacity</th>
<th>Main Propulsion Engines</th>
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<tbody>
<tr>
<td>Alice Austen</td>
<td>Austen</td>
<td>1986</td>
<td>1,280</td>
<td>Caterpillar 3516A (x2)</td>
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<tr>
<td>John A. Noble</td>
<td>Austen</td>
<td>1986</td>
<td>1,280</td>
<td>Caterpillar 3516A (x2)</td>
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<tr>
<td>John F. Kennedy</td>
<td>Kennedy</td>
<td>1965</td>
<td>3,500</td>
<td>GM EMD 567c16 (x4)</td>
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<tr>
<td>American Legion</td>
<td>Kennedy</td>
<td>1965</td>
<td>3,500</td>
<td>GM EMD 567c16 (x4)</td>
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<tr>
<td>Herbert H. Lehman</td>
<td>Kennedy</td>
<td>1965</td>
<td>3,500</td>
<td>GM EMD 567c16 (x4)</td>
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<tr>
<td>Andrew J. Barberi</td>
<td>Barberi</td>
<td>1981</td>
<td>6,000</td>
<td>GM 645e16 (X4)</td>
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<tr>
<td>Samuel I. Newhouse</td>
<td>Barberi</td>
<td>1981</td>
<td>6,000</td>
<td>GM 645e16 (X4)</td>
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<tr>
<td>Guy V. Molinari</td>
<td>Centennial</td>
<td>2004</td>
<td></td>
<td>GM EMD 710GT x3</td>
</tr>
<tr>
<td>TBD</td>
<td>Centennial</td>
<td>2004</td>
<td></td>
<td>GM EMD 710GT x3</td>
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<tr>
<td>TBD</td>
<td>Centennial</td>
<td>2005</td>
<td></td>
<td>GM EMD 710GT x3</td>
</tr>
</tbody>
</table>

Austen Alice  
SCR/DOC  
Demonstration
• **Mobile Source PM Emission Controls**
  
  • Ultra Low Sulfur Diesel Fuels
    – Limit Sulfate PM formation
    – Facilitate NOx and PM emission Control Devices
  
  • Diesel/Gasoline Oxidation Catalyst
    – Ceramic, Foil Configurations
    – 90% CO and 90% VOC emission reductions
  
  • High Performance Diesel Oxidation Catalyst
    – 90% CO, 90% VOC, 50% PM, 25% Opacity reductions
  
  • Diesel Particulate Filters
    – Ceramic Cordierite, Silicone Carbide, Metal Fibril
    – 90% CO, 90% VOC, 90% PM, No Opacity
  
  – Many of these technologies are available for cost effective retrofit on Diesel Vehicles
CRT Diesel Particulate Filter
Source: http://www.johnsonmatthey.com

High Performance DOC
Source: http://www.cleanerfuture.com

Diesel Particulate Filter Inlet
Source: http://www.mjbradley.com

Diesel Particulate Filter Outlet
Source: http://www.mjbradley.com
Drive Cycles, Routes, In-Use Evaluations, Idle
WVU TRANSPORTABLE LABORATORY
CHARACTERIZING FUEL AND PM FILTER
BENEFITS
SUCCESS OF EXHAUST PM FILTRATION
WVU DATA – BP/ARCO-DOE-NREL STUDY IN CA.
RALPHS GROCERY TRUCKS, 42,000Lbs. JOHNSON MATTHEY CRT
Effect of Vehicle Operation

GMC box truck Caterpillar engine

- NOx Emissions (g/mile)
Weight Effects on NOx

![Graph showing the relationship between test weight and NOx emissions. The graph plots test weight (as a percentage of GVWR) on the x-axis and NOx emissions (g/mile) on the y-axis. Different data sets are represented by various symbols and line types.]

- 1989 TB CBD (1)
- 1989 TB NY-Comp (2)
- 1996 TB CBD (3)
- 1998 TT CSHVR (4)
- 1994 TT CSHVR (5)
- 1995 TT CSHVR (6)
- 1995 TT Highway (7)
Variability of Truck NOx

Vehicle Number

<table>
<thead>
<tr>
<th>Model Year</th>
<th>NOx1 Corrected</th>
<th>NOx2 Corrected</th>
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<tbody>
<tr>
<td>1985</td>
<td>12.6</td>
<td>13</td>
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<tr>
<td>1985</td>
<td>38</td>
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<td>1992</td>
<td>21.28</td>
<td>16.2</td>
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<td>1992</td>
<td>17.43</td>
<td>12.7</td>
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<td>1993</td>
<td>50.45</td>
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<tr>
<td>2001</td>
<td>20.3</td>
<td>20.3</td>
</tr>
</tbody>
</table>
Future Concerns
Aftertreatment behavior ruins reproducibility

- CO Emission
- Temperature

Time (s)

Post Aftertreatment Temperature (°F)

CO Emissions (g/s)
Hybrid Drivetrains Confuse Continuous Emissions Prediction
Can We Measure at Low Levels?
• The Move to Onboard Emissions Measurements
Mobile Emissions Measurement System
PATH Station Rebuild Initiatives

Front End Loader Emission Testing

Environment Canada’s equipment setup
CATI Montana PEMS
ESP RSD4000 ORMS
Remote Sensing Unit – Light Duty
ESP RSD4000 Heavy-Duty Diesel and CNG, Elevated Exhaust

ESP Demo, Tucson, AZ

SunTran, Tucson, AZ

Full Scale MBTA demonstration in Boston, 400 buses, 2 depots
Hybrid Design Choices

• Intended purpose of Bus
  – Passenger load, representative activity (terrain), hotel loads, structural
  – Idle stop, EV mode, technological competition, wheel motors, low floor

• Why Hybrid
  – Capture Kinetic/Potential Energy,
  – Manage engine efficiency
  – Manage emissions, smoothing, HCCI facilitation, boost management

• Modeling for Design
  – Advisor NREL, PSAT Argonne, HVSIM WVU
  – Need for system efficiency sub models
    • Engine, motor, battery charge and discharge and inverter
    • Heat rejection handled on a component basis
Fuel Economy

• **Fuel Economy----Engine BSFC Curve**

![Graph showing BSFC curve](image-url)
On a CBD Cycle, 50% of the Drive HP is used accelerating the vehicle and 50% is consumed as road load.
~50% CBD Regen Availability

HP requirements for CBD Cycle

-300.00
-200.00
-100.00
0.00
100.00
200.00
300.00

Drive HP
Regen HP
Road Load HP
Energy Recovered – Ideal Model
Actual Energy Recovery with Component Mass Added
## Results

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Energy Storage (Usable)</td>
<td>Composite w/o mass</td>
<td>Composite w/ mass</td>
<td>Highway w/o mass</td>
<td>Highway w/ mass</td>
<td>City w/ mass No Terrain</td>
</tr>
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<td>60 kW</td>
<td>324 W-hr</td>
<td>24.50</td>
<td>24.38</td>
<td>24.05</td>
<td>23.86</td>
<td>18.57</td>
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<td>80 kW</td>
<td>324 W-hr</td>
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<td>24.24</td>
<td>24.00</td>
<td>23.91</td>
<td>18.57</td>
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<td>648 W-hr</td>
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<td>24.75</td>
<td>24.43</td>
<td>24.13</td>
<td>19.31</td>
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<td>80 kW</td>
<td>1296 W-hr</td>
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<td>25.03</td>
<td>24.81</td>
<td>24.46</td>
<td>20.31</td>
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<td>90 kW</td>
<td>1296 W-hr</td>
<td>25.52</td>
<td>25.02</td>
<td>24.87</td>
<td>24.41</td>
<td>20.36</td>
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<tr>
<td>100 kW</td>
<td>1296 W-hr</td>
<td>25.53</td>
<td>25.02</td>
<td>24.84</td>
<td>24.43</td>
<td>20.34</td>
</tr>
<tr>
<td>110 kW</td>
<td>1296 W-hr</td>
<td>25.52</td>
<td>24.99</td>
<td>24.86</td>
<td>24.40</td>
<td>20.32</td>
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<td>120 kW</td>
<td>1296 W-hr</td>
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<td>24.98</td>
<td>24.85</td>
<td>24.37</td>
<td>20.32</td>
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<tr>
<td>180 kW</td>
<td>1296 W-hr</td>
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<tr>
<td>100 kW</td>
<td>3240 W-hr</td>
<td>26.09</td>
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<tr>
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<td>26.00</td>
<td>25.27</td>
<td>25.17</td>
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