A Cost Effectiveness Analysis of Quasi-In-Motion Wireless Power Transfer for Plug-In Hybrid Electric Transit Buses from Fleet Perspective

L. Wang, J. Gonder, A. Brooker, A. Meintz, A. Konan and T. Markel

4th Annual Conference on Electric Road & Vehicles
May 16-17, 2016
Logan, UT

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Motivation and Objective

I. Motivation:
   A. Wireless power transfer charging technology has made it possible to wirelessly charge a parked vehicle’s battery.
   B. Transit buses provide an early quasi-in-motion application opportunity.

II. Objective:
   A. Perform a cost comparison of plug-in hybrid electric bus (PHEB), hybrid electric bus (HEB), and conventional bus (CB) scenarios.
   B. Explore the fuel displacement opportunity.
   C. Provide incremental rollout solutions for charging stations and PHEBs.
Outline

I. Charging Station Location Selection
II. Economic Assumptions and Design of the Simulation Matrix
III. Cost Comparison of Various Scenarios
   A. Sweep analysis from a PHEB perspective
   B. Charging station incremental rollout
   C. PHEB incremental rollout
   D. More scenarios
IV. Sensitivity Analysis
V. Summary
338 Vehicle-Days of Driving
Charging Station Location Selection

*The overlapped charging stations are considered one

20 Charging Stations Mapped with 338 Day-Trips
### Model Input Assumptions and Design of Experiments Matrix

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB cost ($)</td>
<td>338,892 [2]</td>
</tr>
<tr>
<td>HEB without battery cost ($)</td>
<td>491,951[2]</td>
</tr>
<tr>
<td>Bus stop quasi-static charging station cost ($)</td>
<td>500,000</td>
</tr>
<tr>
<td>Bus depot static charging station cost for each bus ($)</td>
<td>5000</td>
</tr>
<tr>
<td>Demand charge rate per month ($/kW)</td>
<td>12 [3]</td>
</tr>
<tr>
<td>Electricity cost ($/kWh)</td>
<td>0.10 [4]</td>
</tr>
<tr>
<td>Five years average diesel price ($/gallon)</td>
<td>3.71 [4]</td>
</tr>
<tr>
<td>Vehicle life (year)</td>
<td>12 [5]</td>
</tr>
<tr>
<td>First battery cost ($/kWh)</td>
<td>500 [6]</td>
</tr>
<tr>
<td>Second battery cost (after 6 years) ($kWh)</td>
<td>300</td>
</tr>
<tr>
<td>Battery markup factor</td>
<td>1.5 [7]</td>
</tr>
<tr>
<td>Bus service day (days/year)</td>
<td>218</td>
</tr>
<tr>
<td>Discount rate</td>
<td>0.042</td>
</tr>
<tr>
<td>HEB fuel economy (FE) (mpg)</td>
<td>6.65</td>
</tr>
<tr>
<td>CB average FE (mpg)</td>
<td>5.29</td>
</tr>
<tr>
<td>PHEB efficiency in depleting mode (kWh/mi)</td>
<td>2.10</td>
</tr>
<tr>
<td>280 hp engine cost estimation ($)</td>
<td>30,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low</th>
<th>High</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery energy (kWh)</td>
<td>30</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>Charging power (kW)</td>
<td>50</td>
<td>250</td>
<td>20</td>
</tr>
<tr>
<td>Charging station amount</td>
<td>5</td>
<td>30</td>
<td>1</td>
</tr>
</tbody>
</table>
Sweep Analysis Results from A PHEB Perspective

NPC = Net Present Cost

Battery Energy (kWh) vs. Charging Power (kW) graph showing PHEB NPC results.

- CB: 668
- HEB: 767
- Optimal PHEB NPC:
  - Battery Energy (kWh): 20
    - Charging Power (kW): 50
      - PHEB NPC ($K): 765
  - Battery Energy (kWh): 30
    - Charging Power (kW): 50
      - PHEB NPC ($K): 770
  - Battery Energy (kWh): 40
    - Charging Power (kW): 50
      - PHEB NPC ($K): 775
  - Battery Energy (kWh): 50
    - Charging Power (kW): 50
      - PHEB NPC ($K): 780
  - Battery Energy (kWh): 60
    - Charging Power (kW): 50
      - PHEB NPC ($K): 785
  - Battery Energy (kWh): 70
    - Charging Power (kW): 50
      - PHEB NPC ($K): 790
  - Battery Energy (kWh): 80
    - Charging Power (kW): 50
      - PHEB NPC ($K): 794
  - Battery Energy (kWh): 90
    - Charging Power (kW): 50
      - PHEB NPC ($K): 798

- CB: 805
- HEB: 817
- Optimal PHEB NPC:
  - Battery Energy (kWh): 20
    - Charging Power (kW): 100
      - PHEB NPC ($K): 768
  - Battery Energy (kWh): 30
    - Charging Power (kW): 100
      - PHEB NPC ($K): 770
  - Battery Energy (kWh): 40
    - Charging Power (kW): 100
      - PHEB NPC ($K): 775
  - Battery Energy (kWh): 50
    - Charging Power (kW): 100
      - PHEB NPC ($K): 780
  - Battery Energy (kWh): 60
    - Charging Power (kW): 100
      - PHEB NPC ($K): 785
  - Battery Energy (kWh): 70
    - Charging Power (kW): 100
      - PHEB NPC ($K): 790
  - Battery Energy (kWh): 80
    - Charging Power (kW): 100
      - PHEB NPC ($K): 794
  - Battery Energy (kWh): 90
    - Charging Power (kW): 100
      - PHEB NPC ($K): 798

- CB: 815
- HEB: 827
- Optimal PHEB NPC:
  - Battery Energy (kWh): 20
    - Charging Power (kW): 150
      - PHEB NPC ($K): 768
  - Battery Energy (kWh): 30
    - Charging Power (kW): 150
      - PHEB NPC ($K): 770
  - Battery Energy (kWh): 40
    - Charging Power (kW): 150
      - PHEB NPC ($K): 775
  - Battery Energy (kWh): 50
    - Charging Power (kW): 150
      - PHEB NPC ($K): 780
  - Battery Energy (kWh): 60
    - Charging Power (kW): 150
      - PHEB NPC ($K): 785
  - Battery Energy (kWh): 70
    - Charging Power (kW): 150
      - PHEB NPC ($K): 790
  - Battery Energy (kWh): 80
    - Charging Power (kW): 150
      - PHEB NPC ($K): 794
  - Battery Energy (kWh): 90
    - Charging Power (kW): 150
      - PHEB NPC ($K): 798

- CB: 825
- HEB: 835
- Optimal PHEB NPC:
  - Battery Energy (kWh): 20
    - Charging Power (kW): 200
      - PHEB NPC ($K): 768
  - Battery Energy (kWh): 30
    - Charging Power (kW): 200
      - PHEB NPC ($K): 770
  - Battery Energy (kWh): 40
    - Charging Power (kW): 200
      - PHEB NPC ($K): 775
  - Battery Energy (kWh): 50
    - Charging Power (kW): 200
      - PHEB NPC ($K): 780
  - Battery Energy (kWh): 60
    - Charging Power (kW): 200
      - PHEB NPC ($K): 785
  - Battery Energy (kWh): 70
    - Charging Power (kW): 200
      - PHEB NPC ($K): 790
  - Battery Energy (kWh): 80
    - Charging Power (kW): 200
      - PHEB NPC ($K): 794
  - Battery Energy (kWh): 90
    - Charging Power (kW): 200
      - PHEB NPC ($K): 798

- CB: 835
- HEB: 845
- Optimal PHEB NPC:
  - Battery Energy (kWh): 20
    - Charging Power (kW): 250
      - PHEB NPC ($K): 768
  - Battery Energy (kWh): 30
    - Charging Power (kW): 250
      - PHEB NPC ($K): 770
  - Battery Energy (kWh): 40
    - Charging Power (kW): 250
      - PHEB NPC ($K): 775
  - Battery Energy (kWh): 50
    - Charging Power (kW): 250
      - PHEB NPC ($K): 780
  - Battery Energy (kWh): 60
    - Charging Power (kW): 250
      - PHEB NPC ($K): 785
  - Battery Energy (kWh): 70
    - Charging Power (kW): 250
      - PHEB NPC ($K): 790
  - Battery Energy (kWh): 80
    - Charging Power (kW): 250
      - PHEB NPC ($K): 794
  - Battery Energy (kWh): 90
    - Charging Power (kW): 250
      - PHEB NPC ($K): 798
All PHEBs with Charging Station Incremental Rollout

- **NPC ($M)**
- **Lifetime Diesel Use (Million Gallons)**

- **Fuel Cost**
- **Depot Infrastructure**
- **Charging Station Infrastructure**
- **Electricity Demand**
- **Electricity**
- **Battery**
- **Vehicle**
- **Fleet Lifetime Diesel Use**

- **PHEB comparable to HEB cost with triple the fuel savings**

Optimal PHEB design

CS=charging station

Ratio of Incremental Cost to Fuel Saved

<table>
<thead>
<tr>
<th></th>
<th>All HEB</th>
<th>All PHEB, 5 CS</th>
<th>All PHEB, 11 CS</th>
<th>All PHEB, 15CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dollar / Gallon</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
PHEB Incremental Rollout

Fuel savings increase with more PHEBs.

20 PHEB with 1 CS gives the lowest incremental cost/gallon saved.
Fleet Lifetime Cost and Fuel Consumption for More Scenarios

- **NPC ($M)**
- **Lifetime Diesel Use (Million Gallons)**

- **Fuel Cost**
- **Depot Infrastructure**
- **Charging Station Infrastructure**
- **Electricity Demand**
- **Electricity**
- **Battery**
- **Vehicle Cost**
- **Fleet Lifetime Diesel Use**

**Cloud Note:** Depot charging only not as cost effective.

**DC = Depot Charging**

**CS = Charging Station**

### Ratio of Incremental Cost to Fuel Saved

- **20 PHEB, DC Only**
- **20 PHEB, 1 CS**
- **All PHEB, DC Only**
- **All PHEB, 11 CS**

**Dollar / Gallon**
## High/Low Market Potential Assumptions

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Favorable Market Potential Scenario</th>
<th>Unfavorable Market Potential Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus stop charging station cost ($)</td>
<td>300,000</td>
<td>700,000</td>
</tr>
<tr>
<td>Depot charging station cost for each bus ($)</td>
<td>3,000</td>
<td>7,000</td>
</tr>
<tr>
<td>Electricity cost ($/kWh)</td>
<td>0.08</td>
<td>0.12</td>
</tr>
<tr>
<td>Demand charge ($/kW/month)</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Diesel cost ($/gallon)</td>
<td>5.00</td>
<td>2.50</td>
</tr>
<tr>
<td>First battery cost ($kWh)</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>Second battery cost (after 6 years) ($kWh)</td>
<td>0 (no battery replacement)</td>
<td>400</td>
</tr>
</tbody>
</table>
All PHEBs with Charging Station Rollout with Favorable Market Potential Assumptions

- All PHEB scenarios cost effective with large fuel saving.
PHEB Incremental Rollout with Favorable Market Potential Assumptions

All PHEB scenario has lowest cost and largest fuel savings.
More Scenarios with Favorable Market Potential
Assumptions

- Depot charging only is again not as cost effective.
All PHEB with Charging Station Rollout with Unfavorable Market Potential Assumptions

- PHEV unsurprising less cost effective with unfavorable market
- The NPC is higher with more CS, but the dollar per gallon saving is lower.

![Chart showing NPC and lifetime diesel use](chart.png)

<table>
<thead>
<tr>
<th>All CB</th>
<th>All HEB</th>
<th>All PHEB, 1 CS, 30kWh, 250kW</th>
<th>All PHEB, 3 CS, 30kWh, 250kW</th>
<th>All PHEB, 5 CS, 30kWh, 250kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50</td>
<td>$100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$100</td>
<td>$200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$150</td>
<td>$250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$200</td>
<td>$300</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ratio of Incremental Cost to Fuel Saved

- All HEB
- All PHEB, 1 CS
- All PHEB, 3 CS
- All PHEB, 5 CS

![Bar chart showing ratio of incremental cost to fuel saved](ratio_chart.png)
PHEB Incremental Rollout with Unfavorable Market Potential Assumptions

- 20PHEBs give comparable NPC and lowest incremental cost per gallon saved.
More Scenarios with Unfavorable Market Potential Assumptions

- Depot charging only is again not as cost effective.

Chart showing NPC ($M) versus Lifetime Diesel Use (Million Gallons) for different scenarios:
- All CB
- 20 PHEB, DC Only
- 20 PHEB, 1 CS, 30kWh, 250kW
- All PHEB, DC Only
- All PHEB, 3 CS, 30kWh, 250kW

Legend:
- Fuel Cost
- Depot Infrastructure
- Charging Station Infrastructure
- Electricity Demand
- Electricity
- Battery
- Vehicle Cost
- Fleet Lifetime Diesel Use

Graph showing Ratio of Incremental Cost to Fuel Saved:
- 20 PHEB, DC Only
- 20 PHEB, 1 CS
- All PHEB, DC Only
- All PHEB, 3 CS

Note: Dollar/Gallon Ratio of Incremental Cost to Fuel Saved.
Conclusion

I. Comparison results of various scenarios:
   A. Given current economic assumptions, the optimized PHEB scenarios were unable to outpace the NPC of the CB. However, PHEBs could achieve comparable lifetime costs as HEBs but tripled the fuel savings realized relative to CB.
   B. The simulation results suggested the incremental rollout should start from 20 PHEB and 1 charging station.

II. Sensitivity analysis:
   A. For favorable market conditions, each of the PHEB scenarios have a lower NPC than the CB, and the best fuel and cost savings occurs when all the CBs are replaced by PHEBs.
   B. The unfavorable PHEB market potential assumptions unsurprisingly caused the PHEBs to have the highest NPC, but relative to the HEB and the PHEB with depot charging only the PHEBs with charging stations achieved the lowest incremental cost per gallon of fuel saved.
Questions?
References


Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding was provided by U.S. DOE Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office.

The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.