Report

# Total Cost of Ownership Comparison between Fuel Cell and Battery Electric Transit Fleets for Humboldt County

## Final Report for Humboldt Transit Authority

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## About the Schatz Energy Research Center

The Schatz Energy Research Center at Humboldt State University advances clean and renewable energy. Our projects aim to reduce climate change and pollution while increasing energy access and resilience.

Our work is collaborative and multidisciplinary, and we are grateful to the many partners who together make our efforts possible.

Learn more about our work at schatzcenter.org

## Acknowledgements

Collaboration and funding for this study were provided by the Humboldt Transit Authority.

This research would not have been possible without the valuable contributions of the following people: Greg Pratt and Jim Wilson of Humboldt Transit Authority, Leslie Eudy of the National Renewable Energy Laboratory, Tommy Edwards and Jenny Bellinger of Sunline Transit, Cliff Thorne of Orange County Transportation Authority, Jaimie Levin of the Center for Transportation and the Environment, and many others whose knowledge and insight was indirectly essential.

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## Executive Summary

To help prepare the Humboldt Transit Authority (HTA) and other transit agencies in Humboldt and neighboring counties for the transition to zero emissions bus fleets, the Schatz Center was funded to develop an analysis of the total cost of ownership (TCO) of battery electric and fuel cell electric bus options. Recognizing that fueling infrastructure will likely be shared across multiple transit agencies, all transit systems that operate within Humboldt County, including Redwood Coast Transit and Trinity Transit routes that operate in Humboldt County, were included. These are

- Arcata & Mad River Transit System (A&MRTS)
- Blue Lake Rancheria Transit System (BLRTS)
- Eureka Transit System (ETS)
- Klamath Trinity Non-Emergency Transportation (KT-NET)
- Redwood Coast Transit (RCT)
- Redwood Transit System (RTS)
- Southern Humboldt Intercity (SHI)
- Trinity Transit (TT)
- Willow Creek Transit System (WC)

In this analysis, the total cost of ownership was compared for five different technology deployment plans:

> BEB 1: Full fleet conversion to battery electric buses (BEBs). This plan assumes a bus replacement ratio of 1:1, and requires installation of 21 depot chargers (between three locations) and 31 on-route charging stations.
>
> BEB 2: Full fleet conversion to BEBs. This plan assumes a bus replacement ratio of 1.7:1, and requires installation of 40 depot chargers (between three locations) and 8 on-route charging stations.
>
> FCEB: Full fleet conversion to fuel cell electric buses (FCEBs). This plan assumes a bus replacement ratio of 1:1, and requires one hydrogen fueling station.
>
> Mix 1: Mixed fleet conversion to both BEBs and FCEBs. This plan assumes a 1:1 replacement of Arcata, Blue Lake, Eureka, and KT-NET fleets with BEBs, and a 1:1 bus replacement of remaining transit systems with FCEBs.
>
> Mix 2: Mixed fleet conversion to both BEBs and FCEBs. This plan assumes a 1.5:1 replacement of Arcata and Eureka fleets with BEBs, and a 1:1 bus replacement of remaining transit systems with FCEBs.

All deployment plans assume a low bus efficiency for estimating required fueling infrastructure and fleet size. The low bus efficiency is derived from actual in-field performance data from HTA (for BEBs) and Sunline Transit (for FCEBs). Capital as well as operation and maintenance (O&M) costs for these five deployment plans are detailed in Table 1. Capital costs include the following:

- Electric buses: OEM advertised cost plus a 2.5% acquisition cost adder
- Electric bus chargers: OEM advertised cost plus estimated installation costs. Includes on-route and depot chargers, and maintenance bay chargers.
- Hydrogen buses: California Air Resources Board estimated cost assuming volume purchase
- Hydrogen fueling station: National Renewable Energy Laboratory's H2A model[1] , Argonne National Laboratory's HDRSAM model[2], and literature cost values are used to design and cost two station types –
    - Delivery: fueling station has liquid storage, dispenser, and all auxiliary equipment. A supplier delivers liquid hydrogen.
    - Electrolysis: fueling station has an on-site electrolyzer that generates hydrogen, plus gaseous storage, dispenser, and all auxiliary equipment.

All deployment plans assume an <u>average bus efficiency</u> for estimating operation and maintenance costs. The average bus efficiency is also derived from actual in-field performance data from HTA (for BEBs) and Sunline Transit (for FCEBs). Operation and maintenance (O&M) costs include the following:

- Buses
    - Fuel
    - Scheduled and unscheduled maintenance
    - Midlife battery replacement for BEBs, and mid-life fuel cell stack maintenance for FCEBs
- Infrastructure
    - Electric bus chargers
        - Charger maintenance
        - Charger replacement
        - Low Carbon Fuel Standard income estimates
    - Hydrogen fueling station
        - Station maintenance
        - Low Carbon Fuel Standard income estimates

[1] https://www.nrel.gov/hydrogen/h2a-production-models.html
[2] https://hdsam.es.anl.gov/index.php?content=hdrsam

*Table 1: Summary total cost of ownership results for all deployment plans.*

<table>
<tr><th rowspan="2"></th><th rowspan="2"></th><th rowspan="2"></th><th rowspan="2">Electric</th><th colspan="2">Hydrogen</th><th rowspan="2">Mileage Weighted Totals</th></tr>
<tr><th>Delivery</th><th>On-Site</th></tr>
<tr><td rowspan="4">BEB 1</td><td rowspan="2">Capex ($)</td><td>Bus</td><td>$17.0M</td><td rowspan="4" colspan="2"></td><td rowspan="2">$37.8M</td></tr>
<tr><td>Infra</td><td>$20.8M</td></tr>
<tr><td rowspan="2">O&M ($ / mi)</td><td>Bus</td><td>$0.99 : $1.08</td><td rowspan="2">$0.81 : $1.49</td></tr>
<tr><td>Infra</td><td>-$0.18 : $0.41</td></tr>
<tr><td rowspan="4">BEB 2</td><td rowspan="2">Capex ($)</td><td>Bus</td><td>$29.1M</td><td rowspan="4" colspan="2"></td><td rowspan="2">$36.5M</td></tr>
<tr><td>Infra</td><td>$7.40M</td></tr>
<tr><td rowspan="2">O&M ($ / mi)</td><td>Bus</td><td>$0.99 : $1.08</td><td rowspan="2">$0.80 : $1.21</td></tr>
<tr><td>Infra</td><td>-$0.19 : $0.13</td></tr>
<tr><td rowspan="4">FCEB</td><td rowspan="2">Capex ($)</td><td>Bus</td><td rowspan="4"></td><td colspan="2">$18.5M</td><td rowspan="2">$32.5M : $36.2M</td></tr>
<tr><td>Infra</td><td>$14.0M</td><td>$17.7M</td></tr>
<tr><td rowspan="2">O&M ($ / mi)</td><td>Bus</td><td>$1.50 : $1.91</td><td>$1.56 : $1.97</td><td rowspan="2">$1.53 : $2.38</td></tr>
<tr><td>Infra</td><td>$0.19 : $0.35</td><td>-$0.03 : $0.41</td></tr>
<tr><td rowspan="4">Mix 1</td><td rowspan="2">Capex ($)</td><td>Bus</td><td>$6.33M</td><td colspan="2">$12.0M</td><td rowspan="2">$31.9M : $34.9M</td></tr>
<tr><td>Infra</td><td>$5.44M</td><td>$8.2M</td><td>$11.2M</td></tr>
<tr><td rowspan="2">O&M ($ / mi)</td><td>Bus</td><td>$0.95 - $1.04</td><td>$1.53 - $1.94</td><td>$1.59 - $2.00</td><td rowspan="2">$1.36 : $2.17</td></tr>
<tr><td>Infra</td><td>-$0.17 - $0.38</td><td>$0.18 - $0.35</td><td>-$0.05 - $0.41</td></tr>
<tr><td rowspan="4">Mix 2</td><td rowspan="2">Capex ($)</td><td>Bus</td><td>$9.42M</td><td colspan="2">$12.0M</td><td rowspan="2">$32.3M : $35.3M</td></tr>
<tr><td>Infra</td><td>$2.74M</td><td>$8.2M</td><td>$11.2M</td></tr>
<tr><td rowspan="2">O&M ($ / mi)</td><td>Bus</td><td>$0.95 - $1.04</td><td>$1.53 - $1.94</td><td>$1.59 - $2.00</td><td rowspan="2">$1.36 : $2.12</td></tr>
<tr><td>Infra</td><td>-$0.18 - $0.16</td><td>$0.18 - $0.35</td><td>-$0.05 - $0.41</td></tr>
</table>

Table 2 summarizes the assumed battery (kWh) or tank (kg $H_2$) capacity for each of the four deployment plans described in Table 1.

*Table 2: Summary of battery or tank capacity for four different technology deployment plans.*

| | | Deployment Plan | | |
|---|---|---|---|---|
| Bus number (ID) | Transit System | BEB 1 and BEB 2 | FCEB 1 | Mix 1 and Mix 2 |
| 25500 | AMRTS | 440 kWh | 50 kg $H_2$ | 440 kWh |
| 2552150 | AMRTS | 660 kWh | 50 kg $H_2$ | 440 kWh |
| 428 | BLRTS | 660 kWh | 50 kg $H_2$ | 440 kWh |
| 66 | ETS | 660 kWh | 50 kg $H_2$ | 440 kWh |
| 67 | ETS | 660 kWh | 50 kg $H_2$ | 440 kWh |
| 68 | ETS | 660 kWh | 50 kg $H_2$ | 440 kWh |
| 69 | ETS | 440 kWh | 50 kg $H_2$ | 440 kWh |
| 1147 | KTNET | 660 kWh | --- | 440 kWh |
| 886 | RTS | 440 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 888 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 889 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 890 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 891 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 892 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 893 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 894 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 896 | RTS | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 410 | SHI | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 512 | SHI | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 514 | SHI | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |
| 714 | WC | 660 kWh | 50 kg $H_2$ | 50 kg $H_2$ |

Overall, transitioning to BEBs tends to result in higher upfront capital costs and lower operating costs. However, there are a number of challenges associated with adoption of BEBs that are not reflected in the total cost of ownership estimates:

- BEBs are only able to reliably operate on routes that are “electrified” with charging infrastructure. To realize 300+ miles of effective range year-round, there must be sufficient charging infrastructure available along the assigned routes.
- BEBs require charging infrastructure that is spread out over a large geographic area. This makes ownership and maintenance logistics more challenging.
- BEBs require transit systems to either:
    - Overbuild charging infrastructure, or
    - Expand the size of the fleet.

  Much of the overbuilt infrastructure is not needed on the average day, only being used on those days when a particular BEB is realizing lower efficiency. Likewise, much of the expanded fleet is not needed, only being required a handful of days per year. On those days, route and bus schedules must adjust to accommodate buses returning more frequently to the yard.
- The long term performance and useful life of batteries have yet to be proven for duty cycles that are common in our rural communities.

In contrast, FCEBs tend to result in lower upfront capital costs and higher operating costs. In exchange for this higher operating cost, FCEBs offer a number of benefits compared to BEBs:

- FCEBs can effectively replace most diesel duty cycles today. Commercially available low floor buses achieve 300+ miles per day and achieve dependable consistent efficiency across a variety of duty cycles.
- Fueling infrastructure follows the same model as diesel, only requiring a single central fueling station. Fueling times are ~10 minutes, allowing operational flexibility that fleet managers are accustomed to.
- Hydrogen can be generated on-site from electricity, which offers an added layer of resilience if coupled with delivery.

The total cost of ownership for transit systems operating a mix of BEBs and FCEBs does roughly strike a balance in operating costs between solely BEBs or FCEBs, although capital costs are comparable to an all-FCEB scenario. However, operating both technologies can present a couple of notable challenges:

- BEBs present less flexibility in fleet management since they are only able to operate on those routes that have been "electrified". Fleet managers can assign FCEBs to any route when needed, but may not be able to assign BEBs to non-electrified routes.
- There is less opportunity to cooperatively share fueling infrastructure across transit systems.

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## 1. INTRODUCTION

Planning the future of public transit in Humboldt County requires integrating targets for zero-emission vehicles into transit fleets. The following California goals and mandates have aggressively accelerated the implementation timelines of the California Air Resources Board's (CARB) Innovative Clean Transit (ICT) Program:

- EO-B-30-15: Statewide Greenhouse Gas reduction target of 40% below 1990 levels by 2030
- EO-B-48-18: Goal of 5 million zero-emission vehicles (ZEVs) on the road by 2030
- California ZEV Action Plan: Maximize the use of ZEVs by transit agencies

The CARB requires small transit agencies to submit Rollout Plans by 2023. These plans are intended to be living documents that layout strategies for conversion to a zero emission fleet. This report estimates total cost of ownership for different zero emission bus adoption scenarios in order to inform the development of Rollout Plans for all transit agencies in the County.

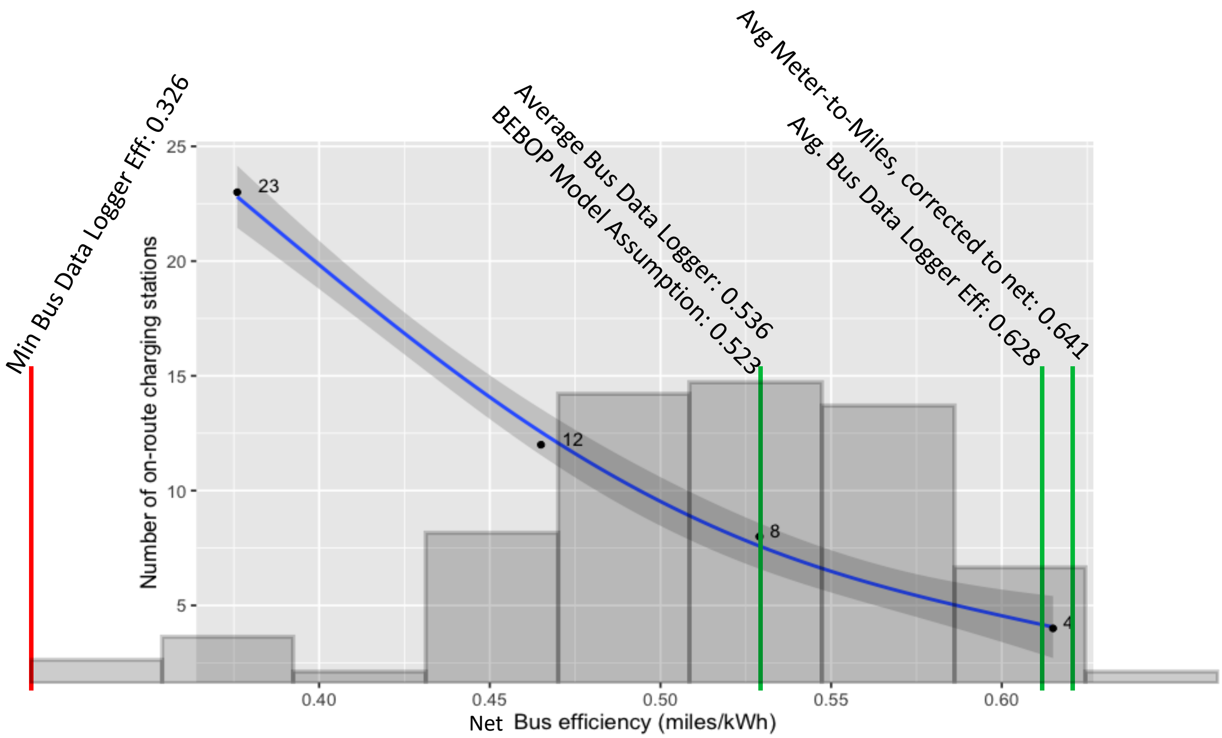
## 2. DISCUSSION OF BEB AND FCEB BUS PERFORMANCE

BEB technology presents challenges regarding 1:1 bus replacement for all transit systems in the County. Real world performance of BEBs shows:

- Significant variability in day-to-day vehicle range due primarily to HVAC and battery management system energy demand.
- Significant degradation in efficiency and performance over time.

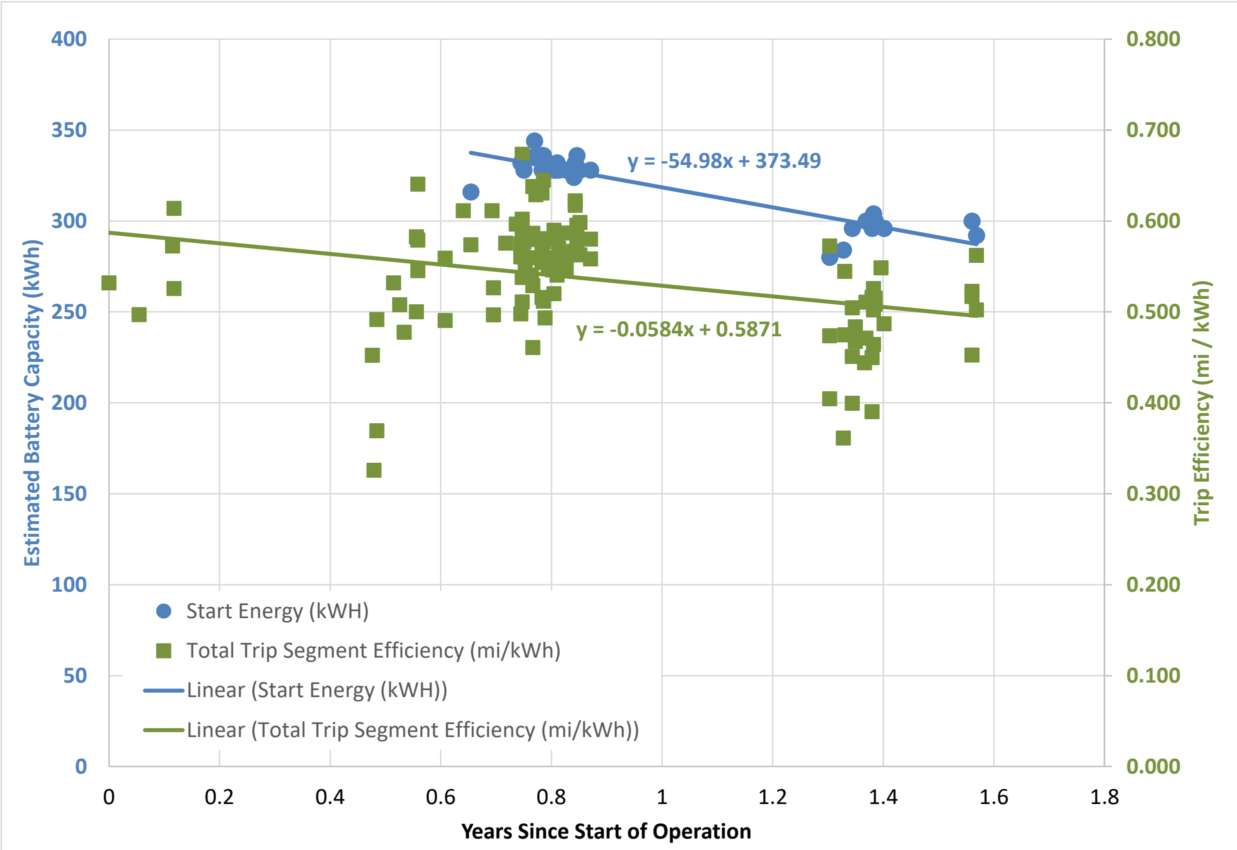
Figure 1 shows the variability in observed bus efficiency for the Proterra XR+ 330kWh bus that HTA deployed to serve an RTS route. This bus traveled between College of the Redwoods and Humboldt State University during the morning and afternoon. This plot exhibits the trade-off between effective fuel efficiency and the extent of charging infrastructure required to service buses. The key point here is that planning for low observed bus efficiencies results in very high on-route infrastructure costs and/or significant required changes to current route schedules and fleet size.

*Figure 1: Range in observed BEB net efficiency from HTA's Proterra XR+ 330kWh 40' low floor bus, and associated required number of on-route bus chargers needed to meet County-wide demand if all buses experience the same bus efficiency.*




Furthermore, Figure 2 shows the degradation in bus efficiency and battery capacity experienced by HTA's electric bus. This shows a loss of 0.0584 mi/kWh per year, or about an 11% drop in bus efficiency per year, and a loss of 55kWh in battery capacity per year, or about a 17% drop in capacity per year.

***Figure 2****: Evidence of degradation of performance of HTA's electric Proterra XC+ 330 kWh low floor 40' bus.*




In comparison, FCEBs do not experience high rates of performance degradation and have strong proven lifetimes. A 2020 analysis[3] of 32 FCEBs across four transit agencies showed 12 have achieved more than 25,000 hours of operation, the remaining having not been on the road long enough to reach that mile stone. Furthermore, over the last five years FCEB reliability has steadily improved, and maintenance resources and trainings are becoming more accessible.

A detailed analysis of Sunline Transit's hydrogen fleet was also performed[4], the results of which are shown in Figure 3 and Figure 4. Sunline has run two difference fleets: an older fleet comprised of fuel cell dominant El Dorado buses, and a newer fleet comprised of battery dominant New Flyer buses (note that fuel cell dominant buses will likely be the design that would meet the duty cycle requirements of RTS, SHI, and WC routes). For comparative context, the average speed experienced by Sunline's buses is 17.0 mph, which is higher than the national average although still lower than the average speed of HTA's electric bus of 24 mph. This means the duty cycle of HTA's electric bus is somewhat similar to the duty cycles of Sunline's FCEB fleet.

[3] Leslie Eudy, May 21, 2020. Technology Acceleration: Fuel Cell Bus Evaluations. Presentation for the DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting. National Renewable Energy Laboratory. Project ID #TA013

[4] Raw data of performance logs obtained with permission from Sunline Transit from Leslie Eudy, private correspondence.

The key takeaways from this analysis are:

- Battery-dominant FCEB designs are more sensitive to HVAC loads impacting bus efficiency.
- Performance during low median temperature days do not drop significantly. This is likely because heating loads can be met much more efficiently on FCEBs compared to cooling loads because waste heat from the fuel cell stack is typically used for cabin heating.
- Shown by the spread in individual bus efficiencies, analysis also showed there is not a strong correlation between bus efficiency and ambient temperature on any given day across the fleet, such that HVAC loads are not the only variable impacting efficiency. There are other factors driving the variation in efficiency that need to be understood.

While FCEBs do also experience a wide range of efficiencies, it is much easier for to manage FCEBs experiencing lower efficiency days as fueling times are less than 10 minutes. Days where BEBs experience lower efficiencies likely would need to involve more frequent rotation of BEBs mid-route presenting management challenges.

*Figure 3: Histogram of daily average efficiency per bus for two hydrogen fleets operated by Sunline Transit.*

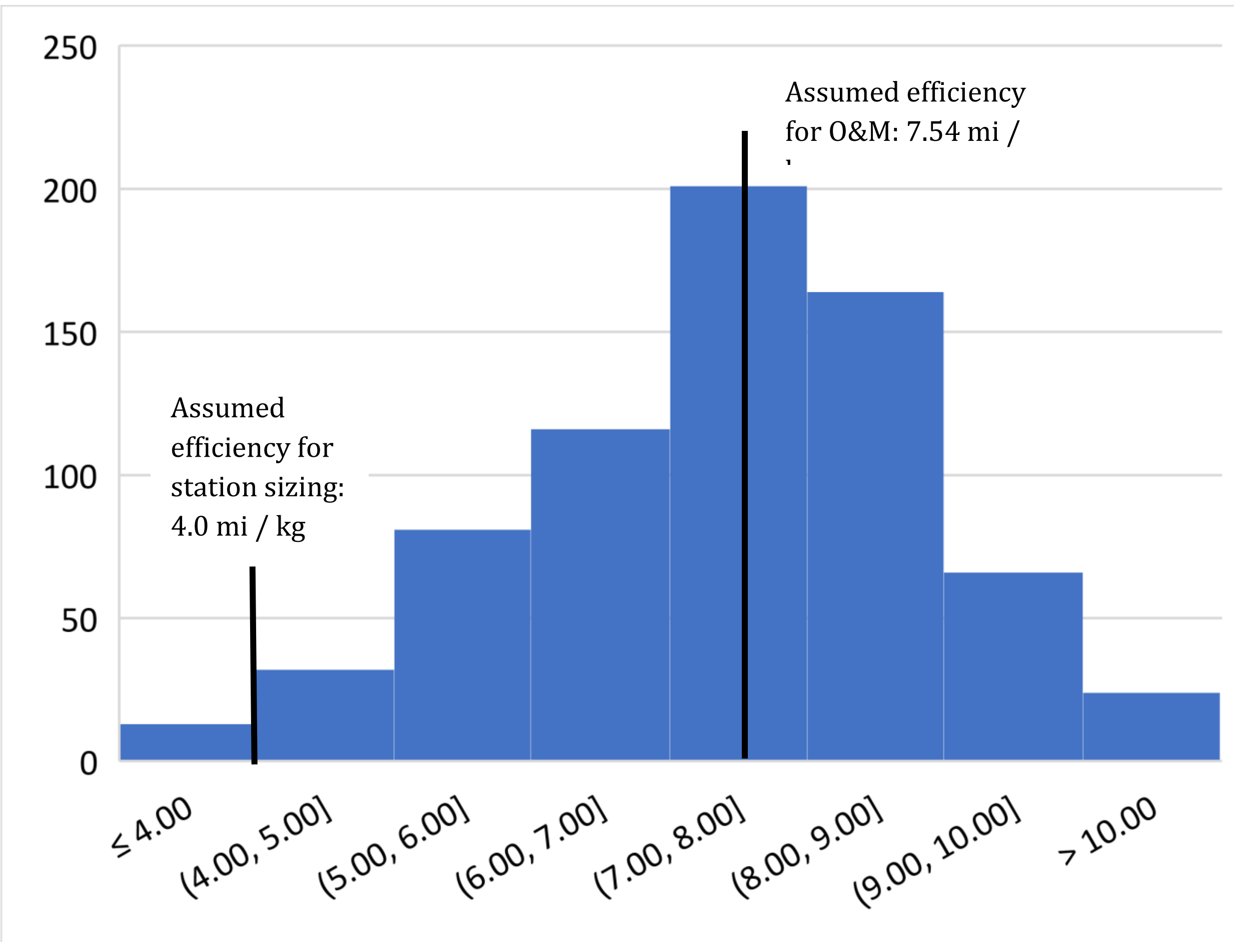
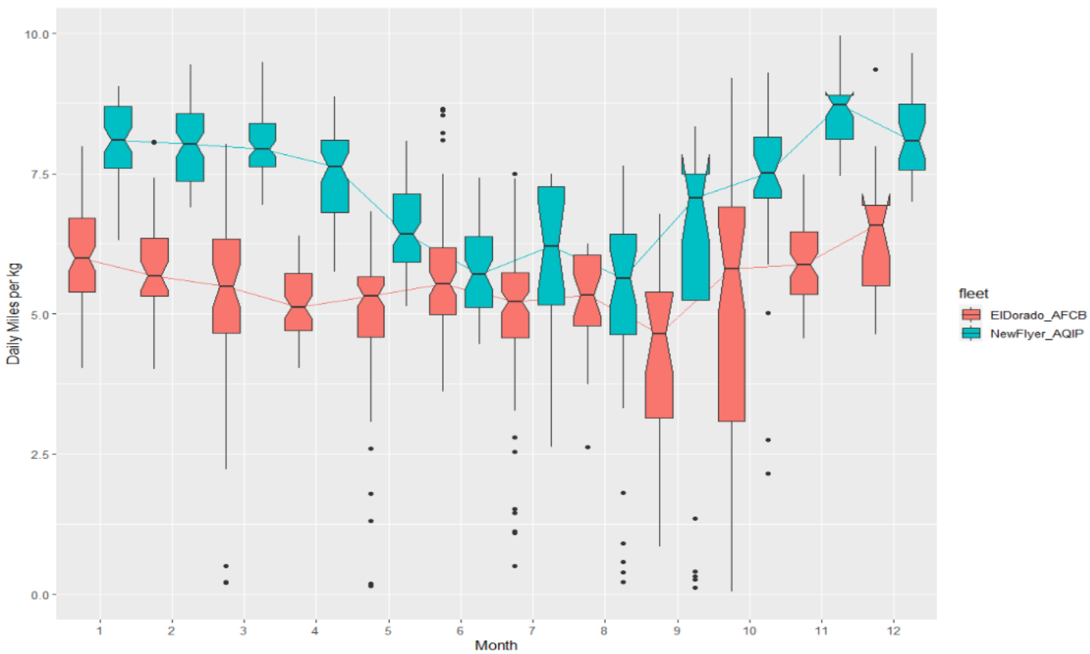


*Figure 4: Fuel Economy analysis of El Dorado and New Flyer FCEB fleets operated by Sunline Transit over a 2.5 year period. Top graph shows distribution of efficiency by month across the full analysis period. The bottom graph shows the median daily efficiency per day and associated maximum daily temperature (historic temperature for Banning, CA). Both graphs show the impact of HVAC load on bus efficiency.*




To translate these performance analyses to transit systems in Humboldt County, Table 3 presents BEB technology constraints and FCEB market constraints for each bus within each transit system. The color scheme is as follows:

- Green: Should be able to be met with the technology
- Orange:
    - BEB: Significant charging infrastructure cost and/or higher than 1:1 bus replacement
    - FCEB: Current commercially available bus models may not meet current route requirements

Note that Table 3 only accounts for active daily buses for each fleet. Additional reserve buses are not detailed.

*Table 3: BEB technology and FCEB market constraints regarding 1:1 bus replacement on existing route schedules. Only daily active buses are shown; reserves are not detailed here.*

<table>
<tr><th>Bus number (ID)</th><th>Transit System</th><th>BEB</th><th>FCEB</th></tr>
<tr><td>25500</td><td>AMRTS</td><td rowspan="7"></td><td rowspan="7"></td></tr>
<tr><td>2552150</td><td>AMRTS</td></tr>
<tr><td>428</td><td>BLRTS</td></tr>
<tr><td>66</td><td>ETS</td></tr>
<tr><td>67</td><td>ETS</td></tr>
<tr><td>68</td><td>ETS</td></tr>
<tr><td>69</td><td>ETS</td></tr>
<tr><td>1147</td><td>KTNET</td><td rowspan="14">Route schedule changes and/or greater than 1:1 bus replacement required.</td><td>Note: refueling in Eureka challenging</td></tr>
<tr><td>886</td><td>RTS</td><td rowspan="9"></td></tr>
<tr><td>888</td><td>RTS</td></tr>
<tr><td>889</td><td>RTS</td></tr>
<tr><td>890</td><td>RTS</td></tr>
<tr><td>891</td><td>RTS</td></tr>
<tr><td>892</td><td>RTS</td></tr>
<tr><td>893</td><td>RTS</td></tr>
<tr><td>894</td><td>RTS</td></tr>
<tr><td>896</td><td>RTS</td></tr>
<tr><td>410</td><td>SHI</td><td rowspan="4">Cutaway options limited and performance unknown.</td></tr>
<tr><td>512</td><td>SHI</td></tr>
<tr><td>514</td><td>SHI</td></tr>
<tr><td>714</td><td>WC</td></tr>
</table>

## 3. Total Cost of Ownership for Full Fleet Conversions

The cost effectiveness of transit electrification is extremely sensitive to the variability of bus performance. Fleet size and charging infrastructure must be sized to serve days when buses perform at lower efficiencies. The following sections detail fleets sizes and fueling infrastructure required to meet Innovative Clean Transit requirements for all public transit fleets in the County, including those not owned or operated by HTA.

All results are based on the size of the active on-road fleet during a given day. Reserve vehicles are not explicitly detailed in the results[5]. It is assumed that all buses will follow the same conversion pathway. For BEB scenarios that explore a replacement ratio greater than 1:1, it is assumed that the reserve fleet would also need to expand by the same ratio. However, this additional cost is not accounted for. Furthermore, for BEBs, it is assumed that the number of depot chargers required is equal to the size of the active fleet, not the total fleet including reserve vehicles.

All results assume current routes, route schedules, and bus schedules. Because model results of 1:1 bus replacement with BEBs results in substantial on-route charging infrastructure, costs associated with an expansion of BEB vehicle count are also explored.

The analysis period is 20 years. Bus replacement is not assumed to occur in common 12-year intervals. Rather, midlife maintenance costs on battery packs and fuel cell stacks are included but it is assumed buses will stay in operation over a full 20 years. While current federal funding requires 12-year replacement schedules, it is anticipated that this may change in the near future.

All buses and equipment are assumed to be purchased in the first year, avoiding procurement timeline assumptions. Operation and maintenance (O&M) costs are not discounted either for inflation or discount rate. O&M costs are presented on a per-mile basis, and reflect cumulative O&M costs over twenty years divided by the cumulative miles traveled over 20 years.

No attempt was made to project possible changes in bus, infrastructure, fuel, or other costs into the future. All per-unit costs (such as $/kg of hydrogen or $/bus midlife bus maintenance costs) are assumed static over twenty years.

### 3.1. Battery Electric Bus Fleet Conversion Summary

The following sections detail two full fleet deployment plans for BEB technology. All analyses were conducted using the Battery Electric Bus Optimization (BEBOP) Model[6] and the Fleet Technology Cost Comparison (FTCC) Model, both of which were developed by the Schatz Center.

There are two possible bus and infrastructure buildout scenarios presented:

- BEB 1: assumes 1:1 bus replacement along with the on-route infrastructure needed to support low bus efficiency

[5] The size of the reserve fleet varies by transit agency. HTA maintains roughly a 1:1 reserve ratio.
[6] https://github.com/schatzcenter/BEBOP

- BEB 2: assumes a 1.7:1 bus replacement ratio along with on-route infrastructure needed to support average bus efficiency

#### *3.1.1. BEB 1 - 1:1 Bus Replacement*

On-route charging infrastructure is built out to serve low efficiencies that a BEB may experience over the course of a year; an efficiency of 0.326 miles / kWh. This represents observed bus efficiency by HTA's Proterra XR+ 330kWh low floor bus as shown in Figure 1. All bus and charging infrastructure O&M costs are calculated assuming an average BEB efficiency of 0.523 miles / kWh. These assumptions result in the following operational assumptions:

- No changes to route and bus schedules are needed, even on days when bus efficiencies are low.
- On average, roughly 75% of on-route charging infrastructure is not necessary, and it is assumed isn't utilized in terms of total cost projections. However, this infrastructure could be utilized to keep bus battery state of charge relatively high which could improve battery lifespan. Fleet operation optimization would be needed to explore these design considerations.
- The majority of the on-route chargers are needed to serve the SHI and WC routes during low bus performance days.

Table 4 and Table 5 below detail the total cost of ownership for converting all buses in the following transit systems to BEBs:

- A&MRTS
- BLRTS
- ETS
- KT-NET
- RTS
- SHI
- WC

Additional details regarding assumptions are included in the appendix.

*Table 4: Summary of fleet and fuel infrastructure specifications for transit technology deployment plan* ***BEB 1.***

| | | |
|---|---|---|
| Fleet | Low Fuel Efficiency (mi / kWh) | 0.326 |
| | Average Fuel Efficiency (mi / kWh) | 0.523 |
| | Bus replacement ratio | 1:1 |
| | Total number of daily active buses | 21 |
| Charging Infrastructure | Total number of depot chargers | 21 |
| | Total number of on-route chargers | 31 |

*Table 5: Non-amortized costs associated with transit technology deployment plan **BEB 1**. All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years. Costs are cumulative across all transit systems in the County.*

| BEB 1: Full Fleet Conversion to BEBs, 1:1 Bus Replacement Ratio *No Resiliency Infrastructure* | | |
|---|---|---|
| Cost Component | Description | Value [d] |
| County-wide Capital Costs ($) | Bus capital and acquisition costs [a] | $17.0M |
| | On-route charger capital and installation cost | $19.2M |
| | Depot and maintenance bay charger capital and install cost | $1.6M |
| | Total capital costs | $37.8M |
| County-wide O&M Costs ($/mi) | Electricity (fuel) [b] | $0.35 |
| | Bus mid-life battery replacement (varies by bus) | $0.09 |
| | Bus scheduled maintenance (low / high literature range) | $0.27 [e] / $0.36 [f] |
| | Bus unscheduled maintenance | $0.28 [f] |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $0.99 / $1.08 |
| | On-route charger maintenance | $0.02 |
| | Depot and maintenance bay charger maintenance | $0.003 |
| | Charger replacement (assuming on-route charger replacement in 15 years) | $0.39 |
| | Low Carbon Fuel Standard (LCFS) [c] | - $0.22 |
| | Total O&M for All Charging Stations<br>Left value: Excludes charger replacement, includes LCFS<br>Right Value: Includes charger replacement, excludes LCFS | - $0.177 / $0.413 |
| | Total Bus and Charger O&M | $0.813 / $1.493 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges.
c. Expected LCFS revenue assuming $150/MT credit value. Note LCFS credit value is driven by an open trading market and changes regularly. In addition, LCFS is designed to phase out overtime such that it cannot be considered a long-term reliable income source.
d. Unless otherwise noted, all values originate from analysis using the FTCC model and inputs from the BEBOP model.
e. Total scheduled plus unscheduled maintenance cost of $0.55 per mile from Horrox, J., & Casale, M. (2019). Electric Buses in America: Lessons from Cities Pioneering Clean Transportation. Unscheduled cost per mile of $0.28 subtracted from $0.55 to get estimated scheduled maintenance of $0.27 per mile.
f. Hanlin, J., Reddaway, D., & Lane, J. (2018). Battery electric buses—state of the practice (No. Project J-7, Topic SA-41).

### 3.1.2. BEB 2 - 1.7:1 Bus Replacement

Because the number of on-route chargers needed to serve a 1:1 BEB replacement path is significant, an additional path is explored that increases the size of the existing active fleet in exchange for a smaller number of on-route chargers. The following key assumptions are made:

- Current route and bus schedules would be modified to allow for mid-schedule vehicle swaps, although impacts to daily mileage traveled (such as potential increase in deadhead miles) is not accounted for. Preliminary route schedule analysis showed that most vehicle swaps can occur in Eureka such that the increase in deadhead miles is likely low fleetwide.

- On-route charging infrastructure projections are developed using an average BEB efficiency of 0.523 miles / kWh. It is assumed that increasing the fleet size would reduce the on-route charging infrastructure to something comparable to that needed for a fleet operating at an average observed efficiency.[7]

Table 6 and Table 7 below detail the total cost of ownership for converting all buses in the following transit systems to BEBs

- A&MRTS
- BLRTS
- ETS
- KT-NET
- RTS
- SHI
- WC

*Figure 5: Example mock-up image of a high power on-route charger integrated with a transit stop. Image from energized.edison.com.*


Schedule changes are required to implement a 1.7:1 bus ratio, and any associated changes in revenue and deadhead miles are not captured here. Additional details regarding assumptions are shown in the appendix.

*Table 6: Summary of fleet and charging infrastructure for transit technology deployment plan* ***BEB 2.***

| | | |
|---|---|---|
| Fleet | Low Fuel Efficiency (mi / kWh) | 0.326 |
| | Average Fuel Efficiency (mi / kWh) | 0.523 |
| | Bus replacement ratio | 1.7:1 |
| | Total number of daily active buses | 36 |
| Charging Infrastructure | Total number of depot chargers | 36 |
| | Total number of on-route chargers | 8 |

[7] Details on a total cost of ownership analysis using average BEB efficiency are shown in the appendix.

*Table 7: Non-amortized costs associated with transit technology deployment plan **BEB 2**. All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years. Costs are cumulative across all transit systems in the County.*

| BEB 2: Full Fleet Conversion to BEBs, 1.7:1 Bus Replacement Ratio<br>*No Resiliency Infrastructure* | | |
|---|---|---|
| Cost Component | Description | Value [d] |
| County-wide Capital Costs ($) | Bus capital and acquisition costs [a] | $29.1M |
| | On-route charger capital and installation cost | $4.79M |
| | Depot and maintenance bay charger capital and install cost | $2.60M |
| | Total capital costs | $36.5 |
| County-wide O&M Costs ($/mi) | Electricity (fuel) [b] | $0.35 |
| | Bus mid-life battery replacement (varies by bus) | $0.09 |
| | Bus scheduled maintenance (low / high literature range) | $0.27 / $0.36 |
| | Bus unscheduled maintenance | $0.28 |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $0.99 / $1.08 |
| | On-route charger maintenance | $0.02 |
| | Depot and maintenance bay charger maintenance | $0.01 |
| | Charger replacement (assuming on-route charger replacement in 15 years) | $0.10 |
| | Low Carbon Fuel Standard (LCFS)[c] | - $0.22 |
| | Total O&M for All Charging Stations<br>Left value: Excludes charger replacement, includes LCFS<br>Right Value: Includes charger replacement, excludes LCFS | - $0.19 / $0.13 |
| | Total Bus and Charger O&M | $0.80 / $1.21 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges.
c. Expected LCFS revenue assuming $150/MT credit value. Note LCFS credit value is driven by an open trading market and changes regularly. In addition, LCFS is designed to phase out overtime such that it cannot be considered a long-term reliable income source.
d. Unless otherwise noted, all values originate from analysis using the FTCC model and inputs from the BEBOP model.

## 3.2. Fuel Cell Electric Bus Fleet Conversion Summary

The Fuel Cell Electric Bus (FCEB) fleet conversion analysis consists of a cost estimate of two possible scenarios for a full fleet conversion. The options are onsite hydrogen production from polymer electrolyte membrane (PEM) distributed electrolysis, and hydrogen delivery by truck. Estimates for the cost of hydrogen (production or delivery), cost of the refueling infrastructure (gaseous or liquid hydrogen refueling station) and the FCEBs cost are all included in the analysis.

The Heavy-Duty Refueling Station Analysis Model (HDRSAM) from Argonne National Laboratory and the H2A Current Distributed Hydrogen Production Model from the National Renewable Energy Lab (NREL) were used to calculate the cost of refueling infrastructure and cost of hydrogen production.

Table 8 shows the specifications of two commercially available FCEB options that are considered. We assume the El Dorado ENC 40' because of the larger fuel tank and fuel cell dominant design. While the OEM published efficiency is lower, we assume the same low and average efficiency for both buses which are derived from the analysis of Sunline Transit field performance data.

*Table 8: Summary of bus models considered in hydrogen fleet conversion of analysis.*

| Bus | | New Flyer Xcelsior 40' | El Dorado ENC AXESS-FC 40' |
|---|---|---|---|
| Efficiency (miles/kg) | Low Fuel Efficiency | 4.0 | |
| | OEM Published | 5.36 | 4.99 |
| | Average Fuel Efficiency | 7.54 | |
| Fuel Tank Size (kg) | | 37.5 | 50 |

A difference between BEB and FCEB technology is in the fueling infrastructure. BEBs may be charged outside the depot, current technology allows BEBs to recharge on-route via overhead charging at a stop. The charging time for BEBs can vary depending on the charger power rate, from minutes of short on-route quick charging to hours of slow charging at the depot. For FCEBs, the infrastructure for refueling is tied to a designated place, similar to traditional diesel or compressed natural gas (CNG) fueling stations. Hydrogen fuel can be produced onsite or delivered and stored in tanks. Pumps can dispense the hydrogen fuel in a similar manner to the way conventional diesel or CNG buses are refueled.

The hydrogen station was designed to support a worst case scenario where all buses happen to operate at a low efficiency of 4 mi / kg on a given day while O&M costs assume an average efficiency of 7.54 mi / kg. The station design features the following characteristics (with additional details on assumptions in the appendix):

- 3 fuel nozzles
- Capable of 1,218 kg per day and a peak demand of 406 kg per hour at 700 bar (to future proof the station as buses are typically fueled at 350 bar)
- Liquid station storage tank size of 5,000 kg (4,736 of which is usable). This provides 3.8 days of fuel at the low efficiency of 4 mi / kg, and 7.4 days of fuel at the average efficiency of 7.54 mi / kg.
- Average required delivery frequency for the liquid station of roughly one truck (3,800 kg) every five days

### *3.2.1. FCEB 1 - 1:1 Bus Replacement*

The capital cost of the bus technology, capital and installation cost of refueling infrastructure, and the estimate of cost per mile of the fuel and operation for the three different scenarios is presented in the following sections. Table 9 shows a summary of fleet and fueling infrastructure for the fleet conversion analysis. Table 10 summarizes the results. One thing to note is the hydrogen station is oversized in anticipation of the need for higher demand to bring down the O&M costs. This is intended to bring a more apples-to-apples comparison with electric bus fueling infrastructure costs as the utilization rate of modeled charging infrastructure could potentially increase significantly if additional buses were added to electrified routes. Furthermore, it is assumed the station is capable of providing 700 bar fueling in order to serve a variety of vehicle types. The hydrogen station design could cover future adoption of hydrogen by other public and private fleets, or by expansion of existing transit systems.

*Table 9: Summary of fleet and fueling infrastructure for transit technology deployment plan **FCEB 1**.*

| | | |
|---|---|---|
| Fleet | Low efficiency (mi / kg) | 4.00 |
| | Average efficiency (mi / kg) | 7.54 |
| | Bus replacement ratio | 1:1 |
| | Total number of daily active buses | 21 |
| Fueling Station | Number of fueling stations | 1 |
| | Design capacity (kg / day) | 1,218 |
| | Storage capacity (kg) | 5,000 |
| | Peak hourly capacity (kg / hr) | 406 |

*Figure 6: Picture of Orange County Transit Authority's 4,500 kg liquid hydrogen storage and fueling infrastructure constructed in 2020. Station footprint inside the bollards is roughly 40' x 80'. This does not include required code setbacks or fuel dispensers and required chillers. This equipment is located on a separate fueling station island and is roughly the size of a typical diesel fuel pump. Images from trilliumcng.com and tass.news.*

*Table 10: Non-amortized costs associated with transit technology deployment plan **FCEB 1**. All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years. Costs are cumulative across all transit systems in the County.*

| FCEB 1: Full Fleet Conversion to FCEBs<br>Average Bus Efficiency, 1:1 Bus Replacement Ratio | | | |
|---|---|---|---|
| Cost Component | Description | Value [d] | |
| | | Liquid Delivery | On-Site Electrolysis |
| County-wide Capital Costs ($) | Bus capital and acquisition costs [a] | $18.5M [e] | |
| | Eureka hydrogen fueling station capital cost | $11.1M | $11.7M |
| | Eureka hydrogen fueling station installation cost | $2.9M | $6.0M |
| | Total capital costs | $32.5M | $36.2M |
| County-wide O&M Costs ($/mi) | Hydrogen (fuel) [b] | $0.80 | $0.86 |
| | Bus mid-life power stack and battery replacement (varies by bus) | $0.36 | |
| | Bus scheduled maintenance (low / high literature values) | $0.09 [f] / $0.50 [g] | |
| | Bus unscheduled maintenance | $0.25 [g] | |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $1.50 / $1.91 | $1.56 / $1.97 |
| | Fueling station maintenance | $0.35 | $0.41 |
| | Low Carbon Fuel Standard (LCFS) [c] | - $0.16 | - $0.44 |
| | Total Fueling Station O&M<br>Left value: includes LCFS<br>Right value: excludes LCFS | $0.19 / $0.35 | - $0.03 / 0.41 |
| | Total fuel and O&M costs | $1.69 / $2.26 | $1.53/ $2.38 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges associated with a TOU E-20 electricity rate schedule. Average of all TOU rates in a weekday is used. kW and kWh values directly from HDRSAM and H2A models.
c. Expected LCFS revenue assuming $150/MT credit value. LCFS credit value changes regularly. In addition, LCFS is designed to phase out overtime such that it is not a long-term reliable income source.
d. Unless otherwise noted, all analyses use the FTCC model and inputs from the HDRSAM model, with additional inputs from the H2A model for hydrogen electrolysis, and from the BEBOP Model for bus duty cycle energy requirements.
e. Capital cost per bus of $900,000 assumed, along with a 2.5% acquisition adder. Cost obtained from the California Air Resources Board (CARB) Transit Fleet Cost Model.
f. The low scheduled maintenance and estimated unscheduled maintenance values originate from Eudy, L., Post, M., Norris, J., & Sokolsky, S. (2019). Zero-Emission Bus Evaluation Results: Stark Area Regional Transit Authority Fuel Cell Electric Buses (No. FTA Report No. 0140).
g. The high scheduled maintenance value comes from a $0.75 per mile total maintenance cost from Alameda-Contra Costa Transit District Fuel Cell Bus Program Fuel Cell Electric Bus Technology: Technical Capabilities and Experience presentation, June 13, 2019. The unscheduled maintenance value of $0.25 per mile is subtracted from $0.75 to obtain the estimated upper end scheduled maintenance cost.

## 4. Total Cost of Ownership for Mixed Fleet Conversion

A mix of battery electric and fuel cell electric buses is explored. Table 11 summarizes the mixed fleet results. Table 12 details capital and O&M cost associated with deployment of FCEBs for RTS, SHI, and WC systems. For the remaining transit systems the same two BEB deployment options are explored: a 1:1 bus replacement option and a fleet expansion option. All results are based on the size of the active on-road fleet during a given day and assume current routes, route schedules, and bus schedules.

*Table 11: Summary results of **Mix 1** and **Mix 2** deployment options.*

| | | | Electric | Hydrogen | | Mileage Weighted Totals | |
|---|---|---|---|---|---|---|---|
| | | | | Delivery | On-Site | | |
| Mix 1 | Capex ($) | Bus | $6.33M | $12.0M | | **Capital:** | **$31.9M** |
| | | Infra | $5.44M | $8.2M | $11.2M | | **$34.9M** |
| | O&M ($ / mi) | Bus | $0.95 - $1.04 | $1.53 - $1.94 | $1.59 - $2.00 | **O&M:** | **$1.36** |
| | | Infra | -$0.17 - $0.38 | $0.18 - $0.35 | -$0.05 - $0.41 | | **$2.17** |
| Mix 2 | Capex ($) | Bus | $9.42M | $12.0M | | **Capital:** | **$32.3M** |
| | | Infra | $2.74M | $8.2M | $11.2M | | **$35.3M** |
| | O&M ($ / mi) | Bus | $0.95 - $1.04 | $1.53 - $1.94 | $1.59 - $2.00 | **O&M:** | **$1.36** |
| | | Infra | -$0.18 - $0.16 | $0.18 - $0.35 | -$0.05 - $0.41 | | **$2.12** |

*Table 12: Non-amortized costs associated with the <u>FCEB component</u> of transit technology deployment plans **Mix 1** and **Mix 2**. All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years.*

| Mix 1 and Mix 2: Mixed Fleet Conversion, FCEB Component<br>No Resiliency Infrastructure | | | |
|---|---|---|---|
| Cost Component | Description | Value [d] | |
| | | Liquid Delivery | On-Site Electrolysis |
| County-wide Capital Costs ($) | Bus capital and acquisition costs [a] | $12.0M [e] | |
| | Eureka hydrogen fueling station capital cost | $4.8M | $6.9M |
| | Eureka hydrogen fueling station installation cost | $3.4M | $4.3M |
| | Total capital costs | $20.2M | $23.2M |
| County-wide O&M Costs ($/mi) | Hydrogen (fuel) [b] | $0.80 | $0.86 |
| | Bus mid-life power stack and battery replacement | $0.39 | |
| | Bus scheduled maintenance (low / high literature values) | $0.09 [f] / $0.50 [g] | |
| | Bus unscheduled maintenance | $0.25 [g] | |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $1.53 / $1.94 | $1.59 / $2.00 |
| | Fueling station maintenance | $0.35 | $0.41 |
| | Low Carbon Fuel Standard (LCFS) c | - $0.17 | - $0.46 |
| | Total Fueling Infrastructure O&M<br>Left value: includes LCFS<br>Right value: excludes LCFS | $0.18 / $0.35 | - $0.05 / 0.41 |
| | Total Bus and Fueling Infrastructure O&M | $1.71/ $2.29 | $1.54 / $2.41 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges associated with a TOU E-20 electricity rate schedule. Average of all TOU rates in a weekday is used. kW and kWh values directly from HDRSAM and H2A models.
c. Expected LCFS revenue assuming $150/MT credit value. Note LCFS credit value is driven by an open trading market and changes regularly. In addition, LCFS is designed to phase out overtime such that it cannot be considered a long-term reliable income source unless otherwise noted, all values originate from an internal total cost of ownership model developed by the Schatz Center using inputs from HDRSAM model, with additional inputs from the H2A model for hydrogen electrolysis, and from the BEBOP Model for bus duty cycle energy requirements.
d. Unless otherwise noted, all analyses use the FTCC model and inputs from the HDRSAM model, with additional inputs from the H2A model for hydrogen electrolysis, and from the BEBOP Model for bus duty cycle energy requirements.
e. Capital cost per bus of $900,000 assumed, along with a 2.5% acquisition adder.
f. The low scheduled maintenance and estimated unscheduled maintenance values originate from Eudy, L., Post, M., Norris, J., & Sokolsky, S. (2019). Zero-Emission Bus Evaluation Results: Stark Area Regional Transit Authority Fuel Cell Electric Buses (No. FTA Report No. 0140).
g. The high scheduled maintenance value comes from a $0.75 per mile total maintenance cost from Alameda-Contra Costa Transit District Fuel Cell Bus Program Fuel Cell Electric Bus Technology: Technical Capabilities and Experience presentation, June 13, 2019. The unscheduled maintenance value of $0.25 per mile is subtracted from $0.75 to obtain the estimated upper end scheduled maintenance cost.

### 4.1. Mix 1 - 1:1 FCEB and BEB Replacement

On-route charging infrastructure is built out to serve low efficiencies that a BEB may experience over the course of a year; an efficiency of 0.326 miles / kWh. This represents observed bus efficiency by HTA's Proterra XR+ 330kWh low floor bus as shown in Figure 1. All bus and charging infrastructure O&M costs are calculated assuming an average BEB efficiency of 0.523 miles / kWh. It is assumed that the number of depot chargers required is equal to the size of the active fleet, not the total fleet including reserve vehicles.

*Table 13: Summary of fleet and charging infrastructure specifications for transit technology deployment plan **Mix 1.***

| | | | |
|---|---|---|---|
| Battery Electric Bus (BEB) Technology | *Fleet specifications* | Low Fuel Efficiency (mi / kWh) | 0.326 |
| | | Average Fuel efficiency (mi / kWh) | 0.523 |
| | | Bus replacement ratio | 1:1 |
| | | Total number of buses | 8 |
| | | Transit systems serviced | AMRTS, BLRTS, ETS, KT-NET |
| | *Charging infrastructure specifications* | Total number of depot chargers | 8 |
| | | Total number of on-route chargers | 8 |
| Fuel Cell Electric Bus (FCEB) Technology | *Fleet specifications* | Low Fuel Efficiency (mi / kg) | 4.00 |
| | | Average Fuel efficiency (mi / kg) | 7.54 |
| | | Bus replacement ratio | 1:1 |
| | | Total number of buses | 13 |
| | | Transit systems serviced | RTS, SHI, WC |
| | *Fueling infrastructure specifications* | Total number of fueling stations | 1 |
| | | Design capacity (kg / day) | 650 |
| | | Storage Capacity (kg) | 2,500 |
| | | Peak hourly capacity (kg / hr) | 200 |

*Table 14: Non-amortized costs associated with the BEB component of transit technology deployment plan **Mix 1**. All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years.*

| Mix 1: Mixed Fleet Conversion, BEB Component, 1:1 bus replacement ratio<br>*No Resiliency Infrastructure* | | |
|---|---|---|
| Cost Component | Description | Value [d] |
| County-wide Capital Costs ($) | Bus capital and acquisition costs [a] | $6.33M |
| | On-route charger capital and installation cost | $4.79M |
| | Depot and maintenance bay charger capital and install cost | $650,000 |
| | Total capital costs | $11.8M |
| County-wide O&M Costs ($/mi) | Electricity (fuel) [b] | $0.31 |
| | Bus mid-life battery replacement (varies by bus) | $0.09 |
| | Bus scheduled maintenance<br>(low / high literature range) | $0.27 [e] / $0.36 [f] |
| | Bus unscheduled maintenance | $0.28 [f] |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $0.95 / $1.04 |
| | On-route charger maintenance | $0.04 |
| | Depot and maintenance bay charger maintenance | $0.01 |
| | Charger replacement (assuming on-route charger replacement in 15 years) | $0.33 |
| | Low Carbon Fuel Standard (LCFS) [c] | - $0.22 |
| | Total Fueling Infrastructure O&M<br>Left value: Excludes charger replacement, includes LCFS<br>Right Value: Includes charger replacement, excludes LCFS | -$0.17 / $0.38 |
| | Total Bus and Fueling Infrastructure O&M | $0.78 / $1.42 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges.
c. Expected LCFS revenue assuming $150/MT credit value. Note LCFS credit value is driven by an open trading market and changes regularly. In addition, LCFS is designed to phase out overtime such that it cannot be considered a long-term reliable income source.
d. Unless otherwise noted, all values originate from analysis using the FTCC model and inputs from the BEBOP model.
e. Total scheduled plus unscheduled maintenance cost of $0.55 per mile from Horrox, J., & Casale, M. (2019). Electric Buses in America: Lessons from Cities Pioneering Clean Transportation. Unscheduled cost per mile of $0.28 subtracted from $0.55 to get estimated scheduled maintenance of $0.27 per mile.
f. Hanlin, J., Reddaway, D., & Lane, J. (2018). Battery electric buses—state of the practice (No. Project J-7, Topic SA-41).

### 4.2. Mix 2 - 1:1 FCEB Replacement and 1.5:1 BEB Replacement

For BEB scenarios that explore a replacement ratio greater than 1:1, it is assumed that the reserve fleet would also need to expand by the same ratio. However, this additional cost is not accounted for. The on-route infrastructure needed is assumed to be equal to that which is required for buses operating at an average efficiency.

*Table 15: Summary of fleet and charging infrastructure specifications for transit technology deployment plan* ***Mix 2.***

| | | | |
|---|---|---|---|
| Battery Electric Bus (BEB) Technology | *Fleet specifications* | Low Fuel Efficiency (mi / kWh) | 0.326 |
| | | Average Fuel efficiency (mi / kWh) | 0.523 |
| | | Bus replacement ratio | 1.5:1 |
| | | Total number of buses | 17 |
| | | Transit systems serviced | AMRTS, BLRTS, ETS, KT-NET |
| | *Charging infrastructure specifications* | Total number of depot chargers | 8 |
| | | Total number of on-route chargers | 3 |
| Fuel Cell Electric Bus (FCEB) Technology | *Fleet specifications* | Low Fuel Efficiency (mi / kg) | 4.00 |
| | | Average Fuel efficiency (mi / kg) | 7.54 |
| | | Bus replacement ratio | 1:1 |
| | | Total number of buses | 13 |
| | | Transit systems serviced | RTS, SHI, WC |
| | *Fueling infrastructure specifications* | Total number of fueling stations | 1 |
| | | Design capacity (kg / day) | 650 |
| | | Storage Capacity (kg) | 2,500 |
| | | Peak hourly capacity (kg / hr) | 200 |

*Table 16: Non-amortized costs associated with the BEB component of transit technology deployment plan **Mix 2.** All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years.*

| Mix 2: Mixed Fleet Conversion, BEB Component, 1.5:1 bus replacement ratio<br>*No Resiliency Infrastructure* | | |
|---|---|---|
| Cost Component | Description | Value [d] |
| County-wide Capital Costs ($) | Bus capital and acquisition costs [a] | $9.42M |
| | On-route charger capital and installation cost | $1.80M |
| | Depot and maintenance bay charger capital and install cost | $939,000 |
| | Total capital costs | $12.2M |
| County-wide O&M Costs ($/mi) | Electricity (fuel) [b] | $0.31 |
| | Bus mid-life battery replacement (varies by bus) | $0.09 |
| | Bus scheduled maintenance<br>(low / high literature range) | $0.27 [e]/ $0.36 [f] |
| | Bus unscheduled maintenance | $0.28 |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $0.95 / $1.04 |
| | On-route charger maintenance | $0.02 |
| | Depot and maintenance bay charger maintenance | $0.02 |
| | Charger replacement (assuming on-route charger replacement in 15 years) | $0.12 |
| | Low Carbon Fuel Standard (LCFS) [c] | -$0.22 |
| | Total Fueling Infrastructure O&M<br>Left value: Excludes charger replacement, includes LCFS<br>Right Value: Includes charger replacement, excludes LCFS | -$0.18 / $0.16 |
| | Total Bus and Fueling Infrastructure O&M | $0.77 / $1.20 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges.
c. Expected LCFS revenue assuming $150/MT credit value. Note LCFS credit value is driven by an open trading market and changes regularly. In addition, LCFS is designed to phase out overtime such that it cannot be considered a long-term reliable income source.
d. Unless otherwise noted, all values originate from analysis using the FTCC model and inputs from the BEBOP model.
e. Total scheduled plus unscheduled maintenance cost of $0.55 per mile from Horrox, J., & Casale, M. (2019). Electric Buses in America: Lessons from Cities Pioneering Clean Transportation. Unscheduled cost per mile of $0.28 subtracted from $0.55 to get estimated scheduled maintenance of $0.27 per mile.
f. Hanlin, J., Reddaway, D., & Lane, J. (2018). Battery electric buses—state of the practice (No. Project J-7, Topic SA-41).

## 5. Infrastructure Space Requirements

Table 17 includes estimates of fueling infrastructure footprint requirements for full fleet conversion to electric and hydrogen. Also included are estimates of the existing HTA facility, and of potential supporting microgrid infrastructure for BEB depot chargers.

*Table 17: Infrastructure space requirements for the transit technologies under consideration.*

| | Electric – Full Fleet | | Hydrogen – Full Fleet | |
|---|---|---|---|---|
| | On-Route | Depot | Delivery | On-site Production |
| Current Facility | 3.4 acres [a] | | | |
| Fueling Infrastructure | Single 500kW Overhead Station<br>0.013 ac [b] | Single Station Serving Two Vehicle Bays<br>20 sq. ft. [b]<br><br>Supporting Electrical Equipment for single station<br>0.0043 ac [b] | All Equipment + Setbacks<br>0.62 acre [c] | All non-production equipment + setbacks<br>0.5 acre [d]<br><br>Electrolyzer<br>0.03 acre [e] |
| Microgrid Infrastructure | ?? | Elec + BESS<br>0.25 acres [f]<br><br>Solar<br>0.6 acre [f] | ?? | ?? |

a. Estimated using Google Earth for existing facility at 2nd St. and V St.. This is the current footprint of the land parcels owned by HTA.

b. Estimated guess based on images of other installations.

c. In HDRSAM, "Refueling Station – Liquid H2" sheet, sum of rows 110 and 117. This should be conservative as this represents a station with six fueling dispensers. Only two or three dispensers are estimated as needed by HTA's fueling station.

d. In HDRSAM, "Refueling Station – Gaseous H2" sheet, product of rows 135 and 136, plus row 137. This should be conservative as this represents a station with six fueling dispensers. Only two or three dispensers are estimated as needed by HTA's fueling station. Note that, per an estimate of 5x HRS 200-350/700 Hydrogenics electrolyzer fueling stations (http://www.hydrogenics.com/wp-content/uploads/Renewable-Hydrogen-Brochure.pdf), physical equipment should occupy roughly 0.25 acre (consistent with past conversations with the California Fuel Cell Partnership). Remaining space is associated with additional storage plus setback requirements.

e. Assuming 1,000 kg/day and 12 hours of electrolyzer operation per day results in ~1,000 $Nm^3$/hr electrolyzer production rate. Referencing Hydrogenics HyLYZER specifications (http://www.hydrogenics.com/wp-content/uploads/Renewable-Hydrogen-Brochure.pdf), this results in a single 5MW HyLYZER-1,000-30 unit. Assuming the width of a single container is 102 inches, and assuming a 2 foot space between containers, this results in a total footprint for 2 40' containers and 1 20' container of 1,200 $ft^2$.

f. From microgrid design completed 2019 in collaboration with McKeever Energy & Electric, Inc. Infrastructure was designed to support six depot chargers plus storage supporting 2+ chargers while islanded.

# 6. Appendix

## 6.1. BEB 1: 1:1 Bus Replacement Additional Details

Additional details are provided regarding scenario BEB 1.

*Table 18: Summary of bus capital and O&M costs for transit technology deployment plan **BEB 1,** organized by transit system.*

| Transit System | Capital Cost [a, b] ($ 2020) | O&M Costs [c] | | | |
|---|---|---|---|---|---|
| | | *Bus maintenance [d] ($/mi)* | *Midlife battery replacement ($/mi)* | *Charging ($/mi)* | *LCFS ($/mi)* |
| AMRTS | $1.58M | $0.64 / $0.48 | $0.11/ $0.08 | $0.45 / $0.34 | -$0.26 / -$0.22 |
| BLRTS | $791,000 | $0.64 / $0.48 | $0.12 / $0.09 | $0.52 / $0.39 | -$0.28 / -$0.24 |
| ETS | $3.20M | $0.64 / $0.48 | $0.13 / $0.09 | $0.52 / $0.40 | -$0.30 / -$0.25 |
| KTNET | $791,000 | $0.64 / $0.48 | $0.10 / $0.07 | $0.59 / $0.45 | -$0.23 / -$0.20 |
| RTS | $7.35M | $0.64 / $0.48 | $0.09 / $0.07 | $0.67 / $0.50 | -$0.20 / -$0.18 |
| SHI | $2.47M | $0.64 / $0.48 | $0.09 / $0.07 | $1.33 / $1.01 | -$0.21 / -$0.19 |
| WC | $824,000 | $0.64 / $0.48 | $0.08 / $0.06 | $0.41 / $0.31 | -$0.19 / -$0.17 |

a. Estimate includes 2.5% added acquisition cost.
b. Estimate does not include additional cost associated with back-up buses.
c. Left values represent non-amortized O&M costs while right values represent amortized O&M costs assuming a 3% discount rate.
d. Bus maintenance estimate is with consideration to both scheduled and unscheduled maintenance cost. A value of $0.36/mi was assumed for scheduled maintenance (Hanlin, J., Reddaway, D., & Lane, J., 2018), while a value of $0.28/mi was assumed for unscheduled maintenance (Horrox, J., & Casale, M., 2019).

*Table 19: Summary of charging station capital and O&M costs for transit technology deployment plan **BEB 1,** organized by station location.*

| Location [a.] | Station type | Capital & Installation Cost ($ 2020 per station) | O&M Costs ($/kWh) [b., c.] |
|---|---|---|---|
| 4th & D St. (Eureka) | On-route | | $0.22 / $0.14 |
| 4th & H St. (Eureka) | On-route | | $0.25 / $0.16 |
| 5th & D St. (Eureka) | On-route | | $0.24 / $0.15 |
| 5th & H St. (Eureka) | On-route | | $0.25 / $0.16 |
| Arcata Transit Center | On-route | | $0.07 / $0.04 |
| Bayshore Mall (Eureka) | On-route | | $0.11 / $0.07 |
| Benbow KOA | On-route | | $0.16 / $0.10 |
| Broadway & Del Norte (Eureka) | On-route | | $0.12 / $0.08 |
| College of the Redwoods (Eureka) | On-route | | $0.10 / $0.06 |
| Deans Creek Resort (Redway) | On-route | | $0.52 / $0.34 |
| Fortuna Blvd. & Smith Ln. | On-route | | $0.31 / $0.20 |
| 11th & N St. (Fortuna) | On-route | | $0.29 / $0.18 |
| Founder's Grove | On-route | | $0.58 / $0.37 |
| Redwood Dr. Melville (Garberville) | On-route | | $1.29 / $0.83 |
| Harris & F St. (Eureka) | On-route | | $0.15 / $0.10 |
| Maple Hills Rd. (Miranda) | On-route | $599,000 | $1.29 / $0.83 |
| Sips Coffee (Miranda) | On-route | | $1.27 / $0.81 |
| Myers Flat | On-route | | $0.58 / $0.37 |
| Orick Redwood National Park Office | On-route | | $2.09 / $1.34 |
| Orick Store | On-route | | $2.57 / $1.65 |
| Phillipsville Fire Department | On-route | | $1.29 / $0.83 |
| Prairie Creek Redwoods Visitor Center | On-route | | $1.72 / $1.10 |
| Redcrest off ramp | On-route | | $1.02 / $0.66 |
| Redway Clinic | On-route | | $0.58 / $0.37 |
| Signature Coffee (Redway) | On-route | | $0.74 / $0.48 |
| Redwood Memorial | On-route | | $0.32 / $0.21 |
| Redwood National Park – Kuechel Visitor Center | On-route | | $1.29 / $0.83 |
| Redwood Village Center | On-route | | $0.33 / $0.21 |
| Trinidad Park & Ride | On-route | | $0.08 / $0.05 |
| Weott off ramp | On-route | | $0.87 / $0.56 |
| Willow Creek | On-route | | $0.12 / $0.08 |
| Humboldt Transit Authority bus yard | Depot + maintenance bay | $1.45M | $0.006 / $0.005 |
| Blue Lake Rancheria office building | Depot | $72,300 | $0.10 / $0.007 |
| Hoopa Tribal Police Station | Depot | $72,300 | $0.007 / $0.005 |

a. Note that additional charging infrastructure would also be necessary in Del Norte and Trinity counties for deployment of plan FFC 1a, Option i.

b. O&M cost includes cost of charger maintenance, as well as charger replacement. It is assumed that on-route chargers must be replaced after 15 years, and depot chargers last the length of the analysis period.

c. Left values represent non-amortized O&M costs while right values represent amortized O&M costs assuming a 3% discount rate.

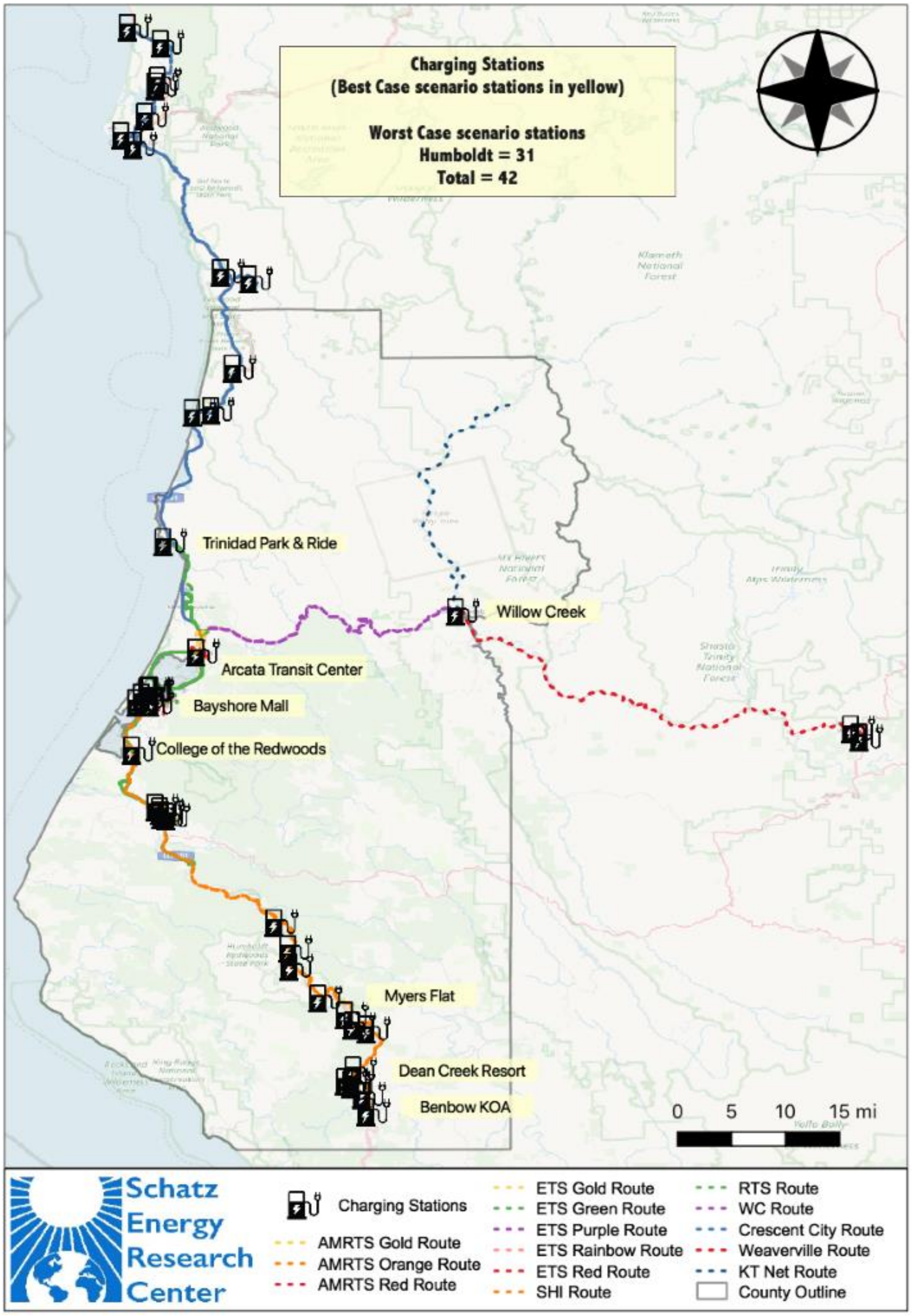



*Figure 7: On-route charging results from the Battery Electric Bus Optimization Model[8] for both an average and low BEB efficiency.*

[8] https://github.com/schatzcenter/BEBOP

### 6.2. BEB 1 Alt: 1:1 Bus Replacement with Average Efficiency

The results are not used, but demonstrate results if an average fleet efficiency is used, rather than a low efficiency, to estimate infrastructure requirements.

*Table 20: Summary of fleet and charging infrastructure specifications for transit technology deployment plan* ***BEB 1 with average bus efficiency.***

| | | |
|---|---|---|
| Fleet specifications | Fuel efficiency (mi / kWh) | 0.523 |
| | Bus replacement ratio | 1:1 |
| | Total number of buses | 21 |
| Charging infrastructure specifications | Total number of depot chargers | 21 |
| | Total number of on-route chargers | 8 |

*Table 21: Non-amortized costs associated with transit technology deployment plan **BEB 1 with average bus efficiency**. All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years.*

| BEB 1 Alt: Full Fleet Conversion to BEBs<br>Average Bus Efficiency, 1:1 Bus Replacement Ratio<br>*No Resiliency Infrastructure* | | |
|---|---|---|
| Cost Component | Description | Value [d] |
| Fleet-wide Capital Costs ($)<br><br>Total capital cost of converting all buses indicated in Table 2, column 3 to BEBs. | Bus capital and acquisition costs [a] | $17.0M |
| | On-route charger capital and installation cost | $4.79M |
| | Depot and maintenance bay charger capital and install cost | $1.59M |
| | Total capital costs | $23.4M |
| Fleet-wide Fuel and O&M Costs ($/mi)<br><br>Total operation and management (O&M) cost associated with converting all buses indicated in Table 2, column 3 to BEBs. | Electricity (fuel) [b] | $0.35 |
| | Bus mid-life battery replacement (varies by bus) | $0.09 |
| | Bus scheduled maintenance<br>(low / high literature range) | $0.27 [e] / $0.36 [f] |
| | Bus unscheduled maintenance | $0.28 [f] |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $0.99 / $1.08 |
| | On-route charger maintenance | $0.02 |
| | Depot and maintenance bay charger maintenance | $0.01 |
| | Charger replacement (assuming on-route charger replacement in 15 years) | $0.10 |
| | Low Carbon Fuel Standard (LCFS) [c] | - $0.22 |
| | Total O&M for All Charging Stations<br>Left value: Excludes charger replacement, includes LCFS<br>Right Value: Includes charger replacement, excludes LCFS | -$0.19 / $0.13 |
| | Total Bus and Charger O&M | $0.80 / $1.21 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges.
c. Expected LCFS revenue assuming $150/MT credit value. Note LCFS credit value is driven by an open trading market and changes regularly. In addition, LCFS is designed to phase out overtime such that it cannot be considered a long-term reliable income source.
d. Unless otherwise noted, all values originate from analysis using the FTCC model and inputs from the BEBOP model.
e. Total scheduled plus unscheduled maintenance cost of $0.55 per mile from Horrox, J., & Casale, M. (2019). Electric Buses in America: Lessons from Cities Pioneering Clean Transportation. Unscheduled cost per mile of $0.28 subtracted from $0.55 to get estimated scheduled maintenance of $0.27 per mile.
f. Hanlin, J., Reddaway, D., & Lane, J. (2018). Battery electric buses—state of the practice (No. Project J-7, Topic SA-41).

*Table 22: Summary of bus capital and O&M costs for transit technology deployment plan **BEB 1 with average bus efficiency,** organized by transit system.*

| Transit System | Capital Cost [a, b] ($ 2020) | O&M Costs [c] | | | |
|---|---|---|---|---|---|
| | | Bus maintenance [d] ($/mi) | Midlife battery replacement ($/mi) | Charging ($/mi) | LCFS ($/mi) |
| AMRTS | $1.58M | $0.64 / $0.48 | $0.11/ $0.08 | $0.28 / $0.21 | -$0.26 / -$0.22 |
| BLRTS | $791,000 | | $0.12 / $0.09 | $0.31 / $0.23 | -$0.28 / -$0.24 |
| ETS | $3.20M | | $0.13 / $0.09 | $0.28 / $0.21 | -$0.30 / -$0.25 |
| KTNET | $791,000 | | $0.10 / $0.07 | $0.42 / $0.32 | -$0.23 / -$0.20 |
| RTS | $7.35M | | $0.09 / $0.07 | $0.32 / $0.25 | -$0.20 / -$0.18 |
| SHI | $2.47M | | $0.09 / $0.07 | $0.47 / $0.35 | -$0.21 / -$0.19 |
| WC | $824,000 | | $0.08 / $0.06 | $0.41 / $0.31 | -$0.19 / -$0.17 |

a. Estimate includes 2.5% added acquisition cost.
b. Estimate does not include additional cost associated with back-up buses.
c. Left values represent non-amortized O&M costs while right values represent amortized O&M costs assuming a 3% discount rate.
d. Bus maintenance estimate is with consideration to both scheduled and unscheduled maintenance cost. A value of $0.36/mi was assumed for scheduled maintenance (Hanlin, J., Reddaway, D., & Lane, J., 2018), while a value of $0.28/mi was assumed for unscheduled maintenance (Horrox, J., & Casale, M., 2019).

*Table 23: Summary of charging station capital and O&M costs for transit technology deployment plan **BEB 1 with average bus efficiency,** organized by station location.*

| Location | Station type | Capital & Installation Cost ($ 2020) | O&M Costs ($/kWh) [a.] |
|---|---|---|---|
| Arcata Transit Center | On-route | $599,000 | $0.08 / $0.05 |
| Bayshore Mall | On-route | | $0.13 / $0.09 |
| Benbow KOA | On-route | | $0.18 / $0.12 |
| College of the Redwoods | On-route | | $0.11 / $0.08 |
| Dean Creek Resort | On-route | | $0.76 / $0.49 |
| Myers Flat | On-route | | $0.77 / $0.50 |
| Trinidad Park and Ride | On-route | | $0.11 / $0.07 |
| Willow Creek | On-route | | $0.18 / $0.12 |
| Humboldt Transit Authority bus yard | Depot + maintenance bay | $1.45M | $0.008 / $0.006 |
| Hoopa Tribal Police Station | Depot | $72,300 | $0.008 / $0.006 |
| Blue Lake Rancheria office building | Depot | $72,300 | $0.006 / $0.005 |

a. O&M cost includes cost of charger maintenance, as well as charger replacement. It is assumed that on-route chargers must be replaced after 15 years, and depot chargers last the length of the analysis period.

## 6.3. BEB 2: 1.7:1 Bus Replacement Ratio Additional Details

*Table 24: Summary of bus capital and O&M costs for transit technology deployment plan **BEB 2,** organized by transit system.*

| Transit System | Capital Cost [a, b] ($ 2020) | O&M Costs [c] | | | |
|---|---|---|---|---|---|
| | | *Bus maintenance [d] ($/mi)* | *Midlife battery replacement ($/mi)* | *Charging ($/mi)* | *LCFS ($/mi)* |
| AMRTS | $2.37M | $0.64 / $0.48 | $0.16/ $0.12 | $0.42 / $0.32 | -$0.39 / -$0.33 |
| BLRTS | $1.58M | | $0.25 / $0.17 | $0.62 / $0.47 | -$0.56 / -$0.48 |
| ETS | $4.00M | | $0.15 / $0.11 | $0.35 / $0.27 | -$0.37 / -$0.31 |
| KTNET | $1.58M | | $0.20 / $0.15 | $0.84 / $0.64 | -$0.46 / -$0.41 |
| RTS | $13.0M | | $0.15 / $0.11 | $0.63 / $0.47 | -$0.34 / -$0.31 |
| SHI | $4.95M | | $0.18 / $0.14 | $0.93 / $0.70 | -$0.42 / -$0.37 |
| WC | $1.65M | | $0.16 / $0.13 | $0.82 / $0.62 | -$0.37 / -$0.34 |

a. Estimate includes 2.5% added acquisition cost.
b. Estimate does not include additional cost associated with back-up buses.
c. Left values represent non-amortized O&M costs while right values represent amortized O&M costs assuming a 3% discount rate.
d. Bus maintenance estimate is with consideration to both scheduled and unscheduled maintenance cost. A value of $0.36/mi was assumed for scheduled maintenance (Hanlin, J., Reddaway, D., & Lane, J., 2018), while a value of $0.28/mi was assumed for unscheduled maintenance (Horrox, J., & Casale, M., 2019).

*Table 25: Summary of charging station capital and O&M costs for transit technology deployment plan **BEB 2,** organized by station location.*

| Location | Station type | Capital & Installation Cost ($ 2020) | O&M Costs ($/kWh) [a.] |
|---|---|---|---|
| Arcata Transit Center | On-route | $599,000 | $0.08 / $ 0.05 |
| Bayshore Mall | On-route | | $0.13 / $0.09 |
| Benbow KOA | On-route | | $0.18 / $0.12 |
| College of the Redwoods | On-route | | $0.11 / $0.08 |
| Dean Creek Resort | On-route | | $0.77 / $0.49 |
| Myers Flat | On-route | | $0.77 / $0.50 |
| Trinidad Park and Ride | On-route | | $0.11 / $0.07 |
| Willow Creek | On-route | | $0.18 / $0.12 |
| Humboldt Transit Authority bus yard | Depot + maintenance bay | $2.75M | $0.012 / $0.009 |
| Hoopa Tribal Police Station | Depot | $145,000 | $0.017 / $0.013 |
| Blue Lake Rancheria office building | Depot | $72,300 | $0.006 / $0.005 |

a. O&M cost includes cost of charger maintenance, as well as charger replacement. It is assumed that on-route chargers must be replaced after 15 years, and depot chargers last the length of the analysis period.

## 6.4. FCEB 1: 1:1 Bus Replacement Additional Details

Details on bus costs and fueling station costs are provided below.

Note that in an interview with Orange County Transit Authority (OCTA) in September, 2020 regarding their new hydrogen fueling station, their contract fuel prices are the following (cost includes both fuel and station O&M):

- First three years: $7.97 / kg
- Years 4 and 5: $9.50 / kg

The assumed combined station fixed O&M plus fuel costs show below are reasonably in agreement with these real contract prices. Note that OCTA's contract price accounts for the delivery costs associated with trucking hydrogen from Sacramento to Santa Ana and does not currently include LCFS credits. Delivery to Humboldt would likely also originate from Sacramento and result in a similar one-way haul time.

*Table 26**: Summary of bus capital and O&M costs for transit technology deployment plan **FCEB 1,** organized by transit system.*

| Transit System | Capital Cost ($ 2020) | O&M Costs | | | |
|---|---|---|---|---|---|
| | | *Bus maintenance ($/mi)* | *Midlife battery replacement ($/mi)* | *Fuel ($/mi)* | *LCFS ($/mi)* |
| AMRTS | $1,845,000 | 0.33 | 0.32 | 0.86 | -0.36 |
| BLRTS | $922,500 | | 0.28 | | -0.34 |
| ETS | $3,690,000 | | 0.33 | | -0.36 |
| RTS | $8,302,500 | | 0.35 | | -0.50 |
| SHI | $2,767,500 | | 0.35 | | -0.40 |
| WC | $922,500 | | 0.35 | | -0.36 |

*Table 27: Summary of liquid delivery fueling station capital and O&M costs for transit technology deployment plan **FCEB 1**.*

| | Liquid Delivery | On-site Electrolysis |
|---|---|---|
| Capital Cost ($ 2020) | $14.0M | $17.7M |
| Fuel Cost ($ / kg) | 6.00 | 6.45 |
| Electricity Cost – Demand ($ / kg)[9] | 1.07 | |
| Electricity Cost – Energy ($ / kg)[10] | 0.46 | |
| Other Costs ($ / kg) | 1.55 | 2.62 |

[9] Assumes $13.95 $/kW derived from average of TOU periods for Redwood Coast Energy Authority's E-20 tariff. This is kept static across the analysis period.
[10] Assumes $0.12 per kWh which is kept static across the analysis period.

*Table 28: Assumptions in HDRSAM for modeling the* ***liquid delivery station*** *for transit technology deployment plan* ***FCEB 1****.*

| HDRSAM inputs | |
|---|---|
| Station Type | Liquid H2 Station |
| Fuel Cell HDV Fleet Size | 21 |
| Dispensing Option to Vehicle Tank | 700 bar via vaporization/compression |
| Assumed start up year | 2021 |
| Construction Period (year) | 1 |
| Desired year dollars for cost estimates | 2016 |
| Real after-tax discount rate (%) | 3 |
| Analysis period (years) | 20 |
| Debt Ratio (%) | 0 |
| Debt interest (%) | 6 |
| Debt period | 10 |
| Max dispensed amount per vehicle (kg) | 58 |
| Fueling Rate (kg/min) | 7.2 |
| Vehicle fill time (min) | 8.1 |
| Vehicle lingering time (min) | 2 |
| Number of Dispensers (Hoses) | 3 |
| Max annual utilization of H2 station as a % of its capacity | 100 |
| Onboard storage type | IV |
| Max # of HDV fills hour 1 | 7 |
| Max # of HDV fills hour 2 | 7 |
| Max # of HDV fills hour 3 | 7 |
| Refueling State - Liquid H2 Adjustments / Settings / Calculations | |
| # of backup evaporators | 1 |
| # of backup pumps | 2 |
| Storage Design Capacity | 5000 kg |
| Desired Liquid Cryogenic Tank Capacity (cell B125) - modified to | 4736 kg |
| Labor Cost ($/person-hr) | 0 |
| Electricity cost ($/kWh) | 0.12 |
| Delivered liquid hydrogen cost ($/kg) | 6 |
| Other fixed operating cost: land rent - zeroed this out | 0 |
| Peak hourly capacity | 406 kg/hr |
| Peak daily capacity | 1,218 kg/day |
| Operational weekdays of storage | 4 to 11 days depending on daily demand |

*Table 29: Assumptions in HDRSAM for modeling the **on-site electrolysis station** for transit technology deployment plan **FCEB 1**.*

| **HDRSAM inputs** | |
|---|---|
| Station Type | Gaseous H2 station (20 bar H2 supply) |
| Fuel Cell HDV Fleet Size | 21 |
| Dispensing Option to Vehicle Tank | 700 bar cascade dispensing |
| Assumed start up year | 2021 |
| Construction Period (year) | 1 |
| Desired year dollars for cost estimates | 2016 |
| Real after-tax discount rate (%) | 3% |
| Analysis period (years) | 20 |
| Debt Ratio (%) | 0% |
| Debt interest (%) | 6% |
| Debt period | 10 |
| Max dispensed amount per vehicle (kg) | 58 |
| Fueling Rate (kg/min) | 7.2 |
| Vehicle fill time (min) | 8.1 |
| Vehicle lingering time (min) | 2 |
| Number of Dispensers (Hoses) | 3 |
| Max annual utilization of H2 station as a % of its capacity | 100% |
| Onboard storage type | IV |
| Max # of HDV fills hour 1 | 7 |
| Max # of HDV fills hour 2 | 7 |
| Max # of HDV fills hour 3 | 7 |
| Refueling State - Gaseous H2 Adjustments / Settings / Calculations | |
| # of backup compressors | 3 |
| Cascade vessel length (m) (cell B110) | 9.1 |
| Low pressure storage vessel capacity (kg) | 256 |
| Low pressure storage vessel length (m) (cell B113) | 15.2 |
| Labor Cost ($/person-hr) | 0 |
| Electricity cost ($/kWh) | 0.12 |
| ~~Delivered liquid hydrogen cost ($/kg)~~ | |
| Other fixed operating cost: land rent - zeroed this out | 0 |
| Peak hourly capacity | 406 kg/hr |
| Peak daily capacity | 1,218 kg per day |
| Operational weekdays of storage | N/A |

*Table 30: Additional hydrogen station specifications and assumptions for the* ***FCEB 1*** *scenario*

| Specification | | Value | Notes | Source |
|---|---|---|---|---|
| On-Site Electrolysis | Capital Cost ($) | $2,328,693 | Assumed 1,050 kg per day production | H2A |
| | Installed Cost ($) | $279,443 | | H2A |
| | Fixed Operating Cost ($/yr) | $159,711 | | H2A |
| | Electrolyzer Stack + BOP Efficiency (kWh/kg) | 54.6 | | H2A |
| | Peak Electrolyzer Demand (kW) | 2,388 | | H2A |
| | Peak Fueling Station Demand (kW) | 1,137 | | HDRSAM |
| | Main Compressor Electricity Consumption (kWh/yr) | 2,986,502 | 9 compressors | HDRSAM |
| | Refrigeration electricity consumption (kWh / yr) | 39,325 | 16.1 ton capacity x 3 units, COP=1.6 | Calculated |
| Liquid Delivery | Peak Fueling Station Demand (kW) | 2,420 | | HDRSAM |
| | Main compressor and liquid H2 pump electricity consumption (kWh/yr) | 1,638,228 | | HDRSAM |
| | Refrigeration electricity consumption (kWh / yr) | 76,344 | | HDRSAM |

### 6.5. Mix 1: 1:1 BEB Replacement Ratio Additional Details

Additional BEB and charging infrastructure details for the Mix 2 scenario.

*Table 31: Summary of bus capital and O&M costs for transit technology deployment plan **Mix 1**, organized by transit system.*

| Transit System | Capital Cost [a, b] ($ 2020) | O&M Costs [c] | | | |
|---|---|---|---|---|---|
| | | *Bus maintenance [d] ($/mi)* | *Midlife battery replacement ($/mi)* | *Charging ($/mi)* | *LCFS ($/mi)* |
| AMRTS | $1.58M | $0.64 / $0.48 | $0.09 / $0.07 | $0.49 / $0.37 | -$0.21 / -$0.19 |
| BLRTS | $791,000 | | $0.12 / $0.09 | $0.62 / $0.47 | -$0.28 / -$0.24 |
| ETS | $3.16M | | $0.09 / $0.07 | $0.51 / $0.39 | -$0.21 / -$0.19 |
| KTNET | $791,000 | | $0.10 / $0.07 | $1.18 / $0.89 | -$0.23 / -$0.20 |

a. Estimate includes 2.5% added acquisition cost.
b. Estimate does not include additional cost associated with back-up buses.
c. Left values represent non-amortized O&M costs while right values represent amortized O&M costs assuming a 3% discount rate.
d. Bus maintenance estimate is with consideration to both scheduled and unscheduled maintenance cost. A value of $0.36/mi was assumed for scheduled maintenance (Hanlin, J., Reddaway, D., & Lane, J., 2018), while a value of $0.28/mi was assumed for unscheduled maintenance (Horrox, J., & Casale, M., 2019).

*Table 32: Summary of on-route BEB charging station locations and costs for the **Mix 1** scenario.*

| Location | Station type | Capital & Installation Cost ($ 2020) | O&M Costs ($/kWh) [a.] |
|---|---|---|---|
| Arcata Transit Center | On-route | $599,000 | $0.13 / $ 0.09 |
| Harris & F St. | On-route | | $0.26 / $0.17 |
| Harris & Lowell | On-route | | $0.25 / $0.17 |
| Harris & Summer | On-route | | $0.25 / $0.17 |
| Hoopa Ray's Shopping Center | On-route | | $1.54 / $0.99 |
| HSU Library Circle | On-route | | $0.16 / $0.11 |
| Weitchpec | On-route | | $6.07 / $3.90 |
| Willow Creek | On-route | | $0.22 / $0.15 |
| Humboldt Transit Authority bus yard | Depot + maintenance bay | $506,000 | $0.010 / $0.007 |
| Hoopa Tribal Police Station | Depot | $72,300 | $0.010 / $0.007 |
| Blue Lake Rancheria office building | Depot | $72,300 | $0.007 / $0.005 |

a. O&M cost includes cost of charger maintenance, as well as charger replacement. It is assumed that on-route chargers must be replaced after 15 years, and depot chargers last the length of the analysis period.

### 6.6. Mix 1 Alt: 1:1 BEB Replacement Ratio with Average Efficiency

Note these results are not used, but presented for complete information. This section details the results of using an average BEB efficiency of 0.523 miles / kWh to calculate the infrastructure and cost projections for a mixed technology fleet.

Hydrogen station costs are assumed to be scaled versions of the FCEB 1 scenario.

*Table 33: Summary of fleet and charging infrastructure specifications for transit technology deployment plan **Mix 1 with average BEB efficiency.***

| | | | |
|---|---|---|---|
| Battery Electric Bus (BEB) Technology | *Fleet specifications* | Fuel efficiency (mi / kWh) | 0.523 |
| | | Bus replacement ratio | 1:1 |
| | | Total number of buses | 8 |
| | | Transit systems serviced | AMRTS, BLRTS, ETS, KT-NET |
| | *Charging infrastructure specifications* | Total number of depot chargers | 8 |
| | | Total number of on-route chargers | 8 |
| Fuel Cell Electric Bus (FCEB) Technology | *Fleet specifications* | Fuel efficiency (mi / kg) | 7.54 |
| | | Bus replacement ratio | 1:1 |
| | | Total number of buses | 13 |
| | | Transit systems serviced | RTS, SHI, WC |
| | *Fueling infrastructure specifications* | Fueling station location | Eureka, CA |
| | | Fueling station capacity (kg) | 650 kg |

*Table 34: Non-amortized costs associated with the BEB component of transit technology deployment plan **Mix 1 Alt**. All capital costs are assumed to be incurred in the year 2020, and the length of analysis is 20 years.*

| Mix 1: Mixed Fleet Conversion, BEB Component<br>Average BEB efficiency scenario, 1:1 bus replacement ratio<br>*Fuel efficiency = 0.523 mi/kWh*<br>*No Resiliency Infrastructure* | | |
|---|---|---|
| Cost Component | Description | Value [d] |
| BEB Fleet Capital Costs ($)<br><br>Total capital cost of converting those buses listed in Table 11 as BEBs. | Bus capital and acquisition costs [a] | $6.33M |
| | On-route charger capital and installation cost | $1.80M |
| | Depot and maintenance bay charger capital and install cost | $795,000 |
| | Total capital costs | $8.93M |
| BEB Fleet Fuel and O&M Costs ($/mi)<br><br>Total operation and management (O&M) cost associated with converting those buses listed in Table 11 as BEBs. | Electricity (fuel) [b] | $0.31 |
| | Bus mid-life battery replacement (varies by bus) | $0.09 |
| | Bus scheduled maintenance<br>(low / high literature range) | $0.27 [e] / $0.36 [f] |
| | Bus unscheduled maintenance | $0.28 [f] |
| | Total Bus O&M<br>Left value: Low bus maintenance<br>Right value: High bus maintenance | $0.95 / $1.04 |
| | On-route charger maintenance | $0.02 |
| | Depot and maintenance bay charger maintenance | $0.01 |
| | Charger replacement (assuming on-route charger replacement in 15 years) | $0.12 |
| | Low Carbon Fuel Standard (LCFS) [c] | - $0.22 |
| | Total Fueling Infrastructure O&M<br>Left value: Excludes charger replacement, includes LCFS<br>Right Value: Includes charger replacement, excludes LCFS | -$0.19 / $0.15 |
| | Total Bus and Fueling Infrastructure O&M | $0.76 / $1.19 |

a. Estimate does not include additional cost associated with back-up buses.
b. Includes energy and demand charges.
c. Expected LCFS revenue assuming $150/MT credit value. Note LCFS credit value is driven by an open trading market and changes regularly. In addition, LCFS is designed to phase out overtime such that it cannot be considered a long-term reliable income source.
d. Unless otherwise noted, all values originate from analysis using the FTCC model and inputs from the BEBOP model.
e. Total scheduled plus unscheduled maintenance cost of $0.55 per mile from Horrox, J., & Casale, M. (2019). Electric Buses in America: Lessons from Cities Pioneering Clean Transportation. Unscheduled cost per mile of $0.28 subtracted from $0.55 to get estimated scheduled maintenance of $0.27 per mile.
f. Hanlin, J., Reddaway, D., & Lane, J. (2018). Battery electric buses—state of the practice (No. Project J-7, Topic SA-41).

*Table 35: Summary of bus capital and O&M costs for transit technology deployment plan **Mix 1 Alt**, organized by transit system.*

| Transit System | Capital Cost [a, b] ($ 2020) | O&M Costs [c] | | | |
|---|---|---|---|---|---|
| | | *Bus maintenance* [d] *($/mi)* | *Midlife battery replacement ($/mi)* | *Charging ($/mi)* | *LCFS ($/mi)* |
| AMRTS | $1.58M | $0.64 / $0.48 | $0.09 / $0.07 | $0.28 / $0.22 | -$0.21 / -$0.19 |
| BLRTS | $1.56M | | $0.12 / $0.09 | $0.37 / $0.28 | -$0.28 / -$0.24 |
| ETS | $3.16M | | $0.09 / $0.07 | $0.26 / $0.20 | -$0.21 / -$0.19 |
| KTNET | $791,000 | | $0.10 / $0.07 | $0.50 / $0.38 | -$0.23 / -$0.20 |

a. Estimate includes 2.5% added acquisition cost.

b. Estimate does not include additional cost associated with back-up buses.

c. Left values represent non-amortized O&M costs while right values represent amortized O&M costs assuming a 3% discount rate.

d. Bus maintenance estimate is with consideration to both scheduled and unscheduled maintenance cost. A value of $0.36/mi was assumed for scheduled maintenance (Hanlin, J., Reddaway, D., & Lane, J., 2018), while a value of $0.28/mi was assumed for unscheduled maintenance (Horrox, J., & Casale, M., 2019).

*Table 36: Summary of on-route BEB charging station locations and costs for the **Mix 1 Alt** scenario.*

| Location | Station type | Capital & Installation Cost ($ 2020) | O&M Costs ($/kWh) [a.] |
|---|---|---|---|
| Arcata Transit Center | On-route | $599,000 | $0.13 / $ 0.09 |
| Harris & F St. | On-route | | $0.25 / $0.17 |
| Willow Creek | On-route | | $0.35 / $0.23 |
| Humboldt Transit Authority bus yard | Depot + maintenance bay | $506,000 | $0.015 / $0.012 |
| Hoopa Tribal Police Station | Depot | $72,300 | $0.009 / $0.007 |
| Blue Lake Rancheria office building | Depot | $72,300 | $0.010 / $0.008 |

a. O&M cost includes cost of charger maintenance, as well as charger replacement. It is assumed that on-route chargers must be replaced after 15 years, and depot chargers last the length of the analysis period.

## 6.7. Mix 2: 1.5:1 BEB Replacement Ratio Additional Details

Additional BEB and charging infrastructure details for the Mix 2 scenario.

*Table 37: Summary of bus capital and O&M costs for transit technology deployment plan **Mix 2**, organized by transit system.*

| Transit System | Capital Cost [a, b] ($ 2020) | O&M Costs [c] | | | |
|---|---|---|---|---|---|
| | | *Bus maintenance [d] ($/mi)* | *Midlife battery replacement ($/mi)* | *Charging ($/mi)* | *LCFS ($/mi)* |
| AMRTS | $2.35M | $0.64 / $0.48 | $0.09 / $0.07 | $0.28 / $0.21 | -$0.21 / -$0.19 |
| BLRTS | $1.56M | | $0.13 / $0.09 | $0.37 / $0.28 | -$0.29 / -$0.25 |
| ETS | $3.94M | | $0.08 / $0.06 | $0.25 / $0.19 | -$0.20 / -$0.18 |
| KTNET | $1.56M | | $0.13 / $0.09 | $0.64 / $0.48 | -$0.29 / -$0.26 |

a. Estimate includes 2.5% added acquisition cost.
b. Estimate does not include additional cost associated with back-up buses.
c. Left values represent non-amortized O&M costs while right values represent amortized O&M costs assuming a 3% discount rate.
d. Bus maintenance estimate is with consideration to both scheduled and unscheduled maintenance cost. A value of $0.36/mi was assumed for scheduled maintenance (Hanlin, J., Reddaway, D., & Lane, J., 2018), while a value of $0.28/mi was assumed for unscheduled maintenance (Horrox, J., & Casale, M., 2019).

*Table 38: Summary of on-route BEB charging station locations and costs for the **Mix 2** scenario.*

| Location | Station type | Capital & Installation Cost ($ 2020) | O&M Costs ($/kWh) [a.] |
|---|---|---|---|
| Arcata Transit Center | On-route | $599,000 | $0.13 / $ 0.09 |
| Harris & F St. | On-route | | $0.25 / $0.17 |
| Willow Creek | On-route | | $0.35 / $0.23 |
| Humboldt Transit Authority bus yard | Depot + maintenance bay | $650,300 | $0.015 / $0.012 |
| Hoopa Tribal Police Station | Depot | $144,500 | $0.017 / $0.013 |
| Blue Lake Rancheria office building | Depot | $144,500 | $0.021 / $0.016 |

a. O&M cost includes cost of charger maintenance, as well as charger replacement. It is assumed that on-route chargers must be replaced after 15 years, and depot chargers last the length of the analysis period.