Natural Resources Canada – Electric Vehicle Infrastructure Demonstration Project

Demonstration of Repurposing of Already Used, Large Format Heavy-Duty Transit Bus Batteries for Electric Vehicle Rapid Charging

Natural Resources Canada Project

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Summary

As part of the Electric Vehicle Infrastructure Demonstrations (EVID) program under National Resources Canada (NRCan), Red River College Polytechnic (RRCP) initially proposed in 2018 and ultimately was awarded funding for a novel demonstration involving the repurposing of already-used large-format batteries from heavy-duty electric transit buses. The project was also supported by assistive funding from the Centre for Emerging Renewable Energy Inc.

The project has been officially entitled "Demonstration of Repurposing of Already-Used, Large-Format Heavy-Duty Transit Bus Batteries for Electric Vehicle Rapid Charging" [1], but is more commonly termed the B2U project, standing for "Battery 2nd Use." In this case, the repurposed set of batteries was incorporated into a successfully operating direct current fast charge (DCFC) station for light-duty electric vehicles, involving a nominal charging level of 25kW and a battery capacity of 50kWh. The station represents a first of its kind in Canada based on repurposed transit bus batteries.

This report summarizes the results of the demonstration, including evaluations of technical, economic, and environmental aspects. Overall, the demonstration has been highly successful, practically in showing the ongoing operability of a functional charging station based on repurposed batteries and conceptually in showing the project approach to be feasible, indeed highly beneficial. As discussed in more detail, multiple benefits include lower comparable charging station costs, reduced peak demand fees, reduced battery wastes, and reduced greenhouse gas (GHG) emissions directly via charging to displace gasoline consumption and avoid embedded emissions associated with batteries.

The project has also fostered important innovation benefits for RRCP as a springboard for involvement in additional advanced technology projects. This notably includes the well-publicized Electric Vehicle (EV) Tundra Buggy project with Frontiers North Adventures [2].

While Manitoba's hydroelectricity-dominated grid is already clean and advantageous for electric vehicle charging, an initially unexpected opportunity with the repurposed-battery charging station involves integrating the energy storage system (ESS) as provided by the batteries, with more-intermittent renewable sources, such as solar or wind for use in electric vehicle charging.

Table of Contents

1.0 Background

Electrification of transportation is identified as critical for reducing GHG emissions across the globe, including within Canada [3]. That said, the rising popularity and rapidly increasing numbers of electric vehicles threaten to pose a new and severe environmental challenge, namely, how to appropriately dispose of batteries after the useful lives of the vehicles [4]? Recycling battery component materials is often viewed as the solution in this case; however, such can impose additional technical and environmental challenges [5,6], leading to a desire to seek out better opportunities, as considered in this project.

In the well-known waste hierarchy of "reduce, reuse, recycle" (and only then dispose of), the concept of repurposing batteries is a preferable choice, one that can also be economically advantageous [7], in particular when used for electrical ESS. Of more than 20 international vehicle-battery second-life ESS projects underway worldwide, as identified in the last article by 2020, all have involved light-duty electric vehicle batteries, none with batteries from heavy-duty electric vehicles. At the same time, using battery systems as economically advantageous to support rapid charging of electric vehicles has also begun to be firmly recognized, including by organizations like McKinsey [8]. These two concurrent emerging trends of (a) reusing batteries and (b) applying batteries for electric vehicle rapid charging systems together provide the genesis for this project.

The final major factors propelling the project forward are research and demonstration projects within Winnipeg directly involving RRCP, both on bus electrification and rapid charging. RRCP has played a significant role in bus electrification for over a decade [9]. In particular, this includes the major consortium pilot project from 2014 through 2018, involving four second-generation electric buses from New Flyer operated in-service by Winnipeg Transit [10]. This activity led to the prospect of heavily-used batteries from transit buses potentially becoming available locally. Around the same time, RRCP also began discussions and interactions with the advanced technology firm e-Camion, which began building battery-based rapid charging systems following the TransCanada highway west from Ontario through into Manitoba [11]. RRCP indeed hosts one of e-Camion's stations.

All these factors together meant RRCP was well-positioned to take on the novel demonstration project involving repurposed heavy-duty transit bus batteries.

2.0 Needs and Opportunities

The global trend toward clean energy sources for transportation to reduce GHG emissions is increasing demand for electric vehicles while generating significant masses of used lithium-ion batteries. Analysts from the International Council on Clean Transportation (ICCT) recently projected that roughly 1.2 million batteries from electric vehicles will reach their end-of-life by 2030 globally (both from light- and heavy-duty vehicles), rising to roughly 14 million by 2040 and roughly 50 million by 2050 [12]. These quantities are staggering, with repurposing ESS a strongly recommended priority. ICCT further projects that if 50% of used batteries could be repurposed for ESS, new demand for mining key lithium, cobalt, nickel, and manganese minerals could be reduced by as much as 28% in 2050, both economically and environmentally.

Interest in battery reuse is sufficiently high that the National Renewable Energy Laboratory (NREL) in the U.S. has undertaken extensive studies on the applicability, suitability, and costs of repurposing [13]. They identify that batteries are anticipated to retain roughly 70% of their initial capacity even after a long vehicle service life. If handled properly, they can be realistically operated in applications such as ESS for at least ten years. NREL has even developed a spreadsheet tool to help evaluate feasibility.

So far, The overwhelming emphasis on battery repurposing and recycling has been on light-duty electric vehicles. This makes sense and is unsurprising given that medium- and heavy-duty applications have lagged significantly on electrification, with significant market presence not anticipated until well into the 2030s, according to NREL [14]. On the other hand, commercial models of light-duty electric vehicles have been available in Canada since 2012, and their domestic and international aggregate numbers are dramatically higher than any heavy-duty applications.

However, there is one notable exception, namely heavy-duty electric transit buses, which have been rapidly developing and expanding, as acknowledged, for example, by McKinsey [15]. As such, finding appropriate end-of-life solutions for batteries from electric transit buses is becoming recognized as important [16]. As a niche market, however, there is much less general information or guidance available on reusing electric transit bus batteries, hence the utility of this project. For example, the feasibility tool from NREL noted earlier is not well oriented to the scale and nature of batteries from electric transit buses and, as such, is much less relevant.

The need to find tailored solutions and understand the nature of higher-capacity, large-format batteries associated with transit buses link directly to the research strengths of RRCP. Initially identified advantages of used batteries from electric transit buses, compared to light-duty vehicles, for application in ESS to support rapid charging of light-duty electric vehicles include:

- Much larger pack sizes with transit buses, such that batteries from a single transit bus are sufficient certainly for one and potentially multiple charging station installations;
- Uniform types of batteries employed within a single transit bus, not involving a possible mix of types;
- Simplified acquisition of sufficient and consistent batteries without the need for any significant amalgamation from a diverse variety of vehicles, including different formats and sizes; and
- Relatively consistent operational exposure of batteries within a single transit bus, compared to potentially divergent and variable exposure of batteries from light-duty vehicles.

3.0 Technical Plan Overview

The planned technical aspects of the project are summarized in the following sections, with actual activities and developments, as they occurred, relatively consistent with the initial plan.

3.1 Technical Objective

The ultimate technical objective of the project was to develop and implement a DCFC station at RRCP suitable for charging light-duty electric vehicles using repurposed lithium-ion batteries, previously used in transit bus applications, as the ESS. Due to the COVID delay, the revised timeframe was by the end of April 2022, with the station ultimately incorporating a 25-kW DCFC with approximately 50-kWh of repurposed batteries.

3.2 Technical Deliverables

The key technical deliverables ended up including:

- 25-kW direct current fast charger (DCFC);
- 50-kWh used-battery energy storage system (ESS);
- Battery rack system; and
- Battery enclosure system (NEMA 3 R rated).

3.3 Technical Deliverables

Early in the project, technical requirements for the overall charging station components were identified and articulated, as outlined in the following table, including necessary deliverables and acceptance criteria. As the project progressed, all identified requirements were either achieved or addressed suitably in an alternative manner (the latter described later).

Requirements	Deliverables	Acceptance Criteria
25-kW CCS and CHAdeMO DCFC charging system (covering two main charge-connection protocols available for light-duty electric vehicles	Identifying the list of equipment vendors Selecting vendors based on cost and quality requirements Procuring equipment	Meeting requirements Vendors meeting cost and quality requirements Confirming equipment is in good condition
50-kWh energy storage system (ESS) based on used lithium-ion batteries	Securing used battery pack from industry partner	Confirming packs in good conditions

	Testing and validating used batteries Designing and building a 50-kWh ESS from used batteries	Confirming 100% pass Passed safety and electrical codes
Battery enclosure meeting type National Electrical Manufacturers Association (NEMA) 3R or IP44/Rack	Designing battery pack enclosure and rack system	Certifying enclosure as NEMA 3R
The overall system meets Canadian Safety Standards; and Electrical Code	High-voltage battery system training Canadian Standards Association (CSA) and Electrical Code approval	Completing training Passing Safety and Electrical Code

Table 1 *Product Descriptions*

3.4 Timeline

The initial project award by NRCan occurred in 2019, and at that time, the station was anticipated to be completed by Summer 2020, with operational testing subsequently [17]. The COVID pandemic, however, interceded and pushed back the project's progress by roughly 12 months. As such, the project ended up occurring over four fiscal years, summarized as follows:

Fiscal 2019-2020: Initial start-up and planning but increasing difficulties due to the onset of COVID

Fiscal 2020-2021: Effectively lost time due to COVID with little progress on the project

Fiscal 2021-2022: Large majority of work undertake toward completing and assembling the station

Fiscal 2022-2023: Operational testing of the completed station

As outlined in Figure 1, a revised roll-out was developed post-COVID, with anticipated completion of the station by June 2022. The system ended up becoming operational in December 2021.

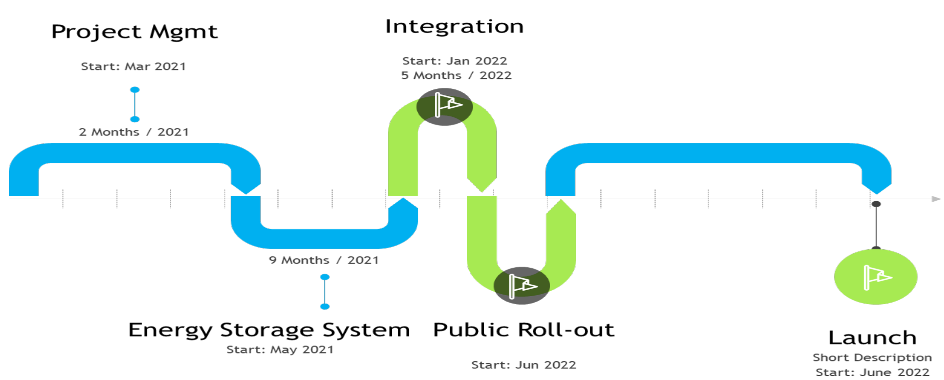

Figure 1 Project Timelines

In terms of aligning operations to the project timeframe, the B2U station was operated for a total of 15 months, as described later, four months during Fiscal 2021-2022 (i.e., December 2021 through March 2022), and 11 months during Fiscal 2022-2023 (i.e., April 2022 through February 2023).

3.5 Project Resource Allocation

The following project resource plan was initially developed, outlining technical skill requirements. The actual roll-out of the project followed this plan reasonably closely.

Project Phase	Task	Resource	Time Needed
Project Management	• Preparatory Project Activities • Project Plan • Charter	Project Manager	50 days
Energy Storage System	• Defined Technical Requirements, Thermal Management Systems • Power/ Electrical Systems • Controller Area Network (CAN Bus) Communication Systems • Battery Rack Design • ESS container • DCFC	Research Coordinator Technologist 1 Technologist 2 Technologist 3 Technical Consultant Research Professional	266 days
Project Integration	• Battery rack assembly • Cooling system integration • Used-battery system integration and testing	Research Coordinator Technologist 1 Technologist 2 Technologist 3 Technical Consultant Research Professional	197 days
Project Closure	• Public roll-out • Final Report • After Action Review	Project Manager Research Coordinator	19 days

Table 2 *High-level Project Resource Plan*

3.6 Identified Risks and Mitigation

Major potential risks and mitigation plans were identified to keep the project on track. Mitigation measures, as outlined, were employed. As noted, the major delay for the project was associated with the COVID pandemic, something generally applicable to all activities across Canada and could not be foreseen.

Risk Items	Mitigation Plans
Safety issue on Lithium-ion batteries	All project members, including the Safety team, attended the Society of Automotive Engineers (SAE) High Voltage Safety Training. Documented battery charging, discharging, and handling process through Safe Work Procedure The safety team is involved in the safety documentation and hazard analysis. Controls, including hazard signs, Material Safety Data Sheets (MSDS), barricades, etc., are maintained in place in the used battery area. Personal protective equipment used as required in work areas
Availability of used batteries	Close collaboration with New Flyer Industries to secure used lithium-ion batteries
Schedule delays	The project manager closely monitors the project's progress. Improve issue resolution and support implemented.
Regulatory issues	Engineering Services support secured on the project certification Specialized industry consultant employed on engineering design and specifications, in particular for the charger component

Table 3 *Risk Items and Mitigation Plans*

4.0 Project Resource Allocation

The actual progress of the research project as it developed and the ultimate results are outlined in the following sections.

4.1 Used-Batteries Quality Validation and Testing

The VTEC team partnered with New Flyer, a subsidiary of NFI Group Inc. (NFI), to acquire suitably used batteries for the project. NFI, based in Winnipeg, is North America’s leading heavy-duty transit and coach bus manufacturer, supplying various transit agencies and transport-provision companies throughout the continent, including across Canada.

Initially, it had been anticipated that batteries could be provided from one of the buses involved with the in-service pilot in Winnipeg, with which RRCP already had familiarity and significant exposure. The pilot involved Winnipeg Transit operating four second-generation electric transit buses from 2014 through 2018. Because of technical and logistical challenges, this ended up not being possible.

Instead, New Flyer donated battery modules from one of a pair of retired Chicago Transit Authority (CTA) transit buses. The latter buses also began operation around 2014 and were operated for a similar period. The batteries involved were all manufactured by XALT Energy, previously known as Dow Kokam. All involved nickel, manganese, and cobalt (NMC) battery chemistry and were very similar to batteries used for two of the four transit buses as part of the Winnipeg pilot.

Unlike the electric buses used by Winnipeg Transit, the pair operated by CTA were more "battery-dominated." The pack sizes were larger, intended effectively for all-day operation, with charging overnight at the bus depot. These buses did not incorporate any on-route rapid charging capabilities and thus differed in being only charged at somewhat slower kW ratings.

The team carefully inspected the batteries for damage or deterioration, including physical defects, burn marks, low voltage, or low State of Charge (SOC) characteristics. The initial voltage of each battery was measured to estimate SOC. Some of the batteries did not meet quality standards and were omitted. Only batteries in good condition and sufficiently high SOC were considered for further testing.

Selected battery modules were subjected to a series of charge and discharge cycles using a high-voltage DC charger and an electronic load. This procedure aimed to estimate the capacity and State of Health (SOH) of the batteries and to identify any faulty units further. The results showed that the selected batteries had an average SOH of 100% and retained 80% of their original capacity. As such, these selected batteries were considered suitable for the project.

4.2 Project Challenges and Scope Changes

As noted already, the project aimed to install a DCFC for light-duty electric vehicle charging, supported by an ESS using repurposed batteries. At least initially, it had been intended to consider a 50-kW charger along with a NEMA 3R-certified shipping container to store the batteries outside any building. This latter design was consistent with e-Camion's, albeit with their new lithium-ion battery system.

The COVID pandemic presented a major obstacle for the project, closing the College to in-person activities and preventing the VTEC team from accessing facilities or obtaining project support. More importantly, the project delay of 12 months due to COVID saw an increase in the costs of desired equipment components by roughly a factor of two.

To overcome these challenges, the team explored cost reduction strategies, particularly evaluating alternative equipment that could be more affordable but still meet the project's intent. Two key alterations were undertaken based on these constraints:

- First involved using a 25-kW DCFC rather than 50-kW; and
- Second involved abandoning the use of a shipping container for the battery modules, with instead batteries located inside a building,

While using a 25-kW charger halved the power level and the associated charging speed, the costs to purchase the charging system components were dramatically lower. Importantly, as outlined in NRCan's Zero Emission Vehicle Infrastructure Program (ZEVIP), a 25-kW charger level is included as eligible as a designated fast-charging system [18]. Further, a 1-hour charge at the station would provide over 100 km of travel for a typical electric vehicle, based on energy consumption of about 20 kWh per 100 km, providing a practically valuable service.

Regarding the use of a container, as outlined by Manitoba Hydro [19], under the Electrical Code, a shipping container, if it is modified or converted, is formally classified as a "building," As such, in this case, the shipping container would have to satisfy all Building Code fully, and Electrical Code requirements, adding significant complexity and cost. The team opted to install the battery modules inside a building instead to avoid these costs.

4.3 Final System Integration

The project scope, as noted, was revised to involve a 25-kW DCFC and indoor storage of battery modules instead of a container. Several deliverables were completed first by RRCP, involving the battery-based 50-kWh ESS: thermal management; power/electrical readiness; CAN communication, power, and cooling system; and rack design. These aspects were undertaken to ensure the quality and safety of the project. The design for the battery rack is provided in Figure 2.

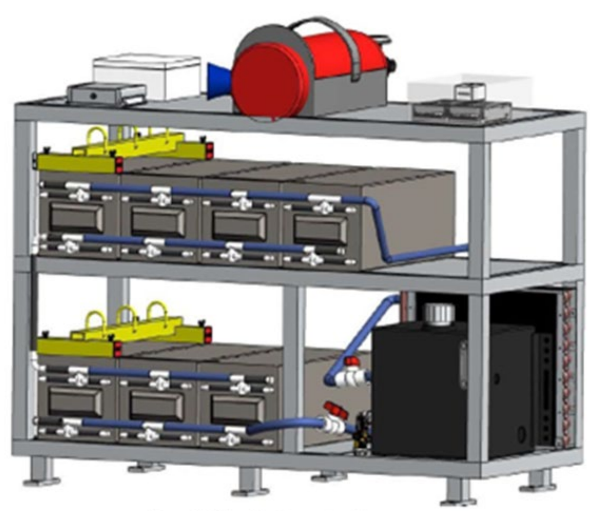

Figure 2 Battery rack design using 3D modeling

Based on the new scope, the project team consulted Rick Szymczyk of Upstartz Energy Ltd for expert guidance. A final integration design was provided by Upstartz Energy, involving entirely off-the-shelf units beyond the battery-based ESS. This approach reduced capital costs and shortened implementation to a manageable timeframe.

The main added components, beyond the 50-kWh battery-based ESS, included:

- 30-kW power conversion system (DC to AC, 3-phase);
- 30-kVA dry-type transformer (700 VAC to 480 VAC);
- 25-kW DC charging unit and system (480 VAC, 3-phase input), providing either CCS or CHAdeMO protocol connection point to the vehicle; and
- System controller, ground fault monitoring unit, circuit protection, and associated components.

The final completed system, as assembled, is illustrated in a linear schematic manner in Figure 3.

As part of the design, one important compromise was converting DC power from the battery to AC to adjust to the correct AC voltage and then back to DC in the charging unit. This was done deliberately to fit existing components easily together and simplify achieving a practically operational unit. While this meant the need for an added converter and transformer, it still involved a substantially lower cost overall. As noted later, eliminating this extra DC-to-AC-to-DC step is an obvious simplification for further design updates that could reduce costs.

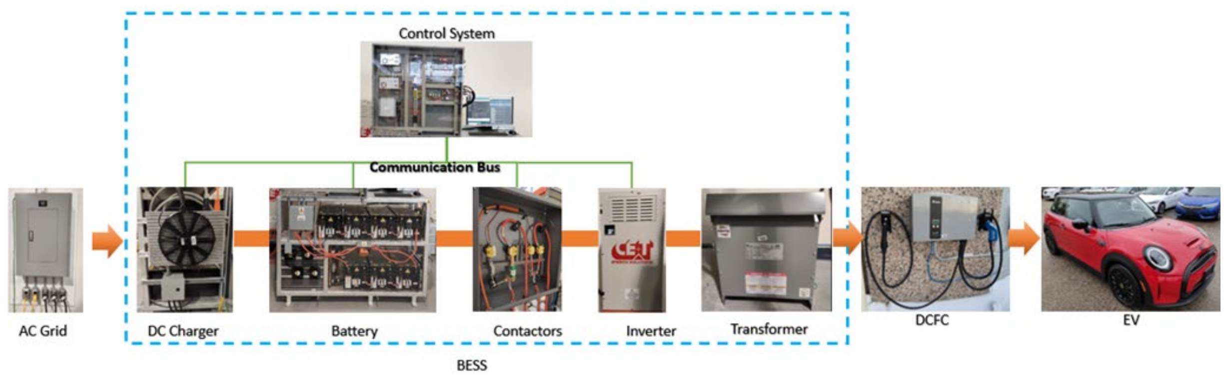

Figure 3 System integration of the B2U project

4.4 Final Confirmation and Start-up

The system was implemented at the selected site based on the completed design. The system equipment and the installation all passed the Electric Code review and were confirmed suitable for other requirements. Final testing of the completed system was undertaken in December 2021, confirming the overall B2U DCFC charging station, including ESS, to be fully operable. As such, practical use and demonstration of the completed station for vehicle charging began in December 2021 continuing from then on.

4.5 Site Location, Access, and Internet Information

The selected site for the B2U DCFC station is the south side of the Centre for Applied Research in Sustainable Infrastructure (CARSI) building at RRCP's main Notre Dame campus in Winnipeg, with the location illustrated on a map presented in Figure 4. This building is just east of the College's main entrance and adjacent to the newest Skilled Trades and Technology Centre (STTC) building. Photographs illustrating the battery pack (inside), and the charge point (outside), are presented in Figure 5 and Figure 6, respectively.

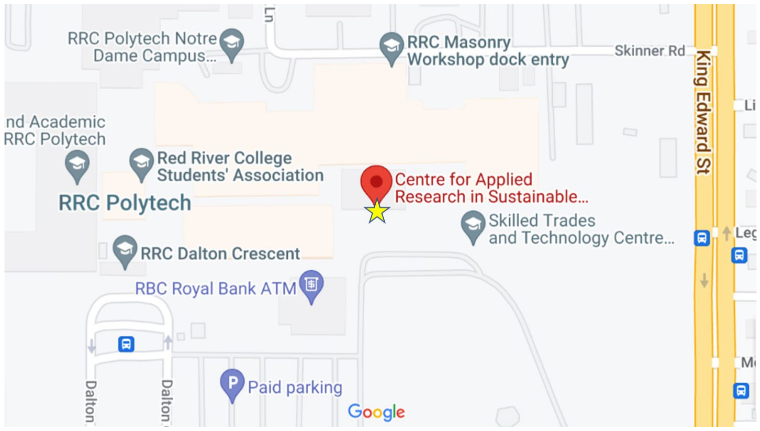

Figure 4 Location of the B2U DC charger

The B2U DCFC station is accessible from Notre Dame Avenue, as illustrated in Figure 4's map. The station has been made available for free use by interested parties, but they must first contact the project manager to gain access privileges. This situation is given its research and testing orientation. The station, for example, is not available to use outside regular business hours or on weekends. Given that the station has not been entirely made publicly available, it does not show up on common electric-vehicle charging infrastructure databases and maps, including NRCan [20], PlugShare [21], ChargeHub [22], or Energyhub [23].

Figure 5 – Battery rack inside

Figure 6 – Charge point outside

To enhance visibility, RRCP also created a dedicated website regarding the station [24]. This website indicates the station's availability in real-time and the current state of charge (SOC) for the ESS batteries.

5.0 B2U Station Results and Data Analysis

Operational results from the B2U station and data analysis are presented in the following sections.

5.1 Data Management Using SteVe Tool

The B2U station began full operation in December 2021. From then forward, operational data have been collected using "SteVe," short for Steckdosenverwaltung [25]. SteVE is a simple and available server application tool for managing electric vehicle charging stations, developed by RWTH Aachen University, located in North Rhine-Westphalia, Germany. This university has been extensively involved in electric vehicle energy utilization and charging system research. As discussed later, data were collected over 15 months from December 2021 through February 2023.

The SteVe tool uses the Open Charge Point Protocol (OCPP) to communicate with the charging station and record various parameters. It also generates reports on monthly usage statistics. The most important parameters provided monthly involve the following:

- The number of charging transactions and their durations; and
- Total and cumulative energy consumption, whether in Watt-hours (Wh) or kilowatt-hours (kWh).

The SteVe tool can also provide some additional inferred data on a monthly basis, including:

- Vehicular CO2e emissions in tonnes generated based on charging as provided by the station;
- Potential vehicle travel distance in km provided by recharging as received; and
- Electricity costs incurred by the vehicle.

Some practical aspects of inferred data are discussed later but are not emissions-related. While providing some notional indication to users, the latter is inaccurate for Manitoba's situation. For illustration, SteVe data suggests total electricity-derived emissions of 503 kg of CO2e based on 1,162 kWh provided. This translates to an implied grid intensity of 430 g per kWh, which is too high for Manitoba's clean electricity grid. Instead, the 430 g per kWh value reflects the rough average German grid intensity from 2017 through 2022. This makes sense because the tool was developed in Germany but limited its practical use elsewhere. As such, this feature is not considered further.

5.2 Station Utilization Data

Summary data from SteVe for the 15 months from December 2021 through February 2023 are provided in Table XX. Over this entire period, a total of 100 recorded charging sessions were undertaken. This translates to a mean of approximately **6.7 charging sessions per month**. Assuming a typical 25-kW grid-connected DCFC station could potentially provide upwards of 360 charging sessions at 1 hour each per month, this suggests the B2U station has been operating at approximately 2% of capacity.

Statistics on charging session periods covering the overall timeframe involve:

- Mean charging session time of **46.9 minutes** (or 0.78 hours);
- Minimum charging session time of **24.3 minutes** (or 0.40 hours); and
- Maximum charging session time of **64.2 minutes** (or 1.07 hours).

Very recent aggregate data from NREL for the U.S. [26] provide relevant benchmarking for the B2U station, covering 30 months of data from October 2019 through March 2022. Their data show:

- Total of 629 DCFC stations in the U.S., involving 1,921 independently operable charging ports, with most DCFC stations rated at 50-kW or less; and

- 567,848 charging sessions were undertaken using 1,921 independent charging ports over 30 months from DCFC stations, translating to a mean value of **9.7 monthly charging sessions** for each independent port.

This indicated utilization, again compared to a typical 25-kW grid-connected DCFC station providing upwards of 360 charging sessions per 1-hour each over one month, suggests the average U.S. DCFC station has been operating at approximately 3% of capacity.

Three important results arise comparing B2U utilization data to aggregate U.S. benchmarks:

- The **25 kW B2U station is mainly consistent** with the size of DCFC stations currently operating within the U.S. market;

- The **B2U station is somewhat below mean utilization** (i.e., 70% of mean) for the U.S., but not significantly low, important given unit involves a testing site and has not been fully available; and

- Capacity utilization of only 2% for the B2U station may appear low but is **comparable to typical U.S. DCFC capacity utilization**, which is only about 3% based on data.

5.3 Station Energy Delivery Data

Over the monitored period, approximately 1,162 kWh was delivered to vehicles based on 100 recorded charging sessions. This translates to a mean energy delivery of **11.6 kWh per charging session**.

NREL [26] shows 10,872,000 kWh delivered during 567,848 charging sessions, translating to a mean energy delivery of **19.4 kWh per charging session.**

Two further essential results arise comparing B2U energy delivery data to aggregate U.S. benchmarks:

- The **B2U station is somewhat below energy delivery** (i.e., 60% of mean), but again not significantly low, important given unit involves a testing site and has not been fully available; and
- B2U practical delivery of 23 kWh within one hour means the **B2U station can fully manage mean DCFC charging requirements** currently within the U.S.

In terms of aligning to the project timeframe, charging sessions and energy delivery by fiscal year are summarized as follows:

- During Fiscal 2021-2022, a total of 25 charging sessions were undertaken, delivering a total of 163 kWh of electricity; and
- During Fiscal 2022-2023, a total of 75 charging sessions were undertaken, delivering a total of 999 kWh of electricity.

These data show that the average electricity delivery increased significantly over the two fiscal years, with a mean of only **2.5 kWh per charging session** in Fiscal 2021-2022, increasing to **13.3 kWh per charging session** in Fiscal 2022-2023. These results reflect increasing experience and confidence in the system.

5.4 Inferred Vehicle Travel Datae

Inferred data on travel distances are provided from the SteVe system, specifically for the Mini Cooper SE, with energy delivery of 1,162 kWh over 15 months, translating to an estimated 5,809 km of equivalent travel. This value is reasonably significant. Dividing these values translates to an assumed energy consumption of 20 kWh per 100 km. Importantly, as part of its 2023 vehicle fuel consumption tabulations, NRCan notes the Mini Cooper SE as having a combined highway/city energy consumption level of 19.1 kWh per 100 km, which is close [27].

While several other electric vehicles employed the station to some degree, the most significant single vehicle involved was a Mini Cooper SE.

5.5 Technology Readiness Level Advancement

An important aspect of this applied research project was to advance the technology readiness level (TRC), specifically regarding using repurposed batteries for light-duty electric vehicle rapid charging, and move this approach to become more commercially marketable. Well-defined readiness levels from TRL1 through TRL9 have been established, as publicly outlined by Innovation, Science, and Economic Development Canada [28].

As part of the proposal, the state of the technology before the project was estimated in the range of TRL5 to TRL6, given that system components were all readily operational and were integrated but not yet operated together at scale or under real-world conditions.

At completion, the state of the technology can be designated at approximately **TRL8**, given that the technology was proven to work in what is effectively a final form and under expected conditions, including developmental testing and evaluation in terms of meeting operational requirements. The system was not entirely taken to TR9, given that while any user was allowed to access the site upon registration, the station was not operated in a fully-open and accessible manner as would be expected in a fully real-world operation environment.

6.0 Cost Benefit Analysis

To support the project from a business perspective, a team of MBA students from the Asper School of Business undertook a cost-benefit analysis (CBA) of the repurposed battery DCFC station, with their report issued through the auspices of the University of Manitoba Transport Institute (UMTI) [29]. Given both size and extensive associated details, a copy of this report is available on the VTEC website for the project noted earlier [24]. The analysis intended to assess the project's economic and environmental aspects, with key results summarized briefly in the following sections.

6.1 Project Novelty

Key novel aspects of the B2U station and the project include:

- Ability to provide about 23 kWh of energy per hour of charging to electric vehicles, translating to additional travel per charge in the 110 to 130 km range. This provides a convenient option for urban drivers who may need quick energy boosts, especially in more urgent or emergency situations.
- Much lower rate of recharging to top-up batteries (i.e., 11-kW) than that imposed by conventional grid-connected DCFC systems (i.e., 25-kW or higher), significantly easing pressure on the grid, as identified by McKinsey too [8] and reducing demand fees.
- Most appropriate for sites where overall daily recharging demand may be less aggressive, i.e., no more than three sequential 1-hour charge events over a daily 12-hour period. This translates to approximately a 25% equivalent monthly station capacity utilization level. The station, as designed, maybe less well suited to inter-city highway travel needs, where higher-power systems are preferred, and charging frequency at individual DCFC stations may become more frequent.

- Reduced environmental impacts with batteries, including reduced embedded GHG emissions in manufacture and reprocessing and reduced lithium losses in battery reprocessing.
- Showcase the feasibility of using second-life batteries for valuable purposes, further stimulating innovation and research in this area.

6.2 Economic Benefits

Key incremental economic benefits of the B2U station and the project include:

- Much lower DCFC station monthly costs for the B2U station, including capital coverage, demand fees, and energy fees, compared to grid-connected DCFC systems, based on assuming 5% equivalent station capacity utilization on a monthly basis. For assumed conditions, grid-connected stations are 20% more expensive for 25 kW, 400% more expensive for 60 kW, and 800% more expensive for 120 kW. Results show how pricy high-powered DCFC stations are (i.e., excessive overkill?).
- Even better comparative economic results for the B2U station (i.e., lower relative monthly costs) occur when equivalent monthly station capacity utilization is lower, for example, in the 2% to 3% range as experienced for the B2U station and more generally for DCFC stations in the U.S.
- Regarding different jurisdictions, the B2U station is most economically attractive in provinces where demand fees for electricity are relatively higher. Indeed, if demand fees are low, the B2U station can sometimes have higher monthly costs than the grid-connected. Two provinces show particular promise because of relatively higher demand fees, Manitoba and Nova Scotia. While Manitoba Hydro shows very low fees for energy, one of the lowest across the country among utilities, demand fees are relatively higher, making Manitoba an ideal location for the B2U and other battery-based charging systems. Demand fees are essential, particularly for controlling electricity peak use.

6.3 Environmental Benefits

Key incremental environmental benefits of the B2U station and the project include:

- GHG savings are associated with not producing a new battery of similar capacity. In this case, for a 50-kWh battery pack, avoided GHG emissions are approximately 3.5 tonnes.
- GHG and lithium metal savings by avoiding currently-popular pyrometallurgical processing, which is aimed as a priority at cobalt recovery exclusively. Avoided GHG emissions correspond to approximately 0.75 tonnes for a 50-kWh battery pack. These are roughly one-quarter of the manufacturing emissions and are additional. Further, approximately 8 kg of lithium is saved, which would otherwise be lost in a typical pyrometallurgical process.

Assuming a social cost of carbon (SCC) of approximately $50 per tonne CO2e [30], and a lithium value of about $50 per kg [28], the monetized value of the above savings translates to more than $600 for the 50-kWh battery pack, with the majority of the value represented by saved lithium.

7.0 Emission Reduction Estimates

Two key GHG emissions reduction components are associated with the B2U station:

- First is through the **ongoing operation** of the station over its full lifespan via the provision of clean electricity to electric vehicles that helps reduce gasoline use.
- The second is **reducing embedded emissions** associated with manufacturing and disposing of the battery pack itself, as outlined in the last section. The latter saving is also a present value rather than a future value, given that it is effectively saved today.

7.1 Station Operations to Provide Clean Electricity

Regarding GHG reductions through the electrification of vehicles and displacement of gasoline, Environment and Climate Change Canada (ECCC) typically presents calculations based on National Inventory Report (NIR) methodologies involving conventional fuels, like gasoline, presented on a combustion-only basis. In this case, ECCC employs an approximate emissions factor of 0.0023 tonne CO2e per Litre for gasoline consumption. ECCC further considers emissions regarding electricity for vehicular operations in clean-grid jurisdictions like Manitoba to be negligible.

On the other hand, NRCan requests emissions to be presented for projects on a life-cycle basis. This more significantly alters values for gasoline, with lifecycle emissions from hydroelectricity within Manitoba again essentially negligible. Based on earlier work by Trottier Energy Futures (see Figure 320) [31], while there is variability in life-cycle emissions, a reasonable emissions factor for gasoline is approximately 0.0034 tonnes CO2e per Litre. In the analysis, emission impacts are thus primarily reported life-cycle, but with NIR combustion-only also noted.

Calculations for operational-related impacts are further presented in two ways for this GHG reduction component: (a) reductions from the project as experienced so far; and (b) reductions as could be expected from the anticipated operation of the B2U station over the projected lifespan as a fully open and accessible charging site.

As outlined earlier, through the project so far, the station has provided 1,162 kWh of electricity (or roughly 77 kWh per month). As a starting point, a simplistic assumption can be made of approximately 2.5 kWh of electricity providing the same vehicle travel distance performance as 1.0 Litre of gasoline. Based on this assumption, total displaced gasoline, so far, translates to approximately 465 Litres (or 31 Litre per month). Further, using emissions factors as noted, overall GHG reductions translate to 1.58 tonnes CO2e life-cycle (or 1.07 tonnes CO2e NIR-based). Using a social cost of carbon of $50 per tonne

CO_2e over 15 operating months recorded, this translates to roughly $79 life-cycle (or $54 NIR) in total or roughly $5.30 per month life-cycle (or $3.60 per month NIR-based)

In terms of project timeframe, GHG reductions breakdown into approximately

- Fiscal 2021-2022: 0.22 tonnes CO_2e life-cycle (or 0.15 tonnes CO_2e NIR-based); and
- Fiscal 2022-2023: 1.36 tonnes CO_2e life-cycle (or 0.92 tonnes CO_2e NIR-based).

As outlined earlier, the anticipated future potential performance of the B2U station, if operating fully open and available, represents about 5% of the monthly equivalent capacity for a 25-kW grid-connected DCFC, with station life assumed as 10 years. Based on eighteen 1-hour charging events over a month (i.e., 5% of 360 sessions possible), each representing 23 kWh of electricity delivery, this translates to about 414 kWh per month (or about 4,970 kWh annually). Using similar assumptions as above, this translates to about 166 Litres of gasoline offset per month, about 0.56 tonnes CO_2e per month life-cycle (or 0.38 tonnes CO_2e per month NIR). This means about 6.76 tonnes CO_2e life-cycle (or about 4.57 tonnes CO_2e NIR) are reduced annually. Using a social cost of carbon of $50 per tonne CO_2e, using life-cycle emission, translates to savings of about $28 per month or $336 annually. (Corresponding NIR-based values translate to about $19 per month or $228 annually).

Regarding the assumed gasoline off-set factor of 2.5 kWh per Litre, specific data regarding energy/fuel the three-door Mini Cooper SE electric and its comparable gasoline counterpart are provided by NRCan in recent 2023 vehicle fuel efficiency data [27]. The electric version has a combined highway/city fuel consumption of 19.1 kWh per 100 km, while the gasoline variant has an average combined fuel consumption of 7.45 Litre per 100 km. Dividing values yields, in this case, a conversion of about 2.56 kWh per Litre of gasoline to travel the same distance. This specific result provides validity to the assumed equivalency value.

7.2 Embedded Emissions Reduced Through Battery Repurposing

As discussed earlier, the analysis undertaken as part of the CBA showed that for a 50-kWh battery pack, as employed, GHG reductions through the repurposing of the battery are approximately 3.50 tonnes of CO_2e avoided for the manufacture of a new battery, as well as 0.75 tonnes CO_2e avoided by not recovering solely cobalt from the battery via a pyrometallurgical process [28]. These values were calculated based on inherent life-cycle bases. Total emission reductions of embedded emissions thus translate to a total of approximately 4.25 tonnes CO_2e, with a monetized value of about $212 life-cycle. These savings can be logically deemed to occur when the battery pack is repurposed and begins its second use, which would be Fiscal 2021-2022 for the project.

7.3 Anticipated Lifespan Emission Reductions

Considering the B2U station operating for 10 years, based on the assumption of utilization at 5% of equivalent capacity of a 25-kW grid-connected DCFC, the station would initially involve a reduction of 4.25 tonnes CO2e life-cycle at the start through avoidance of new battery manufacturing and pyrometallurgical reprocessing, followed by annual reductions of 6.76 tonnes CO2e life-cycle (or about 4.57 tonnes CO2e NIR) reduction through provision of clean electricity to electric vehicles. Total reductions occurring due to a single B2U station thus translate to roughly 85 tonnes CO2e lifecycle (or 50 tonnes CO2e NIR) over operating life.

Emission reductions can also be estimated for a typical electric vehicle itself, with main assumptions of (a) electric vehicle based on replacing a comparable gasoline car with fuel consumption of 8 Litres per 100 km; (b) both traveling 15,000 km annually; and (c) expected life in both cases of 12 years. Reduced emissions, in this case, translate to just under 49 tonnes CO2e life-cycle (or just over 33 tonnes CO2e NIR) over operating life. It is understood that the emission reductions in these cases are not incremental, indeed with significant overlap, both values effectively reflect some of the identical reductions from different perspectives, i.e., charger versus driving. Notably, the anticipated contribution values for the B2U station are higher than the individual vehicle. This makes sense, given that each vehicle, based on assumptions, consumes about 3,000 kWh, whereas each B2U station, based on assumptions, delivers about 4,970 kWh. Based on this, the reductions associated with a single B2U station are at least comparable to a single electric vehicle.

8.0 Implications for Red River College Polytechnic

8.1 Project Strategic Alignment

Since the time of the initial proposal, this project has been identified as firmly aligning with RRCP’s future directions, in particular, the following three specific strategic themes and goals:

- Elevating student success;
- Fostering sustainable growth; and
- Cultivating strategic partnerships.

The project allowed students and staff to work on a novel, ground-breaking project in Canada. The project also involved significant direct interaction with a major industrial partner, New Flyer. The project has helped improve RRCP’s environmental footprint through direct emissions reduction and enabling electric mobility technologies. The B2U station represents the fourth DCFC station on the Notre Dame campus overall. This is in addition to a number of Level 2 (L2) outlets and selected retrofit Level 1 (L1) charging locations also located across the campus. The project also has supported the growth of enterprises through training and applied research.

8.2 Follow-up Benefits

The exposure and experience provided by the B2U project have helped to facilitate and significantly advance further important applied research activities at RRCP, with three projects, in particular, highlighted:

- Most high-profile is the work by RRCP, noted earlier [2], to assist Frontiers North Adventures in undertaking the first conversion of one of their iconic, specialized Tundra Buggy vehicles from diesel to all-electric, in the case of the first unit, specifically using repurposed batteries already well-used from transit buses. This accomplishment received broad media attention locally [32] and nationally [33].
- Second is RRCP's leadership of an important multi-institutional collaboration awarded funding in 2022 under NRCan's Zero Emission Vehicle Awareness Initiative (ZEVAI) [34, 35]. The project involves RRCP, Northern Alberta Institute of Technology (NAIT), and Sask Polytech collaborating to assess and promote the adaption of existing block-heater plug-in infrastructure across the Prairie region to provide low-cost Level 1 (L1) charging capabilities at workplaces. Workplace charging is generally considered the second-most important next to home-based charging, and the project has received media attention [36].
- Third is ongoing work by RRCP in conjunction with e-Camion on their large-scale charging infrastructure development along the TransCanada highway, including into Manitoba, as noted earlier [11], with indeed RRCP acting as a host site for one of e-Camion's new battery-based DCFC stations.

RRCP continues to lead in electric vehicle technology and electric vehicle charging initiatives.

9.0 Emerging Issues and Opportunities

Throughout the project, one new important issue emerged that will need to be addressed for repurposing already-used batteries in charging stations or any other ESS. This involves explicitly the potential obsolescence of battery management systems (BMS) already incorporated within used batteries. Given the already advanced age of used batteries, there is an increasing potential for the effective "legacy" BMS within the batteries to become too outdated and unsupported as the general state of battery technology advances. This issue is also beginning to be identified by other research teams, notably at RWTH Aachen University [37], whose SteVe tool was employed for this project.

To begin addressing this emerging issue, staff from RRCP have begun to investigate the ongoing availability, cost, and suitability of more up-to-date BMS that could be effectively plugged into used-battery packs as an add-on. This issue was not identified initially but did not directly impact the completed B2U station, but it will likely need more attention in the future.

At the same time, an important opportunity for the B2U DCFC charging station concept was also identified: employing used batteries to support solar photovoltaic (PV) derived electricity specifically for vehicle recharging. Such an approach addresses both intermittency and relatively-high solar costs.

Solar PV technology can benefit significantly from battery-based ESS, as identified by the U.S. Department of Energy [38]. A quick analysis of costs and benefits clarifies the advantage of the application to electric vehicle charging. Solar power remains relatively expensive, with data from the Canadian Energy Regulator suggesting breakeven prices required for solar within Manitoba in the range of 14¢ to 25¢ per kWh [39], much higher than current grid-based prices.

Yet even if assuming a relatively high cost of 20¢ per kWh, applying the 2.5 kWh per Litre equivalency discussed earlier translates to an effective fuel cost of about $0.50 per Litre, which is highly attractive, i.e., upwards of a 70% saving from current market prices. Vehicle charging thus represents a practical and economically attractive application for solar energy. A particular opportunity identified by RRCP is in conjunction with building-integrated solar PV. Staff from RRCP will continue to monitor developments and technologies in this area, with a mind to future potential demonstration project(s).

10.0 Conclusions

This applied research project by RRCP showed that already-used transit bus batteries can be successfully and economically repurposed for use in a functional battery-based DCFC system for charging light-duty electric vehicles, which has been termed the B2U station. The project represented a first-of-its-kind in the world for already-used bus batteries in such a second-life application, and as such, was highly novel.

The project fulfilled all requirements regarding budget and outcomes, demonstrating significant technology progress, successful operation over an extended timeframe, and emissions reductions. The latter included GHG reductions by reducing embedded emissions associated with avoiding new manufacture and pyrometallurgical processing and by delivering clean electricity to electric vehicles, displacing gasoline consumption. The project took roughly one year longer than initially anticipated; however, this was specifically due to the COVID pandemic which impacted all activities across the country.

The use of the B2U station, firstly by use of already-used batteries, provided a highly competitive and attractive option for DCFC implementation, and secondly, by virtue of its use of batteries showed, showed a way to ease the burden on the electrical grid from DCFC, saving significantly in terms of demand fees. The project's benefits were also backed up by a significant cost-benefit analysis report prepared at the University of Manitoba [29].

There were also direct benefits to RRCP in helping to advance progress into new areas and new projects, including using repurposed batteries for other specialized applications, improving performance, and reducing charging infrastructure costs to support electric vehicles. RRCP continues to innovate and advance to meet new challenges associated with electric vehicles and charging.

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