Propulsion Electrification Architecture Selection Process and Cost of Carbon Abatement Analysis for Heavy-Duty Off-Road Material Handler

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Abstract

The heavy-duty off-road industry continues to expand efforts to reduce fuel consumption and CO_2e (carbon dioxide equivalent) emissions. Many manufacturers are pursuing electrification to decrease fuel consumption and emissions. Future policies will likely require electrification for CO_2e savings, as seen in light-duty on-road vehicles. Electrified architectures vary widely in the heavy-duty off-road space, with parallel hybrids in some applications and series hybrids in others. The diverse applications for different types of equipment mean different electrified configurations are required. Companies must also determine the value in pursuing electrified architectures; this work analyzes a range of electrified architectures, from micro hybrids to parallel hybrids to series hybrids to a BEV, looking at the total cost, total CO_2e, and cost per CO_2e (cost of carbon abatement, or cost of carbon reduction) using data for the year 2021. This study is focused on a heavy-duty off-road material handler, the Pettibone Cary-Lift 204i. This machine's specialty application, including events like unloading large oil pipes from a railcar, requires a unique electrified architecture that suits its specific needs. However, the results from this study may be extrapolated to similar machinery to inform fuel savings options across the heavy-duty off-road industry. In this study, a unique electrified architecture is determined for the Cary-Lift. This architecture is informed by multiple rounds of a Pugh matrix decision analysis to select a shortened list of desirable electrified architectures. The shortened list is modeled and simulated to determine CO_2e, cost, and cost per CO_2e. A final architecture is determined as a plug-in series hybrid that reduces fuel consumption by 65%, targeting the large fuel and CO_2e savings that are likely to be required for the future of the heavy-duty off-road industry.

Introduction

Decarbonization has become a focus of many industries as the U.S. aims for a net-zero-emissions economy by 2050 [1]. The decarbonization goals often center around greenhouse gas (GHG) reduction, measured in CO_2e [2]. The heavy-duty off-road sector faces a large area of change in the near future since less focus has been placed on the decarbonization of off-road applications than on light-duty on-road [3, 4]. Off-road refers to equipment that does not use roadways in its general applications [4]. Like the on-road industry, the off-road industry finds that electrification is a promising means to reduce fuel consumption and direct emissions [5], where direct emissions are related to a company's operation of equipment, for example, the emissions produced at the site the vehicle is operating at [6]. Companies will be driven to reduce fuel consumption and emissions based on required governmental policy and overall cost [7]. Cost is a primary barrier to introducing new fuel-reducing technologies [1]; hence, cost is a central point of comparison in this work. Also considered are the CO_2e emissions and the cost per CO_2e emissions reductions (cost of carbon abatement) to determine electrification architectures that provide the highest CO_2e benefit for the lowest cost.

Light-duty on-road vehicle CO_2e analyses are plentiful [2, 8], but these analyses are less commonly found in the heavy-duty off-road industry. CO_2e analyses are also found in the medium and heavy-duty sectors [9], again without the off-road application. The CO_2e analysis in this paper and the architecture selection decision matrix provide relevant information to determine electrification architecture lifetime CO_2e analyses in the heavy-duty off-road sector. The cost and CO_2e analyses allow for comparing all electrified architectures based on the cost of carbon abatement, which measures the cost of reducing carbon emissions. The cost of carbon abatement has been explored in the light-duty industry [2] and the heavy-duty sector [10], but this work provides data for the heavy-duty off-road industry.

This paper first reviews the current landscape of electrified heavy-duty off-road hybrid architectures, architecture selection analyses, and CO_2e analyses before looking at the operating conditions and modeling development of the machine of interest, the Pettibone Cary-Lift 204i, shown in Figure 1. Then, multiple rounds of a Pugh-style decision matrix are reviewed, which creates a list of electrified architectures to be studied in greater detail. Each electrified architecture was modeled independently in Simcenter Amesim, informing a CO_2e and cost analysis based on the fuel and electricity consumption, maintenance, and the addition or removal of parts for each architecture. A total cost per CO_2e abated is determined for each electrified architecture, helping to assist manufacturers and customers in determining current and future electrified architectures that could meet governmental regulations and company goals while factoring in total cost.

Figure 1. Pettibone Cary-Lift 204i.

Literature Review

With the trend toward electrification in many mobility sectors [2], the heavy-duty off-road space is placing a greater importance on higher levels of electrification to achieve fuel savings and direct emissions reductions [3]. California has recently committed to having 100 percent of its off-road vehicles and equipment be zero-emission (direct emissions) by the year 2035, while heavy-duty on-road vehicles are targeted at 100 percent zero-emission by 2045 [11]. These requirements pressure these industries to rapidly develop technologies to reduce emissions and move into electrified architectures. Table 1 shows some examples from the current landscape of electrified architectures in the heavy-duty off-road space. Notice the range of electrification architectures, hinting at a need for architectures specific to the application use case.

Table 1. Electrified architectures in the heavy-duty off-road space.

Manufacturer and Model Name	**Type of Equipment**	**Electrification Architecture**	**Fuel Savings**
Volvo L220F [12]	Rubber-Tired Wheel Loader	Parallel Hybrid	10% [12]
John Deere 644K [12]	Rubber-Tired Wheel Loader	Series Hybrid	25% [12]
Caterpillar D6 XE [13]	Dozer	Series Hybrid	25% [13]
Merlo 40.7 Hybrid [7]	Telehandler	Plug-in Series Hybrid	30% [12]
Case 580 EV [14]	Backhoe Loader	Battery Electric	NA

Electrification architectures are numerous, but studies on heavy-duty electrified architectures are limited [15]. Trimming the long lists of electrified architectures to a manageable size requires analyses that factor in cost, reliability, ease of maintenance, fuel economy, and performance, to name a few [4, 16]. In [4], the author introduced a decision matrix that places a weighting factor on different criteria for electrifying off-road equipment. Similarly, the authors of [16] show their version of a decision matrix, in this case in a light-duty application. This decision matrix had several weighting factors for different performance parameters like acceleration, drive quality, and range while also considering risk factors for the project, like packaging complexity and component availability [16]. Other analyses have gone into greater depth to find electrified architectures, looking at payback periods, fuel costs, and initial costs for many electrified architectures [17]. Further, the authors of [18] utilize optimization to achieve the best configuration for a multi-mode hybrid tracked vehicle.

While the optimization techniques may be helpful when significant knowledge of the machine is in hand, the decision matrices discussed previously provide simple comparisons that allow for robust comparisons if done correctly. These decision matrices may be informed by the analysis of other parameters of interest. In this paper, the other parameters of interest are CO_2e and cost, which are studied in detail.

Thorough analyses have been performed in the light-duty on-road environment, analyzing the overall CO_2e emissions from ICEVs, hybrids, and BEVs [2, 8]. Burton et al. [8] found that hybrids often provide the lowest CO_2e when factoring in the marginal emission rates of electricity. BEVs were found to have the lowest cradle-to-grave CO_2e / mile for current and future technologies in [2]. The more notable differences in these papers are that [2] used average electricity emissions instead of the marginal electricity emissions used in [8] and that [2] also factored in changing electricity grid emissions over the lifetime of the vehicle, where [8] assumed grid values were constant. The work performed in this paper assumes an average emission rate of the electricity grid and a constant grid emissions value over the lifetime of the vehicle, all using published data from 2021. These assumptions were made to use known, readily available numbers for the analysis, supported by EPA recommendations to use average mix (total output emission rate) for CO_2e analyses [19].

Cost analyses for decarbonization technologies are also plentiful in on-road applications [2] and heavy-duty on-road applications [9, 17, 20, 21], with some work also analyzing heavy-duty off-road applications [21]. This work will provide new information on electrified vehicle architecture lifetime costs in the heavy-duty off-road space.

Another metric explored in this paper is the cost of carbon abatement (e.g., \$/metric ton CO_2e abated), which allows for a scale of how much cost is required to reduce the overall carbon burden of a certain electrified architecture. Argonne National Laboratory provided a thorough lifecycle analysis of light-duty on-road vehicles in the U.S., including a study of the cost of carbon abatement [2]. Using current technology, the cost of carbon abatement ranged from \$100s to \$1000s per metric ton of CO_2 abated, whereas future technology options had cost reductions for carbon abatement, meaning the future technologies cost less and reduced CO_2 [2]. Carbon abatement cost in future technology cases ranged drastically, pointing to the importance of technology selection. Carbon abatement was also explored in the case of heavy-duty on-road trucks in [10], where carbon abatement costs were as high as 1800 € / metric ton CO_2 (\$1952 / metric ton CO_2 [22]) and as low as -200 € / metric ton CO_2e (-\$217 / metric ton CO_2 [22]) based on architecture and electricity source. This paper will explore the metric of carbon abatement cost for the heavy-duty off-road sector, analyzing multiple electrified architectures.

Baseline Vehicle Model

Description

A model of the baseline machine was developed to accurately quantify the energy consumption of the different components of the baseline Pettibone Cary-Lift 204i. The model was broken into two overarching systems: the propulsion system and the hydraulic system. These systems operated in parallel in the model of the machine, as they do in the experimental machine. To ensure the model performed accurately, the experimental machine was instrumented, and data was recorded on a series of operating cycles that represented the typical operation of the Cary-Lift.

Representative Operating Cycles and Fuel Consumption Analysis

Operating cycles for off-road equipment vary widely [1, 23]. For example, a large agricultural tractor operating at consistent speeds and loads in a field has an operation that differs vastly from a wheel loader that is accelerating and decelerating with variable weight in its bucket. The Pettibone Cary-Lift has a unique operation that is distinguished even from similar equipment, like a wheel loader. The Cary-Lift operates in railyards and lumberyards, where it may be used to lift and carry large pipes or logs around a job site [24]. As such, the Cary-Lift's unique operation meant that custom operating cycles needed to be created that matched what the Cary-Lift does on a typical day [24].

Figure 2 shows a walkthrough of the operating cycle creation process all the way to a vehicle fuel consumption analysis. The operating cycles are designed to replicate the Cary-Lift's four primary operations and are then time-weighted based on the percentage of time the Cary-Lift spends in each operation [24]. This time weighting was based on the in-use recorded operation of the Cary-Lift, and the fuel consumption analysis was based on this time-weighted operating cycle, as seen in Figure 2 [24]. Notice the high amount of time spent at idle conditions. This time percentage was determined based on over 15,000 hours of end-user data on the Cary-Lifts, where operators often leave the machine running. Some examples of idle time are long-duration and predictable, such as during breaks and in between shift changes, while much of the cumulative idle time is made up of short and unpredictable idle such as while waiting for a temporary backup of material to feed into a processing plant, or while communicating with truck drivers, material coordinators, and laborers [24]. The fuel consumption analysis was performed after the baseline model was calibrated and validated using experimental data [24]. This validated model could then introduce electrification technologies for fuel savings in the Cary-Lift.

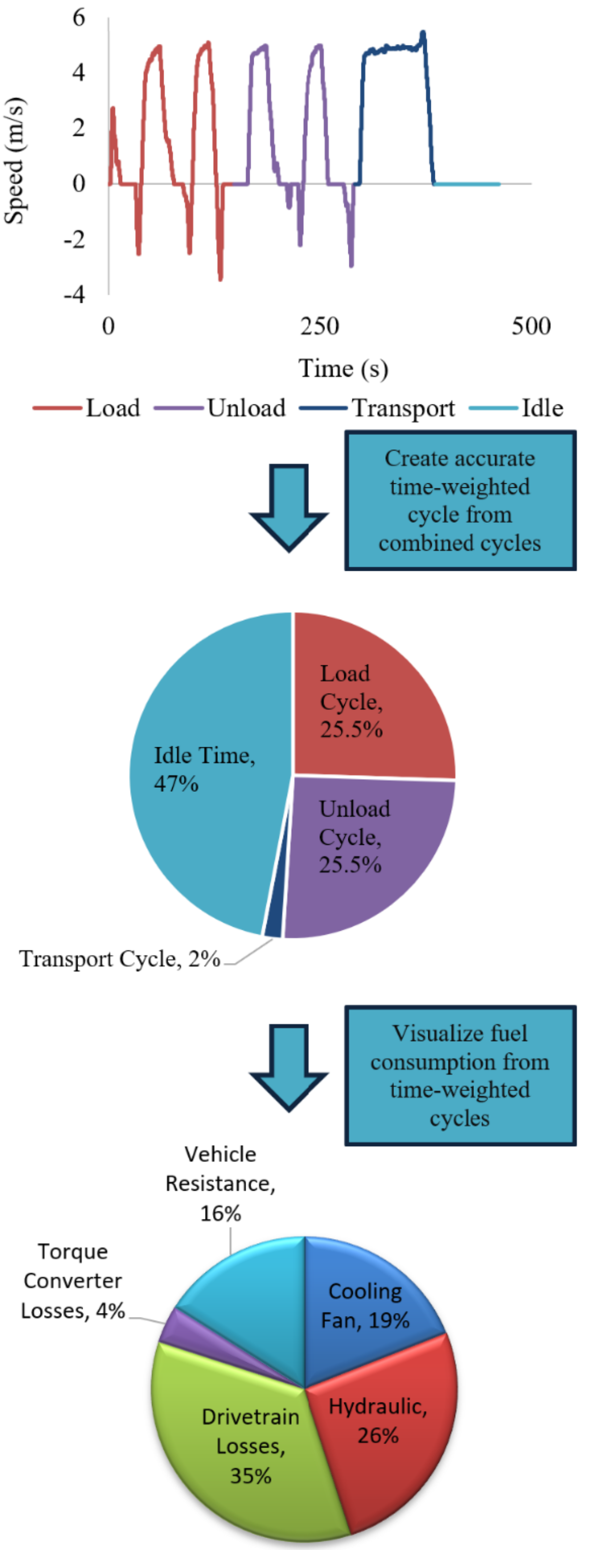


Figure 2. Process of calculating fuel consumption of base Cary-Lift. Combined operating cycle (top), time-weighted operating cycle (middle), and fuel consumption distribution (bottom). Adapted from [24] with permission; copyright SAE International.

Pugh Matrix Decision Analysis

Description

Choosing an electrified architecture requires the consideration of the needs of the end-user (customer) and the manufacturer. In projects where outside entities are performing the research, budgetary and time concerns and research opportunities will inform decisions on architecture options. In this project, a Pugh-style decision analysis was used to determine a list of electrified architectures that could maintain or enhance baseline machine performance while providing fuel savings, cost savings, and other benefits to the end-user and manufacturer. In this work, the Pugh matrices look at a range of electrified architecture options and rank each based on comparison parameters considering performance, design, and risk criteria.

The comparison parameters, represented in the columns, were selected based on the factors that were determined as essential for project success. These were refined as more was understood about the machine and as other considerations took precedence, like where potential energy recovery was removed between the first and second round of the Pugh matrix when it was realized that potential energy recovery would be very complex while maintaining current applicable safety standards.

The weighting factors in the Pugh matrices were chosen based on the importance of the comparison parameters in Figure 3, where a higher weighting factor meant that the parameter had a greater likelihood of impacting the final product. The final product was driven by considerations including the ability to complete the project in a timely manner, the cost of the machine, changes to the baseline machine, carbon emission savings, and overall fuel savings. These weighting factors were reevaluated as the project progressed and as other considerations changed in importance, such as where range decreased in importance as it was deemed less important than other items like propulsion system efficiency.

The scoring of each architecture, seen by the colored cells inside of the Pugh matrix in Figure 3, was determined based on the architecture's score relative to the other architectures. For example, in Figure 3, the P0 architecture scored a +2 in the comparison parameter "Program Time Risk" since it is not a time-intensive architecture relative to other options, but the architecture P3 + P0 EFH+ scored a -1 since it is significantly more time-intensive, but not the most time-intensive architecture. The most time-intensive architectures scored a -2, like the series-parallel architecture seen in Appendix A.

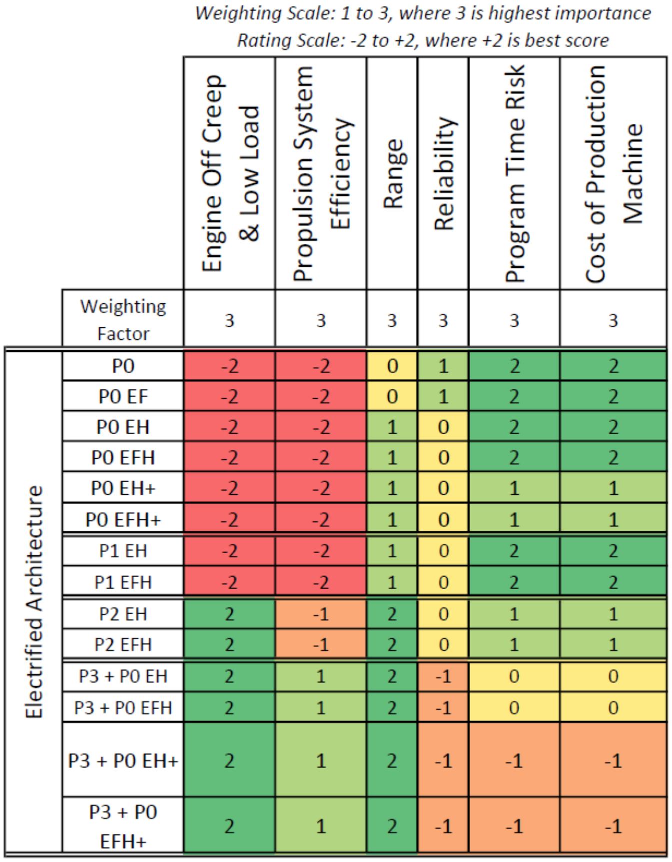
Analysis

First Round of Pugh Matrix

The first round aimed to create a refined list of architectures based on the expected performance of various electrified vehicle architectures. Figure 3 shows a portion of this first round of the Pugh matrix, displaying the highest scoring architectures in the rows and the most influential comparison parameters in the columns. The colored cells inside this matrix are the scores for each architecture for the comparison parameter of interest. The weighting factor is multiplied by the score for each architecture, and then all of the scores are summed for each column to create an overall weighted score. See Equation (1) for the description of this calculation. Appendix A contains the entire Pugh matrix for this first round, including each architecture's weighted score. See Definitions/Abbreviations section for architecture descriptions.

$$Total\ Weighted\ Score = WF_1 * C_1 + WF_2 * C_2 + \cdots + WF_n * C_n \tag{1}$$

Where,
WF_1 = Weighting Factor of column 1
C_1 = Score from Criterion 1 for architecture of interest. For example, in Figure 3, C_1 for the P0 architecture is -2



Weighting Scale: 1 to 3, where 3 is highest importance
Rating Scale: -2 to +2, where +2 is best score

		Engine Off Creep & Low Load	Propulsion System Efficiency	Range	Reliability	Program Time Risk	Cost of Production Machine
	Weighting Factor	3	3	3	3	3	3
Electrified Architecture	P0	-2	-2	0	1	2	2
	P0 EF	-2	-2	0	1	2	2
	P0 EH	-2	-2	1	0	2	2
	P0 EFH	-2	-2	1	0	2	2
	P0 EH+	-2	-2	1	0	1	1
	P0 EFH+	-2	-2	1	0	1	1
	P1 EH	-2	-2	1	0	2	2
	P1 EFH	-2	-2	1	0	2	2
	P2 EH	2	-1	2	0	1	1
	P2 EFH	2	-1	2	0	1	1
	P3 + P0 EH	2	1	2	-1	0	0
	P3 + P0 EFH	2	1	2	-1	0	0
	P3 + P0 EH+	2	1	2	-1	-1	-1
	P3 + P0 EFH+	2	1	2	-1	-1	-1

Figure 3. Highest scoring architectures from Pugh round 1, looking at important factors for scoring. See Appendix A for the full Pugh matrix and see Definitions/Abbreviations section for architecture descriptions.

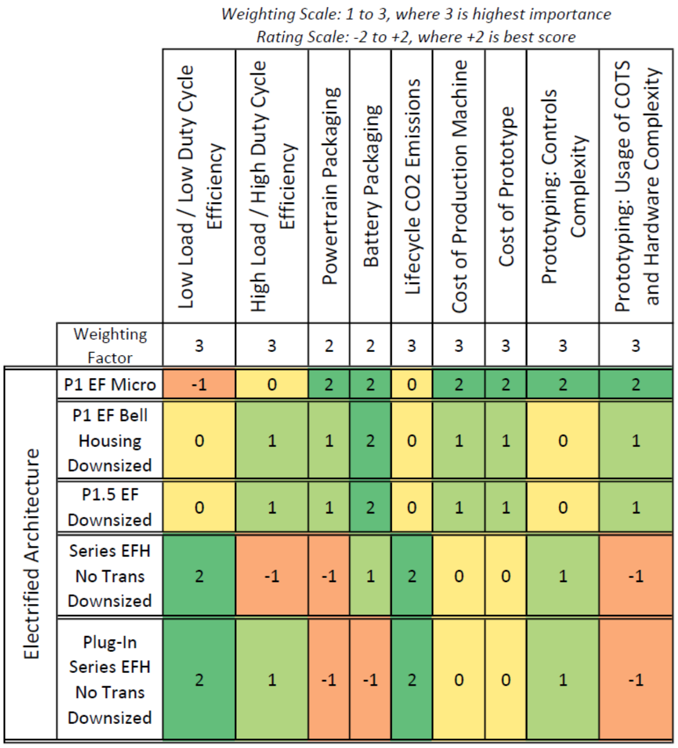
This first round focused on condensing a list to perform higher fidelity analyses on a smaller subset of the most promising electrified architectures. The architectures seen in Figure 3 were the top 25% of all architectures scored, so these moved on to the second round of the analysis.

Other architectures of research interest were also brought to the second round of the Pugh matrix. These included a series hybrid and a battery electric vehicle (BEV), along with variations of these architectures. These were added to the analysis because of the trend toward higher levels of electrification in the on-road and off-road space and because of the current literature showing manufacturers creating series and full BEV versions of their products, as seen previously in Table 1.

Second Round of Pugh Matrix

From a smaller list of electrified architectures and a refined list of performance, design, and risk criteria, the second round of the Pugh matrix was bolstered by a first principles analysis of the architectures of interest. This analysis was performed by looking at the fuel savings expected from the electrified architectures based on the replacement, removal, or addition of components. For example, the base fan, which is mechanically connected to the engine and constantly spinning, could be replaced with an electric fan that only spins when the coolant reaches a higher temperature. The savings for such a system were quantified by removing the load on the engine from the base fan and replacing the fan with curves provided by an electric fan manufacturer.

Figure 4 displays the highest scoring architectures from this second round of the Pugh matrix, along with the essential factors for scoring. Some of these architectures are different than those identified in the first round of the Pugh matrix because further design work revealed electrified architectures that were previously not considered. Like the first round, each weighting factor was multiplied by the score inside the matrix, and these values were summed down the length of each row for a total weighted score. Refer to Appendix B for the entire Pugh matrix for the second round.



Weighting Scale: 1 to 3, where 3 is highest importance
Rating Scale: -2 to +2, where +2 is best score

		Low Load / Low Duty Cycle Efficiency	High Load / High Duty Cycle Efficiency	Powertrain Packaging	Battery Packaging	Lifecycle CO2 Emissions	Cost of Production Machine	Cost of Prototype	Prototyping: Controls Complexity	Prototyping: Usage of COTS and Hardware Complexity
	Weighting Factor	3	3	2	2	3	3	3	3	3
Electrified Architecture	P1 EF Micro	-1	0	2	2	0	2	2	2	2
	P1 EF Bell Housing Downsized	0	1	1	2	0	1	1	0	1
	P1.5 EF Downsized	0	1	1	2	0	1	1	0	1
	Series EFH No Trans Downsized	2	-1	-1	1	2	0	0	1	-1
	Plug-In Series EFH No Trans Downsized	2	1	-1	-1	2	0	0	1	-1

Figure 4. Highest scoring architectures from Pugh round 2, looking at important factors for scoring. See Appendix B for the full Pugh decision matrix and see Appendix C for architecture sketches.

From this second round, five electrified architectures composed the top 25% of scores, as seen in Figure 4. These include the following (in order from highest to lowest score):

1. A parallel P1 micro-hybrid with an electric cooling fan.
2. A plug-in series hybrid (a.k.a. range-extended or extended-range electric vehicle) with the transmission removed, engine downsized, and using an electric fan and electrified hydraulics.
3. A series hybrid with the transmission removed, engine downsized, and using an electric fan and electrified hydraulics.
4. A parallel P1 hybrid with an electric cooling fan and downsized engine. Electric motor mounted on bell-housing pump drive PTO connected to the engine.
5. A parallel P1.5 hybrid with an electric cooling fan and downsized engine. Electric motor mounted to same engine PTO as hydraulic pumps.

In addition to these architectures, the analysis introduced the following architectures for comparison:

6. The base Pettibone Cary-Lift serves as the comparison point as an architecture with no electrification.
7. A parallel P1 micro-hybrid with an electric fan and a multi-function torque converter (MFTC). This is based on a previous publication on the Pettibone Cary-Lift [24].
8. A full BEV with the transmission removed and using electrified hydraulics. The BEV serves as the upper point on electrification in this analysis.

See Appendix C for a schematic representation of each of these architectures. Also, Figure 5 shows the hybridization factor of each architecture versus the battery capacity. The formula for the hybridization factor is seen in Equations (2) to (4), as defined for heavy-duty working vehicles in [25].

$$Hybridization\ Factor = 0.5 * (\mu_1 + \mu_2) \tag{2}$$

$$\mu_1 = \frac{P_{Tractive\ EM_{Total}}}{P_{Tractive\ EM_{Total}} + P_{ICE}} \tag{3}$$

$$\mu_2 = \frac{P_{Hydraulic\ EM_{Total}}}{P_{Hydraulic\ EM_{Total}} + P_{ICE}} \tag{4}$$

Where,
$P_{Tractive\ EM\ Total}$ = *the total power of the tractive electric machine(s)*
P_{ICE} = *the power of the internal combustion engine*
$P_{Hydraulic\ EM\ Total}$ = *the total power of the hydraulic electric machine(s)*

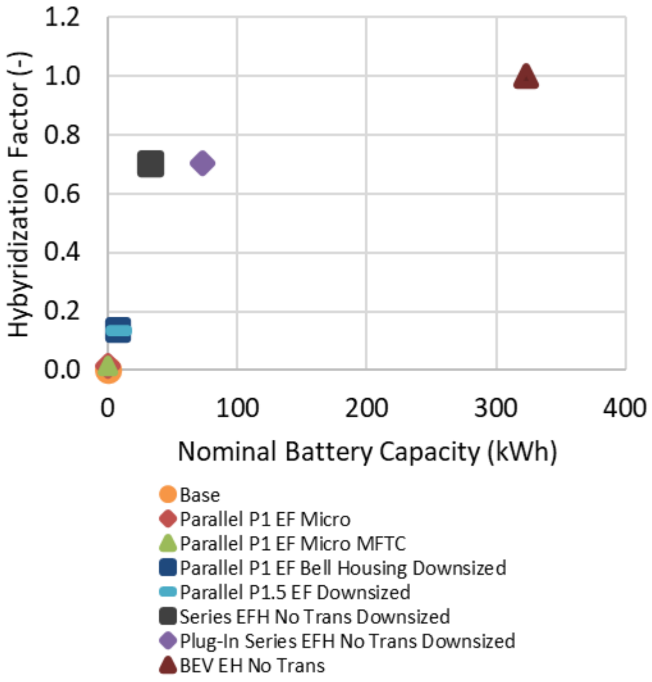


Figure 5. Hybridization factor vs. battery capacity for all architectures studied.

This hybridization factor is also considered in the upcoming cost analysis, where higher hybridization factor values lead to higher costs due to increased electrification components like high voltage battery cabling, connectors, and changes to the thermal management system.

Applications

Pugh matrix decision analyses can be used in other applications to filter a long list of electrified architectures into a smaller list for further analysis. This type of analysis can provide a useful filtering tool for time and resource-constrained projects so that time and money are spent on the more promising options rather than on all possibilities.

Electrified Architecture Modeling

Description

Working from the base model of the Cary-Lift, the seven electrified architectures mentioned previously were modeled (along with the baseline) in Simcenter Amesim. Electrification components, like batteries and electric machines, were added to the model in appropriate positions per architecture. Manufacturer-provided parameterization data were used where possible, and in other cases where component specific parameterization data were not available, Amesim-generated curves, or data from similar components, were used. Figure 6 shows a simplified sketch of the Amesim model for the plug-in series hybrid architecture.

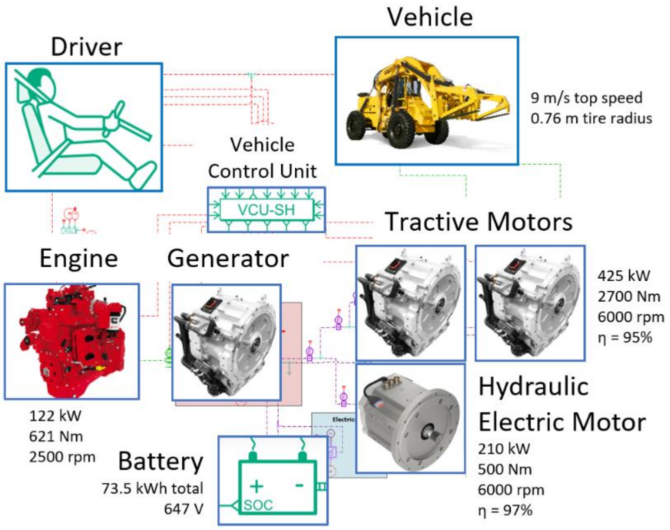


Figure 6. Electrification architecture in Amesim for plug-in series hybrid.

The control of each of the electrified architectures was performed using rule-based controls. The parallel hybrids, including the Parallel P1 EF Bell Housing Downsized and the Parallel P1.5 EF Downsized, followed a max State Of Charge (SOC) of Peaking Power Source (PPS) control strategy, described in [26]. For parallel hybrids, this strategy aims to keep the engine near its optimal fuel consumption curve, with the electric machine supplying torque to the vehicle when the engine torque is above its optimal fuel consumption curve, and demanding torque (regenerating energy to the battery) when the engine is below its optimal fuel consumption curve [26]. The remaining parallel hybrid machines (Parallel P1 EF Micro and Parallel P1 EF Micro MFTC) only enable engine stop-start. Hence, the control logic required is to turn off the engine when the machine is at rest without any hydraulic activity.

The series-type hybrids use a thermostatic rule-based control where once the battery SOC reaches a lower setpoint, the engine turns on to recharge the battery to an upper setpoint, at which point the engine is turned off again. In the case of the plug-in series hybrid, the battery is assumed to be recharged overnight, so in the beginning of the day, the SOC starts at a high point (e.g., 90%) and then operates in charge depleting (CD) mode until reaching a lower setpoint (e.g., 20%). Once this lower setpoint is reached, the machine uses a charge sustaining (CS) mode, following the previously mentioned thermostatic rule-based control. In the case of the plug-in series hybrid, there are 1.6 hours of all-electric operation from 90% to 20% SOC.

Each architecture was run on the same operating cycle, an 8-hour time-weighted operating cycle, as in Figure 2. This 8-hour time assumption comes from a typical 8-hour working day, thus it was determined as a realistic operating period for a workday and was extended through a 5-day working week. In this regard, the duration of continuous operation becomes analogous to the range of an on-road vehicle. Although it is justifiable to use an 8-hour work cycle, it is worth considering some additional factors in the context of this discussion. It is known that some Cary-Lift customers run 10-hour shifts, some run overtime when needed to meet production demand, and some run back-to-back shifts resulting in continuous machine usage that can exceed 16 hours per day. This is an important consideration for the architectures with a high hybridization factor, and in particular the BEV architecture due to available onboard energy storage. Although outside the scope of this paper, the team did conduct an extensive hardware packaging study, and found that although it is possible to package a battery with sufficient capacity to sustain 8 hours of operation, it will require customization / optimization of the battery form factor to fully utilize available space on the machine, and 8 hours appears to be the upper limit for battery capacity. Coincidentally 8 hours is also at the point beyond which SAE Level 2 charging will not be sufficient to replenish the battery energy before the start of the shift the following day. Beyond this point DC Fast Charging is necessary, which will require additional infrastructure cost at the use site, and additional hardware costs onboard the machine. The fuel consumption results for each of the architectures are included in Figure 7.

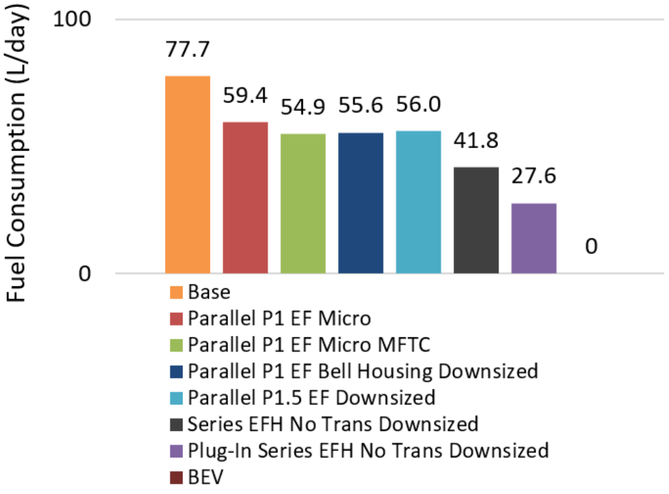


Figure 7. Modeled fuel consumption results from all architectures of interest. Operating on the 8-hour time-weighted operating cycle from Figure 2.

CO_2e Analysis

Description

With each of the architectures modeled in Amesim with an accurate representation of fuel and electricity consumption, a CO_2e analysis was used to compare each architecture over a lifetime of 15 years, as used in [2]. This CO_2e analysis comprehended diesel CO_2e, electricity grid

CO$_2$e, battery CO$_2$e, conventional component CO$_2$e, and electrified component CO$_2$e. These values were compared to the base machine as a zero-reference (i.e., the base machine started at zero emissions at time zero). The base machine as the zero-reference also means CO$_2$e values were not factored in for parts shared between the base machine and all electrified architectures, for example, the tires, wheels, or steel frame.

The following section provides a list of data sources and assumptions for the entire analysis, supported by a complete table of CO$_2$e assumptions in Appendix D. One crucial assumption for this analysis is the use of an average CO$_2$e mix for the electricity grid, which was used because of the availability of data and because the U.S. EPA recommends using an average mix (total output emission rate) for CO$_2$e analyses [19]. If using non-baseload emissions (electricity emissions for power plants that supply electricity only during peak times [27]), the results for lifetime CO$_2$e of the BEV vary drastically, as explored in the next section.

Analysis

Data Sources & Assumptions

The goal of the CO$_2$e analysis was to account for as much of the lifecycle CO$_2$e of the base and electrified architectures as possible, given available data. This included the upstream and direct emissions for each of the architectures of interest. The EPA defines these emissions in three separate bins, including Scope 1, Scope 2, and Scope 3 emissions. Scope 1 emissions are from the direct emissions associated with a company's operation of their equipment, like emissions from generating electricity on-site or operating company vehicles [6]. Scope 2 emissions are indirect emissions from purchasing products like electricity or steam from another company [6]. Scope 3 emissions are also indirect and represent the emissions from outside entities that the company does not control, for example, processing and use of sold products, upstream emissions from battery production, and transmission and distribution of electricity [28]. Table 2 shows the scope of emissions considered in this analysis. Note that the end-of-life CO$_2$e was not considered due to a lack of data for all sources. End-of-life treatment would be in the Scope 3 column.

Table 2. Scope of emissions considered for CO$_2$e analysis.

	Scope 1	**Scope 2**	**Scope 3**
Battery	N/A	N/A	Materials, assembly
Electrification Components	N/A	N/A	Materials, assembly
Conventional Components	N/A	N/A	Materials, assembly
Electricity	N/A	Electricity Generation	Transmission & distribution plus upstream emissions
Diesel	Combustion emissions	N/A	Upstream emissions

In creating an accurate representation of the emissions for the Cary-Lift's architectures, care was taken to include the most reliable data sources using the most recent data available for each of the sources of emissions. 2021 was the most recent year in which all data was published from these sources. Table 3 includes the data sources used in the CO$_2$e analysis, including all items considered in the study.

Table 3. Data sources for CO$_2$e analysis.

Data	**Source**
Diesel	
Diesel combustion CO$_2$e	EIA [29].
Diesel upstream CO$_2$e	GREET 2022 using 2021 data [30].
Electricity	
Electricity grid CO$_2$e	EPA eGRID using 2021 data [27].
Upstream electricity grid CO$_2$e	EPA eGRID and GREET using 2021 data [27, 30].
Electricity grid transmission and distribution losses	EPA eGRID using 2021 data [27].
Components	
Battery CO$_2$e (assembly and bill of materials)	GREET 2022 using 2021 data [30].
Conventional component CO$_2$e: engines, transmissions, etc.	GREET 2022 using 2021 data [30].
Electrification component CO$_2$e: electric machines, inverters	GREET 2022 using 2021 data [30].

An analysis like this requires assumptions, both for the purpose of simplifying and because all variables cannot be accounted for in perfect detail. The key assumptions for this CO$_2$e analysis are listed in Table 4. See Appendix D for the full list of assumptions for the CO$_2$e analysis.

Table 4. Key assumptions for CO$_2$e analysis. See the full table of assumptions in Appendix D.

Category	**Assumption**	**Justification**
Lifetime of Cary-Lift	15 years	15-year lifetime in [2].
CO$_2$e of diesel, electricity, and components	Does not change over lifetime	Assumption for simplicity of analysis and unknown future values.
Battery replacement period	443 days for plug-in battery; other results estimated based on Nickel Manganese Cobalt (NMC) battery curve with 443 days as reference.	Plug-in series battery lifetime modeled by battery supplier [31].
Electricity grid CO$_2$e	Average mix	EPA recommends average mix (total output emission rate) for CO$_2$e analyses [19].

As mentioned in Table 4, the battery lifetime was modeled by a battery manufacturer to obtain an estimate of 443 days to 80% state of health for the plug-in series hybrid Cary-Lift's battery lifetime. This is based on the modeled current into and out of the battery over years of operation on the 8-hour time-weighted operating cycle. The value obtained for the plug-in series served as an anchor point around which the battery lifetime was predicted for the other electrified architectures requiring a lithium-ion battery.

In Figure 8, the lithium-ion Nickel Manganese Cobalt (NMC) curve from [32] was scaled down so that the plug-in series hybrid battery lifetime fell on the curve at its 443-day lifetime. To ensure this scaled curve fell within a reasonable range, curves from the literature for lithium-ion NMC batteries were compared with the scaled curve. Figure 8 displays these other values from the literature, where the scaled curve is seen in between the reference curves, confirming the reasonable assumption. It is worth noting that the differences in lifetimes from the literature are drastic due to differences in configurations studied (cell vs. pack), differences in charge and discharge rates, differences in temperature, and more. This is why the plug-in series hybrid is used as an anchor point, so the battery lifetime curve is calibrated with an established benchmark value.

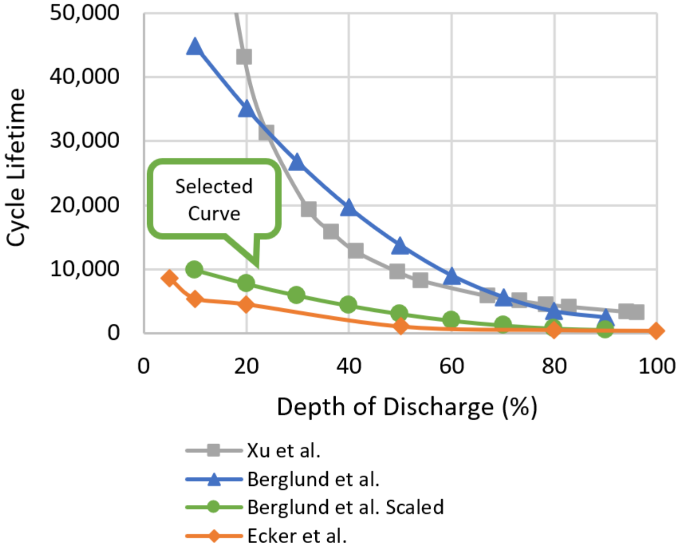


Figure 8. Cycle lifetime of lithium-ion NMC batteries vs. depth of discharge. Data obtained from Xu et al. [33], Berglund et al. [32], and Ecker et al. [34].

The scaled curve from Figure 8 informed the battery lifetime for all electrified architectures requiring a lithium-ion battery. The results from the battery lifetime estimations are seen in Table 5 for all of the architectures requiring a lithium-ion battery.

Table 5. Lithium-ion NMC battery lifetime estimations for electrified architectures that require a lithium-ion battery.

	Parallel P1 EF Bell Housing Downsized	Parallel P1.5 EF Downsized	Series EFH No Trans Downsized	Plug-In Series EFH No Trans Downsized	BEV EH No Trans
Total Battery Lifetime (days)	985.4	895.8	394.1	442.6	1239
Total Battery Lifetime (years)*	3.79	3.45	1.52	1.70	4.77

* Assuming 260 working days per year.

CO_2e Plots

The lifetime CO_2e emissions of eight different Cary-Lift configurations are compared in Figure 9. The step changes seen in the curves for the BEV, for example, are due to battery replacement CO_2e and occur in 4.77-year intervals, corresponding to the value in Table 5. All electricity CO_2e emissions are assuming a U.S. average electricity grid.

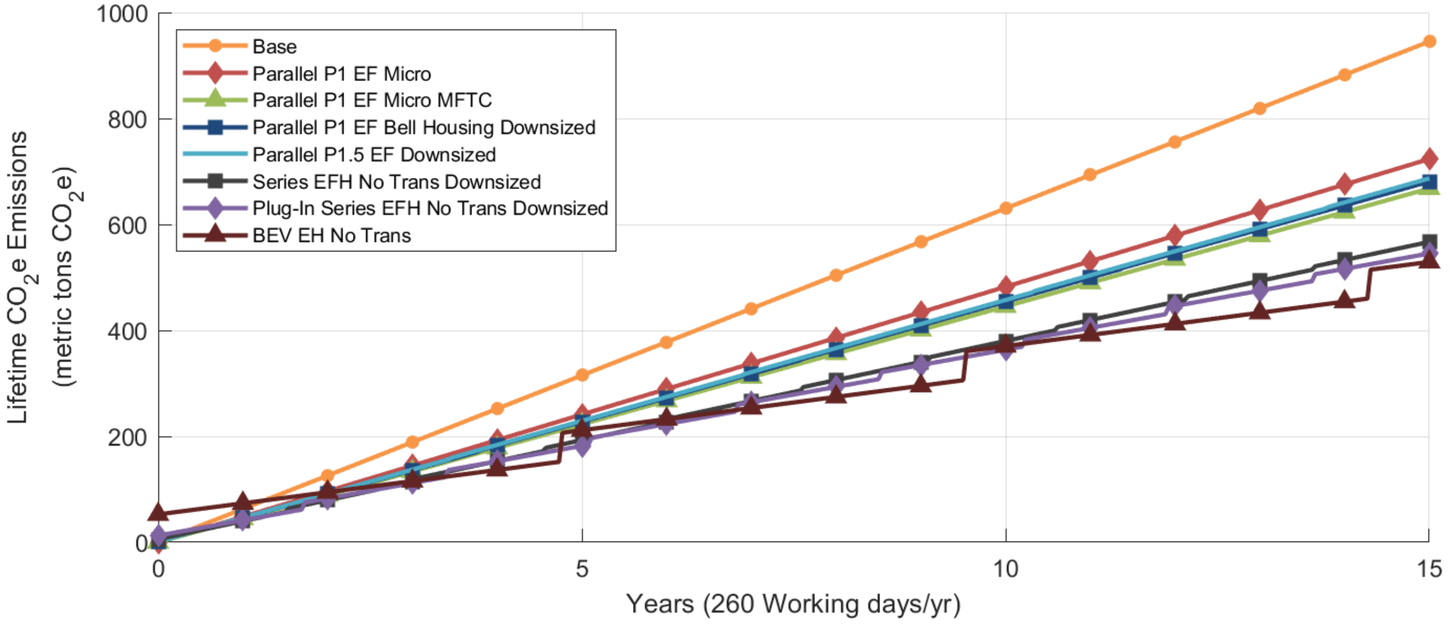


Figure 9. U.S. average total CO_2e emissions over the 15-year lifetime of all architectures. Lifetime CO_2e is relative to the base at time zero, so the base architecture starts at 0 metric tons CO_2e. Step changes in the CO_2e plot represent maintenance events, like replacing the battery.

As mentioned previously, the EPA recommends using the average mix of CO_2e for carbon dioxide analyses [19]. These emissions do not perfectly account for the real-world emissions from plugging in a vehicle like a BEV since the added electric load increases the electricity demand in that region. The increased electricity demand is met through peaker power plants which typically produce electricity at a higher emission rate [8]. This is known as a marginal source, and Burton et al. decided to look at the marginal electricity emissions to more accurately capture the electricity grid emissions from plugging in a vehicle like a BEV [8]. The marginal electricity was not pursued in this paper due to the complexity of the analysis and unavailability of the data; instead, the non-baseload CO_2e emissions were considered. Non-baseload sources of electricity emissions are power plants that supply electricity only during peak times [27], corresponding to a much higher emission rate. These emission rates occur when plugging in a BEV while the grid is already at or beyond its baseload capacity, meaning the high-emitting power plants that operate at peak times are supplying all of the additional electricity [27]. This non-baseload rate served as an upper value of electricity emissions for the case when a BEV or plug-in series is plugged in at a peak time of the day. The non-baseload rate should not be used to compare architectures unless it is known that all charging occurs at a peak time beyond the electricity grid's baseload capacity. In Figure 10, see this comparison using the non-baseload CO_2e emissions from the electricity grid. Only the curves for the plug-in series hybrid and the BEV change since these are the only architectures that use electricity from the grid.

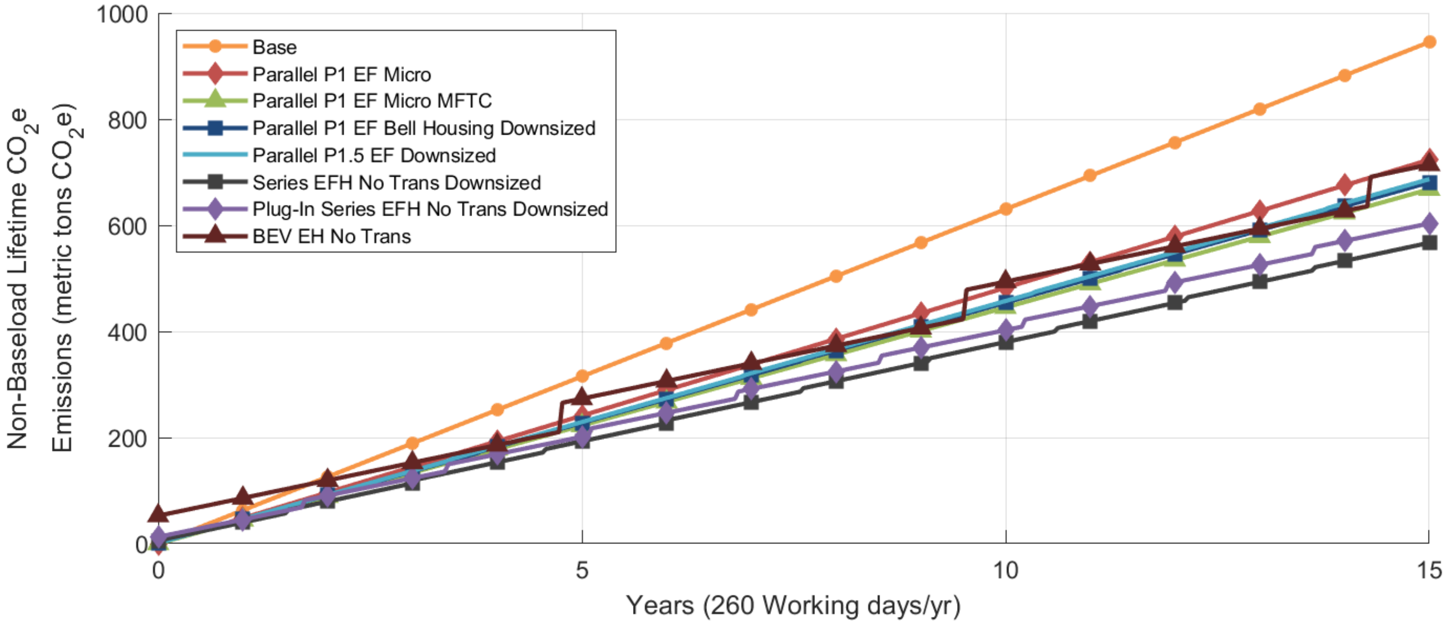


Figure 10. U.S. non-baseload total CO_2e emissions over the 15-year lifetime of all architectures. Lifetime CO_2e is relative to the base at time zero, so the base architecture starts at 0 metric tons CO_2e. Step changes in the CO_2e plot represent maintenance events, like replacing the battery. Non-baseload refers to electricity emissions for power plants that supply electricity only during peak times [27], representing a high level of emissions for charging BEV or plug-in series architectures in the U.S.

Figure 9 and Figure 10 both present comparisons for the eight different architectures studied. In all cases for the U.S. average mix and for the U.S. non-baseload mix, each electrified architecture is reducing the lifetime CO_2e emissions as compared to the base machine. Every architecture also has a relatively short emissions payback period, where the emissions payback period is the amount of time before the electrified architecture emits less than the base architecture. For the U.S. average values, the BEV has the longest emissions payback period at 1.27 years, and all other electrified architectures have emissions payback periods of less than a half year.

The numeric values for the 15-year total values from Figure 9 and Figure 10 are presented in Table 6. The values for the percentage decrease relative to the base architecture are also given in Table 6, where the BEV has the greatest decrease relative to the base architecture using the U.S. average CO_2e electricity emissions, but the series hybrid has the greatest decrease relative to the base architecture when using U.S. non-baseload CO_2e electricity emissions.

Table 6. Lifetime CO_2e emissions, looking at the U.S. Average and the U.S. Non-Baseload electricity grid. Percentage decrease values are included, all comparing lifetime CO_2e to the base machine.

	Base	Parallel P1 EF Micro	Parallel P1 EF Micro MFTC	Parallel P1 EF Bell Housing Downsized	Parallel P1.5 EF Downsized	Series EFH No Trans Downsized	Plug-In Series EFH No Trans Downsized	BEV EH No Trans
U.S. Average Lifetime CO_2e emissions (metric tons CO_2e)	945	723	668	681	687	567	545	529
U.S. Average Lifetime CO_2e Percent Decrease from Base (%)	0.0	23.5	29.3	28.0	27.3	40.0	42.3	44.0
U.S. Non-Baseload CO_2e emissions (metric tons CO_2e)	945	723	668	681	687	567	603	714
U.S. Non-Baseload Lifetime CO_2e Percent Decrease from Base (%)	0.0	23.5	29.3	28.0	27.3	40.0	36.2	24.4

Cost Analysis

Description

Technologies with the lowest total cost of ownership are the most likely to be adopted [1]. Therefore, the lifetime cost analysis plays a crucial role in finding the most effective way to reduce emissions, as customers may prefer to go with a higher-emitting architecture if it is cheaper over the machine's lifetime. However, while the lowest total cost of ownership may be the most logical path to pursue, other customers may prioritize the initial price of a product, particularly those considering capital expenditures rather than operating expenditures. In such cases, the purchase price may be the most straightforward and useful metric for determining the affordability of a product.

This section begins by looking at the data sources and assumptions for the cost analysis before characterizing the costs of all the architectures and comparing them to the base architecture, including maintenance costs. All values for cost are using U.S. Dollars (USD).

Analysis

Data Sources & Assumptions

The cost analysis requires an accurate representation of the main cost factors over the lifetime of the Pettibone Cary-Lift. To match the CO_2e analysis, data from 2021 was used for the cost data sources, as seen in Table 7.

Table 7. Data sources for cost analysis.

Data	Source
Diesel	
Diesel on-road prices	EIA 2021 data [35].
Diesel on-road federal & state taxes	EIA July 2021 data [36].
Electricity	
Cost of electricity per kWh	EIA 2021 data [37].
Cost of electricity demand charges	Estimate from NREL[1] [38].
Components	
Conventional component cost: engines, transmissions, etc.	Values from quotes.
Electrification component cost: electric machines, inverters	Values from quotes, other estimates based on similarity[1].

[1] See Table 8 for key assumptions for cost analysis, and Appendix E for full table of assumptions.

Besides these data sources, assumptions also had to be made to complete the analysis where exact values were unavailable or for simplicity. Table 8 displays a list of the key assumptions for the cost analysis, with a complete list of assumptions found in Appendix E.

Table 8. Key assumptions for cost analysis. See the full table of assumptions in Appendix E.

Category	Assumption	Justification
Lifetime of Cary-Lift	15 years	15-year lifetime in [2].
Cost of diesel, electricity, and components	Does not change over the lifetime	Assumption for simplicity and because of unpredictable pricing
Diesel price	Off-road price is on-road price minus state and federal diesel taxes for 2021	No data available for off-road diesel prices by region.
Electricity price	Average of industrial and commercial for each region for 2021	Cary-Lifts operate in commercial and industrial applications. Data from EIA [37].
Battery replacement period	443 days for plug-in battery; other results estimated based on NMC curve and this data	Plug-in series battery lifetime modeled by the battery supplier [31] and informed by other publications mentioned in Figure 8.
Battery cost	$250/kWh	Cost to manufacturer, based on [39].

Cost Plots

Using the data sources and assumptions previously mentioned, the cost values were obtained for each of the electrified architectures relative to the base machine. See Figure 11 for the purchase price increase of each architecture. Notice the relatively low cost of the parallel hybrids pursued versus the high costs required for the series and BEV machines. This is due to increased amount and power of components needed for these higher levels of electrification, where the series and plug-in series hybrid all require two electric machines for tractive effort, one electric machine as a generator, and one electric machine for hydraulic work. Increasing the number of electric machines and associated components increases the price dramatically, hence the sharp increase in moving from parallel to series hybrid architectures. The BEV has fewer components than the series hybrids without an engine and generator, but a large battery adds over $160,000 to the purchase price. Note that cost decreases are also accounted for, meaning removing a component like the transmission removes cost from the machine.

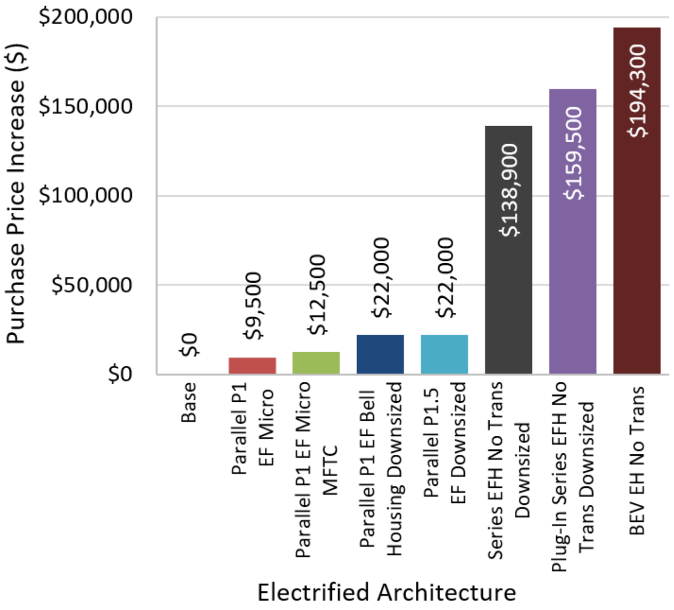


Figure 11. Purchase price increase to the customer. The sharp increase in series hybrid is due to the need for multiple strong electrification components. Base machine starts at zero cost at time zero.

Perhaps more useful than the purchase price increase is the overall cost of the machine over its 15-year lifetime, as seen in Figure 12. The step changes in this figure represent maintenance events on the different architectures, like battery replacements, engine rebuilds, transmission rebuilds, and axle rebuilds. Notice the significant costs associated with the series, plug-in series, and BEV architectures, which all have 15-year costs above the baseline machine. These architectures have a higher overall cost primarily due to the much higher initial cost. These costs stay higher than the base machine due to the frequent expensive battery replacements required. The least expensive architecture is the Parallel P1 EF Micro MFTC, which has a similar lifetime cost to the Parallel P1 EF Micro, Parallel P1 EF Bell Housing Downsized, and the Parallel P1.5 EF Downsized.

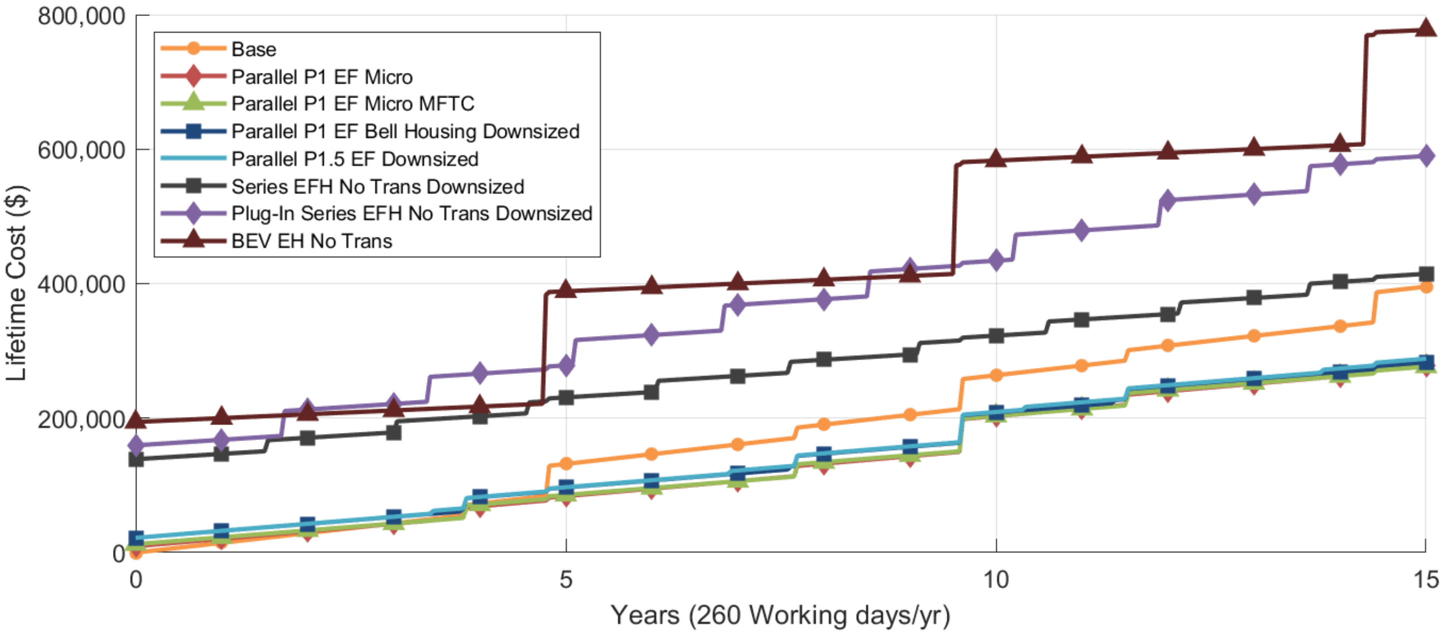


Figure 12. U.S. average total cost to operate machine over the 15-year lifetime of all architectures. Lifetime cost is relative to the base, so the base architecture starts at \$0. Step changes in the cost plot represent maintenance events, like replacing the battery, rebuilding the engine, etc.

Cost of Carbon Abatement: Dollars per metric ton CO_2e Avoided

Description

Current technologies for light-duty on-road vehicles have carbon abatement costs of \$100s to \$1,000s per metric ton of CO_2e avoided [2]. These costs look at the lifecycle of the vehicle, comparing the total cost of ownership over 15 years of different vehicles like a hybrid, a fuel cell electric vehicles (FCEV), and a BEV, all compared to a traditional gasoline internal combustion engine vehicle (ICEV) [2]. Looking at the current technology case, the study found that all technologies lowered the lifetime CO_2e emissions. Still, all current technologies also increased the lifetime price of the vehicle relative to the gasoline ICEV [2].

This paper used U.S. average emissions values and also included Pennsylvania, Oregon, and Indiana. Pennsylvania was chosen because the highest volume of Cary-Lift sales is in Pennsylvania, helping to inform Pettibone on architecture options for their highest volume region. Oregon and Indiana were chosen to represent lower and upper values on electricity grid emissions. Oregon resided around the 15th percentile of average electricity emissions, while Indiana resided around the 85th percentile of average electricity emissions for 2021 [27]. Comparing results from Oregon and Indiana helped to comprehend the effect of a low carbon versus a high carbon grid on lifetime CO_2e emissions. Comparisons may also be made based on the cost of diesel fuel and the cost of electricity, both of which vary by region.

Analysis

Similar to the light-duty on-road study in [2], the Pettibone Cary-Lift's electrified architectures all find lowered lifetime CO_2e emissions. However, due to the relatively low price of some modifications for high fuel savings, certain electrified architectures reduce the lifetime cost of the machine, leading to negative carbon abatement costs. This means that a customer, for example, will spend less money on the machine over its lifetime while also reducing CO_2e emissions. The cost of carbon abatement (cost to reduce CO_2e emissions) using U.S. average values is presented in Table 9, where lower positive values indicate a lower cost to reduce emissions. However, more negative values for cost of carbon abatement do not necessarily indicate a better architecture. For example, see the Parallel P1 EF Micro and Parallel P1 EF Micro MFTC architectures in Table 9, where the MFTC architecture has a higher carbon abatement (better savings) but also a higher cost than the non-MFTC architecture. The cost of carbon abatement of these architectures would indicate the non-MFTC version is better because of a lower value (-\$547 vs. -\$440 / metric ton), while the lower value is actually because of a lower (worse) carbon abatement value (216 vs. 270 metric tons abated). This is a limitation of this metric when lifetime cost values become negative, which Table 9 highlights.

Table 9. Lifetime cost delta, lifetime carbon abatement, and cost of carbon abatement for U.S. average values.

Architecture	Cost Delta to Base ($)	Carbon Abated (metric tons CO_2e)	Cost of Carbon Abatement ($ / metric ton CO_2e)
Base	0	0	0
Parallel P1 EF Micro	-118,119	216	-547
Parallel P1 EF Micro MFTC	-118,926	270	-440
Parallel P1 EF Bell Housing Downsized	-112,244	257	-436
Parallel P1.5 EF Downsized	-107,130	252	-426
Series EFH No Trans Downsized	+19,030	367	+52
Plug-In Series EFH No Trans Downsized	+194,283	387	+502
BEV EH No Trans	+381,732	400	+955

Figure 13 presents a visual representation of the cost of carbon abatement on the left y-axis and total carbon abatement on the right y-axis, varying by region due to differences in the cost of diesel and electricity as well as differences in electricity grid emissions. Other costs and emissions are assumed to be the same in every region. See Appendix D and Appendix E for full tables of assumptions.

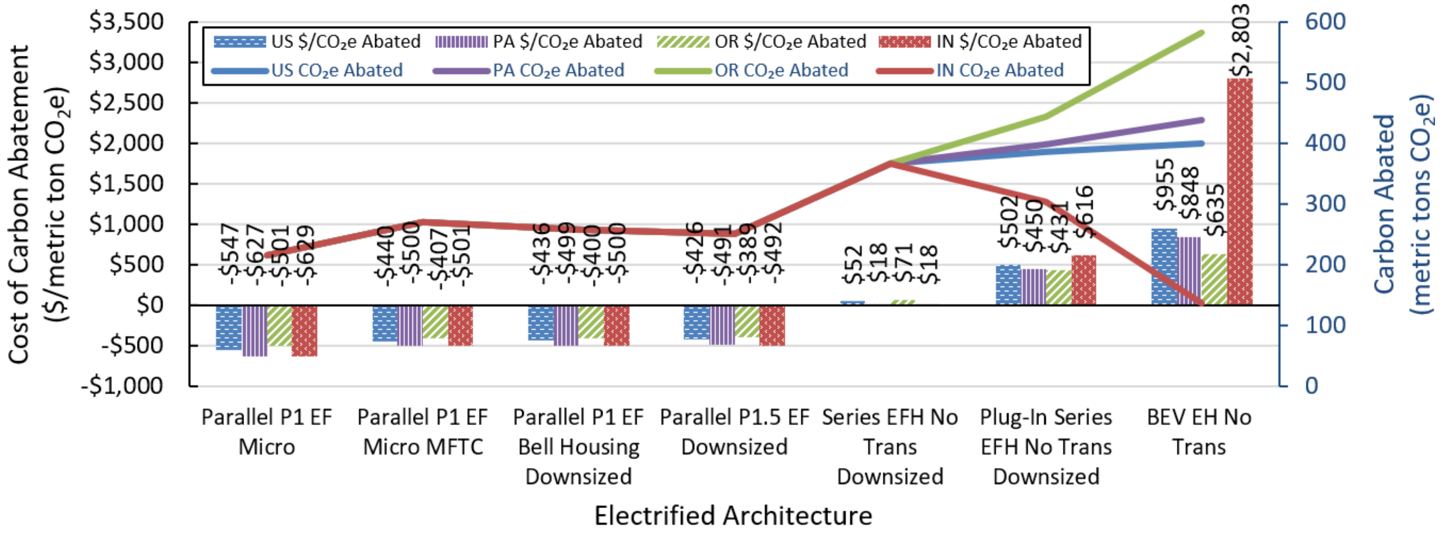


Figure 13. Cost of carbon abatement (represented by bars), and total carbon abated over 15-year lifetime (represented by lines), for each region. Negative bar values mean cost reduction for carbon abatement, meaning lifetime cost is lower than the base machine. All electrified architectures have lifetime CO2e emissions lower than the base machine.

Based on Table 9, the highest cost savings come from the Parallel P1 EF Micro MFTC architecture. This architecture also has the highest carbon abatement of all of the parallel hybrid architectures. This makes the Parallel P1 EF Micro MFTC architecture a desirable option for customers who want to reduce their cost of ownership while also reducing their carbon footprint. This architecture should also be attractive to manufacturers pursuing electrified architectures that come at minimal cost yet yield significant CO_2e benefits. It is worth noting that the Multi-Function Torque Converter (MFTC) in the Parallel P1 EF Micro MFTC architecture is not a product that currently exists in the heavy-duty off-road space [24].

Another measurement that could inform architecture selection is the social cost of carbon. The social cost of carbon places a cost on the negative impact of emitting greenhouse gases (CO_2e) into the atmosphere [40]. This depends on many factors, one significant element being discount rates, which are measures that attribute a value to the future, with higher discount rates meaning the future is valued less relative to the present and lower discount rates meaning the future is valued more relative to the present [41]. Using a high discount rate (less value on the future), estimates range from \$9 to \$40 / metric ton CO_2 emissions [40]. Using a lower discount rate (higher value on the future), this social cost of carbon ranges from \$122 to \$525 / metric ton CO_2 emissions [40]. These values, while not considered in this paper, are significant because they could justify the need to pursue CO_2 savings, even when these savings come at an increased cost. Factoring in the social cost of carbon into Figure 13, for example, would reduce the cost of all architectures while disproportionately favoring the architectures with the highest CO_2e savings.

The data previously seen in Table 9 provides the numerical values for the cost and CO_2e for each of the electrified architectures of the Cary-Lift in the U.S. Figure 14 offers this information in a chart, with error bars representing the upper and lower limits for cost and CO_2e. Notice that the plug-in series hybrid and the BEV are the only architectures with vertical error bars. This is because these are the only architectures that use the electricity grid and will therefore have variable CO_2e values based on what region this electricity was sourced; the other architectures only consume diesel, which is assumed to have the same emissions no matter the region (see Appendix D for full list of CO_2e analysis assumptions). All architectures have horizontal error bars as this represents cost, where cost varies for electricity and diesel by region. Notice the error bars for the BEV, where the upper limit represents charging the BEV in Oregon, where grid emissions are relatively low. The lower limit on the error bar represents charging the BEV in Indiana, where the grid has much higher CO_2e emissions. These emissions become so high with a carbon-intensive grid that the BEV becomes the highest emitting electrified architecture, with only the base machine emitting more over its lifetime. This demonstrates why caution must be taken when choosing a BEV since the grid emissions can be the difference between a BEV being the least emitting electrified architecture or the BEV being the most emitting electrified architecture.

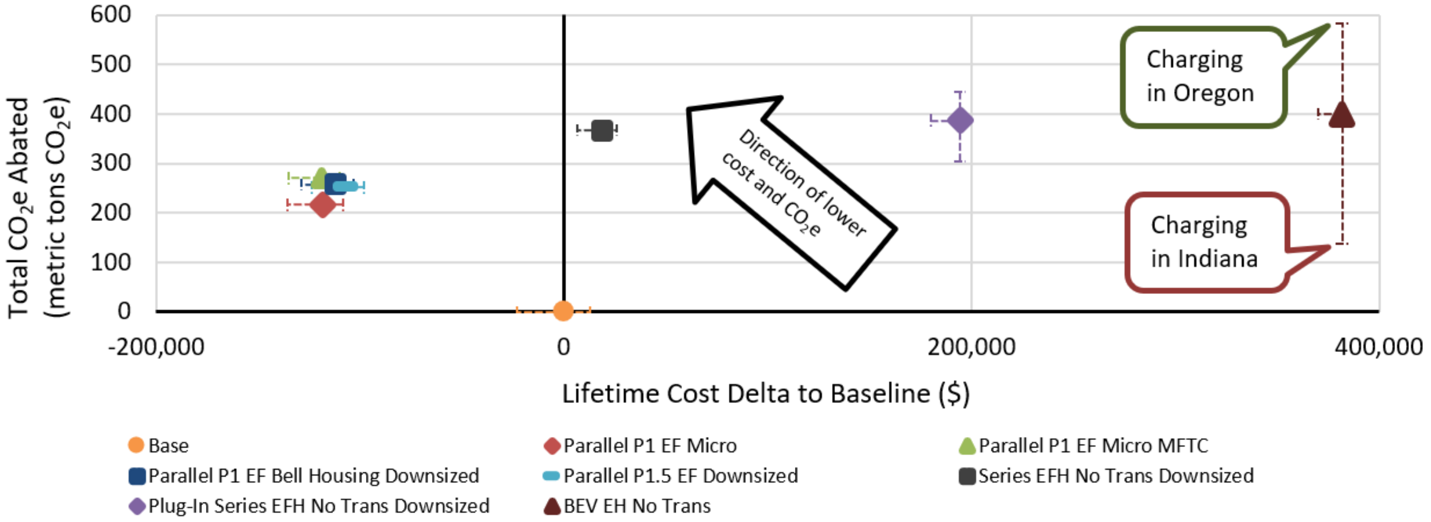


Figure 14. CO_2e avoided vs. operating cost delta over the lifetime of Cary-Lift, including demand charges on electricity. Higher lifetime cost than the base machine for positive x values and lower lifetime cost for negative x values. The data points represent the U.S. average values, and the error bars are the highest and lowest values from U.S., PA, OR, and IN for cost (horizontal) and CO_2e (vertical).

While Figure 14 is a useful visual for lifetime CO_2e and lifetime cost of ownership, some customers may place a higher weight on the purchase price than on the lifetime cost of the machine. This is similar to the light-duty industry, where a new car buyer may look at the car's purchase price to determine affordability rather than looking at the lifetime cost of the vehicle after factoring in fuel costs, maintenance, and other costs. In these instances where the purchase price is the priority, Figure 15 provides a visual for the purchase price increase per CO_2e abated over the lifetime. This figure allows customers to determine what architecture may be best suited for their immediate needs by selecting an amount they are willing to pay to reduce emissions. The Parallel P1 EF Micro architecture, for example, requires a purchase price increase of $44 to save one metric ton of CO_2e over the lifetime of the machine.

Notice how the electrified architectures without plug-in capability are all at level prices for each region since the purchase price is not affected by region and emissions are not affected by region (see complete assumptions in Appendix D and E). For the plug-in series hybrid and the BEV, the electricity grid emissions impact the cost increase per CO_2e abated value, as lower CO_2e abatement means a higher cost per CO_2e abated. With a high-emitting grid like in Indiana, this sharply raises the cost increase per CO_2e. Also, the cost of electricity is higher in Indiana than in other regions studied, leading to a further increase in cost per CO_2e abated for the BEV.

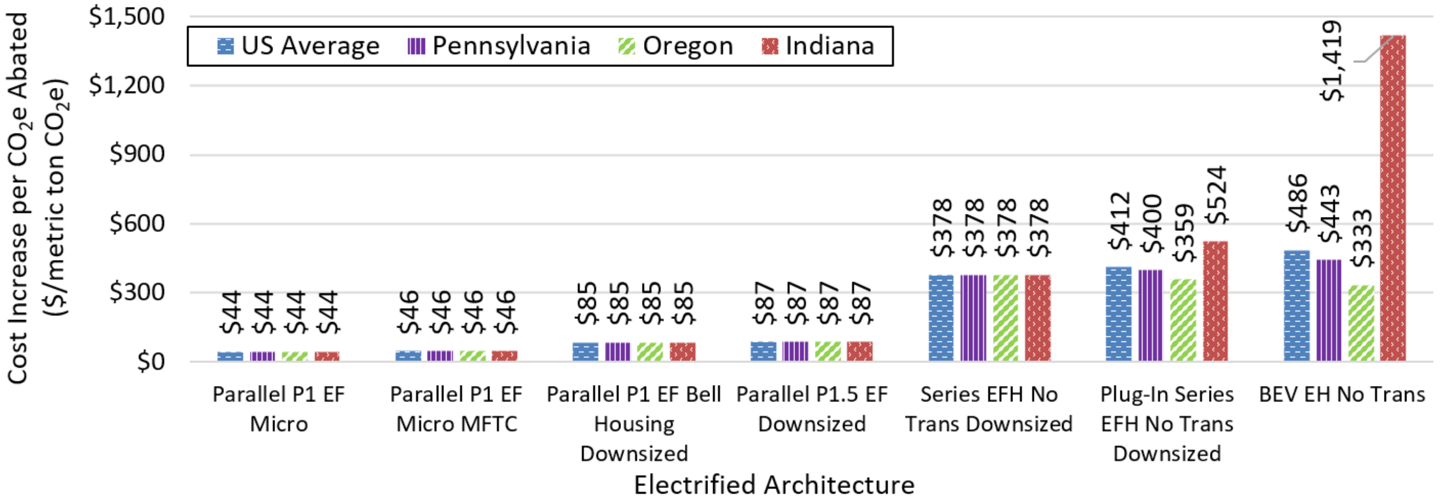


Figure 15. Base machine cost increase per metric ton CO_2e abated. This looks at a cost increase to the customer for the purchase price (not factoring in lifetime costs of diesel, electricity, etc.) and divides that by the lifetime CO_2e abated.

Applications

Carbon abatement cost provides manufacturers and customers with a metric to visualize and enumerate the amount of money to be spent to reduce CO_2e. Other manufacturers of similar equipment can use these metrics to help decide on the technology to achieve their company's carbon footprint or monetary goals. The plot in Figure 14 provides manufacturers with information to determine an architecture that achieves the CO_2e savings desired while also factoring in the overall cost to the customer. Figure 15 looks at the customer’s perspective regarding purchase price. This assigns a cost increase to the base machine per metric ton of CO_2e abated. This visual helps determine the least expensive architecture to purchase to achieve CO_2e savings;

it is useful for customers who may place a higher weight on purchase price than on lifetime price.

These cost per CO$_2$e abated values can also be used to assess the viability of new technologies. Cost is a primary concern in the adoption of new technologies [1], so having an estimated cost to reduce emissions can help manufacturers decide on what technology to pursue. Additionally, these metrics may be used by regulators to see the feasibility of CO$_2$e savings, and the costs associated with achieving certain levels of CO$_2$e reduction.

Final Architecture Selection

The selection of an electrified architecture demands a complex balance of factors important to the manufacturer and the customer. Currently, there is a strong push toward electrification in on-road industries [3], and the heavy-duty off-road sector is following suit with examples like the John Deere 644K series hybrid wheel loader [42] and the Caterpillar D7E series hybrid dozer [43].

Increasingly stringent regulations on CO$_2$e emissions will also drive electrification and other carbon-saving technologies, as the U.S. targets a net-zero-emissions economy by 2050 [1]. These factors demonstrate the increasingly important value of CO$_2$e savings, and how these savings may have a disproportionate impact on architecture selection processes in the future.

With these factors in mind, this project decided on a plug-in series hybrid as the electrified architecture of choice; see Figure 16 for a schematic of this plug-in series hybrid. This decision was made due to the following (in no particular order):

- Countries and companies are beginning to consider carbon neutrality in their goals, as seen with the U.S. target of a net-zero-emissions economy by 2050 [1], hence the push for lower carbon emissions in the plug-in series. Also, CO$_2$e savings were a main tenet of this project.
- The plug-in series enables around-the-clock operation like the current Cary-Lift, where an architecture like the BEV would need to stop to be recharged, and as discussed above, would be challenging for shifts longer than 8 hours.
- This architecture provides a flexible and highly capable platform upon which the research team can further pursue novel research to assist in decarbonizing the heavy-duty off-road industry.
- The plug-in series could be prototyped with mostly Commercial Off The Shelf (COTS) major hardware.
- In addition to significant CO$_2$e abatement, the plug-in series results in more tertiary advantages than any other architecture. These are outside of the scope of this paper, however, include attributes such as increased gradeability, increased acceleration, switchable 2WD / 4WD operation, continuous off-board AC Power Export, silent mode, etc.

The plug-in series hybrid emerged as a superior architecture due to the CO$_2$e savings. As seen in Figure 9 and Figure 10, the lifetime CO$_2$e values for the plug-in series were the second lowest in both average and non-baseload emissions for U.S. values. This was a strong driver for the plug-in series hybrid as the final architecture decision because CO$_2$e savings were the main focus of this research work and because future regulations may require emissions reductions in the off-road space given current carbon neutrality goals [1, 7].

It is worth noting that the plug-in series hybrid comes at a higher cost than all architectures except for the BEV; both for purchase price and lifetime cost. The cost is highly sensitive to the price of electrification components and batteries. With these cost concerns in mind, certain applications will benefit more from an architecture like the Parallel P1 EF Micro, which reduces CO$_2$e considerably while decreasing lifetime cost (see Figure 14).

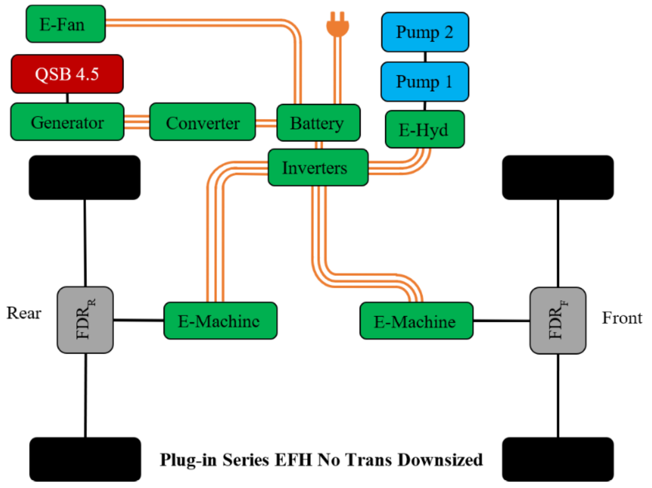


Figure 16. Final architecture selected: Plug-in series hybrid.

Discussion

While many of the plots presented in this paper provide valuable data for manufacturers and customers of heavy-duty off-road equipment, only some will apply to different applications. The highly varied use cases of heavy-duty off-road equipment necessitate different considerations for various equipment types, for different manufacturers, and sometimes for different customers. A plot looking at the purchase price may be valuable to the customer and manufacturer. Still, regulations could require a high level of electrification that pushes out the less expensive architectures.

The high cost of strong electrified options, including the series, plug-in series, and BEV, may eliminate these options from consideration for some. However, these options become more attractive as regulations change, companies place increasing priority on CO$_2$e reduction, and the price for such technology decreases. The architectures studied in this paper represent a variety of electrification options, from micro hybrids to parallel hybrids to series hybrids, all the way to a full BEV. While this does not cover all possible iterations, these detailed studies provide insight into possible electrification options for heavy-duty off-road equipment and where the benefits are found for each unique architecture.

Conclusions

This study analyzed electrified architectures for a heavy-duty off-road material handler, the Pettibone Cary-Lift 204i. The goal was to determine the best electrified architecture that could achieve fuel savings while also maintaining the performance requirements of the base machine. To determine the architectures worthy of detailed studies, two rounds of a Pugh-style decision matrix were used to determine a condensed list of electrified architectures that provided the highest potential for achieving project goals. This condensed list also included other architectures of research interest and architectures for comparison purposes.

An analysis of lifetime CO$_2$e emissions performed on all architectures revealed the base machine with the highest lifetime emissions, with the

BEV having the lowest emissions. For cost, the BEV ended up as the most expensive architecture, with the overall least expensive architecture the Parallel P1 EF Micro MFTC over the machine's 15-year lifetime. The cost per CO2e abated yielded the BEV again with the worst value, with the best value coming from the Parallel P1 EF Micro. Figure 17 summarizes the data in chart form. This figure looks at the normalized values for the categories of lifetime CO2e, cost, and cost of carbon abatement, where 1 is the highest (best) score, and 0 is the lowest (worst) score.

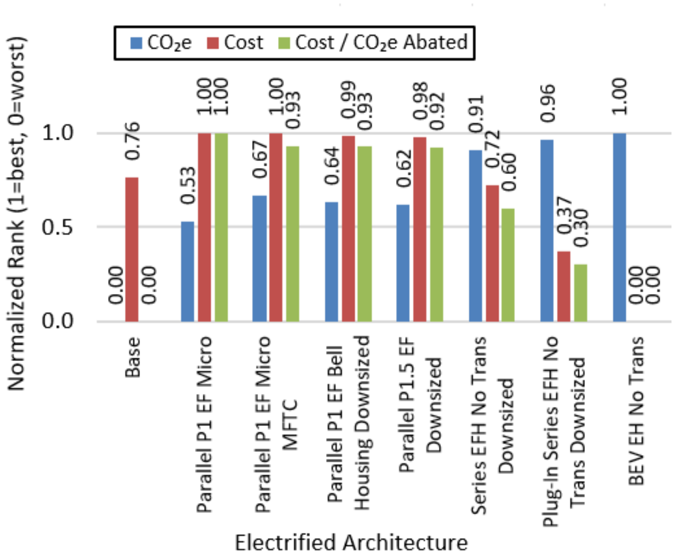


Figure 17. Normalized architecture comparison for lifetime CO_2e emissions, lifetime cost, and lifetime cost per CO_2e abated*. A higher rank is better, where a value of 1 for CO_2e means that architecture had the lowest CO_2e emissions, and a value of 0 would mean the highest CO_2e emissions, for example. This chart uses U.S. average values.

*As noted previously, there are limitations to the cost per CO_2e abated calculation. For example, while the Parallel P1 EF Micro had the best Cost/CO_2e abated score, the Parallel P1 EF Micro MFTC had a lower overall cost and CO_2e, making it better. This is a limitation of the Cost/CO_2e calculation explored in the Cost of Carbon Abatement section.

The final architecture decision, the plug-in series hybrid, saved a total of 387 tonnes of CO2e over its lifetime assuming U.S. average values for electricity emissions, and 342 tonnes of CO2e using U.S. non-baseload electricity emissions when compared to the base machine. Compared to the BEV, the plug-in series emits 13 more tonnes of CO2e, assuming average U.S. grid emissions, but emits 111 fewer tonnes of CO2e than the BEV when using non-baseload electricity emissions, indicating the source of electricity is an important consideration when targeting CO2e savings.

The cost of the plug-in series hybrid over the 15-year lifetime is higher than the base, coming in at around $194,000 over the base machine. This points to the importance of cost considerations when selecting an architecture. While CO2e savings were a main driver for selecting the plug-in series hybrid, this may not be the case for manufacturers or customers considering electrified architectures, where they may place a higher weight on cost. In this case, an architecture like the Parallel P1 EF Micro MFTC may be preferred as it saves over $118,000 and reduces CO2e by 270 tonnes over the lifetime of the machine.

While Figure 17 indicates that an architecture like the Parallel P1 EF Micro MFTC yields the highest overall scores, the manufacturer may not weigh each of these parameters equally. For example, if regulations determine the requirement of steep decreases in overall CO2e emissions, a strong hybrid architecture like the series hybrid may need to be chosen. The decision for which electrified architecture to pursue is ultimately determined by the manufacturer, who must weigh the current regulations, their company goals and ability, and the customer's goals and preferences while weighing the many other factors that go into new product development.

The results of this paper illustrate the benefits of different electrification architectures for different applications. In cost-sensitive applications where cost is primary and CO2e savings are beneficial, an architecture like the Parallel P1 EF Micro MFTC will save substantial money while still making significant reductions in CO2e emissions. In applications where CO2e savings are primary, an architecture like the plug-in series hybrid provides considerable CO2e savings in the U.S. when charged using the average electricity grid or the non-baseload grid, but these savings come at a monetary cost. For architectures with plug-in capability, like the plug-in series and the BEV, the source of the electricity is crucial. As seen in Figure 14, charging a BEV using Indiana's grid results in only 137 tonnes of CO2e saved compared to the base, which is lower than any other electrified architecture. This underscores the importance of considering not only direct emissions but also the electricity grid emissions, as the electricity grid used to charge the BEV can make the BEV the most or the least carbon-intensive electrified architecture.

Assumptions were made in this paper where accurate data was unavailable and where needed to maintain a reasonable scope. These assumptions were made carefully but may not be flawless and are subject to change (see Appendices D and E for all assumptions). Also, most comparisons in the paper were made looking at U.S. average values for CO2e and cost, which do not always represent accurate values since the region can have a large effect on values like electricity grid CO2e. Additionally, electricity grid emissions assumed an average CO2e emissions rate as recommended by the EPA [19], but the average mix of electricity is not always the accurate value to use when adding a load to the grid [8], hence the inclusion of non-baseload emissions in Figure 10. CO2e and cost values are used for 2021 and are assumed to be constant throughout the 15-year lifetime to avoid extrapolating predicted future data for CO2e and cost.

Lastly, it should be noted that although it was outside the scope of this paper to consider ambient temperature, other researchers are finding EV range reductions of nominally 60%, even at moderate winter temperatures (-5°C) [44]. These range losses are a direct result of reduced battery efficiency and diversion of energy to non-propulsion usage (HVAC and battery heating, for example). These effects have a disproportionate and non-linear negative impact on the architectures with the highest hybridization factors, with the largest negative shift being to the CO2e of the BEV case, thus shifting it upward in the plots of Figure 9 and Figure 10 if seasonal fluctuations in temperature are accounted for.

This paper is part of a U.S. Department of Energy-funded project aimed at reducing the fuel consumption of the Pettibone Cary-Lift by at least 20% through the development of an electrified demonstration vehicle. As mentioned in the Final Architecture Selection section, the architecture to be built for this project is a plug-in series hybrid. The authors expect more publications detailing operating cycle development, advanced control development and implementation, advanced thermal system development and implementation, and a final demonstration of fuel savings using the electrified demonstration vehicle.

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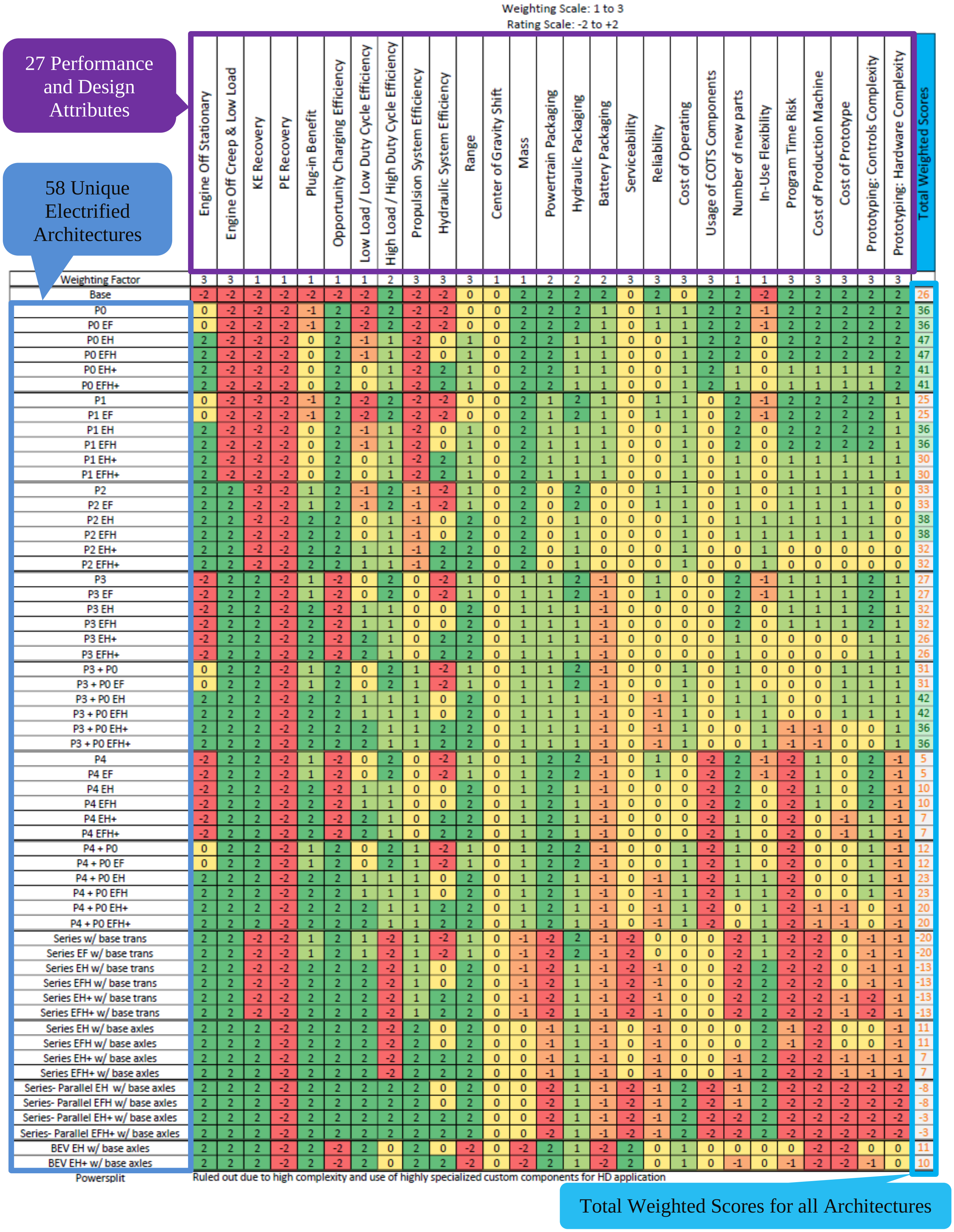
Definitions/Abbreviations

Pugh Matrix	Decision making matrix used to compare different options.
GHG	Greenhouse Gas, measured in CO_2e, or carbon dioxide equivalent, which combines pollutants to come up with an overall global warming potential [45].
CO_2e	Carbon dioxide equivalent. This combines pollutants to come up with an overall global warming potential [45]. This is a measure of greenhouse gases released into the atmosphere.
Off-road	Equipment that does not use roadways in its general applications [4].
U.S.	United States
PA	Pennsylvania
OR	Oregon
IN	Indiana
EF	Electrified Fan
EH	Electrified Hydraulics
EH+	Distributed Electrified Hydraulics
EFH	Electrified Fan and Hydraulics
EFH+	Electrified Fan and distributed Electrified Hydraulics
SOC	State of Charge. In this work, this refers to the level of charge in the battery.
PPS	Peaking Power Source. In this work, this is the battery.
CD	Charge Depleting mode. Vehicle operates with engine off as battery SOC decreases (charge depletes).
CS	Charge Sustaining mode. In this paper, this is the same as the thermostatic rule-based control, where the battery is sustained in a small range of battery SOC by turning on the engine to recharge battery at low setpoint of SOC, then turning back off engine at high setpoint of SOC.
PTO	Power Take-Off
MFTC	Multi-Function Torque Converter which allows for disconnection between engine and transmission. See Appendix C.
ICEV	Internal Combustion Engine Vehicle
FCEV	Fuel Cell Electric Vehicle

P0	Parallel hybrid architecture with electric machine on front end accessory drive (FEAD).
P1	Parallel hybrid architecture with electric machine on crankshaft.
P1 Micro	Parallel micro-hybrid architecture with only stop-start operation. Electric machine is starter motor. See Appendix C.
P1 Micro MFTC	Parallel micro-hybrid architecture with stop-start operation. Electric machine is starter motor. Adding Multi-Function Torque Converter for disconnection between engine and transmission. See Appendix C.
P1 Bell Housing	Parallel hybrid architecture where an electric machine is attached to a bell housing pump drive power take-off (PTO) connection to the engine. See Appendix C.
P1.5	Parallel hybrid architecture with electric machine attached through power take-off (PTO), shared with hydraulic pumps in this machine. See Appendix C.
P2	Parallel hybrid architecture where electric machine is between engine and transmission, and is decoupled from the engine by a clutch.
P3	Parallel hybrid architecture where electric machine is after transmission but before axles.
P3 + P0	Parallel hybrid architecture where electric machine is after transmission but before axles and adds an electric machine on front end accessory drive (FEAD).
Series	Series hybrid architecture powering axles through one electric machine each. Generator mounted on engine. See Appendix C.
Plug-In Series	Series hybrid architecture powering axles through one electric machine each. Generator mounted on engine. Using large battery with plug-in capability, meaning battery can be recharged through the electricity grid. See Appendix C.
EREV / Range Extended	Extended Range Electric Vehicle. Same as plug-in series (see plug-in series definition).
BEV	Battery Electric Vehicle. See Appendix C.
NMC	Nickel Manganese Cobalt chemistry for lithium-ion battery

Appendix A: Round 1 of Pugh Decision Matrix



Weighting Scale: 1 to 3
Rating Scale: -2 to +2

27 Performance and Design Attributes

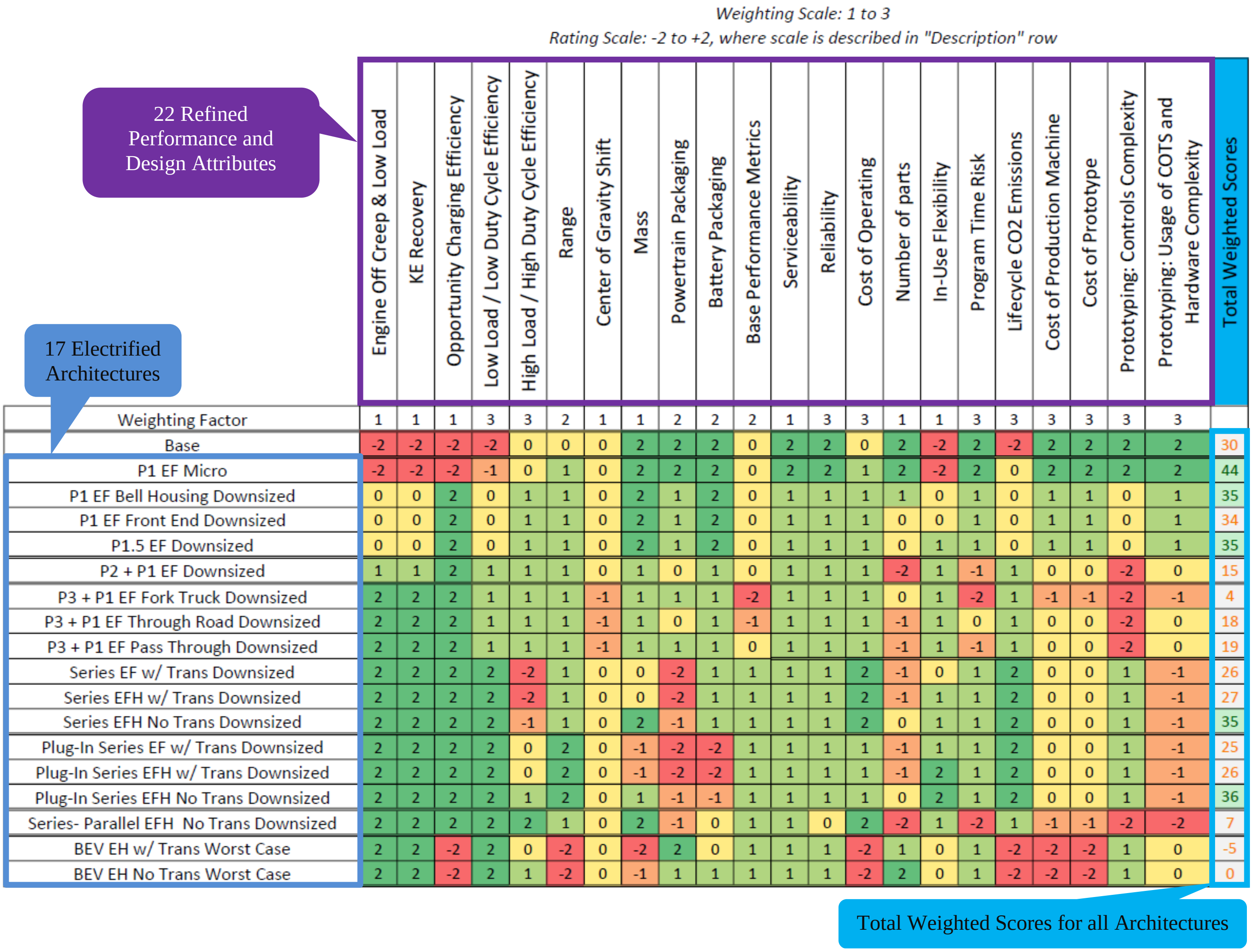
58 Unique Electrified Architectures

Total Weighted Scores for all Architectures

	Engine Off Stationary	Engine Off Creep & Low Load	KE Recovery	PE Recovery	Plug-in Benefit	Opportunity Charging Efficiency	Low Load / Low Duty Cycle Efficiency	High Load / High Duty Cycle Efficiency	Propulsion System Efficiency	Hydraulic System Efficiency	Range	Center of Gravity Shift	Mass	Powertrain Packaging	Hydraulic Packaging	Battery Packaging	Serviceability	Reliability	Cost of Operating	Usage of COTS Components	Number of new parts	In-Use Flexibility	Program Time Risk	Cost of Production Machine	Cost of Prototype	Prototyping: Controls Complexity	Prototyping: Hardware Complexity	Total Weighted Scores
Weighting Factor	3	3	1	1	1	1	1	2	3	3	3	1	1	2	2	2	3	3	3	3	1	1	3	3	3	3	3	
Base	-2	-2	-2	-2	-2	-2	-2	2	-2	-2	0	0	2	2	2	2	0	2	0	2	2	-2	2	2	2	2	2	26
P0	0	-2	-2	-2	-1	2	-2	2	-2	-2	0	0	2	2	2	1	0	1	1	2	2	-1	2	2	2	2	2	36
P0 EF	0	-2	-2	-2	-1	2	-2	2	-2	-2	0	0	2	2	2	1	0	1	1	2	2	-1	2	2	2	2	2	36
P0 EH	2	-2	-2	-2	0	2	-1	1	-2	0	1	0	2	2	1	1	0	0	1	2	2	0	2	2	2	2	2	47
P0 EFH	2	-2	-2	-2	0	2	-1	1	-2	0	1	0	2	2	1	1	0	0	1	2	2	0	2	2	2	2	2	47
P0 EH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	2	1	1	0	0	1	2	1	0	1	1	1	1	2	41
P0 EFH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	2	1	1	0	0	1	2	1	0	1	1	1	1	2	41
P1	0	-2	-2	-2	-1	2	-2	2	-2	-2	0	0	2	1	2	1	0	1	1	0	2	-1	2	2	2	2	1	25
P1 EF	0	-2	-2	-2	-1	2	-2	2	-2	-2	0	0	2	1	2	1	0	1	1	0	2	-1	2	2	2	2	1	25
P1 EH	2	-2	-2	-2	0	2	-1	1	-2	0	1	0	2	1	1	1	0	0	1	0	2	0	2	2	2	2	1	36
P1 EFH	2	-2	-2	-2	0	2	-1	1	-2	0	1	0	2	1	1	1	0	0	1	0	2	0	2	2	2	2	1	36
P1 EH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	1	1	1	0	0	1	0	1	0	1	1	1	1	1	30
P1 EFH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	1	1	1	0	0	1	0	1	0	1	1	1	1	1	30
P2	2	2	-2	-2	1	2	-1	2	-1	-2	1	0	2	0	2	0	0	1	1	0	1	0	1	1	1	1	0	33
P2 EF	2	2	-2	-2	1	2	-1	2	-1	-2	1	0	2	0	2	0	0	1	1	0	1	0	1	1	1	1	0	33
P2 EH	2	2	-2	-2	2	2	0	1	-1	0	2	0	2	0	1	0	0	0	1	0	1	1	1	1	1	1	0	38
P2 EFH	2	2	-2	-2	2	2	0	1	-1	0	2	0	2	0	1	0	0	0	1	0	1	1	1	1	1	1	0	38
P2 EH+	2	2	-2	-2	2	2	1	1	-1	2	2	0	2	0	1	0	0	0	1	0	0	1	0	0	0	0	0	32
P2 EFH+	2	2	-2	-2	2	2	1	1	-1	2	2	0	2	0	1	0	0	0	1	0	0	1	0	0	0	0	0	32
P3	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	1	2	-1	0	1	0	0	2	-1	1	1	1	2	1	27
P3 EF	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	1	2	-1	0	1	0	0	2	-1	1	1	1	2	1	27
P3 EH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	1	1	-1	0	0	0	0	2	0	1	1	1	2	1	32
P3 EFH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	1	1	-1	0	0	0	0	2	0	1	1	1	2	1	32
P3 EH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	1	1	-1	0	0	0	0	1	0	0	0	0	1	1	26
P3 EFH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	1	1	-1	0	0	0	0	1	0	0	0	0	1	1	26
P3 + P0	0	2	2	-2	1	2	0	2	1	-2	1	0	1	1	2	-1	0	0	1	0	1	0	0	0	1	1	1	31
P3 + P0 EF	0	2	2	-2	1	2	0	2	1	-2	1	0	1	1	2	-1	0	0	1	0	1	0	0	0	1	1	1	31
P3 + P0 EH	2	2	2	-2	2	2	1	1	1	0	2	0	1	1	1	-1	0	-1	1	0	1	1	0	0	1	1	1	42
P3 + P0 EFH	2	2	2	-2	2	2	1	1	1	0	2	0	1	1	1	-1	0	-1	1	0	1	1	0	0	1	1	1	42
P3 + P0 EH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	1	1	-1	0	-1	1	0	0	1	-1	-1	0	0	1	36
P3 + P0 EFH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	1	1	-1	0	-1	1	0	0	1	-1	-1	0	0	1	36
P4	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	2	2	-1	0	1	0	-2	2	-1	-2	1	0	2	-1	5
P4 EF	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	2	2	-1	0	1	0	-2	2	-1	-2	1	0	2	-1	5
P4 EH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	2	1	-1	0	0	0	-2	2	0	-2	1	0	2	-1	10
P4 EFH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	2	1	-1	0	0	0	-2	2	0	-2	1	0	2	-1	10
P4 EH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	2	1	-1	0	0	0	-2	1	0	-2	0	-1	1	-1	7
P4 EFH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	2	1	-1	0	0	0	-2	1	0	-2	0	-1	1	-1	7
P4 + P0	0	2	2	-2	1	2	0	2	1	-2	1	0	1	2	2	-1	0	0	1	-2	1	0	-2	0	0	1	-1	12
P4 + P0 EF	0	2	2	-2	1	2	0	2	1	-2	1	0	1	2	2	-1	0	0	1	-2	1	0	-2	0	0	1	-1	12
P4 + P0 EH	2	2	2	-2	2	2	1	1	1	0	2	0	1	2	1	-1	0	-1	1	-2	1	1	-2	0	0	1	-1	23
P4 + P0 EFH	2	2	2	-2	2	2	1	1	1	0	2	0	1	2	1	-1	0	-1	1	-2	1	1	-2	0	0	1	-1	23
P4 + P0 EH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	2	1	-1	0	-1	1	-2	0	1	-2	-1	-1	0	-1	20
P4 + P0 EFH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	2	1	-1	0	-1	1	-2	0	1	-2	-1	-1	0	-1	20
Series w/ base trans	2	2	-2	-2	1	2	1	-2	1	-2	1	0	-1	-2	2	-1	-2	0	0	0	-2	1	-2	-2	0	-1	-1	-20
Series EF w/ base trans	2	2	-2	-2	1	2	1	-2	1	-2	1	0	-1	-2	2	-1	-2	0	0	0	-2	1	-2	-2	0	-1	-1	-20
Series EH w/ base trans	2	2	-2	-2	2	2	2	-2	1	0	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	0	-1	-1	-13
Series EFH w/ base trans	2	2	-2	-2	2	2	2	-2	1	0	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	0	-1	-1	-13
Series EH+ w/ base trans	2	2	-2	-2	2	2	2	-2	1	2	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	-1	-2	-1	-13
Series EFH+ w/ base trans	2	2	-2	-2	2	2	2	-2	1	2	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	-1	-2	-1	-13
Series EH w/ base axles	2	2	2	-2	2	2	2	-2	2	0	2	0	0	-1	1	-1	0	-1	0	0	0	2	-1	-2	0	0	-1	11
Series EFH w/ base axles	2	2	2	-2	2	2	2	-2	2	0	2	0	0	-1	1	-1	0	-1	0	0	0	2	-1	-2	0	0	-1	11
Series EH+ w/ base axles	2	2	2	-2	2	2	2	-2	2	2	2	0	0	-1	1	-1	0	-1	0	0	-1	2	-2	-2	-1	-1	-1	7
Series EFH+ w/ base axles	2	2	2	-2	2	2	2	-2	2	2	2	0	0	-1	1	-1	0	-1	0	0	-1	2	-2	-2	-1	-1	-1	7
Series- Parallel EH w/ base axles	2	2	2	-2	2	2	2	2	2	0	2	0	0	-2	1	-1	-2	-1	2	-2	-1	2	-2	-2	-2	-2	-2	-8
Series- Parallel EFH w/ base axles	2	2	2	-2	2	2	2	2	2	0	2	0	0	-2	1	-1	-2	-1	2	-2	-1	2	-2	-2	-2	-2	-2	-8
Series- Parallel EH+ w/ base axles	2	2	2	-2	2	2	2	2	2	2	2	0	0	-2	1	-1	-2	-1	2	-2	-2	2	-2	-2	-2	-2	-2	-3
Series- Parallel EFH+ w/ base axles	2	2	2	-2	2	2	2	2	2	2	2	0	0	-2	1	-1	-2	-1	2	-2	-2	2	-2	-2	-2	-2	-2	-3
BEV EH w/ base axles	2	2	2	-2	2	-2	2	0	2	0	-2	0	-2	2	1	-2	2	0	1	0	0	0	0	-2	-2	0	0	11
BEV EH+ w/ base axles	2	2	2	-2	2	-2	2	0	2	2	-2	0	-2	2	1	-2	2	0	1	0	-1	0	-1	-2	-2	-1	0	10
Powersplit	Ruled out due to high complexity and use of highly specialized custom components for HD application																											

Figure A1. First round of the Pugh-style decision matrix for different electrified architectures.

Appendix B: Round 2 of Pugh Decision Matrix



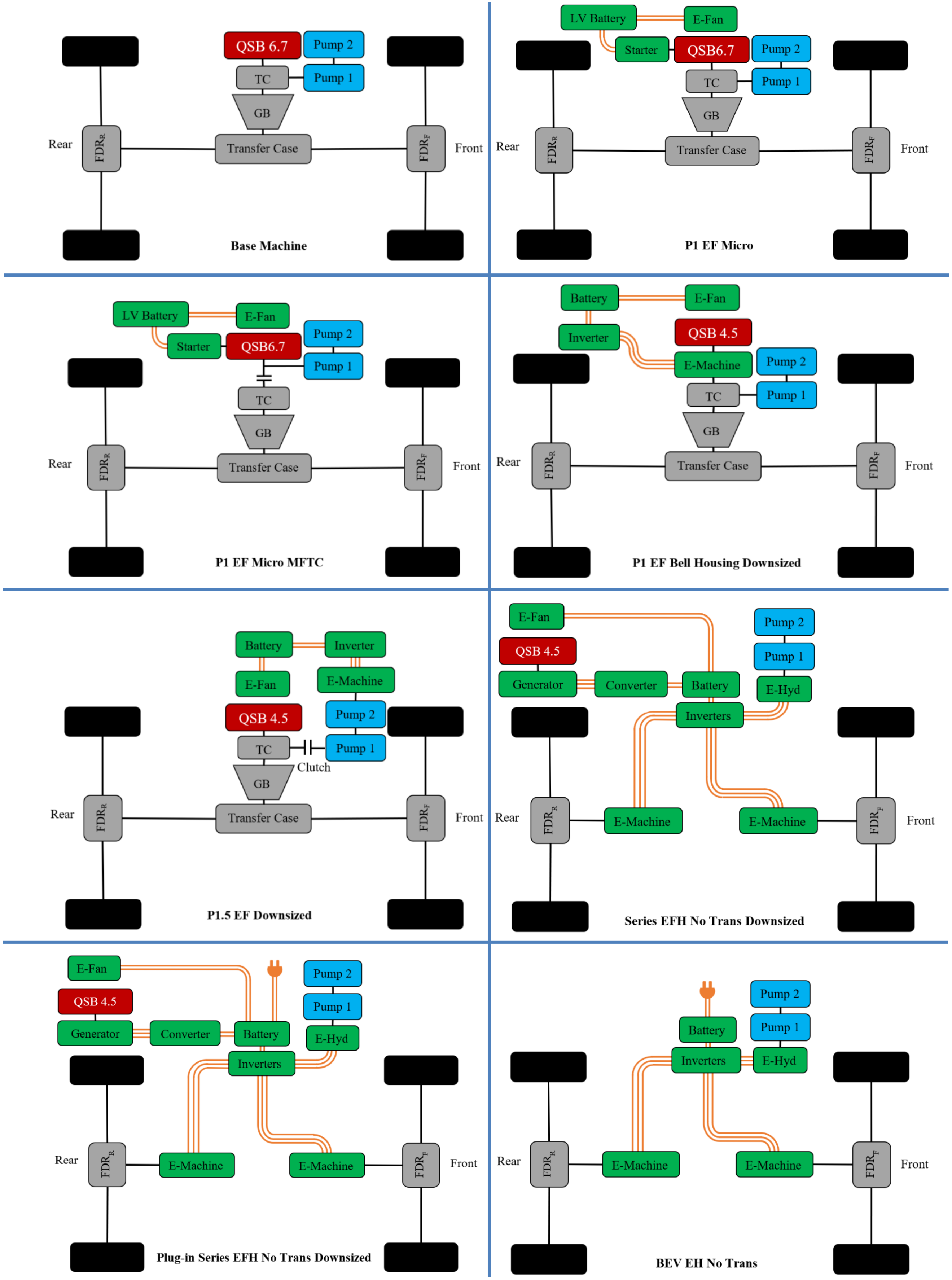
Weighting Scale: 1 to 3

Rating Scale: -2 to +2, where scale is described in "Description" row

	Engine Off Creep & Low Load	KE Recovery	Opportunity Charging Efficiency	Low Load / Low Duty Cycle Efficiency	High Load / High Duty Cycle Efficiency	Range	Center of Gravity Shift	Mass	Powertrain Packaging	Battery Packaging	Base Performance Metrics	Serviceability	Reliability	Cost of Operating	Number of parts	In-Use Flexibility	Program Time Risk	Lifecycle CO2 Emissions	Cost of Production Machine	Cost of Prototype	Prototyping: Controls Complexity	Prototyping: Usage of COTS and Hardware Complexity	Total Weighted Scores
Weighting Factor	1	1	1	3	3	2	1	1	2	2	2	1	3	3	1	1	3	3	3	3	3	3	
Base	-2	-2	-2	-2	0	0	0	2	2	2	0	2	2	0	2	-2	2	-2	2	2	2	2	30
P1 EF Micro	-2	-2	-2	-1	0	1	0	2	2	2	0	2	2	1	2	-2	2	0	2	2	2	2	44
P1 EF Bell Housing Downsized	0	0	2	0	1	1	0	2	1	2	0	1	1	1	1	0	1	0	1	1	0	1	35
P1 EF Front End Downsized	0	0	2	0	1	1	0	2	1	2	0	1	1	1	0	0	1	0	1	1	0	1	34
P1.5 EF Downsized	0	0	2	0	1	1	0	2	1	2	0	1	1	1	0	1	1	0	1	1	0	1	35
P2 + P1 EF Downsized	1	1	2	1	1	1	0	1	0	1	0	1	1	1	-2	1	-1	1	0	0	-2	0	15
P3 + P1 EF Fork Truck Downsized	2	2	2	1	1	1	-1	1	1	1	-2	1	1	1	0	1	-2	1	-1	-1	-2	-1	4
P3 + P1 EF Through Road Downsized	2	2	2	1	1	1	-1	1	0	1	-1	1	1	1	-1	1	0	1	0	0	-2	0	18
P3 + P1 EF Pass Through Downsized	2	2	2	1	1	1	-1	1	1	1	0	1	1	1	-1	1	-1	1	0	0	-2	0	19
Series EF w/ Trans Downsized	2	2	2	2	-2	1	0	0	-2	1	1	1	1	2	-1	0	1	2	0	0	1	-1	26
Series EFH w/ Trans Downsized	2	2	2	2	-2	1	0	0	-2	1	1	1	1	2	-1	1	1	2	0	0	1	-1	27
Series EFH No Trans Downsized	2	2	2	2	-1	1	0	2	-1	1	1	1	1	2	0	1	1	2	0	0	1	-1	35
Plug-In Series EF w/ Trans Downsized	2	2	2	2	0	2	0	-1	-2	-2	1	1	1	1	-1	1	1	2	0	0	1	-1	25
Plug-In Series EFH w/ Trans Downsized	2	2	2	2	0	2	0	-1	-2	-2	1	1	1	1	-1	2	1	2	0	0	1	-1	26
Plug-In Series EFH No Trans Downsized	2	2	2	2	1	2	0	1	-1	-1	1	1	1	1	0	2	1	2	0	0	1	-1	36
Series- Parallel EFH No Trans Downsized	2	2	2	2	2	1	0	2	-1	0	1	1	0	2	-2	1	-2	1	-1	-1	-2	-2	7
BEV EH w/ Trans Worst Case	2	2	-2	2	0	-2	0	-2	2	0	1	1	1	-2	1	0	1	-2	-2	-2	1	0	-5
BEV EH No Trans Worst Case	2	2	-2	2	1	-2	0	-1	1	1	1	1	1	-2	2	0	1	-2	-2	-2	1	0	0

Figure B1. Second round of the Pugh-style decision matrix for different electrified architectures.

Appendix C: Electrified Architecture Sketches



Base Machine

P1 EF Micro

P1 EF Micro MFTC

P1 EF Bell Housing Downsized

P1.5 EF Downsized

Series EFH No Trans Downsized

Plug-in Series EFH No Trans Downsized

BEV EH No Trans

Figure C1. Electrified architectures studied in this paper.

Appendix D: Assumptions for CO_2e Analysis

Table D1. Full table of assumptions for CO_2e analysis.

Category	Assumption	Justification
Lifetime of Cary-Lift	15 years	15-year lifetime in [2].
CO_2e of diesel, electricity, and components	Does not change over lifetime	Assumption for simplicity of analysis and unknown future values.
CO_2e decrease from removing components	Components that are removed, like the engine or transmission, decrease the CO_2e of the machine.	Removing certain components will reduce the overall CO_2e emissions of the machine.
Starting CO_2e	Base machine starts at 0 kg CO_2e. Other architectures start at higher or lower value relative to baseline based on components added or removed.	All architectures are relative to the base machine. When adding a component like a lithium-ion battery or electric motor, the starting CO_2e value is increased based on the CO_2e required to make those components. Values from GREET [30].
CO_2e of diesel combustion	Ideal complete combustion. Diesel combustion produces solely CO_2, N_2, H_2O, and O_2.	Prototype and production machines will be produced compliant with US EPA Tier IV Final emissions, thus, negligible production of methane or nitrous oxide.
CO_2e of diesel by geographic region	Does not change by region	Values are available for U.S. but not broken down by smaller geographic region. This refers to upstream emissions from diesel production, where values were determined using GREET [30].
CO_2e of electricity by geographic region	Changes by region	Data available from EPA eGRID [27] for electricity CO_2e by state.
CO_2e of components by geographic region	Does not change by region	Values are available for U.S. but not broken down by smaller geographic region.
Maintenance	Maintenance CO_2e considered for battery replacements only, using the GREET model [30]	Values for CO_2e of rebuilds like engine rebuild and transmission rebuild are unknown. Electric machine replacements not considered since replacements do not happen in 15-year lifetime. Exact values used for battery replacement.
Battery replacement period	443 working days for plug-in series battery; other results estimated based on NMC curve using 443 days as anchor.	Plug-in series battery lifetime modeled by the battery supplier [31]. This lifetime served as reference point from which other points were extrapolated using NMC lithium-ion curves from literature. See further explanation in CO_2e Analysis section of paper and see Figure 8 and Table 5.
Battery chemistry	All lithium-ion batteries are Nickel Manganese Cobalt (NMC 811)	The manufacturer for this project uses NMC chemistry; NMC 811 specifically assumed, as data was not provided by manufacturer. Battery chemistry affects overall CO_2e.
Battery size	Batteries sized to provide desired operation of electrified architecture	Desired operation includes operating for entire 8-hour day in the case of the BEV, or operating for at least 1 hour under full EV mode for the plug-in series hybrid.
Electricity grid CO_2e mix	Average mix	EPA recommends average mix (total output emission rate) for CO_2e analyses [19].
Charging efficiency	90%	Charging efficiency will vary with SOC, Temperature, etc. 90% is selected as an average charging efficiency.
Non-CO_2 greenhouse gases from diesel combustion	No other greenhouse gases	Assuming complete combustion with no greenhouse gases except CO_2.

Appendix E: Assumptions for Cost Analysis

Table E1. Full table of assumptions for cost analysis.

Category	Assumption	Justification
Lifetime of Cary-Lift	15 years	15-year lifetime in [2].
Cost of diesel, electricity, and components	Does not change over lifetime	Assumption for simplicity and because of unpredictable pricing.
Cost of components	Based on quotes or estimated based on relative size	Quotes give accurate cost of components, and components for which no quote was received are based on size relative to quoted components.
Cost decrease from removing components	Components that are removed, like the engine or transmission, decrease the purchase price of the machine and remove maintenance costs associated with the removed components.	Removing certain components will reduce cost to the OEM and also remove cost to customer.
Cost delta from base to electrified architectures	Cost delta is from component cost differences. Not including potential markup or profit margin percentage for electrified architectures.	Assumption for simplicity of analysis.
Cost to customer vs. cost to manufacturer	Manufacturer pays 50% what a customer would pay for products (like battery, electric machine, etc.)	Assumption based on relatively low volume production. If high volume products, manufacturer discounts would be greater.
Starting cost	Base machine starts at $0. Other architectures start at higher cost based on added components.	All architectures are relative to the base machine. When adding a component like a lithium-ion battery or electric motor, the starting cost is increased based on the cost required to purchase those components. Cost reduction (for example eliminating a transmission or engine) is also accounted for.
Cost of diesel	Businesses operating these types of machines will operate them on off-road diesel, and off-road price is on-road price minus state and federal diesel taxes for 2021.	No data available for off-road diesel prices by region, hence assumption for on-road minus taxes. On-road pricing is based on consumer pricing, thus, does not account for volume discounts that commercial / industrial users may negotiate.
Cost of electricity	Average of industrial and commercial for each region for 2021	Cary-Lifts operate in commercial and industrial applications. Data from EIA [37].
Demand charges on electricity	$15/kW	Data not available in all regions. $15/kW is estimate from map from NREL [38]. This is $15/kW at the peak demand for the month, and reset every month.
Cost of diesel by geographic region	Changes by region	Data is available for on-road diesel prices by state, and then subtracting on-road diesel state and federal taxes yields a state cost.
Cost of electricity by geographic region	Changes by region	Data available from EIA for electricity cost by state [37].
Cost of components by geographic region	Does not change by region	Values are available for U.S. but not broken down by smaller geographic region.
Maintenance	Maintenance cost based on market prices for major components, like engine rebuilds, transmission rebuilds, axle rebuilds, and battery replacements. Labor not considered. Electric machines are assumed to NOT need rebuild or replacement in the 15 year life of the machine.	Maintenance / replacement of parts can be significant cost contributor. Cost values given by Pettibone and using replacement or servicing costs.
Battery cost	$250/kWh	Cost to manufacturer, based on [39].
Battery replacement period	443 days for plug-in series battery; other results estimated based on NMC curve using 443 days as anchor.	Plug-in series battery lifetime modeled by battery supplier [31]. This lifetime served as reference point from which other points were extrapolated using NMC lithium-ion curves from literature. See further explanation in CO_2e Analysis section of paper and see Figure 8 and Table 5.
Battery size	Batteries sized to provide desired operation of electrified architecture.	Desired operation includes operating for entire 8-hour day in the case of the BEV, or operating for at least 1 hour under full EV mode for the plug-in series hybrid. Batteries were sized to enable HVAC operation, however, no HVAC operation was accounted for in the energy consumption analysis. Loss of battery efficiency (chemical kinetics, heating, etc.) at low temperature was not accounted for.
Charging efficiency	90%	Charging efficiency will vary with SOC, Temperature, etc. 90% is selected as an average charging efficiency.
Cost for miscellaneous electrification components	Cost scales linearly with hybridization factor (see equation 2), except for BEV.	Increasing hybridization factor leads to more expensive parts (see Figure 5). This does not hold for BEV, as the BEV has fewer components when compared to plug-in series hybrid, so BEV uses separate scalar value.
Hybridization factor calculation	Power of components is limited by energy storage system.	In an architecture like the series hybrid, the tractive electric machines may be able to produce 425 kW each, but the battery utilized in this example is unable to produce this level of power. As such, the tractive electric machine total power is based on battery peak power output.
Cost increase to customer	Twice as expensive to customer as to manufacturer.	Assumption based on conversations with Pettibone. Assuming same scalar of 2 for all components, so replacing a battery, for example, will cost twice as much $/kWh to the customer as it would to Pettibone.