Total Cost of Ownership of a Compact Battery Electric Agricultural Tractor

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Executive Summary

The objective of this report is to estimate the total cost of owning and operating a compact battery electric tractor in the Pacific Northwest, and to compare these costs with those of owning and operating a similarly sized internal combustion (IC) diesel tractor. Electric tractors (eTractors) provide a host of potential benefits including highly efficient motors, a better working environment for growers (reduced noise pollution and emission fumes), and a lower greenhouse gas (GHG) impact. While these are all important factors, tractors represent one of the most significant investments that growers make and understanding the costs of ownership of eTractors is critical for farmer decision-making.

This analysis compares the 30 HP Solectrac Compact Electric Tractor (CET) and the 32 HP John Deere 2032R. Both tractors are assumed to operate 250 hours a year for 7 years. The total cost of ownership is broken down into four distinct cost segments: 1) Initial purchase price, 2) Financing costs, 3) Energy costs (diesel fuel or electricity), and 4) maintenance and repair costs. Because the cost of owning a tractor is highly dependent on how that tractor is operated, three different operating scenarios are considered which represent three different levels of tractor use intensity: 1) a “Large Farm scenario” where it is expected that the compact tractor is mainly used for transport and mowing while larger tractors take care of the more energy intensive tasks, 2) a “Small Farm scenario” where it is expected that the compact tractor does a large portion of the work on the farm including tillage, mowing, and general utility use, and 3) a “Workhorse scenario”, an edge case scenario where it is expected that the tractor is only used for energy intensive tasks like tilling.

This analysis finds that the eTractor produces substantially lower GHG emissions (1.56 - 4.84 metric tons CO2eq) than the diesel tractor (11.06-30.06 metric tons CO2eq) while having a comparable total cost of ownership (TCO) ($39,853 - $40,738 for eTractor, $37,553 – 43,072 for diesel tractor). In the lower power use intensity scenarios (Large and Small farm scenario) the eTractor TCO is a few thousand dollars greater than the diesel tractor, in the higher power use intensity scenario (Workhorse scenario) the eTractor TCO is less than the diesel tractor.

The analysis relies on near-real time tractor data captured on a Solectrac CET operating on fields in Wasco County, Oregon. The calculation of specific power use per operation performed and all TCO calculations are contained within two Jupyter notebooks. A Jupyter notebook is a web-based interactive computing platform which contains python code, visualizations, and a description of that code. The notebooks are flexible to changes in the input data. This means that the eTractor energy use factors can be improved as more field data becomes available and the TCO can easily be run for different tractor types, different power usage scenarios, and situations where economic input costs are different.

A sensitivity analysis demonstrates that eTractors are less sensitive to changes in the cost of material inputs, potentially making these tractors more resilient to cost changes resulting from energy price shocks or supply chain variability. The analysis also demonstrates that eTractors become more cost effective as the operating hours increase; the largest portion of the eTractor TCO is associated with the initial purchase price (81 - 83%). The caveat here is that the single

charge run time of the eTractor decreases during periods of more intense operation, thus, sustained high intensity work may require an auxiliary battery pack.

The results of the analysis demonstrate that compact eTractors offer a great value proposition for farmers in the Pacific NorthWest. The transition towards eTractors would support the country's goals of combating climate change and because agriculture is one of the industries most vulnerable to climate change impacts [1], the transition to eTractors can serve as an act of self-preservation for agriculture. Given current conditions, and assumptions which may overestimate eTractor costs, the eTractor TCO is still comparable with IC tractors. eTractor TCO values are on the order of $3,000 greater than IC tractor TCO values. This cost difference is small enough that incentives (from the government or other sources), could persuade producers to choose eTractors over IC tractors, incentivizing actions that combat climate change, while also providing many significant benefits to the producers and their communities.

1.0 Introduction:

In 2019, emissions from fuel combustion in the US Agriculture sector accounted for 40 million metric tons of CO2eq, 0.6% of total US emissions [2]. One method for reducing these GHG emissions is the transition from internal combustion to electric powertrain vehicles. The development of battery electric agricultural tractors (eTractors) is advancing, with companies such as Solectrac LLC and Monarch Tractors bringing eTractor vehicles to market. Other major manufacturers like John Deere, Kubota, and Massey Ferguson have released prototype electric tractors in various stages of development. Battery electric vehicles produce no tailpipe emissions, their only operating emissions are those associated with electricity generation. Additionally, electric motors are substantially more efficient than internal combustion (IC) motors, further reducing emissions. Electric motors convert over 77% of electrical energy from the grid into power at the wheels while IC motors convert 12- 30% of energy stored in gasoline into power at the wheels [3]. Furthermore, in agricultural applications, a large portion of tractor operating time is spent idling while the farmer performs other tasks; battery electric vehicles use no power while idling. In addition to these benefits, eTractors may improve health outcomes for farmers by addressing health hazards associated with the noise of tractors [4].

While the potential benefits from the transition to eTractors are global in scope, this study will focus specifically on the Pacific NorthWest (PNW). The PNW may become an early adopter of eTractor technologies thanks to the region's robust agricultural industry and abundant renewable energy. In addition to large industrial scale farms, the PNW has many smaller farms and vineyards which employ compact tractors (40 HP or less). Nation-wide roughly 70% of tractor sales in 2020 were 40 HP or less [5]. This study will focus on the 30 HP Solectrac Compact Electric Tractor (CET) and the 32 HP John Deere 2032R IC diesel tractor. The analysis includes both the total cost of ownership (TCO), and the anticipated greenhouse gas emissions for each tractor. Section 2 details the methodology used for the TCO analysis, Section 3 describes the GHG emissions analysis methodology, Section 4 presents the results of the TCO and the associated sensitivity analysis, Section 5 discusses the results, Section 6 provides conclusions from this work and identifies potential future research.

2.0 TCO Methodology:

This analysis attempts to provide a meaningful TCO by looking at realistic scenarios and drawing from both the best existing cost data and from eTractor power usage data collected in field trials. The total cost of ownership (TCO) of a tractor will vary substantially depending on the type of farming operation it is deployed in, operator tendencies, maintenance practices, regional price discrepancies, and ultimately some level of random chance (accidents, extreme weather events, etc.). The analysis looks at three different operating scenarios which represent three different levels of tractor use intensity: 1) a “Large Farm scenario” where it is expected that the compact tractor is mainly used for transport and mowing while a fleet of more powerful tractors take care of the more energy intensive tasks, 2) a “Small Farm scenario” where it is expected that the compact tractor does a large portion of the work on the farm, including tillage, mowing, and general utility use, and 3) a “Workhorse scenario”, an edge case where it is expected that the tractor is only used for energy intensive tasks like tilling. The workhorse scenario doesn’t necessarily represent realistic conditions, but it gives insight into how the TCO varies for the two tractors in an extreme scenario.

The different operating practices of a compact tractor in these different scenarios are quantified in terms of the fraction of total annual operating time that the tractor spends doing various tasks. As an example, it is assumed that a compact tractor on a small farm will spend more time on tilling operations than a tractor on a larger farm where other, more powerful, machinery is responsible for the tilling operations. The specific time fractions for each scenario are presented in Table 1. Actual farms use tractors for more than three tasks but the three selected tasks, driving, mowing, and tilling, represent a low power use, medium power use, and high power use task, respectively. This analysis assumes that tractors are running for 250 hours a year over a 7 year operating life. To better account for uncertainty related to the choice of input variables, a sensitivity analysis was conducted as described in Section 4.

Table 1: TCO Scenarios. Fraction of total operating time spent on a particular task.

Scenario	**Description**	**Mow Fraction**	**Till Fraction**	**Drive Fraction**	**Annual Energy (gal. diesel)**	**Annual Energy (kWh)**
Large Farm	Compact tractor does lighter tasks, more energy intensive tasks done by larger tractors	0.3	0.0	0.7	144.0	548.2
Small Farm	Compact tractor does most of work on farm	0.3	0.3	0.4	228.1	937.9
Workhorse	Compact tractor only does high intensity work	0.0	1.0	0.0	391.2	1697.0

The entirety of the TCO analysis is coded in the python programming language and contained in a Jupyter Notebook. To foster flexibility and encourage future analysis, the Jupyter notebook can be used to run a TCO analysis for any number of tractors and farming scenarios. The notebook requires an input excel sheet which holds the relevant information about the tractors and implements of interest (initial purchase price, horse power, battery capacity for eTractors, etc.). An interactive version of the Jupyter notebook can be accessed at the following link : https://mybinder.org/v2/gh/proctork/eTractor_TCO/HEAD.

The TCO considers four distinct cost subsections 1) Initial purchase price, 2) Financing costs, 3) Energy costs (diesel fuel or electricity), 4) Maintenance and repair costs. Other subsections including insurance costs, registration costs, and taxes/rebates were considered but the costs were found to be nominal for tractors. Labor is a major cost subsection when considering the TCO of commercial fleets of e-vehicles because drivers must be paid for their labor during refueling periods (a few minutes for diesel vs hours for e-vehicle), however, labor costs were not considered in this analysis with the assumption that farm works will find other tasks to do while the eTractors charge.

2.1 Initial Purchase Price

The initial purchase price includes both the cost of purchasing the tractor itself and any required implements. Costs are based on manufacturer websites and the experiences of the research team sourcing a tractor in 2021. The base John Deere 2032 tractor includes industrial tires; for comparability the Solectrac CET initial purchase price is considered to be the base tractor cost + the cost for industrial tires.

For implements, it is assumed that each tractor will have a mowing attachment and a tilling attachment. The Solectrac CET accepts all Category 1-540 PTO implements & both tractors are assumed to use the same implements. Thus, the implement cost is not particularly important for comparing TCO between tractors but is still considered for the overall total cost.

2.2 Financing costs

Financing costs are the interest and other charges that result from borrowing money to purchase the tractor. Tractors and other agricultural equipment represent some of the largest investments that growers make and generally the purchase of this equipment requires some sort of financing agreement.

Market research by the Cadeo group [5] has found that large equipment manufacturers (John Deere, Kubota, etc.) are able to offer 0% loans on their tractors. Newer companies in the eTractor space such as Solectrac and Monarch cannot lend at such a low rate. To account for this difference in lending ability, this TCO analysis assumes that the diesel tractor has a 60 month 0% APR loan while the eTractor has a 60 month loan with 4% APR. Effectively, the diesel tractors have no financing costs while the eTractors do.

2.3 Energy Costs

The operating energy costs represent the most substantial difference between the two tractor types. The operating energy costs for this analysis are calculated as follows: First, the farming scenario is set (Table 1). Next, the specific power use for each of those actions (mowing, tilling, or driving) is established, with units of energy per time (Liter of diesel per hour for IC tractor or kWh of electricity per hour for eTractor). The power use for each specific action is calculated and the power uses for different actions are summed over the course of a year to determine the total annual energy use for each tractor. Multiplying the total energy use by the fuel or electricity price produces an annual energy cost. (Equation 1)

$$Annual\ Energy\ Use = (SF_M * Q_M + SF_T * Q_T + SF_D * Q_D) * Annual\ Operating\ Time \qquad (1)$$

$$Annual\ Energy\ Cost\ =\ Annual\ Energy\ Use\ *\ Energy\ Price$$

Where SF = Scenario fraction (0-1), Q = Specific power use (L/h or kWh/h), the subscripts M, T, & D refer to the operation taking place (Mowing, Tilling, & Driving)

The calculation of energy costs is relatively simple, more challenging is accurately determining the realistic tractor operating scenarios and specific power usage for each farm task. It is certain that there is no one “correct” scenario which will explain how farmers on a particular “type” of farm are using their tractors. The actual operation depends on factors such as how many tractors are available on site, the crop being grown, and specifics about the farmer’s management practices. Still, this analysis strives to establish representative scenarios for the different types of farms and this information will be supplemented in the future with data collected from stakeholder outreach, asking growers how they actually use their tractors.

2.3.1 Specific Power Use

Specific power usage refers to the quantity of energy consumed (Liters of diesel or kWh of electricity) during a given amount of time (hours), while the tractor is performing a particular operation. In this TCO analysis, specific power use is determined via different methods for each tractor powertrain type. The diesel tractor has been a staple of the agricultural industry for a century and there is a large volume of existing data on power usage; this data has been used to develop empirical equations which can estimate tractor fuel usage based on the rated Horsepower(HP) of the tractor and the required power at the Power Take-Off (PTO) for each operation. The equation used in this TCO calculation comes from a publication by Grisso, Vaughan, & Roberson [6]. This equation is an evolution of the one developed by the American Society of Agricultural and Biological Engineers [7,8] and draws on data collected from years of field tests by the Nebraska Tractor Test Laboratory.

eTractors have not had the same widespread usage and do not have the same body of data available. Thus, it was necessary to collect data and derive our own empirical factors for specific power use by eTractors. A Solectrac CET was outfitted with sensors to measure average voltage, current, power, and battery capacity, along with sensors which tracked whether the tractor was on, whether the PTO was engaged, and the battery temperature. This information was sent via telemetry to an online dashboard and a running record of the tractor's power usage was established. Prior to starting the tractor, operators scanned a QR code with their phones and submitted an online form listing the operation they were about to perform. A Python script was used to relate the periods of time that the tractor was being used for a particular action and the associated power usage. The average specific power usage for each of the considered tasks (mowing, tilling, driving) was acquired and this was the factor used for the TCO. The data used to establish the specific power use parameters was obtained from less than a full season of data (40 operating hours) and using only a single tractor, hence, it is important to be careful in using this data to generalize too broadly. This calculation only considers the energy used by the tractor itself, however, in reality producers pay for the amount of electricity that is drawn from the wall outlet. The transfer of energy from the grid to the eTractor battery is not 100% efficient. It is assumed that 10 % of the energy drawn from the wall outlet is lost to charging losses, this assumption is based on US Department of Energy estimates [9].

2.4 Maintenance costs

Accurately estimating tractor maintenance costs is challenging. The method deployed in this TCO is not perfect, but it sufficiently captures the major costs, although likely overestimating maintenance costs for eTractors. In 2011, researchers at the University of Idaho published a report on the costs of owning and operating agricultural machinery in the Pacific Northwest [10]. The study contacted farm machinery dealers across the PNW in order to establish maintenance costs for various types of agricultural machinery, including tractors of various power levels. The report includes repair costs and presents different maintenance costs depending on the total operating hours of the tractor; tractors later in their lifecycle are more likely to require maintenance and thus have higher costs. While this report is over a decade old at this point, it is still the most comprehensive report on tractor maintenance available, and the data is specific to our region of interest. All values were converted to 2021 dollars using the consumer price index (CPI) [11].

The maintenance costs taken from the University of Idaho report do not include fuel or oil costs. For the purposes of this TCO, it is assumed that the base maintenance costs are the same for the diesel and eTractor and that the only differences in maintenance costs are associated with the requirement of oil and oil filter changes for diesel tractors and battery replacements for eTractors. This is not a particularly sound assumption, the eTractor has substantially fewer moving parts and it is reasonable to speculate that maintenance of eTractors will be significantly less costly than diesel tractors. For some cross-sector analysis, a 2021 report from the US office of Energy Efficiency and Renewable Energy estimated that maintaining medium and heavy duty commercial electric vehicles is about 40% less expensive than similarly sized IC commercial vehicles [12]. However, because data is not currently available about the actual expected costs for maintaining eTractors, this conservative approach is used.

2.4.1 Oil Use

The oil use of the IC tractor is estimated using an empirical equation derived by the American Society of Agricultural and Biological Engineers [7]. This equation determines oil use (L/h) as a function of the rated power of the tractor. It is assumed that the oil filter must be replaced every second oil change.

2.4.2 Battery Replacement

The degradation of the eTractor is calculated based on the rated cycles of the tractor battery. The battery is rated for a number of cycles at a specified depth of discharge (DOD), where DOD represents the quantity of total battery capacity that is used prior to recharging. For the lithium-iron-phosphate batteries used in eTractors, the battery life will deplete more quickly when a higher portion of the battery capacity is depleted prior to recharging [13]. For this analysis it is assumed that the eTractor battery is always drained to the rated battery DOD (80%), this may lead to an overestimation of how quickly the battery will need to be replaced. However, given the long hours that many agriculture tractors work on a given day, this was deemed to be a sound assumption. Using the rated cycles of the battery, the depth of discharge, and the annual energy use, the battery on a Solectrac CET is expected to need replacement after 10 to 32 years. This is roughly in line with the commercial electric vehicle car market where batteries have been shown to last for a minimum of 8-10 years [14]. The actual life of a battery is highly dependent on other factors such as battery temperature and there is some level of “calendar degradation” that occurs over time even if the battery is not used much. Given that the tractor life used for this analysis is 7 years, the cost of replacing batteries never factors in.

Currently the replacement battery price ($10,000) is greater than 30% of the initial purchase price of the Solectrac CET ($28,398) cost. If a farmer elects to purchase an auxiliary battery the initial costs are substantially increased. The eTractor battery drains more quickly during periods of heavy work so it is possible there are situations where having multiple batteries would be beneficial, however because the CET does not have the capability for swapping out batteries, a situation where an auxiliary battery is part of the initial purchase price is not considered.

3.0 GHG emission methodology

This analysis includes an estimate of the operating emissions associated with each tractor type. The analysis includes only the emissions associated with the energy of choice (diesel or electricity) and does not account for the embodied emissions of the manufacturing of tractors, transport of tractors, or end of life processes.

3.1 Internal Combustion Tractor emissions

The GHG emissions of the IC tractor are estimated by using the total energy use (liters of diesel fuel of kWh of electricity) calculated in the TCO and multiplying by emission factors from the GREET (Greenhouse gasses, Regulated Emissions, and Energy use in Technologies) model [15]. The emission factors represent well-to-wheel emissions for diesel fuel used by a 2020 model 50 HP diesel agricultural tractor [16]. The compact tractors used in this study are closer to 30 HP so these emission factors may be an overestimate however 50 HP is the smallest tractor that the GREET model provides data on. The specific emission factors (grams emitted per liter of diesel) for 11 pollutants are provided in Appendix 1 along with the CO2-equivalent emissions for each pollutant. Global warming potential (GWP) conversion factors were used to calculate the emissions in terms of CO2- equivalents. The global warming potentials are found in the GREET model and based on the IPCC Fifth Assessment Report for the 100 year time horizon.

3.2 Electric Tractor emissions

Although eTractors produce no tailpipe emissions, the electricity they use has emissions associated with its production. The emissions associated with electricity use are highly dependent on what source was used to generate the electricity. Two separate methods were used to estimate GHG emissions associated with eTractor use. In the first method, the energy mix for Oregon is established using state data [17] and the GHG emission factor for each portion of the mix is accounted for using the GREET Model [15]. The Oregon energy mix is depicted in Figure 1 and the associated emission factors can be found in Appendix 1. The GWP factors described above are used to calculate the emissions in terms of CO2-Eq. The second method uses self-reported GHG emission factors from individual Oregon electricity providers, this information was collected and aggregated by the Oregon Department of Environmental Quality [18] . The emission factors for the five largest energy providers and Wasco Electric Cooperative are presented in Table 2. Wasco Electric Cooperative was included because this is the energy provider for the region where the eTractor field trials were conducted.

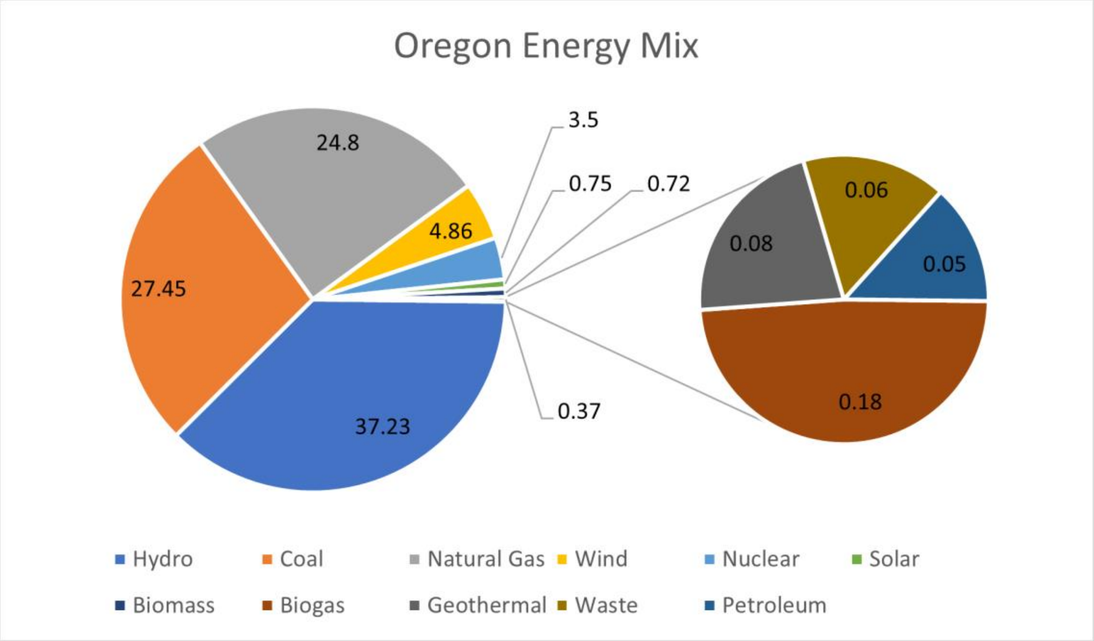

Figure 1. State-wide Oregon Energy Mix in 2019. Values are listed as percentages.

Table 2. Oregon energy providers (2019 data) [18].

Organization Name	Electricity Supplier Type	Megawatt hour (MWh)	Emissions (MTCO2eq)	Emission per megawatt hour (MTCO2eq/MWh)
Portland General Electric (PGE)	Investor-Owned	18,131,567	7,578,660	0.418
Pacific Power (PacifiCorp)	Investor-Owned	13,117,259	9,042,557	0.689
Umatilla Electric Cooperative	Consumer-Owned	3,110,727	569,384	0.183
Eugene Water & Electric Board (EWEB)	Consumer-Owned	2,442,863	133,787	0.055
Calpine Energy Solutions	Electricity Service Suppliers	1,503,806	643,629	0.428
Wasco Electric Cooperative	Consumer-Owned	109,745	2,237	0.020

4.0 TCO Results

The Total costs of ownership for each tractor and each scenario are presented in Table 3. The cost of ownership per 100 hours is presented in Table 4. The breakdown of costs across segments are presented in Figure 2. Tables containing the cost values for each segment are available in Appendix 1

Table 3. Total cost of ownership for tractors under different scenarios (250 annual operating hours)

Tractor Type	Total Cost of Ownership ($)		
	Large Farm Scenario	Small Farm Scenario	Workhorse Scenario
eTractor (Solectrac CET)	39,853.53	40,153.60	40,738.11
IC Tractor (JD2032R)	37,535.61	39,420.56	43,072.03

Table 4. Total cost of ownership per 100 hours

Tractor Type	Cost of Ownership per 100 hours ($)		
	Large Farm Scenario	Small Farm Scenario	Workhorse Scenario
eTractor (Solectrac CET)	2,277.34	2,294.49	2,327.89
IC Tractor (JD2032R)	2,144.89	2,252.60	2,461.26

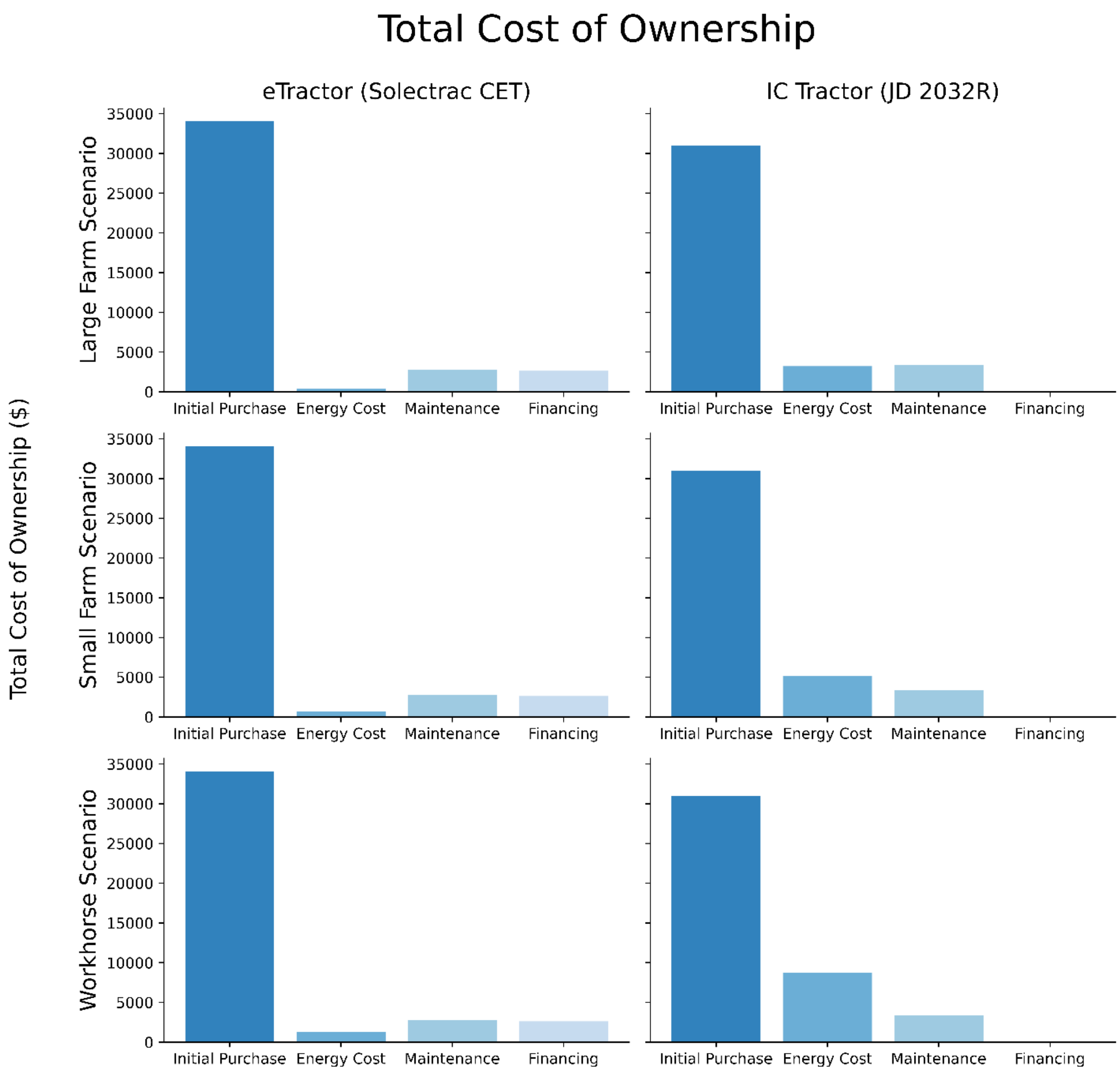

Figure 2. TCO cost breakdown across segments

The total GHG emissions for each tractor and each scenario are presented in Table 5 and the GHG emissions per 100 hours are presented in Table 6. The GHG emissions from the eTractor are based on the 2019 statewide Oregon energy mix. The GHG emissions associated with electricity use are highly dependent on the energy mix used to generate the electricity, Table 7 compares the Oregon energy mix, nationwide US energy mix, and the reported GHG emissions by the top five Oregon electricity providers in 2019 (based on total MWh of electricity produced) as well as emissions from Wasco Electric Cooperative, the local energy provider where the field trials were conducted.

Table 5. Total GHG emissions

Tractor Type	**Total GHG emissions (Metric ton CO2eq)**		
	Large Farm Scenario	**Small Farm Scenario**	**Workhorse Scenario**
eTractor (Solectrac CET)	1.56	2.68	4.84
IC Tractor (JD2032R)	11.06	17.53	30.06

Table 6. Total GHG emissions per 100 hours of operation

Tractor Type	**GHG emissions per 100 hours (Metric ton CO2eq)**		
	Large Farm Scenario	**Small Farm Scenario**	**Workhorse Scenario**
eTractor (Solectrac CET)	0.09	0.15	0.28
IC Tractor (JD2032R)	0.63	1.00	1.72

Table 7. GHG emission from eTractor using different approaches

Tractor Type	**Total GHG emissions Metric ton CO2eq**		
	Large Farm Scenario	**Small Farm Scenario**	**Workhorse Scenario**
Oregon Mix	1.56	2.68	4.84
US Mix	1.65	2.83	5.11
Portland General Electric (PGE)	1.60	2.74	4.97
Pacific Power (PacifiCorp)	2.64	4.52	8.18
Umatilla Electric Cooperative	0.70	1.20	2.17
Eugene Water & Electric Board (EWEB)	0.21	0.36	0.65
Calpine Energy Solutions	1.64	2.81	5.08
Wasco Electric Cooperative	0.08	0.13	0.24

4.1 Sensitivity Analysis

The results of the TCO analysis are highly dependent on the model inputs and given that many input parameters rely on estimates and assumptions, a sensitivity analysis was conducted to better understand which parameters have the largest impacts on the overall TCO. Figure 3 shows spider plots for each of the tractors, the variables altered in the sensitivity analysis are 1) diesel fuel price, 2) electricity price, 3) annual operating hours, 4) initial purchase price, 5) financing APR, and 6) tractor life. The plots show how the TCO responds when each input parameter is varied from a 20% decrease to a 20% increase. Table 8 and 9 show the relative sensitivity (Equation 2) of the TCO of each tractor to changes in the input variables. Individual input parameters were changed by 10% with all other parameters being held at their default/base value. Results for relative sensitivity are only presented for the Small Farm scenario.

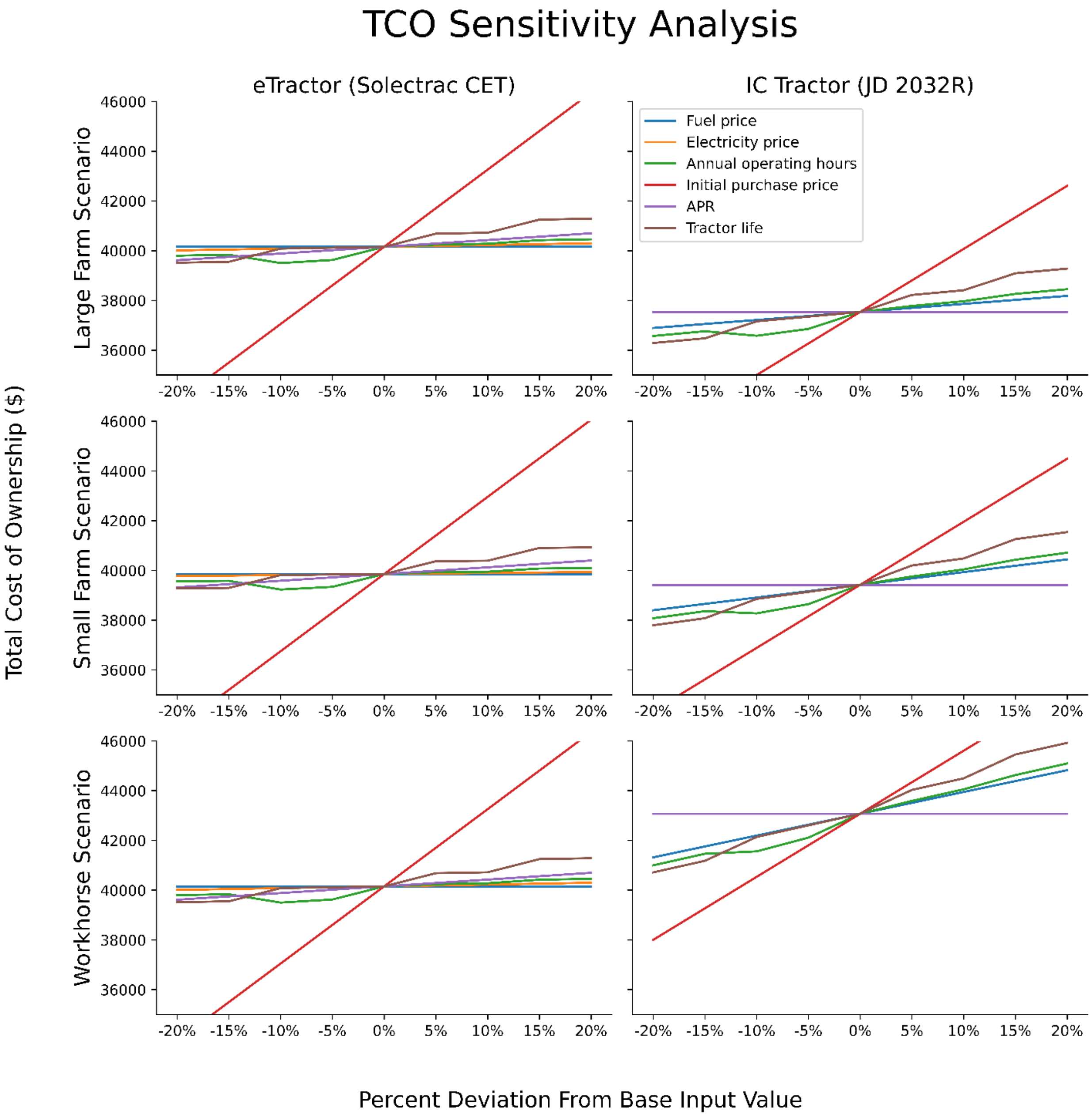

Figure 3. Sensitivity analysis of TCO.

$$S_R = \frac{\frac{\Delta R}{R_B}}{\frac{\Delta P}{P_b}} \tag{2}$$

Where SR is Relative Sensitivity, ΔR is the difference between base (R_b) and altered response value (TCO), and ΔP is the difference between base (P_b) and altered input parameter.

Table 8. Relative Sensitivity of eTractors in Small Farm scenario (Baseline response value = $40,154)

Parameter	Base input Value	10% Increase input value	Response Value ($)	Relative Sensitivity
fuel price ($/gal)	3.20	3.52	40,154	0.00
electricity price ($/kWh)	0.11	0.12	40,226	0.02
annual operating time (hours)	250.00	275.00	40,279	0.03
initial purchase price ($)	28,398.00	31,237.80	43,256	0.77
APR (%)	4.00	4.40	40,425	0.07
Tractor Life (years)	7.00	7.70	40,719	0.14

Table 9. Relative Sensitivity of IC tractors in Small Farm scenario (Baseline response value = $39,421)

Parameter	Base Value	10% Increase value	Response Value ($)	Relative Sensitivity
fuel price ($/gal)	3.20	3.52	39,932	0.13
electricity price ($/kWh)	0.11	0.12	39,421	0.00
annual operating time (hours)	250.00	275.00	40,040	0.16
initial purchase price ($)	25,345.00	27,879	41,955	0.64
APR (%)	4.00	4.40	39,421	0.00
Tractor Life (years)	7.00	7.70	40,480	0.27

4.2 TCO with Increased annual operating hours

Market research from the Cadeo group [5] suggests that compact tractors may be used for 750 hours annually over a period of 7 years. The resulting TCOs under these operating conditions are shown in Table 10 and Figure 4. In this case, the TCO of the eTractor is lower for all usage scenarios when compared to an IC tractor. Also note how the difference between energy costs of the two tractor types grows along with the annual power use.

Table 10. Total cost of ownership with 750 annual operating hours

Tractor Type	Total Cost of Ownership ($)		
	Large Farm Scenario	**Small Farm Scenario**	**Workhorse Scenario**
eTractor (Solectrac CET)	41,364.01	42,264.21	44,017.75
IC Tractor (JD2032R)	45,763.77	51,418.59	62,373.01

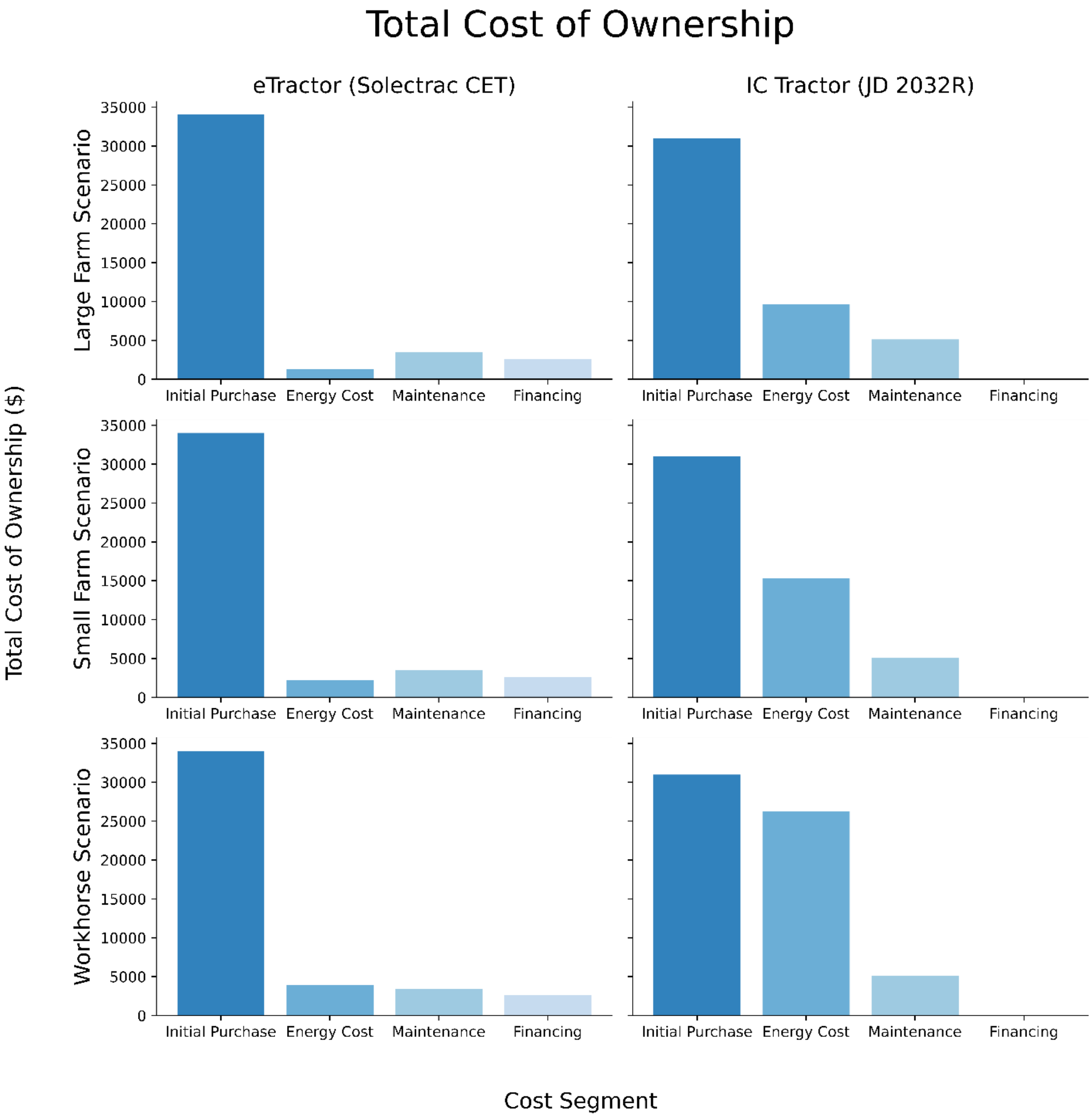

Figure 4. Cost breakdown across segments with 750 annual operating hours

4.3 TCO with 2022 Diesel prices

This analysis was conducted assuming a diesel price of $3.2/gallon, in the time since the analysis was initially started average Oregon diesel prices have risen to $4.6/ gallon, nearly a 44% price increase. Table 11 shows the resulting TCO for 2022 diesel prices and Figure 5 shows how an increase in diesel prices is compounded as annual operating hours increase.

Table 11. Total cost of ownership with 250 annual operating hours and $4.6/gallon diesel prices

Tractor Type	**Total Cost of Ownership ($)**		
	Large Farm Scenario	**Small Farm Scenario**	**Workhorse Scenario**
eTractor (Solectrac CET)	39,853.53	40,153.60	40,738.11
IC Tractor (JD2032R)	38,946.48	41,656.08	46,905.07

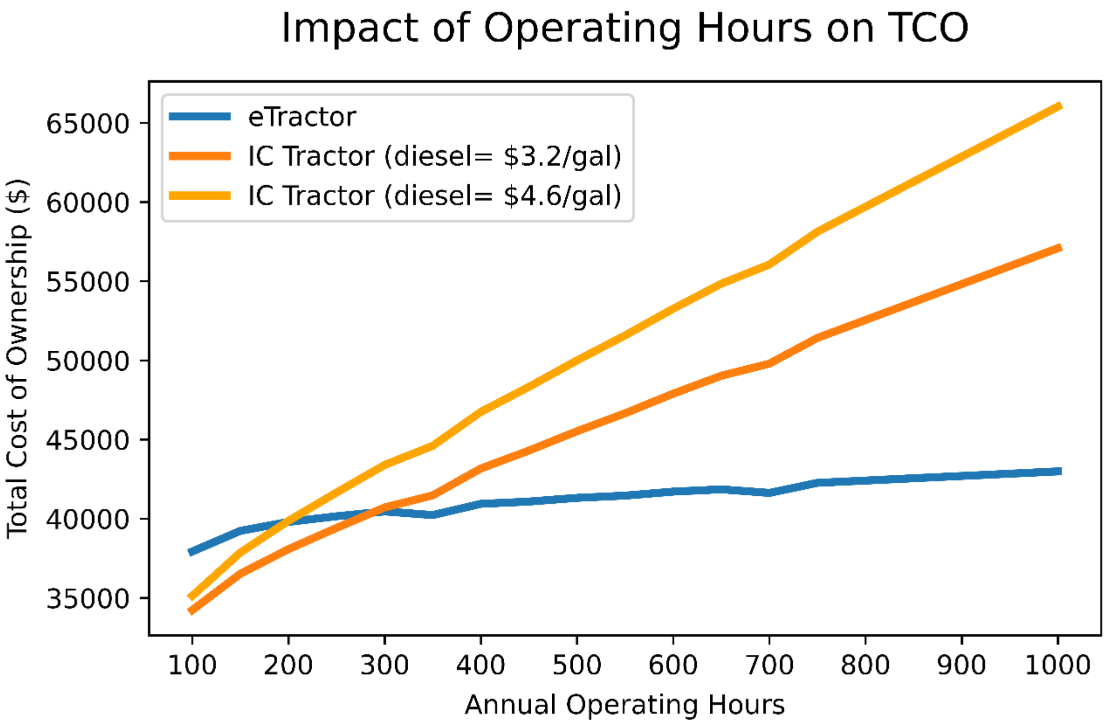

Figure 5. The impact of annual operating hours on overall TCO at two different diesel prices (Small Farm scenario).

5.0 Discussion

This work compares the total cost of ownership of an eTractor with a diesel tractor in three different operating scenarios. The results show that the TCO of the eTractor is greater than the IC tractor in the less energy intensive scenarios (large farm & small farm), while the TCO of the eTractor is less than the IC tractor in the more energy intense workhorse scenario (Table 3). When considering the cost breakdown across different cost segments (Figure 2), it is clear that the eTractor has a higher initial purchase price (representing 81-83% of TCO) than the IC tractor (71-82% of TCO). The energy costs represent a much larger portion of the TCO in the IC tractor (8%-20%) when compared with the eTractor (1%-3%). Thus, the eTractor becomes the more cost effective choice in scenarios which require higher overall energy usage from the tractor (workhorse). This model assumes financing costs for the eTractor and no financing costs for the IC tractor (see Section 2.2 for justification). Financing costs represent a cost difference of $3,700, or about 6.5% of the TCO of the eTractor.

The relative sensitivity analysis (Tables 8 and 9) shows that the eTractor is most sensitive to changes in the initial purchase price, and to a lesser extent the tractor operating life. The eTractor is relatively insensitive to changes in the price of electricity. Given the maturity level of eTractor technologies it is expected that the purchase price of eTractors will decline as the volume of production increases. Furthermore, battery technologies account for a large portion of the overall eTractor cost and prices are expected to decrease as a result of both technological advancements and economies of scale. The IC tractor is most sensitive to changes in the initial purchase price, the tractor operating life, and the annual operating hours. The differences in sensitivity can be seen visually in Figure 3. For all scenarios, changes in the IC input parameters lead to a larger response in the TCO, as shown by the wider spread away from the baseline value (Figure 3). For the eTractor on the other hand, the impact of changing input parameters is less substantial, note how the cost lines stay closer to the baseline value in Figure 3. The sensitivity analysis clearly indicates that TCO of eTractors is generally more resistant to cost volatility.

GHG emissions (Table 5) are substantially lower when using the eTractor (1.56 – 4.84 metric tons CO2eq) than the IC tractor (11.06 – 30.06 metric tons CO2eq) over the operating life of the tractor. Even in conditions when an emission heavy energy mix is used to power the eTractors, the emissions from the eTractor in the most energy intensive scenario (Workhorse) remains less than the emissions of the IC tractor in the least energy intensive scenario (Large Farm) (Table 7).

The majority of the TCO of the eTractor is in the initial investment, thus, the longer a tractor is used the more advantageous it is to use an eTractor. This becomes particularly clear when examining a scenario where the tractor has greater annual operating hours (Table 10, Figure 4). These results also reinforce the conclusions drawn from the sensitivity analysis: the eTractor is much less sensitive to changes in the input factors. While the TCO of the IC tractor increases by up to $20,000 when the annual operating hours are increased, the eTractor TCO only varies by a few thousand. Given that the cost effectiveness of eTractors scales with use of the tractor, eTractors may be particularly well suited for tractor sharing situations where multiple farms utilize the same machine.

There are a number of anticipated financial benefits related to eTractor use that are currently difficult to quantify. Many farms have on-site diesel storage tanks. The delivery of this diesel to the farms has an associated cost and GHG impact which is not accounted for in this analysis. Additionally, the installation of on-site diesel tanks has an additional cost which new farms could avoid if they planned to exclusively use eTractors. However, the infrastructure which allows tractor charging, particularly fast charging, also has an associated cost so further analysis would be required to quantify these impacts. eTractors also offer an opportunity for farms to use renewable energy produced on farm from solar panels or micro-hydro. The tractors can serve as a form of distributed energy storage for the farm. Some eTractors, like those produced by Monarch, have the potential to serve as a mobile energy source. Farmers often need to perform tasks out in the field which previously were powered via diesel generators and now can be powered via the tractor itself. Additionally, the total energy used by idling is not captured within this analysis but likely sums to a substantial amount over many seasons.

The potential for accruing and selling Clean Fuel Credits is another financial benefit of the transition to eTractors that will likely be substantial but is currently difficult to quantify. States like Oregon and California have adopted low-carbon fuel standards that require the reduction of highly carbon intensive fuels like diesel and gasoline. The programs incentivize the use of lower carbon-intensity fuels such as electricity, ethanol, and biodiesel. Credits are generated when one of these lower carbon-intensity fuels is used to replace regular petroleum based fuels for transportation purposes. The Oregon Department of Environmental Quality (DEQ) has not yet produced standards to compare eTractors with their IC counterparts to determine how kWh of electricity used would correspond with clean fuel credits generated. Currently heavy duty vehicles yield roughly one credit per 750 kWh and each credit sells for $120 [19] . Assuming that eTractors yield a similar number of credits as other heavy duty vehicles, farms with large fleets of eTractors may quickly see a value in terms of $1000s of dollars annually from selling these clean fuel credits. Incorporating the impact of these clean fuel credits will be important for future eTractor TCO analyses.

6.0 Conclusions and Future Research

The findings from this analysis on a single tractor during a single season suggest that compact eTractors offer a great value proposition for farmers in the Pacific NorthWest. eTractors provide a substantial reduction in GHGs when compared with IC tractors. Transition towards eTractors would support the country’s goals of combating climate change. The agricultural sector is one of the industries most vulnerable to climate change impacts [1], the transition to eTractors can serve as an act of self-preservation for agriculture. Given current conditions and assumptions which likely overestimate eTractor costs, the eTractor TCO is still comparable with IC tractors. eTractor TCO values are on the order of $3,000 greater than IC tractor TCO values. These results indicate that simple and relatively small incentives (<10% of the 7-year TCO) could be effective at persuading both hobby and commercial producers to purchase an eTractor. An incentive to purchase an eTractor incentives not only combating climate but also improved resilience to price volatility for farmers & improved health incomes resulting from reduced emissions and operating noise.

The work described in this report highlights that today, with current technology, the purchase of a compact eTractor in the PNW is a good value proposition for farmers. However, this work only scratches the surface in terms of fully understanding the impact and potential of eTractor technologies. Research in this area can be expanded in a host of ways. The simplest of which is to continue the analysis of eTractor power use with more tractors, a larger variety of tractors, for more seasons, and on different fields. The relationships between eTractor power use and battery temperature (which is correlated with ambient temperature) should be further explored. Additionally, the relationship between eTractor power use and soil type should be explored and quantified, tilling a heavy clay soil will require a different amount of power than a sandy soil. Longer term explorations of power usage which span a full day will also be beneficial as this approach makes it possible to capture the impacts of tractor idling on overall power use.

This work employs calculation methods which are designed to be flexible enough to easily incorporate new information as it becomes available and to address with these future research questions. The primary work flow consists of two python based Jupyter notebooks: one which uses telemetry based eTractor data to calculate specific power use values for various farm operations and one which combines existing data and assumptions about tractor use to calculate the TCO. This structure means that the entire analysis can be re-run in a matter of seconds to incorporate new tractor data or to look at different operating scenarios or input pricing realities.

Further research should also be conducted to better represent authentic farm scenarios. This can be accomplished via stakeholder interviews which better characterize how farmers use their tractors, how many hours per year, how many hours per day on long harvest days, what fraction of the time is spent doing various tasks, etc. As eTractors become more established, it will also be possible to collect realistic maintenance and repair data to better characterize maintenance costs. The benefits of the stakeholder focused research are two-fold; the TCO of the eTractor can be more accurately estimated, and a deeper understanding of farmer’s opinions about, and understanding of, eTractor technologies can be used to determine what incentives policy makers can use to support eTractor adoption, and ultimately the reduction of GHG emissions in agriculture.

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Appendix 1

An interactive version of the Jupyter notebook used to calculate the TCO can be accessed at the following link: https://mybinder.org/v2/gh/proctork/eTractor_TCO/HEAD.

Table A1. TCO cost break down Large Farm Scenario

	Initial Purchase	**Energy Cost**	**Maintenance**	**Financing**
eTractor (Solectrac CET)	34,022.00	422.08	2,785.70	2,623.76
IC Tractor (JD2032R)	30,969.00	3,224.83	3,341.78	0.00

Table A2. TCO cost break down Small Farm Scenario

	Initial Purchase	**Energy Cost**	**Maintenance**	**Financing**
eTractor (Solectrac CET)	34,022.00	722.15	2,785.70	2,623.76
IC Tractor (JD2032R)	30,969.00	5,109.78	3,341.78	0.00

Table A3. TCO cost break down Work horse Scenario

	Initial Purchase	**Energy Cost**	**Maintenance**	**Financing**
eTractor (Solectrac CET)	34,022.00	1,306.66	2,785.70	2,623.76
IC Tractor (JD2032R)	30,969.00	8,761.25	3,341.78	0.00

Table A4. Emission Factors for IC tractors

Pollutant	**Emission Factors**	
	Grams emitted per gallon	**Grams emitted per gallon (CO2eq)**
CH4	0.29	8.66
CO	10.3	27.3
CO2	10,567.35	10,567.35
NOx	59.62	-655.86
PM10	1.46	0
PM2.5	1.42	0
SO2	0.05	0
VOC	3.19	14.34
BC	1.09	976.78
OC	0.3	-20.85
N2O	0.28	73.54

Table A5. Electricity emission factors from GREET (gram per kWh)

Pollutant	**Type of electricity production**										
	Natural Gas	**Coal**	**Nuclear**	**Wind**	**Hydro**	**Solar**	**Biomass**	**Waste**	**Petroleum**	**Geothermal**	**Other - nonbiogenic**
CH4	0.01	0.17	0	0	0	0	0.12	0	0.04	0	0
CO	0.07	0.31	0	0	0	0	1.24	0	0.53	0	0
NOx	0.12	0.74	0	0	0	0	0.71	0	3.88	0	0
PM10	0.02	0.08	0	0	0	0	0.08	0	0.25	0	0
PM2.5	0.02	0.06	0	0	0	0	0.07	0	0.23	0	0
SOx	0.01	0.99	0	0	0	0	0.7	0	2.41	0	0
VOC	0.01	0.01	0	0	0	0	0.03	0	0.1	0	0
CO2	449.95	1,037.62	0	2.01	2.01	2.01	-2.38	2.01	954.61	95.65	2.01