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Pacific Northwest Electric Tractor Barriers Study

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Table of Contents

- Section 1 Introduction..... 4
 - Background..... 4
- Section 2 Methodology..... 6
 - Literature and Market Data Review..... 6
 - Stakeholder interviews 6
 - Technical and Engineering Review.....7
- Section 3 PNW Market for ICE and Electric Tractors 9
 - Current Tractor Market10
 - E-Tractors 15
- Section 4 E-tractor Benefits 22
 - Total Cost of Ownership..... 22
 - GHG Emissions Reductions 26
 - Increased Reliability.....27
 - Increased Resiliency..... 28
 - Improved Local Air Quality 29
 - Noise Reduction 30
 - Increased Energy Security..... 30
- Section 5 E-tractor Enablers and the Market Opportunity..... 31
 - Enabling Market and Policy Trends 31
 - Market Opportunity in the PNW..... 33
- Section 6 Barriers to E-Tractor Adoption..... 35
 - Technical Barriers..... 36
 - Economic Barriers 39
 - Achievable Barriers..... 42
- Section 7 Recommendations..... 44
 - Technical Barriers..... 44
 - Economic Barriers 45
 - Achievable Barriers.....47
- Section 8 Conclusion..... 49
- Sources..... 5

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Section 1 Introduction

The purpose of this study is to evaluate the current state of the electric tractor (e-tractor) for the agricultural market in the Pacific Northwest (PNW). Electrification of internal combustion engine (ICE) tractors reduces greenhouse gas (GHG) emissions and delivers economic, health, and energy security benefits to agricultural communities. However, despite these benefits, many barriers exist to the adoption of this new technology.

This study, informed by research and regional stakeholders, identifies key barriers to e-tractor adoption. Section 1 of this report starts with the background and context for e-tractors entering the market. Section 2 provides a description of the methodology, followed by Section 3 which then gives an overview of both the current tractor market and that of e-tractors. Section 4 explores the benefits of e-tractors. Section 5 covers market and policy enablers that contribute to adoption of e-tractors. Section 6 identifies the barriers to adoption and provides insight into the significance of each barrier. Finally, the study recommends policy and programmatic interventions in Section 7 that could help increase adoption of e-tractors in the PNW. Section 8 provides a conclusion with a summary of key findings and opportunities.

This report can help regional advocates and stakeholders to understand the current tractor market and help plan interventions that align with state transportation decarbonization goals and the improvement of local air quality among other specific policy goals.

Background

In August 2021, the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC), released their latest report documenting unequivocal human influence causing 1.1°C of net warming, caused primarily by the addition of GHG to the atmosphere.¹ Emissions from fuel combustion in the agriculture sector contributed over 40 million metric tons of carbon dioxide equivalents (MMT CO₂e), or 0.6% of all US emissions in 2019.²

The UN consensus is that averting the direst impacts of warming requires a 50% reduction of GHG emissions by 2030 and reaching net zero emissions by 2050. These ambitious reduction targets indicate that every sector of the economy must reduce emissions and replace direct fossil fuel combustion with cleaner alternatives. Actors across society, politics, and the economy all have a large role in the transition away from fossil fuels.

Market transformations are beginning to decarbonize economic sectors such as electricity, buildings, and light-duty vehicles. Yet in other, harder to decarbonize sectors, emissions from direct combustion remain persistent. Tractors are an example of heavy machinery, powered by diesel, that still faces barriers to electrification.

¹ IPCC. [Web](#).

² U.S. Greenhouse Gas Emissions from Agricultural Sector. [Web](#).

Until recently there were no alternatives to fossil fuel powered ICE tractors outside of demonstration units. Product availability is quickly changing with improved technology and cost declines each, in turn, increasing the demand for e-tractors. The challenge ahead for battery electric tractor advocates is systematically resolving remaining barriers. Market transformation barriers include higher upfront costs, lack of consumer knowledge or preference, and resistant incumbent actors. In some cases, it is a combination of these factors that slow a transition.

Rapid cost declines have occurred and continue to reduce the price of renewable energy and lithium-ion batteries. Both trends are important enablers that make e-tractors economically competitive with ICE tractors on a total cost of ownership basis. Further, electric motors are much more energy efficient than internal combustion engines which results in fuel savings to owners and operators of electric tractors. Using regional electricity and diesel rates, we estimate that e-tractors save over \$3,000 a year in fuel costs. The simpler electric motor, with fewer moving parts also has maintenance savings compared to a diesel engine. Under certain circumstances, the additional upfront cost of electric tractors is offset by operational cost savings within 5-7 years. A full look at fuel costs, energy use, and total cost of ownership is explored in the E-Tractors Section on page 16.

Beyond lifetime operating cost savings, electric tractors have worker health, safety, and quality of life improvements. The lack of tailpipe emissions has direct health benefits to farm workers who were previously exposed to diesel exhaust from tractor use. The Center for Disease Control (CDC) warns of hearing damage from prolonged exposure to noise levels above 70 decibels (dB).³ Based on surveying test results from the Nebraska Tractor Test Lab, ICE tractors regularly exceed these noise levels.⁴

Finally, there are significant GHG emissions reductions when replacing an ICE tractor with an e-tractor. This is because e-tractors have two, symbiotic advantages: (1) more efficient conversion of potential energy into usable work, and (2) a cleaner fuel source. In the PNW, replacing a diesel tractor with a comparable e-tractor will reduce carbon emissions by at least 85%. In some utility regions emissions reductions are even higher, and across the region 100% clean electricity legislation is actively pushing fossil fuels out of the electricity supply mix.

Ultimately, an electric tractor powered with 100% clean electricity will have no operational phase carbon emissions.

Cadeo conducted market research to better understand the tractor market and the current role of electric tractors, particularly focused on the Pacific Northwest region. An initial literature review provided the context for understanding the barriers to widespread adoption of electric tractors. Cadeo then completed interviews with stakeholders including manufacturers, distributors, producers, and other entities engaged in the region. Finally, we worked with researchers at Oregon State University (OSU) to look at total cost of ownership to understand lifetime economics of tractor purchasing and operation. This report presents research results.

³ "What Noises Cause Hearing Loss?" CDC. [Web](#)

⁴ Nebraska Tract Test Laboratory. [Web](#).

Section 2 Methodology

Cadeo's market barrier study included three phases: literature and data review; stakeholder interviews; and a technical and engineering review, which assessed tractor efficiency and tractor operating and capability specifications.

Literature and Market Data Review

Cadeo reviewed a large volume of relevant and current plans, white papers, and studies relating the tractor sales, agricultural markets, and electrification trends. We also focused on vehicle electrification initiatives in the agriculture sector. This included review of the following sources:

Tractor sales data

We reviewed sales data at the national and regional level for various configurations of ICE tractors. This included raw sales data and market forecasts from the Association of Equipment Manufacturers which publishes monthly U.S. Ag Tractor and Combine Reports that detail the volume of retail tractor sales by tractor size in the U.S. Cadeo also reviewed publicly available tractor market projections for both ICE and e-tractors from Grand View Research and IDTechEX, who each produce forward looking reports on tractors in agriculture.

Agricultural market data

Cadeo staff considered regional data on the different crop types, irrigation methods, and farm sizes in the Pacific Northwest from:

- USDA Census of Agriculture Data on Agricultural Production: State and County level data including farm size, crops, and revenue
- American Farmland Trust report on Farmland Threats: A synopsis of trends in how farmland is being converted to other uses

Electric Vehicle Reports on Industry Trends

Electric vehicles are a proxy technology whose demand have increased the manufacturing capacity and driven down the cost of batteries. Inherently, the trends in EVs have rippling impacts on other equipment that uses the same core technologies.

- Bloomberg New Energy Finance, 2021 EV Outlook: EV sales, battery pricing trends, and policy landscape

Stakeholder interviews

To gather stakeholder perspective, our team interviewed individuals across the agriculture space including farmers/producers, distributors, manufacturers of agricultural vehicles, distributors, elected officials, and relevant regional partners.

We talked to 7 stakeholders in total, broken out across the categories below. Each interview covered a variety of topics including cost, maintenance, and use cases. Findings from the literature and market data review task were discussed and validated against the perspective of stakeholders where relevant.

Table 1. Stakeholder Interview Sample Frame

Category	Count
Producer	2
County Official	1
Community Agriculture- Technology Alliance	1
Manufacturer	2
Distributor	1
Total	7

Technical and Engineering Review

Cadeo also tapped our in-house transportation and electrification experts to understand the applicability of different models to likely use cases, fill data gaps as needed, and inform recommendations. This review covered tractor performance, use cases, and specifications. We reviewed various tractor implements and their use case. We also evaluated fueling, maintenance, and comparative energy efficiency of various tractors. Cadeo also consulted with the subject matter experts at Sustainable Northwest, Forth, Wy'East RC&D, and Oregon State University, which is currently conducting a demonstration pilot of electric tractors in Oregon. The primary data gathered from e-tractors in use on farms in the region today will be an ongoing source of information to establish performance and use cases.

Electric Tractor Manufacturer Specifications

Cadeo staff conducted a review of the technical documentation for all existing electric tractor models available or publicly planned. This included the following models:

- Solectrac eFarmer
- Solectrac Compact Electric Tractor (CET)
- Solectrac eUtility
- Solectrac e70N
- Monarch MK-V

Where product specifications did not exist, we reviewed available materials for tractor electrification prototypes from incumbent manufacturers including John Deere, Kubota, and Fendt. We used this documentation to map currently available products to the current mix of uses in the region, considering horsepower, battery size, and available implements. We also considered any case studies made available by the manufacturers.

Tractor Operating Specifications and Studies

Cadeo reviewed literature on operating specifications of diesel tractors to inform the comparison to e-tractors. Sources included:

- Nebraska Tractor Test Laboratory: Independently tested fuel consumption, power output, and decibel level data for hundreds of common tractors in the United States.
- Biosystems Engineering Reports: (1) Cost analysis of battery electric field tractors in agriculture and (2) Analysis of charging infrastructure, battery exchange, and battery state of charge

Total Cost of Ownership

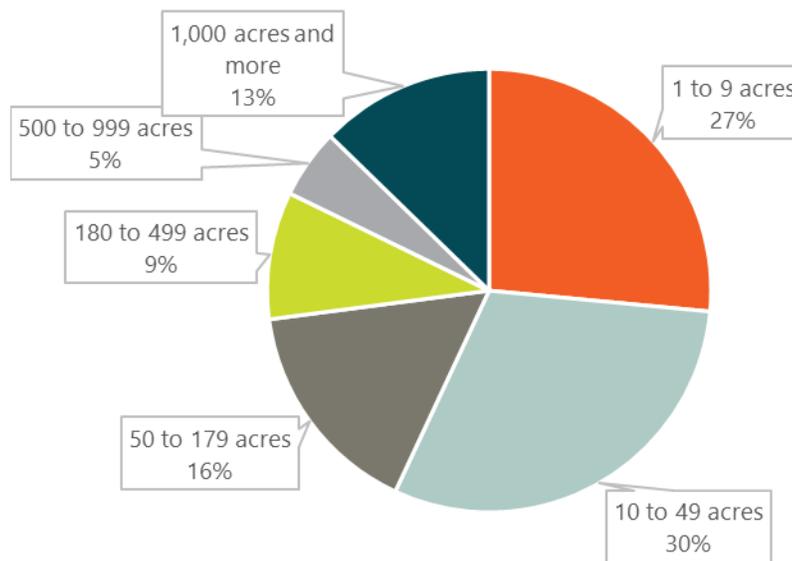
Total cost of ownership (TCO) is an important metric for understanding the affordability of electric tractors. Such analyses account for comprehensive cost considerations including initial purchase price, financing, taxes and fees, fueling, maintenance, and insurance. The Cadeo team worked with researchers at Oregon State University to develop a TCO model that accounts for relevant cost components of ICE and e-tractors. As a reference, Cadeo used a recent study comparing light, medium, and heavy-duty road vehicles.

- Argonne National Lab, Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains

Section 3 PNW Market for ICE and Electric Tractors

The Pacific Northwest, comprised of 100.4 million acres of farming land,⁵ supports a diverse agricultural economy. The region is a top producer of berries, wine grapes, seed crops and wheat. Washington grows about 70% of the apples in the US, Idaho produces over 80% of the world sweet corn seed crop, and Oregon produces 99% of the U.S. hazelnut crops.⁶ The region is characterized primarily by farms sized below 500 acres but there are also large agricultural operations with farm sizes surpassing 2,000 acres (Figure 1),⁷ particularly further East in Montana. This mixture of farm sizes and types provides the backdrop for which tractor capabilities are necessary in the region.

Figure 1: Distribution of Pacific Northwest Farms by Size



As shown in Figure 1, large farming operations greater than 500 acres in size, represent 18% of farms in the region. Such operations will rely mostly on large combines and tractors greater than 100 HP for their farming needs. Given the lack of electric tractor options (beyond prototypes) for this segment today, this study does not focus on tractors greater than 100 HP. On the other hand, the region supports a diversity of crops and abundance of smaller operations. Tractors below 100 HP serve a variety of needs on such properties and are the focus of this study.

⁵ 2017 US Agricultural census.

https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Census_by_State/index.php

Acreage by state: WA 14.7M acres, OR 15.9M acres, ID 11.7M acres and MT 58.1M acres

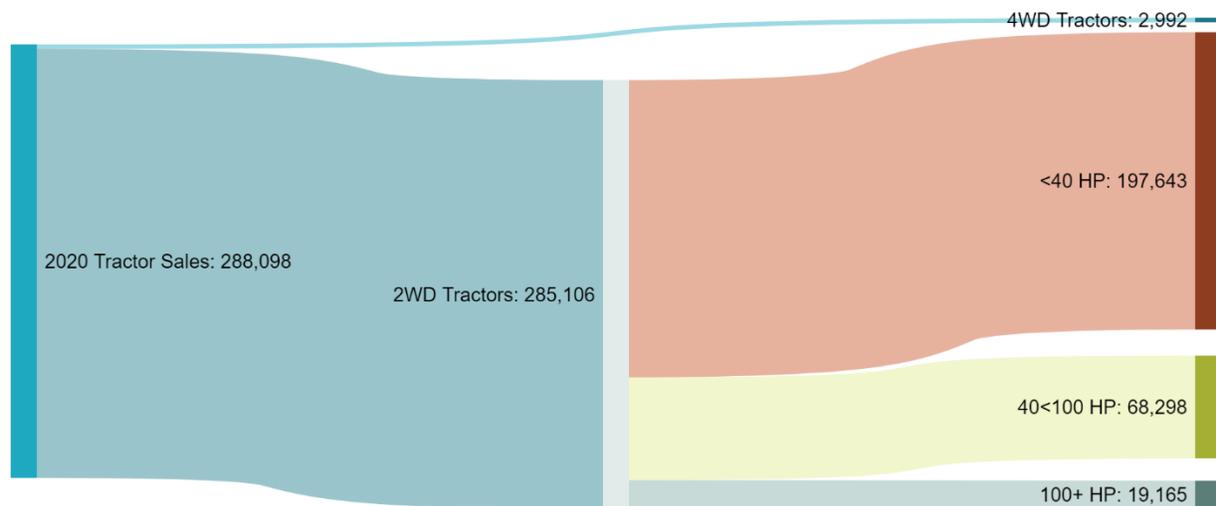
⁶ American Farmland Trust <https://farmland.org/pacific-northwest-more-information/>

⁷ Include Oregon, Washington, Idaho, and Montana. 2017 US Agricultural Census

Current Tractor Market

In 2020, the tractor market size was \$64.8 billion globally and \$12 billion in North America.⁸ In the U.S., agricultural machinery manufacturing is a component of one of the nation's largest industries. When tractor manufacturing is combined with other agricultural machinery manufacturing, the entire industry has a 2021 market size of \$37.8 billion.⁹ This tractor manufacturing contributed to over 288,000 U.S. tractor sales in 2020, according to data from the Association of Equipment Manufacturers (AEM).¹⁰ The majority of those sales went to tractors under 40 HP. Figure 2 shows the relative size of each tractor segment for the full year, 2020 sales. Year-to-date numbers for 2021 predict an overall increase in total sales.

Figure 2. 2020 U.S. Tractor Sales by Type and Volume



Tractor sales provide insight into the flow of new tractors into use, but do not provide insight into the stock of what tractors already exists and how long they persist. More than 85% of the tractors working in the PNW farms were manufactured prior to 2013 according to the 2017 U.S. Agricultural census. This relationship holds true for the previous agricultural census (2012), where more than 85% of the tractors were manufactured prior to 2008. With an average 0.003% growth in the number of tractors from 2012 to 2017 and with tractor turnover of approximately 20 years.

A tractor turnover rate of 20 years and annual sales of at least 250,000 tractors implies that the total stock of tractors in the U.S. is 5 million units. While penetration of a new technology is

⁸ Tractor Market Size to Reach USD 97,906.1 Million by 2030 at CAGR 4.0% - Valuates Report. Cision PR Newswire. 10 Nov. 2021. [Web](#).

⁹ Tractors & Agricultural Machinery Manufacturing in the US – Market Size 2002-2027. 23 Dec. 2021. [Web](#).

¹⁰ AEM monthly tractor and combine reports. [Web](#).

often evaluated based on the percentage of new sales, a large stock means that full stock turnover will take a considerable amount of time.

Manufacturers

The companies with the most tractor market share in North America are John Deere, CNH Industrial NV, and AGCO. The largest and most iconic is John Deere, which has garnered significant brand loyalty after over 200 years in business. Multiple interviews noted that brand loyalty, not solely to John Deere, is an active factor in agricultural communities when purchasing new equipment. While brand loyalty is common, noted by distinct primary colors, brand differentiation in tractor performance and operation characteristics is harder to identify. Most of the main manufacturers have products of all form factors and horsepower. This makes local availability a key driver of tractor selection for a given area.

It is safe to say that most of the tractors utilized in the region are more than 15 years old.

The companies that sell significant volumes of tractors in North America are:

- John Deere
- New Holland (CNH Global)
- Massey Ferguson (AGCO)
- Mahindra
- Kubota
- Valtra (AGCO)
- Fendt (AGCO)
- Challenger (AGCO)

This list is not exhaustive, and interviews indicated that there are several specialty brands that sell to producers with unique needs. One interviewee mentioned that in orchards they commonly import Landini tractors from Italy.

Distributors

Manufacturers work exclusively via distributors for selling their products to end users. For this reason, distributors have a large influence on which company's products are available to consumers in their region. Producers interviewed by Cadeo referenced the brand that their local distributor carries as the likely choice for their next tractor.

The manufacturer and distributor relationship also extends to maintenance and repair. Manufacturers work directly with distributors as opposed to end users for replacement parts making the distributor a necessary intermediary for producers, regardless of whether they are doing the maintenance themselves or hiring the distributor.

In general, most promotions and demand levers are funded by manufacturers and implemented by distributors. Zero percent interest loans are one demand lever commonly used by manufacturers and advertised by distributors.

Purchasing Motivations

Interviews identified a range of factors that result in farms buying a new tractor, including:

- Local availability
- Equipment failure
- Change in tractor needs or capability
- Increased economic efficiency
- Business or tax reasons
- Social influence
- Promotions

Distributors are the primary channel for tractor sales although secondary markets for used vehicles are also influential. Thus, depreciation and residual value of used tractors is a considered factor when purchasing new. One interviewee claimed that the value retention was a main driver of selecting the brand that the local distributor carried.

For new tractors in the sub-100 HP category the price ranges from just under \$10,000 to well over \$50,000. The size and power are the primary determinants of price, although there are other features that also add cost. In some cases, specialty tractors fit certain form factors, such as narrow-bodied tractors to navigate tightly spaced rows of fruit trees.

Financing, which will be discussed more in the barriers section, was a motivation that came up during several interviews. Manufacturers often utilize zero-interest loans as a demand lever. In general, this tactic is effectively used as a marketing tool to increase sales. Multiple interviewees

“After a good season, that’s when you start to see the brand-new trucks and tractors the following spring”

- Stakeholder interviewed

talked about the local zero-percent loan offer as a major factor when deciding which tractor to buy next. No-interest offers are seen as a low-risk opportunity to acquire newer, higher performing equipment particularly when resale value is high.

Finally, tax reasons were identified as another reason for purchasing new equipment. When producers complete a profitable year, there is motivation to invest in equipment for their business that reduces their overall tax burden.

From the producer’s perspective, this is a unique opportunity of profitable seasons, where investing in their operation reduces their tax expense and increases their equipment capability.

Use Cases

Tractors are an essential tool in every farm setting as they provide power and traction to mechanize agricultural tasks including tilling, sowing, mowing, spraying, harvesting, and more. Tractors are intentionally designed for compatibility with a wide range of implements to support the varied farm tasks. For utility tractors, there are three types of hitches.

Table 2: Tractor Hitch Categories

Hitch Categories	Horsepower Range (HP)	Common Tractor Type
Category 0	0 – 20	Lawn and Garden Tractors
Category 1	20 -50	Utility Tractors
Category 2	50 – 90	Utility Tractors

The size and needs of producers drive the selection of a tractor. Regional producers discussed tractor specializations, such as for spraying, where a tractor is rigged for one function and not reconfigured for other uses. This type of specialization can only be supported by higher value or higher volume operations where there are multiple tractors in use and one can be dedicated to a single task such as spraying.

On the contrary, smaller producers use a single tractor to complete necessary farm functions. To accommodate the various needs, such producers have multiple implements that attach to tractor hitches and enable different uses.

The tractor type needed is largely a function of the following factors:

- **Plot size:** How many acres need to be harvested?
- **End use:** What functions does the tractor need to provide: Plowing? Tilling? Spraying? Hauling? Mowing?
- **Terrain:** Is the acreage largely flat or are there large hills? Is it uneven or leveled?
- **Crop characteristics:** How are the crops oriented? Does the tractor need to fit a certain form factor to operate within rows?

Plot size and end use will determine the HP of the tractor needed to carry out farm activities. For instance, mowing and small-scale field cultivation can be achieved with as low as 20 HP tractors. Certain end uses require higher energy intensity and will therefore require higher tractor HP (>50 HP) to complete the task, examples of these are commercial harvesting, cultivation, and tilling.

Certain regions with undulating, inclined terrain or a cold climate with snow and ice require a 4WD instead of a 2WD tractor. In such regions, other additional tactics are occasionally required, such as filling tires with a slurry that adds weight and increases traction.

Fueling

Diesel is the primary fuel used in tractors of all sizes including in the sub-100HP market that this study is focused on. Gasoline was previously more common and can still be found in older tractors. For newly manufactured tractors, gasoline engines are available in smaller tractors such as garden tractors that are used primarily for mowing. Otherwise, diesel is the preferred fuel for ICE tractors.

There are several reasons for the preference toward diesel including fewer maintenance issues and longer lasting engines. Diesel is also a more energy dense fuel than gasoline, with about

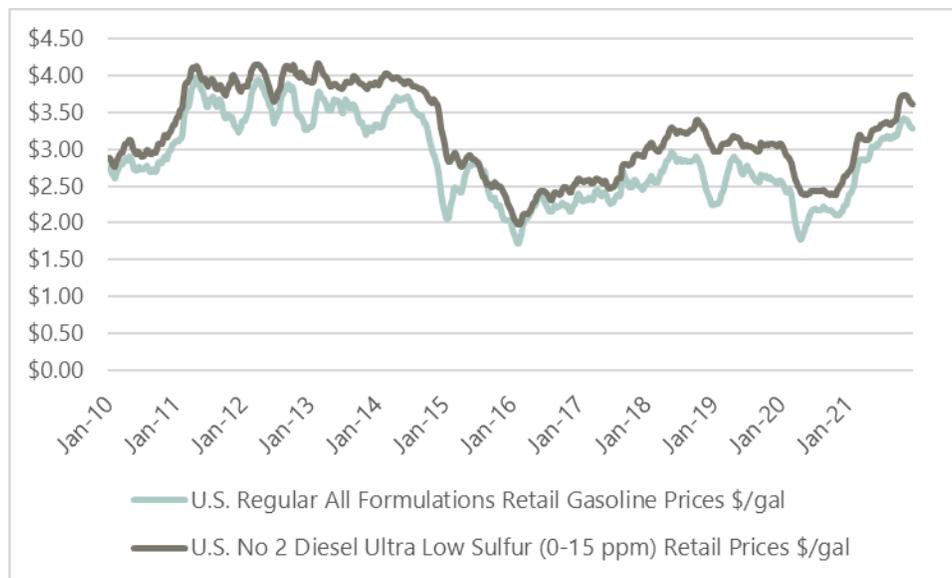
13% more energy content per gallon according to the Alternative Fuels Data Center.¹¹ In addition to the energy content advantage, diesel engines are typically more energy efficient than gasoline engines. These combined factors mean that diesel tractors get more usable work out of a gallon of fuel. This is particularly beneficial for farms that stock a finite volume of fuel and rely on on-site fuel deliveries.

Tractors, unlike passenger vehicles, cannot easily drive to the nearest gas station, nor would it be an efficient use of time or energy. Instead, large tractor-trailers deliver bulk fuels to storage tanks located on working farms. Increased energy density and fuel efficiency both help reduce reliance on expensive fuel deliveries.

Increasing prices since the start of the Covid-19 pandemic have increased interest in alternative fuels such as electricity.

Figure 4 compares the weekly price of gasoline and diesel over the past decade. While diesel is consistently more expensive than gasoline, the increased energy content per gallon make diesel the slightly more affordable option.

Figure 3: U.S. Weekly Retail Gasoline and Diesel Prices¹²



Efficiency and Emissions

The transportation sector is responsible for 28% of the United States primary energy consumption and 36% of energy related carbon dioxide emissions.¹³ Within the transportation sector, agricultural equipment, including tractors, consumed 0.6 quads of energy in 2020.¹⁴ This

¹¹ Alternative Fuels Data Center. [Web](#).

¹² EIA data. [Web](#).

¹³ U.S. Energy Information Administration 2020 data. Accessed at: <http://departmentof.energy/>

¹⁴ A quad is a unit that represents a quadrillion British Thermal Units (btu). In 2020, the U.S. consumed 97.2 quads of energy per EIA.

is equivalent to 4.3 billion gallons of diesel, which produces 44 million metric tons of carbon dioxide emissions.

While agricultural equipment energy use remains less than 1% of all primary energy use in the U.S. annually, it is markedly inefficient. Only 20% of the input energy provides valuable work.¹⁵

This inefficiency is attributed to the internal combustion engine, which is the primary means for powering agricultural equipment. Valuable work for a tractor is usable mechanical energy that moves the tractor or operates an implement such as mowing, tilling, or spraying. Diesel engines, however, are inefficient at converting the chemical potential energy in diesel into usable work. Combustion creates energy losses, most of which are thermal, in other words heat is produced that is not converted into usable work. This can be as much as 70% of the energy content in the fuel, lost to the engine.¹⁶

Additionally, many tractors used in agricultural settings spend a considerable amount of time idling, which consumes over a gallon of fuel per hour for a 50 HP tractor.¹⁷ This idling further diminishes the overall efficiency of the tractor.

E-Tractors

Electric tractors are a technology receiving increased investment and production, and for good reason. Prior studies have documented how increased electric tractor use could reduce greenhouse gas (GHG) emissions, improve system-wide energy efficiency, and reduce dependencies on imported fuels.¹⁸ Modeling from one study suggests that energy consumption could be reduced by 58% and GHG emissions by 92% when a comparable electric tractor replaces a diesel predecessor.¹⁹ Despite these obvious energy system benefits, electric tractors have minimal market adoption today. This section will outline e-tractor market characteristics.

Manufacturers

The electric tractor market is maturing quickly with two main companies, Soletrac and Monarch, specializing in the under 40 HP and 40-100 HP tractor segments (the most common sizes owned by PNW farmers).²⁰ The well-recognized tractor manufacturing companies such as John Deere and Massey Ferguson, have not yet deployed electric tractors but the former showcased electric prototypes and is bringing full electric solutions to market.

¹⁵ U.S. Energy Information Administration 2020 data. Accessed at: <http://departmentof.energy/>

¹⁶ U.S. DOE, Where the Energy Goes. Web. <https://www.fueleconomy.gov/feg/atv.shtml>

¹⁷ This was observed when looking at 50 HP tractors in the Nebraska Test Tractor Lab data

¹⁸ Lagnelöv, Oscar & Larsson, Gunnar & Nilsson, Daniel & Larsolle, Anders & Hansson, Per-Anders. (2020). Performance comparison of charging systems for autonomous electric field tractors using dynamic simulation. *Biosystems Engineering*. 194. 121-137. 10.1016/j.biosystemseng.2020.03.017.

¹⁹ Engstrom, J., & Lagnelov, O. (2018). An autonomous electric powered tractor - simulations of all operations on a Swedish dairy farm. *Journal of Agricultural Science and Technology A*, 8(3), 182e187. <https://doi.org/10.17265/2161-6256/2018.03.006>.

²⁰ 2017 US Agricultural census. [Web](#).

Both Solectrac and Monarch produce e-tractors that are currently working on farms, vineyards, and orchards on the west coast of the U.S. Table 2 provides a comparison of the currently available e-tractor models and their specifications.

Table 3. Current E-Tractor Models Available²¹

Parameters	Monarch		Solectrac	
	MK-V	CET	eUtility	e70N
Horsepower (HP)	40	25	40	70
Battery size (kWh) ²²	Est. ~80+ ²³	22	28	60
Starting price (USD)	\$58,000	\$26,799	\$41,399	\$74,999
Battery run-time (hours) ²⁴	10+	3 to 6	4 to 8	4 to 8
Charging time (hours) at 6.6kW ²⁵	12	3	4	9
Manufacturer stated charge time	4-5 hrs @ 19.2 kW	8 hrs @ 6.6 kW	4 hrs @ 6.6kW	6 hrs @ 11kW
Extra battery pack (USD)	Yes (swappable)	No	Yes	Yes
4WD Option	Yes	Yes (only 4WD)	No	Yes (only 4WD)

Recent Activity

The e-tractor market is gaining momentum. Since the start of this research, multiple announcements by both incumbent and all-electric startups have been released.

In November 2021, Monarch completed a \$61M Series B fundraising round, to further develop tractor technology that incorporates electrification, autonomous use and data management by

²¹ This table is composed of publicly available information gleaned from Monarch and Solectrac’s websites. Where information was not stated, it was derived from other technical specs.

²² All Solectrac battery capacities are posted on their website. Monarch does not disclose battery capacity in kWh.

²³ Monarch discloses that charging takes 4-5 hours on a 240V 80A charger. That charge rate, of 19.2 kW, charging for 4-5 hours indicates a usable battery capacity range of 76.8 – 96 kWh. We chose 80 kWh for simplicity.

²⁴ All these values are self-reported by the manufacturers. Actual run-time is contingent on operating load.

²⁵ 6.6 kW was chosen as the representative charging speed because of the prevalence of 220V and 30 Amp outlets. On manufacturer websites, other charging times are stated, but those are contingent on installation of faster charging equipment. The charge controller on the tractor may also regulate the charge rate which can lengthen charge time.

focusing on sales, services and manufacturing footprint as well as to launch an international pilot test program for regional market validation.²⁶

Solectrac, who has sold e-tractors since 2018, was recently acquired by publicly traded Ideanomics in July 2021 to help scale production and sales.²⁷ Shortly after, Solectrac announced their third model, the e70N, designed for larger agricultural applications with a motor power of 70 HP and four-wheel drive (4WD) capability. While 4WD tractors remain a small portion of the overall U.S. tractor market (1%), their usage is common on higher value agricultural land such as orchards and vineyards. The Pacific Northwest has regions where steep terrains with elevations above 2,000 feet drive the need for 4WD units.

Established manufacturers of ICE tractors are currently on the side lines of the e-tractor market, though recent activities suggest more serious investment in an electrified future. John Deere, Massey Ferguson, and Fendt have all released prototypes that are in varying degrees of development, but no one has announced a near-term delivery or production date for bringing e-tractors to consumers. In 2017, John Deere won an innovation award for a prototype electric tractor in the greater than 100 HP segment, with four-hour run-time and three-hour charge time.²⁸ Following that prototype of several years ago, in December 2021, John Deere acquired a majority stake in Kreisel Electric, a company that specializes in batteries and charging infrastructure.²⁹

Short of full electrification there are producers pursuing hybrid models that significantly improve upon the efficiency of ICE tractors. One example is the Landini REX4 Electra which uses a diesel generator to provide energy to a battery and electric motors that drive the front axle.³⁰ Landini claims 15% fuel savings for their hybrid tractor, which also has some of the other benefits of fully electric tractors such as the elimination of idling when not moving.

The research team perceives electrification announcements as preludes to more announcements and deployments of electrified tractor options in the future from both incumbent and startup companies.

Distributors

Purchasers of electric tractors from both Monarch and Solectrac are working directly with the manufacturers today. Whether this model remains as the two companies grow and sell at higher volumes remains to be seen. Monarch's website invites distributors to send them proposals for carrying Monarch Tractors, though they state that they only sell direct to consumer for the time being. In the electric vehicle space, younger companies have decided to sell directly to consumer and avoid the existing dealership network. This comes with advantages and disadvantages that are discussed further in the barriers section.

²⁶ AgTech Startup Gains Major Funding for its Smart, Driver-optional, Electric Tractor. American Entrepreneurship Today. 19 Nov 2021. [Web](#).

²⁷ Press release. Ideanomics Acquires U.S. EV Tractor Maker Solectrac. Ideanomics. 2021 [Web](#).

²⁸ John Deere. SIMA awards for innovation [Press release]. 2017. [Web](#).

²⁹ John Deere Acquires Majority Ownership in Kreisel Electric. Press Release. 08 Feb 2022. [Web](#).

³⁰ [Landini Website](#)

It can be expected that existing manufacturers of ICE tractors will continue to utilize their distributor networks to sell their newly electrified versions.

Use Cases Today

To understand where e-tractors will be adopted in the coming years, we explore the capabilities and use cases of available e-tractors today. These capabilities can be compared to comparable diesel tractors. Table 3 summarizes the cost and capabilities of the two largest electric tractors as compared with a regionally available diesel counterpart.

Table 4: Comparison of Electric and Diesel Tractors with Similar Specifications

Parameters	Monarch	Solectrac	Kubota
	MK-V	e70N	M6060
Fuel	Electricity	Electricity	Diesel
Gross Engine HP	40	70	66.4
PTO HP	40	55	56
Starting price (USD)	\$58,000	\$74,999	\$37,500
4WD	Yes (+\$10K)	Yes	Yes

Notably, both electric tractors are significantly more expensive than the diesel for comparable capabilities including at least 65 HP gross engine and a 50 HP PTO or greater. We compared pricing and specs for the 4WD tractor versions that had Category 1& 2 hitches, meaning they are interoperable with the majority of implements in the utility tractor space. The Table 3 comparison is meant to be simple and not inclusive of other operating costs or benefits, which are explored in benefits and barriers sections.

Market Adoption

Based on the standard Technology Adoption Curve,³¹ the e-tractor market in the PNW, is at the Innovators stage, where adoption is less than 2.5% of market share. Market data is not yet readily available on adoption in the US or the Northwest specifically, but evidence indicates it is essentially 0%, below 1% of market share. In this nascent stage of adoption, buyers are characterized by increased risk tolerance and willingness to try less established technologies. An example of this less price sensitive group is the hobby farmer, who owns and maintains a small farm for pleasure and not for profit purposes. The farm is not their primary source of income and therefore, they are more willing to try a new technology, based on other motivations such as carbon emission reduction, without risking their long-term economic capability. Interviews with e-tractor manufacturers mentioned hobby farms specifically as an initial target market for their tractors.

³¹ Rogers, Everett M. Diffusion of Innovations. New York: Free Press, 2003. The diffusion curve describes the psychological dispositions of individuals in each category of adoption. When diffusion is low, the population of adopters are characterized as innovators and early adopters. These two camps are known for their increased risk tolerance and willingness to try less established technologies. In general, this camp also has more economic means, insulating them from impacts of product failure.

Recently, Sustainable Northwest, Forth, and Wy'East RC&D developed the Electric Tractor Demonstration Program,³² to enable farmers from the PNW region to test e-tractors for a trial period. Over the next few years, the program team will study the capabilities, limitations, and benefits of e-tractors to the region. The data and partnerships with producers will inform e-tractor performance under different end uses, climates, and terrains as the e-tractors will be rotating to different locations throughout the program. The program is funded by multiple sources including Bonneville Environmental Foundation, U.S. Department of Agriculture, Alumbra Innovation Foundation, Pacific Power, and others. In early 2021, two electric tractors were purchased and delivered. Program expansion is expected for the upcoming years with the acquisition of several more tractors.

Fueling: Rural Electricity

Rural electrification has a long and complex history in the Northwest. The formation of the Bonneville Power Administration (BPA) as a part of the New Deal led to the formation of dozens of rural electric co-operatives and public utility districts (PUDs) along with greater access to low-cost water and electricity for irrigation. Given the heavy reliance of these public utilities on federal hydropower, there remains a highly entangled relationship between the agricultural sector and low-cost, carbon free electricity.

Retail Rates

The Pacific Northwest is known for some of the least expensive electricity rates in the country. Low electricity prices are largely the result of abundant hydropower, which was built decades ago and has zero fuel cost. As a result of these low electricity costs, the Pacific Northwest is an attractive region for electric tractor adoption.

Average retail electric prices are well below the national average for all states in the Pacific Northwest.³³ In addition to the low rates region-wide, much of the agricultural land in the region is serviced by publicly owned utilities which benefit from even lower rates. These lower rates are a result of the relationship of consumer-owned utilities (COUs) and BPA. BPA is a nonprofit, federal agency in charge of marketing power from 31 federal hydroelectric projects and a nuclear power plant. BPA's primary customers are the 138 consumer-owned electric utilities in the region, which are entitled to statutory preference and priority to purchase federal power. As a result, these consumer-owned utilities are eligible for BPA's priority firm rates, which are low.

³² Electric Tractor Demonstration Program. Sustainable Northwest. Accessed Nov 2021. [Web.](#)

³³ "State Electricity Profiles", U.S. Energy Information Administration. Accessed Dec 1, 2021:

<https://www.eia.gov/electricity/state/>

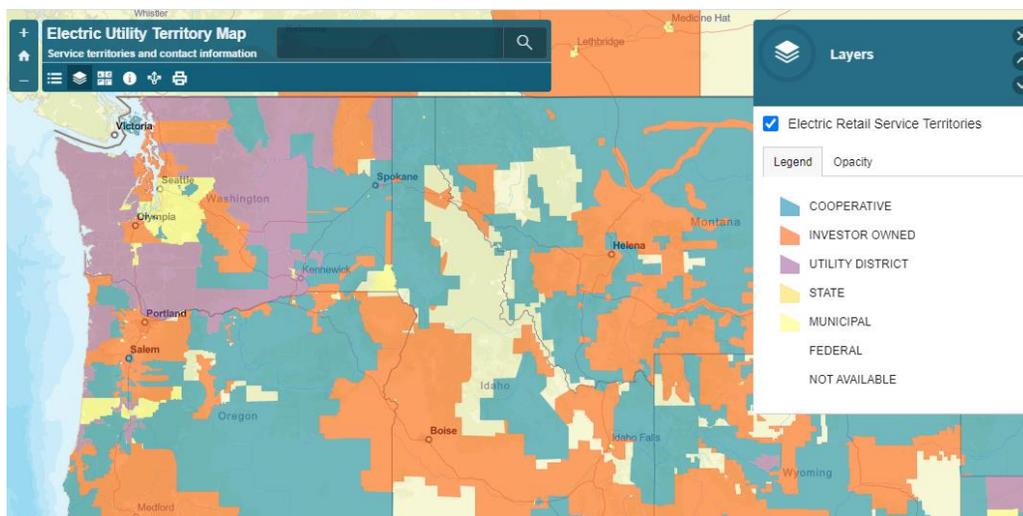
Table 5: Revenue-Weighted Retail Rate (Cents/kWh) Comparison for Investor versus Consumer-Owned Utility³⁴

	Residential		Commercial	
	COU	IOU	COU	IOU
ID	9.4	10.1	7.4	7.8
MT	10.4	12.1	8.5	11.6
OR	9.8	11.7	8.4	9.4
WA	9.5	10.4	8.4	10.0
Overall	9.6	10.9	8.3	9.6

The average retail rates for each state are shown above, broken out on a sale-weighted basis by state and ownership type. Electric tractors typically charge at a level 2 but do so directly from a welding outlet and not from a dedicated charging station. Depending on the size, plot layout, and number of tractors simultaneously charging, the producer may qualify for a residential, commercial, or even potentially irrigation rate. In any case, consumer-owned utility rates are consistently less than the IOU rate, which means electric tractors operating in publicly owned utility districts have a further operating cost advantage.

Many of the producing regions within the PNW fall within consumer-owned utility territories as demonstrated in Figure 4, where only the orange shaded areas represent IOUs and the rest of the colors reflect some version of a consumer-owned utility.

Figure 4: Electric Utility Territory Map³⁵



³⁴ Calculated from EIA data on individual utilities sales

³⁵ Public Arcgis map created from public databases, Accessed December 1, 2021:

<https://www.arcgis.com/apps/View/index.html?appid=4d9b27d9071d498885a7c943e58a2fb1>

Built Infrastructure

Manufacturers and participants alike referenced the frequency with which farms have outlets typically set up for welding located in barns. These welding outlets are 220V and have up to 50 Amp service. A common set up is 220V and 30 Amp which equates to a 6.6 kW charge rate.³⁶ The smallest battery on a currently available e-tractor is 22 kWh, which would take 3-4 hours to charge. The largest battery on a currently available e-tractor is around 80 kWh and would take 12 hours to charge completely at a 6.6 kW rate.³⁷

The attractiveness of charging with a 220V outlet set up for welding is that most farms would not need any electrical upgrades to start regularly using an e-tractor. Also, since e-tractors do not require a charging station, they can plug directly into an existing 220V outlet. However, as batteries get larger such as Monarch MK-V and the Solectrac e70N, there is a desire to increase the charge rate to decrease the down time of the tractor. The Monarch can accept a charge up to 19.2 kW, which requires a 240V and 80 Amp breaker. In an ideal world, the farm would have enough service to accommodate this. If not, a prospective buyer would also need to upgrade their electrical service from the utility, which adds upfront cost. However, charging the Monarch at 19.2 kW would cut the charge time from over 12 hours to under 5 hours.

Battery Swapping

Certain farming operations may need additional battery capacity than what is available in one charge. This leaves the producer with two options:

- 1 |** Install a faster charger and accept the down time needed to charge
- 2 |** Purchase an additional battery to prolong tractor run-time during the workday

Both Solectrac and Monarch offer additional batteries for their e70N and MK-V models respectively. For operations that cannot afford the down time, purchasing an extra battery will add upfront cost, but reduce downtime, ultimately saving cost.

An additional battery pack on site may add flexibility and resilience to the operation which is explored in Section 3 below.

³⁶ Some welder plugs also have 220V and 50 Amp circuits which increases the charge rate to 11 kW. Such circuits reduce charge time by 60%.

³⁷ This is an estimate derived from the posted charging rate and time on Monarch's website.

Section 4 E-tractor Benefits

Advocates of e-tractors can highlight benefits and encourage faster adoption. E-tractors have important benefits directly to the farmers that are their primary end-users. For example, e-tractors do not produce local emissions that producers breathe, so health improvements can be expected. Specifically, particulate matter emissions reductions will go a long way to reducing respiratory/cardiac-related issues. E-tractors can also increase farmers' energy security by reducing the reliance on the prices of highly volatile crude oil. The benefits e-tractors compounds when the electricity is generated on-site by solar power or another renewable energy resource.

Total Cost of Ownership

Electric tractors cost significantly less to fuel than diesel powered tractors in the Pacific Northwest, even using low diesel prices and high regional electricity rates. Due to the competing dynamics of when costs are incurred, total cost of ownership models were created to factor in elements beyond the initial cost and provide an easy to interpret value for prospective buyers to compare costs. A total cost of ownership (TCO) model combines costs including purchase price, financing, maintenance, and fuel to create a picture of how expensive it will be to purchase a tractor over a fixed amount of time, typically 5-7 years. This value is helpful for decision making where the lowest priced option may not be the least expensive to own.

Recently, an Oregon State University researcher created a TCO comparison of an active e-tractor in use on an Oregon farm, and a comparable diesel tractor. The report is titled, "Total Cost of Ownership of a Compact Battery Electric Agricultural Tractor". This section highlights some of those results and discusses the facets of reduced operational costs from e-tractors.

Total cost of ownership for e-tractors is comparable to diesel tractors today.

A key finding of the report is the result that e-tractors are already cost competitive on a TCO basis with ICE tractors. This is an important conclusion, indicating that one of the key barriers to adoption is already resolved. Savvy producers who look beyond upfront cost will be compelled by the results of the OSU study.

Total cost of ownership for e-tractors is less expensive in scenarios of high annual use.

Due to reduced operational costs, the more the tractor is used, the less expensive it becomes compared to a diesel one. The main scenarios in the OSU study compared tractors operating for 250 hours per year. Another scenario was completed that compared TCO under use cases of 750 hours of operation per year. In those three profiles, the e-tractor ranges from 10% - 30% less expensive on TCO, depending on the energy intensity of tasks. For operations with many hours of annual tractor operation, e-tractors could save them significant amounts of money.

Table 6: Total Cost of Ownership with 750 Annual Operating Hours (OSU Results)³⁸

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

The following section will explore the reduced e-tractor operational costs that contributed to the comparable TCO.

Reduced Operational Costs

While e-tractors are more expensive on up-front cost, cost savings from operation defray overall ownership costs and help farms be more profitable on an annual basis.

Energy Efficiency

Values derived from the OSU study provide side-by-side comparison of the energy consumption of the ICE and e-tractor in three different operating modes. Across all three modes of usage the e-tractor uses approximately 90% less energy. This large jump in efficiency decreases costs and emissions of e-tractor operation.

Table 7: Comparison of Energy Consumption for Diesel vs. Electric Tractors³⁹

Tractor Fuel	Tractor Operating Mode	Diesel Consumption Rate (gal/hr)	Electricity Consumption Rate (kW)	Equivalent Units (kBTU/hr)	Percent Less Consumptive
Diesel	Driving	0.44	--	60.4	--
	Mowing	0.88	--	120.9	--
	Tilling	1.56	--	214.3	--
Electricity	Driving	--	1.45	4.9	92%
	Mowing	--	3.27	11.2	91%
	Tilling	--	6.17	21.1	90%

From a resource perspective, this means that if all ICE tractors were electrified at once, there would be a huge, reduced need for energy. At a 90% reduction, the U.S. could eliminate 0.51 quads of the 0.6 quads of annual energy demanded by agricultural equipment.⁴⁰ That's the

³⁸ Table 10 from OSU report.

³⁹ Diesel tractor energy consumption from Nebraska Tractor Lab. Electric tractor consumption from primary data in Oregon field use.

⁴⁰ Numbers from [DOE](#).

equivalent to half a percent of all U.S. annual energy consumption and equal to eliminating 3.6 billion gallons of diesel fuel. Simply put, increased energy efficiency is a huge benefit to consumers for reducing cost and opportunity for resource planners to eliminate energy waste.

Fuel Cost

Low electricity prices in rural COUs mean that it is inexpensive to operate an electric tractor for an entire workday when compared to an ICE equivalent. The OSU study compared a 30HP Solectrac Compact Electric Tractor (CET) and a similarly sized 32HP John Deere 2032R. The model assumed 250 hours of use per year for 7 years. Annual savings were projected between \$400-\$1,000 per year, implying a range of savings from \$1.60 - \$4.00 per hour of operation. The more hours that diesel tractor use is displaced, the higher the fuel savings.

For comparison with the OSU rates, Cadeo derived fueling cost and energy consumption rates for a Monarch MK-V based on values posted on their website from a case study on Wente Vineyard. Table 5 below shows a likely regional cost of approximately \$7 (using the commercial rates for NW COUs shown in Table 5 above).

Table 8: Monarch MK-V Fueling Costs Based on Wente Case Study (assuming 10-hour workday)

	Scenario	Fuel Cost (\$/day)
Electric ⁴¹	NW COUs Average	\$6.96
	CA Statewide	\$13.07
	National Average	\$8.22
Diesel		\$39.70

The fueling cost for the Monarch MK-V was proportionally comparable to the results from the Solectrac CET. The Monarch MK-V and the diesel comparison in the Wente case study each consumed more energy than the tractors in the OSU study, which makes sense as they are higher HP rated. For the larger, MK-V e-tractor hourly fuel savings were \$3.27 per hour. These MK-V savings should be considered moderate as the side-by-side comparison was for mowing which is a farm task with a medium level of power output, more energy intensive than driving, but less than tilling.

Maintenance

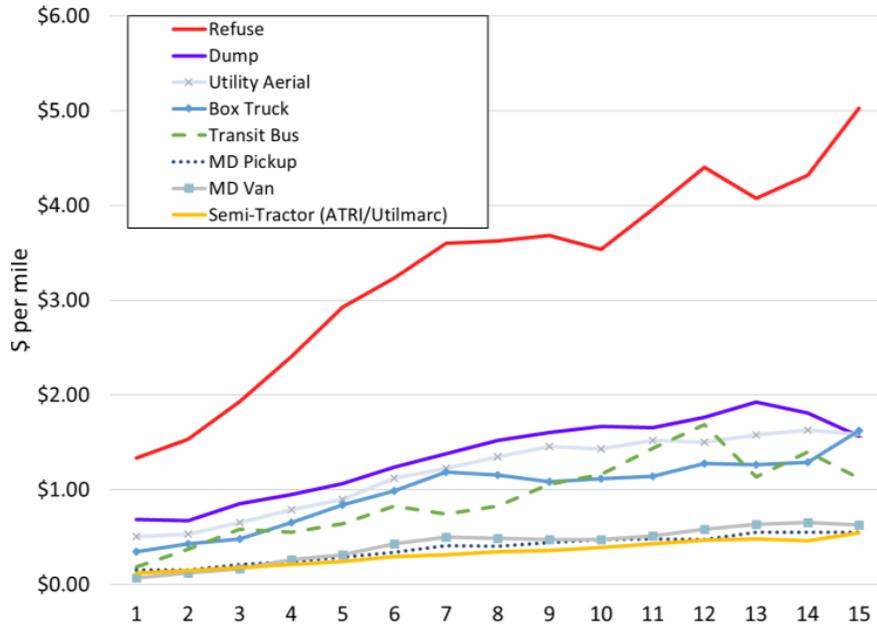
Electric vehicles, including trucks of all sizes, have lower maintenance costs than their ICE counterparts due to fewer moving parts, lower operating temperatures, less vibration, and fewer lubricant requirements. This has been documented in multiple studies as explored below.

The OSU study made conservative estimates of maintenance savings for e-tractors, removing costs associated from oil changes and oil filter changes. This likely underestimates savings from electric motors containing fewer moving parts than diesel engines. Despite the conservative

⁴¹ Using average commercial rates from EIA. See Table 5

estimate, savings are still 17% compared to diesel tractors, which contribute to the relative TCO parity between the two tractor types.

Figure 5: Medium-Heavy Duty Diesel Maintenance and Repair Costs per Mile



While data is still nascent for e-tractors specifically, in their recent study of total cost of ownership across all vehicle weight classes and powertrains, Argonne National Lab estimated that diesel vehicle maintenance and repair costs for diesel medium-heavy duty vehicles in the utility category (most comparable to most tractors) ranged from \$0.35-\$0.50 per mile in year 1 to \$1.55-\$1.60 in year 15.⁴² Evidence from early deployments of transit buses (and validated by experience with LDVs) suggests that maintenance and repair costs for tractors is likely at least 40% lower than comparable ICE vehicles.⁴³ This higher estimate is likely more accurate and would contribute an additional \$780 in maintenance savings for e-tractors in the OSU TCO model.

⁴² Burnham, Andrew, et al. Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains. Energy Systems Division, Argonne National Laboratory. ANL/ESD-21/4. April 2021. <https://publications.anl.gov/anlpubs/2021/05/167399.pdf>

⁴³ Ibid. P. 92.

GHG Emissions Reductions

Similar to electric passenger vehicles, e-tractors eliminate local GHG emissions and vastly reduce life-cycle GHG emissions associated with tractor operation due to higher energy conversion efficiency of electric motors and a cleaner energy source. On average, electric vehicles are between 75% to 80% efficient at converting energy into motion, whereas their ICE-based counterparts are in the range of 25 to 36%.⁴⁴ Evidence suggests, that ICE tractors are even less efficient, around 20%.⁴⁵ This efficiency advantage, as laid out in the Energy Efficiency benefits section above, means that e-tractors need less energy to execute the same amount of work.

One element of combustion tractor inefficiency is idling, which can be a significant portion of tractor energy consumption. Oftentimes, tractors need to complete stop-and-go activities over the course of a workday. Because ICE motors need to be warmed up to work at their full efficiency, it is typical to leave a tractor running to reduce the wear and tear of starting and stopping the engine. When idling, a 50-HP tractor may consume up to 1.5 gallons of fuel per hour.⁴⁶ By comparison, electric tractors do not consume energy while idling, further reducing GHG emissions and accruing savings for the farmers.

The GHG emissions of an e-tractor will vary based on the source of electricity used to power the tractor battery. The PNW power grid is known as one of the cleanest grids in the U.S., with an average of almost 50% of electricity generated from hydropower and renewables.⁴⁷ The average carbon intensity of PNW power is 715.2 lbs/MWh, which is below the national average of 884.2 lbs/MWh (2019 data).⁴⁸ Additionally, most of the COU's in the region have dramatically lower

Wente Case Study

On their website, Monarch Tractors published a case study from a vineyard in Northern California. The farm operated two tractors, one electric, one diesel, for the same amount of time doing the same task.

Tractor Run-time: 7.25 hours

Task: Mowing

Diesel consumed: 9.6 gallons (394 kWh equivalent)

Electricity consumed*: 61 kWh

Electric Tractor Energy Savings:

In equivalent units, the electric tractor consumed 85% less energy to do the same task

At self-reported electricity rates of \$0.156 per kWh and \$2.98 per gallon of diesel, the Wente Farm projects an annual savings of \$2,660.

*Based on derived battery capacity and state of charge at the end of the day

⁴⁴ Where the Energy Goes: Electric Cars. Office of Energy Efficiency and Renewable Energy. [Web](#).

⁴⁵ Analysis of usable work from U.S. DOE data. [Departmentof.energy](#)

⁴⁶ Nebraska Test Tractor Lab Data on 50 HP tractors.

⁴⁷ EIA State electricity data: <https://www.eia.gov/state/>

⁴⁸ <https://www.epa.gov/egrid/power-profiler/>

carbon intensity rates due to the high portion of hydropower for BPA consumer utilities. On average, their carbon intensity rates are 219 lbs/MWh, with some COUs as low as 25 lbs/MWh.⁴⁹

These low carbon intensity rates mean large carbon reductions for converting to electric vehicles. According to data from the Alternative Fuel Data Center, electric vehicles in Oregon and Washington emit 86% less GHG emissions than gasoline-powered cars.⁵⁰ For Idaho and Montana, GHG emissions reductions are 91% and 67% respectively.

To the extent that states in the PNW keep advancing their clean energy goals per the 100% clean legislation and other market forces, the electricity grid will host more renewable energy resources that will, in turn, reduce even further the amount of GHG emissions produced by providing electricity to power cars.

When powered by 100% carbon free electricity, electric tractors will have no operational phase emissions.

Increased Reliability

Reliability is a consideration for producers regardless of which fuel they choose in their tractors. The cadence of agriculture is time sensitive, so reliability is paramount during the finite windows when individual tasks must occur such as sowing or harvesting. Inability to use a tractor during these times could result in loss of harvest and thus jeopardize the income of the producer.

Real or perceived reliability risk is inevitably a consideration for prospective buyers of e-tractors. The EIA collects data from all utilities on the reliability of their electricity service. One metric by which they report reliability is the system average interruption frequency index (SAIFI), which communicates the number of customers affected by each event as a proportion of total customers in the system.⁵¹ It can be used to represent the likelihood of outages for customers. The higher the value, the more often that an interruption can be expected. Table 6 shows the SAIFI values broken down by state and utility type in the PNW. Average values of 1.24 and 1.43 for COUs and IOUs respectively communicate that a typical customer will experience fewer than two outage incidents every year but can expect one.

⁴⁹ Greenhouse Gas Emissions from Electricity Use, Oregon DEQ. [Web](#)

⁵⁰ https://afdc.energy.gov/vehicles/electric_emissions.html

⁵¹ <https://www.eia.gov/electricity/data/eia861/>

Table 9: SAIFI Values for PNW Electricity Customers

State	COU	IOU
ID	1.15	2.14
MT	1.03	0.97
OR	1.33	1.14
WA	1.24	1.47
Overall	1.24	1.43

These SAIFI values indicate that the electricity system is reliable, and producers can expect a low total number of outages each year. If a producer transitions to electric tractors there are additional ways they can mitigate their reliability risk, such as by keeping tractors fully charged when not in use and planning for vulnerable grid conditions such as during summer peaking events and or individual storms. Further, most agricultural operations rely heavily on electrical pumps for irrigation and are familiar with electricity down-time risks associated with outages there. This familiarity should reduce the perception of down-time risk for their tractors associated with electricity outages.

Increased Resiliency

With increased frequency of extreme weather events and their associated impacts on transmission and distribution systems, distributed energy resources (DERs) can significantly increase the resiliency of a farm that uses electric vehicles including tractors. DERs, a broad term that includes on-site renewables, storage, and flexible, connected devices, offer local, clean energy to power e-tractors but also provide electricity for other agricultural operations, ensuring work can be completed smoothly when an outage on the grid occurs.

The direct use of e-tractor batteries as a source to power other agricultural equipment and basic appliances running during an outage builds even greater resiliency. E-tractors as a movable, versatile power source, save time and money for the farmers, and eliminate the need for expensive generators. Monarch advertises mobile capability to power tools of their MK-V tractor on their website.⁵²

The increased resiliency and versatility to tractor owners is apparent. Less obvious, though are the benefits to the utility for creating flexible consumers and users of electricity. E-tractors with bi-directional capabilities could offer load flexibility to absorb or return load depending on grid conditions. Plus, localizing power consumption has transmission and distribution efficiencies. Powering the e-tractor directly with on-site renewable energy generation not only reduces operational emissions but also reduces transmission and distribution losses, increasing the overall efficiency of the system.

⁵² [Monarch Tractor Website](#).

Improved Local Air Quality

Tailpipe emissions from ICE vehicles emit a variety of chemical compounds with detrimental impacts on human health (see Table 7).⁵³ A study from the International Council on Clean Transportation links ambient particulate matter (PM2.5) and Ozone (O3) from vehicle tailpipe emission to approximately 385,000 premature deaths worldwide in 2015, with 70% of these deaths occurring in the 4 largest vehicle markets: U.S., China, EU and India.⁵⁴ The study quantifies 7.8 million years of life lost and approximately \$1 trillion (2015 US\$) in health damages globally in 2015. A recently published study quantifies health damages in 12 states in the Northeast and Mid-Atlantic region of the U.S., finding 7,103 premature deaths in 2016 from vehicle emissions in the studied region, with monetized health damages in excess of \$73 billion.⁵⁵

Table 10: Human Health Impacts of Various Exhaust Compounds

Tailpipe exhaust	Impacts on human health
Carbon Monoxide (CO)	Reduces the amount of oxygen reaching the body's organs and tissues, aggravates heart disease.
Nitrogen Oxides (NOx)	Aggravates lung diseases, can contribute to asthma and other respiratory problems.
Particulate Matter (PM2.5)	Decreased lung function, asthma, development of chronic bronchitis, nonfatal heart attacks, and premature death in people with heart or lung disease.
Sulfur Dioxide (SO2)	Aggravates asthma
Ozone (O3)	Causes lung damage and a variety of respiratory problems
Benzene (C6H6)	Carcinogen
Carbon dioxide (CO2)	Headaches and dizziness when exposed to an abundance of the compound

Most of the tractors currently used in PNW farms do not have enclosed cabs for the driver, nor do they have the same emissions controls as passenger vehicles do. Therefore, the operator is constantly exposed to tailpipe exhaust while operating the vehicle. Additionally, it is common for operators to idle tractors while performing adjacent tasks on foot, such as harvesting fruit, which exacerbates impacts on farmers health due to prolonged exposures.

⁵³ Tailpipe Emissions: How They Effect Human Health. Earthday Network. [Web](#).

⁵⁴ Anenberg, Susan, et al. A Global Snapshot of the Air Pollution-Related Health Impacts of Transportation Sector Emissions in 2010 and 2015. The International Council on Clean Transportation. [Web](#).

⁵⁵ Williams, Emily. "New study identifies leading source of health damages from vehicle pollution in 12 states and Washington, D.C." Institute for the Environment. 8 June 2021. [Web](#).

The adoption of e-tractors significantly improves local air quality as electric motors eliminate 100% of local emissions, thus inducing no negative impacts on farmers' health and resulting in millions of dollars of health savings.

Noise Reduction

During our literature review, we found that high noise at Operator Ear Level (OEL) of tractor is a major cause of fatigue for farmers.⁵⁶ Additionally, another study shows that loud machinery noise can create discomfort, bad communication between operators working in the surroundings, and reduction in physical and mental performance.⁵⁷ Depending on the decibels and duration of exposure, hearing disabilities may occur, which can be irreversible.⁵⁸

Electric tractors emit significantly less propulsion noise than their ICE-based counterparts, especially at lower speeds. Therefore, it creates a safer and more peaceful environment for workers, improving their performance while reducing the potential impacts of extended exposure to high noise levels.

Increased Energy Security

Even though the U.S. became a net exporter of petroleum in 2020, it still imports 7.86 million barrels per day to balance supply and demand forces from domestic and international markets.⁵⁹ These markets can be highly volatile leading to fluctuating diesel prices and uncertainty around farm operating costs. The transportation sector in the country accounts for 70% of U.S. petroleum consumption.⁶⁰ Therefore, e-tractors powered using renewable energy resources increase national energy security, by reducing demand for foreign oil.

This transition to powering farm equipment from fossil fuels to regional renewable energy reduces farmer's exposure to the volatile crude oil market where prices can suddenly spike due to international affairs, politics, or natural disasters. Electricity prices are far less variable, typical electric cooperatives make rate adjustments on an annual basis and benefit from multi-year priority firm rates from BPA. Farmers could increase their income and reduce financial risks even further if on-site renewable energy generation is added.

Many agricultural areas are well-suited for on-site solar. Solar photovoltaics can be sited on agricultural lands, either via agrivoltaics where the solar arrays are interspersed among other productive crops, or via utilizing already disturbed areas of the property such as along driveways and on building rooftops.

⁵⁶ Yadav, P., Gaikwad, A., Badgular, S., Surkutwar, Y. et al., "Noise Reduction on Agricultural Tractor," SAE Technical Paper 2013-26-0103, 2013, <https://doi.org/10.4271/2013-26-0103>.

⁵⁷ Celen, I.H. and S. Arin. Noise Levels of Agricultural Tractors. Pakistan Journal of Biological Sciences, 6:1706-1711. 2003. <https://scialert.net/fulltext/?doi=pjbs.2003.1706.1711>

⁵⁸ Guidance on the Safe Use of Tractors and Machinery on Farms. Health and Safety Authority. [Web](#).

⁵⁹ Idle Reduction Benefits and Considerations. U.S. DOE Alternative Fuels Data Center. [Web](#)

⁶⁰ Ibid. Agricultural equipment is considered "non-highway" transportation.

Section 5 E-tractor Enablers and the Market Opportunity

Due to the age of the tractor stock and prevalence of many, smaller farms, the Pacific Northwest region is an excellent candidate for widespread adoption of electric tractors with significant economic, environmental, and health benefits for farmers, in addition to dramatic GHG emission reductions.

E-tractors reduce GHG emissions in the region, partially because the region boasts one of the cleanest electricity mixes in the U.S. (with an average of almost 50% of electricity generated from hydropower and renewables⁶¹). The transition to e-tractors is an important tool for states to adopt more stringent climate commitments and invest in their agricultural communities at the same time.

Enabling Market and Policy Trends

Market maturation and policies are enabling increasing amounts of vehicle electrification. This section will explore some of the mechanisms that are facilitating broader adoption of electric vehicles and how those policies enable e-tractor adoption.

Zero Emissions Vehicle Policy

The transportation sector accounted for 29% of total GHG emission in the U.S. in 2019,⁶² which makes electrification of vehicles a key strategy to achieve the nation's climate goals. The Biden Administration has recently signed a new executive order setting net zero emissions goals which establishes that all new federal vehicle acquisitions will be zero-emissions vehicles (ZEV) by 2035.⁶³ Similarly, several states have established policies to diversify the transportation sector fuel mix by encouraging the use of alternative fuels, such as electricity, hydrogen or biofuels. In the PNW, Oregon and Washington have adopted low-emission vehicles (LEV) and zero-emission vehicle standards requiring manufacturers to sell a certain number of ZEVs per year. More recently, both states joined the multistate agreement to increase ZEVs in the medium- and heavy-duty sector.⁶⁴ As different transport sectors keep advancing towards zero-emission vehicles, and there is an increasing urgency to achieve the country's climate objectives, these types of policies will target the remaining segments of the transportation sector, including non-highway uses such as agricultural equipment.

⁶¹ EIA data by state. [Web.](#)

⁶² Inventory of U.S. Greenhouse Gas Emissions and Sinks. EPA. Accessed Dec 2021. [Web.](#)

⁶³ White House Executive Order Sets Net Zero Emissions Goals. USGBC. 09 Dec. 2021. [Web.](#)

⁶⁴ Hartman, Kristy and Laura Shields. "State Policies Promoting Hybrid and Electric Vehicles." National Conference of State Legislatures. 20 Aug 2021. [Web.](#)

Clean Fuel Program OR and Clean Fuel Standard (HB 1091) in WA

Pacific Northwest states, Oregon and Washington, both have clean fuel standards in place that encourage the use of cleaner transportation fuels including electricity. Both programs set a 2035 target to reduce the carbon intensity of transportation fuels by 20% in WA and 25% in OR.

In these programs, the carbon intensity of all transportation fuels is established, and targets are set to reduce the carbon intensity over time. The program works on a system of credits and deficits. Fuels with a higher carbon intensity than the target incur deficits in increments of 1 metric ton of GHG emissions. Companies that use low-carbon fuels for transportation purposes can generate credits by utilizing those lower carbon-intensive fuels to power their vehicles. Those credits can then be sold on the marketplace provided by the state to deficit generating, fuel-importers. Revenue from the sales of credits can be used to encourage projects that utilize or produce lower carbon intensive fuels.

At the end of each year, fuel importers must balance their credits and deficits to comply with state targets.

Utilities who sell electricity to fuel electric tractors could generate credits under these programs. There are two types of clean fuels credits available to Oregon utilities:

- 1 | Residential credits which are tabulated by the state DEQ. These are dependent on an algorithm and the number of EVs in their territory as defined by DMV.
- 2 | Electric vehicle supply equipment (EVSE) that the utility has registered and then the utility uploads kwh data corresponding to each individual charger and what type of vehicles charged there (either predominantly LDV or HDV and a few others options). The vehicle type determines the energy efficiency ratio that grants a benefit to EVs that replace ICE vehicle types that are less efficient

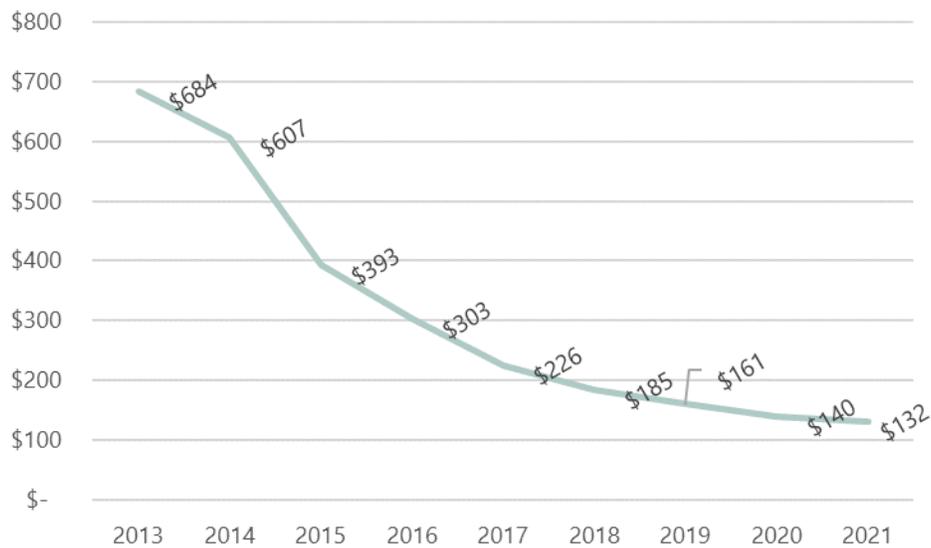
Electricity already has a significantly lower carbon intensity than gasoline and diesel and is aligned to become even less polluting. Both Oregon and Washington have passed 100% clean energy legislation that will eliminate carbon emissions from electricity generation.

Battery Prices

According to Bloomberg New Energy Finance (BNEF), lithium-ion battery prices fell 89% between 2010 and 2020, with the average price reaching \$132/kWh in 2021.⁶⁵ BNEF projects that battery prices will fall below \$100/kWh by 2024 allowing electric vehicles to reach price parity with ICE vehicles without the assistance of subsidies. Further R&D of lithium-ion batteries, together with increased demand, will keep driving down the cost of batteries making all electric battery-powered vehicles more accessible for the public.

⁶⁵ BNEF. [Web](#).

Figure 6: Battery Cost per kWh of Capacity⁶⁶



The emerging e-tractor market has benefited greatly from battery price reductions and will continue to do so as the lithium-ion battery market expands further. This phenomenon is known as a learning curve in which increased deployment results in decreasing price, as producers become more sophisticated and realize cost savings. Despite being a few years behind electric vehicles, the learning curve, driving down battery prices means e-tractors will likely reach price parity with their fossil fuel-based competitors on up-front cost within the decade.⁶⁷ This prediction is rooted in the BNEF modeling that anticipates price parity between ICE vehicles and EVs to be 2024. When price parity occurs for e-tractors, deployment and investment is expected to increase further making the overall e-tractor market more attractive for investors as well.

Market Opportunity in the PNW

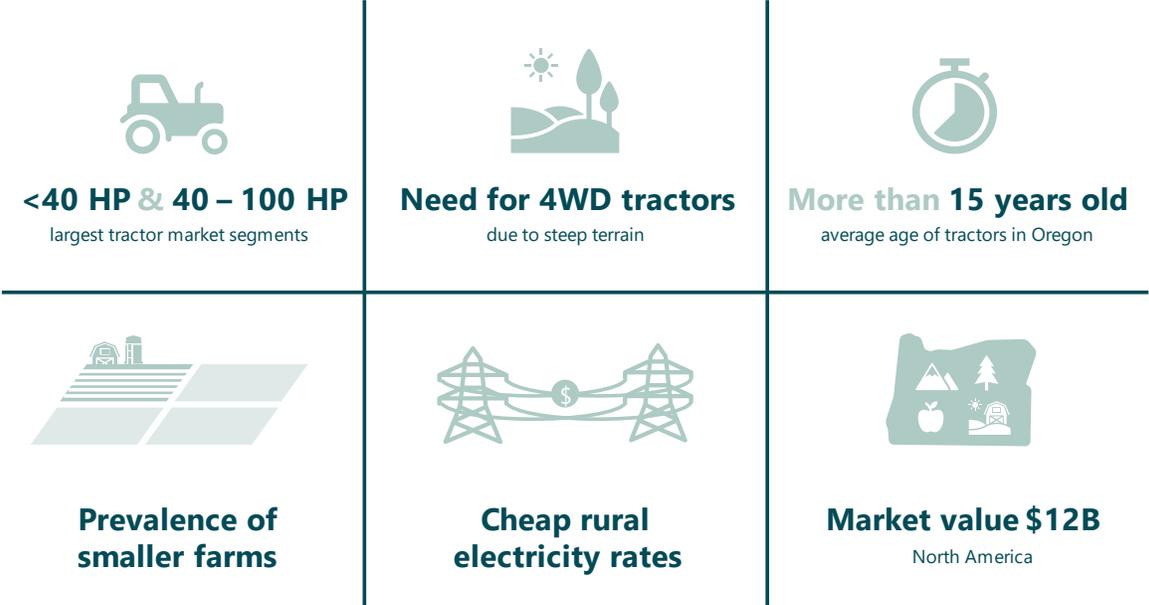
E-tractor manufacturers are producing products in the <40 HP and 40-100 HP tractor segments, which are the most owned, in equal shares, by PNW farmers. Manufacturers are also bringing to market 4WD products, which make sense for some of the region’s steep terrain. Additionally, according to the last two U.S. agricultural census, the average PNW tractor is over 15 years old. This indicates that there are many old and inefficient units in use today. Finally, as stated previously, rural PNW electricity rates are some of the cheapest in the nation making the use of e-tractors inexpensive compared to their fossil fuel-based counterparts.

Figure 7, below, captures in icons the key market characteristics of tractors and farms in the PNW.

⁶⁶ Bloomberg New Energy Finance. <https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/>

⁶⁷ Ibid.

Figure 7: Market Characterization of Tractors and Farms in the PNW



All the regional characteristics outlined in Figure 6 plus the market and policy trends make the PNW region an excellent area for widespread adoption of electric tractors. Adoption of e-tractors will deliver significant economic, environmental, and health benefits to tractor operators, their communities, and the PNW region more broadly.

Section 6 Barriers to E-Tractor Adoption

We organized the identified barriers to e-tractor adoption from market stakeholders' perspective in three main categories, which leverage terminology commonly used as part of energy potential studies:

- **Technical:** Barriers related to technical aspects of electric tractors capabilities and maintenance ecosystem.
- **Economic:** Barriers associated with costs incurred to adopt, install, operate, or maintain electric tractors.
- **Achievable:** Regulatory, behavioral, or programmatic market barriers that prevent or slow electric tractor adoption.

Each of these categories includes a summary table with the main discussion and qualification of the barrier. Below each table is a more comprehensive review of the barrier with a discussion of the significance of the barrier and a rationale for why the barrier exists.

Technical Barriers

The table below and details on the following pages capture the technical barriers, their magnitudes, and impacted stakeholders.

Barrier	Description	Stakeholder Impacted
Maintenance	Even though interviewees acknowledged reduced maintenance needs of e-tractors versus ICE tractors, the lack of a proximate repair network for e-tractors was highlighted as a barrier for their adoption. Current maintenance providers of tractors lack the knowledge to maintain or repair e-tractors. The lack of maintenance providers in the area makes the downtime of an e-tractor unaffordable for farmers, especially for those counting on only one tractor to fulfill their activities.	Farmers
Lack of Product Availability	Given the early stage of the market, the current manufacturers are taking orders to produce e-tractors. The lack of mass-production limits the availability of the product, which in turn discourages adoption, especially for farmers looking to replace their old tractor due to failure of equipment. Another limitation is the limited choice of models to choose from, which might not cover all end uses and specialty needs.	Farmers
Battery Life	Interviewees expressed concerns over the battery life due to the heavy use in the field. The belief is that this heavy use on off-road applications will degrade the battery faster, making the equipment economically uncompetitive.	E-tractor manufacturers
Battery Run-Time	Our research shows that battery run-time is another concern for farmers. Given the diversity of end uses and the lack of extensive e-tractor deployment to lean on, farmers are unsure whether e-tractors will be able to cover the required amount of daily work under one charge. One interviewee mentioned that a tractor that runs only 6 hours would not be of use to them.	Farmers
Charging Time	We found that battery charging time is a barrier for e-tractor adoption as different stages of the growing season will require different energy intensive uses. A farmer shared with us that for the large part of the growing season their current ICE tractor uses approximately 1 tank of fuel per week but when tilling and sowing the amount of fuel goes up by 5 times. For the most energy intensive end uses, they cannot afford the charging downtime of the tractor.	Farmers

Maintenance

Significance: Minor

There is reason to believe that this technical barrier is only minor in nature and can quickly be overcome. Interviews indicated that the agricultural community is well-versed in maintenance and repair. A small, organic vegetable producer mentioned that among themselves and their neighbors, there is a strong culture of sharing knowledge or assistance for common issues. Such a network is often relied upon as a first step before seeking formal maintenance.

Similarly, a larger fruit producer we talked to, mentioned full-time maintenance staff as their primary means of tractor upkeep. Such larger productions will be able to hire staff to provide e-tractor maintenance.

Further, electric motors are a technology that are prevalent in other places in the agricultural sector such as irrigation pumps and wind machines. For this reason, expertise may already be available for much of the maintenance needs that arise. Finally, e-tractor manufacturers mentioned remote, and in-person support available, if needed.

Lack of Product Availability

Significance: Major

The available options cover the 2 most used tractor segments (less than 40 HP and between 40-100 HP), but they might not be applicable for all end uses at the current market development stage.

In the short term, product availability is a major barrier. If willing producers cannot acquire an e-tractor when they have an investment window or equipment failure, then that becomes a lost opportunity and locks in another 15-20 years of life for a polluting ICE tractor. Furthermore, less product availability means less exposure which all but guarantees slower adoption rates when product availability is no longer an issue.

Battery Life

Significance: Minor

There is evidence from battery use in electric vehicles, including medium and heavy-duty vehicles, that battery life is longer and more productive than initial estimates. Therefore, we believe that battery life is a minor technical barrier that will be overcome with increased exposure to the technology. In the adjacent, electric vehicle space, batteries have been showing an impressive lifetime, so much so, that a regional dealership of used electric vehicles offers a battery warranty that warrants 70% of the initial capacity for unlimited time and up to 150,000 miles.⁶⁸ The battery technology and sophistication is the same for e-tractors and once consumers become familiar with the capabilities and longevity, we believe the battery life barrier concerns will diminish.

⁶⁸ Electrify Now. EV's Cheaper than you think. Web. <https://www.youtube.com/watch?v=cSxB8-D6BOU>

Battery Run-Time

Significance: Major

This is a major barrier for more widespread adoption of electric tractors. If the tractor cannot run long-enough under the various tasks needed of the tractor, it will diminish the value to the farmer. More data from operations are needed to explore the run-times and energy intensity of each task. The Wente case study reported a Monarch MK-V, using over 8 kWh per hour for mowing. For more energy intensive tasks such as tilling or hauling, a higher hourly consumption rate could significantly reduce the total run-time.

Familiarity with run-time and backup options will be essential to overcoming this barrier. Fast charging and battery swapping may be necessary to address the most energy intensive farming days or use cases. Knowledge of the capabilities will also increase the tractor's utility. For electric vehicles, many cars are in use with short ranges for daily commuting and local travel. For lighter agricultural tasks, a similar phenomenon could occur in which older electric tractors with smaller battery packs are used for certain activities and not others.

Charging Time

Significance: Minor

Ultimately, we believe that charging time is a minor issue that will be resolved with increased familiarity of e-tractor constraints. Electric vehicles have different constraints than gasoline vehicles that initially present as challenges but can also be benefits. Plugging in electric tractors every night means that each morning the tractor is fully charged for the day's work. In instances where more than a full battery capacity is needed in a single day, battery swapping, or faster charging may be needed. While accessory battery packs are available for current e-tractors, charging rates of 20 kW have not been announced.

Economic Barriers

Economic barriers are particularly persuasive in their ability to prevent adoption of electric tractors. Consumers are typically cost sensitive when first acquiring equipment and since tractors are part of operating machinery their costs directly contribute to the overall profitability of farms.

Barrier	Description	Stakeholder Impacted
Upfront Cost of Equipment	Our research shows that upfront cost is one of the largest barriers for electric tractor adoption. While there are limited options available currently, our comparison of two e-tractors and one ICE tractor showed a significant price premium for the electric options. This gap is proportionally larger than passenger EVs.	Farmers
Electrical Infrastructure Upgrade	Even though most farms have welding outlets that provide 220 V and up to 50 Amp service, farmers expressed their concerns about having to upgrade the electrical infrastructure for the battery to be charged in a time frame consistent with their needs. This is especially applicable to larger tractors where battery charging may take more than 12 hours at levels existing power infrastructure can provide.	Farmers
Financing	Our research shows that the company sizes of current ICE tractor manufacturers enable them to attract low-cost capital and subsidize financing rates with low- or zero-interest rates. E-tractor manufacturers shared with us that while they have been able to attract capital investment, they are not well-positioned yet to offer this kind of lending at zero or low rates.	E-tractor Manufacturers and Farmers
Increases in Electricity Bill	Electricity prices vary across the PNW region, and the added cost of electricity could pose a barrier for some farmers to adopt e-tractors in the long term. Whether this is a barrier or not will depend on the fossil fuel prices, electric utility demand charges, and the presence of DERs on the farm.	Farmers

Upfront Cost of Equipment

Significance: Moderate

While upfront cost is a significant factor, it may be muted in certain circumstances. The Internal Revenue Service (IRS) Section 179 allows businesses to take an immediate deduction for business expenses instead of depreciating those assets over future tax years. Section 179 can be applied to the purchase of agricultural equipment such as tractors. During successful growing seasons, it is common for farms to purchase new equipment and deduct those expenses during that tax year to offset tax liability.

"After a good season, that's when you start to see the brand-new trucks and tractors the following spring", stated one interviewee.

This type of investment, while not immune to price sensitivity, provides an opportunity for producers to buy more expensive equipment than they may otherwise have done. This increased appetite for risk due to a good year of production can lead to larger adoption of e-tractors.

This option will be less available to the many smaller producers across the region who may have thinner margins. For this reason, we still believe upfront cost is a moderate barrier in the near term, until e-tractors reach price parity with ICE tractors.

Electrical Infrastructure Upgrade

Significance: Moderate

This is a moderate barrier if it becomes an additional cost and burden to acquiring an electric tractor. There are varying degrees to electrical infrastructure upgrades that might be needed, the most cost intensive being a full service upgrade and installation of one or more DC chargers. In these scenarios, the additional cost may be a go/no-go barrier to selecting an electric tractor. For smaller operations that can get by with one tractor and may not be considering as large of an investment, these upgrades may not pose much of a barrier.

This barrier is perceived to be moderate due to responses during interviews. It was noted that most farms already have a very large service because they run lots of tools in addition to pumps for irrigation and sometimes wind machines to prevent freezing.

Financing

Significance: Moderate

Financing is a moderate, near-term barrier as it advantages ICE over e-tractors. Interviews indicated that 0% loans are a motivating factor when considering a new tractor and may even motivate consumers to purchase equipment before the useful end of life of their existing equipment. For this reason, we believe in the short term, financing is a moderate barrier that simply disadvantages e-tractors and will be overcome in time with market maturation.

While the total cost of ownership sensitivity analysis demonstrated that 0% offers don't much impact the overall cost of owning the tractor long term, it is an effective sales tool to influence consumers who think more about upfront cost than total cost.⁶⁹

As e-tractor production scales, there will be more financing options available and at more competitive rates. Long term we anticipate the same financing options will be available regardless of fuel source, but in the near-term financing may be a barrier.

Increases in Electricity Bills

Significance: Moderate

One element that farmers may not anticipate when acquiring e-tractors are the rate design and structure of their electricity schedules. Farms may have multiple meters and rates which they pay for electricity including residential, commercial, and irrigation rates. Each of these rates has different costs per kWh and typically commercial and irrigation rates also come with demand charges on a \$/kW basis. If a farmer charges their tractor at the same time as other peak loads on their property, the extra demand, 6.6 kW or more depending on the infrastructure, can add a significant monthly cost that will not be anticipated when comparing simple costs per kWh. This phenomenon could erode both trust and confidence in the cost-effectiveness of electric tractors over diesel. Electric utilities that create rates that incentivize electric tractors will likely see an increase in electric tractor adoption.

⁶⁹ Proctor, Kyle W. Total Cost of Ownership of a Compact Battery Electric Agricultural Tractor. Oregon State University. February 2022.

Achievable Barriers

Beyond technical and economic barriers there are cultural, social, or knowledge barriers that prevent further adoption of electric tractors. This section explores those barriers and qualifies how pervasive of a barrier it is.

Barriers	Description	Stakeholder Impacted
Brand Loyalty	Our interviewees highlighted brand loyalty as a barrier. More common than not, farmers are loyal to major tractor brands with whom they have worked with for a long time. Major brands have an associated color that identifies them, and brand loyalty is strong to the extent of farmers wearing t-shirts with the inscription "I bleed [brand color]".	E-tractor manufacturers
Lack of Awareness and Information	Some interviewees, when asked to consider purchasing an e-tractor, have acknowledged they were not even aware of their existence. This speaks to a lack of information in the market. Farmers rely on their trusted sources of information like associations, other farmers, representatives of the sector, such as distributors. Distributors are both brand advocates and often the only source of ICE tractor replacement parts, which can create information asymmetries. They can further exacerbate the lack of awareness of new products and technologies.	Farmers E-tractor manufacturers
Risk Aversion	Farming is an inherently risky enterprise, vulnerable to weather and sensitive to minor chemical changes in soil composition. Add on the thin economic margin by which producers operate, and those forces combine to create a risk averse population. As one interviewee described it, "farmers basically have 40 opportunities to perfect their craft, where one failed season could be fatal to their viability."	E-tractor manufacturers

Brand Loyalty

Significance: Moderate

We believe brand loyalty can be overcome by a superior product in e-tractors. However, brands may continue to play an important role in shaping consumer opinion of e-tractors. For that reason, we believe this is a long-term barrier that will be minimized when the favorable economics of e-tractors is realized. Plus, ultimately the major manufacturers of tractors are expected to offer electric options that will increase confidence in e-tractors while consumers get to maintain some of their brand loyalty even as the technology changes.

Lack of Awareness and Information

Significance: Moderate

Lack of good information and awareness can be a pervasive barrier that endures for some time. More familiarity with e-tractor technology is needed to start eroding the existing product bias for ICE tractors. In the absence of direct, positive consumer experience and 3rd party, neutral information, consumers will be susceptible to misinformation or misconceptions on the capabilities of e-tractors. Information on both the benefits and limitations of e-tractors are important.

Risk Aversion

Significance: Major

We perceive risk aversion to be a major barrier to e-tractor adoption. The risks may be hyped by distributors or vested interests who do not want their product market share eroded by e-tractors. More importantly, ICE tractors are a familiar technology, where users know the risks and limitations. E-tractors present new risks and opportunities that need to be considered and which take time to adjust to.

Section 7 Recommendations

Our recommendations are organized according to the framework used to categorize the key barrier for e-tractor adoption in the PNW. For each category we describe different activities and interventions that can help promote increasing adoption of e-tractors in the region. As with other complex market transformations, there is no single action or program that converts all tractors to electric overnight. Rather, advocates can pursue and support multiple interventions that all contribute to a supportive ecosystem that encourages businesses and individuals to use e-tractors.

Technical Barriers

Training for maintenance service providers. Manufacturers should develop training and relationships with experienced maintenance service providers at local levels across key regions, including the PNW. A reliable maintenance network increases the chances of farmers adopting e-tractors as it reduces tractor downtime and thus the potential economic risk. E-tractor manufacturers should establish at least one representative of the brand in each state who is able to travel and work with individual e-tractor owners and educate maintenance professionals.

Where any given farm turns for their repair needs depends upon the size and sophistication of that operation. Often, small operations rely upon their own or neighbor's maintenance capabilities. Interviews suggested that at least some places have this informal, resourceful community of producers.

Another complementary option is to partner with existing independent service providers for tractors and train them in the maintenance of e-tractors. Furthermore, to increase potential buyer confidence in the brand, e-tractor manufacturers could offer a 24-hour virtual assessment service where customers can talk to a technician who can direct them to fix the problem or assess if an in-person visit is required.

In parallel, as the transport sector progresses towards electrification to achieve GHG emission reductions, universities, technical schools, and/or private companies with associated courses should include in their offerings agricultural electric vehicle maintenance and operation training to build the workforce that can navigate the clean energy transition. These new jobs are an opportunity to induce equity by ensuring marginalized and low-income communities have access and are prepared for the jobs of tomorrow.

Third party studies on battery run-time and battery life. Primary research helps demonstrate viability for electric tractors. Colleges, universities and other independent third parties will continue to play a role in testing, researching, and documenting benefits and challenges to all electrified agricultural equipment, especially electric tractors.

An example of this is the University of Nebraska that has a long-standing tractor fuel efficiency testing program. The program provides detailed energy consumption data for hundreds of different tractors operating under different conditions. Outside of manufacturer provided

information, this independent, third-party knowledge can help farmers choose equipment that suits their needs and efficiently completes their required uses. Electric tractors will need the same rigor and detail in testing so that future owners can be confident that the tractors will perform as intended.

Auxiliary batteries and battery swap. Our research indicates that because certain agricultural processes are more energy intensive than others some producers will be unable to afford the charging down time of an e-tractor without quick “refueling”. Labor is one of the most expensive costs of operating farms, therefore, idle labor, waiting for a tractor to charge, is prohibitively expensive. To this end, having an extra battery fully charged that can be added or swapped for the empty one in the e-tractor minimizes “refueling” times and maximizes labor productivity.

Both Solectrac and Monarch, have some e-tractor models (e70N/eUtility and MK-V respectively) capable of utilizing a supplemental battery either via addition or substitution. The Monarch MK-V uses battery swapping, utilizing a cart to remove and replace batteries on the tractor. Monarch claims the swapping procedure takes less than ten minutes for a single individual. Extra battery packs for both Solectrac and Monarch are sold separately, offering a solution to energy intensive end uses. E-tractor manufacturers should consider supplemental battery features in all their tractor designs to increase the utilization rate of the tractor and reduce tractor and personnel downtime.

Economic Barriers

Rebate programs for equipment and charging infrastructure. A widely used tool for the introduction of new technology is the use of rebates or tax incentives to create upfront price parity with existing technologies. As a nascent technology, e-tractors are more expensive than their ICE-based counterparts. To promote their adoption, as many states and municipalities implement regulations towards clean energy, rebates programs could be established with the purpose of reaching price parity with ICE tractors. Similar rebates have been implemented via public policy at both the state level and federal level for electric vehicles. Rebates may also be feasible via utilities where an electric tractor will be deployed. In either case, advocates can encourage these types of interventions to help reduce upfront costs.

Incentives can be oriented for either e-tractors directly or even charging infrastructure for tractors with large battery sizes or fleets. Due to the lower volume of tractor sales compared to light-duty vehicles, incentive programs could be delivered at less cost while promoting rural investment, decarbonizing a hard-to-reach industry, and achieving beneficial environmental outcomes.

E-tractor zero-interest loan programs. Programs and advocates could create specific agricultural electrification, zero-interest loan programs, which would level the playing field with ICE tractors and help attract potential, undecided buyers. Program funding could come from private, public, or grant sources and be raised on the attractiveness of multiple desired policy outcomes:

- Reduced emissions

- Increased rural investment, or
- Improved agricultural workers' health conditions

Regardless of source, a program could use funding to de-risk the lending process and make purchases less expensive. The following actions are cost-efficient methods for establishing a low- or zero-interest loan:

- 1 |** Set up a loan loss reserve to lower the risk and reduce the cost of capital
- 2 |** Buy down the interest rate
- 3 |** Pay for underwriting and closing costs
- 4 |** Make the fund revolving - Use startup capital and revenue streams from loans to return proceeds to a revolving fund

Setting up a low- or zero-interest loan involves upfront cost, as evidenced by the activities outlined above. However, most of the capital is ultimately returned and the program cost becomes the capital used to buy-down the interest rate and pay for underwriting and closing costs. These costs may have high leverage in their ability to deliver on other objectives such as emissions reductions or rural economic stimulus.

Zero-interest loans are an attractive demand lever and programs could expect to see increases in e-tractor deployment if a successful program was established.

In the absence of establishing a policy or program to ensure zero-interest loans for e-tractors, programs could provide information about existing options to prospective e-tractor buyers. The USDA offers attractive low-interest microloans for producers with only 2.125% interest rate on operating equipment.⁷⁰ States may have additional loan and grant opportunities for producers to access. For example, Oregon established the Aggie Bond program to provide affordable financing to new farmers for capital purchases.⁷¹ There are many loan, grant, and business opportunities to support prospective e-tractor buyers and the number of opportunities is expected to grow over the coming years.

Utility programs for E-tractor adoption. COU's can offer incentives in the form of time varying rates (TVR) to encourage the adoption of e-tractors. Establishing TVR or specific e-tractor charging rates can help the grid to manage the load and defer investments. These types of incentives also reduce the TCO, increasing the attractiveness of buying an e-tractor for producers. COU's may realize additional system benefits if e-tractors can be used to flexibly adjust when they charge to grid conditions and participate in emergency demand response programs. While no announcements have been made, if e-tractors were capable of bi-directional charging (commonly known as vehicle-to-grid) they could send electricity back to the grid to reduce peak demand. Such value streams bring flexibility to the grid in times of need, defer the construction of additional generation resources, and thus generate savings for the utility and ratepayers.

⁷⁰ <https://www.fsa.usda.gov/programs-and-services/farm-loan-programs/index>

⁷¹ <https://www.oregon.gov/biz/programs/AggieBond/Pages/default.aspx>

Electric utilities who are interested in adding load to their system can prepare for this by providing guidance on when and how to charge. Such utilities may also consider electric tractor specific charging rates to encourage charging during certain windows over others to help minimize consumer costs and maintain or increase grid reliability and resiliency.

As states establish more stringent clean energy goals, utilities are mandated to acquire clean energy generating resources and phase out fossil fuel-based power plants. Many e-tractors can operate normally while providing a source of flexible electricity demand, which will support renewable energy resource integration and therefore, climate goals.

Achievable Barriers

Promote farmers' e-tractor awareness. All stakeholders in the market have a role to play when it comes to information communication and awareness. For e-tractor manufacturing companies, raising awareness of their products is a key aspect of their development and marketing strategy. Partnering with different local organizations and agricultural associations will be key to transferring information via trusted sources to farmers.

Advocates of e-tractors can increase the amount of independent, third-party information available to regional consumers. Sharing and promoting the farmers' firsthand experiences with e-tractors to a larger audience, whether at agricultural expos or group meetings, can help accelerate awareness as well as build trust in and awareness of e-tractors. Independent resources could include methods for connecting prospective buyers with other producers or information for making an informed decision.

Development of case studies. Like with any other new technology, case studies are a great resource to provide fact-based evidence to end users of the opportunities and benefits of using such technology. The e-tractor market is no different. Given that farmers are risk averse, the best way to promote the technology is by providing examples of e-tractor performance for different end uses and in a variety of locations.

Our research shows that due to the nascent state of the market, there are not yet many case studies available to promote the technology and confidently answer use case questions for individual farm operators' use. The range of published run times for e-tractors is insufficient to convince mainstream buyers without more evidence. E-tractor manufacturers reported run times range a lot depending on the use. The lack of precision in estimating run-time is too ambiguous for operators needing to know if they can mow, till, or haul for six hours or more.

Programs that enable trial of e-tractors, are an excellent way to obtain these case studies. Data from individual e-tractors, combined with program participant interviews, could provide both qualitative and quantitative understandings of e-tractor performance. These third-party data are an unbiased source of information. Moreover, incorporating the voices of farmers that have participated in e-tractor trials makes it more relatable for the target audience.

Case studies documenting the energy use, performance and run time under varied end uses will enable farmers to understand the real opportunities and limitations of e-tractors, providing producers the information they need to know to make decisions confidently. .

Section 8 Conclusion

Electric tractors are an emerging product built on top of established technology. Research and conversations indicate that e-tractors are not well known, with several interviewees who were not aware that electric tractors existed or were readily available. This lack of awareness is compounded by the fact that there are currently very few options and those that exist are currently produced at low volumes. These factors indicate that it will take time before e-tractors are commonplace in the PNW.

That said, there are reasons to believe that e-tractor adoption could scale quickly given the right circumstances, and we believe the PNW has the right set of market conditions to be a leader in e-tractor adoption. For one, the PNW acknowledges an urgency to act on climate change within this decade to avert the most damaging impacts. E-tractors have the potential to dramatically reduce emissions at the necessary scale. The IPCC urges a 50% reduction of emissions by 2030; e-tractors powered by clean electricity have zero operational emissions. Today, replacing a diesel tractor with an e-tractor will easily cut the associated emissions by more than 50%, with PNW number indicating the difference is closer to 90%.

Emissions reductions and rural investment are two policy goals that can drive e-tractor adoption in the region. Policy support for both clean energy and rural investment can help provide necessary incentives that support e-tractor adoption. Both Oregon and Washington have clean fuel standards which will advantage vehicles powered by cleaner fuels such as electricity.

While e-tractors are currently more expensive on an upfront cost, they offer significantly lower operating costs to their owners.⁷² Rural investment priorities to help producers transition to e-tractors will help them lock in annual operational savings. In the PNW, electricity is inexpensive, and e-tractors use less total energy than ICE tractors. The more time that electric tractors are used instead of diesel, the higher the savings to the producer, with every hour of use saving more than \$2.40 in fueling.⁷³ Annual fuel savings could be in the thousands of dollars.

As with any new technology, there is an adoption curve by which the market is initially slow to adopt a new technology until it is proven undeniably better by consumers. In the early stages of adoption, consumer awareness and familiarity with the technology is key, so interventions that increase the supply of e-tractors and enable greater awareness of the technology will quicken adoption for the early majority and eventually late adopters.

At this early stage of e-tractor deployment in the region, advocates, programs, and policy makers can work to break down near-term barriers and deliver long-term benefits not just to the farmers who will no longer have to breathe in diesel fumes, but the broader region at the same time.

⁷² Pricing pulled from manufacturer websites and shared in Table 4. Operating costs discussed in Reduced Operational Costs section.

⁷³ Based on tractor efficiencies and COU commercial rates at 8.3 cents per kWh and \$2.98 per gallon of diesel.

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