Schweizerische Eidgenossenschaft
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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

SWEET Call 1-2020: SWEET EDGE

Deliverable report

Deliverable n°	2.6
Deliverable name	Report with the results of market analysis for electrifying agricultural transport
Authors The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.	Sabrina, Mili, UNISG, **sabrina.mili@unisg.ch**
Delivery date	March 2025

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sweet swiss energy research for the energy transition

Summary

Zero-emissions vehicles become increasingly important in the agricultural sector. They contribute to combatting climate change while protecting farmers and the soil from harmful pollutants. Battery-electric tractors (BETs) not only provide considerable technological benefits, but in combination with the use of solar energy on farms, they contribute to further decarbonizing agricultural operations. While the electrification of the automotive sector has seen significant progress in the past decade, the BET market is still in its infancy, with only a few prototypes available. Why is the agricultural sector slower in adopting electric mobility? Based on 15 expert interviews with tractor manufacturers and an industry expert, this study aims to shed light on the most important drivers and barriers for tractor manufactures to produce BETs. I found that the technological benefits of the electrification of agricultural vehicles, corporate sustainability goals and anticipation of regulatory changes towards carbon emissions reduction in the tractor sector are key drivers for the development of BETs. However, battery limitations, high production costs, a lack of clear regulatory incentives, low market demand as well as path dependence related to internal combustion engines are key barriers and make most tractor manufacturers focus on developing BETs for niche applications such as municipalities and small-scale farming. While our findings show that the tractor sector takes action to overcome carbon lock-in, they also point to the need for stronger policy incentives to produce BETs and a paradigm shift among stakeholders across the entire supply chain.

1 Introduction

The agricultural sector is responsible for about 10-14% of greenhouse gas (GHG) emissions worldwide (Jantke et al., 2020). While most of the emissions stem from activities related to livestock farming, agricultural vehicles like tractors also contribute to climate change. Today, these vehicles predominantly run with internal combustion engines (ICE) using diesel (Hagan et al., 2023). The use of fossil fuels not only causes environmental hazards, but the air pollutants are also harmful to the workers operating the vehicles (IARC, 2012). Decarbonizing the vehicles is a crucial element to reach climate neutrality in the sector (Ghobadpour et al., 2022).

Battery-electric tractors (BETs) offer a promising pathway to decarbonization and have various advantages over ICE tractors (Lajunen et al., 2018). They eliminate tailpipe emissions while enhancing farmers' productivity with precision control, improve safety and comfort, and offer potentially lower operating and maintenance costs compared to ICE counterparts (Ghobadpour et al., 2019; Malik & Kohli, 2020). Additionally, many farmers produce renewable energy on-site through photovoltaic (PV) systems, which can be used to charge BETs, simultaneously improving energy self-consumption and sustainability (Gorjian et al., 2021). While the electrification of passenger cars and heavy-weight vehicles as busses and trucks have become more established (ACEA, 2024; EEA, 2024), the market for BETs remains at a very early stage, with only a few prototypes currently available (dpa, 2024; Göggerle, 2024). Why is this so?

Previous research has predominantly focused on farmers' preferences and perceived hurdles for the adoption of BETs (Bessette et al., 2022; Lombardi & Berni, 2021; Rübcke von Veltheim & Heise, 2021; Sok & Hoestra, 2023; Weisbach et al., 2020) and technological advances of BETs (Moreda et al., 2016; Rodnei R. Melo, 2019; Stirnimann et al., 2021).

However, there is a crucial gap in understanding why the electrification of agricultural vehicles is lacking behind from a supply-side perspective. There is limited knowledge about the factors influencing manufacturers' decisions to produce BETs and their perceived drivers and barriers. To address this research gap, study explores the following research question:

What are tractor manufacturers' perceived drivers and barriers to introducing battery-electric tractors to the market?

To address this question, I conducted 15 semi-structured interviews with tractor manufacturers and an industry expert. The interviewed tractor manufacturers together hold almost 80% of the European market share (Göggerle, 2022; Tastowe & Wilhelmstroop, 2023), therefore, offering a wide-ranging perspective of the industry. This approach allowed me to shed light on the key drivers and barriers to the adoption of BETs and identify bottlenecks preventing the electrification of agricultural vehicles among manufacturers.

This study provides a significant contribution to the research on the electrification of agricultural vehicles by offering empirical insights into how tractor manufacturers perceive this innovation. In particular, our findings show that manufacturers focus on the development of small to medium-sized BETs for niche applications with a capacity of up to 75 kW. Key drivers of BET production include the technical benefits of electrification, such as enhanced precision and control of the vehicle, emission-free operations, corporate sustainability goals, and the anticipation of stricter emissions regulations for agricultural machinery. The interviews revealed that most tractor manufacturers consider the limited energy density of current battery technology a major barrier to developing higher-performance BETs. Further barriers to BET market uptake include a lack of demand due to high acquisition costs as well as perceived limitations related to the operation of BETs. Issues related to path dependence and carbon-lock in the industry further hinder an accelerated production of BETs. Based on our findings, I offer implications for policy makers and manufacturers to help overcome bottlenecks towards greater market integration of BETs.

This article is structured as follows: Section 2 provides an overview of the existing literature. Section 3 presents the methodological approach. Section 4 includes and discusses the results of the empirical analysis. Section 5 concludes by offering a summary of the key findings, a reflection on policy implications, limitations and opportunities for further research.

Deliverable content

2 Literature Review

2.1 General information about tractors and the European tractor market

The tractor is a cornerstone of agricultural machinery, enabling essential farming activities such as plowing, mowing, and seeding (Cavallo et al., 2014). Designed to pull and power a variety of implements, tractors have diverse applications depending on their capacity and design. To understand the electrification of tractors, it is important to recognize that there is not just one type of tractor. Especially the power load used in the application has an impact on the (battery) capacity requirement of a tractor. For example, row-crop tractors are used in high-power-load tasks, such as pulling heavy agricultural implements, and thus require substantial horsepower (hp) or kilowatt (kW) capacity. In contrast, compact tractors are designed for lighter tasks such as small-scale farming, mowing, or gardening, and typically operate with lower power loads (Eusebio, 2022). Table 1 provides examples of tractor categories that cover different applications.

Tractor type	**Compact tractor**	**Utility tractor**	**Row-crop tractor**
Capacity	15-37 kW	30-75 kW	108-300+ kW
Application range	Small-scale farming, mowing, snow removing, gardening	Mowing, plowing, seeding, pull of heavy implements, easy to manoeuvre	Large-scale farming, cultivate crops, pull of heavy implements
Power load requirements	Low to middle power load	Middle to high power load	High power load

Table 1: Examples of tractor categories and their applications (own illustration based on Eusebio (2022))

A key component of a tractor is the propulsion system that enables to transfer the generated power for moving the attached implements (Babu, 2022). There are different transmission systems that transform the energy source such as fuel (or electricity) into mechanical energy to run the tractor. There exist mechanical, pneumatic, hydraulic and electric transmission systems, while each of them has their advantages depending on the specific application needs (Babu, 2022; Southwell, 1960). Studies have shown that electric transmission can be particularly beneficial for precision farming (Gonzalez-de-Soto et al., 2016).

The European tractor market is highly consolidated, with six companies collectively accounting for almost 80% of total sales volume (Tastowe & Wilhelmstroop, 2023). Current technological innovation trends in the industry focus on Agriculture 4.0, which emphasizes the integration of digitalization and smart technologies in agricultural machinery to enhance productivity and efficiency. Examples include precision farming and autonomous machinery innovations (CEMA, 2024; Mordor Intelligence, 2024). A few large companies, known as full-liners, manufacture not only tractors and other agricultural machinery, but also agricultural implements in-house (Hill, 2020). In addition, there are specialised agricultural implements manufacturers that collaborate with various tractor brands to provide suitable equipment (Farmers Weekly, 2012).

When it comes to the regulatory environment in terms of tailpipe emissions of agricultural vehicles, the European tractor sector is subject to the EU regulation of emissions for internal combustion engines for non-road mobile machinery (NRMM). These norms set maximum levels of allowed pollutant emissions from these vehicles (EC, 2016). They have first been established in 1997 starting with Stage I and have continuously been developed (ICCT, 2016). Today, Stage V is the strictest NRMM emissions standard worldwide and limits pollutant emissions such as carbon oxide, hydrocarbons, nitrogen oxides and particulate matter. However, unlike on-road vehicle regulations, these standards do not currently address GHG emissions such as carbon dioxide (EC, 2019). Stage V is currently only available in Europe while other markets worldwide are at earlier stages (Dieselnet, 2023; EC, 2016; ICCT, 2016).

The relatively progressive environmental regulatory context and the technological innovation make the European tractor market a suitable case for this study.

2.2 Technical characteristics of BETs

The electrification of a tractor can provide numerous advantages compared to traditional ICE tractors. Farmers can control the machinery more precisely and easier due to greater maneuverability (Malik & Kohli, 2020; Weisbach et al., 2020). Their productivity is also increased through a better acceleration of the tractor thanks to an improved power take-off (PTO) load response. PTO is a method to use the tractor's engine, or in this case the battery, to power other agricultural equipment or machineries attached to the tractor (Ghobadpour et al., 2022). The comfort and safety of operating the tractor is improved compared to ICE tractors due to eliminated excessive heat and hydraulic pressure as well as reduced vibration and noise emissions of the tractor (Malik & Kohli, 2020). The latter factor also allows operation at night or in residential neighborhoods (Weisbach et al., 2020). Charging the BET with on-farm solar energy avoids GHG emissions and can drastically save fuel costs. The eliminated tailpipe pollution also improves the overall air and crop quality (Gorjian et al., 2021; Riedner et al., 2019). Additionally, if farms are located far from fuel stations, charging them directly on the farm reduces their travel needs (Ghobadpour et al., 2022). In addition, BETs reduce maintenance and operating costs due to their high energy efficiency, robustness and reduced number of components compared to conventional tractors (Khatawkar et al., 2019). Sisson (2017) suggests that the maintenance and operating costs can be as low as 50 to 67% of ICE tractors.

Despite the benefits, shifting to BETs comes with challenges and limitations. Due to the high weight and intensive workload the batteries of BETs only have a limited range per charging (Ghobadpour et al., 2022). They range from four to eight hours, which might not correspond to farmers' work schedule. Although battery technology is expected to improve over the next decade, optimizing the operation and charging cycles of BETs or the use of swappable batteries will be likely solutions to overcome the short range of the batteries (Caban et al., 2018). Other key challenges involve lengthy charging time and the limited availability of charging infrastructure which is a significant concern for farmers that are reluctant to adopt e-tractors (Bessette et al., 2022). Gorjian et al. (2021) recommend the development of relevant policies that enable the installation of charging stations and encourage farmers' acceptance of this technology.

2.3 Farmers' preferences of BETs

Riedner et al. (2019) found that organic farmers and farmers with on-farm solar energy production are more likely to consider the investment in electric agricultural machinery. This tendency might be explained by the higher environmental concerns of organic farmers compared to conventional farms (Sullivan et al., 1996). Combining the use of solar PV and BET not only improves self-consumption of the PV system and the profitability of both technologies, but it also contributes to the energy transition in society. A crucial factor for an innovation to be diffused successfully is that the expected perceived benefits should be higher than the expected perceived risks (Rogers et al., 2014). Several studies have found that farmers have a neutral to positive attitude towards the adoption of electric agricultural vehicles despite them being in the very early stage of their technology development (Bessette et al., 2022; Rübcke von Veltheim & Heise, 2021).

One of the biggest barriers for farmers to purchase BETs are the high initial investment costs (Ahmed et al., 2020; Bessette et al., 2022; Sok & Hoestra, 2023). This may also be due to the new technology and rather few manufacturers in the market who cannot benefit from economies of scale yet (Sisson, 2017). Additionally, the battery can only bear a finite number of charging cycles until it needs to be replaced which generally happens throughout the lifetime of the BET. Batteries are costly and their replacement increases the overall capital investment compared to ICE tractors (Bessette et al., 2022). Most of the Dutch farmers surveyed by Sok and Hoestra (2023) also indicated that they were unlikely to purchase a BET within the next 10 years. The major technical concerns were related to the short battery range and doubts that the charging and field operations schedule would fit together (Sok & Hoestra, 2023). Uncertainty about maintenance and operating costs as well as the performance of BETs in the long-term, and the lack of experience are further barriers to the purchase intentions of farmers (Bessette et al., 2022). In addition, the lifetime of the existing traditional tractors is around 20 years. This long period also prevents many farmers to purchase a new BET in the short term which, on the other hand, would be beneficial for the climate (Ahmed et al., 2020).

3 Research Design

3.1 Methodological approach

To investigate the perceived drivers and barriers for tractor manufacturers to produce BETs, I conducted semi-structured expert interviews with tractor manufacturers operating in Europe and a representative of an industry association. I chose this qualitative method for several reasons. First, qualitative data collection makes sense especially in cases where historical and quantitative data is missing. The BET market in Europe is still in an early stage so that sales numbers are not yet publicly available for a quantitative market analysis (dpa, 2024). Second, interviews have been widely used in social sciences to gather rich in-depth data (Kvale & Brinkmann, 2009). The sample size was identified through the approach of saturation (Hennink & Kaiser, 2022). The latter is reached during data collection when additional interviews provide no new and relevant information. According to Mwita (2022) the average sample size in qualitative data collection consists generally of 15 interviews.

3.2 Data

The sample consists of 14 representatives from nine tractor manufacturing companies[1], which together account for around 80% of the European tractor market (Göggerle, 2025; Tastowe & Wilhelmstroop, 2023). I also interviewed a representative from an international agricultural machinery industry association to get the context of the whole tractor industry. The interviews took place between July and October 2024 and were conducted via video conferencing (expect one that was done via phone call). Each interview lasted between 40 and 90 minutes, and was recorded, transcribed verbatim, and analysed. All interviewees agreed to be recorded on the condition that they remain anonymous. The interviews were conducted in either German or English, and certain quotes that appear in the study have been translated into English where necessary.

I recruited the respondents as follows: First, I defined the target group for this study, both on company level and on individual interviewee level. At the company level, I considered as many tractor brands in Europe as possible. As the tractor market is fairly consolidated, a relatively small number of six companies dominate the market with a combined market share of around 80% (Göggerle, 2022, 2025; Tastowe & Wilhelmstroop, 2023). Within the companies, I targeted professionals in the areas of innovation, machine electrification, research and development, strategy, and engineering, ideally in a leadership role. Against this background, I used LinkedIn to identify suitable interviewees. I used the search function and included keywords such as “Head of Innovation”, “Head of Engineering”, “Innovation Manager”, “Director”, “Electrification” and other related keywords, and combined them with the tractor brands identified. A total of 87 potential candidates were contacted. 78 of them declined or did not respond, while 9 accepted to take part in this study. Five interviewees were recruited through referrals from interviewees who were asked for recommendations at the end of each interview, and two interviewees were selected through the researcher’s network. One remaining interviewee was recruited through a Google search. In total, 99 people were invited to participate in the interviews, of which 15 were successfully recruited (response rate of 15%).

[1] One of them was employed at a tractor manufacturer for more than ten years and has recently in the meantime switched to a position for electrification of heavy-duty vehicles due to a corporate restructuring.

The interviewees had between one and 45 years of experience in the tractor industry, and 80% of them held management positions. Most had an educational background in engineering or management. In the case of a few large manufacturers, and depending on interviewee availability, I interviewed two people from the same company to get complementary perspectives and to validate the company's position. Next to tractor manufacturers, I included an industry association representative in the sample to ensure a broader contextual understanding and validation of the manufacturers' perspectives (see Appendix I for an anonymized list of the interviewees).

The semi-structured interviews were set up using an interview guide that included a series of open-ended questions (see Appendix II). It was developed based on literature and two pre-study interviews with tractor manufacturers to gain understanding of the issues relevant to BETs from the manufacturers' perspective. The guide was structured into 5 thematic sections. First, the interview started with the professional background of the interviewee. The second section was about the strategic orientation of the company, including the role of sustainability in the company, as well as the main drivers and barriers to producing BETs in their perspective. The third part involved questions about the BET market including their perception of the demand for BETs, the range of applications, as well as their perception on the future development of the BET market within the next decade. The fourth section addressed the regulatory environment and how it influences the development of BETs. The last section covered the organizational dimension and the production process. Thus, I was able to capture the factors that influence the production of BETs. In most of the interview, I asked the interviewees at the end if they wanted to add any further information about BETs that was not covered in the interview to ensure that I did not miss any important information.

3.3 Data analysis

The interviews were analysed with respect to the research question about the perceived drivers and barriers to the production of BETs. To do this, I analysed the data using qualitative methods, specifically, I used thematic analysis following Braun and Clarke (2006). Thematic analysis is widely used in qualitative research and allows for the identification of patterns – or themes – within a data set. The patterns can be identified in two ways – either deductively or inductively. The first approach generally uses a theoretical framework as a basis with a relatively pre-defined coding-scheme to identify patterns in the data. The inductive approach, on the other hand, is more bottom-up or data-driven, where the researcher identifies the themes that emerge from the data without being driven by a particular theory or framework. The choice of approach is highly dependent on the research goal and question (Braun & Clarke, 2006). For this study, I used the inductive approach. It is especially effective in exploring new research fields where existing literature is limited (Creswell & Creswell, 2017).

4 Findings and Discussion

In this section, I present the findings from the interviews and discuss them based on existing literature to provide a nuanced understanding of the drivers and challenges in the electrification of agricultural vehicles.

4.1 Market Pull: Perceived customer value

A key theme that influences tractor manufacturers' decision to produce BETs is their perception whether and how the innovation meets their customers' needs. This aligns with existing literature emphasising the importance of customer-orientation in product development and innovation (Wilson & Dowlatabadi, 2007). Farmers are the main customer segment for tractor manufacturers. Their goal is to offer farmers machineries that support them in their agricultural activities.

"We have a very clear strategy that we want to make our customers the best in their working environment. (…) In other words, the farmer has to be the best if he uses our [brand] products" (T.M. 1).

This customer centric approach translates into a product objective to develop machines that offer the best cost-effectiveness from the farmer's point of view. This can be achieved in two ways. Firstly, the machinery should help to reduce farmers' operating costs, for example by improving fuel efficiency, which directly reduces fuel costs. Second, it should increase the productivity of farm work by incorporating features that enable farmers to complete tasks more quickly and efficiently.

The perceived customer value of BETs among tractor manufacturers is based on three key experiences. First, all interviewed manufacturers have conducted research and development (R&D) efforts related to BETs. These efforts range from running internal innovation workshops to developing market-ready BET prototypes. This hands-on experience with BETs shapes their perceptions of customer value. Second, many interviewees noted that the manufacturers closely monitor each other and showcase their innovations at industry fairs. In some cases, respondents referred to competitors' advances and used them to draw conclusions about the potential customer value of BETs. Thirdly, their perceptions are influenced by their understanding of farmer characteristics and how BETs fit with farmers' specific needs. In the following subsections, I present their perceived customer value using the innovation diffusion framework developed by (Rogers, 2003). This framework consists of 5 attributes that need to be present for an innovation to be adopted by the market, namely *relative advantage, compatibility, complexity, trialability and observability* (Rogers, 2003). I use this framework to categorise the tractor manufacturers' arguments in terms of the perceived customer value of BETs. In the following, therefore, I will adopt this framework from the tractor manufacturers' perspective on the fit between BETs and their perceived customer needs.

4.1.1 Relative Advantage

A key criterion for market adoption of an innovation is whether the innovation is perceived to have relative advantages over an incumbent reference technology. Relative advantages can involve cost savings or improved user comfort (Wilson & Dowlatabadi, 2007). The tractor manufacturers reflected that BETs have several advantages over ICE tractors when it comes to user comfort such as no tailpipe emissions. Depending on the tractor application and customer segment, the avoidance of emissions appears to be more relevant to some customer segments than others. For indoor farming activities, such as in barns or vegetable tunnels, they see the improved well-being and comfort for the farmer when using a BET tractor compared to an ICE tractor. However, a few mentioned that for farmers working in an open field, this advantage becomes secondary as they perceive that air pollution emissions per person per hectare are minimal compared to indoor areas or densely populated cities. Some feel that the majority of farmers do not prioritize carbon emissions or air pollution reduction because they work in open fields. Swallow and Barkemeyer (2024) found that there is a general low intention by farmers to adopt practices to reduce carbon emissions. Many tractor manufacturers recognize that municipalities are increasingly interested in using electric vehicles, not only to reduce CO_2 emissions as a climate change measure, but also to improve air quality and public health. This trend was also noted by Fulton et al. (2017).

The technological benefits of BETs in relation to precision farming were highlighted as one of the key relative advantages over traditional tractors. The electric propulsion system allows for more precise control of agricultural implements, increasing the productivity and accuracy of agricultural tasks such as planting seeds or applying pesticides. The integration of BETs with precision and smart farming is seen as a great opportunity for future and sustainable farming (Gul et al., 2024). As one interviewee elaborated:

> *"So, if we think about precision automation and being able to control machinery very precisely in the field, electrification gives us that ability to control much better than with diesel engines"* (TM. 5)

Instant torque and high energy efficiency of the battery technology were also considered as important advantages of BETs (Albatayneh et al., 2020; Bessette et al., 2022).

The quietness of BETs is seen as another relative advantage over ICE tractors. This feature is considered to be particularly important for customer segments such as municipalities or golf courses, where tractors are used in public areas and they want to reduce noise emissions. The manufacturers feel that farmers tend to see this as a secondary benefit, a nice add-on.

Another relative advantage of BETs is that if farmers have on-site solar PV systems, they can not only charge their BETs at low cost and reduce the operating costs of the machinery, but they can also improve the profitability of their PV systems by increasing the self-consumption of the solar system (Gorjian et al., 2021). The combination of using on-site solar energy to charge BETs is viewed by several interviewees as an important market driver for the adoption of BETs and therefore a key motivation for producing BETs.

Despite the relative advantages, tractor manufacturers considered two main relative disadvantages compared to ICE tractors, namely limited energy density compared to diesel and high acquisition costs. The limited energy density leads most tractor manufacturers to conclude that heavy-duty tractors cannot be fully electrified with current battery technology. Due to their need to pull heavy implements and operate at full power, there would be issues with limited battery range, weight and battery packaging.

“A 100 kilowatt tractor is going to need a 100 kilowatt-hour battery (…) If you go plowing, you're on 100%. You've got one hour use. Now a diesel could run for 12, but there's a reason why diesel has been the best for the last 50 years and it's because of its power density (…) Then you've got to try and find a battery that's big enough to run it for, let's say, half a day. But that's massive” (TM. 2).

These limitations lead most interviewed tractor manufacturers to concentrate on developing BETs for small and compact tractors up to about 75kW. Such smaller tractors are generally used for light work and therefore the battery range can be extended compared to heavy work (Eusebio, 2022).

The interviewees mentioned that the high acquisition costs are mainly driven by battery costs and due to the fact that BETs are still at prototype level, not yet benefiting from economies of scale. This high production cost results in a high purchase cost compared to traditional tractors. In order for BETs to become commercially competitive, the experience of the automotive industry suggests that a rapid reduction in battery costs and potential policy measures to support a reduction in overall production costs are necessary (Nilsson & Nykvist, 2016; Nykvist & Nilsson, 2015). However, BETs have potentially lower operating and maintenance costs than ICE tractors (Sisson, 2017).

Increased demand would lead to increased BET production. Some tractor manufacturers with BET prototypes mentioned that they have more production capacity than current demand for BETs due to the high purchase cost. Most tractor manufacturers mentioned that they would welcome subsidies for farmers to adopt BETs in order to increase demand. While there were subsidies for municipalities and farmers in Germany for the purchase of zero-emission machines such as BETs, these were abolished in 2024 (Pehl, 2024). Some tractor manufacturers have seen demand for their BET prototypes decline as a result of these developments. However, Switzerland, for example, recently announced the launch of a subsidy programme to promote the adoption of BETs from 2025. (röt, 2024). Some interviewees also suggested that for BETs to be commercially viable, farmers would need to receive a premium for growing their vegetables in a carbon neutral way, similar to organic produce. While several interviewees questioned whether consumers would pay more for carbon neutrality today, one interviewee mentioned that one of their farmer clients was asking for a BET because they were receiving funding from their investors for carbon neutral farming activities. There may therefore be a potential future market for BETs from organic farms aiming for carbon neutrality. This aligns with the study of Riedner et al. (2019) showing that organic farmers are more inclined to adopt BETs.

Overall, the relative advantages and disadvantages of BETs lead most tractor manufacturers to focus on developing BETs for niche applications in the power range up to 75 kW.

4.1.2 Compatibility

Compatibility refers to the requirement that a new technology should be compatible with existing consumer needs or prevailing behavioural and social norms (Wilson & Dowlatabadi, 2007). Tractor manufacturers commented that, depending on the farming activity, limited battery range and long charging times would not fit in with farmers' working schedules in the field. They said that farmers have specific working times and long working hours, sometimes up to 12 hours a day in the field. If a BET had to be recharged after only a few hours, this would disrupt their familiar working patterns and reduce their willingness to adopt the technology. According to Sok and Hoestra (2023), working hours and battery range is the most important technical issue when deciding to adopt a BET and they found that farmers are doubtful about using BETs due to the perceived operational limitations and disruption of their working schedule. Additionally, the tractor manufacturers mentioned that on the fields there are generally limited to no charging infrastructure which would affect the farmers' working schedule negatively, because they would need to use public charging stations. Several studies in Germany showed that the average distance between farms and their farmland was about 2 kilometres (Bathke & Tietz, 2016; Weise & Engelhardt, 1999). This suggests that distance to farm may not be a main barrier to BET adoption.

Most tractor manufacturers see a market for small to medium sized BETs in specific applications that are better suited to the prevailing working conditions, such as farm work in the barn or municipal work. In both cases, the BETs are potentially close to a charging infrastructure and may only be used for a few hours at a time, making them more likely to be charged during habitual work breaks.

In addition to the focus on small to medium-sized BETs, most tractor manufacturers also see hybridization as a means of overcoming the operational limitations for electrifying heavy-duty tractors. However, if used with diesel as the main fuel, hybrid tractors will not solve climate change issues and allocating resources to hybridization could lead to a delay in the transition to fully zero-emission vehicles (Dia, 2024; The Economist, 2024). Several respondents stressed that traditional tractor frames are not optimally suitable to accommodate battery technology and emphasized the need to fundamentally redesign tractors in order to increase the capacity and working hours of BETs (see section 4.4.1 for further details). Fast charging and battery swapping systems were also suggested as potential solution for BETs. Battery swapping are already offered by a few entrepreneurial tractor manufacturers (Asscheman, 2023; Tadus, 2025). In the automotive industry, battery swapping has received some attention in the past to address the issue of range anxiety, and despite remaining challenges in the implementation and business model, it is a growing market (Lin, 2024). While battery swapping can increase productivity, a study of electric trucks showed that it can be up to 65% more expensive (Rafi et al., 2020).

There is another compatibility issue related to agricultural implements. Most of the implements available today are designed for hydraulic or mechanical transmission. An interviewee explained that to make the most of the efficiency of electric transmission of BETs, implements would need to be designed for electric transmission, otherwise there will be an energy loss when converting electric power to hydraulic or mechanical power (Khatawkar et al., 2019). Being aware of the current implements market and the potential energy losses, tractor manufacturers have adapted the design of their BETs to be able to power hydraulic and mechanical implements, so that farmers can use BETs with their existing equipments.

4.1.3 Complexity

Complexity refers to the idea of what kind of skills and (potentially additional) effort consumers need to adopt the new technology (Rogers, 2003). Complexity associated with BETs did not emerge as a relevant issue in the interviews. Tractor manufacturers do not seem to think that BETs are more complex to use than conventional tractors from the farmers' point of view. Today's BET prototypes are similar in design to traditional tractors, so there does not seem to be much additional effort to switch to BETs. One issue that was mentioned several times is that some farmers are used to maintaining and repairing their tractors themselves. Compared to a mechanical ICE engine, handling a high voltage battery connected to an electric motor is perceived as very dangerous and farmers would need to be informed not to repair

BETs themselves. At the same time, battery-electric vehicles have fewer moving components than ICE vehicles and tend to require low maintenance (Colella & Pons, 2024).

4.1.4 Trialability

Trialability refers to the possibility for potential consumers to test the innovation before making a purchasing decision. This also includes peer experience and social feedback, where consumers can rely on each other's experience with the innovation to reduce uncertainty about the new technology (Wilson & Dowlatabadi, 2007). The trialability of BETs is limited at present, as the BET market in Europe is currently limited to prototypes (dpa, 2024). Tractor manufacturers exhibit their BET prototypes at trade fairs where potential customers and competitors can see them. However, several interviewees felt that farmers do not have sufficient access to BETs and therefore have a limited understanding of the benefits of BETs. Based on the experience of passenger car electrification, incentives to improve familiarity with a new technology are essential for adoption (Nilsson & Nykvist, 2016). As an interviewee reflected on this issue:

"And most importantly, there is still very little knowledge. Especially among farmers. Knowledge of what electrification can look like, what I can do, what makes sense for which farm. There is still very little knowledge (…) Even though some farmers may already be familiar with this from electric cars, it's simply a completely new area. And these prejudices in particular - how long will they operate for? What do I do if the battery runs out in the middle of the field? There are a lot of prejudices about things like that" (TM. 11).

To increase the trialability of BETs, one interviewee suggested that there should be more showcases and test applications for consumers in the market who would then share their experiences with their peers. Some interviewees expect early adopters of BETs to be characterized by either technological curiosity, high financial capital and possibly on-site solar energy production. Early adopters are seen as key actors in the diffusion of new technologies (Rogers, 2003). Frattini et al. (2014) suggest identifying these customer segments and targeting them with appropriate marketing efforts. Leveraging their experience and positive social feedback may potentially support the adoption of BETs (Wilson & Dowlatabadi, 2007). Furthermore, studies have shown that farmers who have experience with electric cars are more likely to adopt BETs because they are familiar with the technology (Lombardi & Berni, 2021). One interviewee confirmed this observation:

"Well, I think that, on the one hand, electro mobility is proving itself a bit in the automotive sector. (…) In other words, many farmers, for example, already have an electric car and realize that it works perfectly. I think that's a bit of a groundbreaker" (TM. 11)

Such spill-over effects can play a crucial role in the adoption of new clean technologies. In the context of the energy transition, household investments in solar energy have been shown to positively influence the adoption of electric vehicles (Cerruti et al., 2024; Lyu, 2023; Wen et al., 2023). Similarly, the growing use of solar energy and electric cars by farmers is likely to support the adoption of BETs through co-benefits and increased technology experience (Landwirtschaftskammer Steiermark, 2018; Schürer, 2024).

4.1.5 Observability

Observability refers to how an innovation can be noticed or seen by potential adopters. For example, when it comes to renewable energy innovations, solar panels are more likely to be adopted than insulation measures because the former are more observable (Wilson & Dowlatabadi, 2007). The tractor manufacturers agreed that today, there a only a few prototypes available in the market, so there is not many BETs to see for potential adopters. Flagship projects and increased education for farmers on potential applications with BETs are necessary for increased observability, as one interviewee noted:

“They (the farmers) need to see that they can actually do more and that it's better. And so, I don't think the industry has done a good job of communicating that just yet for all the different use cases. So that's going to be the biggest challenge“ (TM.5).

4.1.6 Market potential for current BETs from manufacturers’ perspective

Most tractor manufacturers view the product-market fit and corresponding market potential for BETs in certain areas of applications based on the reflected customer value. With today’s battery technology, BETs are considered to be suitable for certain niche applications in the lower capacity range. Table 1 summarizes the perceived market potential in terms of customer segments and applications due to their characteristics that fit BETs.

Target Activities (Customer segment)	Characteristics
Communal activities, e.g mowing or snow clearance (Municipalities)	• Political guidelines for CO2 reduction that demand emission-free machineries • Reduction of air pollution for public health reasons • Accessible charging infrastructure • Care about reduced noise emissions • Work hours can be adapted to charging cycles
Speciality crop cultivation & small-to medium-scale farming (Farmers)	• Farming activities requiring light to medium power load
Indoor farming, e.g. in barns or vegetable tunnels (Farmers)	• Farming activities requiring light to medium power load • Reduction of air pollution for health reasons • Accessible charging infrastructure
Organic farmers and/or farmers with their own solar PV systems (Farmers)	• Increase self-consumption of solar energy production • Can make business case from using zero emission machineries (e.g. demand premium for their products or get funding)

Table 2: Tractor manufacturers’ perspective on the market potential of BETs: compact tractors of up to 70 kW (own illustration based on interviews)

4.2 Sustainability Push

Sustainability plays a crucial role in tractor manufacturers' decisions to develop BETs. It affects them in two main ways: emissions regulations and corporate sustainability goals. This chapter provides insights into both aspects.

4.2.1 Anticipations about emissions regulations

Regulations have a strong influence on manufacturers, and the tractor industry is no exception. Several interviewees pointed out how much they had to adapt and innovate in the area of fuel efficiency since the introduction of emissions regulations for internal combustion engines for NRMM (see chapter 2.1). They have developed approaches not only to reduce the diesel consumption of their machineries, but also to minimize the emission of certain polluting particles. These emission regulations are an example of how environmental policy interventions can be effective in shaping an industry to become more sustainable (Stojčić et al., 2024). As the current emission regulations for NRMM do not address the reduction of carbon emissions, some of the tractor manufacturers stated that there is currently no immediate legislative pressure to develop BETs. However, as one interviewee said:

“Let's say that the agricultural sector follows the automotive sector in the regulation” (T.M. 3).

As emissions regulations in the automotive industry include the phase-out of ICE passenger cars to reduce carbon emissions, while encouraging the uptake of electric vehicles (EC, 2019; Kar-Gupta, 2024), the majority of tractor manufacturers anticipate that the next stage of emissions regulations for NRMM will either do the same or at least include the reduction of carbon emissions. In contrast, some interviewees expressed their sceptics that emissions regulations for NRMM would introduce a phase-out of ICE agricultural vehicles in the near future. They argued that the phase-out of ICE passenger cars has had negative impacts on the European car industry. They attribute the financial challenges faced by several European car manufacturers to the phase-out of ICE vehicles (Meredith, 2024), and doubt that policymakers would impose a phase-out on tractor manufacturers while risking financial instability in this sector. However, there are also public debates that the European automotive industry has been too slow in transitioning to electric vehicle while losing market shares to Chinese manufacturers (Gonzalez, 2024; Kirsch, 2025; Subran et al., 2023; Wolf, 2024). Consequently, a further delay in the electrification may lead to potential reduction of tractor manufacturers' competitiveness in the future, as observed in the European automotive industry.

Also, some tractor manufacturers believe that the technological and operational limitations of BETs (see Chapters 2.1 and 4.2) would prevent policymakers from requiring their production in the near future. One manufacturer expressed this view in the context of lobbying efforts against BETs:

"But I assume that state regulation will only come when there are reasonable solutions (…) So the EU is already discussing the fact that we need to improve the environment and that something needs to be done, but of course they always include experts from industry in such discussions. And there is still no, shall I say, meaningful solution. In other words, the industry lobby is of course trying to make the legislators realise, yes, all well and good, but just wait a little longer." (T.M. 1).

Either way, one of the main reasons for the tractor manufacturers to invest in the development of BETs is because they aim to be prepared and ready to offer BETs in order to remain competitive and comply with possible future regulations.

4.2.2 Corporate Sustainability

Most of the interviewed manufacturers publish sustainability reports, while others emphasized the importance of sustainability in their corporate strategy. Sustainability efforts were evident both in manufacturing processes and at the product level in the interviews (Jayal et al., 2010). Examples at manufacturing level included the use of renewable energy, e.g. by installing solar panels on the roofs of their factories, and resource management, e.g. using recycled materials or reducing input materials. At the product level, they take quite a holistic view and consider sustainability in the agricultural sector as part of their product vision, as their machineries are a tool for farmers' activities. For instance, with digitalization and precision farming they aim to improve the design of their machineries to support farmers improve soil quality and reduce the use of water or other resources such as pesticides and seeds. This is part of Agriculture 4.0, which tractor manufacturers aim for (CEMA, 2024). While reducing carbon emissions is generally taken into account in their product development, for some it is not seen as a primary goal when it comes to the sustainability of their machinery, as the carbon emissions of agricultural machinery are considered to be lower than in other industries. However, for more than half of the tractor manufacturers, BETs are part of their corporate strategy, and they have been investing in R&D activities to develop BETs. While some have BET prototypes that have been launched in the market or are about to be launched within the next two years, others are still working on them. For instance, one of them mentioned:

"In the area of agricultural technology, we have committed ourselves to launching a fully autonomous, battery-powered small tractor in the range of 100 horsepower by 2026" (T.M. 7).

A key driver for tractor manufacturers to explore BETs is the potential to combine two aspects: sustainability and customer value. As a result, the interviewed manufacturers have been exploring small- to medium-sized BETs for specific markets. Several technical studies have also examined small-sized BETs, recognizing the limitations of battery energy density (Rodnei R. Melo, 2019; Vogt et al., 2018). To reduce the carbon emissions of larger tractors, several manufacturers are looking at alternative fuels that may promise higher energy densities, such as hydrogen, biofuels or synthetic fuels. The hybrid combination of electrification and alternative fuels was also mentioned as potential low-carbon solution in order to benefit from the technological benefits of electric transmission while overcoming the battery range limitations.

4.2.3 Availability of external funding

Another theme that emerged was the possibility of attracting public or private funding through the development of BETs. This was mentioned by one of the larger tractor manufacturers:

"And by producing the right machines, we also have to, or no, we don't have to, but we also have the ability to attract investment from sustainable funds" (T.M. 2).

On the other hand, for small to medium sized tractor manufacturers, external funding appears to be necessary to develop BETs:

"And honestly, all the innovation projects, the electric, the electric hybrid project, and the project we are developing now, a full electric, are made thanks to the European finance *(…) So it's not possible to make innovation also for a little or medium little company with our money without help. And the European Fund for Innovation is mandatory, is necessary, for this kind of activity and this kind of project and development (T.M. 3).*

As mentioned in chapter 4.1.1., incentives to reduce production costs are important to promote BET production (Nilsson & Nykvist, 2016).

4.3 Influence from automotive industry

The automotive industry has a strong influence on the tractor sector in terms of technology and regulations. Several interviewees stated that the tractor industry is about five to ten years behind the automotive sector in terms of technology and regulations. In general, many regulations from the automotive industry are adopted for the tractor sector at a later stage. For example, the regulatory discussion on reducing GHG emissions in the automotive industry and the phase-out of ICE passenger cars a decade ago is seen as a main driver for the tractor industry to focus on BETs (see section 4.2.1). On a technological level, the tractor manufacturers mentioned that they use suppliers, components and know-how from the automotive sector. As the tractor sector is much smaller than the automotive industry, the latter can use economies of scale to reduce technology costs and boost technology diffusion. For example, batteries were first introduced in cars and then in buses. One interviewee mentioned that they use now the battery technology from buses for their BET prototype. Economies of scale reduced technology costs and increased the supply of batteries to the point where they were available to tractor manufacturers. As one interviewee confirmed:

"I think for us, and if we think about agricultural trends over time, we have always had to work very closely with automotive suppliers and partners because automotive will generally lead the way. And it's because of the economies of scale and just that they're building capital infrastructure investments at such a large scale and at such a fast pace that we're never going to outpace them in a lot of different technology categories" (TM. 5).

A tractor manufacturer also mentioned that they work closely with their sister company from the automotive sector, taking successful innovations from the electrification of heavy-duty trucks and applying them to tractors, while discarding ideas that did not work for the transport sector. This is an example of cross-industry innovation, where innovations from other industries are creatively imitated and reconfigured to meet the needs of the company's customers (Enkel & Gassmann, 2010).

While the phase-out of ICE passenger cars puts pressure on BET innovation, it is also seen as a major threat to the current tractor industry. The manufacturers rely on ICE motors from automotive suppliers, and the phase-out of ICE cars could make these motors scarce and more expensive. However, this transition is also seen as an opportunity by some to accelerate BET development. As one interviewee noted:

„Well, it already happened with the car, that where the European community planned to stop the production of internal combustion engines within 2035, although it looks like they have some, they are still thinking about. So, this kind of political action could affect significantly the development and the speed in which this switch can happen“ (TM. 8).

Our findings show that the tractor industry is highly dependent on the automotive industry in terms of supply, cost trends, innovation and the regulatory context. The future development of electrification in the automotive industry will continue to affect the tractor industry and should be considered as a cross-reference industry when analyzing the tractor industry.

4.4 Path Dependence and carbon lock-in the tractor industry

The development of BETs in the tractor industry appears to be slow. The interviews also revealed a pattern in the industry related to path dependency and carbon lock-in. Path dependence refers to the phenomenon whereby institutions base their decisions on past events, investments and processes and become locked into systems and trajectories, such as carbon-based technologies, when alternatives may be more beneficial (Unruh, 2000). In the following, I discuss this phenomenon in the tractor industry and potential solutions to escape carbon lock-in.

4.4.1 Carbon lock-in in the manufacturing process

The production of a BET requires a different process to that of a conventional ICE tractor which involves significant additional investment not only in a new production line, but also in new employees and suppliers, which is seen as a challenge. For example, BETs require more electrical engineers rather than mechanical engineers, and the high-voltage batteries require additional safety measures in the factories. In addition, many respondents mentioned that running two production lines is expensive and complex. Incumbents often introduce innovations in small extensions of their existing product line rather than disruptive changes (Hockerts & Wüstenhagen, 2010). Furthermore, the tractor manufacturers are focused on selling their traditional ICE tractors and rely on revenues from their existing product portfolio to cover their costs, which hinders a rapid and exclusive shift to BETs. These conditions are consistent with the path dependence literature on the lock-in effects of existing production processes that can hinder low-carbon innovation (Unruh, 2000). Additionally, an interviewee mentioned that BETs currently offer lower margins than traditional tractors. For example, several interviewees mentioned that specialist or smaller tractor manufacturers are better suited to producing BETs because they can produce a small quantity of BETs more economically than large tractor manufacturers who need to sell much larger quantities to make the production line profitable. Large incumbents tend to face challenges to introduce disruptive innovations because they are restricted by their fixed costs and past investments, reinforcing the carbon lock-in (Apajalahti & Kungl, 2022; Hockerts & Wüstenhagen, 2010). These cost issues, together with the perceived slow market development and current low regulatory pressure, have limited the interest of several large tractor manufacturers in accelerating the production of BETs. In sustainable transformation, incumbents often need sufficient external pressure to react accordingly with disruptive innovations (Hockerts & Wüstenhagen, 2010).

„And it must also be economical for manufacturers to offer such a technology (…). So, simply costs and complexity. As long as I have to offer two technologies in parallel, it's just not that interesting“ (TM.9).

“And usually the margins on the electrified products are not as good. So I think companies that are doing this, they're really serious about it because it's sustainable and it's giving their customers the flexibility they need“ (TM. 5).

In addition to a different production line, the development of a BET also requires a new design of the tractor at an engineering level compared to conventional tractors, which is seen as a major challenge by many tractor manufacturers. Some manufacturers acknowledge that simply swapping the internal combustion engine for a battery, while keeping the traditional tractor frame, is not optimal for BETs. However, with their current focus on conventional tractors, many manufacturers face challenges in developing entirely new tractor designs. This reflects a common issue in sustainable innovation, where incumbents often struggle to realize full potential of sustainable alternatives, because they are limited to leverage technological spillovers from their existing products (Rennings, 2000).

"First of all, it's the layout of the tractor, because the tractor cannot be, cannot ever, from our point of view, exactly the same layout of the current machinery. We saw several experiments from our competitors that are quite interesting for sure, but we think that it's not the right direction from our side to keep the same layout of the current machinery. But we are still struggling to find the right layout, because we have several ideas, but they are quite hard to, let's say, implement, and it requires from a manufacturer like us heavy investments, because we need to rethink completely the layout of the machine" (TM. 8).

"All the tractor manufacturers I know, I imagine I know many, are focused on the conventional product. Okay, so, but electric requires a complete new approach at the engineering level" (TM. 6)

On the other hand, new market entrants tend to be free from such historical limitations and often disrupt the market (Hockerts & Wüstenhagen, 2010). I interviewed a start-up company that developed a new design for a BET, improving the battery range of the tractor compared to using conventional tractor designs for BETs. She argued:

"We then have much better efficiency, so the battery that we can integrate on board, just from the actual dimensions alone, we can get much more power out of it. (…) In our case, however, we place various electric motors in the vehicle and place them as close as possible to the actual load" (TM. 11).

Compared to other BET designs, this new engineering approach enabled them to develop a BET prototype with higher capacities of over 100kW. This new manufacturing approach may inspire other established companies to further innovate in BETs (Unruh, 2002).

While there are barriers to the production of BETs at the firm level, the next section provides insights into a more macro-level path dependency issue.

4.4.2 Paradigm shift needed in the whole industry

Several interviewees reflected on the need for a paradigm shift in the industry as a whole, among all stakeholders in the supply chain. As the industry is perceived to be rather conservative, system change in the industry is seen as particularly challenging. For example, agricultural implements manufacturers would need to produce implements that use electrical rather than mechanical or hydraulic transmissions, so that BETs can benefit from higher efficiencies and avoid energy losses in the conversion of energy forms. Another example is service providers, who will need additional training to handle the high-voltage batteries used in the maintenance and repair of BETs. For tractor manufacturers, the paradigm shift is seen as challenging, as they would have to adapt their business practices to a large extent, as one interviewee reflected:

"Actually, whenever there is a transition shift and a company, an OEM, needs to change paradigm, it's not so easy, even more for the bigger one. Because if you have a structure, a company with people that are doing sales, production, whatever, to change perspective, it's more tricky" (TM. 4).

Another challenge to the paradigm shift is the economic and geopolitical importance of ICE tractor manufacturing to the European market. While ICE engines and tractors are manufactured in Europe, a shift to BETs would mean relying on battery imports from other markets such as China (Wells & Nieuwenhuis, 2012). The industry association representative sees BETs as a threat to the strategic importance of European tractor manufacturers. This corresponds to the path dependence literature, suggesting that in sustainable innovation, incumbents often fear that disruptive innovations cannibalize the market share of their existing products (Hockerts & Wüstenhagen, 2010). In response to this risk, some tractor manufacturers are investigating into alternative fuels that are compatible with ICE engines in order to maintain their traditional production capacity.

"If you talk about a strategic open geopolitical independence, the European Union is using to produce your own fuels is very attractive. And everybody recognizes that, the energy companies, the commission, everybody has high hopes for alternative fuels also for airlines and shipping e-fuel, synthetic fuels" (IA. 1)

However, e-fuels face many challenges such as increased energy demand, high costs and production uncertainties (Wietschel et al., 2023), and some interviewed tractor manufacturers also recognize these limitations.

While China's increasing production of low-cost electric cars is seen as a threat to the European automotive industry, China does not seem to be perceived as a major competitor for the interviewed tractor manufacturers. So far, China has introduced only small and specialized BETs have been introduced (Bakker, 2024), which some tractor manufacturers consider a niche segment. The European tractor industry therefore hopes to maintain its manufacturing position by introducing alternative fuels for large tractors in order to offer net zero emissions vehicles. However, public debates suggest that a decade ago, the European automotive industry failed to anticipate China's rapid advancements in the electrification of cars, which subsequently weakened Europe's global competitiveness for electric cars today (Feininger et al., 2024). In this context, European tractor manufacturers may need to draw lessons from the automotive sector's experience.

Furthermore, carbon lock-in is also observed on the consumer side by the tractor manufacturers.

"I think that the farmer loves the thermal engines a lot today" (TM. 3).

Many arguments therefore suggest that the entire tractor industry faces path dependence challenges. The next section discusses possible solutions.

4.4.3 Starting points for overcoming path dependence

There are various measures that policymakers and the private sector can take to overcome path dependence. Examples include reducing fossil fuel subsidies that encourage the externalisation of environmental costs, research into clean energy technologies as well as voluntary actions by industry (Unruh, 2002). The tractor industry has already started to take action to overcome path dependence. A key measure involves building partnerships that facilitate innovation (Unruh, 2002). Several tractor manufacturers have acquired companies with complementary capabilities such as battery or agricultural implement manufacturing, autonomous field robotics or other innovations related to electrification. This is consistent with previous studies, which show that incumbents engage in corporate venture capital investments in cleantech startups as a strategic response to sustainability transitions and based on expectations of these startups' present and future value creation (Hegeman & Sørheim, 2021; Hockerts & Wüstenhagen, 2010). The development of human capital and necessary skills are a further measure to overcome path dependence. Developing human capital and skills is another way to overcome path dependency. Some tractor manufacturers are adding electrical engineers to their workforce and training mechanical engineers to work with electric drives. The expansion of new suppliers is another measure taken by some tractor manufacturers. In addition, new entrepreneurial entrants generally introduce new technologies because they are outside the dominant technological design (Hockerts & Wüstenhagen, 2010; Unruh, 2002). We can already observe this phenomenon in the tractor sector as mentioned in chapter 4.4.1. Unruh (2002) also suggested starting with niche applications of clean energy technologies to stimulate development and allow it to grow until economies of scale reduce technology costs. This approach was mentioned by many of the interviewees, starting with smaller tractors and increasing capacity as experience and technological capabilities develop.

5 Conclusion

The electrification of agricultural vehicles is a promising step towards decarbonising agricultural operations. In addition to eliminating tailpipe emissions, BETs offer various benefits over ICE tractors in certain applications such as productivity, precision and efficiency improvements. While the automotive industry has made progress with electrification, the BET market is still in its infancy. Previous research has mainly focused on farmers' willingness to adopt BETs, with little evidence on the state of technology diffusion from the supply side. To address this gap, I conducted 15 expert interviews in the European tractor industry to shed light on the key drivers and barriers for manufacturers in introducing BETs in the market, and to explore measures to promote their production.

The interviewed tractor manufacturers represent about 80% of the European market share and our findings reveal that most of them have been investing in research and development for BETs. The key drivers include the technological advantages of electrification, such as improved energy efficiency and precision of tractor operation, as well as the aim to reduce emissions of their manufactured tractors according to their corporate sustainability goals. While current emissions regulations for tractors do not involve carbon emissions, the expectations of future regulatory developments influenced by the automotive industry represent a key motive for the development of BETs. Furthermore, a growing market demand for BETs, particularly from environmentally conscious farmers and municipalities, represent market opportunities for tractor manufacturers.

At the same time, challenges remain to the introduction of BETs to the market. Current battery technology, particularly in terms of energy density, limits the operating range of BETs compared to diesel tractors. In addition, high acquisition costs, and long charging times are seen as key barriers to adoption and consequently reduce the production incentives due to low demand. Most tractor manufacturers design BETs using traditional tractor frameworks, which are not optimal for battery integration and hinder the full utilization potential of battery electric power. This path dependence within the industry as well as the battery-related limitations has led most manufacturers to a focus on developing BETs with smaller capacities of up to 75 kW, targeted primarily at applications like municipal services and small-scale farming.

Despite these challenges, the industry is beginning to take steps towards further electrification. New market entrants are introducing innovative BET designs with higher capacities above 100 kW, and some manufacturers are forming strategic partnerships within the industry to accelerate electrification. However, incumbents remain invested in ICE technology and are exploring alternative fuels as a way to maintain their existing business models with ICE motors. Based on the findings of this study, policymakers could introduce incentives that reduce production and acquisition costs to accelerate BET diffusion. Furthermore, tractor manufacturers could co-create more flagship projects with early adopters to enable peer experience for potential adopters and disseminate knowledge on BET applications to increase their market reach.

The findings of this study further raise critical questions about the future direction of the tractor industry and carbon lock-in mechanisms. Will tractor manufacturers adapt to the electrification trend or face a trajectory similar to some European car manufacturers that struggle with the transition to electric vehicles? Further research could compare the path dependence of the tractor and automotive industries to draw valuable lessons for navigating this transition.

5.1 Limitations and further research

There are some limitations in this study that represent opportunities for future research. First, this qualitative study was conducted in an explorative way. While it provided rich data, it is based on a limited number of expert perspectives. Future studies could use quantitative approaches to test our findings with a larger sample of tractor industry stakeholder along the supply chain of BETs. Second, I found that there is room for further investigation into the redesign of tractors to enhance the efficiency of BETs that enable the electrification of larger tractors. I recommend further engineering-based research in this area. Third, I focused on the European tractor market. While it represents a highly interesting case for innovation and we can draw conclusion for other markets, it could be interesting to explore the BET market state in other markets outside of Europe such as Asia or the US.

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Appendix

Appendix I – List of interviewees (anonymized)

Nr.	Company[2]	Experience in the tractor sector	Professional field in the company	Interview duration
TM.1	Tractor manufacturer	15 years	Head of Engineering Processes	60min
TM.2	Tractor manufacturer	20 years	Product Marketing	75min
TM.3	Tractor manufacturer	19 years	Head of Design Department	80min
TM.4	Tractor/heavy-duty vehicles manufacturer	13 years	Electrification Technologies Director	50min
TM.5	Tractor manufacturer	14 years	Senior Research Technologist	50min
TM.6	Tractor manufacturer	37 years	Innovation Director	75min
TM.7	Tractor manufacturer	17 years	Manager External Relations	60min
TM.8	Tractor manufacturer	20 years	R&D Group Director	60min
TM.9	Tractor manufacturer	20 years	Head of Global Sales	45min
TM.10	Tractor manufacturer	23 years	Engineering Manager	75min
TM.11	Tractor manufacturer	3 years	Member of Board of Directors	70min
TM.12	Tractor manufacturer	45 years	Member of Board of Directors	45min
TM.13	Tractor manufacturer	1 year	Lead Sustainability Innovation	60min
TM.14	Tractor manufacturer	25 years	Director Distribution Performance	90min
IA.1	Industry association	2 years	Secretary General	60min

[2] TM. 1 & 9, TM. 2 & 4, TM. 3 & 6, TM. 7 & 10 are representatives of the same company, respectively.

Appendix II – Interview guide

Introductory questions:

1) What is your professional background and what is your current position at XY?
2) For holding companies: Are all brands handled strategically in the parent company or more independently? Which brands are you responsible for?

Corporate strategy (incl. climate strategy):

3) What competencies/capabilities make your company stand out from other tractor manufacturers?
    a) What role does sustainability and the issue of climate change play in your corporate strategy? (Does your company have a sustainability strategy?)
    b) Are battery-electric tractors included in your strategic orientation?
    c) What would it take for e-tractors to be more strategically relevant?
4) What are the three main reasons why your company would be interested in manufacturing e-tractors?
5) What are the three main challenges why your company may not want to completely switch to /(not) manufacture e-tractors?
6) In your opinion, what would it take for e-tractors to become strategically more relevant for you?

Market development / diffusion of e-tractors:

7) How do you estimate the demand for e-tractors compared to traditional tractors?
8) Please describe all the possible applications you would see for today's e-tractors.
9) What developments would have to take place for the demand for e-tractors to increase?
10) How do you expect the e-tractor market to develop over the next 5-10 years?

Regulatory and political influences / barriers:

11) To what extent do regulatory and political requirements influence your decisions on the production of e-tractors?
12) Are there already regulatory or political measures that point in the direction of e-tractors? (e.g. subsidies for production or industry standards)
13) How do you think policy could help reduce barriers and facilitate the transition to etractors?
14) How does the phase-out of motor vehicles (cars) by 2035 in Europe affect the tractor industry?

Innovation processes:

15) Can you describe the innovation process from the idea to the market launch of a new tractor? How long does such a process take?
16) Next to e-tractors, there are other innovations that are being discussed in the market, such as hydrogen tractors / bio-methane - how do you deal with these alternatives in the company? How are you investing in these alternatives compared to battery-electric tractors? What about autonomous tractors/robots?

Organizational and technical processes:

17) If you are already developing battery electric tractors/prototypes, how does the manufacturing process differ from the traditional tractor. in the company? Are the processes and teams very separate or are there synergies?

18) What technological and organizational challenges do you see in the transition from traditional to e-tractors in the company?

Final questions:

19) Is there anything else that you would you like to add relevant to the topic that we have not discussed yet?
20) Who else from your company could I talk to for my study?