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Cost comparison of energy supply concepts for electrical agricultural machinery

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As in the transport sector, it is also necessary to investigate alternatives to fossil diesel fuel in the agricultural sector. In addition to technical feasibility, ecological viability and social acceptance, economic viability is ultimately decisive in determining whether an alternative energy source is competitive. Against this background, in this paper, a cost calculation model is described to analyze the competitiveness of different future technologies and applied on the case of future electrical energy supply concepts. The model is applied to compare a continuous energy supply system via a wide span system (WSS) with a discontinuous battery swapping system (BSS) on the example of tillage. The results show that on area sizes of more than 100 ha, a continuous energy supply for agricultural machinery with a WSS is competitive to a discontinuous BSS.

Keywords
Battery swapping system, electrification, energy supply, process simulation, wide span system

In the course of decarbonizing the mobility sector, it seems to be possible that in the long-term fossil diesel fuel for agricultural machinery needs to be substituted. Therefore, it is necessary to develop future agricultural machinery and energy supply concepts with alternative energy sources. Beside technical feasibility the economic competitiveness will determine which concept will prevail. Therefore, the aim of this paper is to present a cost calculation model which is applied to compare the economic performance of two future agricultural electrical energy supply concepts on the example of tillage operation: WSS (Wide Span System) versus BSS (Battery Swapping System). In this paper, the focus is deliberately not placed on a comparison of future and current machine concepts, as only a few reliable investments in electrically powered tractors have been published to date. Nevertheless, the paper concludes with an investment comparison based on existing data of electric-powered trucks and buses compared to diesel-powered trucks and buses.

First, the technical parameters of the WSS and the BSS are laid out. Afterwards, the main characteristics of the cost calculation model are explained. The results are presented for different initial situations regarding the existing infrastructure and field sizes for a 200-ha farm to consider possible synergy levels between energy supply and irrigation as well as economies of scale regarding the field size.

Electrical energy supply via wide span system and battery swapping system

Frerichs et al. have presented the continuous supply of electrical energy to agricultural machinery via a WSS based on linear and circular sprinklers, among others, in 2014 (Frerichs and Thielke 2014), 2022 (Frerichs and Buck 2022) and 2023 (Buck and Frerichs 2023). The WSS considered in this paper is shown in Figure 1 and is used for both energy supply and irrigation. In opposite to previous linear sprinkler systems, the boom is aligned parallel to the main working direction so that the

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machines can work underneath. For the energy supply, additional a side-mounted overhead line and a pantograph are required. The WSS follows orthogonal the tracks of the agricultural machines. For turning maneuvers, headland cultivation and road travel the agricultural machine runs battery-electric with one battery. For headland turns between two lanes, no additional time is required for docking and undocking to the WSS. As soon as contact with the WSS is interrupted at the end of a lane, the working machine is supplied with battery power until contact with the WSS in the new lane is automatically re-established via the pantograph.

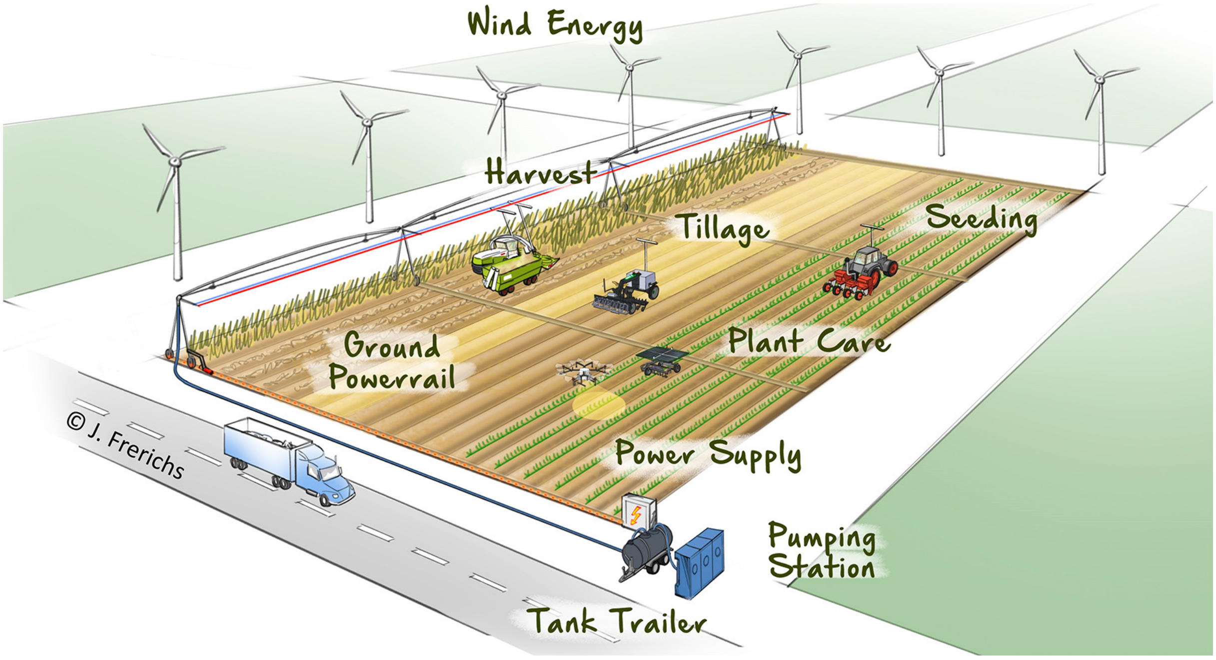

Figure 1: Continuous energy supply to agricultural machinery via a wide span system based on a linear sprinkler system

On one side of the field, power is transmitted via electrical contacts to the WSS. Due to the system architecture and size, the WSS is predestined for rectangular areas of over 50 ha, which can be found in Australia, Hungary or North America for example (Bayerische Landesanstalt für Landwirtschaft 2008). As linear irrigation systems of this architecture are also used in hilly terrain with gradients of up to six percent, it is assumed that WSS are also suitable for such terrain (Smith and North 2009). Of course, the natural conditions such as hills, knolls, trees and other obstacles must be considered when implementing the WSS. However, as this paper is an initial model analysis, such obstacles are not considered for the time being.

The BSS considered here adopts the idea of John Deere to carry the replaceable batteries in the front hydraulics instead of a front weight (Pickel 2020). The assumed battery weights 1,800 kg and has a gravimetric energy density of 200 Wh/kg, with a possible depth of discharge of 90 percent; cf. Mercedes-Benz, Vision EQXX (Mercedes-Benz AG 2020). If additional support structures for mounting in the front hydraulics are considered, a battery has a capacity of 260 kWh. The batteries are charged at the farmyard so that no additional grid connection is required in the field. In favor of lower investments as well as less battery aging, a low charging power of 22 kW is assumed for the charging points. The batteries have to be charged before the field work, transported to the field and recharged during the field operation. The required battery number for a planned exchange interval depends on the charging and possible field working time of the assumed battery. In this paper, the number of required batteries is set for a farm-to-field battery exchange interval which allows an independent field working time of six hours. This corresponds to a number of 14 batteries. It is assumed that a second worker with an additional transport vehicle is on duty for two hours for every six hours of field working time to replace the empty batteries with charged ones. The additional battery changing times of five to six minutes per battery change (Engström et al. 2023) are not taken into account in this paper.

Procedure and assumptions of the cost calculation model

The procedure to determine the operating cost of WSS and BSS is divided into four steps. Operating costs include fixed cost for machinery and field infrastructure (depreciation, interest) and variable costs (repairs, power, labor).First, the agricultural process chain is simulated; second, general assumptions for the cost calculation model are presented; third, comparative scenarios are defined and fourth the calculation model of operating cost is described.

Simulation of agricultural process chain

The energy demand and the working times of the agricultural process steps are determined with a process simulation further developed on the basis of Trösken et al. (2020). This paper aims to demonstrate the feasibility of WSS and BSS based on a very energy-intensive agricultural process step. Since the harvesting processes require comparatively exorbitantly more programming effort due to the logistics chains in the process simulation, the tillage operation is chosen as an energy-intensive process step in this paper as an example. From an energy perspective, it can be assumed that the less energy-intensive process steps (e. g. sowing, plant protection, etc.) are then also realistic. For a final evaluation, the simulation model will be further developed in the future to compare entire farms.

The tillage operation is conducted on light to medium soil with a 233-kW tractor and a 4 m wide cultivator. The working depth is 25 cm. For the entire conversion chain from the grid connection point to the tractor wheel, an efficiency of 0.77 is assumed for operation via the WSS and 0.73 for battery-electric operation (acatech 2018). Unlike agricultural machinery (tractors, combine harvesters, etc.), the investments required for WSS and BSS are infrastructure objects, some of which remain permanently on the field. Therefore, it is not the size of the farm but the size of the field that is decisive for economies of scale. Against this background, field sizes of 50, 100 and 200 ha have been considered. It is assumed that even for the 50 ha fields, land consolidation would be necessary in most regions of Germany. The considered field shapes are rectangular; the width-to-length ratio is one to two.

General assumptions for the cost calculation model

The assumptions and references in Table 1 are used to for the cost calculation model. The WSS requires a grid connection point at the field, which is dimensioned to 750 kW, so that even the very power-intensive harvesting processes can be implemented. It is assumed that the energy supply infrastructure is implemented within a land consolidation process for a larger area and the grid connection point is centered in four fields of the same size and shapes. For the BSS the batteries are charged at the farmyard.

Table 1: General assumptions and references for the cost calculation model

Component	Technical data	Capital cost without tax in €	Reference
Transformer station	750 kW	100,000	Böhm et al. 2022
Power cable to field	1 km	100,000 per km	Böhm et al. 2022
Water supply	Field size dependent	100,000–250,000	KTBL 2013
Boom	Field size dependent	260,000–500,000	KTBL 2013
Overhead line	Field size dependent	50 per m	Metallstore 2023
Pantograph	-	15,000	Kunith 2017
Li-ion battery	200 Wh/kg	450 per kWh	Mauler et al. 2021
Charging point	22 kW	3,000	Helvetica Versicherungen 2023

3) Definition of comparative scenarios

Since the boom can be used for both power and water supply, the capital cost of the boom can be divided between the power and water supply. Two scenarios are used to allocate the capital cost:

A) New construction of energy supply & no irrigation: The boom is used entirely for energy supply.

B) New construction of boom, water and energy supply: The capital costs of the boom are allocated to the irrigation and energy supply depending on the use time for both applications.

4) Calculation model of operating cost

The cost calculation model (Figure 2) supplements the further developed agricultural process simulation of the Institute of Mobile Machines and Commercial Vehicles (IMN) based on Trösken et al. (2020) and the cost calculation scheme of the KTBL (2016). The energy demands and partial times (working, turning, travel, etc.) generated via the agricultural process simulation and the previously described assumptions on the required investments are supplemented in the cost calculation model. The operating cost are allocated to the various components on the basis of their respective share of the total operating time. All costs are stated in Euro before tax. As no reliable investments in electric tractors can yet be determined, this paper deliberately compares two electrical energy supply concepts, the WSS and the BSS, in order to be able to exclude the investments in electric tractors. Nevertheless, the results chapter classifies the costs of electrically powered machine concepts in comparison to diesel-powered machine concepts. The water supply and the power grid connection are depreciated over 30 years (KTBL 2013, Böhm et al. 2022). The depreciation period for all other components is 12 years. The salvage values amount to 20 percent of the initial investment. An electricity price of € 0.23 per kWh is assumed. The wage rate for permanent employees is € 24 per h (KTBL 2024a).

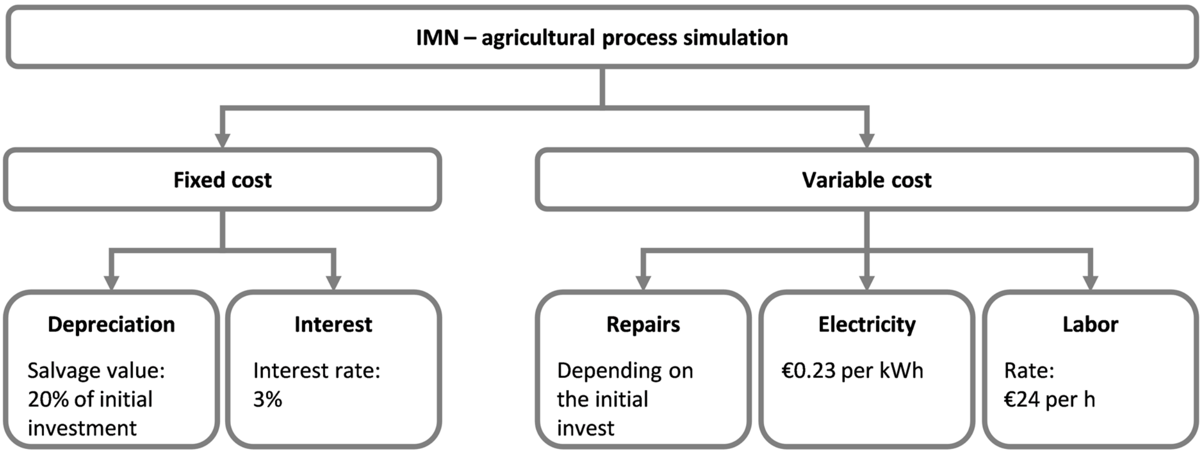

Figure 2: Cost calculation model (KTBL 2016, Trösken et al. 2020)

As already described, the WSS and the BSS are compared in this paper using tillage as an example. It is therefore necessary to reduce the cost incurred to the share for tillage. For this purpose, the proportion of working time for tillage in all process steps was determined is 18 percent over the four-year crop rotation (Figure 3) (KTBL 2024b). The irrigation crop rotation under consideration consists of spring barley, potatoes, winter wheat and sugar beets. The share of the capital costs of WSS and BSS is therefore reduced to the tillage time of 18 percent.

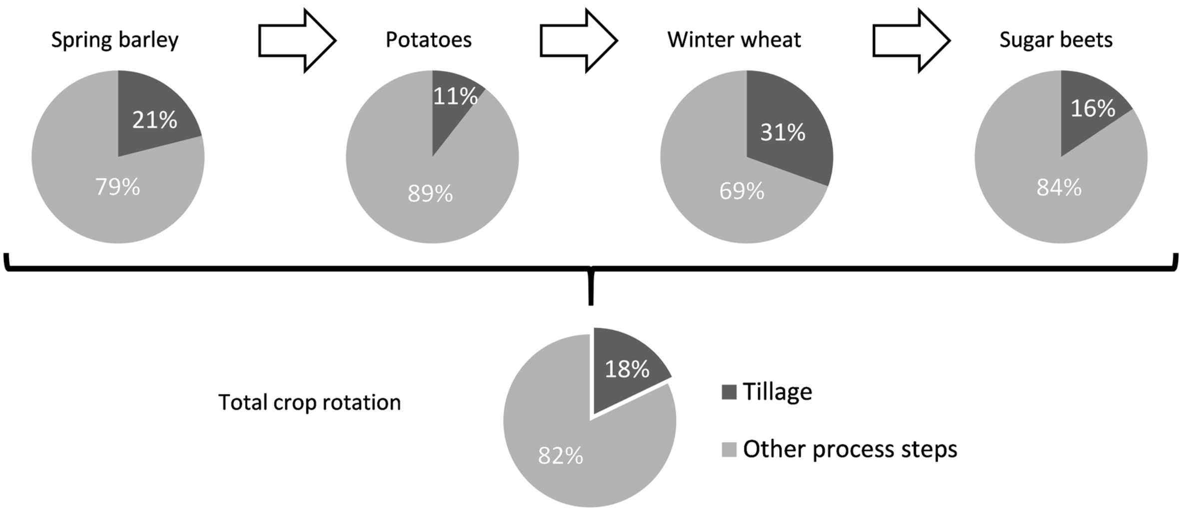

Figure 3: Time share of tillage compared to all other process steps over the crop rotation

Results on the competitiveness of energy supply: wide span system versus battery swapping system

First Figure 4 shows the operating cost of the compared baseline scenarios. Without the possibility to irrigate, all fixed costs must be carried by the energy supply system (scenario A: new construction and no irrigation). In scenario A economies of scale lead to a reduction of approx. € 490 per ha (60 percent) for the energy supply between the 50-ha and the 200-ha field size. If the energy supply is combined with irrigation (scenario B: new construction) the operating cost for the energy supply can be reduced by around € 325 per ha or 63 percent between the 50-ha and the 200-ha field size.

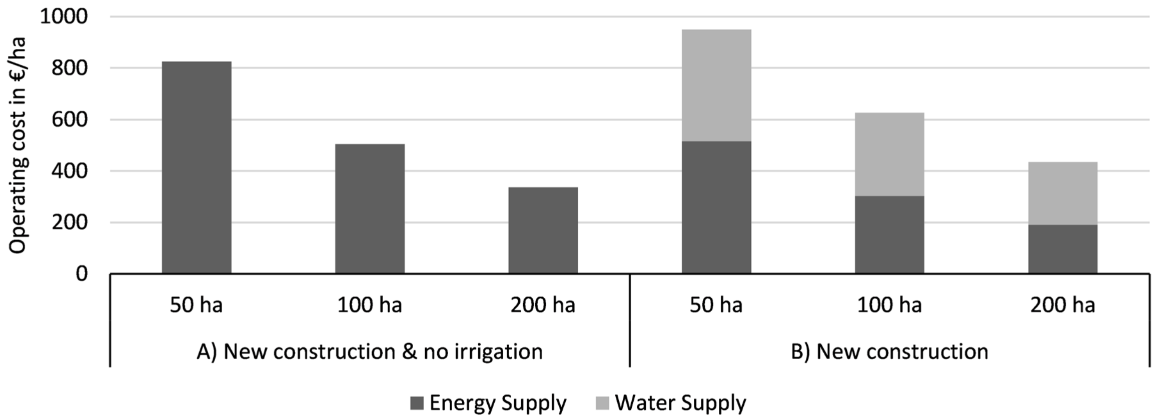

Figure 4: Operating cost of a wide span system divided in energy and water supply in different scenarios

It can be assumed that irrigation is only financially viable for high-value crops (potatoes, special crops, etc.) and that it cannot be implemented on all areas due to restrictions on groundwater extraction rights (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2019; Singh and Su 2022). Therefore, in the further analysis no irrigation is carried out and the WSS is used exclusively to supply electricity (scenario A: new construction & no irrigation). Figure 5 compares the operating cost excluding machine cost (tractor, implement) of an energy supply via a WSS with an energy supply via batteries (14 batteries, five charging points, one battery transport vehicle with a second worker) disaggregated in electricity, depreciation, interest, repairs and labor. It can be seen that the electricity costs for tillage do not vary much over the different plot sizes and amount to about € 10 per ha. This is not surprising, as the area-specific electricity costs depend on the energy required to cultivate the land, which is almost identical in the concepts. Depreciation and interest costs vary depending on the investment and repair costs are relatively low. Labor costs are only considered in the case of energy supply via the BSS, since this concept requires additional labor for charging and transporting the batteries. However, the additional labor costs are almost neglectable, which gives room for economic improvements if the time of farm-field intervals are shortened to reduce the number of required batteries. It is noticeable that the total area-specific operating cost of the WSS decrease with increasing individual field size, but the area-specific operating cost of the BSS are always identical. There are three reasons for this. Firstly, in all cases an area of 200 ha in total is cultivated. Secondly, a WSS is permanently installed on a field and can therefore only be depreciated on this field; the larger this field is, the cheaper a WSS is per area. Thirdly, the number of batteries required depends on the charging and possible field working time of the batteries assumed and not on the total area worked. Since an area of 200 ha is always worked in this paper and the number of batteries is designed for a field working time of six hours, the batteries are always 100% utilized. One battery is in use in the working machine and the other batteries are empty or full at the edge of the field, on the transport vehicle or at the charging station.

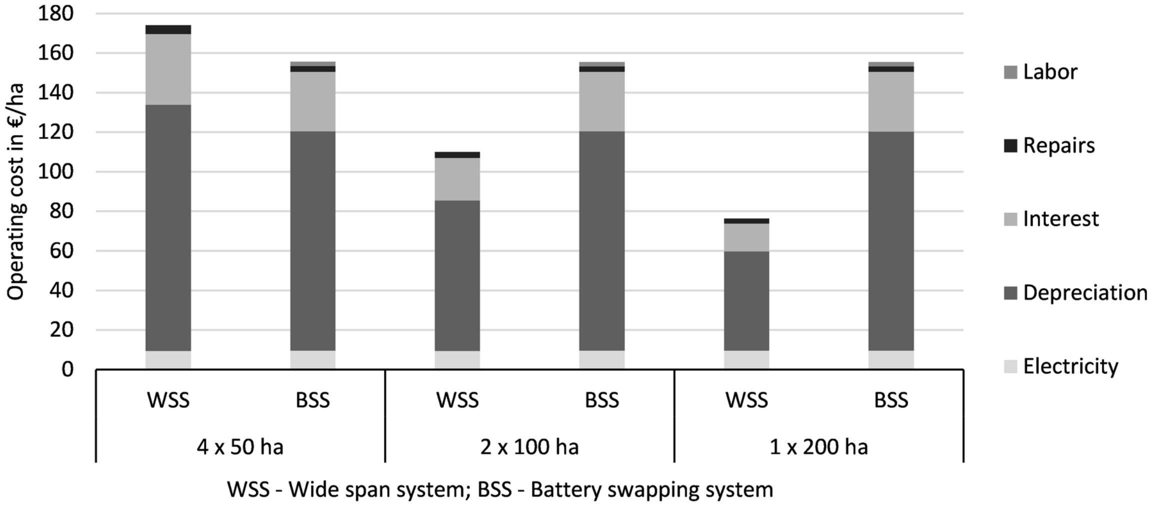

Figure 5: Operating cost excluding machine cost (tractor, implement) for wide span system and battery swapping system based on tillage

Since the WSS is permanently installed on the field it is crucial for the capital cost that the capital-intensive grid connection can be amortized over a large area. It is obvious that above a certain area size of about 100 ha in this case, the operating cost of the WSS is less than the operating cost of the BSS of about € 155 per ha.

A major difference between the continuous energy supply via a WSS and a battery electric energy supply is that the WSS also enables the harvesting processes on the fields to be carried out. The batteries in this paper are designed to provide the energy needed for tillage. Performing the harvesting operations battery-electrically would result in much shorter usage times per battery for identical battery use, requiring a much larger number of batteries (30 to 40) that would not be needed for the less energy-intensive operations. A number of 30 to 40 batteries would increase the financial investment in batteries by € 2 to € 3 million, not including the necessary addition of charging points.

Finally, the operating costs of WSS and BSS will be compared with the operating costs of the status quo of field cultivation with diesel-powered agricultural machinery. According to KTBL (2024b), the machine costs (depreciation, interest, repairs, operating materials, other costs) for the tillage operation assumed in this paper amount to approximately € 36 per ha. This clearly shows that even the operating costs of the most favorable scenario in figure 5 (WSS on 200 ha field) are still more than twice as high as the current operating costs with diesel-powered agricultural machinery.

As already described, this paper deliberately compares two electrical energy supply concepts. The reason for this is that the insufficiently documented investments in electric tractors do not have to be considered. As there are a large number of published investments in electrically powered trucks and buses, an attempt will be made to forecast the necessary investments for electric tractors on the basis of trucks and buses. The investment ratio of electrically powered trucks and buses to diesel-powered trucks and buses is depending on the use case approximately 1.7 to 4:1 (Seeliger et al. 2016, Kunith 2017, Kühnel et al. 2018). The underlying investments in each case do not include charging infrastructure or additional exchangeable batteries. From this, it can be concluded that in the long term, investments in electrically powered tractors will be approximately around two to four times higher than those in diesel-powered tractors (without charging infrastructure and exchangeable batteries). Remmele et al. (2020) and Eckel et al. (2023) confirm this impression, as they are of the opinion that the investment requirements of electrically powered tractors will be “high” compared to diesel-powered tractors.

Under the current framework conditions, an electrical energy supply via both the WSS and batteries is not cost-competitive with diesel. If only the costs for electricity and diesel of tillage are considered, these are more favorable for electric tillage than for tillage with diesel. Approaches for further reducing the operating cost in the future include reducing the electricity costs from the current € 0.23 per kWh to approx. € 0.06 per kWh, assuming that the farm produces the electricity itself, e. g. via photovoltaic systems (Remmele et al. 2020, Böhm et al. 2022). However, the main obstacle is the required infrastructure, which leads to significantly higher fixed costs. Options for reducing these costs include large-scale implementations of grid connections in rural areas and combination with irrigation. Additionally, the required components (transformer stations, cables, batteries, charging points) will become cheaper in the long term with the ongoing technical progress by the expansion of renewable energies (Hillebrand et al. 2006, Mauler et al. 2021, Zhou et al. 2022). Electrification of the external agricultural sector therefore still appears ambitious, but not impossible.

Conclusions

In this publication, the operating cost of electrical continuous energy supply via a wide span system (WSS) based on a linear sprinkler system are investigated in comparison with discontinuous energy supply via a battery swapping system (BSS), on the example of tillage. In scenario B the boom of the WSS is used for energy supply and irrigation and in scenario A for energy supply only. For the WSS, the operating cost of energy supply on a 200-ha field can thus be reduced by about 43 percent from about € 340 per ha (scenario A) to about € 190 per ha (scenario B). In the subsequent comparison of WSS and BSS, it is clear that the operating cost for the WSS decrease with increasing field size and become competitive at field sizes around 100 ha. In contrast, the BSS is competitive in smaller areas. In the use case considered in this paper, electrification with renewables is not yet competitive with diesel, but has the potential for cost reduction if renewables are expanded and farmland is connected to the grid. There is also great cost-cutting potential in the reduction of battery prices. Further investigations should concentrate on the development of the cost calculation model in order to be able to represent more realistic field conditions and a cross-farm use of the energy supply infrastructure. In addition, the cost comparison in further research should map the entire agricultural process chain over a cultivation year or an entire crop rotation, as the exclusive consideration of individual work processes (such as tillage in this case) is not very meaningful in terms of the profitability of an energy supply concept.

It has been shown that the combination of process simulations and cost analyses is a suitable instrument for estimating the competitiveness of future systems and that the economic analysis can be used to identify levers for future optimization potential.

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