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Continuous power supply of electrical agricultural machinery via wide span systems

Lennart Buck, Ludger Frerichs

The move away from fossil diesel fuel, the increasing demand for irrigation, and changes in the regulations on the use of fertilizers and pesticides make it necessary or offer the opportunity to systemically transform established agricultural processes. In this article, the wide span system is used to provide an infrastructure for continuous electric agricultural machinery, for irrigation and for the application of fertilizers and pesticides. A process simulation is used to calculate the additional energy requirements of the system. This is then compared with the energy demand of other energy supply and drive concepts based on renewable energy sources. When the system is aligned parallel to the main working direction of the agricultural machine, the additional electrical energy demand is less than 0.5 kWh/ha. An economic implementation of the wide span system as an agricultural production system remains to be investigated.

Keywords
Electrification, power supply, linear irrigation, process simulation, wide span system

Due to the low energy density of batteries (Stöhr et al. 2015), which is also to be expected in the future compared to diesel fuel, the substitution of internal combustion engine powertrains by electric powertrains is not to be expected for all agricultural machinery, at least in the short to medium term. For example, in some operations, temporary autonomy and process-related high energy expenditure combined with weight and dimensional limitations require high-density energy sources. However, in order to be able to operate more energy-intensive processes with electrical energy, alternative energy supply concepts are therefore being discussed, such as battery exchange concepts, associations of smaller robot units (Blender et al. 2016) or also continuous energy supply concepts via cables (Cullmann et al. 2018). In addition, fuel cell solutions are being investigated (Breu and Reuter 2022).

Against the background of ongoing climate change, it can be assumed that, in addition to the need for decarbonization, the need for irrigation of agricultural land will continue to increase. The most irrigation-intensive regions in the world are Asia with 73% and the Americas with 16% of the actually irrigated agricultural land (Siebert et al. 2013). In the global view, semi-stationary large-scale irrigation systems such as circular irrigation machines and linear irrigation machines play a significantly greater role than in Europe due to the agricultural field structures. For example, in the USA in 2018, 57% of the total irrigated arable land was irrigated by sprinkler systems (circular, linear irrigation machines, etc.) (United States Department Of Agriculture 2019).

The TU Braunschweig and the HBK Braunschweig, with the support of the Landwirtschaftskammer Niedersachsen, investigated possible changes to prepare agriculture for future requirements

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(decarbonization, irrigation, etc.) in the "Energy-4-Agri" research project. Among other content, various electrically powered machine concepts such as Unmanned Aerial Vehicles (UAVs), robot units, gantries, standard tractors and harvesters, but also energy distribution concepts such as catenary concepts, cables and battery exchange systems were investigated conceptually and simulatively (Frerichs 2022).

Via an infrastructure system - called "wide span system" - electrical energy could be provided as well as liquid (water, fertilizer and pesticide) could be distributed. This article presents the idea of adding a catenary to linear irrigation systems so that, on the one hand, agricultural machinery can be supplied with electrical power and, on the other hand, fertilizer, pesticide and water can be applied via the piping system. Catenary concepts for heavy trucks and buses exist (Jöhrens et al. 2022). Frerichs et al. have already presented a continuous supply of electrical energy to agricultural machinery via a catenary concept based on linear and circular sprinklers in 2014 and 2022 (Frerichs and Thielke 2014; Frerichs and Buck 2022). Further advantages of the implementation of a so-called wide span system are the substitution of applications with the fertilizer spreader and the crop protection sprayer and thus savings in energy and emissions as well as prevention of soil compaction.

The aim of this article is to specify a catenary concept based on a wide span system and to present its energy requirements. This is followed by a comparison of the energy requirements of an agricultural process chain, which is continuously supplied with electrical energy via a wide span system, with the energy requirements of process chains, which are operated via other alternative electrical drive concepts.

This article is organized as follows: First, the basics of wide span systems for the continuous energy supply of electrical agricultural machinery are described and the two alignment variants of the system across and parallel to the main working direction are explained. Then the methodology used is presented by describing the agricultural process simulation, outlining the calculation of the energy requirement of wide span systems and describing the simulation parameters. Finally, the simulation results are presented and discussed and conclusions are drawn.

Wide span system for continuous power supply of electrical agricultural machinery

Linear irrigation machines belong to the group of semi-stationary irrigation systems, as they are bound to a fixed installation site, but move during operation (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2019). Just like gantries, linear irrigation systems are also classified as wide span systems. Gantries and linear sprinkler systems are designed as implement carriers in gantry construction and have a large working width relative to tractor-implement combinations. In contrast to gantries, which are designed as a heavy vehicle concept for the entire agricultural process chains, including harvest and tillage, linear irrigation systems are built much lighter as piping systems and are intended exclusively for fertilization, crop protection, irrigation and (if necessary) energy supply. Due to the system size, linear irrigation systems are preferably suitable for straight, rectangular areas of more than 50 ha in regions with appropriate structures, such as North America, Australia, and Hungary (Bayrische Landesanstalt für Landwirtschaft 2008), and are built with a total length of 400 to more than 1,200 m (Smith et al. 2014). Solutions for smaller, more complex field contours common in Central Europe also exist (Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. 2014).

As explained at the outset, today's agricultural practices need to be systemically adapted to changing environmental conditions in many ways. Changes in regulations on the use of pesticides and fertilizers, changes in cultivation methods (less tillage, less soil compaction), but also an increasing need for irrigation are, in addition to the move away from fossil fuels, opportunities that must be exploited in order to equip agriculture for future challenges. It therefore seems sensible to develop future systems in such a way that they address as many of the aforementioned challenges as possible. Wide span systems could be used for both fertilizer and pesticide application, for irrigation, as well as for the provision of electrical energy with an additionally attached catenary and thus achieve synergy effects.

Experts from agriculture, industry and science are still at odds as to what future agricultural machine concepts will look like. In addition to conventional mobile machines, smaller robots and UAVs are also discussed, which can be supplied with energy via battery exchange concepts, rapid charging stations or photovoltaics. Larger mobile working machines can also be continuously supplied with electrical energy on demand in the field via a wide span system. To be able to bridge the farm-to-field distance, the agricultural machines are equipped with a battery that is dimensioned in such a way that it can be driven a certain distance on the road battery-electrically. Frerichs suggested, because of the increasing diversity, the term "prime mover" that can flexibly pick up and drive implements, i.e., tractors as well as system vehicles, mobile drive systems, gantries, robots, and even UAVs (Frerichs and Buck 2022). This is adopted here.

A wide span system consists of self-supporting spans that are supported by towers. The self-supporting spans form a segment together with the towers. A tower has two wheels as standard. The first tower at the edge of the field is called the main tower and is larger in size to accommodate other equipment, such as the drive system or water pump. Previous systems are powered by a diesel generator installed on the main tower, which generates electricity for the electric motors. Control is via Global Navigation Satellite System, induction or mechanical tactile levers. The segments function as independent units and are connected to the adjoining segment by a flexible coupling so that even cropped terrain can be traversed (Smith and North 2009). In wide span systems, the application units must be flexibly adjustable in height so that drift and evaporation during the application of water, fertilizer and crop protection products is minimized by a small target area distance. In addition, it must be possible to realize a minimum clearance height for corresponding agricultural machinery. Since the infrastructure for supplying the wide span system with water and electricity, such as water-bearing ditches or pipelines and power-carrying cables, is required, the actual field area cannot be fully utilized; an average of 95% is assumed here. In principle, linear irrigation systems have so far been used exclusively on fields with slopes of up to 6% (Smith et al. 2014).

For the calculation of the energy demand, the orientation of the wide span system is relevant. Such infrastructure systems can be installed in the field across or parallel to the main working direction. The following subchapters describe the two orientations.

Alignment across to the main working direction

Figure 1 presents a vision of future agricultural machinery. The left part of the figure shows the generation of regenerative energy via agri-photovoltaic, biogas and wind power plants and the right part shows the use of regeneratively generated energy of future electrified agricultural machinery. In addition, the alignment of the wide span system is shown across to the main working direction of the agricultural machine. In this orientation, the system has the same width as the field and is used in the Controlled Traffic Farming cultivation method, since the same tracks are always used and also compacted. Therefore, for the main field, the rolling resistance coefficient for driving over a compacted track is assumed to be f_R = 0.05 (Reich 2018). In order to be able to continuously supply the agricultural machine with electrical energy, the wide span system must travel at the working speed of the agricultural machine. If the application technology and power were not adapted to the system, then the towers would have to be designed in such a way that the agricultural process can be implemented at the highest travel speed (e.g. fertilizer spreading at 4.4 m/s) (American Society of Agricultural Engineers 1999).

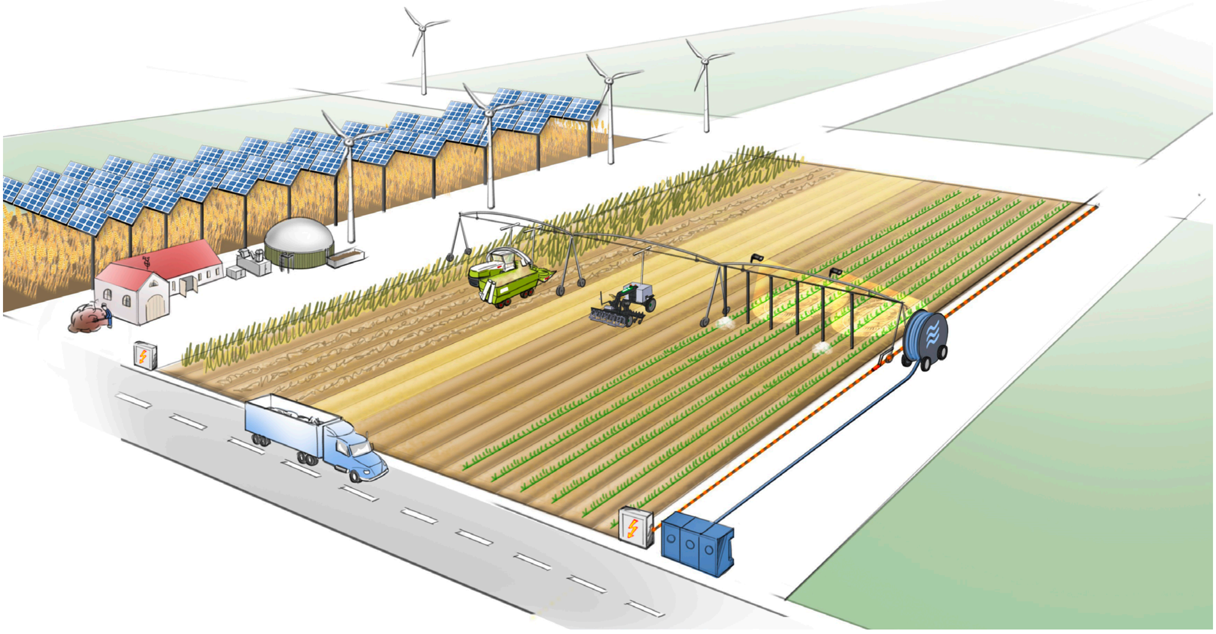


Figure 1: Continuous energy supply via a wide span system across to the main working direction

The tracks of the headland are rotated by 90° to those of the main field. In this respect the agricultural machines on the headland in this example run parallel to the wide span system, which no longer has to travel continuously with the agricultural machine. An alternative strategy for working the headland would be for the agricultural machine to drive battery-electrically. The battery would have to be sized accordingly.

Alignment parallel to the main working direction

Figure 2 shows representative examples of both smaller robots and UAVs which can be powered by battery swapping concepts, rapid charging stations or photovoltaics. However, larger self-propelled machines and prime movers are also shown with equipment that can be continuously supplied with electrical energy on demand in the field via a wide span system. In addition to the machine concepts, the second alignment variant of the wide span system parallel to the main working direction of the agricultural machine is shown. The wide span system has the same length as the field. Due to the towers required for support, the agricultural machine cannot drive directly under the span while working the main field, but requires a laterally designed catenary and, if necessary, a swing-out pantograph. In the main field, the wheels of the infrastructure system generate new tracks in the uncultivated area of the field at right angles to the main working direction, so that the calculation is based on a rolling resistance coefficient for cultivated field of $f_R = 0.12$. In front of the wheels, rutting shields or similar can be fitted to eliminate major ground unevenness.

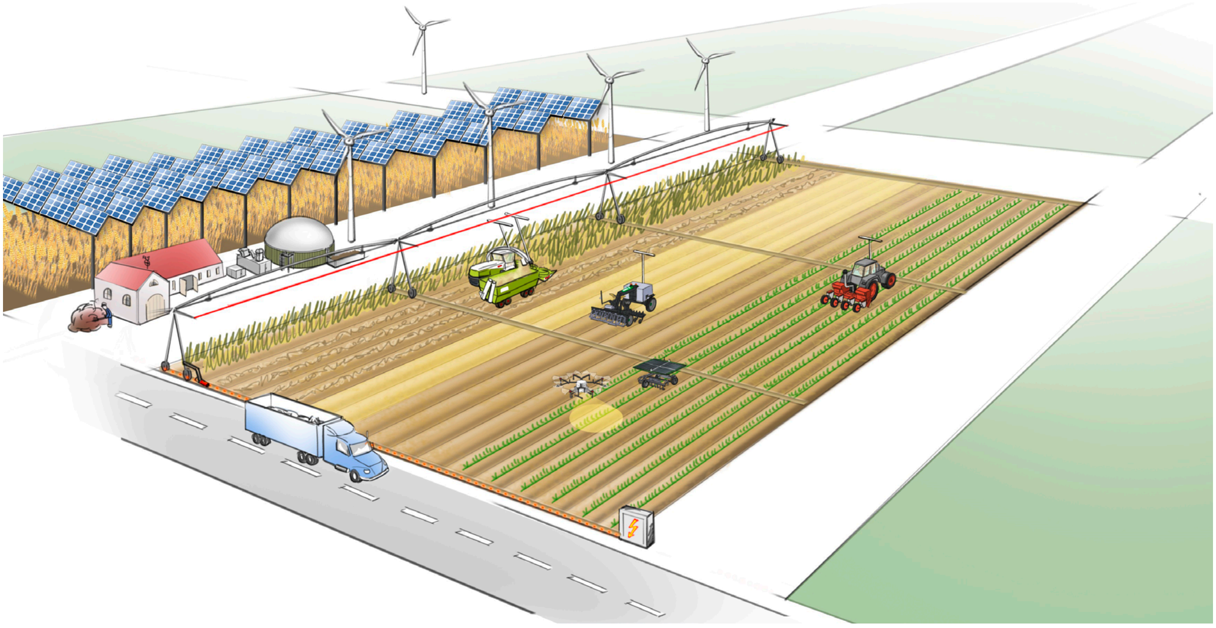


Figure 2: Continuous energy supply via a wide span system parallel to the main working direction

Methodology

The calculation of the additional energy requirement of wide span systems for the continuous energy supply of agricultural machinery is carried out via a process simulation. The energy demand of wide span systems is calculated via the driving resistance equation, considering the input parameters of the model field. In the following subchapters, the underlying methodology is explained.

Agricultural process simulation

At the Institute of Mobile Machines and Commercial Vehicles (IMN), Hanke et al. (2018) and Trösken et al. (2020) developed an agent-based process simulation model for the simulation of fuel consumption in agricultural technology (EKo-Tech). Figure 3 shows the interrelationships of this process simulation. Via a self-programmed Graphical User Interface, the parameters of agricultural model farms such as fields, machine fleets, farmyards and process chains within crop rotations are entered into the process simulation. The simulation is carried out by the two independent modules "machine model" and "process model".

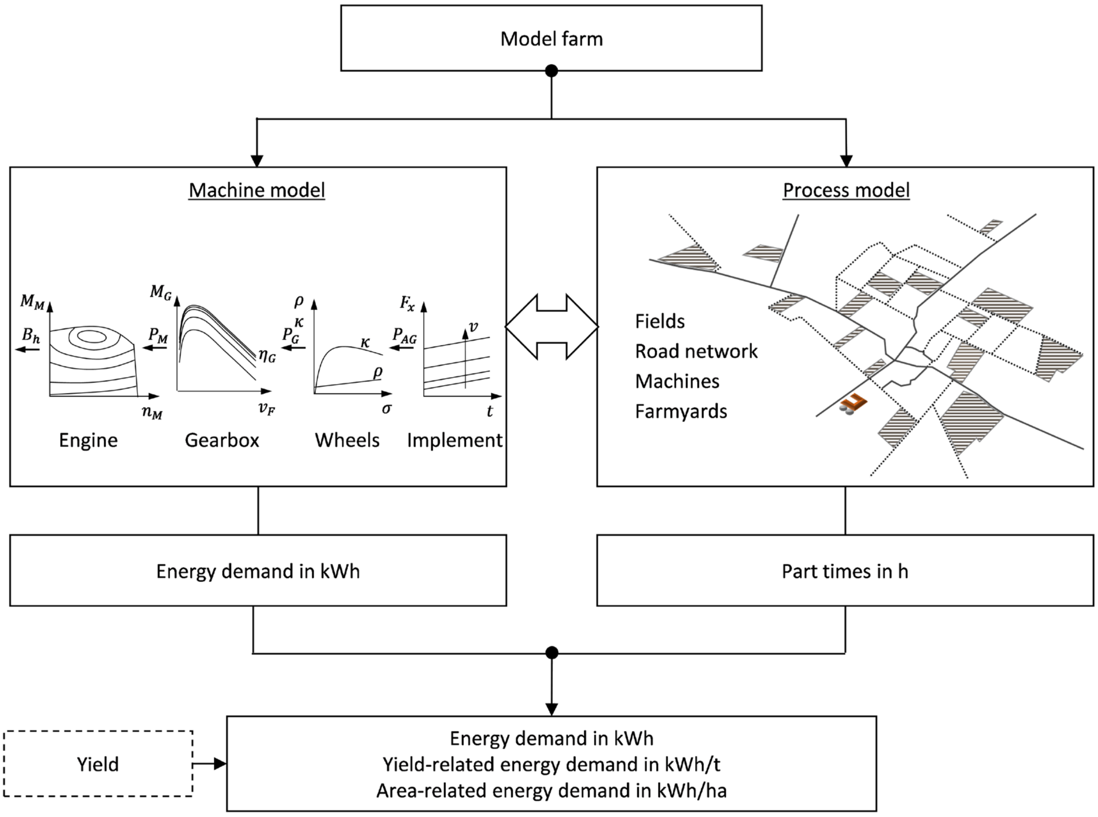


Figure 3: Agricultural process simulation of the TU Braunschweig based on Trösken et al. (2020)

The machine model can be used to calculate the energy required for agricultural process steps. For conventional agricultural machinery based on fossil diesel fuel, the calculation is performed for different combinations of engines, gearboxes, wheels and implements. The process model incorporates the parameters of farmyards, fields, roads and other technical machine data, such as power, mass, tank and container capacity, working width, overloading capacity and travel speed. The result of the process model are partial times according to the time breakdown scheme of the Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL), such as working time, turning time and travel time.

Depending on the farm structure, the process step and the machine concept, the power requirement during these partial times result in different performance time series for field cultivation. In addition, other parameters such as the yield are included in the simulation, so that finally the total energy requirement, the energy requirement per area and the energy requirement per ton of crop produced. The calculation of the costs of agricultural process chains is also possible via the simulation.

A further development of the simulation model makes it possible to simulate the energy requirements of future agricultural machinery concepts, such as UAVs, robot units, gantries, and current tractors and harvesters based on regeneratively generated electrical energy (Frerichs 2022). The machine model is supplemented by mathematical calculations of the energy requirements for the alternative machine concepts. Using the calorific value of diesel (9.8 kWh/l) and the static efficiencies of diesel engine (η = 0.32) and electric motor (η = 0.85), the conversion into electrical energy demand is performed. Energy supply concepts, such as the wide span system described in this paper, are also simulated.

Calculation of the energy demand of wide span systems

The calculation of the energy requirement of both alignment variants of the wide span system is carried out based on the driving resistance equation from vehicle dynamics. The total driving resistance F_T is composed of the rolling resistance F_R, the air resistance F_A, the gradient resistance F_G, the acceleration resistance F_I and any additional pulling force F_{pull} (Reich 2018). Since the wide span system moves at relatively low speeds (< 5 m/s) and there is no additional pulling force requirement – the agricultural machines are equipped with their own drives –, F_A, F_I, and F_{pull} are neglected. F_G can also be neglected, since for comparison purposes with the diesel-driven process chain, the state of motion in the plane is considered. The driving resistance thus results exclusively from the rolling resistance F_R. The other equations for calculating the energy requirement are derived below. The number of segments $n_{segment}$ can be calculated in the orientation across to the main working direction from the field width W_{field} and in the orientation parallel to the main working direction from the field length $L_{fieldand}$ the distance between the towers. In Europe, due to the compatibility with the usual implement working widths of the implements, a distance between the towers of 36 m, 42 m, 48 m, 54 m or 60 m is common (Smith and North 2009). The calculation in the present article is made using a 54 m spacing of the towers. A segment is supported by a tower on each side.
The total number of turning operations $n_{turn,total}$ of a field can be calculated from the number of tracks of the main field (MF) $n_{track,MF}$ and the number of tracks of the headland (HL) $n_{track,HL}$. In the logic of the process simulation, the first field travel of the agricultural machine after pre-fitting on the field entry to the first track and the last field travel after completion of the last track to the field entry in order to re-fit there are also referred to as "turning time". For this reason, one is added to calculate the total number of turns $n_{turn,total}$ of a field.
The rolling resistance F_R of a single, middle tower is composed of the rolling resistance coefficient f_R of the corresponding ground condition, the total mass m_{total} and the acceleration due to gravity g with 9.81 m/s^2. The total mass m_{total} consists of (equation 1):

$$m_{total} = m_{pipeline} + m_{tower} + m_{catenary} + m_{liquid} \qquad \text{(Eq. 1)}$$

The two outer towers each support only half the weight of a self-supporting pipeline, so to calculate the driving resistance of the entire wide span system F_T, a loaded tower is subtracted in total and an unloaded tower is added in its place. With a distance between the towers of 54 m, the mass of a single pipeline $m_{pipeline}$ and the mass of the towers m_{tower} result in a mass of 1,730 kg loaded on one tower (Pierce Corporation 2004). In addition, the mass of the catenary $m_{catenary}$ must be considered, which is assumed to be 500 kg per segment. The mass of the catenary $m_{catenary}$ is composed of the mass of the two contact wires (positive and negative pole) as well as the mass of additionally required support structures for the contact wires. The mass of a contact wire can be assumed to be approximately one kg/m (Rail Power Systems 2022). From the turning time added over the processing of the entire field, the turning time per track t_{turn} can be calculated via the number of tracks of the entire field $n_{track,total}$.

From this point on, it is necessary to calculate the energy demand for the two orientations of the wide span system, across and parallel to the main working direction, separately.

Calculation of the energy demand of wide span systems across to the main working direction

The power requirement for continuously moving the wide span system along in the main field $P_{across,MF}$ is calculated from the travel resistance of the entire system F_T, the field working speed v_{work}, and the overall efficiency of the wide span system (WSS) η_{WSS} (equation 2). For the total efficiency η_{WSS}, the efficiency from the power connection of the tower via an electric motor and the drive train to the wheel is assumed to be 0.77 (ACATECH 2018).

$$P_{across,\mathrm{MF}} = \frac{F_T \times v_{work}}{\eta_{WSS}} \quad \text{(Eq. 2)}$$

Subsequently, the energy demand for processing the main field $E_{across,MF}$ can be calculated from the power requirement $P_{across,MF}$, the length of a single track in the main field L_{track}, the number of tracks in the main field, and the field working speed v_{work} (equation 3).

$$E_{across,\mathrm{MF}} = P_{across,\mathrm{MF}} \times \frac{L_{track} \times n_{track,\mathrm{MF}}}{v_{work}} \quad \text{(Eq. 3)}$$

The length of the track in the main field L_{track} results from the length of the field L_{field}, the working width of the agricultural implement W_{work} as well as the number of tracks in the headland $n_{track,HL}$. For working the headland, the wide span system is used according to the alignment parallel to the working direction. The infrastructure system no longer travels continuously with the agricultural machine, but is aligned parallel to the respective track in the headland and shifts by one track at a time during the turning period. The power required to move the wide span system on the headland $P_{across,HL}$ is made up of the driving resistance of the entire system F_T, the shifting velocity v_{shift} and the total efficiency of the wide span system η_{WSS} (equation 4). The shifting velocity v_{shift} of the wide span system can be calculated from the working width W_{work} and the turning time t_{turn}:

$$P_{across,\mathrm{HL}} = \frac{F_T \times v_{shift}}{\eta_{WSS}} \quad \text{(Eq. 4)}$$

The energy requirement $E_{across,HL}$ is then obtained via equation 5:

$$E_{across,\mathrm{HL}} = P_{across,\mathrm{HL}} \times t_{turn,\mathrm{HL}} \quad \text{(Eq. 5)}$$

The energy requirements for the main field $E_{across,MF}$ and the headland $E_{across,HL}$ are used to calculate the total energy demand for the field E_{field} and the energy demand per ha $E_{per\ ha}$.

Calculation of the energy demand of wide span systems parallel to the main working direction

When the wide span system is aligned parallel to the main working direction the required power demand for the shifting $P_{parallel,MF}$ results from the driving resistance of the whole system F_T, the shifting velocity v_{shift} and the total efficiency. From the power demand for the shifting of the wide span system in the main field $P_{parallel,MF}$ and the turning time in the main field $t_{turn,MF}$ the total energy demand for the shifting in the main field can be calculated as follows $E_{parallel,MF}$:

$$E_{parallel,\mathrm{MF}} = P_{parallel,\mathrm{MF}} \times t_{turn,\mathrm{MF}} \quad \text{(Eq. 6)}$$

At the headland, a segment of the wide span system is uncoupled, which then travels at the working speed of the agricultural machine, thus ensuring a continuous power supply even at the headland. The power requirement of the wide span system in the headland $P_{parallel,HL}$ is calculated from the total driving resistance of a segment $F_{T,middle\ segment}$, the field working speed of the agricultural machine v_{work} and the efficiency of the wide span system η_{WSS}. The energy demand for the cultivation of both headlands $E_{parallel,HL}$ comprises the power required by the wide span system in the headland $P_{parallel,HL}$, the width of the field W_{field}, the number of tracks in the headland $n_{track,HL}$, as well as the field working speed of the agricultural machine v_{work} (equation 7).

$$E_{parallel,\mathrm{HL}} = P_{parallel,\mathrm{HL}} \times \frac{W_{field} \times n_{track,\mathrm{HL}}}{v_{work}} \quad \text{(Eq. 7)}$$

Last, the total energy demand of the wide span system for the field E_{field} can be calculated as well as the energy demand per ha $E_{per\ ha}$ can be calculated.

Simulation parameters

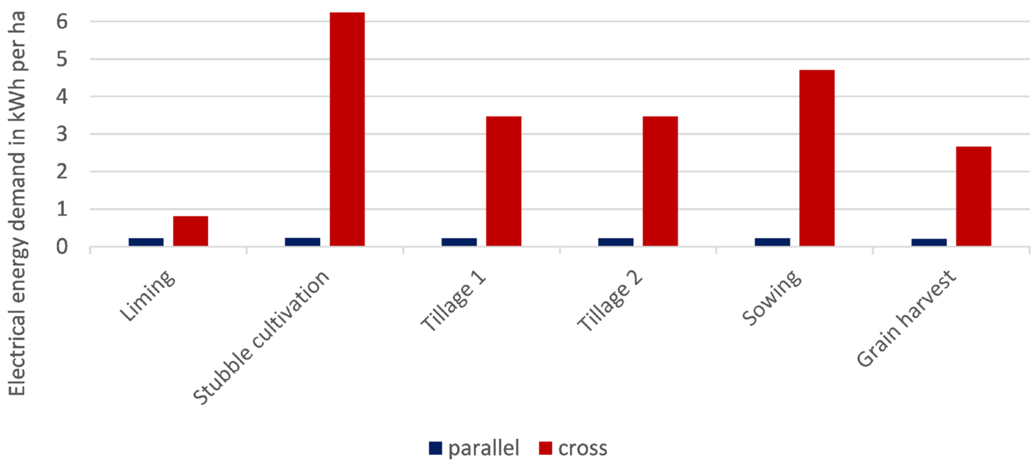
The simulation of the process chain is carried out using the example of a rectangular field with a size of 30 ha and light soil. The field has a width of 320 m and a length of 930 m. On the field barley is grown with a yield of 7.4 t/ha. Table 1 shows the agricultural process chain simulated for this paper.

Table 1: Process chain for the cultivation of barley on the example field (30 ha)

Process	**Machine combination (power; working width)**
Liming	157 kW; Centrifugal spreader 36 m
Stubble cultivation	176 kW; Compact disc harrow 4.5 m
Tillage (2 x)	338 kW; Cultivator 8 m
Sowing	200 kW; Mulch seeder 6 m
Chem. crop protection (3 x)	157 kW; Crop protection sprayer 36 m
Mineral. fertilization (3 x)	157 kW; Centrifugal spreader 36 m
Grain harvest and transport	400 kW; Combine 10.5 m & two auger wagons

Simulation results and discussion

The wide span system is intended to serve four purposes. On the one hand, transmission of electrical energy and the application of fertilizer, pesticides and water, so that the various applications with the fertilizer spreader and the crop protection sprayer can be saved. For the traction drive of the wide span system, the additional energy requirement per hectare was calculated in the alignment variants parallel and across to the main working direction (Figure 4).

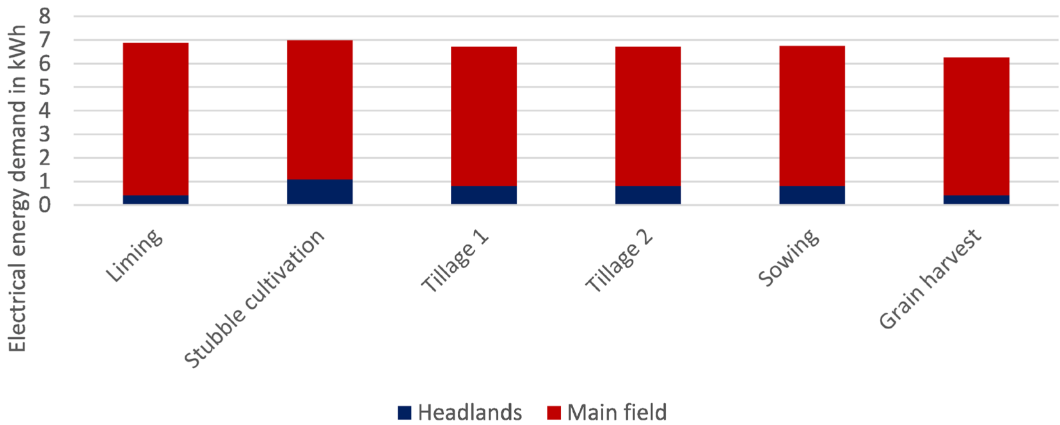


Field size: 30 ha; light soil; barley yield: 7.4 t/ha
Farm and machine specification according to a model farm in Lower Saxony

Figure 4: Comparison of the additional electrical energy demand per hectare only for the traction drive of the wide span system parallel and across to the main working direction

The energy demand for the traction drive of the wide span system is significantly greater in the alignment across to the main working direction than in the direction parallel to the main working direction. This is due to the fact that the wide span system in the alignment across to the main working direction travels continuously with the working speed of the machine combination. In the case of the unchanged transfer of agricultural process steps with small working widths, such as the stubble cultivation with 4.5 m, the number of tracks is compared to liming with a working width of 36 m much higher, so that the wide span system has to cover significantly longer distances. Since the energy demand per hectare for all processes is significantly lower in the alignment variant parallel to the main working direction than in the alignment variant across to the main working direction, only the alignment variant parallel to the main working direction is considered.

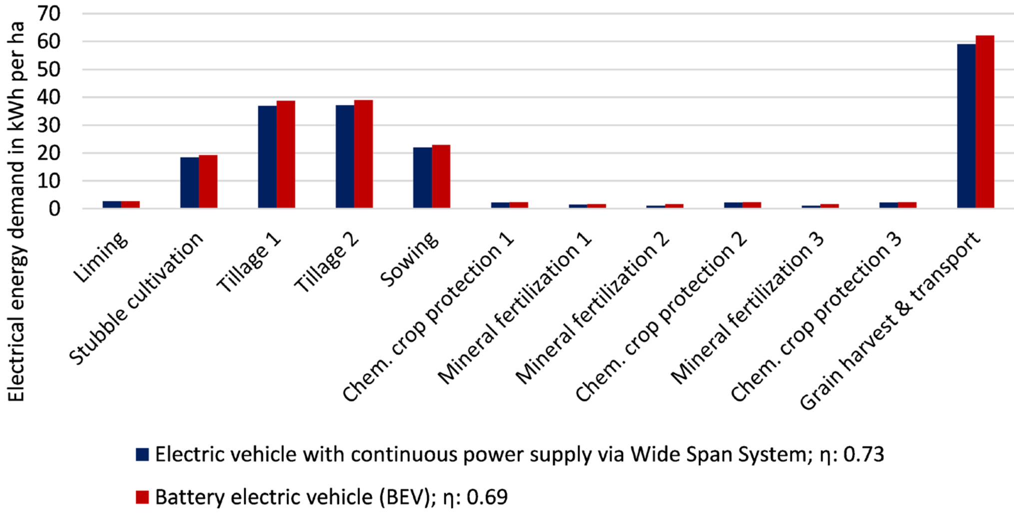
The electrical energy demand on the 30-ha example field varies from 6.3 kWh during grain harvest to 7.0 kWh during stubble cultivation (Figure 5). The grain harvest involves one combine harvester and two auger wagons. The three vehicles can be supplied by the same wide span system. The lower energy demand for the traction drive of the towers during the grain harvest compared to stubble cultivation can be explained as follows: Most of the energy demand results from the cultivation of the main field. For work during cultivation of the main field, the energy demand for both grain harvest and stubble cultivation is 5.9 kWh. The higher total energy demand of the stubble cultivation is due to its higher energy demand for processing the headland. This is due to the fact that the wide span system here has to travel continuously at the field speed of the machine combination. Due to the relatively small working width of 4.5 m, this is much more frequent during stubble cultivation than during grain harvest with a working width of 10.5 m and therefore the energy demand of the stubble cultivation for the headland is higher.



Field size: 30 ha; light soil; barley yield: 7.4 t/ha
Farm and machine specification according to a model farm in Lower Saxony

Figure 5: Electrical energy demand of the traction drive of a wide span system in the alignment parallel to the main working direction on an example field

In Figure 6, the total energy demand of the process chain, which is continuously supplied with electrical energy via a wide span system, is compared to the energy demand of a battery-electric (battery electric vehicle = BEV) process chain.



Field size: 30 ha; light soil; barley yield: 7.4 t/ha
Farm and machine specification according to a model farm in Lower Saxony

Figure 6: Comparison of different electrical energy supply systems using the example of an agricultural process chain for the cultivation of barley on an example field; wide span system parallel to the main working direction

The energy requirement of the process chain, which is continuously supplied with electrical energy via a wide span system, is slightly below the energy requirement of the battery-electric process chain for all process steps. For the first tillage operation, the energy requirement for the battery-electric system is 39 kWh and via a wide span system (continuously supplied with electrical energy) 37 kWh. For the processes of crop protection and mineral fertilization, the energy demand of both energy supply concepts is almost identical. The energy requirement of the first mineral fertilization is 1.7 kWh battery-electrically and 1.5 kWh continuously supplied with electrical energy via a wide span system. For these process steps, the piping system is filled with fertilizer or crop protection agent, so that the mass of the liquid m_{liquid} must be considered. In contrast, compared with application with a fertilizer spreader or crop protection sprayer, the energy requirement for the applications is omitted. In comparison, the energy requirements for these process steps and the differences between the supply systems are small in each case.

In this article, typical efficiencies of the respective conversion chains from the energy-generating plant (wind and solar energy) are used according to a study by ACATECH (2018). The overall efficiency of the battery-electric process chain η_{BEV} = 0.69 is composed of the individual efficiencies of power transmission from the energy-generating plant to the battery charging station (η = 0.95), battery use (charging and discharging η = 0.9), the electric motor (η = 0.85), and the mechanical system (η = 0.95). In contrast, in the total efficiency of the process chain continuously supplied with electrical energy via a wide span system of η_{LM} = 0.73 the efficiencies of the power transmission from the energy generating plant to the field edge (η = 0.95), the power transmission via the wide span system in the field (η = 0.95), the electric motor (η = 0.85), and the mechanical system (η = 0.95) are considered.

In Figure 7, the energy requirements of different electric drive concepts are compared on the basis of tillage: continuous energy supply via a wide span system to a battery electric vehicle, fuel cell vehicle (FCEV) and vehicle with hydrogen-powered internal combustion engine for which the hydrogen was obtained on the basis of renewable energy (vehicle with internal combustion engine = ICV-H2).

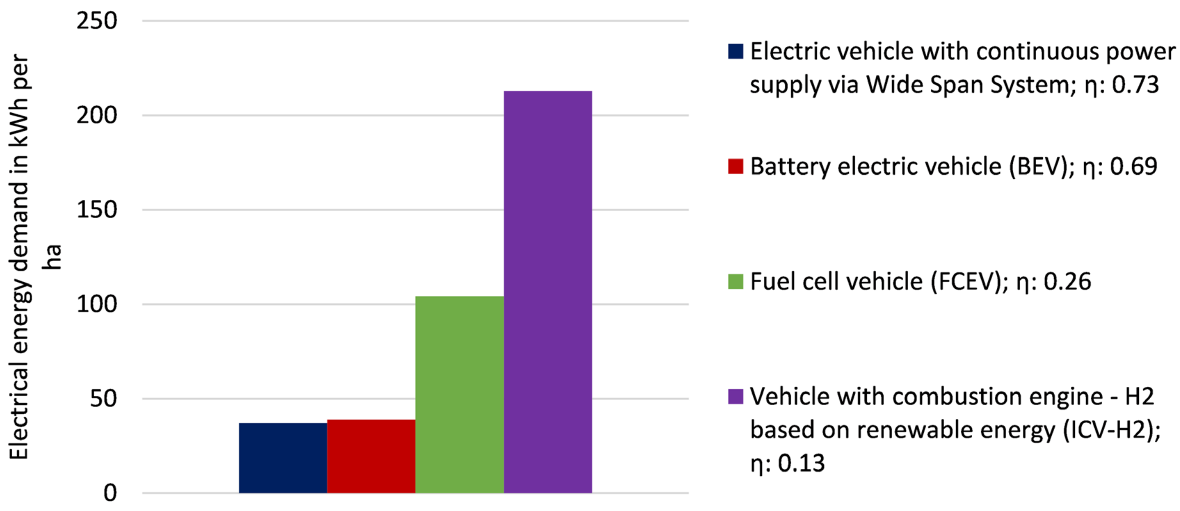


Figure 7: Comparison of different energy supply and drive concepts based on renewable energy sources using the example of tillage, specifying the overall efficiencies used; efficiencies of BEV, FCEV and ICV according to ACATECH (2018)

The system boundary is the grid feed-in point downstream of the energy-generating plant (wind and solar energy), so that the entire conversion chains are considered in each case. For the electric vehicle continuously supplied with energy via a wide span system and the battery-electric vehicle, the efficiencies already mentioned apply. For the fuel cell vehicle an overall efficiency of η_{FCEV} = 0.26 is estimated, which includes the transfer of energy from the energy-generating plant to the electrolyzer (η = 0.95), electrolysis (η = 0.7), compression and transport (η = 0.8), the fuel cell (η = 0.6), the electric motor (η = 0.85) and the mechanical system (η = 0.95). For the vehicle with hydrogen-powered internal combustion engine an overall efficiency of $\eta_{ICV\text{-}H2}$ = 0.13 applies, in which the power transmission from the power-generating plant to the electrolyzer (η = 0.95), the electrolysis (η = 0.7), the conversion Power-to-Liquid (η = 0.7), the transfer of the liquid hydrogen (η = 0.95), the combustion engine (η = 0.3), and the mechanics (η = 0.95) are considered.

Taking these efficiencies into account, the fuel cell vehicle requires about two and a half times as much electrical energy as a battery-electric vehicle to operate the same example field. A vehicle with a hydrogen-powered internal combustion engine even requires five and a half times as much electrical energy as a battery-electric vehicle. The difference in the amount of energy required to carry out the same process steps lies solely in the difference in efficiency that needs to be discussed. The efficiencies of the subsystems are sometimes given differently by other authors. For example, Schwaderlapp and Plumpe assign a battery electric vehicle an efficiency of η_{BEV} = 0.49 instead of the efficiency of η_{BEV} = 0.69 used in this article (Schwaderlapp and Plumpe 2022); both efficiencies take into account the entire conversion chains starting from the energy-generating plant. The difference in efficiency exists because additional subsystems in the conversion chain are partially considered. For example, Schwaderlapp and Plumpe consider at grid level a battery buffer with an efficiency of η = 0.86. Beidl estimates for a battery electric vehicle - but only from the charging station up to and including the mechanics of the vehicle - an efficiency of η_{BEV} = 0.5 to 0.65 (Beidl 2022). Also, with regard to the efficiency of a fuel cell vehicle, the figures of acatech differ with η_{FCEV} = 0.26 (from energy-generating system to incl. mechanics), Schwaderlapp and Plumpe with η_{FCEV} = 0.21 (from energy-generating plant to incl. fuel cell) and Beidl with η_{FCEV} = 0.4 to 0.5 (from hydrogen fueling station to incl. mechanics). This difference also results from the assumption of different efficiencies for the individual subsystems.

In comparison with the other energy supply concepts, it becomes clear that a continuous electrical supply of agricultural machinery in the field appears to be quite valid in an efficiency comparison. This is a core statement of the present paper. However, this consideration does not mean that a continuous or battery-electric supply of agricultural machinery in the field is always the best option, since efficiency is only one of many other evaluation criteria that need to be considered in detail when evaluating new and conventional systems. In the end, what counts for the user in particular are agricultural usability and the Total Costs of Ownership (TCO). For example, a wide span system, as described here, can only be installed on rectangular large fields, due to the geometry of the infrastructure system. For individual areas in small-structured regions it seems unsuitable, unless it is possible to use it across fields.

Nevertheless, it can be discussed how a wide span system could be sensibly positioned in an existing, more complex field polygon so that the conditions are optimally used. As part of the Energy-4-Agri project, it was investigated with the participating Braunschweig Institute for Geoecology whether the "remaining" field areas could be used as flower strips or whether agri- photovoltaic systems could be installed there. From a geoecological perspective, such areas could improve the so-called landscape connectivity and thus the migration of animals and organisms, with the effect of maintaining or increasing biodiversity. Agri-photovoltaic systems on these areas would possibly increase the economic attractiveness of such approaches.

Conclusions

In this article, a wide span system based on a linear irrigation system is presented, which is intended to perform various tasks in agriculture. This infrastructure system continuously provides electrical energy for the operation of agricultural machinery in the sense of a catenary concept, on the one hand. On the other hand, the pipeline of the infrastructure system is used for irrigation and the application of fertilizers and pesticides. Via this approach is intended, to save applications with the fertilizer spreader and the crop protection sprayer. For the installation of the wide span system, the paper presents two alignment options, across or parallel to the main working direction of the agricultural machine. The process simulation shows that the energy requirement for alignment across to the main working direction is significantly greater than for alignment parallel to the main working direction in all agricultural processes. The difference in energy requirements is particularly serious for small working widths.

Ultimately, in addition to the technical and agricultural issues that need to be further investigated, the total cost of ownership (TCO) and the agricultural usability will be decisive factors whether a wide span system can be used in agricultural practice.

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Autoren

M. Sc. Lennart Buck is a research associate and **Prof. Dr. Ludger Frerichs** is the institute director of the Institute of Mobile Machines and Commercial Vehicles (IMN) at the TU Braunschweig, Langer Kamp 19a, 38106 Braunschweig, e-mail: l.buck@tu-braunschweig.de

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