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An Autonomous Electric Powered Tractor—Simulation of All Operations on a Swedish Dairy Farm

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Abstract: For a conventional agricultural tractor the main environmental effects originates from the usage phase, more specifically from the diesel use and exhausts. To decrease the environmental effect, it is vital to find a substitute for fossil diesel as a fuel for agricultural machinery. This study investigated the feasibility of an autonomous battery electric tractor through simulation. The simulated farm is an organic dairy farm of 200 ha with five crops in the crop rotation cycle and a traditional plough among the used implements. Based on the result from the simulation cost calculations, sensitivity analysis and a limited life cycle analysis (LCA) was made. The results show that it is in theory possible to replace a conventional tractor (160 kW) with two autonomous battery powered machines (36 kW engine, 113 kWh battery) with 15% lower costs. Energy consumption would be reduced by 58% and greenhouse gas emissions by 92% compared to diesel when energy consumption and greenhouse gas emissions from battery manufacturing were included. Today the technology for autonomous control is under fast development, but there are yet no systems on the market that can handle all machinery tasks like assumed in this study. Challenges yet to solve are, among others, legislative, relevant sensors, logistics and fleet management. Further research is needed to verify the results in practical farming.

Key words: Autonomous, agriculture, electric, battery, tractor, farming, fossil free, sustainable.

1. Introduction

Agriculture today is based on the use of machinery mainly powered by fossil diesel. The emissions from the machinery have a substantial negative environmental impact [1] and it is vital to find a substitute for fossil diesel as a fuel. In Sweden 2016, agricultural tractors emitted 17% of the CO_2-emissions from usage of work machinery, which in turn emitted 7% of Sweden's total CO_2-emissions [2].

Electro mobility makes it possible to reduce the use of fossil fuels and vehicle operating costs and at the same time eliminating local emissions including sound [3]. The high reduction in both energy usage and global warming potential (GWP) emissions can be explained by the higher efficiency of electric power drivelines and by the very low greenhouse gas emissions and environmental impact in the Swedish electricity mix. Electro mobility is also an enabler for precision farming, since electric motors are much easier to control and therefore they are preferable to combustion engines when precision is needed, and precision control is essential in precision farming [4].

There is contemporary research on both autonomous agricultural vehicles [3] and electric agricultural vehicles [4-7], but the current knowledge on the combination of both technologies and the possible synergy effects is limited.

2. Description

This study aims to investigate from an economical and environmental perspective the feasibility and synergy effects of a battery electric, autonomous tractor [8]. There are many advantages with both battery electric drive and autonomous control in general, but also new challenges, such as the needed compromise between battery size and work range. By combining battery power with autonomous control,

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the machine can work 24/7, charge whenever needed, and then return to work.

The method used is simulation of all machinery tasks during one year on an average Swedish dairy farm. A battery powered autonomous tractor system is simulated as well as a conventional diesel powered, manually controlled tractor. The two systems are then compared when it comes to total cost of operations (TCO), energy usage and greenhouse gas emissions. The simulated farm is an organic dairy farm of 200 ha with five crops in the crop rotation cycle (winter wheat, barley, green fodder and two kinds of ley). Only in-field machine operations are included in the simulations, except for transportation of inputs (manure, fertilizer, seeds etc.) and outputs (grain, silage bales etc.) to and from the farm. The simulation is a linear, continuous and dynamic model that utilizes Excels evolutionary solver algorithm for optimization of the lowest TCO on a farm by varying the power, the number of tractors and the battery size of the tractors (Fig. 1). For the simulation of diesel-tractor(s), only the engine power and number of tractors are varied.

(1) Conditions: The crop rotations, all the operations and the data needed to model these, as well as the different crop requirements [9].

(2) Capacity: Modeling of how wide or large the implements can be given a certain power on the tractor and then in turn their operational capacity, cargo capacity, costs, ask completion time and energy consumption they have.

(3) Timeliness: The fictional timeliness costs are costs that occur when the machines have too low capacity and an operation is being delayed. This segment also includes modeling of dependencies between different operations [10].

(4) Battery: The battery is modeled with charge cycles, service life, capacity, costs, as well as energy consumption and carbon dioxide emissions for the manufacture of the battery. Swedish electricity mix is used as a basis for the carbon dioxide emissions calculations [11, 12].

(5) Charger: Modeling of charger and electricity consumption with power, greenhouse gases and costs [13]. Swedish electricity mix is used as a basis for the carbon dioxide emissions calculations.

(6) Tractor: Modeling of driver and operator, tractor costs, control system, electric driveline, weight and transport distance. Costs were deducted for cabin and diesel engine and added for electric driveline and autonomous control system (assumed to a fixed cost of 11,300 USD, no running cost included) [14, 15].

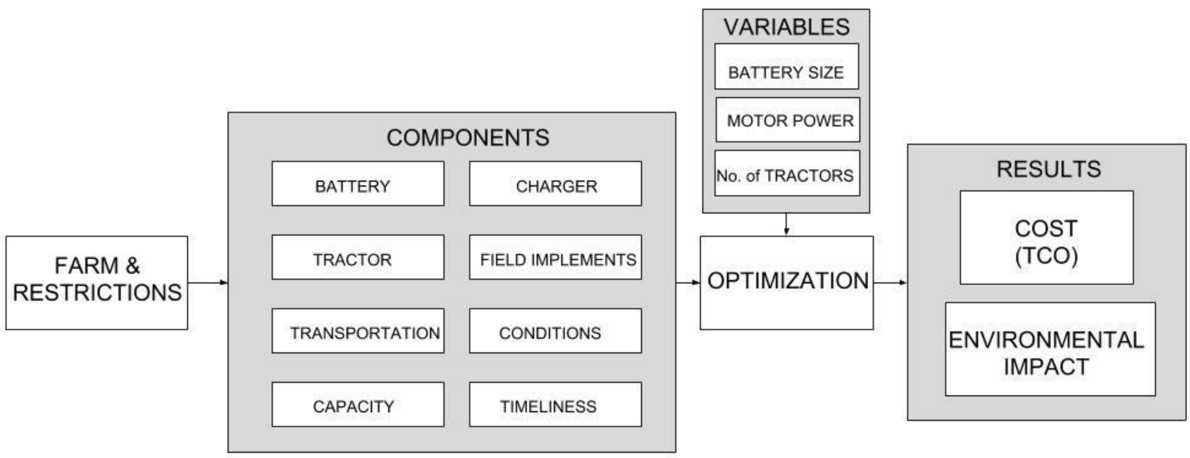

Fig. 1 Graphic representation of the different parts in the simulation model.
The model boundaries are input in "Farm & Restrictions". The information is then used by the "Components" part that is dependent on the "Variables". Each part of "Components" has an attached cost, as well as other features like time and energy consumption and environmental impacts.

(7) Field implements: Modeling of implements pulled or powered by the tractor. Maximum power requirements, energy use, harvesting, maximum width, capacity and costs are calculated. Costs are based on list prices for implements in Sweden [16].

(8) Transportation: Modeling parameters for transport and the collection, loading, unloading and distribution of goods. Max power requirements, energy use, load capacity and costs are calculated. Costs are based on list prices for implements in Sweden [17].

The simulation can be expressed as a mathematical function (Eq. (1)), where the TCO is the sum of all component costs for one year's machine activities. The component costs are dependent on the variables vehicle power, the number of vehicles and the battery size. The optimization then consists of varying *P*, *N* and *E* to find the lowest *TCO*.

$$TCO = \sum_{Components} C(P, N, E) \quad (1)$$

where, *C* is the component cost (total for one year); *P* is the vehicle power; *N* is the number of vehicles; *E* is the available energy in the battery, dependent on battery size.

In the model, some relevant restrictions and boundaries were implemented. The power for the tractor could be 0-500 kW and the battery size could be 0-3,000 kWh and maximum 40% of the total vehicle weight, which was limited to 75 kg/kW to get pulling characteristics like conventional tractors. The number of tractors could be 0-100 and the working width of the implements were limited to the largest models currently on the market. As a part of the timeliness factor the probability for acceptable weather was included to model poor weather conditions [8].

Based on the result from the simulation cost calculations, sensitivity analysis and a limited life cycle analysis (LCA) were made and compared to the same optimization system using a diesel driven tractor. The LCA focused on the difference in fuel systems, was limited in scope and had system boundaries that included the production and use of diesel and electricity as fuels for the tractors, and the manufacturing of the battery cells (including materials and energy use). All other factors were assumed to be identical or very similar between the diesel and electrical tractor.

3. Results and Discussion

The results show that the optimum setup for an autonomous battery powered machine on the simulated farm was two machines, each at 36 kW motor power and a battery capacity of 113 kWh, as shown in Table 1. When a conventional diesel-powered tractor with a driver was modeled the economic optimum was one tractor of 160 kW. The vehicle weight was estimated to be 75 kg/kW rated power for both types of tractors, which means that the autonomous electric machine would be four times lighter [8].

When comparing the two machine systems the total cost for the two autonomous battery powered machines was 15% lower. The size of the tractors are similar to the one in Ref. [6] and the diesel tractors machine hours per year is close to the Swedish average which is 600 h/year [14].

The different costs for the modeled machines had a distribution as shown in Fig. 2. The single largest cost

Table 1 Comparison of specifications between two autonomous controlled and battery powered machines and one diesel powered and driver-controlled machine managing all the farms tasks for one year.

Alternative	Number of machines	Power per machine (kW)	Machine hours per machine (h/year)	Energy reservoir (kWh)	Work hours per day (h)	Total cost (USD/year)
Diesel powered with driver	1	160	545	2,940	10	74,200
Autonomous battery powered	2	36	995	113	24	63,300

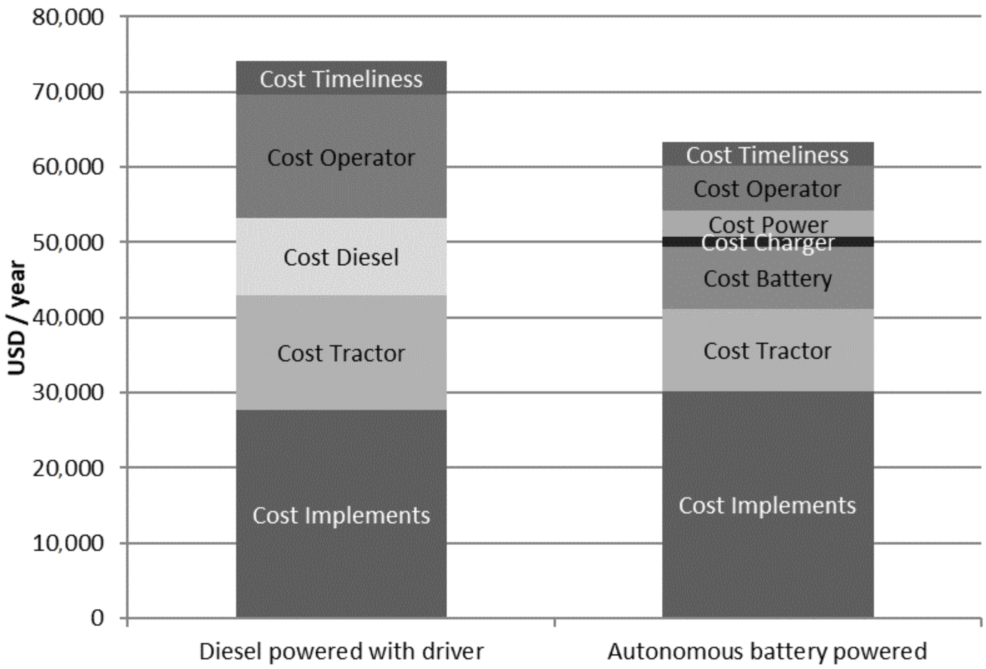

Fig. 2 Comparison of costs between two autonomous controlled and battery powered machines and one diesel powered and driver-controlled machine managing the farms all task for one year.

for the diesel machine was the implements, followed by the operator and the tractor itself. For the autonomous battery powered machines, the single largest cost was also the implements followed by the machine and the battery costs.

When comparing the energy usage for the different set-ups the diesel-powered machine needed almost 90 MWh of energy for one year, while the autonomous battery-powered machines ended up with a usage of 37 MWh (when adding the energy needed for the battery production). That is a reduction of 58% in energy usage (Fig. 3).

One big driver for changing to a battery electric driveline is the big potential in reducing the carbon dioxide footprint of using the machine. In this simulation the reduction of GWP was 92%, including the emissions when producing the battery [6]. The electricity needed to produce the battery and for charging the machines is assumed to be Swedish electricity mix. If the battery production is powered with average European electricity mix, then the reduction in GWP is 82%. These numbers are comparable to those found in Ref. [8], as the methods of calculation are similar.

The LCA performed in the study was limited in scope and focused only on the difference the fuel change had on the greenhouse gas emission. Any reduction in maintenance materials due to changing from diesel to electric drive was ignored, as was the advantages in having smaller vehicles (less material used in production, less soil compaction). In further studies, a more thorough LCA was recommended where these factors among others are included and investigated.

To investigate the sensitivity of the model, several scenarios were simulated where different key input figures were changed (Tables 2 and 3). The scenario for a manually driven battery tractor and an autonomous diesel tractor were also simulated. The manually driven battery tractor increased the TCO with 61% and the autonomous diesel tractor decreased TCO with 22%, both cases compared to their opposite. In both cases, the optimal vehicle size was changed as well, to a smaller diesel tractor and a bigger battery tractor.

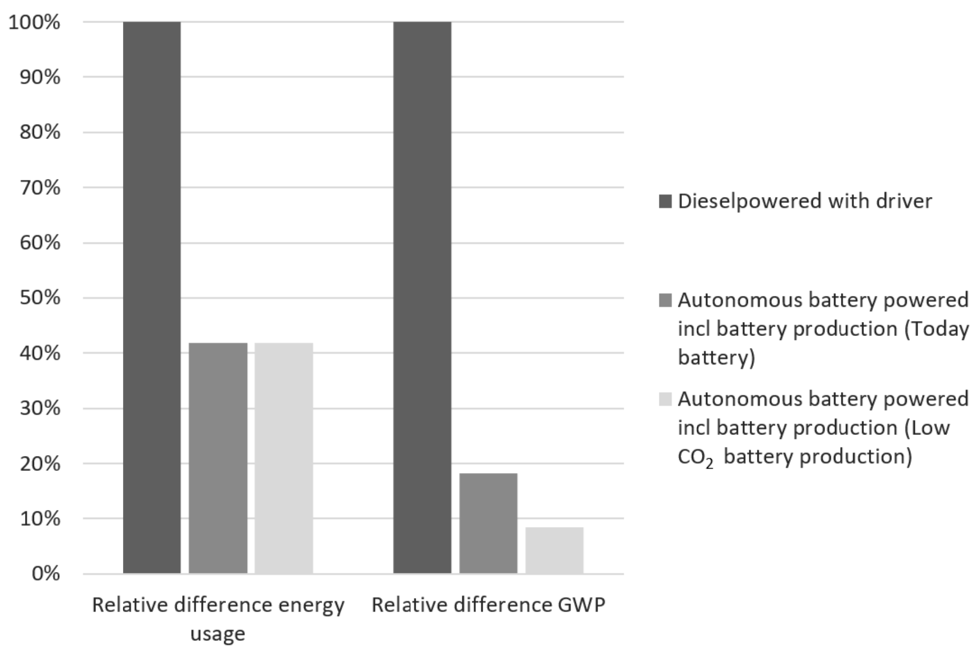

Fig. 3 Relative energy usage and GWP for diesel powered and driver controlled compared to autonomous controlled and battery powered, including the difference between batteries produced today and battery produced with Swedish electricity mix with low GWP.

Table 2 Sensitivity analysis for relevant cost factors.

	Change in TCO		
	Base value	-50% of base value	+100% of base value
Battery price (incl. battery management system)	392 USD/kWh	-4%	+12%
Distance to charger	4 km	-16%	+12%
Implement cost	28,900 USD	-25%	+48%

TCO: total cost of operations.

Table 3 Sensitivity analysis for TCO with variable charger power.

	Base value	25 kW	300 kW
Charger power	100 kW	+30% TCO	+0% TCO

TCO: total cost of operations.

4. Conclusions

The results show that a machine system with the combination of autonomous control and battery electric drive in theory can replace a conventional diesel-powered tractor and still manage all operations on the simulated farm at a slightly lower cost. This means that both the energy consumption and greenhouse gas emissions would be significantly reduced and makes it possible to produce the power for the machinery locally on the farm. There are also other advantages like lower weight and probably lower sound with the proposed system.

Today there is no autonomous tractor system that can handle all machine activities like assumed in the study, but the technology is under fast development. Challenges yet to solve are, among others, legislative, relevant sensors, logistics and fleet management.

The sensitivity analysis showed that the resulting TCO was sensitive to changes in the cost for implements, as that was one of the main cost factors. Battery price, contrary to assumptions, had a low impact on the TCO while the degree of automation (here either fully autonomous or fully manual) had a notable impact. Charger power had a notable negative impact when decreased beyond certain amounts but had a low impact when increased. Distance to charger followed the same trend, both effectively having a threshold for efficient operation after which further increases had diminishing returns.

Continued research is needed to verify the theoretical simulation by building a test platform where knowledge can be gathered about the problems and opportunities in practical work—both in the field of battery-electric operation and autonomous driving for agricultural machines.

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