A Study of Solar Electric Tractor for Small Scale Farming

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1 author:

Amit Subhash Vaidya
Maharashtra Academy of Engineering and Education Research

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Dr. Amit S. Vaidya

Doctorate of Management Studies, ISBM, Mumbai, Maharashtra, India

Abstract: ***Small Scale or Family farming is in many parts of the world still a significant factor in food production. However, farms in underdeveloped regions often lack the appropriate means to carry out agricultural activities in accordance with the state of the art, i.e. with the help of motorized machinery. On the other hand, especially in tropical regions, they generally own a reliable renewable energy source, principally in the form of solar radiation. In an effort to help to improve the returns of farming in an environmentally acceptable way, the project's objective is to investigate the feasibility of a small size electric farming tractor, which shall be able to use locally generated renewable energy. The crucial technical challenge is (as with other electric vehicles) to store sufficient electrical energy on the tractor for an extension of its operating time. On the other hand, economic competitiveness with comparable combustion engine tractors is a prerequisite for the project's success. Consequently, the project investigates an electric tractor system using alternative technical solutions in order to extend the operating time to a maximum and to compare the tractor's tractive power and its hourly operating cost to a combustion engine tractor of a similar power rating. To this end, an electric prototype tractor in conjunction with an appropriate electric generation, storage and transmission system are considered within this work.***

1. Introduction

Historically, agricultural electric tractor systems [1], [2] were developed and employed nearly a hundred years ago but vanished with the increasing availability of fossil fuels and the progress in the development of combustion engines. Today, due to the perspective of locally available renewable electric energy there is a completely different scenario for rural areas, which justifies the efforts to resume the development of electric tractors for agriculture.

The main application of an agricultural tractor is to power implements by pulling plows, seeders, harvesters etc. [3]. At this stage of the project, the envisaged tractor has in the first place to ensure its performance and endurance on the draw bar. Additionally, the design of an electric tractor has to consider the specific properties of the electric motor and its controls in conjunction with the tractor's onboard energy source. Compared to a combustion engine driven tractor, this leads to a different configuration of the drive train and the associated energy supply system.

The project's aim is to evaluate the feasibility of an electric micro tractor system for small-scale family farming that can be propelled by locally generated renewable energy.

The specific objectives are:

1) Design, build and test a digital prototype electric tractor.
2) Evaluate an energy transmission or supply system that is able to ensure extended tractor operation.
3) Compare tractive power and operating costs of the electric tractor system to the ones of a combustion engine tractor of a similar power rating.

2. Tractor Prime Movers

The electric motor's torque and speed characteristic exposes one of the most important differences in comparison to the performance characteristic of combustion engine powered tractors [4]. Whereas the torque curve of the combustion engine reaches a peak next to the maximum speed Ilmax, the electric motor delivers its nominal torque Mn from standstill no to nominal speed nn (see Fig. 1). Another characteristic of the electric motor that has a significant influence on the tractor's pulling performance, is its torque reserve. For a limited time it is able to generate several times the nominal torque (see Table I).

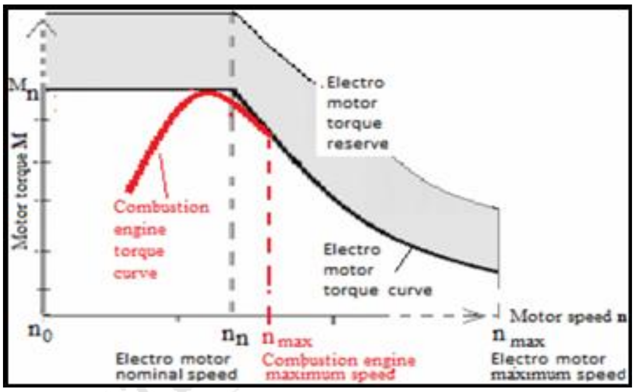

Figure 1: Typical torque characteristic of both combustion engine and electric motor

3. Prototype Tractor

The design of an electric tractor has to consider the specific properties of the electric motor, its controls and the tractor's onboard energy source. Compared to a combustion engine powered tractor, this needs a different configuration and layout of energy storage and supply, mechanical power transmission, speed and torque control.

Table I: Technical data & DMU of prototype tractor

Motor power rating	9 kW (2 x 4.5 kW)
Nominal motor speed	1,715 rpm
Rated motor torque	25.1 Nm
Maximum torque	330% (maximum two minutes)
Nominal speed	7 km/h
Maximum speed	21 km/h

Figure 2: DMU of Solar electric Tractor

For the project's digital prototype tractor a design with two motors, each one dedicated to a driving wheel, is identified to be most suitable to design a very simple but efficient direct chain drive (see Fig. 2). With respect to an optimum weight distribution, the motors on the prototype where placed above the rear axle, below the driver seat with the batteries in front of the driver.

Energy System

In its simplest form, a local energy generation unit consists of photovoltaic panels, transforming solar irradiation into electrical energy and powering a charging station for battery packs. Where available, a grid connection functioning as an energy buffer would improve the reliability of the system (Fig. 3).

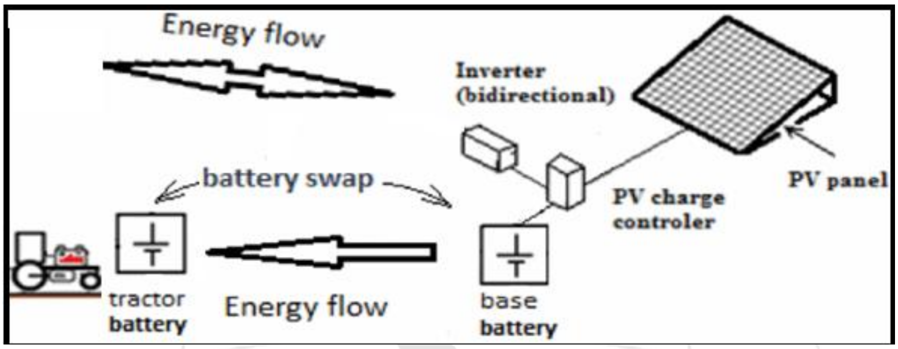

Figure 3: Local power supply scheme with exchangeable battery packs for tractor

Energy Transmission System

One of the key criteria of the technical viability of an agricultural tractor is an extended operating endurance, e.g. during harvesting times. This is a challenge for electric tractors, firstly since energy density in batteries is extremely low when compared to liquid fuels and secondly because recharging of batteries can take several hours, especially when a photovoltaic generator is used. To overcome this bottleneck, systems hooking up the electrical tractors via a cable to the grid (when it is working on the planting area) have been favored already a century ago [1], [2]. The project's proposed architecture is considering a similar technical approach as a combination of onboard batteries, a cable based power supply system and alternatively exchangeable battery packs for the tractors onboard power supply.

a) Exchangeable Battery Packs
b) Cable System with Pivot and Boom

This concept bases on exchangeable battery packs for the tractor when working in plantations for an extended period. The tractor transports a trailer with a set of exchangeable battery packs to the place of work (Fig. 4). Whenever a battery pack on the tractor is exhausted, it is replaced with a fully charged one. Work continues until the last battery pack is down to a margin, which ensures a return to the base. To exploit this concept to a maximum, a second set of mobile exchangeable battery pack is simultaneously charged at the home base. This concept bases on exchangeable battery packs for the tractor when working in plantations for an extended period. The tractor transports a trailer with a set of exchangeable battery packs to the place of work (Fig. 4). Whenever a battery pack on the tractor is exhausted, it is replaced with a fully charged one. Work continues until the last battery pack is down to a margin, which ensures a return to the base. To exploit this concept to a maximum, a second set of mobile exchangeable battery pack is simultaneously charged at the home base.

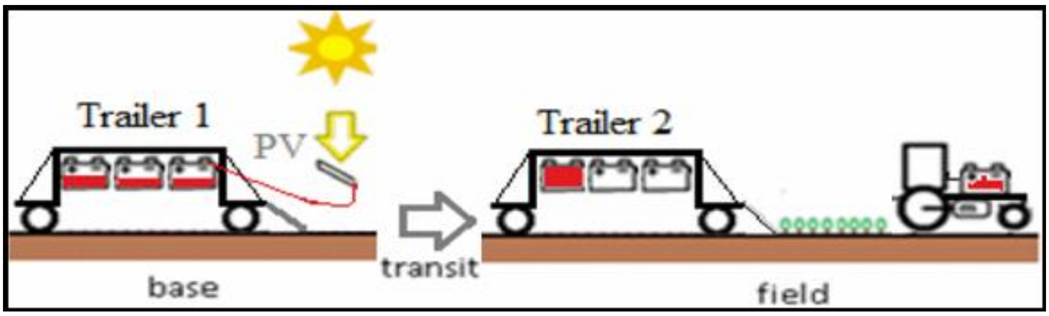

Figure 4: Charging batteries at the home base and operating the tractor in the field using the on-board battery pack. Operating time extension by battery-swapping between trailer and tractor

Comparative Cost Consideration of the Electric Tractor System

The project team selects family farming in the northeast of Brazil as a reference for the cost study since this is a favorable scenario for the implementation of an electric tractor system. One of the main reasons is that there is abundant solar irradiation exceeding >5 kW/h per square meter per day and that basically throughout the year (Fig. 6).

A comparative cost study based on the electric tractor system and a common combustion engine tractor (with the same power level) is favored to a direct cost-benefit analysis since reliable data on expenditures and earnings are not available for such farms in this region.

The applied method bases upon the conversion of investment costs and direct operating costs into total hourly operating costs of the two alternatively powered tractors. For the combustion engine powered micro tractor, the costs considered are the market purchase price and the fuel cost. Overheads, like insurance and maintenance are considered for both alternatives as percentage of the investment cost and the period of use. (Fig. 6)

Battery costs enter the calculation process as operational costs since the degradation occurs in proportion to the number and depth of the charge - discharge cycles. For the electric tractor li-ion batteries were considered, based on an expected future price level of 120 US$ per kWh storage capacity from the year 2020 on [6], [7]. It is assumed that the battery can sustain 2.800 charge-discharge cycles at 100% depth of discharge each time [8] until the batteries storage capacity is reduced to 80%.

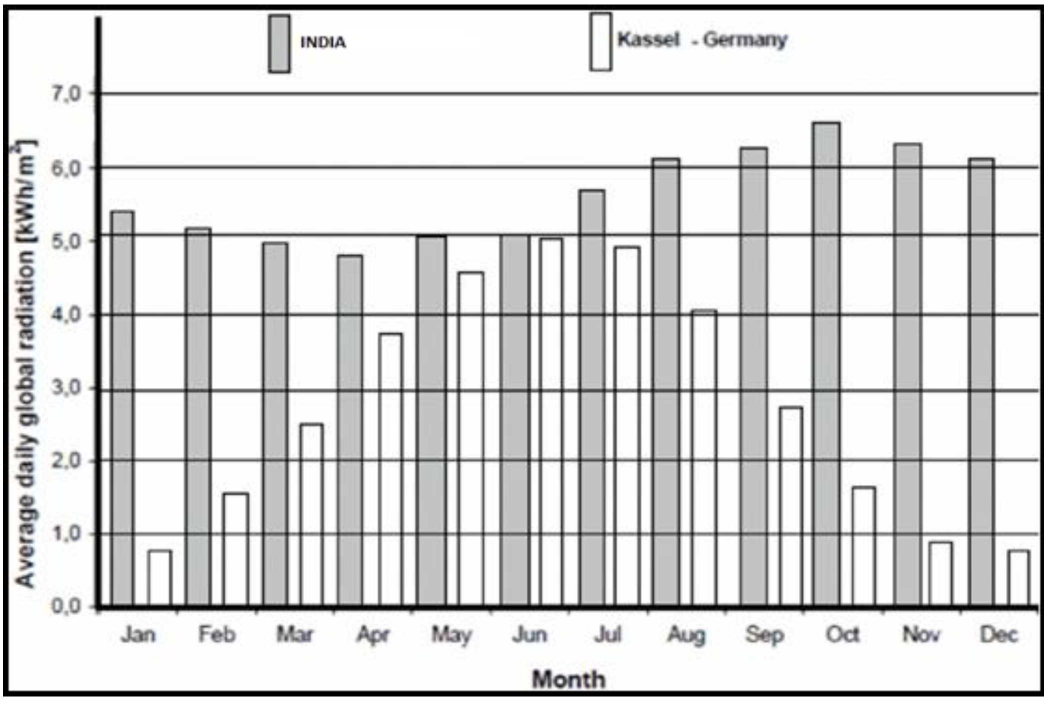

Figure 6: Annual distribution of solar radiation at India and kasselgermany [5]

For calculating the depreciation of the equipment value, the following periods are considered: 12 years for the tractor including the cable system with pivot and boom and 25 years for the PV -panels. Insurance costs are included with 1.5% yearly on the initial investment and maintenance costs with 0.5% per 100 tractor operating hours. Interest rates are not taken into account. The determination of the electrical system's generation and storage capacity takes into account the efficiency of the all system components. The maximum daily energy consumption is based on a maximum of 15 tractor working hours at 80% power level (of the rated tractor power). Furthermore, the accumulated yearly operating hours are assumed to be in the order of 1,000 h/year (tractor in community use by 4 semiarid farming families). Based on the above boundary conditions the required capacity of the battery packs and the PV -System is calculated.

Table II: Required capacity of the battery packs and the PV-system

	Battery capacity [kWh]	PV-panel active area [m^2]
Power supply using exchangeable battery packs	144	189

Table III: Investment for solar electric tractor systems in euro

	Power supply using exchangeable battery packs
Tractor	10,746
Trailers	3,784
Battery	14,502
PV-panel	20,654
Pivot*	-
Total	**49,686**

In order to implement an electric tractor system of this capacity, investment costs amounting to the figures below are predicted (TABLE III).

The common tractor used for comparison purposes is a YanmarAgritech TC14S single axle micro tractor powered by an internal combustion 4-stroke diesel engine (10.3 kW, 2,400 rpm, Weight 433 kg [10]) with a market price of 5,964 Euro plus a diesel storage tank at a cost of 535 Euro. This makes a total of 6,481 Euro for the combustion engine tractor.

Table IV: Tractor total hourly operating costs [euro/h] (not considering surplus energy)

	Total hourly operating costs
Power supply using exchangeable battery packs	3.14

By using these figures as input for calculating the total hourly operating costs, the values as shown in the above table are obtained (TABLE IV). With respect to the common tractor, a fuel price of 3.2 Real (0,865 Euro) per liter of diesel and a fuel consumption of 3 liters were considered [11].

Sizing an electric power supply system to provide the energy for a maximum of 15 tractor working hours per day and a total of 1,000 h per year leaves a significant surplus of energy which will not be consumed by the tractor on days when the tractor is only used a fraction of the daylight hours or idle. On the other hand, this amount of energy could be used for other applications as water pumping and lightening or, if a grid connection is available, be injected in the grid. Taking the benefit of this surplus energy at 0.03 Euro/kWh into account, the total hourly operating costs of the electric tractor system drop to the values listed in TABLE V.

Table V: Total hourly operating costs [euro/h] (considering surplus energy at 0.03 euro/kwh)

	Total hourly operating costs [Euro/h]
Power supply using exchangeable battery packs	1.76

4. Advantages of the Electric Tractor System

#1: Cheaper than Fossil Fuels

On many large farms, solar energy is actually much less expensive than fossil fuel. That is for a number of reasons. The installation of solar energy will cost you more – that's a given. However, with incentives from the state and increasing demand, it usually pays off to use solar energy. We all know that solar energy cuts down that electric bill. But, many are unaware of just how cost efficient renewable energy can be. Electric companies will charge more during the daytime, or when it's the hottest. With solar energy, you can avoid those grueling costs while maintaining your farm. Also, solar energy frees farmers from electricity spikes or times when electricity is all consumed at once. Electric companies will bill farmers much more for 'disrupting' the power system.

#2: Sensible Solution to Drought-Related Problems

The past 5 years have been exasperating for California farmers. Many are finding a safe haven through the use of solar energy. Solar energy is a more viable route to take during this relentless drought because it requires minimal water delivery. For many, agriculture has grown sparse and with limited water resources, things aren't looking up. Solar energy allows for the growth of photovoltaic panels as opposed to crops. While solar energy doesn't produce quite the same yield, for affected land, it may be the best solution.

#3: Not a Permanent Switch

One misconception of solar energy is that it is a permanent decision. But, in most cases, that is simply not true. Farmers can use solar energy as long as need be before reverting back to electricity. After the tenure, future crops will not be affected by formerly using renewable energy. Some aren't interested in permanently converting, but are seriously affected by the drought. Using solar energy can help farmers sustain through the drought. Then, if they decide it's not for them, they are able to go back.

#4: Potential Changes in Law

The advantages of solar energy extend are picking up in Congress. By 2030, it's likely that California farmers may be required to use solar energy. In an effort to combat climate change, lawmakers are proposing half of the electricity comes from renewable sources. Governor Jerry Brown believes that the transition away from fossil fuel energy may be difficult. For years, it has been the most profitable and economically wise solution. But, this step will help lead to a decarbonized future, according to Brown. He hopes this will ultimately serve as a model for other states and nations to follow.

#5: Solar Energy is currently on the rise

It's no doubt that the use of renewable energy has been growing exponentially in the last decade. This trend is expected to continue. For farmers, this means that the cost to install solar energy is likely to decrease. According to the Solar Energy Industries Association (SEIA), has grown 60% in the last decade. The cost, however, has dropped over 70%. With the growing popularity of renewable energy, prices are predicted to continue declining. The advantages of solar energy will be seen through price reductions in upcoming years.

#6: Becoming More Advanced

Like everything in our tech-savvy world, solar panels have developed greatly from its initial state. Now, many solar panels do not feature the glass substrate that the traditional models held. They are still attachable to roofs and walls. Also, panels tend to be much more environmentally friendly now. That is due to less energy being needed for its manufacturing process. The convenience of installation is one of the major advantages of solar energy.

#7: Solar storage is also becoming more affordable

In past decades, storing solar energy has been quite costly for everyone. Thankfully, it's growing much more widespread due to accessibility. So far, battery storage has been growingly popular for the use of solar energy. Many are using lithium ion batteries to preserve. In 2016, the price to store renewable energy dropped aggressively. Lithium ion battery storage is predicted to drop 20% to 30% in upcoming years. Energy storage is essential for areas that are prone to natural disasters. For California farmers, this could be helpful in preserving energy for future crisis. For California farmers, preserving energy for future crisis is one of the advantages of solar energy.

#8: Soil becomes better habitat

Powering through solar energy creates a more habitat-friendly environment for plants and wildlife. Solar panels are typically surrounded by grasslands. The installation does not pose any harm or threat to plants. Also, it can be easily maintained through hedging. Additionally, animals are able to have more room to graze through, creating a pasture-like setting. They will not be harmed by the above or underground panels.

#9: Most efficient way to halt global warming

Global warming has been a hot topic on everyone's radar for years. Utilizing renewable energy is one of the most productive methods of reducing a carbon footprint. Solar panels produce renewable energy. Not only that, but solar farms are able to disperse large amounts of clean energy. This is because of the excess power being distributed onto main grids.

5. Conclusion

For agricultural applications in remote areas without (or with) access to the grid, the electric tractor system provides the option to utilize locally generated renewable energy. In equatorial regions with a reliable and low-cost energy source in the form of a PV -plant, the concept of an electric tractor represents already today an economic and technical feasible solution using exchangeable battery packs. The most remarkable result is that in equatorial regions electric energy generated by a photovoltaic system would not only sustain the electric tractor operation but could in parallel contribute to recover the investment for it and provide an extra income to the semiarid family farmer (if a way is found to commercialize the surplus energy). Apart from that, the performance of an electric tractor is in some aspects superior to the common combustion engine tractor. The rated power is with 9 kW less than the 10.3 kW of the combustion engine tractor, but the pull force with 3,600 N (plus the 330% torque reserve for two minutes. See TABLE I) substantially exceeds the 2,100 N of the combustion engine tractor measured at test runs of both alternatives. On the other hand, there are up to 10 times higher investment costs to be encountered for implementing the electric tractor system (49,686 Euro compared to 6,481 Euro for the combustion engine tractor). But one has to bear in mind that the electric tractor investment includes the energy capture and transformation system, costs that are hidden in the diesel fuel price for the combustion engine tractor. And last but not least, it should also not be forgotten that with this change of technology significant benefits will be expected for the environment in addition to economic opportunities for the local population.

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