Optimization study on the design of utility tractor powered by electric battery

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Abstract. Powertrain by electric battery has been a growing trend in various industries including automotive, manufacture, and agriculture. Electric battery has been applied on several agricultural robots for multiple purposes such as liquid distribution, autonomous harvest, and sensors. In agricultural utility tractor, powertrain by electric battery has potential to replace powertrain by Internal Combustion Engines (ICEs) which commonly use fossil fuel as source of energy. However, application of electric battery power system has not been feasible due to overweight which lead soil compaction, lower speed, and high energy consumption. This study aims to optimize the design of utility tractors which will reduce the weight to standard operational weight dependent on tractor size. Alternative components are considered including Li4.4Si battery, Li-S battery and Permanent Magnet Synchronous Motor (PMSM) for component selection, system design, and simulation on MATLAB/Simulink – Simscape. Alternative components have contributed to reduce weight of the tractor significantly, from 93% to 12%-56% range of overweight. Improvement in weight contributed to less significant soil pressure, improve maximum speed and state of charge (SOC). Further, electric battery power system is expected to be applied on utility tractors, replacing the use of ICE and fossil fuel within conventional tractor.

1. Introduction
Concerns towards global warming and climate change as the consequences of various fossil fuels combustion have been raise for the last few decades. Fossil fuels combustion contributed to greenhouse gases (GHGs) emission in a form of CO₂, methane, nitrous oxide, and F-gases [7, 24]. CO₂ emission has increased significantly to approximately 10 thousand metric tons in 2010 from 500-600 metric tons in 1970. Non-CO₂ emissions have been reported to be significantly increasing since. Agricultural sector is the second highest contributor to total emissions after fossil fuel combustions and industrial processes [1]. Along with fossil fuel depletion, GHGs emissions have become such a major pressure for policy makers to consider about alternative power system, in which application of internal combustion engines (ICEs) should be replaced.
Contrary with ICE tractor, electric utility tractor does not produce emission on a vehicle level. Emissions were produced on electricity production by mainly coal combustion which will support the electric utility tractor. Various research suggested that electric vehicle doesn’t reduce GHGs emission by fossil fuel combustion on ICE vehicle. However, series of advantages can be generated including higher efficiency in energy production, easier emission management and control, reduction in acoustic pollution and petrol dependence [5].

Motorized power system with electric battery have been an increasing global trend, especially in transportation and industry sectors. Electric vehicles with this power system have been manufactured and commercialized by multiple multi-national companies. In agricultural sector, motorized power system with electric battery has been applied widely including in grain conveyors, agricultural robots and drones, and actuators with various purposes [7, 19]. However, electric tractor has not been feasible due to high value of overweight. Previous studies suggested overweight values on series of different tractor models come within range of 36% to 99%, compared to conventional tractors. Motorized tractors with other sources of energy such as fuel cell (FC) [8, 17, 32] and reformed methanol fuel cell (RMFC) [6] contributed to significantly less overweight values, which has gained more attraction globally [12, 15]. In addition, hybrid plan which involve the use of ICE along with alternative power sources has been a global trend, in comparison to a fully electric vehicle [21, 31].

Overweight plays an important role of electric tractor potential development. Soil pressure at static load comes within range of 74.40 kPa to 95.10 kPa with series of different electric tractor models. The values of soil pressure are considerably higher than tractors with other power sources as the impact of overweight. At this point, the value does not reach the limit for soil compaction at 130 kPa. However, dynamic load is known to be several times higher than static load which will lead to soil degradation in a long run. The soil compaction commonly contributes to reduction in soil porosity which affect root growth and in advance reduce farming yield and productivity [10, 12]. In addition, overweight has notable impacts on maximum speed and state of charge (SOC) of the tractor. Simply, overweight reduces potential maximum speed of tractor which will affect the common scenario for agricultural practices. The overweight tractor consumes notably higher energy in which electric tractor will be able to work under ideally 4 hours of working time. Poor performance of these two properties would affect the sustainability of electric tractor in a long run [12, 13]. Thus, this research will optimize the design of motorized agricultural tractor with electric battery by applying alternative components and scenarios to reduce overweight value to an applicable level through simulations.

2. Materials and Methods
Utility tractor was selected as the type of tractor used for optimization. It is 4-Wheel-Drive (4WD) low to medium horse power tractor that is mainly used with additional attachments such as loader, backhoe, rotary cutter, landscape equipment, tillage equipment, and other equipment for agriculture and construction. Utility tractor was selected due to its functionality, global scale application, and its similar structure with common 4WD vehicles where motorized electric battery power system has been widely applied.

2.1. Component Selection and Specification
The motorized electric utility tractor has significant overweight value, up to 99%. Lithium-ion battery (LIB) 18650 with commercial gravimetric energy density at 243 Wh/kg, contributed to 43% of the total weight of the tractor. Thus, two alternative batteries with higher energy density were considered for further optimization; Li_{4.4}Si, and Lithium Sulphur (Li-S) battery [3, 25, 30]. High energy density battery is crucial for many purposes, especially power generation for off grid areas and industrial sector. In agricultural tractor, the alternative batteries are expected to reduce the weight and soil pressure of the utility tractor significantly by providing sufficient energy with lightweight properties [11]. Li_{4.4}Si is a Si-based anode LIB which has been a growing attention due to its specific capacity, environmental friendliness, and low cost. However, there are several practical drawbacks to be considered [16]. Li-S battery is a type of rechargeable battery, which is considered as a promising
successor of LIBs due to its notable specific energy. There have been growing academic research related to development of Li-S and commercialization has been available since 2014 [18, 22]. The following table shows specification of each battery.

**Table 1.** Comparison of basic specifications of LIB (lithium ion battery), Li4.4Si (lithium ion with Si anode battery), and LIS (lithium sulphur).

| Type of Battery | GED (Wh/kg) | VED (Wh/kg) | Mass (Max g) | Rated Capacity (Ah) | Nominal Voltage (V) |
|----------------|-------------|-------------|--------------|---------------------|---------------------|
| LIB 18650      | 243         | 676         | 48.5         | 3200                | 3.6                 |
| Li4.4Si        | 350         |             |              |                     |                     |
| Li-S           | 500         |             |              |                     |                     |

Additionally, Permanent magnet synchronous motor (PMSM) were selected to replace AC induction motor that has been used on previous studies. PMSM has smaller and more compact structures with higher motor efficiency, in comparison to AC induction motor [2]. Dual motors plan will be considered for the simulation to improve high performance of working range of the motors, which lead to greater efficiency of the tractor plans. The improvement in motor efficiency has an important role to save significant amount of valuable electrical energy [20, 28].

### 2.2 Tractor Remodeling and Equation for Calculation

Tractor remodeling is compulsory due to application of different power system on utility tractor. Essentially, tractor remodeling will affect physical and mechanical properties such as weight, volume, and soil pressure based on specification of each components. Major components to be considered are the chassis, AC/DC inverter, and planetary gear, which are not commonly applied into conventional tractor. Additionally, control system of motor and battery were implemented. The design was implemented into selected models of utility tractor 17.5kW-75kW. Remodeling on each model might affect the physical and mechanical properties differently. The following figure is the simplified scheme of remodeled utility tractor design.

**Figure 1.** Layout of motorized utility tractor with electric battery power system by using LIB (lithium ion battery), Li4.4Si (lithium ion with Si anode battery), and LIS (lithium sulphur) on rated output power 17.25-75 kW by using MATLAB/Simulink.
The followings are the equations to be considered to understand the physical and mechanical properties of the remodeled utility tractor.

\[ E = \frac{P \times t}{\eta} \]  \hspace{1cm} (1)

where \( E \) is the required electricity for specific tractor [kWh]; \( P \) is the output power which specify the model of utility tractors [kW]; \( t \) is the working hours of the tractor [h], in this case the working hour is fixed considering common 4 hours and 2 shifts plan; \( \eta \) is the fuel efficiency of electric battery [%], the value is fixed at 66.5% [23].

\[ W_{BP} = \left( \frac{E_{GED}}{GED} \right) + \left( \frac{E_{GED}}{GED} \right) \times 28.5 \% \]  \hspace{1cm} (2)

where \( W_{BP} \) is weight of total battery packs [kgf]; GED is gravimetric energy density of series of different batteries [Wh/kg]; and 28.5% is the percentage of total weight of the packs where heat management system is implemented including radiator, air flow, etc.

\[ P_P = \frac{W_{MAX}}{100 \times AC} \]  \hspace{1cm} (3)

\[ P_P = \frac{W_{MAX}}{100 \times (2 \times W_F \times L_F + 2 \times W_R + L_R)} \]  \hspace{1cm} (4)

where \( P_P \) is the soil pressure from the tractor [kPa]; \( W_{MAX} \) is the total weight of the utility tractor [kgf]; and \( AC \) is the total contact area from the wheels to the soil [m²]. \( AC \) can be calculated by width (\( W_F \) and \( W_R \)) and length (\( L_F \) and \( L_R \)) of front and rear wheels.

2.3. Simulation

Simulation was used to predict the drivability and performance of remodeled utility tractor. Through simulation, a better understanding of the relationship of overweight with speed and SOC of the battery is expected. With alternative components and remodeling to utility tractor, maximum speed and SOC consumption are expected to be improved. The following parameters have major impacts for heavy duty and extended range vehicles such as utility tractor. The simulation would combine these parameters with other parameters on a component level [29].

**Table 2.** Major parameters of motorized utility tractor with electric battery power system for speed and SOC (state of charge) simulation by using MATLAB/Simulink.

| Major Parameters     | Unit   | Value          | Source |
|----------------------|--------|----------------|--------|
| Output Power, \( P \) | kW     | 17.5-75        | [12]   |
| Fuel Efficiency, \( \eta \) | %      | 66.5           | [12, 23] |
| Working Hour, \( t \) | h      | 4              |        |
| Gravimetric Energy Density |       | 243, 350, 500  | [3, 4, 16] |
| Battery Weight, \( W \) | kgf    | 0.0485         | [3]    |

Simulation on remodeled utility tractor powered with electric battery was conducted by using MATLAB-Simulink software. The software provided a feature called Simscape in which common electrical and mechanical items can be utilized. The specification can be conducted on overall system and individual component or group. In the simulation, 75 kW tractor was chosen with other models with the
least overweight percentage which will be determined from previous process. Simulation under full load condition will be conducted by controlling the voltage and Center of gravity of selected plans. Figure 2 shows simulation scheme to be applied for each model. Model and simulation condition were selected by changing the values on component level based on parameters used for simulation.

Figure 2. Simulation scheme by MATLAB/Simulink – Simscape for selected output power and batteries for drivability and maximum speed estimation.

To estimate the SOC of each plan, separate simulation scheme will be conduction based on the properties and battery dynamics shown in figure 3. In this plan, voltage and current will be major parameters to be considered [9].

Figure 3. Simulation scheme by MATLAB/Simulink – Simscape for batteries SOC estimation.
3. Result and Discussion

3.1 Weight and Soil Pressure

Weight and soil pressure by using alternative components for motorized electric battery power system in rated output power from 17.25-75kW utility tractors was calculated. Weight and soil pressure of ICE-UT (utility tractor with conventional internal combustion engine) was used as a base for comparison. The calculations shown within ±2% of weight fluctuations.

Figure 3 shows the application of alternative batteries (Li4.4Si and LIS) reduce the total weight of utility tractor, significantly. It reflected higher gravimetric energy density [Wh/kg] of alternative batteries compared to LIB. LIS battery has highest weight reduction for all models of utility tractor. However, the weight of tractors with LIS battery is still noticeably higher than conventional utility tractor.

![Figure 3](image-url)

Figure 4. Comparison of weight of UT (utility tractor) for ICE (internal combustion engine), LIB (lithium ion battery), Li4.4Si (lithium ion with Si anode battery), and LIS (lithium sulfur) on rated output power 17.25-75 kW.

Figure 4 shows comparison of overweight percentage on each model to understand the influence of alternative batteries among utility tractors with different rated output power. Light utility tractor, 17.25kW, has highest overweight percentage with all three different batteries. With assumption that overweight has impact to tractor performance in terms of speed and battery consumption, it reflected that 17.25 kW tractor would not be suitable for electric battery power system. In reverse, 33.75 kW and 41.25 kW utility tractors with lowest overweight percentage, were chosen for further simulation. In addition, 75 kW utility tractor was also selected to be simulated for comparison purposes.
Figure 5. Overweight value of UT (utility tractor) for LIB (lithium ion battery), Li4.4Si (lithium ion with Si anode battery), and LIS (lithium sulphur) on rated output power 17.25-75 kW.

Table 3 shows influence of weight fluctuations to soil pressure by different power system on models of utility tractor. LIB-UT has highest pressure on all rated output power under static load. Dynamic load is several times higher than static load, in which it may exceed permitted limit for pressure at 130 kPa. The simulation considers normal road condition, in which soil compaction will not be an issue. However, soil compaction will have a significant impact on agricultural land when soil profile is applied, depending on farming type when utility tractor is utilized [18].

Table 3. Comparison of soil pressure of UT (utility tractor) for ICE (internal combustion engine), LIB (lithium ion battery), Li4.4Si (lithium ion with Si anode battery), and LIS (lithium sulphur) on rated output power 17.25-75 kW under static load condition.

| Output Power | 17.25 kW | 33.75 kW | 41.25 kW | 48.75 kW | 75 kW |
|--------------|----------|----------|----------|----------|-------|
| Front Tire Model | 18x8.5−10 R1 | 7.5−16 R1 R1 | 9.5−24 R1 R1 | 9.5−24 R1 R1 | 12.4−24 R1 |
| Rear Tire Model | 26x12−12 R1 | 13.6−28 R1 | 14.9−28 R1 | 16.9−28 R1 | 18.4−30 R1 |
| Contact Area [m2] | 0.16 | 0.35 | 0.44 | 0.49 | 0.61 |
| ICE-UT Soil pressure [kPa] | 37.36 | 68.60 | 56.80 | 51.00 | 57.84 |
| LIB-UT Soil pressure [kPa] | 71.91 | 94.62 | 82.33 | 80.12 | 93.09 |
| Li4.4Si-UT Soil pressure [kPa] | 57.29 | 84.02 | 71.30 | 66.78 | 79.28 |
| LIS-UT Soil pressure [kPa] | 50.32 | 77.79 | 63.70 | 60.34 | 71.34 |
| Limitation of soil compaction [kPa] | 130.00 |
3.2 Hypothesis on Vehicle Performances: Speed and SOC

Relationship between overweight and performances of remodeled utility tractor is being studied using simulation on MATLAB/Simulink. The remodeled plans are being simulated by considering energy delivery from energy sources to wheels of the tractor. 33.75 kW and 41.25 kW utility tractor were remodeled and simulated as the least affected plans by overweight on component measurement level, in which is expected to have better performance than other models. Additionally, 75 kW tractor was selected for simulation for comparison purposes with previous study.

Figure 5 shows speed fluctuations on each output power by using different batteries. On 33.75, 41.25, and 75 kW remodeled utility tractors, maximum speed can be achieved by using Li-S battery as the least overweight plan. The maximum speeds reach 18.71, 18.83, and 17.74 km/h, with respective output power. The 41.25 kW tractor is expected to reach the highest maximum speed among two other models. It suggested that overweight has a significant negative influence with tractor speed. Alternative batteries with higher energy density are required to optimize the potential maximum speed. In addition, application of motorized power system with electric battery is highly potential on medium horse power utility tractor and not recommended to be applied on heavy duty utility tractor. However, in comparison to conventional tractor on each output power, the maximum speeds were slightly behind due to overweight. The ideal maximum speed for these plans is 20 km/h.

Figure 6 shows battery SOC consumption on one hour simulation plan by using series of tractor models and batteries. On LIB plan, simulation result showed that SOC was decreased from 98% to 69% (29% was consumed) after one hour of working time. It implied that remodeled utility tractor with LIB can only work up to 3.45 hours on one charging cycle of the battery. With alternative batteries, SOC consumptions were observed to be lower, with LIS plan as the least consumptive on SOC of the battery. Similar with tractor speed, 41.25 kW remodeled utility tractor was the most durable plan with maximum working hour up to 3.88 hours. The expected results are not sufficient for common farming work with 2 shifts per day, at 4 hours of working time per shift. The result suggested that overweight has significant impact on SOC consumption of the battery.

![Figure 6. Expected Speed of UT (utility tractor) for LIB (lithium ion battery), Li4.4Si (lithium ion with Si anode battery), and LIS (lithium sulphur) on rated output power 33.75, 41.25, and 75 kW.](image-url)
Figure 7. Expected Speed of UT (utility tractor) for LIB (lithium ion battery), Li4.4Si (lithium ion with Si anode battery), and LIS (lithium sulphur) on rated output power 33.75, 41.25, and 75 kW.

Validation is highly required to these plans to improve the accuracy of the results into real scenario. The simulation considers normal road condition which will not be a valid scenario for agricultural tractors. Thus, selection of agricultural applications and soil profile will be necessary for further prediction through simulation. Addition of soil profile is expected to affect the soil compaction and can be used to estimate the yield based on farming plan by using electric battery [26, 27].

4. Conclusion

Based on the optimization study, the following conclusion can be mentioned:

1) Application of alternative batteries (Li4.4Si and LI-S) have shown significant improvement in tractor weight and soil pressure. The LI-S battery has the highest weight reduction in comparison to tractor powered with commercialized battery (LIB 18650).

2) 33.75 kW and 41.25 kW utility tractors were the least influenced by overweight which suggested those models are suitable for motorized electric battery power system.

3) Remodeled utility tractors are expected to gain improvement for maximum speed and SOC, but don’t reach standard value due to remaining overweight on the tractor plans.

4) The accuracy of the study is not guaranteed and further studies are still needed, especially on the additional features such as soil profile, control system, temperature effect, and 3D model simulation.

5) Motorized utility tractor with electric battery power system is still too heavy to conduct farming work. However, in the future, this technology is expected to replace the use of fossil fuel within ICE (internal combustion engine).
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