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CHALLENGES AND POSSIBILITIES OF THE INTEGRATION OF ELECTRIC DRIVES IN MOBILE MACHINERY

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ABSTRACT

This paper provides an overview of the challenges and possibilities of the integration of electric drives into diesel-hydraulic excavators. Due to the drivers of emission reduction, the use of renewable energies and more energy efficient systems, a global push leads to the integration of electric drives in excavators. In mobile machinery such as excavators, new possibilities and challenges of the adaptation of the drive train and energy storage arise.

Rotational actuators can be powered by direct electric drives to avoid losses of the hydraulic system. Adapted hydraulic system topologies enable recuperation and reduce throttling losses in hydraulic systems. Variable and overall higher electric motor speeds reduce the size of the electric and hydraulic components and enable operation in more efficient operating points.

To evaluate possible changes to the traditional hydraulic excavator systems, a simulation model is built and the proposed adaptations are implemented. The paper concludes with the evaluation of the proposed system changes and an outlook for further possibilities of hydraulic system adaptions in relation to the electric drive.

Keywords: Excavator, Electric, Mobile Machinery, Battery, Energy, Emissions

1. INTRODUCTION

1.1. Motivation

In order to counteract climate change and improve air quality, it is necessary to reduce relevant sources of greenhouse gases and air pollution. Considerable CO_2 emissions are caused by the construction industry. In the construction industry fossil fuels alone produce 300 million tons of CO_2 per year, representing 1 % of global CO_2 emissions [1]. Furthermore, research by Helms show in 2014, the emission rate of NO_x from mobile machinery was 20 % of the emissions from the transport sector and the particulate pollution from mobile machinery was on a par with the transport sector [2]. The environmental and health burdens caused by NO_x and particulate matter can only be reduced by complex exhaust gas after treatments. In particular, the avoidance of CO_2 emissions directly in combustion engines is not possible [3].

Restrictions are being imposed politically worldwide to reduce emissions. In the transport sector, for example, Norway will forbid the registration of new cars driven by combustion engines from 2025, the Netherlands and Germany from 2030 and France from 2040 [4]. Whilst currently effective bans are limited to passenger cars, there are already efforts to extend these developments to all machines with combustion engines, such as Japan's plans to integrate the use of hydrogen in all energy sectors from 2030 to 2050 [5].

In order to reduce emissions for mobile machinery, clean energy sources have to be used. Compared to the emissions of the Diesel engine, electric energy, especially from renewable sources, can lower the CO_2 emissions, as the CO_2 equivalents of the Diesel engine and electric energy sources imply and is in the diagram including the electric grid and charging losses in **Figure 1**.
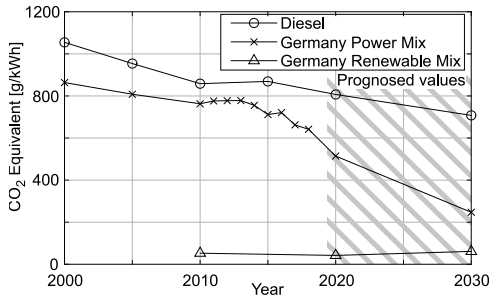
Figure 1: CO_2 Emissions of power sources based on mechanic output [6–8]

As it already has emerged in the transportation sector, electric drives can achieve this task by using electric energy from renewable energy sources. Therefore, the challenge arises to integrate electric drives into mobile machinery, for which the example of an excavator is used as a baseline in this paper.

1.2. Challenges

It has already proven possible and feasible to integrate electric drives with lithium-ion batteries into mini excavators, as there are models with a weight up to 4 t to be released from different manufacturers [9–11]. Nevertheless, for larger machines, challenges arise in the storage of the necessary electrical energy, as on the one hand the performance class of the machines increases and on the other hand the degree of utilization also rises. A 26-ton Caterpillar excavator prototype uses 300 kWh of batteries, with a battery weight of 3.4 tons [12]. Considering the large amount of required batteries in relation to global demand, not only the cost of batteries but also their availability is challenging [13].

In addition to the challenges of storing the energy, the electric drive induces a changed system behavior and additionally enables new possibilities of variable engine speeds, direct electric drives and recuperation. Traditional hydraulic systems however are built for a single direction power flow using variable displacement pumps running at constant speeds [14]. By adapting the hydraulic system, the advantages of the electric drive system can be utilized to improve the excavator system in terms of energy efficiency, thus reducing the necessary stored energy [15].

2. STATE OF THE ART

The current development in the electrification of excavators is driven by requests of energy-efficient and emission-free construction machinery [15]. Developments of battery technology and power electronics make it possible to build battery powered excavators, which can be operated for a working day without down time [9].

2.1. Batteries and Power Electronics

The first documented mobile application of electric was an electric car in 1827, even before the invention of the diesel engine in 1893 [16]. Nowadays, electric drives are used in a wide range of mobile applications, from small drives of only several watts for auxiliary drives to the 16.56 MW traction drive of a bucket-wheel excavator [17]. There are three types of electric machines which are used in most mobile drive applications: induction machines, synchronous machines and switched reluctance machines. The preferred machine type depends on the application. While switched reluctance machines are interesting for high-speed applications, synchronous machines achieve higher efficiency, and induction machines are cheaper and more reliable [18].

In most mobile drive applications, power-electronic inverters are applied to control the machine speed and torque, especially when variable speed is required or the machines are fed from a dc source. These inverters consist of semiconductor switches, a control unit, and several filter elements. They can reach efficiencies of up to 98% [19].

The electric power for the drive can be supplied from a battery (dc source) or directly from the grid (ac source). For mobile machinery, batteries are preferable, as they allow full freedom of movement. They offer an efficiency of up to 97 % from charging to discharging and energy densities of up to 240 Wh/kg [20]. For high-power applications and nearly uninterrupted operation, a direct connection to the grid is still the only feasible option.

2.2. Electric Excavators

There are three types of commercially available excavators using electric drives: Mining excavators, mini excavators and hybrid

excavators. The history of electric mining excavators reaches back over 100 years with electric rope excavators [21]. Today electric excavators are still widely used in surface mining, especially in large machines. Main reasons for electric mining excavators are reduced fuel costs, reduced emissions and a higher up-time [22]. Electric mining excavators are generally powered by cable as the large amounts of energy cannot be stored in batteries and, as the excavators move very little, the use of a cable is possible. An example for a cable-based mining excavator is the Liebherr R 9200 E [23]. The 850-kW engine power of the 210 t machine is made possible by a 6 kV cable. A limit for larger scales does not exist, as the largest machine in the world is an electric mining excavator, the Bagger 288. The machine weighs 12.840 t and the electric drives provide a sum of 16.56 MW of power with a voltage supply of 30 kV [17].

In contrary to mining excavators, mini excavators face different working environments and requirements. The installed engine power of available machines range from 7.5 kW in the Bobcat e10 excavator to 75 kW in the Suncar TB260E [10, 24]. In addition, the utilization of the machines is lower compared to large excavators. This results in an overall low energy consumption and it can be feasible to use batteries as an energy source. In the available electric mini excavators, no adaptations of the hydraulic systems besides the integrated electric drives are published by the manufacturers.

Hybrid excavators use electric drives to improve energy efficiency and reduce the fuel consumption of their combustion engines. Hybrid crawler excavators by Komatsu and Hitachi rely on electric swings to recuperate the kinematic energy from the heavy machines. The manufacturers state fuel savings from 20 % up to 40 % [25, 26].

2.3. Excavator drive train

The drive train of the excavator can be split up into the energy source, energy conversion and energy output. Traditionally, a diesel engine supplies the energy to the hydraulic system, which then directs it to the cylinders or engines. Topologies of the drive train of excavators are traditionally based on valve-controlled closed-center or open-center systems. The key drives of an excavator include the cylinders of the working equipment, the swing to turn the upper carriage

and the travel drive to move the excavator, as it is displayed in a simple form in **Figure 2** [14, 27].
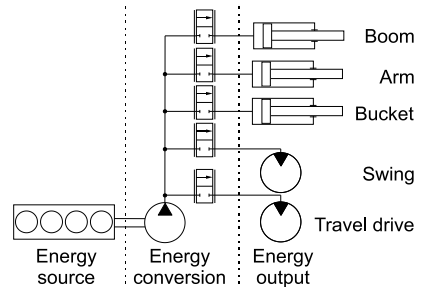

Figure 2: Traditional excavator system

3. POSSIBILITIES FOR ELECTRIC DRIVE INTEGRATION

In mobile applications, the diesel engine mostly runs at a fixed speed and it is physically impossible for the engine to recuperate energy. Based on those properties, the hydraulic systems are designed. The pumps run at a fixed speed and a possibility to recuperate negative loads is not included in the Load-Sensing or Open-Center systems [28]. With changing the energy transmitter to an electric machine, adaptations to the drive train are necessary to fully use the benefits of the electric drive.

3.1. Direct Electric Drives

In a hydraulic system, efficiency losses of the components cannot be avoided. Additionally, systematic losses due to throttling increase the required power of the system [29]. When using direct electric drives, the overall efficiency of the system can be improved. Rotational drives are directly powered by electric motors, while linear drives are powered by linear actuators or rotational motors with spindle drives. A major restriction for electric linear drives is the power density. Power densities of the hydraulic linear actuators are of magnitude 10 to 1000 higher compared to spindle drives with electric motors [30].

In contrast to electric linear drives, the power density of rotational high-speed drives is in the same order of magnitude as that of hydraulic drives. In 2009, Jacobs presents a comparison of the power densities of an electric high-speed drive with gearbox to an inclined axis and swashplate units with gearbox [31].The presented

power density of the electric unit is 0.11 kW/kg and that of the hydraulic units is 0.16 kW/kg. The application under consideration is a Baitrack BP 130/85 B mobile crusher. The benefit of a direct electric drive is the improved efficiency, especially in partial loads where the efficiency of the hydraulic units is sub-par [31].

In an excavator, the travel drive and the swing rotational movements can be powered by direct electric drives. To demonstrate a comparison of efficiency of the excavator, in chapter 4 the integration of an electric swing into the machine is evaluated based on a 90° digging cycle.

3.2. Dynamic Motor Speeds

The use of power electronic inverters enables variable motor speeds. When combing a variable speed electric drive with a constant displacement pump, the hydraulic volume flow can be controlled by the motor speed and the losses of the pump controllercan be avoided. Another possibility is to use variable drive speeds in combination with a variable displacement pump. This gives the option of a dynamic operating point to improve the efficiency of the components.

As the power density of the electric drive improves with increasing speed, high speed drives are an interesting option for mobile applications [32]. For traction drives, a gearbox is required to achieve a reasonable rotational speed of the wheels. But especially for the working hydraulics, high speed machines combined with high speed constant displacement pumps can offer a large increase in power density. In combined research by the Institute for Machine Elements and Systems Engineering and Institute for Fluid Power Drives and Systems of the RWTH Aachen, it is demonstrated that an increased speed by an electric drive can reduce the necessary installation space considerably. An increase of the maximum rotational speed from 2200 1/min to 3800 1/min reduces the required installation space by 68%, at 10000 1/min the installation space is reduced by 89% [33]. Using mechanic transmissions, high engine speeds can be integrated with moderate pump speeds.

3.3. Recuperation

As electric drives inherently allow bidirectional transformation of electrical and mechanical

energy, they can be used to recuperate the breaking energy of the swing and the saved potential energy of the working hydraulics. Depending on the operating point, an efficiency of up to 95 % of the electric drive can be reached. Electric recuperation systems are traditionally used in swings of hybrid excavators, such as products from Hitachi and Komatsu [25, 26]. In an excavator with an electric swing, the recuperation system can be integrated without further adaptions. The recuperation of negative loads of the linear drives proves more challenging, as the movement must be transferred into a rotational movement for the electric drive.

4. DEMONSTRATION ON A COMPACT EXCAVATOR

In order to evaluate the proposed adaptions for the electric excavator, the integration into the machine is demonstrated with a simulation model. In this simulation model, the kinematic and hydraulic system of a 9 t compact excavator is modelled and used as a basis. In a 90 ° dig and dump cycle, the adapted system behavior of the machine is evaluated.

4.1. Modelling

The simulation model consists of three parts, power source, hydraulic system and kinematic structure. The kinematic structure represents the movement of the excavator and determines the cylinder and swing load. The engine, in this model a diesel engine is compared to an induction motor, provides the power for the system. The most common hydraulic system for compact excavators is an Open-Center system [14]. The Open-Center system distributes the power to the hydraulic drives and defines the system behavior. For the excavator model, a public layout by Hitachi is used as a basis [34]. The simulation is built in AMEsim as a 0D simulation model.

The modelled compact excavator uses a 40.5 kW diesel engine. The specific fuel consumption of the diesel engine is optimal in a small area of the engine map, as it is displayed in **Figure 3**.
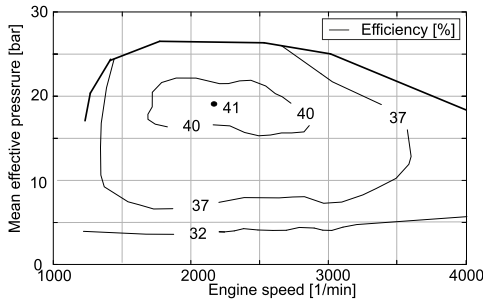
Figure 3:   Diesel fuel consumption [35]

In contrast to the restricted work point of the diesel engine, the induction motor can be varied in a larger area without a major efficiency drop. In **Figure 5** the efficiency map of an asynchronous machine with inverter is displayed.
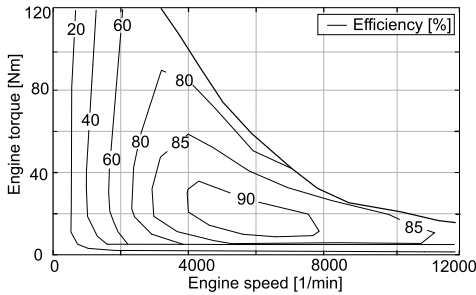

Figure 5:   Efficiency   induction   motor   with inverter [36]

Two variable displacement axial pump-motor-units size 36 are used in Open-Center system of the simulation model. The pump adjustment and valve actuation are modelled with a hydraulic pilot system but also with a direct electric actuation. A pilot system with a pilot pump volume flow of 20 L/min and a pilot pressure of 36 bar is used. To model the hydraulic losses of the pump controller, a bypass orifice is set according to measurements from Lux [37]. At a pump pressure of 200 bar, a volume flow of 2.8 L/min is used for the controller. The energy consumption of 28 W of the Parker RE06M*W is used for the electric pump controllers without a pilot pressure system [38]. For the electric swing break, the ROBAstop-M of the manufacturer Mayr is assumed [39]. For direct actuated valves, the energy consumption of the Parker D3FB, a proportional NG10 4/3 way valve is considered as data for the energy consumption of a direct controlled open-center valve of this size is not available [40].

In case of the electric engine, the engine speed can be set dynamically to run the pumps and the electric drives at more efficient operating points. In addition, the possibility of fixed displacement units with variable engine speeds arise. This method of flow control avoids using a pump controller and reduces by-pass losses [37].
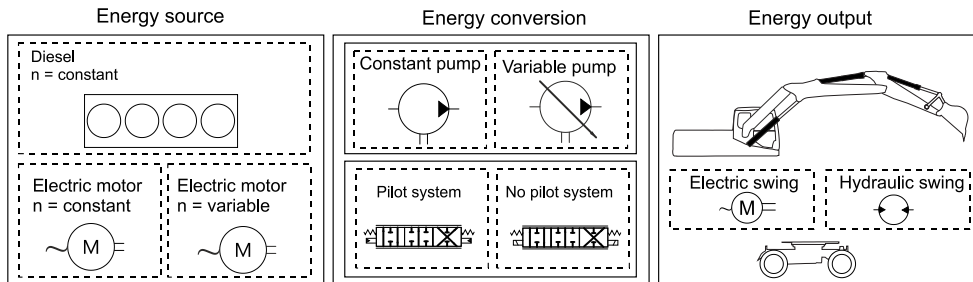

Figure 4:   Excavator system layout and variants

An overview of the possible adaptions and the model layout presents **Figure 4** and as a list the explicit tested variants **Table 1**.

Table 1:   **Model combinations**

#	Motor	Motor speed	Swing	Pump	Pilot system
1	Diesel	Constant	Hydr.	Variable	Yes
2	Electric	Constant	Hydr.	Variable	Yes
3	Electric	Constant	Electr.	Variable	Yes
4	Electric	Variable	Electr.	Constant	Yes
5	Electric	Variable	Electr.	Variable	Yes
6	Electric	Variable	Electr.	Constant	No

4.2. Test Cycle

In order to determine the forces impressed on the bucket, a model is used in which the digging forces are determined based on the current grave cross section, the grave movement and material parameters [41].

The movement of the test cycle is according to a 90° dig and dump cycle. The excavating movement of the excavator bucket is displayed in **Figure 6**.
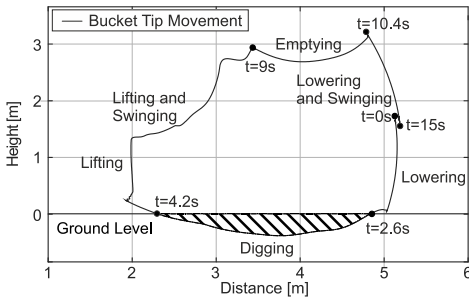
Figure 6:   Excavating movement

The cycle starts with the empty bucket in the air. At first the boom is lowered, then in movement of all three cylinders the surface is dug out. It is followed by a lifting of the boom whilst turning the bucket to keep the dug ground material in it. With an upwards movement of the bucket by a movement of the boom and arm, the machine swings to the side. In a height of 2.8 m, the bucket is emptied and the excavator moves back to the initial position.

4.3. Evaluation

In the evaluation, the required power, operational costs and the impact on the carbon footprint are compared. Systematic losses appear in the hydraulic system due to throttling losses. Efficiencies of the pumps, the Diesel or electric

engine further increase the required power. Considering a battery powered excavator, additional losses of charging and discharging the battery are considered. Research of Huss determined expected efficiencies of electric batteries in the year 2020 of $\eta_{\text{Battery}} = 80.9\%$ [7]. An additional power loss is induced by losses in the power grid, which are elaborated by Mehlhorn with an average grid efficiency in Germany of $\eta_{\text{Grid}} = 95.3\%$ [8]. This concludes in a required power for the electric machine P_{Grid} as shown in Equation 1.

$$P_{\text{Grid}} = \frac{P_{\text{Load}}}{\eta_{\text{Grid}} \cdot \eta_{\text{Battery}} \cdot \eta_{\text{Drive}} \cdot \eta_{\text{Pumps}} \cdot \eta_{\text{Hydraulic}}} \quad (1)$$

For the Diesel engine, the required chemical power is determined as in Equation 2.

$$P_{\text{Diesel}} = \frac{P_{\text{Load}}}{\eta_{\text{Diesel}} \cdot \eta_{\text{Pumps}} \cdot \eta_{\text{Hydraulic}}} \quad (2)$$

The energy consumption is defined as the use of diesel or electric power. The operational expenditure (OPEX) is the calculated cost based on the energy consumptions. Based on the lower calorific value of Diesel H_{u} with 43 MJ/kg and the density ρ_{Diesel} with 0.84 kg/L, the required Diesel consumption $\dot{V}_{\text{Diesel}}$ is determined as in Equation 3 [28].

$$\dot{V}_{\text{Diesel}} = \frac{P_{\text{Diesel}}}{H_{\text{u}} \cdot \rho_{\text{Diesel}}} \quad (3)$$

With the relative costs of the Diesel C_{Diesel}, the OPEX are determined. As a basis, the Diesel costs of 2018 in Germany is used. The average price without value added taxes is 1,009 €/L and with value added taxes 1,289 €/L. The OPEX is determined as in Equation 4 [42, 43].

$$OPEX_{\text{Diesel}} = \dot{V}_{\text{Diesel}} \cdot C_{\text{Diesel}} \quad (4)$$

For the electric excavator, the OPEX is based on the electricity costs for industry users with and without taxes. Without taxes, the price $C_{\text{Electricity}}$ in 2018 is at 8.97 €cent/kWh and with taxes 18.44 €cent/kWh [44]. The determination of the OPEX excludes the grid losses, as the price calculations of the consumers is based on the delivered energy.

$$OPEX_{\text{Electric}} = P_{\text{Grid}} \cdot \eta_{\text{Grid}} \cdot C_{\text{Electricity}} \quad (5)$$

The CO_2 emissions of the electric excavator $E_{\text{Electricity}}$ are determined based on the CO_2 equivalent of the German power mix and also based on the German electro mobile renewable mix. For the general German power mix, the

specific CO_2 equivalent $e_{Electricity}$ for 2019 is 445.7 gCO$_2$/kWh and for the renewable mix for electro mobile applications, the CO_2 equivalent is 43.3 gCO$_2$/kWh [6]. Included in the consideration of the CO_2 equivalent is the production and recycling of the lithium ion batteries. For this, a battery with a lifetime of 2000 h, a size to be able to run 4 hours under maximum load and a CO_2 equivalent of 175 kgCO$_2$/kWh is considered [45].

$$E_{Electricity} = P_{Grid} \cdot e_{Electricity} + E_{Battery} \qquad (6)$$

The CO_2 equivalent of the Diesel engine E_{Diesel} is specified by a [6] CO_2 equivalent e_{Diesel} of 819.5 kgCO$_2$/kWh. The value is based on the mechanic power output of an average Diesel engine in Germany in 2019 [6].

$$E_{Diesel} = P_{Diesel} \cdot \eta_{Diesel} \cdot e_{Diesel} \qquad (7)$$

The required power and the losses in the drive train is displayed in **Figure 7**. The average power consumption is displayed at the top, the efficiency losses of the drive train relative to its required power next to the bars. The variants are detailed in Table 1.
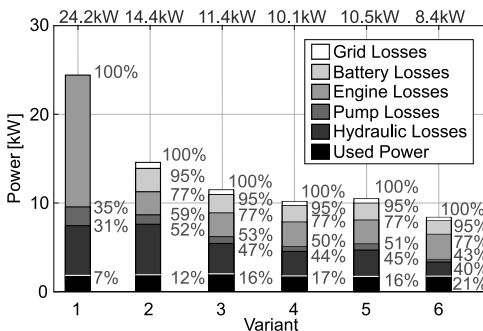

Figure 7: Power variants

Starting with the sole replacement of the diesel engine, first variant, by an electric motor, second variant, a significant change in the system behavior and efficiency cannot be noted. A 32 kW electric drive is able to power the system. In the third variant, in addition to the electric traction drive, the swing is electrically powered by an 8 kW electric drive. The electric drive allows negative energies to be recovered with corresponding efficiencies and additionally reduces throttle losses in the system. With the electric rotary actuator, a significant improvement of the drive system is possible, as

the consumption of the electrical input power is reduced by 21% compared to the second variant.

In variants four and five, in addition to the electric swing, variable motor speeds are considered, on the one hand with a constant pump and on the other hand with a variable displacement pump. In both variants the power consumption of the machine is reduced even further. In case of the variant with constant pumps, the average efficiencies of the constant pumps are higher compared to the dynamic use of the variable displacement pumps and the hydraulic pump controller losses are avoided. In case of the variable displacement pumps at variable speeds, the relation of the pump rotation speeds and swivel angles is set for the most optimal work point based on the pressure and volume flow. Overall, the variable speed variants are able to reduce the power consumption further by 8-11% for a total 30% in variant four.

In the last adaption, an electric actuation system is considered and variant four is adapted with the electric actuation system. As the pilot system is not used, the power intake of the machine is lowered by another 17% and the total efficiency is improvement by 42%. The avoidance of the pilot system is displayed in more detail in **Figure 8**, as the power consumption of the electric actuation is compared to the required electric power to drive the pilot pump.
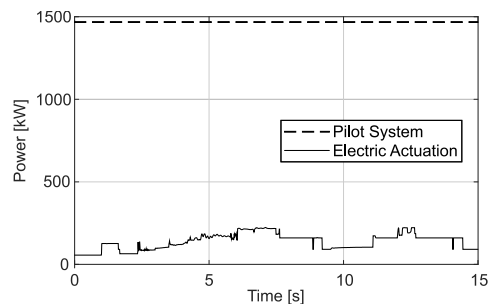

Figure 8: Electric valve actuation power consumption

With the required average power intake of the electric actuation of 138 W, 1329 W of electric power can be saved.

According to the power intake of the machine, the operational expenditure (OPEX) displayed in **Figure 9**.
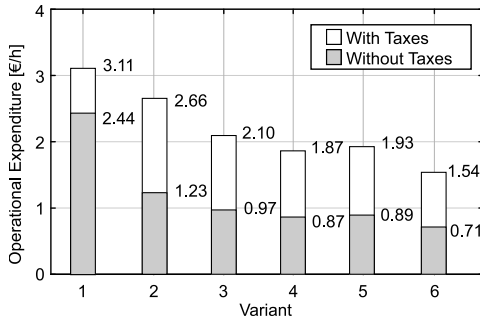
Figure 9: Operational expenditure

Even in the variant two without an electric swing, the operational costs are reduced by 15% while in the system with the lowest power intake, the costs to operate the machine are reduced by 50% compared to the Diesel engine. Further reductions are possible with tax breaks, which currently exist for electric cars.

The CO_2 equivalents of the different variants are displayed in **Figure 10**. The CO_2 production is elaborated for the Diesel engine, the use of the overall German power mix or the use of the renewable energy mix (RE) and under the use of a battery powered excavator or without the battery.
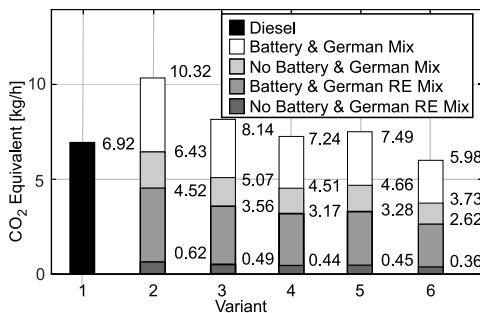

Figure 10: CO2 emissions

As it can be seen, the possible CO2 emissions of the excavator heavily depend of the system variant. Under the use of the German power mix and a battery, a CO_2 reduction is not possible. But under consideration of the use of renewable energy sources, even with a battery the CO_2 equivalent can be reduced by 68% in variant six. The largest contributor remains the battery production, as without the consideration of the battery, the CO_2 emissions are reduced from 6.92 kg/h of the Diesel engine to a 0.36 kg/h with renewable energy sources.

5. CONCLUSION AND OUTLOOK

Electrically powered excavators present a possibility to reduce CO_2 emissions and operational costs. In this paper system adaptations are elaborated and compared.

A major contribution to efficiency improvements are electric swings. Using a direct electric drive of the excavator rotation, hydraulic losses are reduced and parts of the kinetic energy can be recovered while breaking. In the simulated compact excavator, efficiency improvements of over 21% are possible.

Under the use of electric drives, variable motor speeds are able to further improve the system efficiencies. The use of constant displacement pumps with variable speeds improves the efficiencies of the components and avoids pump controller losses. Variable displacement pumps can be powered in more efficient operating points with variable motor speeds. With variable motor speeds, the efficiency of the system with electric swings is further improved by 8-11%.

Electric valve, pump and break control can be used to remove the losses of the pilot system. In the case of the electric excavator, the system losses are reduced by 17%.

With the proposed adaptations of the hydraulic system, a total efficiency improvement of 42% of the electric excavator is possible.

Further improvements can be focused on the adaptions of the layout of the hydraulic excavator, as the hydraulic losses are 74% of the total losses under the use of the hydraulic swing and 48% under the use of the electric swing.

NOMENCLATURE

Electr.   Electric
Hydr.   Hydraulic
OPEX   Operational Expenditure
RE   Renewable Energy

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