Cent. Eur. For. J. 70 (2024) 41–50 sciendo DOI: 10.2478/forj-2023-0024
CENTRAL EUROPEAN Forestry Journal

REVIEW PAPER

# Advancing sustainability in forestry machinery: Electro-Hybrid drives for greenhouse gas reduction and enhanced energy efficiency

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**Abstract**

This article deals with the possibility of reducing greenhouse gas emissions and fuel consumption in machines using cut-to-length (CTL) technology with the help of electro-hybrid systems. The text discusses the individual components of these systems. Furthermore, the article contains technical solutions for current electro-hybrid drive systems of harvesters, forwarders and forwarding trailers, including their description and available parameters. The current technical and technological development of electro-hybrid drive systems and their components leads to a significant improvement in the performance of drives of the new generation of CTL machines and to higher energy efficiency. Thanks to this, the use of electro-hybrid drive systems in these machines could significantly reduce greenhouse gas emissions as well as operating costs.

**Key words:** CTL (cut-to-length) technology; harvester; forwarder; hybridization; emissions; fuel consumption

Editor: Tomáš Gergeľ

## 1. Introduction

At present, there are concerns about the insufficient availability of fossil fuels, as well as the damage caused by emissions created by their combustion. The emissions include carbon monoxide (CO), carbon dioxide ($CO_2$), and nitrogen oxides ($NO_X$), along with particulate matter (PM) (Wasilewski et al. 2020; Di Blasio et al. 2022; Mizik 2022). As the consequence of these concerns, special regulations or so-called STAGE standards were introduced for all non-road machines, which include excavators, harvesters and forwarders from the forestry sector. To reduce emissions from internal combustion engines and meet these standards, several methods could be used. The first method uses already well-known conventional filters or system with AdBlue placed in the exhaust system of the machine (Sejkorová et al. 2017; Hurtová et al. 2019). Furthermore, the production of emissions can be reduced with alternative fuels, such as liquefied petroleum gas (LPG) (Fabiś & Flekiewicz 2021), compressed natural gas (CNG) (Khan et al. 2015), or its liquefied form (LNG) (Langshaw 2020). Besides, development of alternative fossils fuels of the diesel fraction groups could be expected in the future (Labaj & Barta 2006; Górski et al. 2018; Hissa et al. 2019; Hunicz et al. 2022; Rayapureddy et al. 2022). The last most common way of reducing emissions is the hybridization of machine drives. This method, together with filters in the exhaust system, makes it possible to reduce fuel consumption, which is a considerable financial expense for CTL technology machines. According to Klvač et al. (2003) fuel consumption accounts for 82% of the cost. Hybrid drive systems in forestry can reduce this consumption by between 10 and 50% (Lajunen et al. 2016). Today, hybrid harvesters are commercially produced by Logset Oy and forwarding trailers by Agama JSCo. However, new concepts of hybrid harvesters and forwarders are emerging and showing first results.

Currently, two types of hybrid (Fig. 1) systems have been utilized within the forestry sector. The first of them is a hydraulic hybrid system that uses a conventional hydraulic circuit. A hydraulic accumulator or a pump-hydromotor can be connected in this circuit (Erkkilä et al. 2013; Linjama et al. 2019) (Fig. 1). Hydraulic

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hybrid systems are demanding when it comes to the the weight and installation space of the machine (Einola 2013). For this reason, the second type of hybrid system, which will be the focus of this article, is increasingly being used commercially. This type uses electrical energy. The advantage of the electro-hybrid system is the size reduction of internal combustion engines, which reduces the weight and dimensions of the given machine (Sellgren 2023).

The electro-hybrid drive uses several sub-components. The first of them is an electric motor. The use of this component in hybrid systems offers an advantage in the form of its ability to change the magnitude of the developed torque very quickly (Elforest Technologies AB 2023). The generation of driving force is mediated by electromagnetic forces between the stator and rotor of the electric motor (Tong 2014). Due to their simplicity, reliability and low cost, the most frequently used electric motors are the asynchronous ones (Kocman 2002). These electric motors can work in three modes. In motor mode, electrical energy is converted into mechanical energy, in generator mode, the opposite phenomenon occurs, while in electric brake mode, regenerative braking takes place (Rahman et al. 2011; Kůs 2016).

Before electrical energy is consumed by a motor or stored in a storage unit, it must be adjusted to meet the current and voltage input values of the electric motors or storage. For this purposes, converters are used. According to the type of current and voltage at the input and output, converters can be divided into direct current (DC) converters, alternating current (AC) converters, inverters and rectifiers (Černík 2014; Tkotz 2014). DC converters change the magnitude of the voltage, while the voltage remains DC. In the same way, AC converters change the parameters of the alternating voltage, its magnitude and frequency (Lee 2009; Kůs 2016). DC voltage is supplied to the inverters and it is converted to alternating voltage in the inverter, on the other hand, the opposite process occurs in the rectifier, i.e. the change of alternating to direct voltage (Pavelka & Čeřovský 2009; Rahman et al. 2018; Hughes & Drury 2019). The converters are therefore connected to the circuits within the drive systems between the electrical energy storage and the electric motor.

The last sub-component of electric hybrid drives in CTL technology machines is the electrical energy storage, such as batteries or supercapacitors. Batteries store electrical energy in chemical form using electrochemical reactions (Lemian & Bode 2022). These reactions take place in a basic cell between two electrodes immersed in an electrolyte when an electrical circuit is connected to the terminals of the cell (Hadjipaschalis et al. 2009). The reaction involves the transfer of electrons from one electrode to another through an external electrical circuit. In contrast, a supercapacitor stores electrical energy with the help of an electrostatic charge (Hadjipaschalis et al. 2009). It consists of two electrodes and an electrically non-conductive separator, while the free space can be filled with an electrolyte (Iqbal & Aziz 2022). During operation, one electrode is then charged with an electric current and an electric charge of the opposite sign is induced in the other electrode (Olabi et al. 2021). In supercapacitors, there is no diffusion and the energy is stored as an electrostatic charge bound to the electrode, making the entire charging process faster than in batteries (Raza 2018). When compared to batteries, the supercapacitor has a higher energy density and a longer lifetime (Sani et al. 2018). It also has a high discharge current and a higher discharge voltage than standard batteries (Patel & Desai 2012). However, the voltage loss during discharge is faster (Sani et al. 2018; Karthikeyan et al. 2021). The specific power of a supercapacitor is 10 to 20 times higher than that of a battery and up to 100 times higher than that of a capacitor (Hromádko 2012). According to the arrangement of these sub-elements, several configurations of electro-hybrid systems can be distinguished: series, parallel, power split configuration, and configuration with fuel cells (Fig. 2) (Linjama et al. 2019). The parallel configuration is the most common one for CTL machines, followed by series configuration. Currently, there is also one fuel cell solution.

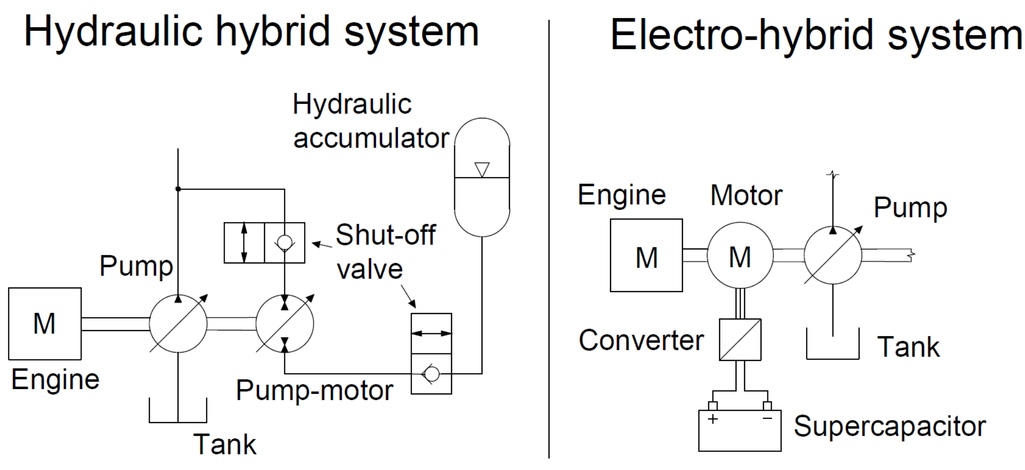


**Fig. 1.** Two hybrid systems for one solution.

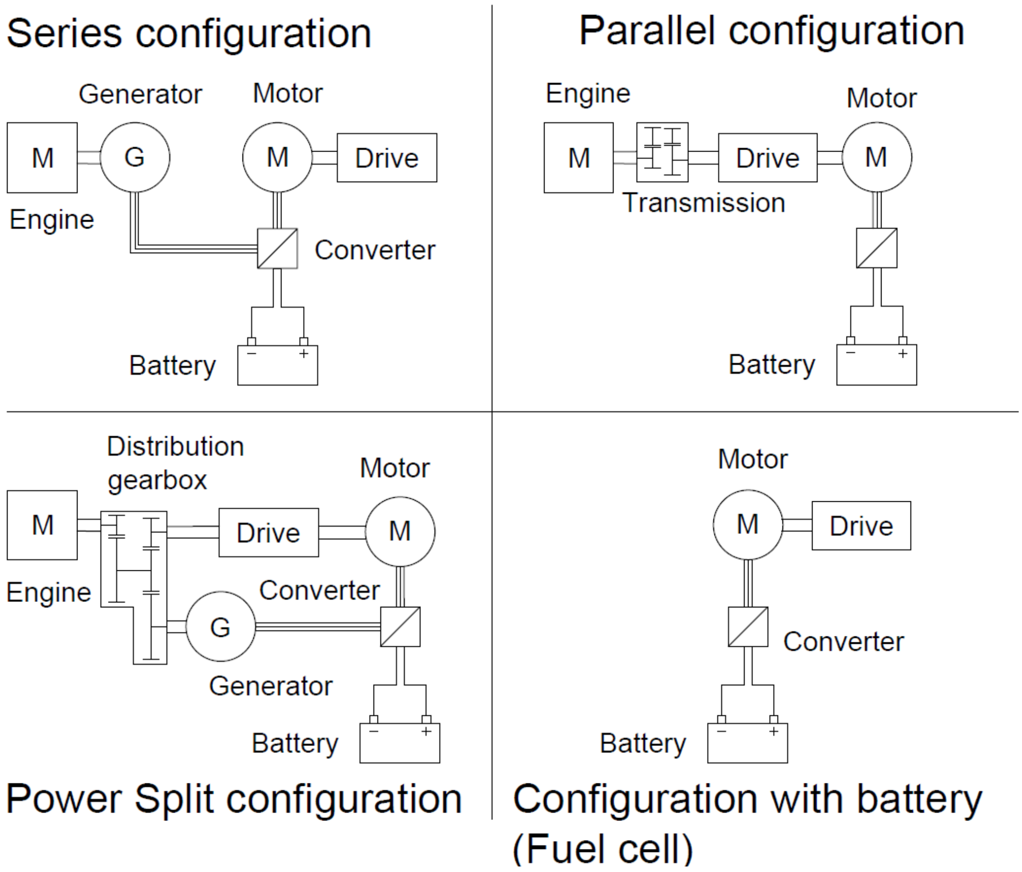


**Fig. 2.** Configurations of electric-hybrid systems.

## 2. Technical solutions

One of the currently used electro-hybrid machines in mechanized CTL technology is the harvester from Logset Oy. This manufacturer uses an Editron hybrid unit from Danfoss A/S (Pandur et al. 2021). It is a unit with the parallel arrangement of a hybrid system. The goal of the hybrid harvester system is to cover the necessary power peaks for the smooth running of the combustion engine at optimal speeds. The technical solution of this machine can be seen in Fig. 3. An electric motor is placed on the shaft coming from the combustion engine in front of the pump, which is able to work in both motor and generator mode. A supercapacitor is connected to the electric motor, in order to store the produced electrical energy (Robert Easton Ltd. 2023a). The supercapacitor can only store enough electricity to run the electric motor for nine seconds, but this is enough to boost energy during the harvester's short working cycles when power is needed (Johnsen 2023a). The system also includes a control unit that monitors the load on the internal combustion engine and decides whether the electric motor will work in engine mode, thereby delivering the necessary peak power, or in generator mode. An increase in the load on the combustion engine will be reflected in a decrease in its revolutions (RPM) (Elforest Technologies AB 2023). The load on the combustion engine and thus the necessary peak power increase occurs, for example, when the chainsaw of the harvester head is engaged in felling or shortening assortments (Johnsen 2023a). A similar hybrid drive system – Elturbo – is also used by the manufacturer Elforest Technologies AB. Elturbo is mounted on the output shaft of the combustion engine, where it reacts to small deviations in speed and immediately adds torque to reduce the load on the combustion engine

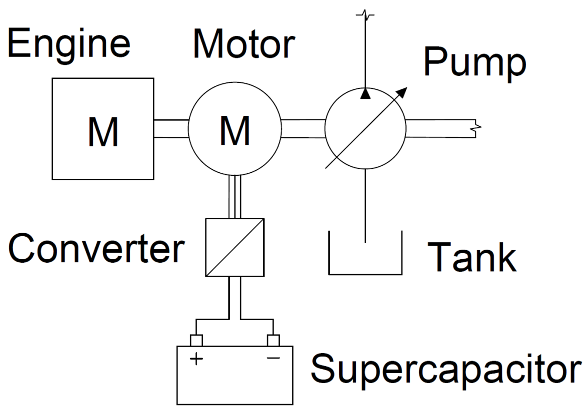


**Fig. 3.** Parallel hybrid harvester drive system by Logset Oy and Elforest Technologies AB.

(Elforest Technologies AB 2023). The output of this unit is up to 50 kW (Johnsen 2023b). This system was tested on the harvesters Pro Silva 910 EH from ProSilva Qyj and Ponsse Ergo from Ponsse Plc. (Einola 2013; Elforest Technologies AB 2023).

Another manufacturer that uses a parallel arrangement of the hybrid system is Agama JSCo, that created a prototype of a thinning harvester called AH6. Figure 4 shows a schematic representation of the connection of the relevant components to the drive unit. The internal combustion engine creates mechanical energy, which is then converted by the gearbox to the electric motor and pump of the hydraulic circuit (Mergl 2022). In the electric motor that operates in generator mode at low load, excess mechanical energy is converted into electrical energy. This energy passes through the converter to be subsequently stored in the batteries (Procházka et al. 2019). In the case of high load, the electric energy from the battery is used to drive the electric motor, which converts this energy back into mechanical energy and supplies the necessary power via a distribution gearbox to drive the pump. This system is operated by the control unit, which switches the individual modes of the electric motor based on the percentage load of the combustion engine. When the load is between 40 and 70% of the total load, the electric motor is switched off (Ulrich et al. 2021).

Other electro-hybrid solution for CTL technology machines is a drive system that uses the F14 forwarder prototype, which was created in cooperation between Elforest Technologies AB and AB Volvo. A scheme of the drive system of the forwarder is shown in figure 5. The internal combustion engine is connected via the transfer case to the pump of the hydraulic circuit and the electric motor. The electric motor works only in the generator mode and thus changes the mechanical energy from the combustion engine into electrical energy. The electrical energy passes through the inverter and is then stored in batteries. Stored energy is taken from the batteries via another converter to six electric motors in the wheels (BioAge Group LLC. 2023). These electric motors have the task of driving the traction system of the forwarders, where one 30 kW motor with a final gear is allotted to each wheel (Stoddart 2010). When driving downhill, the electric motors for driving the wheels can operate in generator mode, thus recuperating electrical energy from braking. It can already be concluded from the mentioned connection that this is a series configuration of the hybrid system. A peculiarity of forwarders apart from its drive is the division of the machine frame into three parts by an articulated connection. Thanks to this division and the use of electric motors in the wheels, less soil damage and higher maneuverability were achieved (Edlund et al. 2012). Elforest Technologies AB also created its hybrid forwarder in a conventional version called F15 (also known as B12). This version includes a two-piece frame machine and differs from its predecessor by using electric motors to drive the bogie axles. The same system as the F15 was also chosen by Rong-feng et al. (2017) for their hybrid harvester prototype.

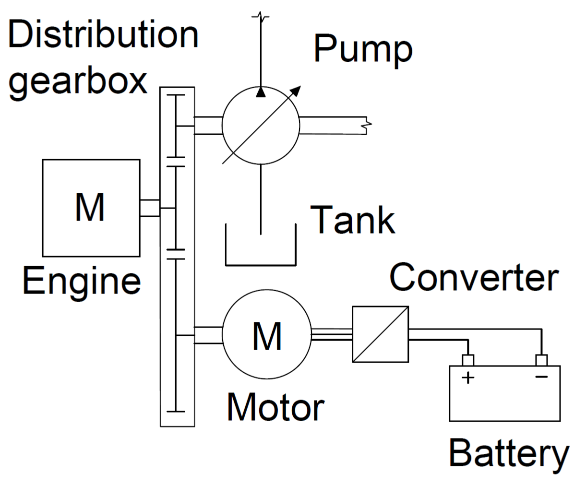


**Fig. 4.** Parallel hybrid harvester drive system according to Agama JSCo.

The latest addition to the series electro-hybrid solutions of CTL technology machines is the EV1 concept from Ponsse plc and Epec Oy. The scheme of the drive system of the EV1 machine is shown in figure 6. The mechanical energy created by the internal combustion engine is converted into electrical energy by the electric motor in the generator mode. Subsequently, this energy passes through the converter to the batteries, from which the electrical energy is then directed through another converter to the electric motors. EV1 uses electric motors to drive the traction device as well as the pump of the hydraulic system that controls the crane (Robert Easton Ltd. 2023b). The electric motors for the traction drive are connected by a shaft to the differential of the front or rear axle. The front and rear axles always have their own electric motor. The differential transfers mechanical energy to the bogie axles. The pump of the working hydraulic circuit is powered by mechanical energy produced by a separate electric motor, which is connected to the battery via an inverter from where it draws electrical energy. The battery can be recharged from an external source (Beneš 2023). A forwarder with this electro-hybrid system can work for approximately 30–45 minutes powered only by the energy stored in the batteries. As soon as the battery has exhausted to 40% of its capacity, it will be recharged with the help of an electric motor driven by the combustion engine of the forwarder (Reuter 2023). When charging reaches 80% of battery capacity, the combustion engine is turned off and charging ends (Beneš 2023). The arrangement and use of the drive system of the EV1 machine may seem similar to that of Elforest Technologies AB and their forwarders. These two systems are, however, distinguished by the use of an internal combustion engine, since the EV1 only uses the internal combustion engine when the battery is recharged, while

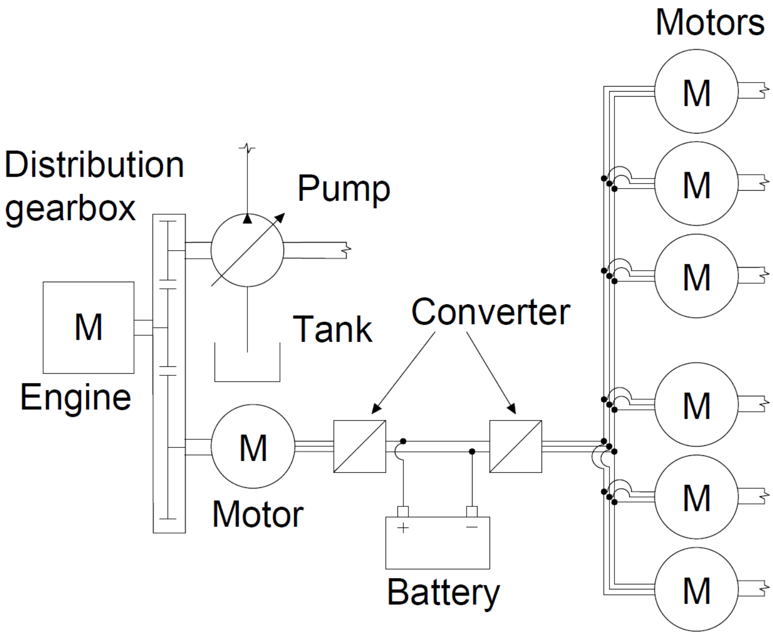


**Fig. 5.** Series hybrid drive system according to Elforest Technologies AB.

the engine is used continuously in the Elforest Technologies AB forwarders.

Thus far, hybrid drive systems of CTL technology machines in series or parallel arrangement were discussed. Nonetheless, new systems using fuel cells have started to emerge. Specifically, a Malwa Electric Combi prototype from the manufacturer Malwa Forest AB (Lesprom 2023). This machine is dual-purpose, meaning it can work as a forwarder and, after a quick modification, as a harvester, and it was created in collaboration with the Research Institutes of Sweden AB (Johnsen 2023c). The aim of the research project is to create an electric drive system with modular battery exchange for agricultural and forestry machines (Research Institutes of Sweden AB 2023). The Malwa Electric Combi drive system includes two electric motors as well as two differently sized batteries (Jensen 2023). The larger battery is intended for operating purposes and the smaller one for its replacement with the help of a hydraulic crane (Jonsson 2023). The drive system of the Malwa Electric Combi machine is schematically shown in figure 7. After passing through the converter, the electrical energy supplied by the large

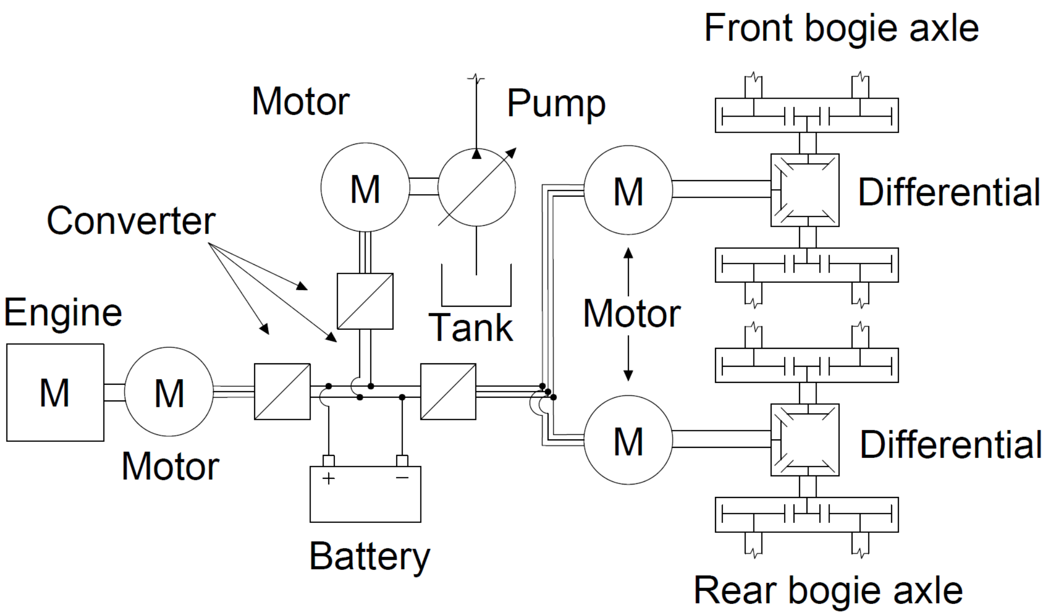


**Fig. 6.** Series hybrid drive system according to Ponsse Plc. and Epec Oy.

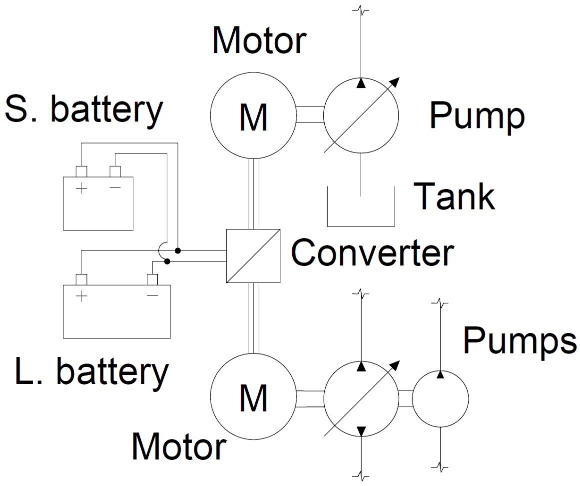


**Fig. 7.** Hybrid drive system with fuel cells according to Malwa Forest AB.

battery is used to drive the electric motor connected to the pump of the working hydraulic circuit (marked as pump in Fig. 7). The converter is further connected to the electric motor, which drives the pumps of the hydraulic circuit of the traction drive. In electric motors, electrical energy is converted into mechanical energy, which is subsequently converted by pumps into hydraulic energy used to drive individual parts of the machine. The operating time of the machine according to the current battery capacity is two hours per charge (Lesprom 2023).

The last electro-hybrid solution existing in CTL technology machines is a system with a series arrangement from the manufacturer of the already mentioned AH6 harvester. It is the LV10 HP forwarding trailer from the company Agama JSCo. A schematic drawing of the system can be seen in figure 8. The hydraulic circuit of the trailer is connected to the circuit of the tractor, whose pump produces hydraulic energy. This energy is led through the control valve located on the trailer either into the working circuit of the crane or further into the auxiliary drive system of the traction device (wheels). If energy is directed to the traction device, it is directed to the hydraulic motor, which converts hydraulic energy into mechanical energy. This is then converted to electricity thanks to the electric motor, which works in the generator mode (Procházka et al. 2017). The electrical energy is then connected via the converter to the battery (Neruda 2021). When using the traction system of the trailer, the stored energy is consumed by the electric motors. Converters are placed between batteries and electric motors (Zemánek et al. 2019). Electric motors are driven by hydromotors via pumps, which turn the front axle wheels of the trailer (Neruda 2021). This traction device drive is only able to develop a speed of up to 5 km/h (Agama JSCo 2023), and therefore it is suitable only in difficult off-road conditions.

## 3. Discussion

At present, the pressure on CTL technology machine manufacturers is constantly increasing. Higher attention is paid to the reduction of emissions caused by the burning of fossil fuels by engines and the reduction of their consumption. Fuel consumption affects up to 82% (Klvač et al. 2003) of the financial costs of felling with this

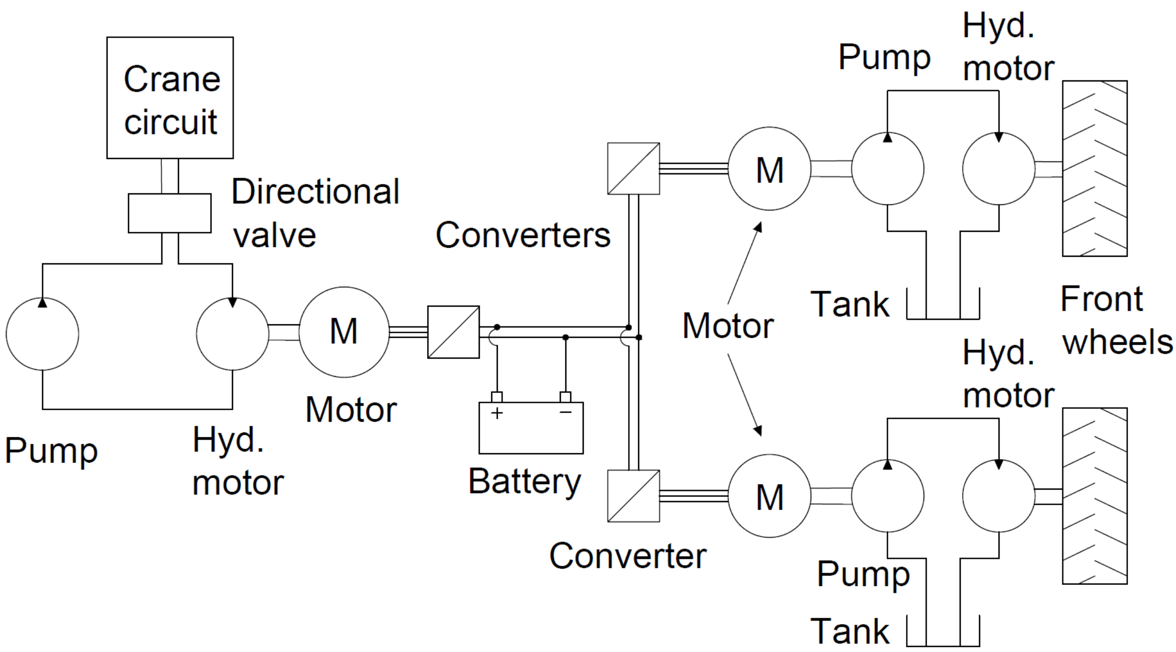


**Fig. 8.** Series hybrid trailer drive system according to Agama JSCo.

technology. According to Kärhä et al. (2023) the average consumption for the harvester and forwarder in final felling is a combined 1.4 l $m^{-3}$. According to the authors, this value rises to 2.2 l $m^{-3}$ in the first thinning. Eliasson et al. (2023) recorded an average consumption in the range of 1.4 to 3.4 l $m^{-3}$ depending on the transport distance. With the help of electro-hybrid solutions, this financial component can be reduced in the range from 10 to 50% (Lajunen et al. 2016). More specific information available on fuel consumption reduction can be seen in Table 1. ProSilva Oyj's prototype 910EH achieves the greatest reduction thanks to the Elforest Technologies AB system (similar to Logset Oy), which enabled downsizing of the combustion engine from 155 kW to just 60 kW, making a significant difference compared to the EV1 forwarder (210 kW to 150 kW). The difference between the performance of the two harvesters manufactured by Logset Oy is also noteworthy, as the Editron unit used delivers different performance (difference 100 kW). This solution makes it possible to use the same internal combustion engine to more models and thereby save production costs for one machine. In addition to downsizing the combustion engine, a reduction in fuel consumption can be achieved by adjusting the machine or working technology (Prinz et al. 2018). Consumption is also affected by the volume of the processed log (Prinz et al. 2018; Kärhä et al. 2023).

Despite the lower fuel consumption, lower emissions and lower weight, electro-hybrid machines also have several disadvantages. For example, the environmental cost of the production of electrical storage units. The extraction of precious metals for batteries alone produces 15 tons of $CO_2$, while their subsequent treatment requires additional energy and thus further $CO_2$ production (Massachusetts Institute of Technology 2023). Therefore, the recycling of precious metals from these units is already getting more and more attention (Al-Thyabat et al. 2013; Ruffino et al. 2013). In addition to this, these metals are hazardous to the environment during their disposal, and therefore there is an effort to develop alternative ways to produce electrical energy storage (Dyatkin et al. 2013). Another disadvantage is the life cycle of the energy storage, which is not specified by the manufacturer for CTL technology machines. However, there is a lot of research on this topic dedicated to different combinations of electrical storage types (Propp et al. 2016; Ayodele et al. 2018; Pozo et al. 2018; Huang et al. 2019; Sedlakova et al. 2019). The new type of storage unit that could also be suitable for CTL technology machines is Supercapattery. This storage is an intermediate between a battery and a supercapacitor (Iqbal & Aziz 2022). The operating temperature of the storage can also be considered a very pressing problem, since at lower temperatures there is a loss of electrical voltage and thus a loss of energy (Procházka et al. 2019). Currently, the question of fire safety is also being discussed (Wang et al. 2019; Diaz et al. 2020; Sun et al. 2021).

## 4. Conclusions

The current technical and technological development of electro-hybrid drive systems of CTL technology machines is driven by the increased requirements of the European Union and United States Environmental Protection Agency to reduce emissions and fuel consumption. Nevertheless, it is necessary to maintain the required high performance of the machine, especially with harvesters. Thanks to the recent rapid development of the individual components of the given type of drive system, especially the electrical energy storage, the performance of the machine is preserved, while the energy efficiency of the drive systems is improved and greenhouse gas emissions are reduced. The deployment of CTL technology electro-hybrid machines will also be accelerated by the price of fuel, which tends to increase.

The future development of electro-hybrid machine drives in CTL technology is a very important task. New drives with fuel cells are already being presented, but it is necessary to further develop them for the forestry sector according to logging technology and energy intensity, which is proving to be a key element for the hybridization of machines. It can therefore be said that research should be devoted to determining the energy demand of individual operations, especially with the possibility of using hydrogen fuel cells in the future as a source of zero emissions taken into account. However, it is important

**Table 1.** Available parameters of hybrid systems of CTL technology machines.

| Type of machine | Model | Manufacturer | Fuel consumption reduction (%) | $CO_2$ emission reduction | Power of combustion engine (kW) | Power of hybrid system (kW) | Electric storage type/capacity |
|---|---|---|---|---|---|---|---|
| Harvester | 8H GTE Hybrid | Logset Oy | up to 25 | 15–30 | 214 | 104 | Supercapacitor/— |
| | 12H GTE Hybrid | Logset Oy | up to 25 | 15–30 | 214 | 175 | Supercapacitor/— |
| | 910EH | ProSilva Oyj | 40 | — | 60* | 60 (2 el. motors) | Battery/— |
| | AH6 | Agama JSCo | — | — | 55 | 20 | Battery/82 Ah, 12 V |
| | CFJ20H | Rong-Feng et al. (2017) | — | — | 60 | 60 per bogie axle | Li-on battery/70 ah, 12 V |
| Forwarder | F14 | Elforest Technologies AB | 30–35 | — | 60 | 30 per wheel | Battery/84V |
| | F15 | Elforest Technologies AB | 25 | — | — | — | Li-on battery |
| | EV1 | Ponsse Plc. and Epec Oy | — | — | 150** | 100 (el. generator) | Battery/31.5 kWh |
| Dual machine | Electric Combi | Malwa Forest AB | — | — | Full electric | — | 2 batteries |
| Trailer | AGA LV 10 HP | Agama JSCo | — | — | 66+ | 40 | Li-on battery/144 Ah, 73.6 V |

Note: *Engine downsizing from 155 kW to 60 kW, **Engine downsizing from 210 kW to 150 kW.

to realize that new and current hybrid systems increase the purchase price of machines, which can be risky for manufacturers. Moreover, the serial production of CTL machines and the subsequent demand does not reach the same parameters as, for example, in the construction industry, which represents a risk from the point of view of the return on investment in the development of hybrids for the given company.

## Acknowledgements

*The authors gratefully acknowledge funding from the Specific research on BUT FSI-S-23-8235.*

## References

Al-Thyabat, S., Nakamura, T., Shibata, E., Iizuka, A., 2013: Adaptation of minerals processing operations for lithium-ion (LiBs) and nickel metal hydride (NiMH) batteries recycling: Critical review. Minerals Engineering, 45:4–17.

Ayodele, T. R., Ogunjuyigbe, A. S. O., Olateju, B. E., 2018: Improving battery lifetime and reducing life cycle cost of a PV/battery systém using supercapacitor for remote agricultural farm power application. Journal of Renewable and Sustainable Energy, 10:013503.

Černík, M., 2014: Výkonová elektronika. Liberec, Technical University of Liberec, 200 p. (In Czech).

Di Blasio, G., Agarwal, A. K., Belgiorno, G., Shukla, P. C., 2022: Introduction to Clean Fuels for Mobility. In: Di Blasio, G., Agarwal A. K. (eds.): Clean Fuels for Mobility. Berlin, Springer Nature, p. 3–7.

Diaz, L. B., He, X., Hu, Z., Restuccia, F., Marinescu, M., Barreras, V. J. et al., 2020: Review—Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions. Journal of Electrochemical Society, 167:090559.

Dyatkin, B., Presser, V., Heon, M., Lukatskaya, M. R., Beidaghi, M., Gogotsi, Y., 2013: Development of a green supercapacitor composed entirely of environmentally friendly materials. ChemSusChem, 6:2269–2280.

Edlund, J., Bergeten, U., Lögren, B., 2012: Effects of two different forwarder steering and transmission drive systems on rut dimensions. Journal of Terramechanics, 49:291–297.

Einola, K., 2013: Prestudy of a Power Management of a Cut-To-Length Forest Harvester with a Hydraulic Hybrid System. 13th Scandinavian International Conference on Fluid Power, 3–5 June 2013, Sweden, Linköping, p. 71–83.

Eliasson, L., Kärhä, K., Arlinger, J., 2023: Fuel consumption in logging operations in Sweden. International Journal of Forest Engineering, 34:1–7.

Erkkilä, M., Bauer, F., Feld, D., 2013: Universal Energy Storage and Recovery System – A Novel Approach for Hydrailic Hybrid. The 13th Scandinavian International Conference on Fluid Power, 3–5 June 2013, Sweden, Linköping, p. 45–52.

Fabiś, P., Flekiewicz, M., 2021: Optimalisation of the SI Engine Timing Advance Fueled by LPG. Scientific Journal of Silesian University of Technology, 111:33–41.

Górski, K., Sander, P., Longwic, R., 2018: The Assessment of Ecological Parameters of Diesel Engine Supplied with Mixtures of Canola Oil with N-Hexane. IOP Conference Series: Materials Science and Engineering, 421:042025.

Hadjipaschalis, I., Poullikkas, A., Efthimiou, V., 2009: Overview of current and future energy storage technologies for electric power applications. Renewable and Sustainable Energy Reviews, 13:1513–1522.

Hissa, M., Niemi, S., Sirviö, K., Niemi, A., Ovaska, T., 2019: Combustion Studies of a Non-Road Diesel Engine with Several Alternative Liquid Fuels. Energies, 12:2447.

Hromádko, J., 2012: Speciální spalovací motory a alternativní pohony: Komplexní přehled problematiky pro všechny typy technických automobilních škol. Prague, Grada Publishing, a. s., 160 p. (In Czech).

Huang, S., Zhu, X., Sarkar, S., Zhao, Y., 2019: Challenges and opportunities for supercapacitors. APL Materials, 7:100901.

Hughes, A., Drury, B., 2019: Electric Motors and Drives. London, Newnes, 511 p.

Hunicz, J., Mikulski, M., Shulka, P. C., Gęca, M. S., 2022: Partially premixed combustion of hydrotreated vegetable oil in a diesel engine: Sensitivity to boost and exhaust gas recirculation. Fuel, 307:121910.

Hurtová, I., Sejkorová, M., Verner, J., 2019: A Study of Diesel Particulate Filter Impact on Engine Oil Quality. In Proceedings of the Transport Means–Proceedings of the International Conference, 2–4 October 2019, Lithuania, Palanga, p. 691–695.

Iqbal, Z. M., Aziz, U., 2022: Supercapattery: Merging of battery-supercapacitor electrodes for hybrid energy storage devices. Journal of Energy Storage, 46:103823.

Karthikeyan, S., Narenthiran, B, Sivanantham, A., Bhatlu, L. D., Maridurai, T., 2021: Supercapacitor – Evolution and review. Materialstoday: Proccedings, 46:3984–3988.

Kärhä, K., Haavikko, H., Kääriäinen, H., 2023: Fossil-fuel consumption and $CO_2$eq emissions of cut-to-length industrial roundwood logging operations in Finland. European Journal of Forest Research, 142:547–563.

Khan, M. I., Yasmin, T., Shakoor, A., 2015: Technical Overview of Compressed Natural Gas (CNG) as a Transportation Fuel. Renewable and Sustainable Energy Reviews, 51:785–797.

Klvač, R., Ward, S., Owende, P. M. O., Lyons, J., 2003: Energy Audit of wood harvesting systems. Scandinavian Journal of Forest Research, 18:176–183.

Kocman, S., 2002: Asynchronní stroje. Ostrava, VŠB–TU, 26 p. (In Czech).

Kůs, V., 2016: Elektrické pohony a výkonová elektronika. Pilsen, University of West Bohemia, 181 p. (In Czech).

Labaj, J., Barta, D., 2006: Unsteady Flow Simulation and Combustion of Ethanol in Diesel Engines. Communications, 8:27–37.

Lajunen, A., Suomela, J., Pippuri, J., Tammi, K., Lehmuspelto, T., Sainio, P., 2016: Electric and Hybrid Electric Non-Road Mobile Machinery – Present Situation and Future Trends. World Electric Vehicle Journal, 81:172–183.

Langshaw, L., Ainalis, D., Acha, S., Shah, N., Stettler, M. E. J., 2020: Environmental and Economic Analysis of Liquefied Natural Gas (LNG) for Heavy Goods Vehicles in the UK: A Well-to-Wheel and Total Cost of Ownership Evaluation. Energy Policy, 137:111161.

Lee, M. Y., 2009: Three-level Neutral-point-clamped Matrix Converter Topology. Dissertation thesis, University of Nottingham, 253 p.

Lemian, D., Bode, F., 2022: Battery–Supercapacitor Energy Storage Systems for Electrical Vehicles: A Review. Energies, 15:5683.

Linjama, M., Huova, M., Tammisto, J., Heikkilä, M., Tikkanen, S., Kajaste, J. et al., 2019: Hydraulic hybrid working machines project – lessons learned. The Sixteenth Scandinavian International Conference on Fluid Power, 22–24 May 2019, Finland, Tampere, p. 423–437.

Mergl, V., 2022: Multicriteria analysis of harvester use with support drive system in thinning. Dissertation thesis, Brno, Mendel University, 174 p.

Mizik, T., 2022: Sustainable Fuels in Private Transportation–Present and Future Potential. In: Di Blasio, G., Agarwal A. K. (eds.): Clean Fuels for Mobility. Berlin, Springer Nature, p. 9–26.

Neruda, J., 2021: Soustřeďování dříví vyvážecí traktorovou soupravou s vyvážecím traktorovým přívěsem LV10 HP. Brno, Mendel University, 32 p. (In Czech).

Olabi, A. G., Onumaegbu, C., Wilberforce, T., Ramadan, M., Abdelkareem, M. A., Al-Alami, A. H., 2021: Critical review of energy storage systems. Energy, 214:118987.

Pandur, Z., Šušnjar, M., Bačić, M., 2021: Battery Technology – Use in Forestry. Croatian Journal of Forest Engineering, 42:135–148.

Patel, K. R., Desai, R. R., 2012: Calculation of Internal Parameters of Super Capacitor to Replace Battery by Using Charging and Discharging Characteristics. International Journal of Engineering and Innovative Technology, 2:1–5.

Pavelka, J., Čeřovský, Z., 2009: Výkonová elektronika. Prague, Czech Technical University in Prague, 277 p. (In Czech).

Pozo, B., Garate, J. I., Ferreiro, S., Fernandez, I., Fernandez de Gorostiza, E., 2018: Supercapacitor Electro-Mathematical and Machine Learning Modelling for Low Power Applications. Electronics, 7:44.

Prinz, R., Spinelli, R., Maggagnoti, N., Routa, J., Asikainen, A., 2018: Modifying the settings of CTL timber harvesting machines to reduce fuel consumption and $CO_2$ emissions. Journal of Clearner Production, 197:208–217.

Procházka, P., Pazder, I., Vítek, O., Hutak, P., 2017: Forwarder Trailer with Auxiliary Electric Drive Unit. ECS Transactions, 81:249–254.

Procházka, P., Pazdera, I., Cipín, R., 2019: Hybrid Tree Harvester Machine with Battery Powered Hydroelectric Drive. ECS Transactions, 95:1–6.

Propp, K., Marinescu, M., Auger, D. J., O'Neill, L., Fotouhi, A., Somasundaram, K. et al., 2016: Multitemperature state-dependent equivalent circuit discharge model for lithium-sulfur batteries. Journal of Power Sources, 328:289–299.

Rahman, M. F., Patterson, D., Cheok, A., Betz, R., 2011: Motor Drives. In: Rashid, M. H. (eds.): Power electronics handbook. Oxford, Butterworth-Heinemann, p. 915–991.

Rahman, M. F., Patterson, D., Cheok, A., Betz, R., 2018: Motor Drives. In: Rashid, M. H. (eds.): Power electronics handbook. Oxford, Butterworth-Heinemann, p. 945–1021.

Rayapureddy, S. M., Matijošius, J., Rimkus, A., Caban, J., Słowik, T., 2022: Comparative Study of Combustion, Performance and Emission Characteristics of Hydrotreated Vegetable Oil–Biobutanol Fuel Blends and Diesel Fuel on a CI Engine. Sustainability, 14:7324.

Raza, W., Faizan, A., Nadeem, R., Yiwei, L., Ki-Hyun, K., Jianhua, Y. et al., 2018: Recent advancements in supercapacitor technology. Nano Energy, 52:441–473.

Ruffino, B., Zanetti, M., Marini, P., 2013: A mechanical pretreatment process for the valorization of useful fractions from spent batteries. Resources, Conservation and Recycling, 55:309–315.

Sani, A., Siahaan, S., Mubarakah, N., Suherman, S., 2018: Supercapacitor performance evaluation in replacing battery based on charging and discharging current characteristics. IOP Conf. Series: Materials Science and Engineering, 309:012078.

Sedlakova, V., Sikula, J., Sedlak, P., Cech, O., Urrutia, L., 2019: A Simple Analytical Model of Capacity Fading for Lithium–Sulfur Cells. IEEE Transactions on Power Electronics, 34:5779–5786.

Sejkorová, M., Šarkan, B., Verner, J., 2017: Efficiency Assessment of Fuel Borne Catalyst. MATEC Web of Conferences, 134:00051.

Stoddart, N., 2010: El-forest hybrid forwarder. Forestry Journal, 10:20–21.

Sun, J., Mao, B., Wang, Q., 2021: Progress on the research of fire behavior and fire protection of lithium ion battery. Fire Safety Journal, 120:103119.

Tkotz, K., 2014: Fachkunde Elektrotechnik. Wien, Verlag und Vertriebs Gesellschaft m. b. H., 623 p. (In German).

Tong, W., 2014: Mechanical design of electric motors. Boca Raton, CRC press, 736 p.

Ulrich, R., Neruda, J., Zemánek, T., 2021: Application of harvester with multifunctional travel and hybrid drive for thinning. Brno, Mendel University, 49 p.

Wang, Q., Mao, B., Stoliarov, S., Sun, J., 2019: A review of lithium ion battery failure mechanisms and fire prevention strategies. Progress in Energy and Combustion Science, 73:95–131.

Wasilewski, J., Szyszlak-Bargłowicz, J., Zając, G., Szczepanik, M., 2020: Assessment of $CO_2$ Emission by Tractor Engine at Varied Control Settings of Fuel Unit. Agricultural Engineering, 24:105–115.

Zemánek, T., Neruda, J., Ulrich, R., Vítek, O., Procházka, P., 2019: Operational evaluation of a timber trailer with the hybrid drive. Proceedings of the 52nd International Symposium on Forestry Mechanization, 6–9 October 2019, Hungary, Sopron, p. 162–171.

*Other sources*

Agama JSCo: Aga LV10 HP, 2023. Available at https://www.agama-as.cz/aga-lv10-hp-plug-in-hybrid.

Beneš, P., 2023: Nová technologie na trhu: elektrický lesní stroj. Available at https://mechanizaceweb.cz/novatechnologie-na-trhu-elektricky-lesni-stroj/. (In Czech).

BioAge Group LLC, 2023: Volvo Group Launching Series Electric Hybrid Technology for Forestry Machinery. Available at https://www.greencarcongress.com/2009/05/volvo-f14-20090527.html.

Elforest technologies AB, 2023: Ponsse Ergo with Elturbo. Available at https://elforest.se/news.php?lang=en&id=142355923.

Jensen, V., 2023: Malwas nya kombimaskin drivs av el. Available at https://www.skogsaktuellt.se/artikel/2230818/malwas-nya-kombimaskin-drivs-av-el.html?fbclid=IwAR0_m1WlCBfRGmzUJSoiAKJue5Mv_bSLQHSrb9NbGVbPfw06EFFeFgt-2SLA. (In Swedish).

Johnsen, T., 2023a: Logset 12H GTE hybrid-electric harvester. Available at https://nordicwoodjournal.com/editorial/logset-12h-gte-electric-hybrid-harvester/.

Johnsen, T., 2023b: El-Forest Elturbo provides an extra 50 kW in the harvester. Available at https://skogsforum.se/viewtopic.php?f=10&t=27873.

Johnsen, T., 2023c: Första batteridrivna skogsmaskinen – Malwa Electric (video). Available at https://skogsforum.se/viewtopic.php?f=112&t=42302. (In Swedish).

Jonsson, P., 2023: Malwa – it's electrifying! Available at https://nordicwoodjournal.com/editorial/malwa-its-electrifying/.

Lesprom Network, 2023: New 100% electric logging machine of Malwa Forest operates for two hours on single. Available at https://www.lesprom.com/en/news/New_100_electric_logging_machine_of_Malwa_Forest_operates_for_two_hours_on_single_charge_103491/.

Massachusetts Institute of Technology, 2023: How much $CO_2$ is emitted by manufacturing batteries?. Available at https://climate.mit.edu/ask-mit/how-much-co2-emitted-manufacturing-batteries.

Research Institutes of Sweden AB, 2023: Modular battery swap system as an enabler for fossilfree mobile work machines. Available at https://www.ri.se/en/what-we-do/projects/modular-battery-swap-system-as-an-enabler-for-fossilfree-mobile-work-machines.

Reuter, F., 2023: Ponsse EV1 – new electric concept for forest machines. Available at https://skogsforum.se/viewtopic.php?f=104&t=42573.

Robert Easton Ltd., 2023a: Hybrid Harvester: Hybrid Power. Available at https://forestmachinemagazine.com/hybrid-harvester-hybrid-power/.

Robert Easton Ltd., 2023b: PONSSE EV1: A Technological breakthrough. Available at https://forestmachinemagazine.com/ponsse-ev1-atechnological-breakthrough/.

Rong-feng, S., Xiaozhen, Z., Chengjun, Z., 2017: Study on Drive System of Hybrid Tree Harvester. The Scientific World Journal, 7:1–7.

Sellgren, U., 2023: Engineerimg Education for Industrial Innovation. Available at https://www.researchgate.net/publication/266291963_ENGINEERING_EDUCATION_FOR_INDUSTRIAL_INNOVATION.