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Article

Hydraulic Hybrid Cut-to-Length Forest Harvester—Evaluation of Effects on Productivity and Fuel Efficiency

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Abstract: A cut-to-length (CTL) forest harvester is a purpose-built, hydraulically actuated mobile work machine used for felling, delimbing, and cross-cutting trees into dimensions and assortments. In such a machine, the diesel engine load is known to fluctuate greatly over the work cycle. To manage these changing power demands, a hydraulic hybrid system is implemented into a full-scale proof-of-concept machine to discover its functionality and to collect experimental results in real operating conditions. The hydraulic hybrid system installed on a CTL harvester machine was tuned to enable the collection of two actual datasets of timber harvesting, and data collection over a period of production use was carried out. In addition to updating the state-of-the-art research into heavy non-road mobile machinery regarding hybrid systems, this paper discusses the two tests carried out in actual production conditions with the studied hydraulic hybrid system. The adaptations and modifications to the studied and tested system since earlier papers are discussed—especially the improvements in the system dynamics and response as well as the control of the hybrid system. In conclusion, the tested system can be said to operate satisfactorily and shows clear advantages over the conventional system, even though it still has some limitations. The results show that the system has the potential to increase the productivity of the machine through the demonstrated higher peak power, as well as showing improvement in fuel efficiency under highly fluctuating loads, especially with heavy or large-volume tree stems.

Keywords: hydraulic hybrid; hydraulic energy storage; forest machinery; cut-to-length harvester; power management; engine downsizing

Citation: Einola, K.; Kivi, A. Hydraulic Hybrid Cut-to-Length Forest Harvester—Evaluation of Effects on Productivity and Fuel Efficiency. *Actuators* **2024**, *13*, 126. https://doi.org/10.3390/act13040126

Academic Editor: Ioan Ursu

Received: 13 October 2023
Revised: 1 March 2024
Accepted: 5 March 2024
Published: 29 March 2024

1. Introduction

Climate change has been a topic of global discussion for years or even decades, and as seen in the latest IPCC report [1], the word 'forestry' is found up to 758 times, and it is described as a 'climate-exposed sector' when adverse economic impacts are discussed. Climate change is also impacting our forests and thus also forestry in many forms. More extreme weather conditions like storms are faced globally, as well as milder winters becoming more standard in the Northern Hemisphere. Mild winters with no considerable frost on the forest floor, for example, make it more difficult and costly to operate the equipment needed in forestry operations [2] especially when avoiding heavy soil impact. Central Europe has already been hit hard by forest insects killing, in particular, spruce stands [3], and this phenomenon is moving forward towards the north, e.g., the Baltics and Scandinavia. All of this is drawing more attention towards the energy efficiency and emissions of today's diesel-powered forestry equipment—which are for their part advancing this negative development. On the other hand, CTL forestry carried out the right way can be seen as an excellent way of replacing—on a remarkable industrial scale—unrenewable and fossil-based raw materials like concrete, steel, plastics, and oil in various industries with renewable wood-based and timber products. Through good forest management, i.e., selective thinning timed right and effectively renewing forests, more CO_2 can then be sequestrated [4] to growing forest stands.

In addition, for various reasons, diesel fuel prices peaked in 2022, and the fuel efficiency of forestry equipment seems to be more important than ever. As an example, the diesel fuel price [5] in Finland peaked at EUR 2.44 per litre in June 2022, which is an all-time high and shows an over 106% price increase in just 2 years. A remarkable part of the running costs of forestry equipment is caused by fuel and its logistics at the forestry site. Depending on the market area and local fuel prices, fuel costs can be relatively high and well comparable to input costs [6] for operator salaries for a forestry contractor or a forest industry wood procurement organisation. In addition to cost, more discussion is going on around, e.g., equipment lifecycle emissions and carbon neutrality; it is also a known fact that, typically, most of the life cycle emissions are caused during the operation of forestry equipment, not during the manufacturing process. As an example, a study on the fossil fuel consumption and respective CO_2 equivalent emissions of cut-to-length industrial roundwood logging operations in Finland is presented in article [7], which also concludes that CTL operations in Finland in 2020 totalled a fuel consumption of 126.6 million litres with the calculated CO_2 equivalent emissions of 334,209 tons. As of today, the fuel efficiency of forestry equipment is poor as most if not all of the functions are implemented hydraulically, and energy recovery or hybrid systems are not at all or only rarely implemented. It is also known that so-called green procurement incentives exist for those selecting equipment with technology such as hybrid drives aiming to lower emissions.

Engine emission regulations are also becoming more fragmented [8] from one market area to another, e.g., Europe and North America have somewhat similar regulations and solutions technically, like exhaust after-treatment, but, e.g., China and Brazil are less regulated markets. Even though Chinese and Brazilian emission regulations are technically not that far away from each other, their engine emission certificates are different, which means that actual engines have separate part numbers and must be stored in parts inventory separately for these mentioned markets, which means a lot of tied-up equity in spare parts inventory. If it were possible to skip some engine power categories thanks to power peak management through hybridisation, this would also be a clear advantage and would actually have a significant economic impact on the OEM's operations.

A CTL forest harvester is a piece of self-propelled forestry equipment purpose-built to fell, delimb, and cross-cut trees into logs of predetermined dimensions. The actual work tool processing the tree stem is called a harvester head, which is carried by the tip of a hydraulic boom to the standing tree to be felled. The work cycle of this kind of machine is very challenging for the prime mover, conventionally a diesel engine, to manage as there are high power peaks present. However, the basic sequence of the work cycle is repeated continuously during operation, for each tree to be felled, but the duration of this is not very long and is somewhat limited in energy consumption, which makes it interesting as a hybridisation project also with a hydraulic accumulator acting as energy storage. It also has a very constant sequence of events, which makes it more manageable to handle in terms of control algorithms. The harvester head's main function and power-consuming functions, chainsaw, and feeding roller drive are hydraulically operated for the time being and will be for quite some years to come and therefore, using a hydraulic energy storage system such as a high-pressure accumulator is advantageous in terms of minimizing energy conversions. As the CTL forest harvester is a critical piece of equipment in this kind of forestry, its work cycle has been studied in time studies [9] as well as performance evaluations [10].

In this article, a review of the state of the art is given in the framework of cut-to-length forestry equipment, especially harvesters and hybrid solutions, which are targeted to improve fuel efficiency as well as the productivity of the equipment. This review also discusses the different known hybrid solutions used. Furthermore, experimental tests and measurements are carried out with the hydraulic hybrid system installed on a cut-to-length harvester and the results are further analysed and discussed.

1.1. Review of the State of the Art

Hybrid technology has been of great interest in the field of various non-road and construction machinery since the 1990s. Typically, there has been more development activity in machine types with higher production volumes such as tracked excavators and wheeled loaders. As an example, Hitachi launched the world's first hybrid wheeled loader in 2003 as Komatsu developed the first commercial hybrid excavator in 2008 [11]. This paper discusses several different hybrid topologies for both the wheeled loader as well as excavators, some of them being mentioned to be in the scope of various patents. Various energy storage solutions are applicable and their advantages as well as limitations are discussed. The hydraulic accumulator used as an energy storage in hybrid construction machinery is raised as a potential solution option having strengths such as a high power density and being well suited to frequent and short start–stop cycles.

The hydraulic hybrid was seen as a potential technology even in passenger cars back in 2013—however, it looks like this development has later been discontinued and light-duty vehicles have turned quickly towards BEVs, battery electric vehicles. However, hydraulic hybrid vehicle architectures and systems are still studied and simulated [12], especially for urban transportation purposes, typically for medium-duty and commercial vehicles. Energy savings are available, especially in start–stop operations and driving cycles like those typical in refuse and delivery trucks.

There are also systems where energy is stored in an electric form, either in a battery or, e.g., supercapacitor, but hydraulics are used in the energy recovery phase and to drive the electric generator. One example of this kind of approach [13] is presented in the context of the hybrid hydraulic excavator and called the motor-generator energy regeneration system (MGERS). Furthermore, energy can also be stored in a hydraulic accumulator and electric energy storage simultaneously and the topology was named by the author as the accumulator motor-generator energy regeneration system (AMGERS). The latter topology is said to deliver a recovery efficiency of 22% with further potential to be increased 45%. It is also stated that the hydraulic motor and generator can be dimensioned smaller than in conventional systems.

In the article [14], a relatively complex powertrain architecture for a hydraulic hybrid excavator implementing a CVT transmission is presented. Through connecting a diesel engine to an excavator's main hydraulic pump via a continuous variable transmission, precise control of both the engine's rpm and torque is enabled and the operating points at high efficiencies are enabled. The boom potential energy recovered can be used to either charge the battery or directly supply power to the main pump.

Recovery possibilities in the CTL harvester's boom are somewhat limited compared to, e.g., excavators which typically have significantly heavier boom constructions. However, some of the presented concepts might be suitable for this application as well. In the article [15], an energy recovery and direct reuse system of the hydraulic hybrid excavator using a digital pump as a key component is presented. The needed energy input to the boom hydraulics was lowered over 78% in comparison to a conventional system as an outcome of the study.

The closest prior work relevant to this study and hydraulic hybrid system is described in the article discussing a CTL harvester with a hydraulic hybrid system driving the harvester head while also using a hydraulic accumulator as the energy storage [16]. This system was built and studied by the German forestry machine manufacturer HSM GmbH in 2011. A hydraulic bladder accumulator of nominal volume of 60 L was installed to support the diesel engine of 175 kW with a hybrid assist power of 90 kW for a maximum time of four seconds. The accumulator was connected to the harvester head hydraulic circuit with a mandatory safety block, one 2/2 charge valve, one 2/2 discharge valve, and the actual proportional directional valve to control the feed rollers of the harvester head. The manufacturer of this harvester claimed a fuel saving of up to 20% in litres of fuel used per cubic metre of timber harvested. Other advantages observed were a more even diesel engine load profile, higher tree delimbing power, better dynamics, and strong acceleration in the beginning of feeding which helps in cutting the branches with harvester heads and the tree stem's inertia. The drawback of the system is that when the pressure in the accumulator goes below the working pressure in the harvester head hydraulic circuit, no assist power is available. This article was referred to by the author in 2013 in reference [17]. It also looks like this technology is in series production, for example, in HSM 405H4 that was introduced at the Interforst 2022 exhibition in July 2022. A hydraulic hybrid drive with a hydraulic accumulator is mentioned in Forst Praxis magazine [18].

The highly fluctuating nature of the CTL forest harvester load cycle has been discussed in an earlier paper by the author [17], and it can be stated that power peaks can easily be more than twice as high as the average power level over the cycle. This makes the CTL harvester a very interesting application for hybridisation with a power peak management approach.

Furthermore, the paper [11] discusses various hybrid solutions, both hydraulic as well as electric, implemented in mobile equipment such as construction and forestry equipment. It is a fair assumption that the solutions implemented in construction equipment are considered applicable to forestry to some extent. The first electric hybrid tracked excavators with an ultracapacitor serving as energy storage have already been in production for several years, whereas a hydraulic hybrid system with somewhat simple charging and discharging circuitry was studied. In this article, a novel hydraulic hybrid concept for a CTL forest harvester was introduced and its possibilities were discussed based on work cycle measurement data. As a conclusion, it was found that the hydraulic hybrid seemed very suitable to meet the demands of the CTL forest harvester application. The described hydraulic hybrid circuitry is also within the scope of a granted European patent [19].

As a continuation of the work in the next paper [20], the performance characteristics of the diesel engine in question were studied in more detail and initial simulations of the system dynamics and fuel efficiency were carried out. Simulations showed a potential fuel saving of roughly 10% during a given reference work cycle. Later, based on the work cycle and the hydraulic hybrid system's key components, a bladder accumulator of a nominal volume of 50 L was selected to accompany an over-centre variable displacement pump–motor unit having a displacement of 100 cm^3. The use of a closed-circuit hydrostatic pump this way somewhat differs from the original purpose—but it was expected to be possible anyway. The expected advantages of the proposed hydraulic hybrid system architecture were discussed to some extent and clearly the most important advantages over some other architectures were its somewhat simple system design, minimal number of energy conversions, and superior properties in using the installed energy storage (hydraulic accumulator) capacity efficiently. Finally, an initial control approach was introduced, with the possibility to use the hybrid system as an enabler for diesel engine downsizing, assuming the same maximum total output power or as an enabler to switch the diesel engine's operating point to a more favourable one and as needed to give the possibility of a higher peak power as needed. The basic control approach to keep the diesel engine running at a favourable constant load point and also use harvester head control system data as a feed-forward input was seen as a feasible option.

In the third paper [21] of the preceding series of publications by the author, the first experimental results were shown and discussed. The most important finding was that the variable displacement closed-circuit pump–motor unit became a system performance limiting component. It was clear that the dynamics of the standard over-centre closed-circuit pump was insufficient for the application and the hybrid system had too much delay to successfully react to the work cycle, even though displacement control was implemented as closed-loop control. As future work, an analysis of the hybrid pump dynamics and its improvement possibilities was proposed, even though the basic circuitry and principle were seen as having potential with many earlier discussed advantages.

After the publication of author's earlier papers [17,20,21], vehicle hybridisation electrification has proceeded a lot in many industries, especially in passenger cars and other light-duty vehicles as well as commercial vehicles but also in several non-road mobile machinery like mining and material handling equipment. In many applications where grid charging infrastructure is available, the trend seems to be directly towards BEV technology. In applications where the battery electric range is simply not enough, hybrid and, e.g., hydrogen fuel cell technology is more feasible. Also, battery swap systems can be competitive in some applications. In forestry, the development in the field of electrification has been more conservative, probably mainly because of missing charging possibilities on forestry sites. In other words, battery electric systems do not seem to be feasible now in forestry because of missing charging possibilities.

Examples of hybrid systems have also been introduced to forestry after the author's earlier papers. The article [22] quite widely discusses and compares known technical hybridisation solutions for forestry machines and includes a list of various concepts and categorises them into three classes being 'electro-hybrid', 'hydraulic hybrid', and 'electro-hydraulic hybrid'. These systems are mainly research concepts with only a few exceptions and their fuel consumption reductions vary from some percentage up to 50%; however, it remains unclear if these values are measured results as litres of fuel per operating hour or litres of fuel per production, e.g., cubic meter of timber harvested, and in which kind of conditions the evaluation has been carried out. In most of the discussed concepts, the installed diesel engine power has also been downsized while a supercapacitor, battery, or hydraulic accumulator has been selected to serve as energy storage. An electric hybrid drive system of a tree harvester (cut-to-length harvester) is studied and discussed in [23] and, a bit surprisingly, the focus for simulation and calculations is solely on the drive transmission functions of the machine. In a cut-to-length harvester, drive transmission is typically not used at a high power for any remarkable time of the operation.

An interesting concept [24] was launched in 2022 by Malwa Forest Ab in the form of a battery electric combi machine—a combination of a CTL harvester and forwarder. The machine works fully on battery electric roughly two hours at a time with one battery. After that, the battery can be swapped to a fully charged one and another two hours of range are available. The manufacturer states that this machine is intended for urban forestry like parks, etc., where it could be a good match with minimal soil impact and emissions like diesel engine noise and exhaust.

Furthermore, Ponsse has recently launched an electric series hybrid forwarder concept EV1 with a downsized diesel engine [25], a series hybrid configuration which is claimed not only to provide a great performance and response but also significant fuel savings. This concept machine is shown in Figure 1.

Figure 1. Ponsse EV1 electric series hybrid forwarder concept. Photo: Ponsse Plc.

The Ponsse EV1 machine includes a fully electric drive transmission as well as electrically driven work hydraulics. Its downsized 150 kW four-cylinder Stage V diesel engine is only run as a range-extender part of the working time—when the SOC of the battery reaches its lower limit of 40%. When the SOC again reaches 80%, the range-extender is shut down. It is also clear that a diesel engine is not the only prime mover possible for the future, but cleaner and renewable energy sources such as hydrogen can be used for the generation of recharging power. It is important to note here that the work cycle of the forwarder differs remarkably from that of the CTL harvester. Drive transmission plays a much more important role in a forwarder and in given situations the electric powertrain can enable remarkable energy recovery in the battery when driving downhill, especially fully loaded. Having said that, the boom drive of a forwarder is also a high-power application and almost constantly operated with high speeds.

Outside forestry applications, it looks like compact material handling and construction machinery is turning towards battery electric drive first, but there are also examples such as a heavy pile driving rig being electrified [26]. Probably the biggest driver for both equipment categories is that large metropolitan areas and city centres are prohibiting diesel engines completely in some equipment markets.

There is even 'oil less' concept equipment shown, where linear actuation that is conventionally implemented with hydraulic cylinders is also realised with EMAs—electro-mechanical actuators; examples of this kind of machine are Komatsu's compact, fully electric wheel loader [27] and Bobcat's fully electric tracked skid steer loader [28].

As a conclusion, in forestry it looks like Logset's electric hybrid harvesters 12H GTE and 8H GTE and some of HSM's harvester models are the only hybrid powered forest machines available as series-produced products [29]. These harvesters are featuring ultracapacitor packs as energy storage and an electric generator/motor unit connected in parallel with a conventional diesel engine between flywheel and hydraulic pumps. Downsizing has not been a priority but to be able to run a six-cylinder diesel engine on an economical engine speed. Therefore, improved fuel efficiency can most likely be shown as a lowered number of litres of fuel per cubic metre of timber harvested. On the website of the manufacturer, there is no indication given of the current lowered fuel consumption.

1.2. Purpose and Objectives of This Paper

As a continuation of earlier papers [19,22,30], this article brings the hydraulic hybrid concept into tests in actual production conditions—a regeneration felling site. This is seen as an essential part of the research as it is otherwise difficult to develop the system further without having the actual process available to trial, e.g., control systems against.

The hydraulic hybrid system is now equipped with a hybrid pump with improved dynamics, and it is expected to perform better now. The key objective of this paper is to provide measurement results regarding the basic functionality of the system, which is tested with real timber. System performance and dynamics as well as the functionality of the hydraulic hybrid system is evaluated, and fuel consumption and productivity are logged simultaneously, with fuel consumption per cubic metre harvested being the most interesting performance criteria. As this productivity-based performance is very much dependent on the average tree stem volume and tree dimensions, the volume is logged automatically through the reporting software of the harvester. The energy storage capacity is also evaluated based on the measurements, with the main point being to check if the energy storage is sufficient to cope with the work cycle and whether it can recover in between the trees processed.

This paper also discusses the main drawbacks and challenges related to the system and chosen control design. Finally, the future opportunities are discussed, and some future research is proposed.

As an extension to the article [30] some later system modifications are introduced in Section 2.1.1., and the new results are discussed in Section 3.1. Furthermore, conclusions, including the discussion on the additional measurements, can be found in Section 4.1.

2. The System Studied and Methods

In this section, the studied hydraulic hybrid system and its basic control approach is presented and discussed. It should be noted that the overall power system of a CTL harvester is complex, as discussed in an earlier paper [17], and therefore not all features are considered in this study. The studied subsystem includes only the harvester head's hydraulic circuit and at this stage its feeding function. Even with the limitation to the harvester head circuit, a total of 46 signals were logged continuously for the developed measurement and control system.

2.1. Hydraulic Hybrid Concept System Description

The studied system is discussed based on Figure 2 shown below.

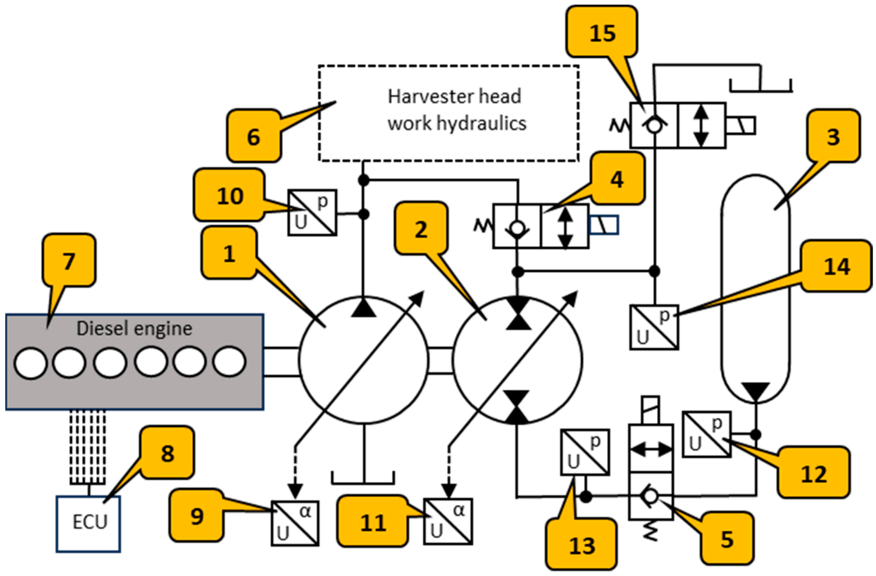

Figure 2. A simple presentation of the studied hydraulic hybrid system installed on a Ponsse Ergo CTL harvester.

The studied hydraulic hybrid concept system is built on and around a standard powertrain of a Ponsse Ergo CTL harvester by installing an additional over-centre variable displacement pump, Pump 2 (2), connected in parallel on the same diesel engine (7) driven input shaft as the standard harvester head pump, Pump 1 (1). Furthermore, a 50 l nominal volume hydraulic accumulator (3) serving as the energy storage is added and connected to Pump 2. Lockup valves (4 and 5) are added to both sides of Pump 2 and both the harvester head circuit (6) pressure and energy storage pressure are measured with pressure transmitters (10 and 12). Both the Pump 1 and Pump 2 swivel angles (9 and 11) are measured and various engine bus signals such as the engine speed, load torque, and fuel consumption are followed through the ECU (8) over CAN as SAE J1939 messages. The Pump 1 maximum displacement and maximum pressure is controlled by the concept system—as well as the Pump 2 swivel angle. On Pump 2, a pressure cut-off functionality is active towards the harvester head circuit with a pressure setting of 28.5 MPa.

The pre-charge pressure of the hydraulic accumulator is in these measurements 13 MPa; however, this could also be higher based on the measured results, as the pressure is typically kept well above 20 MPa over the measured work cycles. Also, Pump 2 is now changed to a 125 cm^3 Bosch Rexroth A4VG which is specifically tuned by the component supplier for high-speed swivel angle adjustment.

2.1.1. Modifications to the System for Additional Measurements of August 2023

As discussed in an earlier paper [30], there was some leakage in the lockup valves (4 and 5) and thus these valves were replaced with new ones of a very low leak poppet seat design. The valves proved to be of low leak, as required, but in addition quite remarkable closing delay issues were introduced—which is discussed later. To be able to follow these leakages, and later on to take them into account in further analysis, additional pressure transmitters (13 and 14) were introduced into the system. Furthermore, a direct tank discharge valve (15) was also introduced to provide assist power to functions other than the harvester head functions of the cut-to-length harvester; however, this feature was neither tested nor developed further due to time and actual test site availability constraints, even though it was implemented into the system circuitry.

The pump divider gear was replaced with one with a 19 percent higher speed increasing ratio to allow more volume flow to the harvester boom pump with a lowered engine speed of 1400 rpm, which was discovered to be an issue with earlier measurements. This modification allows more productive work from the boom operation point of view with a lower engine speed.

The energy storage maximum pressure was lowered from 32 MPa to 30 MPa based on evaluations that this would be more feasible for Pump 2 efficiency and its foreseeable useful lifetime. This resulted in a greater difference between the energy storage pressure relief setting and the energy storage maximum pressure. Also, 30 MPa was seen as a high enough maximum energy storage pressure for the logging conditions (tree stem size) and this was also demonstrated—the energy storage state of charge was sufficient at all times.

The hydraulic pressure cut-off functionality was taken out of the system through completely removing the swashplate control piston orifices from Pump 2. This way, the maximum dynamics for the displacement control were achieved and displacement control was now freely adjustable electrically. With hydraulic pressure cut-off functionality, some unwanted displacement control issues were encountered at pressures above 24 MPa in the Pump 2 output port. Furthermore, an electric pressure cut-off feature was developed and implemented to control Pump 2 to avoid the hybrid assist pressure peaking higher than the desired level.

2.2. Hybrid System's Control Principles and Limitations

The main objective in controlling the hydraulic hybrid system is to try to 'disconnect' the diesel engine from the highly fluctuating load peaks generated by the harvester head's hydraulic circuit, especially its tree feeding function. This is currently performed by following, e.g., actual engine torque and speed through CAN. In Figure 3, the power management graph is shown to include the engine's maximum power and reference power as a function of the engine speed. The main engine control principle is that when the actual engine power exceeds the engine reference power, the hydraulic hybrid assist is activated, and when it goes below charging the energy storage is allowed. In the same graph, it can be seen as the main characteristics of the diesel engine that both the maximum torque as well as the lowest specific fuel consumption are simultaneously available for the engine speed range between 1200 and 1400 rpm. The engine's specific consumption is shown for the maximum torque as measured by the engine manufacturer. Despite this, in the conventional setup a machine like this would be needed to run on 1700 rpm minimum to be able to provide the necessary volume flow and power to all functions and consumers. Thanks to the hydraulic hybrid system, the engine speed can be reduced to a favourable area without compromising productivity.

Currently, the hydraulic hybrid assist is made available through the control system to the automatic feeding function only. Automatic feeding means that the harvester head's control system is 'locked' to the next target cross-cutting distance and feeding to that target, so the control system continuously knows the distance to the next stop. The operation is quite dynamic as feeding speeds can typically be over 5 m per second and typical log lengths for the mechanical timber industry are between 3 and 6 m.

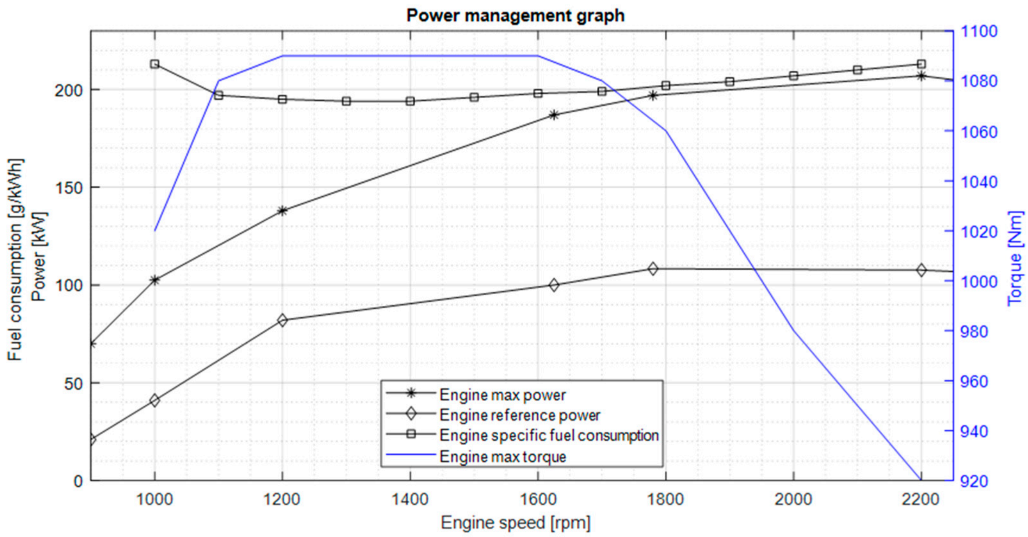

Figure 3. The hydraulic hybrid system's power management graph.

The feeding function is clearly dominating in the power demand during tree processing and is dynamically such that the system has the capability to meet the need. However, there are still several preconditions which need to be met before the hybrid assist is allowed to take control—some of these preconditions are as follows:

- Energy storage pressure higher than 15 MPa;
- Distance to next cross-cut length more than the predetermined minimum;
- Diameter of the tree more than the predetermined minimum;
- Feeding control current must be active and not declining;
- Harvester head circuit pressure must be below the set upper limit (above which the feeding is stated as stopped to a standstill in front of a big branch, etc.).

Respectively, allowing conditions for the energy storage charging function exist, as shown in the following examples:

- No feeding or sawing function active;
- Energy storage pressure below 32 MPa;
- Harvester head pressure above 12 MPa.

Additionally the maximum energy storage charging volume flow and power are also limited. It is necessary to keep the pressure above 12 MPa in the harvester head circuit to maintain harvester head functions as operational and safe. While charging the energy storage, oil is taken from the harvester head circuit and there is a risk of pressure dropping; for this reason, charging is not performed below 12 MPa.

Modifications to Control Principles and Limitations for Additional Measurements of August 2023

In general, the whole control concept has undergone quite extensive developments regarding single limit settings and parameters as well as in general avoiding step-like limitations and seeking a faster response and smoother general system behaviour. This is also crucial for the efficiency of the system as feeding excess hybrid assist power into the system leads to losses in the system.

The most important changes are related to Pump 2 volume flow and pressure control during an actual dynamic work cycle phase, which is of course in detail defined by processing of a tree log or stem. This development is advancing but it is also clear that there is also much future work ahead.

2.3. Test Environment and Conditions

The hydraulic hybrid was installed on a used Ponsse Ergo harvester with a C33 parallel boom and H7 harvester head as seen in Figure 4—the same machine as used in an earlier paper [30] by the author.

Figure 4. On the test site with the hydraulic hybrid Ponsse Ergo CTL harvester.

The machine now has over 10,000 working hours on the meter but is still in a reasonably good operating condition. However, it is clear that the hydraulics components like the harvester head circuit Pump 1 and, e.g., the feed motors and saw motor are not as new anymore and most likely have more leakage than their new counterparts. In the tests, the situation is the same for both compared situations, so it is not seen as a problem. The operator operating the concept harvester during the tests is a professional operator trainer and frequently operates various forest machinery. The test site was located near Tampere, Finland, and roughly 300 m^3 of timber was processed to tune and set up the hydraulic hybrid system's parameters prior to actual test runs covering a bit less than 100 m^3. The site was a final cut site, so all of the trees were felled, and it will be renewed with new seedlings soon after. The tree species harvested for industrial use represented a typical Finnish forest, pine [pinus sylvestris], spruce [picea abies], and birch [betula bendula], and the average stem volume during the measurements was slightly over 0.7 m^3—which fits well to the size of the harvester head and the harvester used. The ambient temperature during measurements was steadily between +5 °C and +7 °C. Due to the high losses of the CTL harvester's hydraulic systems, the ambient temperature plays an important role in the fuel consumption, since the cooling power needed is relatively high. Natural cooling is possible with a lower cooling fan power when the temperature difference is higher between the hydraulic fluid and ambient air. The machine's hydraulics were also warmed up to a working temperature between 55 °C and 60 °C (cooling circuit thermostat high and low settings) prior to starting actual measurements.

Prior to the actual forest tests, the Pump 2 response was measured as part of the study, since last time the pump dynamics were the biggest problem. During this measurement, the harvester's engine was running at 1400 rpm and the feeding function was controlled without a tree in the harvester head. The Pump 2 swivel angle response was measured for half of the displacement, and for full displacement both the energy storage charge and discharge direction, and the results are shown in Figure 5 below.

Going forward to a larger displacement, both the charging and discharging direction response is quite symmetrical and takes 120. . .140 ms for half displacement and between 200 and 300 ms for full displacement. The discharging direction appears to be a bit faster. Some overshoot is visible when operating in this way.

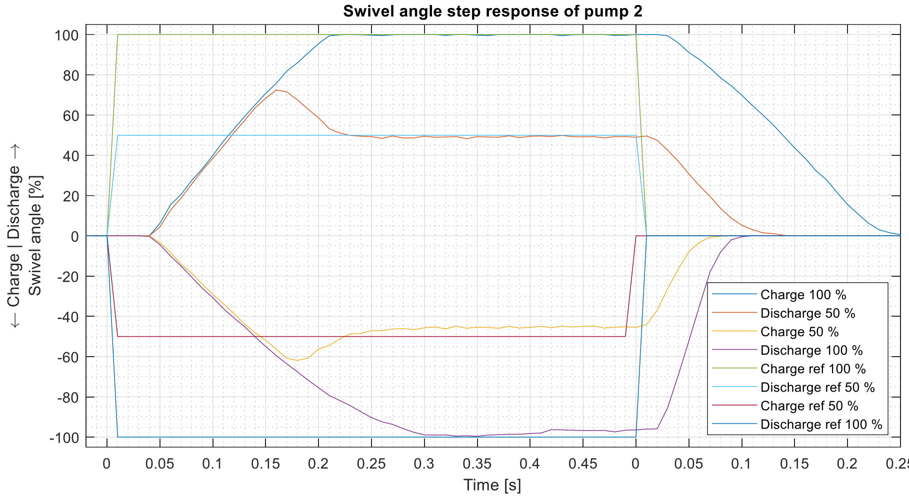

Figure 5. Pump step response.

Going towards zero displacement, the pump swivel angle response is no longer symmetric between the discharge and charge directions. This is considered to be related to the actual pump port pressures but was not studied in more detail. Going from full discharge now takes 250 ms, which has some effect on the system performance since the hybrid assist must be discontinued early enough, before feeding has to stop. However, this is seen as much better Pump 2 dynamics compared to the author's earlier paper [30] where the 100 cm^3 pump's response time was 700 ms for a similar test. The pump delivered originally was even faster, being capable of a 200 ms 'round trip', but orifices were added to the swivel angle control cylinder ports, as well as an external pressure cut-off valve to enable cut-off functionality without the need to limit the energy storage side pressure.

Test Environment and Conditions for Additional Measurements of August 2023

Thanks to the electrically implemented Pump 2 pressure cut-off functionality, the step response was improved radically, reaching 120. . .140 ms for full displacement as a comparison to earlier values of 200. . .300 ms. This plays an important role when controlling the volume flow to the feeding function which is highly dynamic and is a great improvement. The faster Pump 2 dynamics also improved the hybrid assist performance in practice during the tests.

The logging site used for the August 2023 measurements was mainly comparable to the earlier site, except the average stem size which was remarkably lower—being below 0.5 m^3 as in comparison to earlier 0.7 m^3. This typically makes a big difference in fuel consumption per cubic metre harvested, with the lower stem volume leading to higher consumption figures.

2.4. Test Cases and Measurement Planning

Originally, three different test settings were planned to be measured. Those settings were: 'conventional 1700 rpm', '1400 rpm with hybrid assist', and '1700 rpm with hybrid boost'. Based on the operator's feedback, the '1700 rpm with hybrid boost' was not measured, as there was no advantage to be seen with the forest and trees available at the site. One operator's argument was also that the feeding speed would need to be increased to utilise the extra power with the size of trees available and the operation of the machine would no longer be possible to manage properly. Therefore, only those two first mentioned cases were taken into the measurements of this study. An engine speed of '1400 rpm with hybrid assist' was tested and seen as the lowest feasible to still provide a reasonable volume flow to the boom.

Regarding fuel consumption measurements, a decision was made to only use engines' CAN messages—which has in earlier projects proven to be a very reproducible way of measuring fuel consumption. Absolute fuel consumption readings may differ a bit from reality, but the difference between the two settings can be assumed accurate enough for this study and, this way, no external flowrate sensors were needed.

Production-related data like work time, number of stems and logs, and stem volumes were decided to be logged using normal work time and production reporting software, Ponsse OptiReport, which is used in everyday operations. A separate 'operator' was created in this software for both test cases to make things a bit easier. As the tests need to be carried out with an actual production site and timber is sold for further uses in the wood processing industry, the diameter, length, and volume measurement system also has to be calibrated officially; this way, we can also trust the processed volumes quite well.

The productivity of the harvesting operations is critical for forestry contractors, and it is thus important to follow the amount of fuel consumed per timber volume processed—not only per operating hour. However, it needs to be considered that the average tree stem volume plays a big role when measuring fuel consumption per timber volume processed. In measurements conducted during actual forestry operation, there are also other phenomena that can hardly be filtered out—for example the variation inside the forest stand itself. In these measurements, as similar sections of forest site as possible were selected for the measurement.

Test Arrangements for Additional Measurements of August 2023

Principally, the same two setups '1700 rpm hybrid OFF' and '1400 rpm hybrid ON' were used as in the earlier measurements. Partly due to improved Pump 2 dynamics and the control method allowing higher harvester head circuit pressure (while discharging energy storage), more assist power than needed was available during short stem feeding moments. During advancing measurements, the diesel engine power was targeted to be lowered and kept at the reference power level.

3. Results and Analysis

In this section, the results of the test are shown and discussed. Figure 6 shows the feeding of a tree stem with hybrid assist on. The hydraulic accumulator serving as energy storage was charged to the full charge of 32 MPa in the beginning and its pressure level reacts to the hybrid system activity; there are sections of discharge and charge over the plotted period. In the end of the tree stem, the stem diameter of course goes down and more engine power is available for charging; and at the end, the energy storage is again fully charged and ready for the next tree as planned. We can also see clearly that there are six sections or logs of tree being processed, with the 'relative saw position' peaks showing the felling cut at 2...3 s and then feeding and sawing taking turns after that all the way to the top of the tree. The SOC of the hydraulic accumulator can be seen to climb back to the full level in the end of the plot.

Respectively, Figure 7 shows the feeding of a single log of a tree stem, during which a decreasing SOC of the energy storage can be seen. In this plot, the combined power of the diesel engine and the energy storage is also plotted, reaching 200 kW at a couple of moments. This is a power that would not be available from the diesel engine alone.

In Figure 8, some Pump 2 dynamics issues can be seen. The energy storage power does not quite follow the energy storage power reference at 208. . .209 s and 213. . .214 s and this is most likely caused by simultaneous high pressures in both ports of Pump 2.

Figure 9 shows the feeding of four stems in a row. The energy storage appears to have a large enough capacity and the average power in the diesel engine over this period is 81.4 kW, which is actually very close to the average engine power in the first paper [1] when the harvester work cycle was initially analysed. The energy storage pressure seems to be decreasing quite rapidly—e.g., 1 MPa in 30 s—when charged to the full 32 MPa charge and not directly used to assist. The reason for this could be the natural thermal behaviour of the accumulator to change heat with hydraulic oil as well as ambient air, but some leakage through the lockup valves (4 and 5) was noticed during the tests.

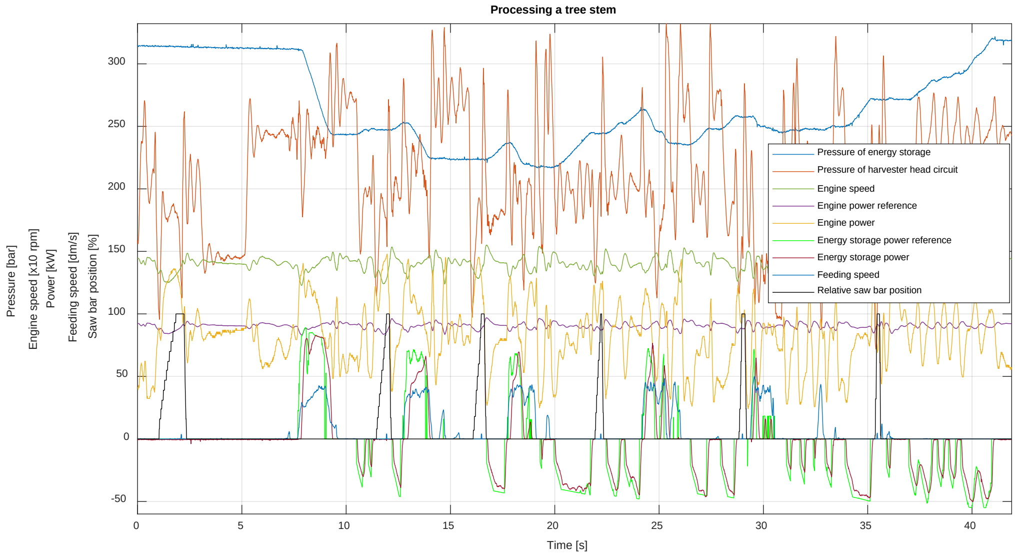

Figure 6. Processing a tree stem with hybrid ON.

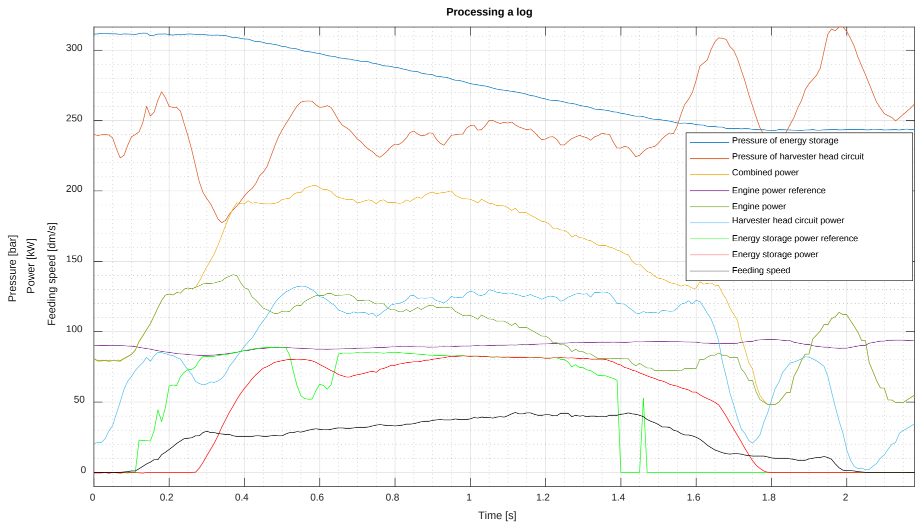

Figure 7. Processing a single log of a tree stem with hybrid ON.

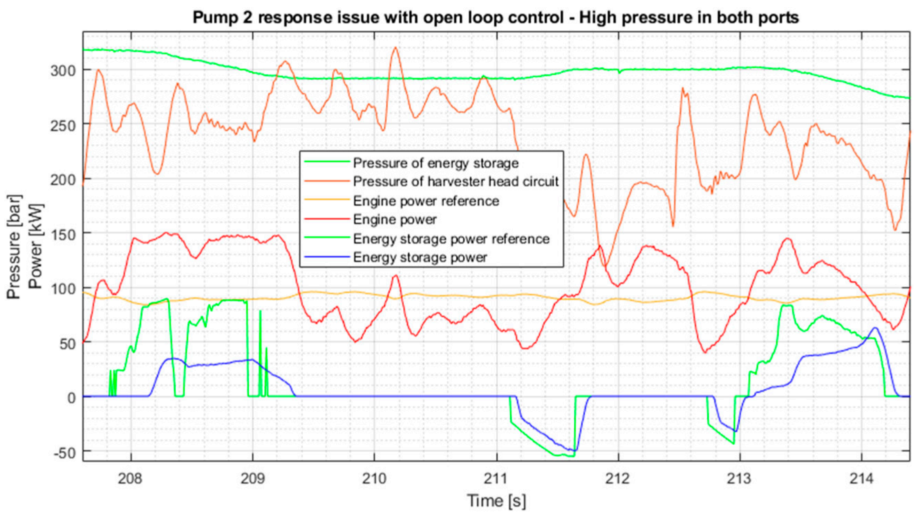

Figure 8. Response issues during feeding of a log with hybrid ON, when high pressures are present in both ports of Pump 2.

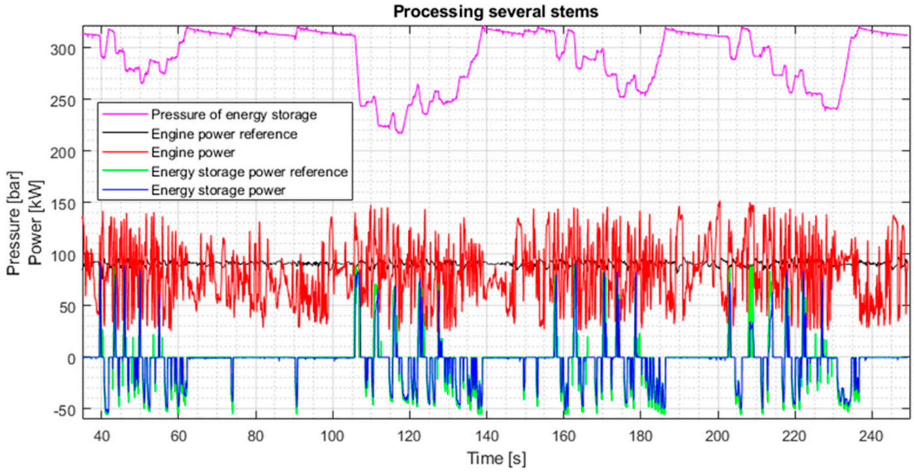

Figure 9. Processing several (four) tree stems with hybrid ON.

In Figure 10, the processing of a tree stem without an hybrid assist at an engine speed of 1700 rpm is seen to generate high power peaks to the diesel engine. This is also visible as the highly fluctuating diesel engine speed. The maximum feeding speed is seen to vary between 4 and 5 m/s.

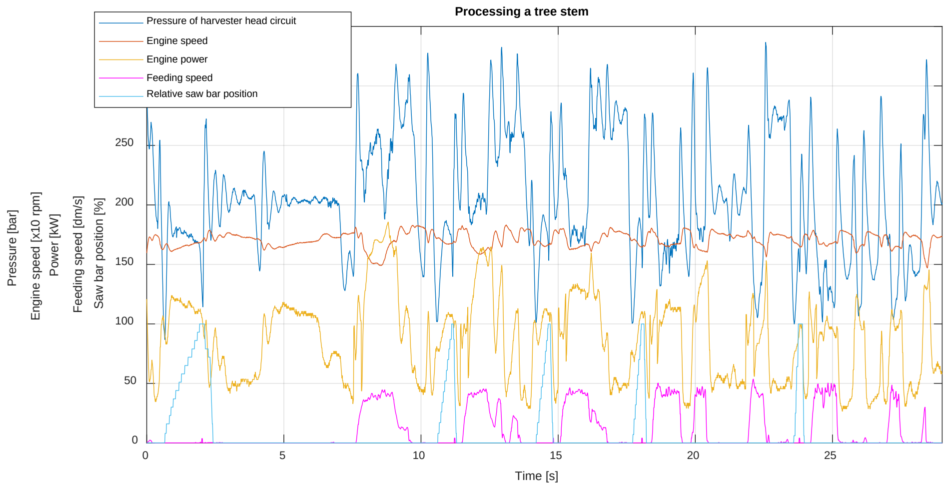

Figure 10. Processing a tree stem with hybrid OFF.

In Table 1, the outcome of the tests is shown. We can see that a bit more than 40 m3 of timber was harvested with both settings and the average stem sizes were close to each other, which means that similar test conditions were available. There was no remarkable difference in productivity or fuel consumption per cubic metre of timber harvested. The engine speed was clearly more stable with the hybrid assist, even though the set engine speed was set as low as 1400 rpm. Especially when looking for 'automatic feeding only' sections, the standard deviation of engine speed was as high than 101 rpm without hybrid assist, as with hybrid assist it was only 68; in other words, the diesel engine's load was much more stable over the measurement.

When comparing fuel consumption and productivity results for these two competing settings, it is clear that '1400 rpm hybrid ON' suffered from the lower volume flow available to boom functions and in this way moving the harvester head from a tree to the next one was slower. A respective issue was present in this setting with Pump 1 feeding the harvester head circuit in parallel with Pump 2, as the volume flow of Pump 1 alone did not reach 310 L/min which was targeted as the maximum feeding volume flow. In other words, the feeding speed reached the target only during feeding with the summed volume flow of Pumps 1 and 2.

Table 1. Fuel consumption and standard deviation (SD) of engine speed.

	Processed Timber Stem Volume Total [m^3]	Average Stem Volume [m^3]	Average Productivity of Processing [m^3/h]	Average Fuel Consumption per Production [L/m^3]	SD of Engine Speed (Automatic Feeding Sections Only) [rpm]	SD of Engine Speed (Complete Measurement Period) [rpm]
1400 rpm hybrid ON	40.9	0.73	54.8	0.35	68.0	62.5
1700 rpm hybrid OFF	43.9	0.71	56.7	0.34	101.6	69.4

Respectively, '1700 rpm hybrid OFF' suffered from some extra losses that existed during measurement as the hydraulic hybrid system was running at idle and thus Pump 2 caused continuous parasitic losses due to the charge pump and standby pressure and losses in the actual axial piston group as well. These losses can be roughly estimated to be close to 5 kW at an engine speed of 1700 rpm—which corresponds to a fuel consumption of 1.2 L/h if the engine's specific fuel consumption is assumed to be 200 g/kWh.

3.1. Results of Additional Measurements of August 2023

In Figure 11, the feeding of one tree stem is seen with the hybrid system on. The assist sections are rather clean and the hybrid system assists in feeding much better than in earlier measurements and test runs. The energy storage capacity seems to be sufficient with the lowered maximum pressure of 30 MPa.

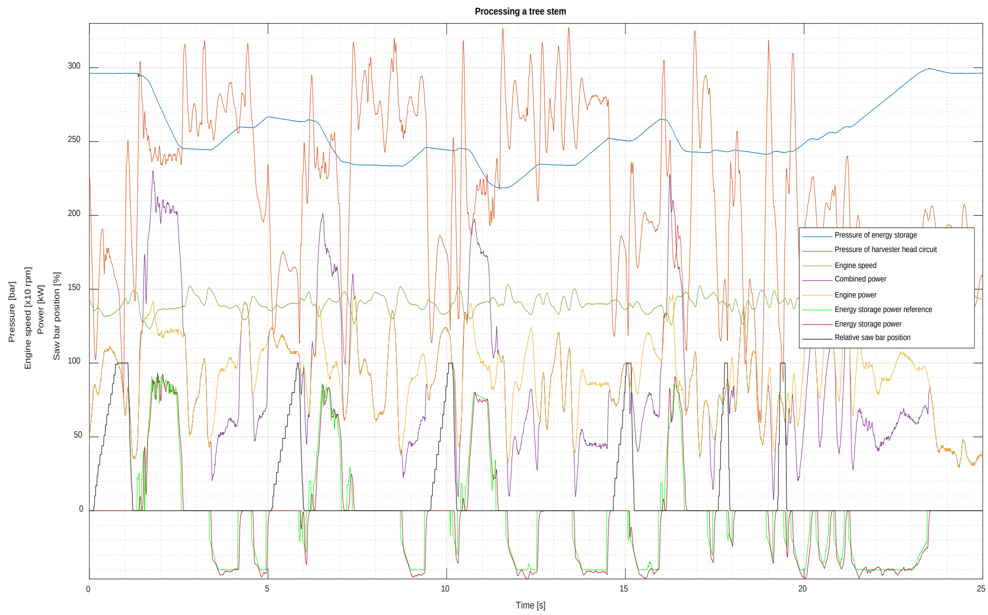

Figure 11. Processing a tree stem with hybrid ON.

In Figure 12, the feeding of one log is seen with the hybrid system on. During the assist section, we can see that the control of assist power works reasonably well, as the energy storage power follows the energy storage power reference quite well. We can see that there would be room for further lowering the engine power while still having enough combined power available. Currently, a feasible aim for hybrid assisted feeding would be to always reach the power of the '1700 rpm hybrid OFF' setup—roughly 190 kW.

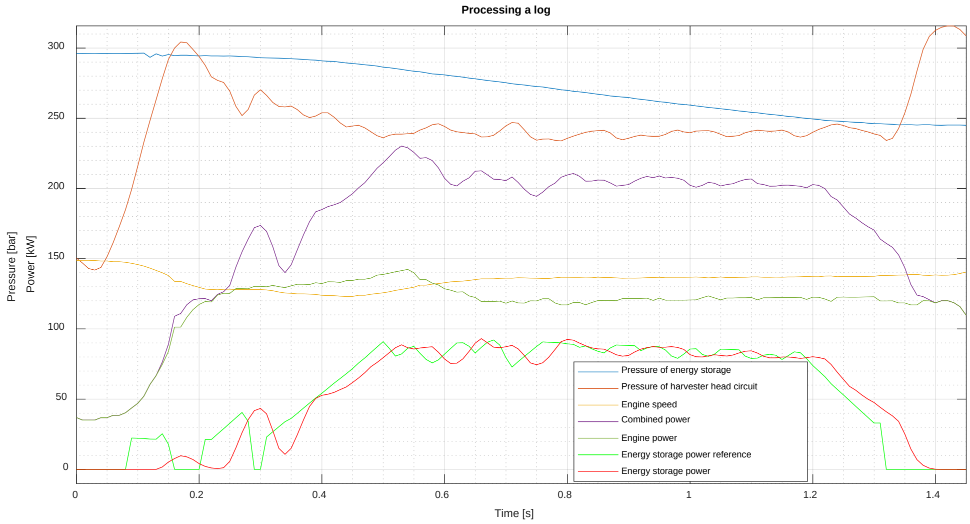

Figure 12. Processing a log with hybrid ON.

In Figure 13, the feeding of a single log is seen with the hybrid system on. A combined power as high as 230 kW is demonstrated over a lengthy period of time as a part of the work during the measurements. This is a remarkable achievement, as the diesel engine alone could theoretically put out only 155 kW at 1400 rpm. The diesel engine RPM is also kept reasonably constant thanks to the hybrid assist. Basically, this also demonstrates the potential for downsizing the prime mover, the diesel engine, to a smaller displacement, e.g., from the current six-cylinder unit to a four-cylinder unit—which is also commercially an interesting possibility.

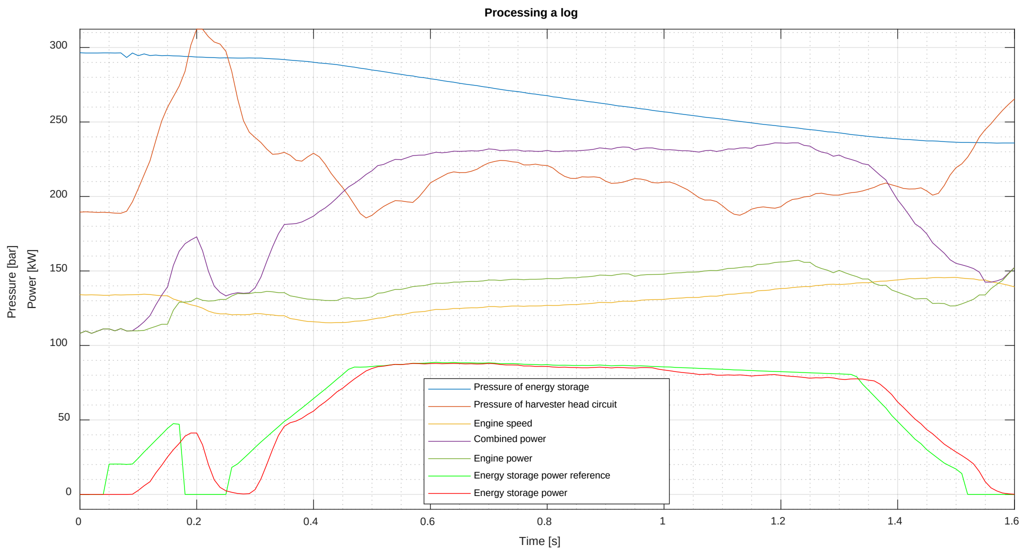

Figure 13. Processing a log with hybrid ON, showing the high combined power available.

The new poppet seat type lockup valves were introduced in order to obtain a more leak-free operation but soon showed considerable delay when closing, which naturally introduces additional losses in the system. Actually, these delays can be avoided with the right kind of valve, but this was not possible in the timeframe of the measurements. Thus, these losses related to the closing delay needed to be post-calculated and for this purpose Figure 14 shows the method used to define lockup valve delays from the measurement file to form a basis for the loss calculations. The normal maximum closing delay was assumed to be 100 ms. In other words, it is assumed that the right kind of lockup valve would meet this criterion and said losses would be avoided. The method is based on the lockup valve port pressure difference, lockup valve control state and Pump 2 swashplate swivel angle data.

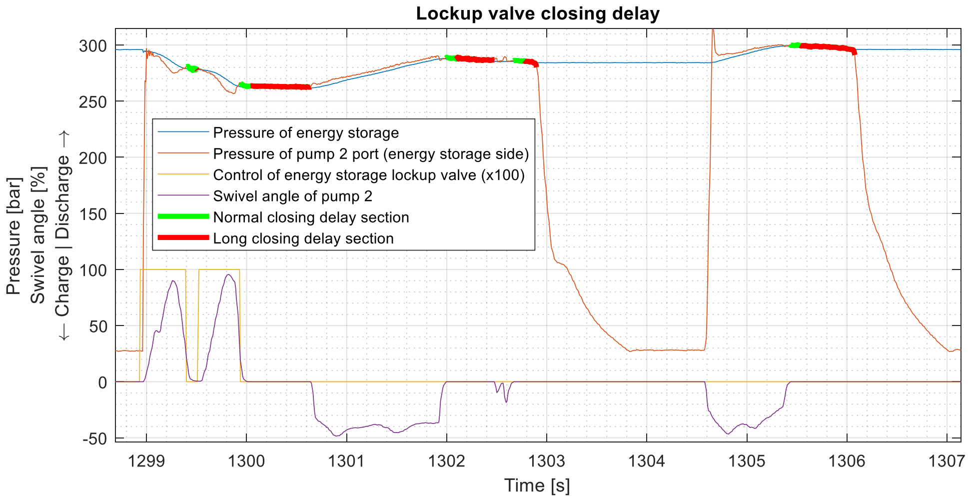

Figure 14. Lockup valve delay section recognition as the basis for loss calculations.

When Pump 2 is idling and lockup valves stay open unintentionally, the pump port pressures follow the pressure of the energy storage and harvester head circuit, causing additional leakage flow to the pump drain. In Figure 14, the thick red line annotates the sections during which the leakage losses are summed together for analysis. As the prevailing port pressures are known, the leakage flow for both ports and thus the extra power loss can be calculated. Pump 2 leakage flow can be estimated based on the general pump model. Power loss estimation is performed individually for both the lockup valves and the Pump 2 ports—even though only the direction is shown in Figure 14. Later on, these loss estimations are used when analysing the overall fuel consumption.

4. Conclusions

It has been proven that the studied and implemented hydraulic hybrid system is capable of providing enough hybrid power assist to enable the further optimisation of the CTL harvester's powertrain. In practice, the demonstrated hydraulic hybrid system delivered an assist power of up to 90 kW to the harvester head's hydraulic circuit. Over 200 kW of combined power was available on the 1400 rpm setting with the hydraulic hybrid assist. Upon the switching of the engine operating point to a more favourable one, a 300 rpm lower engine speed was also successfully demonstrated. Optionally, there seems to be potential for downsizing the diesel engine (e.g., from the current 6-cyl and 210 kW unit to a 4-cyl and 150 kW unit) or running it at an even lower engine speed but requiring larger pumps or optionally having a higher pump divider gear ratio in place. Being able to run a diesel engine at a more constant load also has positive effects on the operation of today's exhaust diesel after treatment systems like EGR, SCR, and DPF.

Substantial fuel savings were not possible to demonstrate during these first forest tests and the most logical reason for this is that the control of the hybrid assist is not yet developed enough and is not timed perfectly against the work cycle due to the complexity of the work cycle. This means that some of the assist effort is not timed optimally or takes place at the wrong magnitude and eventually results in increased power losses in the system. To make the comparison more equal between the two test cases, the boom circuit flow should be adjusted to be at the same level in both cases. However, this would mean modifications to the boom circuit pump and/or its drive setup.

Also, some other unfavourable phenomena such as internal system leaks were discovered during the measurements, which also makes it harder to improve the efficiency. These findings will be subject to development in later phases of the research.

The hydraulic hybrid system demonstrated in these measurements is still supposed to be techno-economically very competitive against respective high-voltage electric systems.

It is also a system that is easier to maintain and service for the customers and field service not used to high-voltage drives—and no further mandatory training is necessary.

Some ideas for future work arose during the measurements and analysis of the results. In addition to assisting the feed function, a cross-cut saw could also be assisted after feeding is handled properly; however, this is an even more dynamic event of the work cycle and therefore more challenging to manage with this circuitry. For this hybrid assist purpose, a direct tank discharge route from Pump 2 could also be a feasible future feature—possibly being easier to control than the studied circuitry. This way, the assist power would come to the harvester head circuit through a mechanical connection between Pumps 2 and 1 eventually.

It was also noticed that the boom hydraulics with their standard LS pump were not able to deliver enough volume flow to boom functions with a lowered engine speed. The presented hydraulic hybrid system could be used to assist and also feed the boom circuit—considering the LS system's special needs.

The dynamics of the current Pump 2 are already on a feasible level, but some improvements could be thought of. Probably, it would be interesting to build a closed-loop control for the Pump 2 swivel angle and forget about the hydraulic pressure cut-off functions and take care of the pressure control electrically through the control system.

The installation of a large hydraulic accumulator on a CTL harvester—especially one of a bladder design which should be mounted in an upright position—will be somewhat challenging. The piston accumulator could be of interest as well—as it gives more freedom in component placement and could be installed inside the machine outlines. Based on these measurements, the nominal volume could be less than what is now installed.

The maximum productivity could have been improved with the hybrid assist but this was not set as the target for this study. However, various 'boost' functionalities could also be a topic for future work—a feature that could be advantageous with heavier trees.

4.1. Conclusions on Additional Measurements—August 2023

The most important objective was to prove sufficient dynamics of the over-centre variable displacement unit with the latest revisions to the component itself as well as the control system. Due to getting rid of the hydraulic pressure cutter functionality, the dynamics of Pump 2 improved greatly and could be analysed as sufficient for the application. Pressure management was now performed electronically and also seemed to be working reasonably well. This enables a somewhat smooth introduction of the hybrid assist to feeding a log which is a short yet dynamic phase in the cut-to-length work cycle. This is also a key to efficiency as the excess hybrid assist flow would end up in losses in the system.

The energy capacity of the hydraulic accumulator is also sufficient for the work cycle, even with the new reduced high pressure limit. This can be seen from Figure 11, as the pressure of energy storage takes a turn upwards at t = 12 s while the top of the tree is still being processed. This means that energy storage is able to manage the basic element of the work cycle well—one tree at the time.

As seen in Table 2, test runs with two setups '1400 rpm with hybrid ON' and '1700 rpm hybrid OFF' were compared in terms of productivity and fuel consumption, the latter being the baseline measurement for comparison. The most interesting figures are the loss compensated for average fuel consumptions which can be seen in the right column of the table. This means that the test setup of '1400 rpm hybrid ON' was the slightly more fuel efficient of these two test runs, even though the average productivity was this time lower than with the '1700 rpm hybrid OFF'. Usually, the average productivity is very defining for fuel efficiency which means that with a higher hourly productivity and larger average stem volumes, lower fuel consumption figures are shown.

Table 2. Measurement results from August 2023 test runs—including the loss compensated fuel consumption.

	Processed Timber Stem Volume Total [m^3]	Average Stem Volume [m^3]	Average Productivity of Processing [m^3/h]	Average Fuel Consumption per Production Measured [L/m^3]	Average Fuel Consumption Loss Compensated [L/m^3]
1400 rpm hybrid assist on	33.60	0.49	50.33	0.387	0.380
1700 rpm hybrid assist off	55.98	0.49	55.26	0.415	0.391

For the test setup '1400 rpm hybrid ON', a reasonably remarkable loss power which was on average 1.37 kW—caused by slowly closing the lockup valves—was estimated as described earlier in this article in Figure 14.

Respectively, loss compensation in this connection means that the Pump 2 idling losses are considered in the test setup '1700 rpm hybrid OFF' calculations. In other words, the estimated constant idling loss power of 5.4 kW for that engine speed was calculated as an extra loss, which was later reduced in comparison calculations.

Finally, it must be mentioned that after the recent system modifications, not much if any optimisation was carried out for the complete hybrid system. In this respect, the results reported are promising. In addition to improved fuel efficiency, the system unquestionably also provides the possibility for power boosting functionality, which was this time not in the scope of the study.

Author Contributions: Conceptualisation, K.E. and A.K.; control system and control software development, A.K. and K.E.; field measurements, A.K. and K.E.; writing—original draft preparation, K.E.; writing—review and editing, K.E. and A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from Business Finland grant number 35537/31/2020 and the APC was funded by Ponsse Plc.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to commercial restrictions.

Conflicts of Interest: Authors Kalle Einola and Aleksi Kivi were employed by the company Ponsse Plc. All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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