Energy efficiency of a hybrid cable yarding system: A case study in the North-Eastern Italian Alps under real working conditions

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Abstract

In order to reduce greenhouse gas emissions, low emission or zero-emission technologies have been applied to light and heavy-duty vehicles by adopting electric propulsion systems and battery energy storage. Hybrid cable yarders and electrical slack-pulling carriages could represent an opportunity to increase the energy efficiency of forestry operations leading to lower impact timber harvesting and economic savings thanks to reduced fuel consumption. However, given the limited experience with hybrid-electric systems applied to cable yarding operations, these assumptions remain uncertain. This study assessed an uphill cable yarding operation using a hybrid cable yarder and an active slack-pulling electric power carriage over thirty working days. A total of 915 work cycles on four different cable lines were analysed. Long-term monitoring using Can-BUS data and direct field observations were used to evaluate the total energy efficiency, total energy efficiency (%), and fuel consumption per unit of timber extracted (L/m³). The use of the electric-hybrid system with a 700 V super capacitor to store the recovered energy made it possible to reduce the running time of the engine by about 38% of the total working time. However, only 35% to 41% of the Diesel-based mechanical energy was consumed by the mainline and haulback winches. Indeed, the remaining energy was consumed by the other winches of the cable line system (skyline, strawline winches and carriage recharging or breaking during outhaul) or dissipated by the system (e.g., by the haulback blocks). With reference to all work cycles, the highest net energy consumption occurred during the inhaul-unload work element with a maximum of 1.15 kWh, consuming 70% of total net energy consumption to complete a work cycle. In contrast, lower energy consumption was recorded for lateral skid and outhaul, recording a maximum of 23% and 32% of the total net energy consumption, respectively. The estimated recovered energy, on average between the four cable lines, was 2.56 kWh. Therefore, the reduced fuel need was assessed to be approximately 730 L of fuel in the 212.5 PMH15 of observation, for a total emissions reduction of 1907 kg CO2 eq, 2.08 kg CO2 eq for each work cycle.

Introduction

The impact of fossil fuel-based energy is considered one of the main environmental threats facing the planet. Alternative fuels and different propulsion systems have been proposed to perform low emission or zero-emission vehicles (Daziano and Chiew, 2012). The use of full electric and hybrid vehicles, especially in the transport sector, has increased substantially in the last few years compared to internal combustion engine vehicles (Correa et al., 2019). As a result, different studies have been conducted to analyse the energy efficiency of these power systems applied to light and heavy-duty vehicles, such as road vehicles, city mobility vehicles, and non-road vehicles (Chan, 2002; Chasse and Sciarretta, 2011; Kärhä et al., 2018; Ehrenberger et al., 2020; Weiss et al., 2020; Kulor et al., 2021; Zhou et al., 2021). Even though hybrid and full electric propulsion systems are widely studied for road vehicles and city mobility applications (European Commission, 2018), there is currently a considerable knowledge gap about hybrid and full electric propulsion systems in heavy-duty vehicles (Vijayagopal and Rousseau, 2020). Although heavy-duty vehicles are not as widespread as road vehicles, they are responsible for over 5% of greenhouse gas emissions (GHG) of the EU-27 countries (ACEA, 2020). For these reasons, new regulations (e.g. EU Regulation 2016/1628) have been progressively introduced in non-road mobile machineries (ARCADIS et al., 2010).

To achieve the ambitious climate change targets, low emission and zero-emission engines have also been introduced in the agricultural and forestry sectors. The first result of the electric-hybrid application in the agricultural sector shows that the electric traction drive applied to a farm tractor can reduce energy consumption by 12% (Deryabin and Zhuravleva, 2020). In comparison, hybrid powertrains with smaller Diesel engines can reduce energy consumption by up to 16% compared to bigger ones, ensuring more efficient energy usage in hybrid electric tractors (Mocera and Somà, 2020). The first application of hybridisation or electrification in heavy-duty machines in the forest sector involved the CFJ20H 320 V harvester (Rong-Feng et al., 2017), EcoTrac 120V skidder (Karlušić et al., 2020) and Kesla’s C 860 H hybrid wood chipper (Prinz et al., 2018). As reported in Rong-Feng et al. (2017), the hybridisation of the CFJ20H 320 V harvester met the design requirement concerning grade, maximum speed, acceleration time, and fuel consumption. The backward powertrain model of a skidder, optimised through a cascade optimisation approach
using specific transmission components constraints (Karlušić et al., 2020), shows an efficiency improvement of over 15%. The algorithm optimisation can lead to a fuel reduction of 0.4 L per driving cycle and, consequently, of approximately 6516.00 € in fuel cost and 15,900 kg in CO2 emissions over the li-ion cells battery lifetime (15,000 cycles). Kesla’s C 860 H hybrid wood chipper achieved higher efficiency than conventional wood chippers (Kesla C 1060 A and Kesla C 1060 T). A study by Prinz et al. (2018) demonstrated lower fuel consumption of 0.2 L of fuel and 0.4 L of fuel per o.d.t. (oven dried ton) of pulpwood for high power truck-mounted and medium power tractor-mounted wood harvesters, respectively.

In 2015, Koller Forsttechnik presented the first prototype of a hybrid cable yarder (Koller K507e-H) (Visser, 2015). This Diesel-electric configuration of the Koller K507e-H cable yarder was expected to reduce fuel consumption by up to 3-5 L/h thanks to an energy recovery system. Furthermore, noise exposure for workers was also expected to be reduced due to a decrease in time with the engine on. However, to date, no study has tested the hybrid cable yarders, in order to assess the energy efficiency in terms of energy and fuel consumption.

In cable yarding operations, an active slack-pulling electric power carriage with an energy-recovery system (SPC), powered by the mainline, when pulled or the load is lowered, proves to be useful in order to reduce fuel consumption during timber extraction. As reported by Varch et al. (2020), the 13 electric carriages, which are currently available on the market, recover energy during different working elements: when the carriage runs from the landing to the hooking area (outhaul), when the load is pulled up to the carriage (lateral skid), or when the carriage stops at the landing area, and the load is lowered (unload).

The hybrid cable yarders and SPC could present an opportunity to increase the energy efficiency of forestry operations, which would lead to lower emissions and economic savings due to reduced fuel consumption. However, there is still a considerable knowledge gap about energy efficiency and fuel consumption of these electric-hybrid technologies. Therefore, this study aims to cover partially this knowledge gap by assessing energy efficiency and fuel consumption of a hybrid cable yarder equipped with an EC. The specific objectives of this study are: i) to quantify the energy consumption (kWh) of cable yarding operations using a hybrid cable yarder and an SPC; ii) to assess the total energy efficiency of the yarding system estimated by the percentage ratio between the energy consumed during working activity (kWh) and the energy generated by the Diesel engine (kWh); iii) to estimate the CO2 equivalents emissions (CO2 eq) saved due to the energy recovery system.

### Materials and methods

#### Machine description

The machine monitored in the study is a Koller K507e-H hybrid yarder. This hybrid yarder is a mobile tower yarder for standing skyline logging operations mounted on a 2-axle trailer (Table 1).

| Characteristics                  | Unit            | Value / Description |
|----------------------------------|-----------------|---------------------|
| Engine                           | Deutz F3L2011, 3 cylinders, Stage IIIA* | 35.8 kW |
| Power                            | kW              | 35.8                |
| Vehicle base                     | 2-axle trailer  |                     |
| Tower height                     | m               | 11                  |
| Skyline                          | 6/26 IWRC       |                     |
| No. Diam.                        | mm              | 18                  |
| Lenght                           | m               | 1000                |
| Tensile force                    | kN              | 89                  |
| Mainline                         | 6/26 IWRC       |                     |
| No. Diam.                        | mm              | 10                  |
| Lenght                           | m               | 2000                |
| Tensile force                    | kN              | 25                  |
| Haulback line                    | 6/26 IWRC       |                     |
| No. Diam.                        | mm              | 10                  |
| Lenght                           | m               | 2000                |
| Tensile force                    | kN              | 25                  |
| Strawline                        | AnSteel-Blue    |                     |
| No. Diam.                        | mm              | 6                   |
| Lenght                           | m               | 2000                |
| Tensile force                    | kN              | 11                  |
| Carriage                         | Koller Ecko Flex|                     |
| Mass                             | kg              | 600                 |
| Payload                          | kN              | 20                  |

*Homologation declared by the cable yarder manufacturer (Koller GmbH, 2020); °tensioning drum; #constant over the entire drum diameter.

The hybrid cable yarder is equipped with a Koller Ecko Flex carriage, an automatic clamped carriage with active slack-pulling system. The slack-pulling system is controlled by an electric motor which is powered by the 300 V electric capacitor. The electric motor consists of two batteries of 12 V and 7.2 Ah (86.4 Wh). The mainline runs inside the carriage through a pulley system. When the mainline is pulled by the electric winch of the cable yarder or when the load is lowered, the pulley system allows the battery pack to be recharged. This condition occurs during the lateral skidding and the lifting of the loads to the carriage.

The Koller K507e-H Hybrid is equipped with a control panel consisting of the Koller Multi Matik screen and two joysticks. Through the Koller Multi Matik screen, it is possible to adjust settings and to monitor operating parameters in real-time (e.g., the maximum tensile force of the skyline, mainline, haulback line, strawline, and guyline; modify or deactivate the mainline drum and haulback drums; monitor the charging voltage of the supercapacitor). In addition, due to the Koller Ecko Flex carriage compatibility with the Koller Multi Matik, it is also possible to monitor the charging voltage of the carriage electric capacitor.

### Table 1. Characteristics of hybrid cable yarding system.
Study area and cable line configurations

The study area was located in the Natural Park of Paneveggio Pale di San Martino (Trentino Province, coordinates in WGS84: 46°17’53.9592”, 11°45’23.9940”), in the North-Eastern Italian Alps, at 1555-1680 m a.s.l. (Figure 1). The ground was characterised by an average slope of 20 % and an uneven rough terrain. The area was covered by a mixed even-aged stand composed by Norway spruce (*Picea abies* Karst.), silver fir (*Abies alba* Mill.), and European larch (*Larix decidua* Mill.). The stand area was affected by a large scale windthrow caused by the Vaia storm at the end of October 2018 (Motta et al., 2018; Chirici et al., 2019).

The observation was focused on four different cable lines. Three of the four lines were in multi-span configuration and one in single-span configuration (Table 2). The longest cable line was cable line 1 with an horizontal length of 502 m, while the shortest was cable line 3 with 109 m of horizontal length. The four cable lines were in three cable uphill yarding configurations (skyline, mainline and haulback line). The logs were extracted at the roadside landing where an excavator, equipped with a log grapple, piled them up along the forest road.

Data collection

The monitoring period was between July 2020 and September 2020. The position (coordinates) of the tower yarder and tail anchors of each cable line was taken with a Garmin 64s GNSS. QGIS® software was used to estimate horizontal length and vertical length of each cable line calculated as the horizontal and vertical distance from the cable line tower yarder to the anchor from the digital elevation model (DTM) with a resolution of 1 m. Data were collected through the integration of long-term monitoring (LTM) using Can-BUS data, self-monitoring data, and direct field monitoring (FM). Can-BUS data were downloaded directly from the cable yarder at the end of the monitored period. Can-BUS data were recorded at 4 Hz and saved in 8 bits. The following pieces of information were collected from the Can-BUS data: i) energy-storage (V); ii) electric power of the winches (kW); iii) speed of wire (m/s); iv) distance of carriage off the tower (m); v) power electric generator (kW); vi) tensile force of mainline (N); vii) tensile force of haulback (N).

For the self-monitoring data collection, the operator was instructed to record the daily data about fuel consumption (recorded measuring the volumes of fuel tank refills), number of work cycles and type of activity (cable yarding extraction or cable yarding installation) for each cable line.

Finally, the FM aimed at evaluating and checking the LTM data (e.g., check the correctness of the automatic time and motion study) and covered a total of four different working days (22.5 PMH15). Cable line 1 was monitored for 11.1 PMH15 and 46 work cycles, while cable line 2 was monitored for 11.5 PMH15 and 46 work cycles.

![Figure 1. Location of the logging area and cable lines.](image)

Table 2. Cable line configurations.

| Cable line | HL (m) | VL (m) | N° span | Slope (%) |
|------------|--------|--------|---------|-----------|
| 1          | 502    | 107    | 3       | 21.3      |
| 2          | 480    | 70     | 3       | 14.5      |
| 3          | 109    | 20     | 1       | 12.0      |
| 4          | 164    | 31     | 2       | 18.6      |

HL, horizontal length, measured from the tower yarder to the anchor; VL, vertical length, measured as altitudinal difference between the starting point (tower yarder) and the endpoint of the corridor (anchor); Slope (%): average slope of the cable line, measured from the cable yarder to the anchor.
In order to evaluate the input of time in the production process of each work cycle, as reported by Björheden (1991), a time study of the cable yarding operations at cycle level was carried out using a time study board. In addition, the fuel consumption of each cycle, as displayed on the Koller Multi Matik screen, was noted, and the timber volume extracted (m\(^3\) o.b.) by each cycle was measured scaling each log, using a calliper and a measuring tape.

Data analysis

About 900 MB of Can-BUS data and more than 4 million raw data were downloaded from the cable yarder. The Can-BUS data were converted from 8 bits information (0 to 255) to decimal encoding and subsequently resampled at 1 Hz data using the R software (R Core Team, 2021). Days spent for cable line set-up were excluded from the analysis using self-monitoring data collected by the operator. Automatic time study data was retrieved from the Can-BUS data. Each yarding cycle and related work elements were obtained from the decoded Can-BUS data using the winches power and the distance of the carriage from the tower yarder (Table 3, Figure 2).

Non-productive time was determined when the electric power of the winches, speed of the wire rope, the tensile force of mainline and tensile force of haulback line were equal to zero. Non-productive times longer than 15 min suggested that the machine was completely shut down and, therefore, were excluded from the analysis leading to the adoption of the Productive Machine Hour, which includes delays not exceeding 15 minutes (PMH\(_{15}\)). Finally, the actual yarding operations involved 915 complete work cycles over 30 working days, for a total of 212.5 PMH\(_{15}\).

The parameter used for evaluating the yarding system total energy efficiency was the net energy consumption (Net EC, kWh) of the winches, and the energy generated by the Diesel engine expressed as electric energy (kWh). The net power supplied to drive the winches - Net PC - was calculated for each work element and cycle using Equation 1:

\[
\text{Net PC (kW)} = \text{PC (kW)} - \text{PG (kW)}
\]

where PC was the power consumed, calculated from the sum of energy consumed from the mainline winch and haulback winch, expressed in kW; PG was the power generated, calculated from the sum of energy generated from the mainline winch and haulback winch, expressed in kW. To calculate net energy consumption during working activity, the averaged Net PC (kW) for each work element was multiplied by the time required to complete the work element - WEPMH\(_{15}\) - (Equation 2):

\[
\text{Net PC (kWh)} = \text{Net PC (kW)} \times \text{WEPMH}_{15} (\text{h})
\]

Table 3. Description of the work elements.

| Work element       | Description                                                                 | Carriage motion |
|--------------------|-----------------------------------------------------------------------------|-----------------|
| Outhaul            | Begins when the haulback line is rolled up and mainline is rolled out, while the carriage moves from the landing site to the hooking area, and ends when the carriage stops at the hooking area | Yes             |
| Lateral skid       | Begins when the mainline is rolled up, while haulback does not generate or consume energy (inactive), and ends when the carriage moves from the hooking area back to the landing site | No              |
| Inhaul-unload      | Begins when the mainline is rolled up and haulback line is rolled out, while the carriage moves from the landing site, and ends when the carriage moves from the landing site to the hooking area | Yes             |
The energy produced during a work cycle by the Diesel engine - EP - expressed in kWh, was estimated multiplying the mean power generated by the Diesel generator, while the Diesel engine was running - PGE - expressed in kW, by the time the engine was on - TO - expressed in hours and represents part of PMH15 (Equation 3):

\[ EP \text{ (kWh)} = PGE \text{ (kW)} \times TO \text{ (h)} \]  

Equation (3)

Typically, the energy stored in the supercapacitor during a single cycle can be used in subsequent cycles. Due to the dependence on the powertrain between work cycles, total energy efficiency (TEF) was evaluated in term of the percentage ratio between the net Energy Consumed (Net EC) and the Energy Produced (EP) at each work cycle (Equation 4):

\[ TEF \% = \frac{\sum \text{Net EC (kWh)}}{EP \text{ (kWh)}} \times 100 \]  

Equation (4)

Automatic time study and energy information at cycle levels collected through LTM and data obtained through FM were synchronised and combined with extracted timber volume and number of logs per cycle. The correctness and completeness of the data were checked. The fuel consumption model was tested through linear regression analysis using EP (kWh) as an explanatory variable for the fuel consumed for each cycle (L) collected during FM. The hypothesis of the normal distribution of the residuals was checked using the Shapiro-Wilk normality test (P-value >0.05). In the case of statistical significance, the regression coefficients of the regression were used to extend the fuel consumption estimation to the LTM data.

The emissions saved were estimated by applying the TEF parameter for each line to the average energy saved (kWh) to obtain the EP (kWh) of the engine. As proposed by De la Fuente et al. (2017), CO2 emissions were estimated using an emission factor of 2.61 kg CO2 eq per litre of Diesel fuel consumed.

Energy consumption model

Different independent variables were checked as explanatory variables for the Net EC evaluated at each work element. The independent variables were: yarding distance, estimated by the maximum distance travelled by the carriage - YD (m), maximum speed - MS (m/s), mean tensile force of mainline - MTFM (kN), mean tensile force of haulback line - MTFH (kN). Due to the diversity of the Net EC per work element within cable lines, the response variables were considered as repeated measures within each individual cable line, as reported by different studies (e.g., Hiesl and Benjamini, 2013; Bates et al., 2015; Mologni et al., 2019; Cadei et al., 2020). The different cable lines were assumed to be random factors, and a random intercept for the different cable lines was introduced in the regression analysis, leading to the adoption of linear mixed-effect models. The likelihood ratio test was used to evaluate the significance of the individual variables, with the significance level of the statistical analysis set to 0.05. A linear mixed-effect model was fitted with the lme4 package available for R (Bates et al., 2015). The normal distribution of the residuals was checked using residual plot distributions. In the case of non-normal distribution of the residual, logarithmic, quadratic, and square root transformations were tested on both response variables and continuous explanatory variables. The goodness of fit of linear mixed-effect models was tested through the coefficient of determination ($R^2_{LR}$) proposed by Magee (1990) (Equation 5) and based on likelihood ratio joint significance:

\[ R^2_{LR} = 1 - \exp(-2/n \times (l_M - l_0)) \]  

Equation (5)

where ‘$l_M$’ and ‘$l_0$’ are the log-likelihoods of the model of interest and of the intercept-only model, respectively, and ‘n’ is the number of observations.

Results

Monitored work cycles and days varied between the cable lines (Table 4).

The shortest single span cable line (1) recorded the lowest Net EC during the lateral skid and inhaul-unload work element, 0.086 and 0.237 kWh per work cycle, respectively. On the contrary, cable lines 1 and 2 with higher yarding distances, 380 and 281 m respectively, recorded a higher value of Net EC for the whole work element than cable lines 3 and 4. Also, in cable lines 1 and 2, the engine was running for more than two-thirds of the working time (PMH15), producing 35 to 40% of the Net EC. As expected, Net EC for all work elements increased as the yarding distance increased (Figure 3).

The percentage of the time with Diesel engine on varied considerably between the cable lines, from a minimum of 38% for cable line 4 to 73% for cable line 1. Also TEF varied from a minimum of 35% to a maximum of 41% for cable lines 3 and 4, respectively. The lowest TEF was related to cable line 3, characterized by the lowest line slope (12%).

Because of the uphill yarding, the inhaul-unload work element was the most energy-consuming. Net EC during lateral skid exceeded Net EC during outhaul only in cable lines 3 and 4. This suggests that the reduced yarding distance of lines 3 and 4 led to a reduction in the energy consumed during outhaul and inhaul-unload. Subsequently, Can-BUS data were evaluated and controlled according to FM data (Table 5). During the FM, a total of 100.6 m³ were yarded and measured, 57.1 m³ in cable line 1 and 43.4 m³ in cable line 2. Descriptive statistics related to FM are reported in Table 5. The emissions related to the FM yarding activ-

Table 4: Descriptive statistics of long-term monitoring.

| Cable line | Total time PMH15 | Cycle No. | Net EC outhaul kWh Mean | SD | Net EC lateral-skid kWh Mean | SD | Net EC inhaul-unload kWh Mean | % SD | TEF | Engine on % | Yarding distance m Mean | SD |
|-----------|-----------------|-----------|-------------------------|----|-----------------------------|----|-----------------------------|------|-----|-------------|-------------------------|----|
| 1         | 114.94          | 422       | 0.273                   | 0.12| 0.231                       | 0.16| 1.150                       | 0.36 | 40.7%| 73.6%       | 380.3                    | 93.6|
| 2         | 81.99           | 338       | 0.336                   | 0.27| 0.287                       | 0.26| 0.837                       | 0.59 | 35.6%| 68.7%       | 281.0                    | 129.7|
| 3         | 3.14            | 42        | 0.045                   | 0.03| 0.086                       | 0.03| 0.237                       | 0.06 | 35.3%| 51.8%       | 85.5                     | 15.4|
| 4         | 12.44           | 113       | 0.035                   | 0.04| 0.132                       | 0.08| 0.245                       | 0.10 | 41.4%| 38.2%       | 80.4                     | 39.5|

Engine on: sum of the time engine on divided by the total working time (PMH15). TEF, total energy efficiency; SD, standard deviation.
ity were 84.04 kg CO₂ eq and 93.77 kg CO₂ eq equal to 1.47 kg CO₂ eq/m³ and 2.16 kg CO₂ eq/m³ for cable line 1 and cable line 2, respectively.

Electric energy produced by the Diesel engine (kWh) significantly affected fuel consumption (L). Therefore, the predicted fuel consumption (L) showed a correlation to the electric EP (R²=0.52, P<0.001) (Table 6). Using the relationship between EP and fuel consumption, it was also possible to estimate fuel consumption for the LTM activity. During the LTM, the hybrid technology allowed for the recovery of an average of 2.56 kWh per cable line, ranging from a minimum of 0.91 for cable line 3 to a maximum of 5.01 kWh for cable line 4. An estimated total of 730.7 l of fuel was saved. This fuel saved can be considered as a reduction of the emission impact equal to 1907.1 kg CO₂ eq and 2.08 kg CO₂ eq for each work cycle. The estimated productivity, fuel consumption and emissions are shown in Table 7. The lower productivity was estimated for the longest cable lines (1-2); therefore, cable lines 1 and 2 consumed more fuel per unit of timber extracted (0.54 and 0.55 L/m³, respectively) compared to cable lines 3 and 4 (0.28 and 0.27 L/m³, respectively). Consequently, the estimated CO₂ eq emissions per unit of timber extracted were highest for the longest cable lines than the shortest ones (1.41, 1.44, 0.73 and 0.70 kg CO₂ eq/m³ for cable lines 1, 2, 3 and 4, respectively).

![Figure 3. Net EC (kWh) for outhaul, lateral skid and inhaul-unload working element in respect of the yarding distance (m).](image)

**Table 5. Descriptive statistics of field monitoring.**

| Cable line | Total time PMH15 | Cycle No. | Yarding distance m | Lateral skid distance m | Load m³/cycle | Productivity m³/PMH15 | Fuel consumption L/m³ |
|------------|------------------|-----------|--------------------|-------------------------|---------------|------------------------|-----------------------|
|            | Mean             | SD        | Mean               | SD                      | Mean          | SD                      | Mean                  |
| 1          | 10.99            | 51        | 15.5               | 1.2                     | 1.20          | 0.30                    | 5.70                  |
|            | 46               |           |                    |                         |               |                        |                      |
| 2          | 11.44            | 52        | 17.5               | 2.5                     | 1.00          | 0.20                    | 5.00                  |
|            | 50               |           |                    |                         |               |                        |                      |
| SD, standard deviation. |

**Table 6. Linear regression model to predict fuel consumption (L) from the electric energy (EP) produced by the Diesel engine (kWh).**

| Coefficient | Estimate | SE   | t value | P-value | R² |
|-------------|----------|------|---------|---------|----|
| Intercept   | 0.236    | 0.642| 3.667   | <0.001  | 0.52 |
| EP (kWh)    | 0.089    | 0.104| 6.323   | <0.001  | 0.52 |

SE, standard error.

**Table 7. Estimated productivity, fuel consumption and fuel emission based on FM data.**

| Cable line | Extracted volume m³ | Productivity m³/PMH15 | Fuel consumption L/m³ | CO₂ eq emission kg CO₂ eq/m³ |
|------------|---------------------|------------------------|-----------------------|-----------------------------|
| 1          | 464                 | 4.04                   | 0.54                  | 1.41                        |
| 2          | 372                 | 4.53                   | 0.55                  | 1.44                        |
| 3          | 46                  | 14.71                  | 0.28                  | 0.73                        |
| 4          | 124                 | 9.99                   | 0.27                  | 0.70                        |

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Energy consumption equations

As shown in Figure 3, the yarding distance - YD (m) - suggested a significant and positive correlation on Net EC for all the elements of the work cycle. The three equations (A, B and C) carried out for each work element, shown in Tables 8 and 9, explain the energy consumption equation.

Equation A is related to the Net EC during outhaul and explains 53% of the variability, where each metre of increase in YD leads to an increase of Net EC of 1.3 Wh. Equation B explains 30% of the variability. The mean tensile force of the mainline during the lateral skid - MTFMl (kN) - had a negative effect on Net EC, meaning that increasing MTFMl during the lateral skid can lead to a reduction of the energy consumed. On average, the MTFMl was 10.3, 10.7, 11.7 and 11.2 kN for cable lines 1, 2, 3 and 4, respectively. Equation C explains over 78% of the variability. As expected, the mean tensile force of the haulback line during the inhaul-unload work element - MTFHin (kN) - had a negative influence on the Net EC of the same work element.

In conclusion, the YD had a significant effect and positive correlation on Net EC for all the work elements. The influence of YD on energy consumption changed according to the work element (Figure 4). Although inhaul-unload is the most energy-consuming, outhaul made it possible to obtain an increase in energy recovery. In fact, for short YD (<150 m) in uphill cable yarding configurations, the Net EC showed negative values and therefore represented an energy-producing element of the work cycle.

Table 8. Explanatory variables of fixed effect in Net energy consumption, Net EC (kWh), during the different work elements.

| Equation | Response variable                  | Coefficient | Estim. | SE   | t value | P-value |
|----------|------------------------------------|-------------|--------|------|---------|---------|
| A        | Net ECouthaul (kWh)                | YD (m)      | 0.0013 | 0.037| –2.47   | <0.001  |
| B        | Sqrt(Net EC_lateral skid) (kWh)    | YD (m)      | 0.0008 | 0.00005| 18.06   | <0.001  |
|          |                                    | MTFMl (kN)  | –0.0088| 0.00130| –6.54   | <0.001  |
| C        | Ln(Net EC_cinhaul unload) (kWh)    | MTFHin (kN) | –0.0182| 0.006 | –2.928  | 0.002   |
|          |                                    | Sqrt(YD) (kN) | 0.1455 | 0.002| 60.67   | <0.001  |
|          |                                    | SDTFMin (kN) | 0.1048 | 0.008| 12.53   | <0.001  |

Ln, logarithmic transformation; YD, yarding distance (m); MTFMl, mean tensile force of mainline during lateral skid (kN); MTFMin, mean tensile force of mainline during inhaul unload element (kN); Sqrt, square root transformation.

Table 9. Random intercepts and goodness of fit of the linear mixed-effect models.

| Equation | N  | Variance | SD  | L_M | L_0  | R²_LR |
|----------|----|----------|-----|-----|------|-------|
| A        | 915| 0.01774  | 0.133| 594.4| 253.2| 0.527 |
| B        | 915| 0.00660  | 0.081| 536.4| 371.7| 0.302 |
| C        | 915| 0.45420  | 0.674| –34.2| –733.3| 0.783 |

N, number of observations; L_M, log likelihoods of the model; L_0, log likelihoods of the intercept; R²_LR, coefficient of determination proposed by Magee (Magee, 1990).
Discussion

Hybrid powertrains are expected to reduce fuel consumption thanks to an energy recovery system. Excluding set-up/installation of the cable lines, the Net EC of the system is based on the use of mainline and haulback winches alone. However, it can also be considered that a certain amount of energy may be consumed by the carriage (energy recuperation system and the breaking of the carriage during the outhaul) or by the skyline winch during the skyline tensioning.

The monitored rigging configurations were the most energy disadvantageous due to the low line slope (limited to a maximum of 21%) and the uphill yarding. Fuel consumption is highly dependent on the slope of the line and the yarding direction, with higher fuel consumption recorded in uphill extraction than in flat conditions (Oyier and Visser, 2016). Consequently, due to the high fuel consumption for uphill yarding, it is expected that the related energy consumption is also higher. In general, YD significantly affects the Net EC of each work element, causing an increase in Net EC. Similarly, other authors reported the positive effect of yarding distance on time consumption (Spinelli et al., 2010; Lindroos and Cavalli, 2016; Proto et al., 2016; Lee et al., 2018; Stoilov et al., 2021). Hybrid powertrains of the cable yarder in an uphill configuration recover most of the energy when the carriage moves from the landing to the hooking area, using the excess potential energy generated by the mainline drum when the mainline is rolled out. A small amount of energy can also be recovered when the carriage moves from the hooking area to the landing, using the haulback drum excess potential energy, when the haulback line is rolled out. However, the energy consumed by the mainline drum, when the carriage moves from the hooking area to the landing, carrying the loads against gravity, is much greater than that recovered by the haulback drum during the same work element. The higher the MTFHin, the lower the Net EC during the inhaul unload work element. This finding suggests that the rise and fall of tensile force during inhaul unload causes an increase in energy consumption. The change in tensile force may be due to the reduced tensioning of the skyline, which caused an increase in the mainline tensile force, while passing a support structure.

In terms of fuel consumption, Varch et al. (2020) demonstrated that the SPC uses less fuel than an engine-powered slack-pulling carriage over short yarding distances (25 and 100 m) and with average tree volumes lower than 0.7 m³. Our results show that also in disadvantageous energy consumption conditions (low line slope and uphill yarding) with yarding distances lower than 150 m, the movement of the carriage from the landing to the hooking area can take place without consuming energy and, under certain circumstances, can even generate energy effectively exploiting the conversion of potential energy into electrical energy. Assuming an efficiency of conversion of mechanical energy into electrical energy, the relationship between fuel consumption (L) and electrical energy produced by the Diesel engine (kWh) is consistent with the average fuel consumption of 0.09 L per unit of power (L/kW) for the cable yarding harvesting system reported in Oyier and Visser (2016). The fuel consumption of the hybrid cable yarder ranged from 0.5 to 0.8 L/m³ for a yarding distance of 300 and 450 m and an average load of 1.2 and 1 m³ respectively (Table 4). Considering the total energy efficiency - TEF - and the relationship between EP and fuel consumption (Table 5), the predicted fuel consumption (Figure 5) was considerably lower compared to Diesel engine cable yarders, which range from 2.35 to 3.98 L/m³, as reported by Oyier and Visser (2016). Furthermore, Varch et al. (2020) reported the comparison between fuel consumption of Diesel engine and SPC in similar working conditions (uphill yarding) using a truck-mounted tower yarder.

Diesel engines, which powered both the carriage and the tower yarder, consumed 1.27 L/m³, while the base machine used with an SPC consumed 0.88 L/m³, with an average yarding distance of 62.2 and 54.7 m, respectively. In our study, at the same yarding distance, the predicted fuel consumption varied between 0.25 and

![Figure 5. Predicted fuel consumption depending on the yarding distance.](image-url)
0.32 L/m³, resulting in more than a quarter of the fuel consumption of a fully equipped Diesel engine tower yarder and carriage and about one third of the fuel consumption of the SPC and Diesel engine tower yarder. The gap in the literature on energy efficiency and fuel consumption on cable yarding did not allow for further comparison with other studies. The fuel consumption of a hybrid cable yarder and SPC per unit of timber extracted would therefore be lower than a traditional Diesel engine tower yarders and carriages. The fuel consumption is also lower than SPC with Diesel engine based machines. In contrast, the average productivity of the hybrid cable yarder of 5.35 m³/PMH was lower than the conventional Diesel engine cable yarder in similar conditions. Therefore, in terms of energy balance, the hybrid cable yarder and SPC are more advantageous than traditional Diesel based cable yarders. However, this study is focused on energy efficiency and not on productivity. Finally, further economic and cost analyses are needed to establish the economic benefit of these applications.

Conclusions

This study monitored cable yarding operations under real working conditions and demonstrated that hybrid cable yarders and SPC have the potential to reduce energy consumption and save fuel and emissions. Although this study provides information about energy efficiency and fuel consumption, the main limitation of the study is related to the cable line configuration. In fact, to better understand the efficiency of the energy recovery system of the hybrid cable yarders in the Alpine context, further studies are needed, including downhill and uphill extractions as well as two- and three-line cable yarding systems. The study also found that the Can BUS system allows to easily collect long-term information of the performance of the powertrains, as well as integrate and analyse long-term data correctly, particularly when combined with field observations.

Finally, given the reduced time during which the yarder engine was running, the study suggests that the noise exposure of forest operators could be lowered by using hybrid solutions compared to conventional machines. In addition, a powerful Diesel engine with high performance can reduce the charging time of the supercapacitor, further reducing the time engine on and optimising fuel consumption. However, further studies need to be carried out to determine the effect of hybrid powertrains on noise pollution. The smaller amounts of hydraulic and engine lubricants for the operation of the hybrid propulsion systems should also be taken into consideration, because they may lead to lower impact timber harvesting and ensure safety of forest operators.

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