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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/m^3). 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 PMH$_{15}$ of observation, for a total emissions reduction of 1907 kg CO$_2$ eq, 2.08 kg CO$_2$ eq for each work cycle.

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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 (Karlušíc *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 algorithms to minimise fuel consumption and satisfying transmission components constraints (Karlušíc *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 CO_2 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 chippers, 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 CO_2 equivalents emissions (CO_2 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).

The machine is equipped with an F3L2011 Deutz 3-cylinder Diesel engine (35.8 kW), with specific fuel consumption at 1800 rpm and 75% of the load of 225 g/kWh (Deutz AG, 2011). The Diesel engine drives the electric generator, while each one of the four main drums (skyline, mainline, haulback line, and strawline) is driven by an electric motor and equipped with spring-loaded, hydraulically-opening, multi-disc brakes. When the energy balance is positive (*i.e*., the energy generated by the drums is greater than the energy consumed), the surplus of energy is converted and stored in the 700 V supercapacitor through an electric generator. The 'start and stop' parameters of the Diesel engine can be modified from the machine settings. When the electrical potential of the battery pack falls below the set threshold (conventionally 15-20%), the Diesel engine automatically switches on to charge the battery pack by converting mechanical energy into electrical energy via the electric generator (Koller Forsttechnik, 2019).

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.

Characteristics	Unit	Value / Description
Engine	-	Deutz F3L2011, 3 cylinders, Stage IIIA*
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		AmSteel-Blue
No. Diam.	mm	6
Lenght	m	2000
Tensile force#	kN	11
Carriage		Koller Ecko Flex
Mass	kg	600
Payload	kN	20

No. Diam.: nominal diameter. *Homologation declared by the cable yarder manufacturer (Koller GmbH, 2020); °tensioning drum; #constant over the entire drum diameter.

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 PMH_{15}). Cable line 1 was monitored for 11.1 PMH_{15} and 46 work cycles, while cable line 2 was monitored for 11.5 PMH_{15} and 50 work cycles.

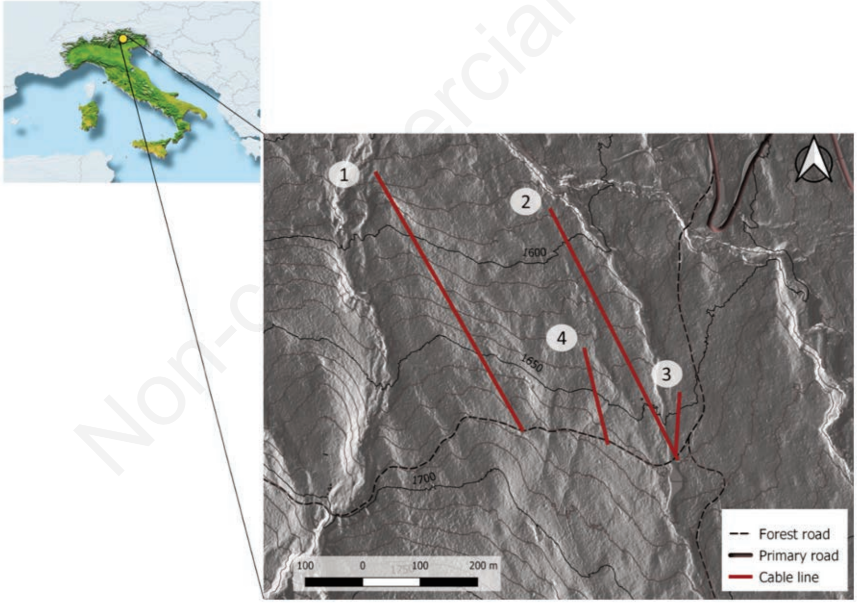

Figure 1. Location of the logging area and cable lines.

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:

$$Net\ PC\ (kW) = PC\ (kW) - PG\ (kW) \qquad (1)$$

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 - WE_{PMH15} - (Equation 2):

$$Net\ PC\ (kWh) = Net\ PC\ (kW) * WE_{PMH15}\ (h) \qquad (2)$$

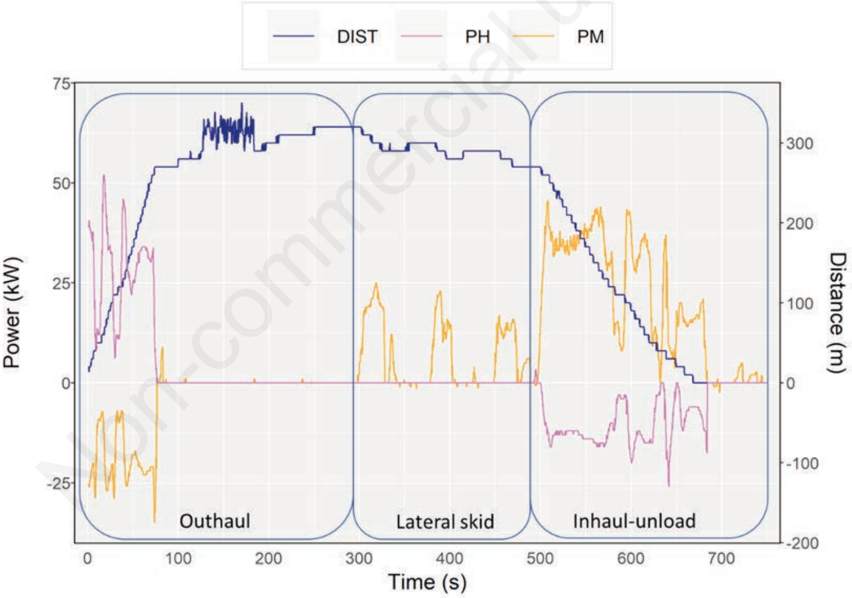

Figure 2. Automatic time and motion study retrieved from Can-BUS data. DIST, distance of the carriage off the tower (m); PH, power generated or consumed by the haulback winch (kW); PM, power generated or consumed by the mainline winch (kW); positive values of power (kW) refer to an energy consumption, while negative values refer to energy recovery.

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 hooking area to 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 electric generator powered by the Diesel engine - EP - expressed in kWh, was estimated multiplying the mean power generated by the electric 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 PMH$_{15}$ (Equation 3):

$$EP\ (kWh) = PGE\ (kW) * TO\ (h) \tag{3}$$

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):

$$TEF\ (\%) = \frac{\sum Net\ EC\ (kWh)}{EP\ (kWh)} * 100 \tag{4}$$

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), CO$_2$ emissions were estimated using an emission factor of 2.61 kg CO$_2$ 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 Benjamin, 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:

$$R^2_{LR} = 1 - \exp(-2/n * (l_M - l_0)) \tag{5}$$

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 (PMH$_{15}$), 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 m^3 were yarded and measured, 57.1 m^3 in cable line 1 and 43.4 m^3 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	Tot time PMH$_{15}$	Cycle No.	Net EC$_{outhaul}$ kWh		Net EC$_{lateral-skid}$ kWh		Net EC$_{inhaul-unload}$ kWh	%	TEF	Engine on %	Yarding distance m	
			Mean	SD	Mean	SD	Mean	SD			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 CO_2 eq and 93.77 kg CO_2 eq equal to 1.47 kg CO_2 eq/m^3 and 2.16 kg CO2 eq/m^3 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 (R^2=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 CO_2 eq and 2.08 kg CO_2 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/m^3, respectively) compared to cable lines 3 and 4 (0.28 and 0.27 L/m^3, respectively). Consequently, the estimated CO_2 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 CO_2 eq/m^3 for cable lines 1, 2, 3 and 4, respectively).

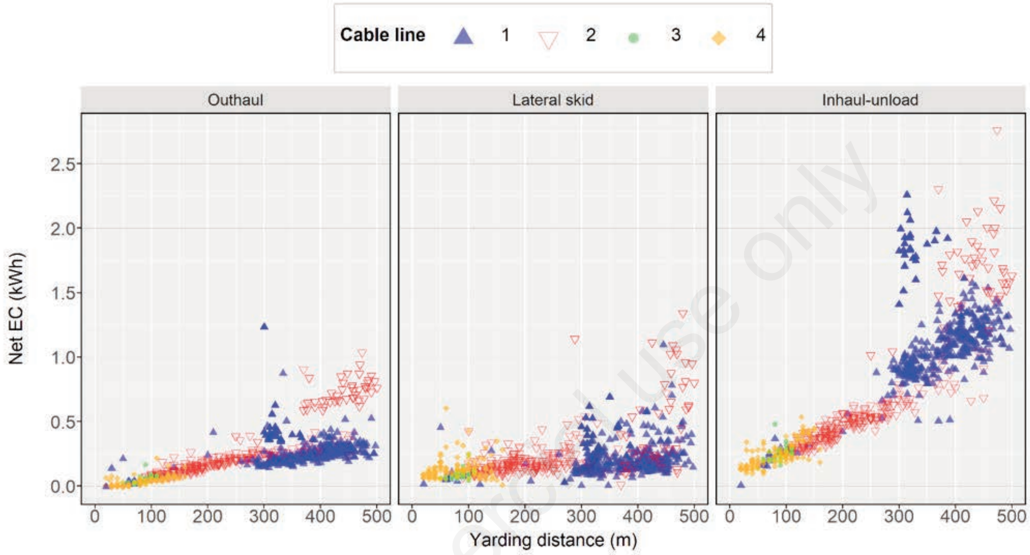

Figure 3. Net EC (kWh) for outhaul, lateral skid and inhaul-unload working element in respect of the yarding distance (m).

Table 5. Descriptive statistics of field monitoring.

Cable line	Tot 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	SD	Mean	SD
1	10.99	46	309	51	15.5	1.2	1.20	0.30	5.70	2.40	0.56	0.21
2	11.44	50	447	52	17.5	2.5	1.00	0.20	5.00	1.70	0.80	0.18

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	R^2
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 m^3	Productivity m^3/PMH_{15}	Fuel consumption L/m^3	CO_2 eq emission kg CO_2 eq/m^3
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

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 elements, 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 - MTFM$_l$ (kN) - had a negative effect on Net EC, meaning that increasing MTFM$_l$ during the lateral skid can lead to a reduction of the energy consumed. On average, the MTFM$_l$ 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 - MTFH$_{in}$ (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.

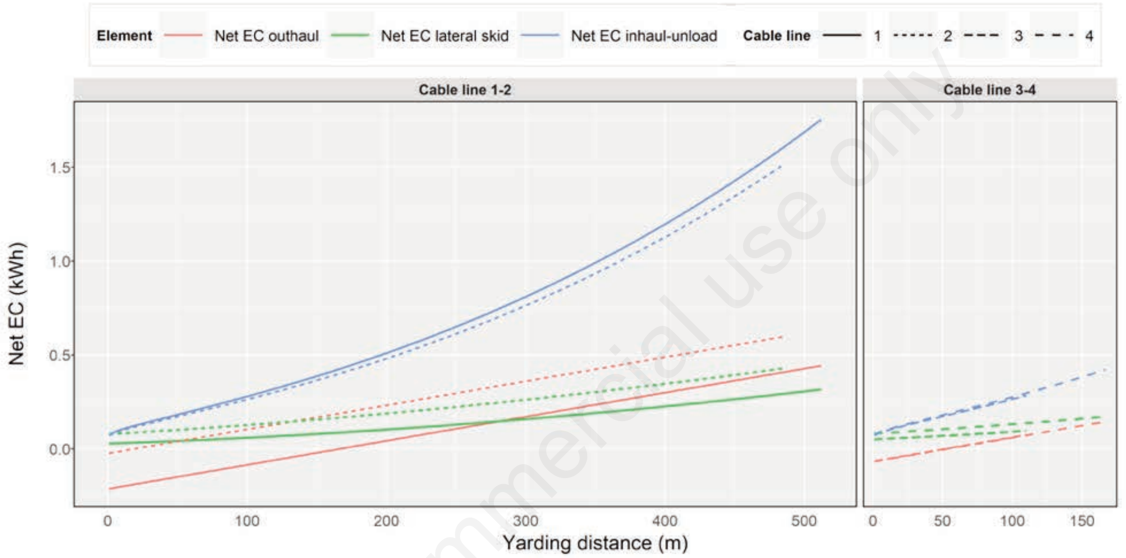

Figure 4. Net EC energy consumption (kWh) plotted over yarding distance in the four monitored cable lines.

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 EC$_{outhaul}$ (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
		MTFM$_l$ (kN)	–0.0088	0.00130	–6.54	<0.001
C	Ln(Net ECci$_{nhaul\ unload}$) (kWh)	MTFH$_{in}$ (kN)	–0.0182	0.006	–2.928	0.002
		SDTFM$_{in}$ (kN)	0.1048	0.008	12.53	<0.001
		Sqrt(YD) (kN)	0.1455	0.002	60.67	<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$_0$	R$^2_{LR}$
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; R$^2_{LR}$, 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, suggesting the conversion of the tensile force into energy stored in the supercapacitor. In contrast, the standard deviation of the tensile force of the mainline - SDTFMin (kN) - had a positive effect on 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 m^3. 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/kWh) 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/m^3 for a yarding distance of 300 and 450 m and an average load of 1.2 and 1 m^{3,} 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/m^3, 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/m^3, while the base machine used with an SPC consumed 0.88 L/m^3, 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

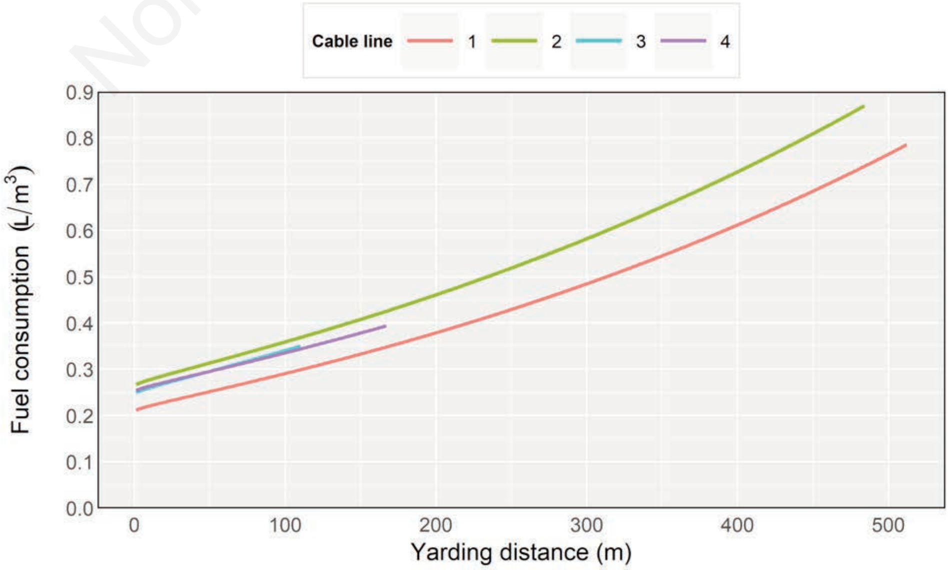

Figure 5. Predicted fuel consumption depending on the yarding distance.

0.32 L/m^3, 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 m^3/PMH_{15} 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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