



# Greenhouse gas emissions, energy and cost-efficiencies associated with liquefied biogas-powered heavy-duty timber trucks in industrial roundwood transportation

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## ABSTRACT

Forestry transportation is a difficult sector for decarbonization. Liquefied biogas (LBG)-powered heavy-duty vehicles have the potential to reduce greenhouse gas (GHG) emissions across a range of transportation tasks. In this study, we investigated energy consumption, GHG emissions and operational costs of a heavy-duty LBG-powered timber-truck combination and compared the results to a regular diesel-powered heavy-duty reference timber-truck combination. The investigation was undertaken over a nearly year-long follow-up study under arctic conditions in northern Finland. The results revealed that the LBG combination consumed 15.4 % more energy per tonne-kilometer (tkm) than the reference combination. However, it produced substantially less GHG emissions when well-to-wheel emissions were considered. Using the default emission factors provided by the ISO 14083:2023 standard, the LBG combination produced 44.6 % less carbon dioxide equivalent (CO<sub>2</sub>eq) tkm<sup>-1</sup>. Moreover, the operational costs of the combinations were similar. In a scenario where 10 % of timber transportation was carried out by LBG-powered trucks, a 4.5 % reduction in total emissions was achieved, which equates to approximately 12,000 t CO<sub>2</sub>eq annually when GHG emissions from all timber transportation in Finland are considered. We found that LBG-powered timber trucks are cost-effective and can achieve substantial emissions reductions under challenging operating conditions, which is crucial to accomplish emission reduction goals. Furthermore, the LBG combinations were found to be functional under harsh arctic conditions and have sufficient operational range for long-distance timber transportation from forests where electrification is currently not cost-effective.

## 1. Introduction

In 2015, world leaders agreed to limit global warming to less than 2 °C compared to pre-industrial levels, with additional efforts promised to keep the temperature increase below 1.5 °C (Paris Agreement, 2015). The surface temperature of the planet has increased by 1.1 °C between 2011 and 2020 compared to 1850–1900 (Intergovernmental Panel on Climate Change [IPCC], 2023) but increasing actions are needed from all sectors to prevent these set targets being breached.

The European Union (EU) aims to decrease greenhouse gas (GHG)

emissions by at least 55 % by 2030 compared to 1990 levels and to achieve climate neutrality within the EU by 2050 (EU, 2021). Proposed GHG emissions reductions have been divided among three sectors—the emissions trading system (ETS), the effort sharing sector (ESS), and the land use, land-use change and forestry (LULUCF) sector (Ministry of the Environment Finland, 2024). The ESS consists of transportation, agriculture, residential heating, non-road mobile machinery, waste management, and fluorinated gases (Ministry of the Environment Finland, 2024). Specifically, GHG emissions reductions have been found to be very difficult to achieve in the transportation sector, which is a major

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GHG emissions source, globally accounting for 15 % of all emissions (Environmental Protection Agency, 2024).

In Finland, road transportation of forest raw materials and products is significant. In recent years, transportation performance (measured in tonne-kilometers [tkm]) of forest industries has accounted for 27–29 % of all domestic road freight in Finland (Official Statistics of Finland, 2024a). Poikela and Strandström (2023) estimated that domestic transportation of industrial roundwood in Finland alone generated emissions of almost 300,000 t of carbon dioxide equivalent (CO<sub>2</sub>eq) in 2022. For comparison, GHG emissions of all domestic road traffic in Finland were 9.2 million t CO<sub>2</sub>eq in 2022 (Official Statistics of Finland, 2024b), of which 36 % were produced by trucks and truck combinations (Ministry of the Environment Finland, 2023). In Finland, road transportation is the most important way to deliver industrial roundwood, and truck-trailer combinations transport 95.2 % of the timber (in 2023), of which 68.4 % was transported directly from roadside landings to the mill yards (Strandström, 2024). In order to reduce the cumulative GHG emissions caused by forestry-sector supply-chain logistics, emissions from forestry transportation operations must be addressed.

Alternative powertrains that produce less emissions are one way to reduce the substantial GHG emissions associated with heavy-duty road transportation (Kluicininkas et al., 2012; Song et al., 2017; Hagos and Ahlgren, 2018; Smajla et al., 2019; Pernestål et al., 2023; Zhai et al., 2023; Ho et al., 2025). Previous studies that have evaluated alternative powertrains have concentrated mainly on vehicles that are lighter and smaller than the regular heavy-duty (gross vehicle weight (GVW) > 60 t) timber trucks in Finland, but there is potential for other powertrains that can reduce GHG emissions. For instance, Hagos and Ahlgren (2018) investigated the potential of natural gas and biogas from a range of sources, Kluicininkas et al. (2012) tested compressed natural gas, compressed biogas (CBG) and electricity as alternatives, while Song et al. (2017) and Smajla et al. (2019) concentrated on liquefied natural gas (LNG). Pernestål et al. (2023) investigated electric trucks for timber transportation, while Zhai et al. (2023) and Ho et al. (2025) studied ammonia fuel cells and ammonia as potential vehicle fuel.

Forestry-sector transportation is a difficult operational field for alternative powertrains for two main reasons: 1) graveled forest roads represent a harsh operating environment, and 2) the vehicles mainly operate in rural areas far away from the distribution networks that could supply alternative fuels, the majority of which are located in or near large cities. Thus, the operating environment also requires vehicles to have greater reserve in engine power and operating range. However, according to Finnish Transport and Logistics (2023), by 2030, 9 % of the total transportation performance (tkm) in Finland will be operated using LBG-powered heavy-duty (GVW >60 t) truck combinations, and the share will increase to 23 % by 2040, whereas the projections for electric heavy-duty truck combinations is only 0.5 % and 10 %, respectively.

In Finland, alternative fuel distribution networks for trucks are either sparse or non-existent, depending on the fuel type. Of the alternative fuels, biogas has the most extensive distribution network with 74 CBG stations and 21 LBG stations across the country (Gasum, 2024a; St1, 2024). However, the biogas distribution network, especially LBG stations, is mainly centered in southern Finland.

Consequently, the aim of this study was to investigate the usage and possibilities of LBG-powered heavy-duty (GVW >60 t) vehicles in road transportation of forest products, which has not been comprehensively investigated to date. This study reports the energy consumption, GHG emissions and operational transportation costs associated with a LBG-powered heavy-duty timber-truck combination operating under arctic conditions and compares the results to a diesel-powered reference timber-truck combination, particularly in relation to the sparse LBG distribution network.

## 2. Materials and methods

### 2.1. Timber-truck combinations

To the best of our knowledge, the first heavy-duty (GVW >60 t) timber-truck combination powered by liquefied gas began operating in northern Finland in 2022 (Fig. 1). The combination was tendered out as a pilot by Metsähallitus Forestry Ltd. to examine the fit of a LBG-powered combination in industrial roundwood transportation under arctic conditions. The combination consisted of a tractor with three axles and a timber trailer with five axles and had a maximum GVW of 69 t. The tractor of the LBG combination (a Volvo FH 460 LNG) had a 12.8 L inline-6 high-pressure direct injection (HPDI) dual-fuel engine with a rated power of 338 kW.

The LBG combination was compared with a traditional diesel-powered timber-truck combination with a maximum GVW of 76 t (Fig. 1). The reference tractor combination (a Scania R660) had a 16.4 L V8 diesel engine with a rated power of 485 kW. The two combinations are described in detail in Table 1.

Both combinations were equipped with timber cranes, which were removed from the trucks when permitted by the transportation task, for example when the mill yard had its own unloading machinery and there was no possibility of backhauling. During the study, both combinations were loaded by their own cranes. Where applicable, unloading was carried out by the machinery at the mill yard, otherwise by the truck crane.

In the follow-up study, the LBG combination was driven by one of seven drivers with timber-hauling experience that ranged from 0 to 9 years. By contrast, the reference combination was driven by one of four truck drivers with timber-hauling experience that ranged from 2 to 30 years.

### 2.2. Follow-up study data collection

The data consisted of the laden and unladen driving parts of the transportation cycle per payload. To complete the transportation cycle for the calculations, we also collected short-term data for the loading and unloading portions. Our long-term follow-up study, conducted from January to December 2023, covered seasonal variations in the Arctic, where air temperatures ranged from −31 °C to +30 °C. Both vehicles had manufacturer-installed advanced fleet management systems (FMS), data from which informed the follow-up study. For the reference combination, we used the Scania Fleet Manager app and its successor, the My Scania platform (hereafter, Scania FMS) and, for the LBG combination, the Volvo Connect platform (hereafter, Volvo FMS).

At the beginning of data collection, the refresh interval of the Scania FMS was approximately 1 min and was approximately 10 min for the Volvo FMS. In the middle of data collection, the refresh interval of the Volvo FMS rose to approximately 1 min. The Volvo FMS timestamps (at 1-min intervals) recorded specific events, such as ignition on/off, stops, start of driving, use of auxiliary power take-off (PTO), and tachograph status change. The Scania FMS timestamps recorded ignition on/off and PTO usage. The measurement resolution was 1 L for the reference combination and 1 kg for the LBG combination. Distance measurement resolutions for both combinations were 1 km.

Measurement of driving with an unladen truck started when the vehicle left the mill or terminal yard and ended when the truck arrived at the roadside landing or terminal and started to load the next payload. This endpoint was identified using the FMS “PTO on” message. Measurement of driving with a laden truck started when the vehicle had loaded its payload and was ready to transport this to its destination (mill or terminal yard). This calculation ended when the vehicle arrived at the destination. The starting point was identified using the FMS “PTO off” message. For the laden portion of the transportation cycle, we combined specific events, such as leaving the timber crane at the roadside instead of carrying it with the truck all the way or loading the payload at



Fig. 1. Liquefied biogas (LBG)-powered (left) and diesel-powered (reference) (right) timber-truck combinations evaluated in this study.

**Table 1**  
Properties of the vehicles in this study.

Truck and trailer	LBG combination	Diesel combination (reference)
Manufacturer	Volvo	Scania
Model	FH 460 LNG	R660
Model year	2022	2022
Drivetrain	6 × 4	8 × 4
Number of axles (truck + trailer)	3 + 5	4 + 5
Tare weight w/o crane (with crane) (t)	19.7 (23.5)	21.6 (25.7)
Maximum GVW (t)	69	76
Max. payload w/o crane (with crane) (t)	49.3 (45.5)	54.4 (50.3)
Transmission	AT2612F	Opticruise G33
Crane	Kesla 2110 ZT-95	Kesla 2212 ZT-102
Crane weight (t)	3.8	4.1
Engine model	G13C460	DC16 122
Engine layout	I6	V8
Displacement (cm <sup>3</sup> )	12,800	16,350
Rated power (kW@rpm)	338@1700–1800	485@1900
Rated torque (Nm@rpm)	2300@1050–1400	3300@950–1400
Engine standard	EURO VI	EURO VI
Fuel	LBG (or LNG) + Diesel	Diesel
Fuel tank	205 kg + 170 L	450 L

multiple separate locations.

From the FMS, we retrieved fuel consumption data and other variables per the transportation cycle part. The Volvo FMS reported total diesel and LBG consumption for each vehicle status, including partitions of driving, PTO use, and idling. However, it failed to report the pilot diesel consumption per the transportation portion. To obtain this value, diesel consumption was divided by LBG consumption for the three vehicle statuses (i.e., driving, PTO use, and idling).

The data from the follow-up study were collected from multiple sources, which included the FMS, the payload weight from the Metsähallitus enterprise resource planning system, and from inquiries of the payloads that were transported for other forest companies. In the follow-up study, the LBG combination transported 565 payloads, of which 553 had weight information available. The reference combination transported 743 payloads, of which 676 had weight information. Payloads with no weight information were discarded from the final data. The locations of the starting storage areas (i.e., roadside landings or terminals), destinations (i.e., terminals or mill yards), and the LBG fueling station in the city of Oulu are presented in Fig. 2.

The LBG combination traveled 57,723 km and transported 26,026 t during the study, while the reference combination drove 82,412 km and

carried 33,897 t. The total mileage of the LBG combination during the study was 112,740 km, which included discarded payloads and driving unladen, while the total mileage of the reference combination was 173,344 km.

### 2.3. Truck operation profiles

Specific dummy variables were created to take important qualitative factors into consideration and express the effect of qualitative factors in linear regression analysis. These included carrying the timber crane with the truck (hereafter, crane dummy), loading one payload from multiple locations (hereafter, multipoint payload dummy), transportation season (hereafter, season dummy), and timber assortment (hereafter, timber assortment dummy).

The crane dummy was defined as zero when the collected payload data noted that the timber crane was left at the roadside. Where available, the note was validated by the unladen weight of the vehicle from the weighing platform data at the destination, and otherwise from features of the destination, such as no unloading at specific mill yard sites. The multipoint payload dummy was defined as where the payload data had noted that the payload had been loaded at multiple locations. The season dummy was defined by the date of payload transportation: Winter was set between 1 November and 30 April and summer between 1 May and 31 October to represent the real weather in the operating area. Lastly, the timber assortment dummy was defined using timber assortment data from the weight data information, where applicable. The data were validated using the destination features or, where no applicable data were available, the weight data information associated with the payload.

### 2.4. Altitude difference and road grade

The altitude difference between the starting storage area (roadside landing or terminal) and the destination (terminal or mill yard) was calculated using the coordinates of both locations. The altitudes were acquired from a digital elevation model from the [National Land Survey of Finland \(2024\)](#). The resolution of the digital elevation model was 2 × 2 m, and the elevation accuracy was 1 m (worst case). The average road grade of the trip portion was calculated by dividing the altitude difference by the driving distance. Average road grade was presented in meters per kilometer, equivalent to a 0.1 % grade.

### 2.5. Conversion of energy consumption

Vehicle fuel consumption was converted into energy consumption so we could compare the energy usage of the different powertrains. The conversion was implemented by first converting diesel consumption into

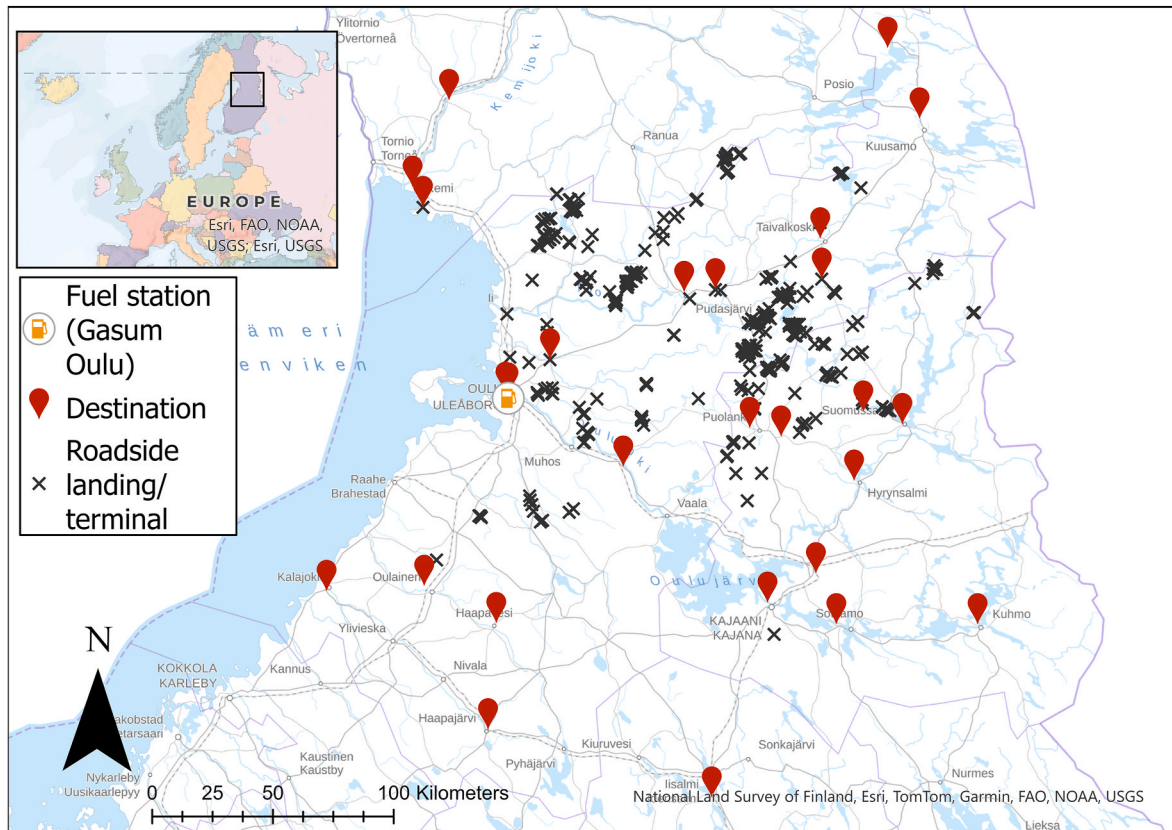


Fig. 2. Map showing the starting storage locations, destinations (i.e., terminals and mill yards), and the liquefied biogas (LBG) fueling station in Oulu, Finland.

kilograms and then converting fuel consumption into joules. The mean values of the diesel-fuel density factors for the summer and winter blends (provided by Neste Futura Diesel) were used (Neste, 2020, 2021). The mean density of the summer blend was  $832.5 \text{ kg m}^{-3}$  and the mean density value of the winter blend was  $820.0 \text{ kg m}^{-3}$ . The summer blend value was used between 1 May and 31 October, and the winter blend value was used between 1 November and 30 April. For LBG, the density of the fuel did not vary between seasons. The conversion of fuel consumption into energy consumption was performed using the lower heating value factors of  $42.8 \text{ GJ t}^{-1}$  for diesel and  $49.3 \text{ GJ t}^{-1}$  for LBG (Statistics Finland, 2024). The LBG combination used both LBG and diesel. Fuel usages were collected from the Volvo FMS as cumulative consumption for the entire data collection period. The consumption was summarized and proportions per fuel were calculated. The LBG consumption of the LBG combination was 94.1 % of total energy consumption while driving, while diesel consumption was 5.9 %. While loading and unloading, the corresponding portions were 86.0 % for LBG and 14.0 % for diesel, and while idling, 74.8 % for LBG and 25.2 % for diesel. These proportions were used to include the pilot-diesel consumption to total energy consumption of the LBG combination.

## 2.6. Data analysis

For the laden part of the transportation cycle, energy consumption was modeled as follows:

$$y = a + bx_1^{-1} + cx_2 + dx_3 + ex_4 + fx_5 + gx_6 + hx_7 \quad (1)$$

where  $y$  is energy consumption ( $\text{GJ } 100 \text{ km}^{-1}$ ),  $x_1$  is transportation distance (km),  $x_2$  is the mean road grade (0.1 %),  $x_3$  is the size of the payload (t),  $x_4$  is the crane dummy,  $x_5$  is the multipoint payload dummy,  $x_6$  is the timber assortment dummy, and  $x_7$  is the season dummy.

On the unladen part of the transportation cycle, energy consumption was modeled as follows:

$$y = a + bx_1^{-1} + cx_2 + dx_3 \quad (2)$$

where  $y$  is energy consumption ( $\text{GJ } 100 \text{ km}^{-1}$ ),  $x_1$  is the distance (km),  $x_2$  is the mean road grade (0.1 %), and  $x_3$  is the season dummy.

The suitability of the models was investigated by statistical significance ( $p < 0.05$ ) and the adjusted coefficient of determination (adjusted  $R^2$ ).

## 2.7. Calculation of GHG emissions

GHG emissions were calculated by multiplying the energy consumed per fuel type by the corresponding emission factor. For the LBG combination, emissions were calculated for the proportions of both fuels. Default emission factors provided by the ISO 14083:2023 (2023) standard were applied. For the LBG combination, both the LBG and pilot diesel GHG emissions were calculated from their proportions of energy usage. The emission factors for LBG (bio-LNG from biowaste) and diesel were utilized.

## 2.8. Calculation of the transportation cycle

Energy consumption of the transportation cycle was modeled using gigajoule per 100 km models for the laden and unladen portions of the cycles. The portion of unladen driving was defined as 50 %, meaning backhauling was not included. Total energy consumption ( $E_{Total}$ ) was calculated (in gigajoules) by multiplying  $\text{GJ } 100 \text{ km}^{-1}$  ( $E_{Unladen}$  and  $E_{Laden}$ ) by the distance, and multiplying  $\text{GJ h}^{-1}$  ( $E_{Loading}$  and  $E_{Unloading}$ ) by the mean time taken for loading and unloading (Equation (3)). Then, the total energy consumed was converted to megajoules and divided by tkm, which gave the energy consumption of the entire transportation cycle per transported payload (Equation (4)). The distance ( $D_{Trip}$ ) and payload weight ( $W_{Trip}$ ) correspond to the values of the laden part of the trip as all

the measurable work occurred during driving with the laden combination.

$$E_{Total} = E_{Unladen} + E_{Loading} + E_{Laden} + E_{Unloading} \quad (3)$$

where  $E_{Total}$  is total energy consumed (GJ), and  $E_{Unladen}$ ,  $E_{Loading}$ ,  $E_{Laden}$ , and  $E_{Unloading}$  are the energy consumed (GJ) in the separate phases of the transportation cycle.

$$E_{Trip} = E_{Total} \times (W_{Trip} \times D_{Trip})^{-1} \quad (4)$$

where  $E_{Trip}$  is the energy consumption of the transportation cycle (MJ tkm<sup>-1</sup>),  $E_{Total}$  is total energy consumption (GJ),  $W_{Trip}$  is the payload weight (t) of the trip, and  $D_{Trip}$  is the distance (km) of the laden part of the trip.

The GHG emissions of the transportation cycle were calculated using the specific energy consumption values from each portion of the cycle as the loading and unloading portions had different diesel-LBG ratios to the driving portions. The GHG emissions from the driving portions were taken from the kg CO<sub>2</sub>eq (100) km<sup>-1</sup> calculations for the laden and unladen combinations. For the loading and unloading portions of the LBG combination, energy consumption was calculated by dividing energy consumption per fuel with the corresponding ratios, by calculating the values of the emissions of the different fuels, and summing the values as for the driving portions (Equation (5)). Then, all the cumulative GHG emissions values were summed in the same way as in energy consumption phase (Equation (6)). Finally, the GHG emissions were converted to g CO<sub>2</sub>eq tkm<sup>-1</sup> by dividing total emissions ( $GHG_{Total}$ ) by the distance ( $D_{Trip}$ ) multiplied by the payload weight ( $W_{Trip}$ ) of the trip (Equation (7)).

$$GHG_{Loading} = E_{Loading} \times DC_{Stationary} \times F_{Diesel} + E_{Loading} \times (1 - DC_{Stationary}) \times F_{LBG} \quad (5)$$

where  $GHG_{Loading}$  is the GHG emissions of the phase (g CO<sub>2</sub>eq),  $E_{Loading}$  is the energy consumption of the phase (GJ),  $DC_{Stationary}$  is the proportion of diesel consumption in the stationary phase (%),  $F_{Diesel}$  is the emission factor of the diesel fuel (g CO<sub>2</sub>eq MJ<sup>-1</sup>), and  $F_{LBG}$  is the emission factor of LBG (g CO<sub>2</sub>eq MJ<sup>-1</sup>).

$$GHG_{Total} = GHG_{Unladen} + GHG_{Loading} + GHG_{Laden} + GHG_{Unloading} \quad (6)$$

where  $GHG_{Total}$  is the GHG emissions of the transportation cycle (g CO<sub>2</sub>eq),  $GHG_{Unladen}$ ,  $GHG_{Loading}$ ,  $GHG_{Laden}$ , and  $GHG_{Unloading}$  are the GHG emissions (g CO<sub>2</sub>eq) associated with the separate phases of the transportation cycle.

$$GHG_{Trip} = GHG_{Total} \times (W_{Trip} \times D_{Trip})^{-1} \quad (7)$$

where  $GHG_{Trip}$  is the energy consumption of the transportation cycle (g CO<sub>2</sub>eq tkm<sup>-1</sup>),  $GHG_{Total}$  is total energy consumption (g CO<sub>2</sub>eq),  $W_{Trip}$  is the payload weight (t) of the trip, and  $D_{Trip}$  is the distance (km) of the laden part of the trip.

## 2.9. Cost analysis

The costs associated with the LBG and reference combinations were evaluated. In the calculations, some assumptions were used as information on the LBG fleet was not complete. Basic information on the cost analysis used is presented in Table 2.

The purchase price of the LBG-powered tractor was estimated to be 30 % higher than that of the reference (diesel) tractor (Ojala et al., 2024). Annual road tax was calculated using the vehicle tax calculator provided by the Finnish Transport and Communications Agency and applying the GVW of the truck tractor (Traficom, 2024). Other fixed costs were assumed to be similar between the vehicles.

The variable costs included maintenance, repair, fuel, and driver wages. Fuel costs were calculated from the fuel consumption of the vehicles with unladen driving (calculated at 50 %). The baseline fuel

**Table 2**

Basic information on the cost analysis.

Cost element	LBG combination	Diesel combination (reference)
<b>Basic information</b>		
GVW (combination) (t)	69	76
Tare weight (w/o crane) (t)	19.7	21.6
Vehicle lifespan in km (%)	100	100
Purchase price of tractor (%) <sup>a</sup>	130	100
<b>Fixed costs</b>		
Annual depreciation (%)	25	25
Annual vehicle tax (€) <sup>b</sup>	1430.8	1660.8
Annual administration, insurance, etc. (%)	100	100
<b>Variable costs</b>		
Fuel consumption of LBG (kg 100 km <sup>-1</sup> )	33.2	–
Fuel consumption of diesel (L 100 km <sup>-1</sup> )	2.8	48.05
Price of LBG (baseline) (€ kg <sup>-1</sup> ) <sup>c</sup>	1.50	–
Price of fossil diesel (baseline) (€ L <sup>-1</sup> ) <sup>d</sup>	1.60	1.60
Maintenance, repair, and other variable costs (%)	100	100
<b>Work details</b>		
Annual working days (count)	235	235
Average payload distance (km) <sup>e</sup>	100	100
Share of driving with unladen combination (%)	50	50
Annual number of payloads (pcs)	1079	1056
Annual mileage (km)	215,821	211,209
Average payload density (kg m <sup>-3</sup> )	864	864
Average payload size (t)	49.3	54.4
Average payload size (m <sup>3</sup> )	57.1	63.0
Annual haulage (t)	53,212	57,462
Annual haulage (m <sup>3</sup> )	61,588	66,507

<sup>a</sup> Ojala et al. (2024).

<sup>b</sup> Traficom (2024).

<sup>c</sup> Gasum (2024b).

<sup>d</sup> Official Statistics of Finland (2024c).

<sup>e</sup> Strandström (2024).

prices used were the median prices of the fuel in 2023. The biogas price was acquired from the fuel distributor website (Gasum, 2024b). The price on the website was for CBG, but we considered the price of LBG to be almost identical. The price of diesel was acquired from the Official Statistics of Finland (2024c).

The average payload weight was the average payload size from this study without a crane attached. The average payload size in cubic meters (over bark) was calculated from the payload weight and density. Annual haulage was calculated by multiplying the annual number of payloads by the average payload size. The LBG combination could transport more payloads annually as it had a smaller payload capacity, and therefore, was faster to load at the same hourly productivity rate.

A sensitivity analysis was also performed to visualize the effect of fuel price changes. The analysis had three scenarios—business as usual (BAU), in which the baseline fuel prices were used, inflated diesel price (IDP), in which the LBG price remained at the baseline price and the diesel price was inflated by 20 % (€1.92 L<sup>-1</sup>), and the inflated (bio-)gas price (IGP), in which the diesel price remained at the baseline price and the LBG price was inflated by 20 % (€1.80 kg<sup>-1</sup>).

## 3. Results

### 3.1. Laden combinations

Specific parameters were used to define the operating conditions:

Transportation distance was set at 100 km; the starting storage area (roadside landing or terminal) and destination (terminal or mill yard) were specified as being at the same height above sea level; vehicles were loaded to the maximum legal payload; the timber crane was attached, and the payload was defined as being a normal single-point pulpwood payload; season used was summer.

The energy consumption of the laden LBG combination was 2.08 GJ 100 km<sup>-1</sup>, which corresponds to 39.7 kg 100 km<sup>-1</sup> of LBG and 3.4 L 100 km<sup>-1</sup> of diesel consumption. The laden reference combination had an energy consumption of 2.15 GJ 100 km<sup>-1</sup>, which corresponds to 60.3 L 100 km<sup>-1</sup> of diesel consumption (Fig. 3, Table 3). The energy consumption of the LBG combination was 3.2 % lower than the reference combination.

The GHG emissions from the laden LBG combination were 87.8 kg CO<sub>2</sub>eq 100 km<sup>-1</sup> and the emissions from the reference combination were 190.1 kg CO<sub>2</sub>eq 100 km<sup>-1</sup>. The GHG emissions of the LBG combination were 53.8 % lower than the reference combination.

### 3.2. Unladen combinations

The energy consumption of the unladen combinations was modeled on the basis of no altitudinal difference, summer, and a distance of 100 km. The energy consumption of the unladen LBG combination was 1.40 GJ 100 km<sup>-1</sup>, which corresponds to 26.7 kg 100 km<sup>-1</sup> of LBG and 2.3 L 100 km<sup>-1</sup> of diesel consumption. In turn, the unladen reference combination had an energy consumption of 1.27 GJ 100 km<sup>-1</sup>, which corresponds to 35.8 L 100 km<sup>-1</sup> of diesel consumption (Fig. 4, Table 4). The energy consumption of the LBG combination was 9.9 % higher than the reference combination.

The GHG emissions of the unladen LBG combination were 58.98 kg CO<sub>2</sub>eq 100 km<sup>-1</sup> and 112.56 kg CO<sub>2</sub>eq 100 km<sup>-1</sup> for the reference combination. Thus, GHG emissions from the LBG combination were 47.6 % lower than the reference combination.

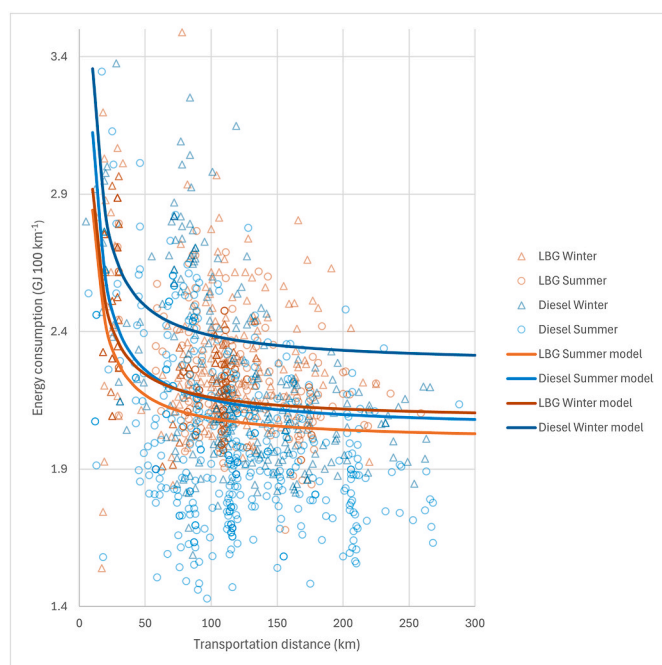


Fig. 3. Energy consumption as a function of transportation distance in laden combinations in summer and winter with payloads of 45.5 t (Liquefied biogas, LBG) and 50.3 t (reference) (Table 3). Individual points represent single payloads, and the lines are the modeled functions.

### 3.3. Transportation cycle

During loading, the LBG combination had an energy consumption of 0.33 GJ per payload and the reference combination had an energy consumption of 0.23 GJ per payload. In the calculations, unloading was assumed to have been carried out by machinery at the mill, and so fuel consumption for unloading was zero because the truck was either idling or was turned off at the time. As fuel consumption was negligible, it was not adequately captured by the FMS.

The basis of energy consumption during the transportation cycle involved the same assumptions as used for the separately calculated models. The LBG combination had an energy consumption of 0.84 MJ tkm<sup>-1</sup> for a 100 km transportation distance, which equated to a 200 km trip in total. The reference combination had an energy consumption of 0.73 MJ tkm<sup>-1</sup> (Fig. 5). Thus, the energy consumption of the LBG combination was 15.4 % higher than the reference combination when the energy consumption of the whole transportation cycle was considered per transported payload.

The GHG emissions of the LBG combination during the transportation cycle were 35.53 g CO<sub>2</sub>eq tkm<sup>-1</sup>, and 64.10 g CO<sub>2</sub>eq tkm<sup>-1</sup> from the reference combination. Therefore, GHG emissions from the LBG combination were 44.6 % less than the reference combination.

From this, we calculated that transportation of 10 % of domestic industrial roundwood in Finland with LBG-powered timber trucks would decrease GHG emissions by approximately 4.5 %. Given that transportation of domestic industrial roundwood results in annual emissions of 277,000 t CO<sub>2</sub>eq (Poikela and Strandström, 2023), the use of a LBG fleet to transport just 10 % would represent an annual decrease of 12,465 t CO<sub>2</sub>eq. If 20 % and 30 % were transported using a LBG fleet, total annual GHG emissions would decrease by 9.0 % and 13.4 %, which equates to 24,930 and 37,118 t CO<sub>2</sub>eq year<sup>-1</sup>, respectively.

### 3.4. Cost analysis

The costs of the combinations in this study were investigated from the perspective of a single year, with the results calculated in euros per cubic meter and converted to relative proportions (Fig. 6). In the baseline scenario (BAU), the combinations costs were similar.

In the IDP scenario, the increased diesel price resulted in a higher proportion of fuel costs for the diesel combination, resulting in 6.8 % lower costs for the LBG-powered combination. However, in the IGP scenario, the LBG combination had 4.9 % higher costs than those of the diesel combination.

## 4. Discussion

### 4.1. Data and methods

In this study, the data were manually collected during each trip by visual interpretation from the FMS. The FMS provides low-resolution distance and fuel consumption data, as also found by Anttila et al. (2022, 2023). However, the effects of low resolution were found to be small in this study, especially for the longer trips, where one unit of distance or fuel consumption had a smaller impact than on the shorter trips. In addition, as shown by Anttila et al. (2023), modeling done at the trip-level decreases the importance of higher-resolution data.

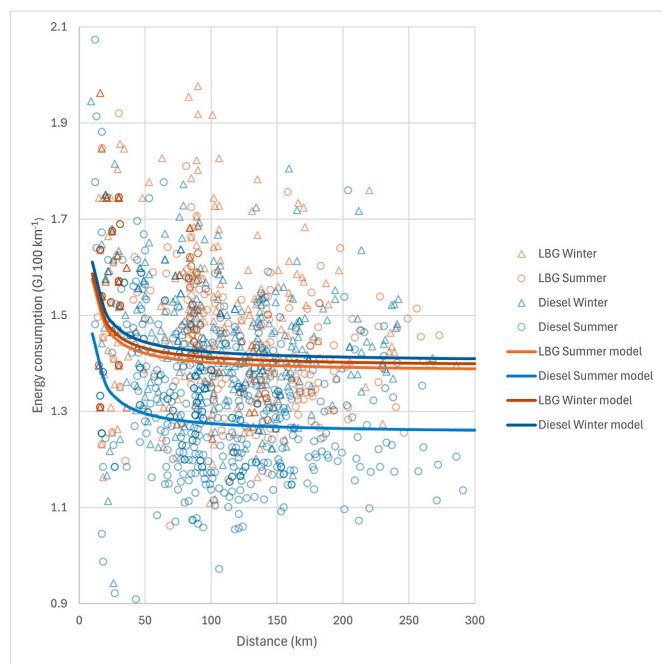
Emission factors play a crucial role in the reduction of emissions. In the case of LBG, the origin of the fuel has a significant impact on biogas emissions, as production is the greatest emissions source in the production chain. Feedstock material can be a factor in GHG emissions—for example, using cow manure to produce biogas can decrease GHG emissions values as a result of decreasing the methane and nitrous oxide emissions from the manure (Cuéllar and Webber, 2008). Hagos and Ahlgren (2018) revealed that digestate from biogas production could replace the synthetic fertilizers used in agriculture, thereby reducing emissions caused by fertilizer production. In Finland, automotive

**Table 3**  
Modeled energy consumption of the laden combinations.

$y = a + bx_1^{-1} + cx_2 + dx_3 + ex_4 + fx_5 + gx_6 + hx_7$   
 where  
 $y$  = energy consumption (GJ 100 km<sup>-1</sup>)  
 $x_1$  = transportation distance (km)  
 $x_2$  = road mean grade (0.1 %)  
 $x_3$  = payload size (t)  
 $x_4$  = crane dummy (0 = w/o crane, 1 = with crane)  
 $x_5$  = multipoint payload dummy (0 = single-point payload, 1 = multipoint payload)  
 $x_6$  = timber assortment dummy (0 = pulpwood, 1 = sawlog)  
 $x_7$  = season dummy (0 = summer, 1 = winter)  
 $a$  = constant  
 $b, c, d, e, f, g, h$  = coefficients of variables

Coefficient	Estimate of coefficient	Standard error of coefficient	t value
<b>LBG</b>			
a	1.653	0.168	9.867 <sup>b</sup>
b	8.421	0.989	8.516 <sup>b</sup>
c	-0.043	0.024	-1.819
d	0.009	0.003	2.724 <sup>a</sup>
e	-0.062	0.024	-2.626 <sup>a</sup>
f	0.186	0.042	4.445 <sup>b</sup>
g	0.098	0.025	3.844 <sup>b</sup>
h	0.076	0.019	3.982 <sup>b</sup>
Adjusted R <sup>2</sup> = 0.270; F = 30.151 <sup>b</sup> ; standard error of model estimate = 0.2054			
<b>Diesel (Reference)</b>			
a	0.836	0.159	5.241 <sup>b</sup>
b	10.792	0.756	14.275 <sup>b</sup>
c	0.191	0.014	13.708 <sup>b</sup>
d	0.022	0.003	7.362 <sup>b</sup>
e	0.102	0.032	3.189 <sup>a</sup>
f	0.040	0.040	0.982
g	-0.096	0.022	-4.324 <sup>b</sup>
h	0.233	0.020	11.385 <sup>b</sup>
Adjusted R <sup>2</sup> = 0.429; F = 73.540 <sup>b</sup> ; standard error of model estimate = 0.2554			

<sup>a</sup> p < 0.01.  
<sup>b</sup> p < 0.001.



**Fig. 4.** Energy consumption as a function of distance traveled with unladen combinations in summer and winter (Table 4).

biomethane is mainly produced from municipal organic waste and sewage sludge (Finnish Biocycle and Biogas Association, 2024). There is also considerable interest in increasing the use of livestock manure in

biomethane production. As Prussi et al. (2020a) reported, biomethane produced from manure can have significantly negative well-to-wheel emissions, while biomethane produced from municipal organic waste and sewage sludge has significantly lower total emissions compared to LNG. In contrast to the results reported by Prussi et al. (2020a), the ISO 14083:2023 (2023) standard default emission factor value is considerably higher when the origin distribution of the biogases is applied. Therefore, the default emission factor from the ISO 14083:2023 (2023) standard may overestimate GHG emissions from LBG combinations and thus decrease their GHG emissions reduction potential compared to diesel combinations. However, we chose the ISO 14083:2023 (2023) standard as it makes generalization of the results possible.

The cost analysis was performed using several assumptions due to a lack of adequate information with regard to the LBG timber-truck combinations currently employed in Finland. Unfortunately, these assumptions decreased the precision of the analysis, but were essential to enable the analysis. Most of the assumptions were related to using the same values for both combinations. For instance, the working time values were assumed to be the same, even though detouring to refuel the LBG combination would have decreased the annual haulage, and therefore altered the calculations. The assumption with regard to work details (hourly productivity of loading and unloading) ignored that the LBG combination had lower hourly productivity than the reference, but these were taken as the same to simplify the calculation and to generalize the results.

#### 4.2. Results

The primary contributions of this paper were to investigate and report the energy consumption, GHG emissions and operating costs of LBG-powered combination. The energy consumption of the LBG

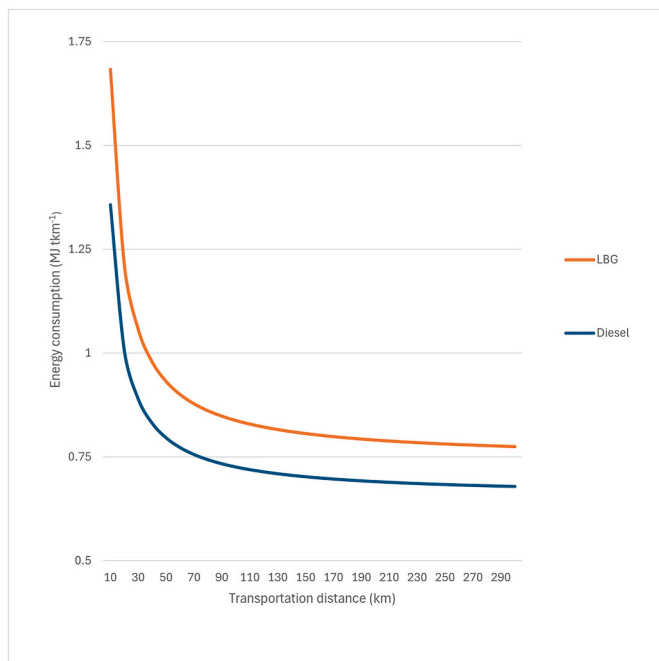
**Table 4**  
Modeled energy consumption of the unladen combinations.

$$y = a + bx_1^{-1} + cx_2 + dx_3$$

where  
 $y$  = energy consumption (GJ 100 km<sup>-1</sup>)  
 $x_1$  = distance (km)  
 $x_2$  = road mean grade (0.1 %)  
 $x_3$  = season dummy (0 = summer, 1 = winter)  
 $a$  = constant  
 $b, c, d$  = coefficients of variables

Coefficient	Estimate of coefficient	Standard error of coefficient	t value
<b>LBG</b>			
a	1.382	0.013	106.433 <sup>a</sup>
b	1.934	0.359	5.380 <sup>a</sup>
c	0.077	0.012	6.722 <sup>a</sup>
d	0.011	0.012	0.898
Adjusted R <sup>2</sup> = 0.135; F = 29.471 <sup>a</sup> ; standard error of model estimate = 0.1427			
<b>Diesel (Reference)</b>			
a	1.254	0.010	123.284 <sup>a</sup>
b	2.077	0.426	12.586 <sup>a</sup>
c	0.028	0.008	3.684 <sup>a</sup>
d	0.149	0.012	12.586 <sup>a</sup>
Adjusted R <sup>2</sup> = 0.210; F = 65.240 <sup>a</sup> ; standard error of model estimate = 0.1539			

<sup>a</sup>  $p < 0.001$ .



**Fig. 5.** Modeled energy consumption functions as a function of the transportation distance of the combinations in the transportation cycle. The transportation distance represents the distance driven laden. Driving unladen was not represented in transportation distance.

combination was found to be 15.4 % higher than the reference combination during the transportation cycle. Prussi et al. (2020b) reported that LNG-HPDI vehicles had slightly higher rates of energy consumption compared to vehicles with traditional compression ignition diesel engines. Their study modeled consumption using the same payload for both vehicles so the energy consumption per payload was not affected. In our study, the maximum payload allowed for the LBG combination was 9.5 % smaller than the reference combination. Kärhä et al. (2023) found that increasing the payload decreased the energy consumption per payload by as much as 8–11 %; although the high-capacity transport combination in their study had a 27.4 % larger payload than the reference combination. Therefore, the difference in energy consumption

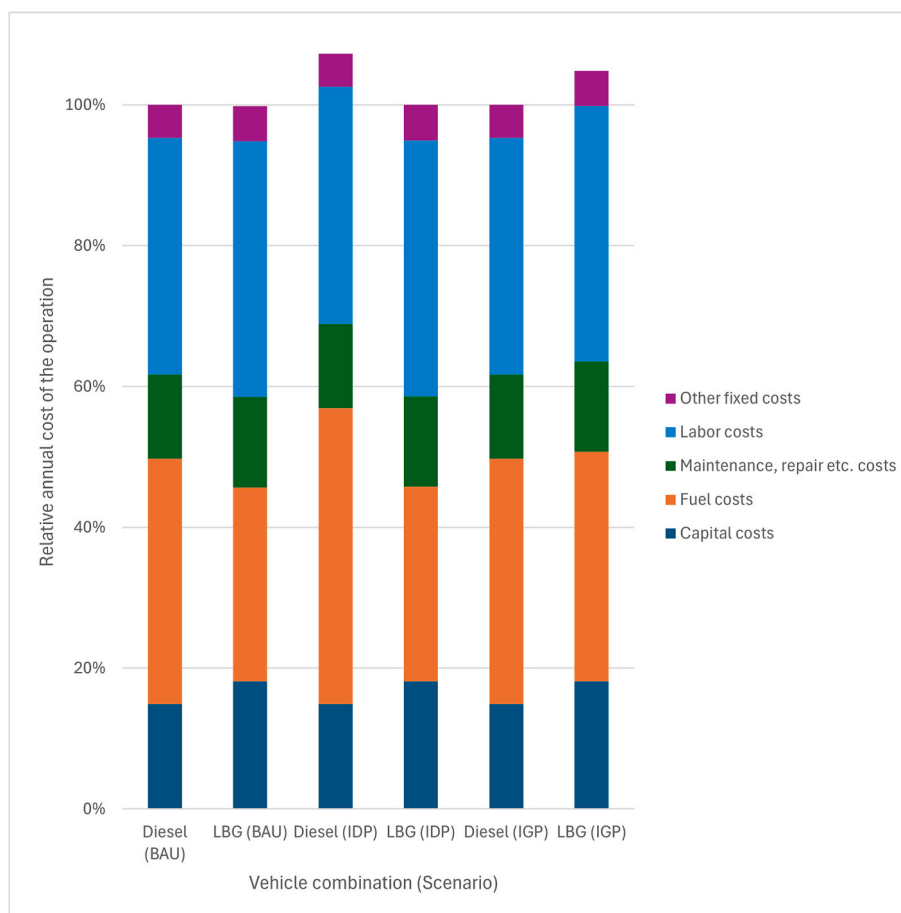
between the combinations could have been smaller if the payloads had been the same size.

In the modeling of energy consumption, some of the variables produced slightly conflicting values. In the laden model, the mean road grade variable caused a decrease in the energy consumption of the LBG combination when the value of the variable increased, whereas the energy consumption of the reference combination increased when the value of the variable increased. In previous studies, an increase in road gradient was found to increase fuel consumption (Demir et al., 2011; Holzleitner et al., 2011; Svensson and Fjeld, 2015; Pandur et al., 2022). Therefore, the response of the reference combination was to be expected, unlike the response of the LBG combination, which could be explained, at least in part, by the fact that it was mostly driven laden from inland to the coast. In other words, the LBG combination was mostly driving downhill, and there were insufficient uphill events in the dataset. Therefore, other factors, such as road properties, could have influenced the variable response of the LBG truck (cf. Svensson and Fjeld, 2015; Kärhä et al., 2023).

The season dummy variable values used in this study were also somewhat doubtful as season had a much greater impact on the energy consumption of the reference combination than on the LBG combination. There was no obvious reason for this issue, although one explanatory factor was identified as the road properties, as the reference combination operated from a wider range in roadside landings compared to the LBG combination, which could only operate from roadside landings within the range of the refueling network. Road properties can be assumed to have been more challenging on the eastern side of the operating area (Fig. 2), which were operated mainly by the reference combination, because the road network on the eastern side included a relatively greater proportion of lower-class roads compared to the western side.

Truck-driver experience has also been found to have an impact on fuel consumption (e.g., Walnum and Simonsen, 2015; Palander, 2017). In this study, the experience of the drivers was investigated, but its effect was not modeled. The drivers of the LBG combination, almost half of whom had less than two years of experience, were less experienced than the drivers of the reference combination, who had at least two years of experience driving timber-truck combinations.

In this study, we found that the LBG-powered combination emitted 44.6 % less GHG than the diesel-powered combination. This is on the lower side of the 45–75 % reduction range reported by Gustafsson and Svensson (2021). However, our findings differ considerably from the



**Fig. 6.** Results of the comparative cost analyses for the different scenarios. In the business as usual (BAU) and inflated gas price (IGP) scenarios, costs of the diesel combination were set at 100 %. In the inflated diesel price (IDP) scenario, costs of liquefied biogas (LBG) combination were set at 100 %.

70–75 % reduction found by [Gustafsson et al. \(2021\)](#) and the 81–211 % reduction reported by [Hagos and Ahlgren \(2018\)](#), but can be explained to a large extent by the different emission factors used in this study. In this study, we identified that GHG emissions reductions are also possible with heavy-duty (GVW >60 t) combinations as previous studies have mostly been carried out with lighter vehicles.

The cost analysis showed that the LBG combination can economically compete with diesel combinations. This result validates the findings of [Ferraz Júnior et al. \(2022\)](#). However, the results of our study did not consider the sparse fuel-station network and its knock-on effect on costs. Detouring to refuel an LBG combination truck can significantly increase costs compared to diesel combinations. Moreover, the cost analysis did not include the extra work involved in planning the payloads. Nevertheless, extra planning is not costly if the LBG-powered vehicle is only a part of a larger fleet of diesel combinations because the LBG vehicle can target the more optimal routes while the remainder of the (diesel) fleet covers the more unsuitable routes. Only using LBG vehicles with a poor fuel-station network would involve vehicles driving suboptimal routes, which would decrease their cost efficiency.

The LBG fuel-station network in Finland is expected to expand significantly before 2030 to achieve the national targets required by the Alternative Fuels Infrastructure Regulation ([Ojala et al., 2024](#)). This expansion will reduce the extent of suboptimal routes but will not eliminate them completely because the stations will most likely be located along the higher-class road network and thus have only a minor impact on operations on the lower-class road network. However, the expansion will most likely enable LBG-powered vehicles to operate over larger areas, which would permit simplified planning of optimal routes for those vehicles.

Of the alternative powertrains identified to date, LBG currently has the greatest potential in forestry transportation; LBG-powered heavy-duty vehicles have sufficient operating range to operate in harsh conditions away from the fuel infrastructure. Electrification of forestry transportation is more difficult for the same reason; the operating range of electric heavy-duty vehicles is inadequate for normal timber trucking operations, especially with heavier GVWs (>60 t).

This study has reported novel information with regard to the operation of heavy-duty LBG-powered timber-truck combinations, which had not been previously investigated. In general, our results could also be used in other sectors as LBG-powered vehicles have the potential to be effective in a wide range of conditions.

## 5. Conclusions

The main objective of this study was to evaluate the usage and possibilities of LBG-powered heavy-duty (GVW >60 t) vehicles in road transportation by the forestry sector. The dual-fuel LBG-powered HPDI timber-truck combination was found to be able to achieve significant GHG emissions reductions compared to the more traditional diesel-powered timber-truck combinations. The GHG emissions of the LBG combination for the complete transportation cycle were 44.6 % lower (per tkm) than those of the diesel combination.

One of our objectives was also to evaluate possible emission reductions possibilities with the large-scale deployment (10 % of domestic industrial roundwood transportation performance) in Finland of LBG-powered timber-truck combinations. The LBG combinations were found to reduce GHG emissions by over 12,000 t CO<sub>2</sub>e<sub>q</sub> annually, which proves that it is possible to substantially lower GHG emissions from

otherwise challenging industries and meet national GHG reduction targets.

The final objective was to investigate the operational costs of the LBG combination and compare them to the operational cost of the reference combination. Operational costs are important for the comparison of different emission reduction possibilities. In this study, the LBG combinations were found to be a cost-effective way to reduce GHG emissions from industrial roundwood transportation; the costs were similar to those of diesel-powered combinations.

The bottlenecks that limit expansion of LBG-powered heavy-duty vehicle use were also detected during the study. The main bottlenecks identified were the lack of refueling infrastructure and the lower GVW ratings due to the lower engine power. After the commencement of this study, Volvo brought out a more powerful model (368 kW), powered by liquefied gas, in which the GVW gap between the diesel and LBG combinations has been narrowed, allowing a GVW of 75 t to be achieved by the LBG combination. However, the lack of refueling infrastructure is a longer-term bottleneck, as the construction of new fuel stations takes time. In addition, it is important to consider where to site these new fuel stations to best serve the forestry transportation industry. Globally, it is advisable to evaluate the possibilities of using LBG-powered vehicles in more challenging use-cases, such as forestry transportation, where electrification is difficult.

### CRedit authorship contribution statement

**Sami Huuskonen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jouni Karjalainen:** Writing – review & editing, Methodology, Conceptualization. **Asko Poikela:** Writing – review & editing, Methodology, Formal analysis. **Pirjo Venäläinen:** Writing – review & editing, Methodology. **Kirsi Riekkii:** Writing – review & editing, Formal analysis. **Petri Helo:** Writing – review & editing, Supervision. **Pertti Kauranen:** Writing – review & editing, Supervision. **Aki Tilli:** Writing – review & editing, Supervision. **Kalle Kärhä:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Data availability

The authors do not have permission to share data.

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