



# Alternative Powertrains and Fuels in Heavy Non-Road Mobile Machinery and Their Future Expectations - A Review

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## Abstract

**Purpose of the Review** This literature review focused on studies on alternative powertrains and fuels of non-road mobile machinery (NRMM) during the last 15 years and investigated their future potential and expectations. The goal was to evaluate different alternative powertrains based on previous research and highlight the possibilities and challenges of each technology. Additionally, the aim was to conduct a comprehensive overview about the technology development phase of alternative powertrains.

**Recent Findings** This review covered a total of 115 studies consisting of hybrid, full-electric, biofuels, biogas, and hydrogen solutions. The results highlighted that hybrid and full-electric technologies have the greatest potential to replace conventional diesel engines in the future. The main challenges identified were battery reliability and high technology costs. Regarding biofuel, biogas, and hydrogen, the benefits were mainly lower emissions while the challenges were high costs and low production. Full-electric and hydrogen powertrains were found to reach zero local emissions during operations, while compared to diesel, repair and maintenance caused less emissions of 36–46% during the life cycle with full-electric and hydrogen solutions. With hybrid, biofuels, and biogas powertrains, the emission reduction potential ranged from 37 to 81% during operations and 36–66% during the entire life cycle. The highest Technology Readiness Levels (TRLs) were identified for hybrid and full-electric technologies in industrial machinery (6.9–7.4). The lowest measurable TRL (2.5) was with biogas powered construction machinery. The TRLs of biogas and hydrogen of forest machinery were excluded from this review due to the lack of research.

**Summary** Alternative powertrains can eventually replace diesel engines, if the challenges with implementation, production, and reliability are solved. Furthermore, the benefits of electric and renewable technologies/fuels are unambiguous from the emission reduction and energy efficiency perspectives. Consequently, we recommend that future research focus especially on the implementation of alternative technologies as well as the improvement of the manufacturing infrastructure.

**Keywords** Hybrid · Electrification · Renewable fuels · Biofuels · Biogas · Hydrogen · Technology readiness level (TRL)

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## Introduction

Over the past decade, greenhouse gas (GHG) emissions have increased on our planet; in 2022 they set a record of almost 37 Gt [1]. For the Effort Sharing Sector (ESS), this crisis necessitates setting new obligations that focus on, inter alia, reducing emissions from industry, agriculture, transport, and non-road mobile machinery (NRMM). These requirements also focus on reducing fluorinated greenhouse gas (F-gas) emissions and energy consumption from residential heating [2]. A European Union target is to reduce GHG emissions by 55% by 2030 [3] and 100% by 2050 [4]. The vision is to move towards carbon efficient economy and achieve net-zero GHG emissions through new technological solutions and comprehensive collaboration between the government, research community, and citizens [5].

In recent decades, due to the lag in emission standards, concern about NRMM emissions has increased [6]. In Finland, the ESS target achievement requires further actions [7]. Additional actions include, among others, additional taxes on fossil fuels and stronger promotion of new low-emission solutions for NRMM [2]. In addition, there are actions that financially support electric and biofuel-powered machines and to include carbon dioxide (CO<sub>2</sub>) emissions to Stage Regulation (2016/1628) [8]. The upcoming revision of the Emissions Trading System (ETS) introduces regulations for fuel suppliers in the form of higher prices for fossil CO<sub>2</sub> emissions. The aim is to increase the share of renewable fuels in NRMM operations [9]. These regulations will mainly apply to machines used in industrial environments, wherein, needed electrification is feasible.

Currently, NRMM accounts for 9% of the total GHG emissions caused by the ESS sector in Finland. These emissions originate mostly from agricultural machinery, such as farm tractors; forest machinery, mainly harvesters and forwarders; construction and industrial machinery, including excavators, wheel loaders, and forklifts [2]. For instance, in 2020, GHG emissions originating from harvesters and forwarders accounted for approximately 13% of the total NRMM emissions [2]. Previously, NRMM emissions have been studied primarily regarding fuel consumption of diesel-powered machines, for example, Lijewski et al. [10], Numazawa et al. [11], Prinz et al. [12], Spinelli and De Arruda Moura [13], Haavikko et al. [14], Kopešek et al. [15], Bacescu et al. [16], and Kärhä et al. [17, 18]. For other NRMM, the fuel consumption and emissions were investigated less exhaustively, although Lee et al. [19] examined diesel excavators and Kolator [20] diesel tractors. Even though reducing fuel consumption on diesel-powered machines is possible, these studies show that a further reduction is challenging. Furthermore, the emission levels

from diesel machinery have largely levelled out hindering a further decrease of global GHG emissions [21].

NRMM emission awareness has accelerated the development of alternative powertrains feasible in high-power operations, these alternatives are hybrid, electricity, hydrogen, biofuels, and biogas. For forest machines, a possible alternative is a hybrid solution, since hybridization can improve the performance and efficiency of forest machinery [22–28]. However, the benefits offered by a hybrid-powered engine must be exploited to enhance profitability [29, 30]. Nevertheless, a recently presented hybrid forest machine concept with full-electric powertrain and a diesel-powered battery recharge is estimated to further accelerate the NRMM electrification [31].

In Finland, 43% of the NRMM emissions occur from construction and industrial machinery [2], which has made hybrid and full-electric powertrains distinguishable to other powertrains. Hybrid technology was found to improve the efficiency of excavators [32–34], while full-electric solution reportedly reduces costs and energy consumption [35–37] due to the lower friction between the components in the system [38]. Few studies also including wheel loaders [39–42] and forklifts [43–46], highlighted promising results regarding hybrid and full-electric powertrains. Hydrogen was studied as well in few industrial machines [45, 47, 48] and the results indicated higher cost-efficiency than with electricity. However, the production rate of hydrogen is rather low (2%) nowadays [49]. Thus, generalizing hydrogen as an alternative fuel requires more hydrogen production and lower manufacturing costs [49].

According to Puricelli et al. [50], biofuels accounted for 4.5% of the total energy consumption in road transport and NRMM. Biofuels, such as rapeseed (*Brassica napus*) oil and hydrotreated vegetable oil (HVO) have been in the scope of the research in recent years particularly in agricultural machinery [51, 52]. Moreover, Hosseinzadeh-Bandbafha et al. [53] found that mixing biodiesel and bioethanol with diesel improved efficiency and reduced emissions. Moreover, similar fuel efficiency than conventional diesel engines have been found with rapeseed oil in forestry harvesting operations [54].

A recently presented agricultural tractor powered with biogas is stated to have the same performance with lower costs than conventional diesel engine [55]. However, Lacour et al. [56] showed that utilizing biogas causes similar problems as conventional diesel engines. Furthermore, blending biogas with diesel containing approximately 50% of both fuels is feasible [57], hence it can reduce emissions significantly [58].

This literature review included studies from the past 15 years and focused on studies affiliated to alternative powertrains and fuels of NRMM fleet based on their potential

**Table 1** Keywords of the literature searches ( $n=52$ )

<i>Forestry machinery</i>	<i>Industrial machinery</i>	<i>Powertrain</i>
Chipper	Crane	Battery technology
Crusher	Forklift	Biofuel
Feller-buncher	Industrial machine	Biogas
Forest machine	Industrial tractor	Electricity
Forest tractor	Log stacker	Electrification
Forwarder	Material handling machine	Fuel cell
Grinder	Telehandler	Hybrid
Harvester	Wheel loader	Hybridization
Harvesting machine		Hydrogenation
Logging machine	<b>Agricultural machinery</b>	Hydrogen
Skidder	Agricultural machine	Renewable fuel
Yarder	Agricultural tractor	
	Cultivator	<b>General</b>
<b>Construction machinery</b>	Farm tractor	Non-road mobile machine
Bulldozer	Tractor	NRMM
Construction machine		
Construction tractor	<b>Other keywords</b>	<b>Methods</b>
Dump truck	Decarbonization	Technology assessment
Dumper	Low carbon	Technology Readiness Level
Excavator	Low emission	TRL assessment
Mining machine		TRL determination

and future visions. The aim was to gather global research information and provide a comprehensive overview to support and accelerate the technology development in this field. The specific goal was to present the current stage of technology development in each machinery segment and single machinery type by assessing Technology Readiness Levels (TRLs). The assessment specified the requirements of further research and technology development with detailed knowledge on the potential of each alternative powertrain solution, thereby promoting new low-emission solutions in NRMM operations.

## Literature Review

### Data Collection and Analysis

Studies were collected from the early 2010 to June 2024. The literature databases of Google Scholar, Science Direct, and Web of Science were used to find suitable studies. This review focused on peer-reviewed articles and non-reviewed

publications, which were classified based on country, publication year, machine, and powertrain for further analysis. After each literature search round, studies were screened and selected based on their suitability for this review. Furthermore, the methodology, results, and conclusions of each selected study were highlighted and combined with other studies. Finally, the results of this review were presented in tables, figures, and charts as well as discussed and evaluated.

Literature searches were conducted by using several keywords (Table 1). In addition, a combination of different keywords, for example, “Technology assessment of Hybrid NRMM” and Boolean operators (AND OR) were used to refine the search results. Only articles in English and Finnish were collected due to language barrier with other languages. Based on those criteria, a total of 115 studies were found.

### Machinery Types and Powertrain Alternatives

This review concentrated on heavy non-road mobile machinery, including machines from forestry, industrial, construction, and agriculture sectors. Lightweight machines, such as snowmobiles, all-terrain vehicles (ATVs), and mowers were excluded from this review. A total of 17 machinery types were identified and used to classify collected studies. A total of 20 studies included 2–5 powertrains or machine types. These studies were classified in multiple groups, which increased the total number of observations from 115 to 143 (Table 2). Few machine types, such as feller-bunchers, grinders, and cultivators were excluded from this review due to the lack of studies.

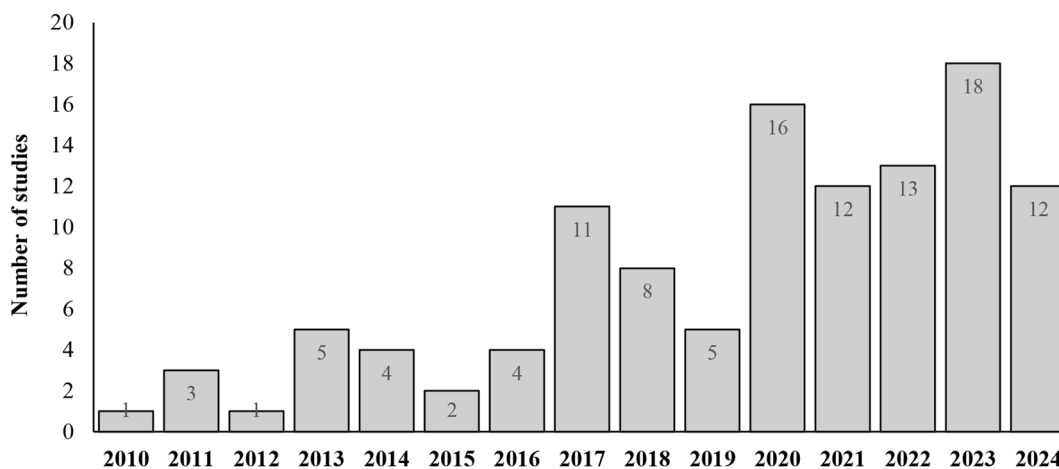
Six machine types were identified in forestry machinery, five machine types in industrial machinery, four types in construction machinery, and one machine type in agricultural machinery segments. Moreover, one segment concentrated on general NRMM development. As with forestry machinery, the machines included in this review were commonly used felling-processing, extraction, soil preparation, and chipping machines. Within the industrial machinery segment, machines operating stationary or within a small area were identified. The construction machinery segment highlighted the machines used in construction and mining operations. Moreover, the agricultural machinery segment included mainly farm tractors. The general NRMM development segment included studies which examined NRMM engines, which were challenging to attribute to a specific machine type (Table 3).

**Table 2** Total number of studies and observations used in this literature review

	Number of powertrains/machines					Total
	1	2	3	4	5	
Number of studies	95	15	3	1	1	<b>115</b>
Number of observations	95	30	9	4	5	<b>143</b>

**Table 3** Machinery types and powertrains classified in this review, as well as the number of studies in each class including studies examining more than one powertrain or fuel ( $n=143$ )

Class	Machinery type	Alternative powertrain/fuel					Total
		Hybrid	Full-electric	Biofuels	Biogas	Hydrogen	
Number of studies reviewed							
Forestry machinery	Chippers	1	-	-	-	-	1
	Crushers	1	-	-	-	-	1
	Forwarders	1	-	-	-	-	1
	Harvesters	5	-	1	-	-	6
	Skidders	3	-	-	-	-	3
	Yarders	4	-	-	-	-	4
Industrial machinery	Cranes	-	5	-	-	-	5
	Forklifts	4	4	-	-	4	12
	Log stackers	1	-	-	-	-	1
	Telehandlers	1	1	-	-	1	3
	Wheel loaders	6	4	-	-	2	12
Construction machinery	Bulldozers	2	-	1	-	-	3
	Construction tractors	-	-	-	2	-	2
	Dump trucks	-	-	-	1	3	4
	Excavators	9	11	-	1	3	24
Agricultural machinery	Farm tractors	4	8	8	5	3	28
General NRMM development	NRMM engines	5	7	10	4	7	33
	<b>Total</b>	<b>47</b>	<b>40</b>	<b>20</b>	<b>13</b>	<b>23</b>	<b>143</b>

**Fig. 1** Publication years of the studies used in the literature review ( $n=115$ )

Furthermore, this review identified five alternative powertrains based on their ability to replace diesel engines: hybrid, full-electric, biofuels, biogas, and hydrogen. Multiple technologies and fuels were included within the hybrid, full-electric, biofuels, biogas, and hydrogen groups. As for NRMM electrification, this review focused especially on supercapacitor, hydraulic hybrid, and battery electric solutions. With biofuels, the focus was on biodiesel, bioethanol, and rapeseed oil. Biogas was described as biomethane in this review, and hydrogen solution as fuel cell and hydrogen combustion technologies (Table 3).

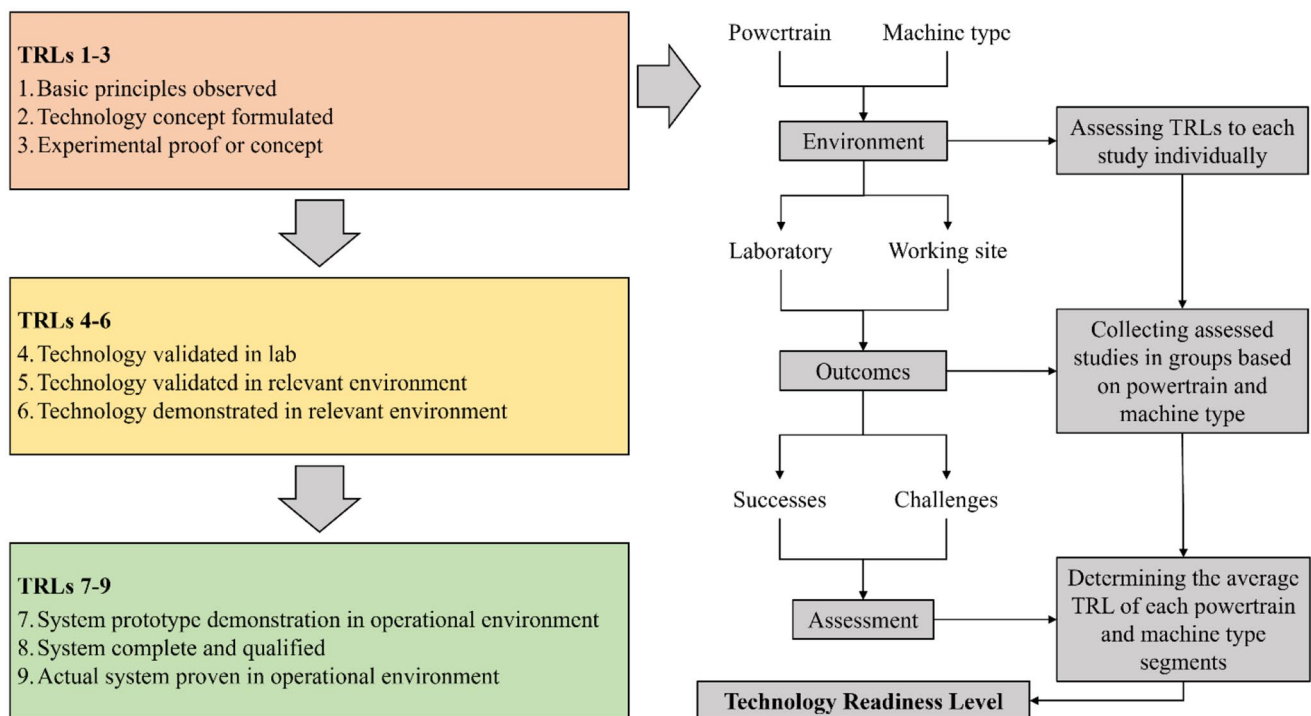
### Final Data of the Review

A total of 115 studies were published in the period of interest (2010–2024), with most of the studies (71 studies) published from the year 2020 onwards (Fig. 1). 74 studies (64%) were collected from European countries, whereas 31 studies (27%) originated from Asian countries. Altogether, 9 studies from North and South America covered approximately 8% of the total, while the one remaining study originated from Africa.

## The Assessment of Technology Readiness Level (TRL)

A total of 83 studies were used to assess TRLs of different powertrains and machinery segments. Of those, 73 studies included only one machine or powertrain and 10 studies between 2 and 4 machines or powertrains, increasing the total number of observations to 97. The assessment of TRL was conducted based on the classification by European Commission [59]. Furthermore, studies were sorted to groups based on machinery type, such as forestry machinery, industrial machinery, construction machinery, agricultural machinery, and other NRMM. This was followed by identifying the investigated powertrain from each study and determining the prevalence of those in each machine group.

As the first step of the analyses, the studies of alternative powertrains were investigated in general to emphasize whether the respective study included the testing of machine or powertrains in an actual working environment or laboratory. In a second step, the studies were examined more specifically regarding the outcomes, which expressed the successes and challenges besides being used to determine TRLs. In a final step, the average TRL of solutions presented in each study were defined. As a result, TRLs were presented from the perspective of each alternative powertrain or machine category (Fig. 2).



**Fig. 2** Data analyzing and TRL determination process to each alternative powertrain and machine type based on the TRL classification by European Commission [59]

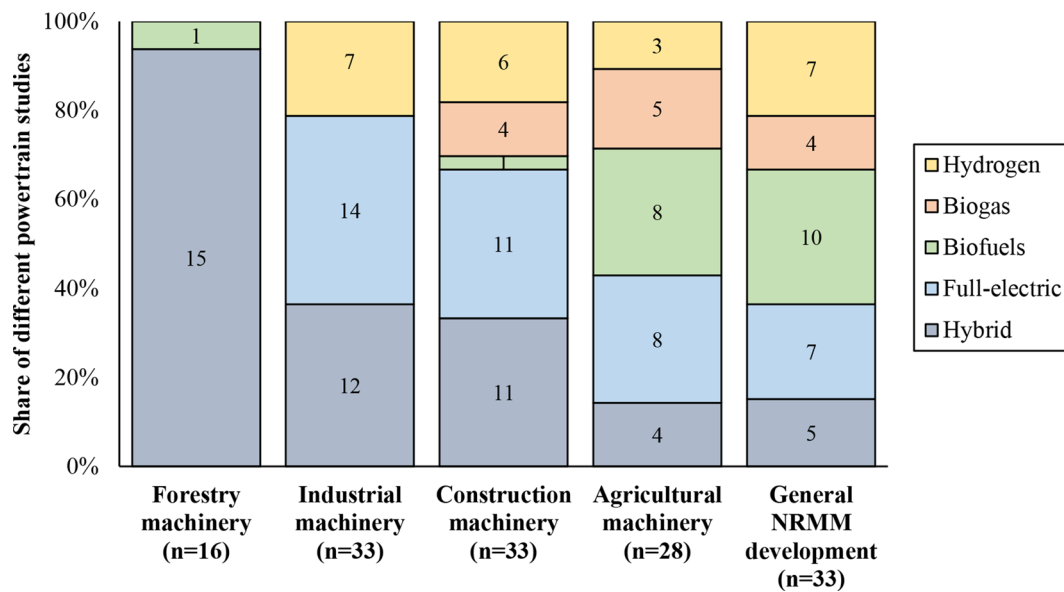
## Results

### Alternative Powertrains

The development of alternative powertrains has focused primarily on NRMM electrification (Fig. 3), although Emberger et al. [54] examined rapeseed oil in harvesters in Bavarian harvesting conditions. In industrial machinery and construction machinery, the focus of the research was on full-electric technology alongside hybrid technology [60–63]. Moreover, Honkanen [48] highlights the potential of hydrogen and biofuel powered excavators in Finland. Biofuel and biogas technologies have been studied more comprehensively in agricultural tractors [52, 64]. Furthermore, there are also studies related to hybrid, full-electric, and hydrogen technologies used in agricultural tractors [65–68]. In addition, hybrid, full-electric, biofuel, biogas and hydrogen technologies were continuously investigated in NRMM engines under laboratory environment (Fig. 3).

### Hybrid

The most common hybrid solutions in NRMM include a rechargeable battery in addition to diesel engine and hydraulic hybrid solution, where, for instance, kinetic energy from braking is stored to the battery. As Leitner et al. [69] reported, the hybridization of a tower yarder is feasible, which has major potential for reducing energy consumption.



**Fig. 3** Total number of studies and their shares of alternative powertrain in forestry, industrial, construction, agricultural, and general NRMM development ( $n=115$ ). These observations also include 20

studies with more than one powertrain, increasing the total number of observations to 143

Furthermore, Leitner et al. [70] concluded that a hybrid tower yarder reduced fuel consumption 45% in uphill transport and 63% in downhill transport. Cadei et al. [71], on the other hand, found that with a supercapacitor, the running time of the yarder was 38% lower, resulting in approximately  $0.4 \text{ L m}^{-3}$  lower fuel consumption and  $1.07 \text{ kg CO}_2 \text{ eq m}^{-3}$  less emissions.

In cut-to-length forestry, the fuel consumption of the hydraulic hybrid forestry harvester was  $10\text{--}15 \text{ L h}^{-1}$  [22]. Furthermore, Poikela and Ovaskainen [30] expressed that the fuel consumption of the hybrid harvester with rechargeable electric motor was approximately 3% lower than that of a diesel harvester with a higher productivity of 14–15%. With skidders used in tree-length forest operations, hydraulic hybrid with battery energy storage and electrical power generator reduced fuel costs by 14% and improved efficiency [26, 27]. Nevertheless, the productivity of the electric-driven hydraulic hybrid forwarder was 3% lower than that of the diesel engine, while the fuel consumption was 7% lower [31].

In an industrial environment, an extensive charging infrastructure together with lower fuel consumption and  $\text{CO}_2$  emissions advocates the generalization of hybrid alternatives in industrial machinery [39] and in construction machinery [72]. For instance, hybrid reduced the total energy consumption in forklifts by 21% with hydraulic hybrid and 55% with electric hybrid solution [73]. On the other hand, using continuously variable transmission (CVT) in bulldozers resulted in an 18% reduction of fuel consumption [74].

In cases when the charging connection was extensive and the hybrid technology matched the power demand, fuel consumption could be 11–13% lower with an engine speed of 2000–2200 rpm [75]. Correspondingly, Wang et al. [76] stated that implementing prescient model predictive controller (MPC) to a wheel loader saves approximately 21% of fuel. In bulldozers, on the other hand, the fuel consumption was 28% lower with a hybrid [77]. With telehandlers, a 13% lower fuel consumption was identified [78]. Moreover, the machine testing of a hybrid solution revealed the potential to improve energy efficiency by approximately 10–48% in excavators [32, 63, 79]. The energy efficiency improvement has also been identified in the general research of NRMM [80, 81]. Notable is that Khan and Huang [33] found that the energy efficiency of battery-electric engine was 2% lower compared to a conventional diesel engine, even though the efficiency was still at 96% (Table 4).

The availability of charging connections especially under forestry or agricultural environments is a real challenge, highlighting the requirement for large high-power batteries. However, battery implementation will cause heavier machines, affecting usability, costs, and maintenance time, thus limiting technology generalization [82]. On the other hand, Mäki [85] suggested that the best option in log stackers was to use a conventional diesel engine as the main source of power and add a generator to power the transmission. This improves the ability for the machine to adapt to various operating conditions [66]. However, Ratzinger et al. [83] claimed that series hybrid is a better solution for wheel-driven construction machinery due to its better capability to reduce emissions. Furthermore, the productivity of the

**Table 4** Advantages, disadvantages, and limitations of alternative powertrains in forestry, industrial, construction, agricultural machinery, and general NRMM development based on the analysis of selected studies

Hybrid	Advantages	Disadvantages	Limitations
Forestry machinery	Lower fuel consumption and CO <sub>2</sub> emissions, more stabilized operations [30, 31, 71]	Reliability, higher costs, and increased weight of the machinery due to battery implementation [82]	Lack of recharge possibilities and implementation of batteries is difficult [48], profitable operations require higher productivity than with diesel [30]
Industrial machinery	Extensive charging connection, lower fuel consumption, suitable for short-term high-power operations, less noise and improved efficiency [39, 72, 73]	Reliability and higher costs [82]	Limited adequacy of electricity [45]
Construction machinery	Lower fuel consumption and CO <sub>2</sub> emissions, more stabilized operations [83]	Reliability, higher costs, and increased weight of the machinery due to battery implementation, no infrastructure to cable connection [84]	Lack of recharge possibilities, high costs of electric components, short operating area with cable connection [48]
Agricultural machinery	Lower fuel consumption and CO <sub>2</sub> emissions [58], adaptability to various operating conditions [66, 85]	Reliability, higher costs, and increased weight of the machinery due to battery implementation [82], no infrastructure to cable connection	Lack of recharge possibilities and challenging implementation of batteries [48]
General NRMM development	Fuel consumption is lower when boosting diesel engines with hybrid [75, 76]	Size and weight causes challenges when implementing large batteries [82]	Manufacturing process of large batteries causes emissions as much as the emission savings produced are [33]
<b>Full-electric</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Limitations</b>
Forestry machinery	Environmentally friendly, smooth and continuous power control, and better ergonomics [86]	Increases weight due to battery implementation [86, 87], no possibilities to cable connection	Lack of charging connection, cold working conditions cause reliability issues [48]
Industrial machinery	More extensive charging connection, improved efficiency, lower costs, and zero emissions during operations [41, 45]	Reliability of batteries in extreme conditions, disposal process and high energy consumption of batteries [87], and limited operation area due to cable connection [60–62]	Battery-technology requires more development [84], cable charging requires stationary operations [88]
Construction machinery	Lower energy consumption during operations [89]	Reliability of batteries in extreme conditions [84], limited operation area due to cable connection	Lack of charging connection, cold working conditions cause reliability issues [48]
Agricultural machinery	Possible to build a compact engine, which still meets the performance and power requirements [65], more stabilized operations [90]	Increased weight of the machinery due to battery implementation [91], no possibilities to cable connection	Lack of charging connection, cold working conditions cause reliability issues [48]
General NRMM development	Lower CO <sub>2</sub> emissions and no fuel consumption [86, 92]	Costs of the batteries and maintenance, lower reliability in extreme conditions [93]	Storing possibilities, availability of electric components and high costs [87]
<b>Biofuels</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Limitations</b>
Forestry machinery	Lower emissions (CO <sub>2</sub> , NO <sub>x</sub> , PM) [94]	Productivity and fuel consumption is at the same level than conventional diesel engine [54]	More research is required regarding the properties of biofuels under extreme conditions, and cooling down the system [54]
Industrial machinery	Lower emissions (CO <sub>2</sub> , NO <sub>x</sub> , PM) [94]	Availability of renewable fuels causes additional costs and time due to increased transportation [48]	Low availability of biofuels [95] and lack of knowledge regarding the properties of biofuels [54]
Construction machinery	Lower emissions (CO <sub>2</sub> , NO <sub>x</sub> , PM) [94]	Availability of renewable fuels causes additional costs and time due to increased transportation [48]	Low availability of biofuels [95] and lack of knowledge regarding the properties of biofuels [54]
Agricultural machinery	Higher temperature of the fuel allows cleaner combustion [96], lower CO <sub>2</sub> , SO <sub>2</sub> , and PM emissions [53]	Higher fuel consumption and reduced performance [51, 97]	The profitability issues with local biofuel production [95]
General NRMM development	Lower emissions (CO <sub>2</sub> , NO <sub>x</sub> , PM) [94, 98]	Higher fuel consumption, issues with sustainability criteria [98]	Large scale generalization requires significant amount of bio-based resources [95]
<b>Biogas</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Limitations</b>
Forestry machinery	Lower CO <sub>2</sub> emissions [99]	Specialized design in new engines is required due to the costs of retrofitting the technology to the old machinery [81]	Lack of sufficient solutions and methodologies [56]

**Table 4** (continued)

Hybrid	Advantages	Disadvantages	Limitations
Industrial machinery	Lower CO <sub>2</sub> emissions [99]	Specialized design in new engines is required due to the costs of retrofitting the technology to the old machinery [81]	Lack of sufficient solutions and methodologies [56]
Construction machinery	Lower emissions and increased torque [55, 100]	The availability of renewable fuels causes additional costs and time due to increased transportation [48]	Lack of sufficient solutions and methodologies [56]
Agricultural machinery	Lower emissions [101], less maintenance and repair costs [102]	Specialized design in new engines is required due to the costs of retrofitting the technology to the old machinery [81]	Low availability of biogas [57]
General NRMM development	Lower CO <sub>2</sub> emissions [99], compatibility with different fuel blends [64, 103]	Specialized design in new engines is required due to the costs of retrofitting the technology to the old machinery [81]	Current infrastructure requires compatibility and adaptability to generalize profitable biogas production [103]
<b>Hydrogen</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Limitations</b>
Forestry machinery	-	-	-
Industrial machinery	Lower emissions and cost-efficient operations [104], higher efficiency, and more stabilized power control [105]	High costs of fuel-cells and re-fueling infrastructure [48], the size of required hydrogen storage in high-power vehicles [106]	Further development could reduce costs significantly [47]
Construction machinery	Higher energy efficiency, lower fuel consumption and emissions [107, 108]	High costs of hydrogen technology [48], increased weight due to large hydrogen storage [106]	Lack of hydrogen production [47]
Agricultural machinery	Lower CO <sub>2</sub> emissions while maintaining performance [68]	Performance is at the same level than diesel [68], requires a large storage [106]	Lack of hydrogen production [47]
General NRMM development	Lower emissions (CO <sub>2</sub> , HC, NOx) [109]	Higher energy consumption [95]	Lack of hydrogen production [47]

hybrid machine must be greater than diesel machine while pursuing benefits from either hybrid solution [30].

### Full-Electric

Full-electric powertrains have potential when reducing emissions and maintaining performance, although they often require comprehensive charging connection and recharge possibilities nearby working sites. Thus, for instance, full-electric powertrain development is currently more familiar among industrial machinery than that of forestry machinery.

Hao et al. [110] stated that the energy efficiency of the hydraulic system of existing electric excavators is less than 30%, and Ge et al. [35] reported that it could be improved by 13% with full-electric powertrain. Furthermore, with full-electric powertrain, the energy consumption can be 35–38% lower in excavators with variable speed control or hydraulic-electric system [38, 110]. In turn, similar performance improvements and emission reductions can be achieved in forklifts and wheel loaders [41, 45]. Electrification can also stabilize and promote efficient operations [36, 111] since power (i.e., torque and speed) can be exploited and adjusted more efficiently when needed [90, 112]. Moreover, the size of an electric engine is more compact than that of a conventional diesel engine, while achieving the performance requirements [65] (Table 4).

Challenges in battery-electric powertrains with forestry or agricultural machinery are increased weight, costs, and maintenance time [86, 87]. The increased weight of the machinery can be also a positive feature in industrial machinery, when it can improve the balance while lifting heavy loads. However, Khan and Huang [33] and Lin et al. [84] underlined that the challenges with excavators occur from the reliability of batteries in cold weather conditions and the disposal processes of batteries. One challenge in agricultural machinery is also the decreasing overall efficiency of the batteries due to increased weight [91]. However, da Silva et al. [113] investigated battery management system (BMS) in electric forklifts, highlighting promising results on the suitable battery models in industrial machinery. Furthermore, according to Fassbender et al. [114], a displacement-controlled boom in an electrified telehandler lowers the energy consumption by approximately 21–31%.

An additional electrification solution for industrial machinery is cable charging. For instance, a cable-electrified crane with energy storage system (ESS) and active front end (AFE), resulted in a 30–47% reduction in energy consumption [61]. Correspondingly, with hydraulic pumps and a battery, energy consumption can be 49% lower [115]. Furthermore, Alasali et al. [62] specified that a Stochastic Model Predictive Control (SMPC) model reduces costs by approximately 7%, outperforming other models. Moreover,

compared to diesel, an electrified crane decreases annual costs by 10% [60]. On the other hand, cable charging outperformed battery-powered excavator by lowering the total energy consumption by 5% and CO<sub>2</sub> emissions by 68% [89]. However, cable charging prevents the mobility of the machine as well as limiting the operating area. For instance, a full-electric crane can cause electromagnetic interferences due to the number of cables, necessitating a concentration on the suitable structure of the crane [88]. Thus, a cable connection is suitable in indoor forklifts, cranes, and other stationary material handling machines, where the movement of the machine is limited.

## Biofuels

With rapeseed oil, similar productivity (17.81–17.87 m<sup>3</sup> h<sup>-1</sup>) than with diesel was achieved, although the fuel consumption with rapeseed oil was 8% lower with emission savings of approximately 700–1050 t CO<sub>2</sub>eq per machine per year [54]. In turn, other vegetable oils, such as coconut (*Cocos nucifera* L.) oil, palm oil, and sunflower (*Helianthus annuus*) oil provided approximately 8% higher fuel consumption compared to diesel [97]. As a limitation, the lack of knowledge about the properties of biofuels under very cold or hot weather appeared [54, 97]. For example, Vojtišek-Lom et al. [96] reported that one of the key challenges in utilizing vegetable oils is their high viscosity, requiring optimized fuel injection with a higher pressure to achieve proper fuel combustion. Moreover, the low distribution of biofuel production also causes challenges especially in the sectors of forestry and agriculture (Table 4).

In the past decade, lower emissions have been the main drivers for utilizing biofuels. For example, Pirjola et al. [52] found that HVO fuels reduce nitrogen oxide (NO<sub>x</sub>) emissions by 20% during field tests. Correspondingly, Hosseinzadeh-Bandbafha et al. [53] reported 14% lower CO<sub>2</sub> emissions, 5% lower sulfur dioxide (SO<sub>2</sub>) emissions, and 14% lower particulate matter (PM) emissions during the life cycle of an agricultural tractor. Ettl et al. [116] highlighted that rapeseed oil lowers CO<sub>2</sub>, NO<sub>x</sub>, and hydrocarbon (HC) emissions by 80–93%, as well as 69% less PM emissions during field tests in agricultural tractors. Moreover, rapeseed oil resulted in approximately 3–7% lower fuel consumption compared to jatropha (*Jatropha curcas* L.) oil and biodiesel, depending on the proportion of the biofuel in the fuel mixture [51]. Biodiesel, on the other hand, increased fuel consumption approximately by 11–16% [98]. Correspondingly, Jhang et al. [109] stated that gasoline-bioethanol blend will increase the total fuel consumption of the machine by over 50% compared to pure gasoline. Moreover, biomethanol contains approximately 53% less energy than diesel [117],

increasing the total fuel consumption and thus, costs and transportation distances [48].

According to Mohite et al. [118], hydrogen and bio-diesel blends with optimized engine load and fuel injection pressure increase the performance of NRMM engine. On the other hand, blending vegetable oil ester and biogas is feasible, although the environmental effects are the highest with a 70% or higher biofuel share [64]. However, the low profitability of local biofuel production restrains the spreading of biofuel utilization. Thus, biofuel production should be scaled up when moving towards cost-efficient and low-emission operations [95] with the help of subsidies and new market-based instruments [117].

## Biogas

Biogas is a rather unutilized powertrain in forestry, industrial, and construction machinery. However, biogas has an approximately 50% higher combustion temperature, which reduces emissions in dump trucks [100]. Moreover, biogas can be mixed with diesel and the most suitable blend includes 50% biogas [57]. On the other hand, it is possible to apply a 30% share of biogas in vegetable oil ester-biogas mixture [64]. Blending biogas with other fuels offers flexibility and better efficiency [103]. It has been found that a biogas-biodiesel-butanol mix resulted in the lowest CO<sub>2</sub> and HC emissions, while a biogas-Di-ethyl ether-biodiesel-butanol mix resulted in the lowest NO<sub>x</sub> and smoke emissions. With a biogas-gasoline-butanol mix, CO<sub>2</sub> emissions were also at a low level, but HC, NO<sub>x</sub>, and smoke emissions were rather high due to the joint burning of high and low reactive fuels [99].

Konepörssi [55] highlighted that an agricultural tractor operating with pure biogas increased the torque by 36–40% and reduced total emissions by 80% during the life cycle. Moreover, Baker et al. [101] revealed that biomethane has the potential to reduce emissions by approximately 77% in mobile machinery due to equivalent performance to diesel machinery. In addition, biogas was found to be more suitable for new than older machinery due to major upgrade requirements in engines [81]. Biogas can also reduce the stress of the engine as well as the maintenance and repair costs [102].

The agricultural environment has the potential for local manufacturing of biogas since the ingredients of biogas are located near working sites. Nevertheless, the challenge in biogas-powered machinery is a low availability of biogas, which is derived from low processing possibilities especially in small-sized farms [57]. This is complemented by Vasan et al. [103] who highlighted the challenge to make the current infrastructure compatible with biogas. Small-scale biogas production tends to be less viable than large-scale

production due to higher production costs and thus, less affordable fuel [101] (Table 4).

## Hydrogen

Regarding hydrogen, Keränen et al. [105] investigated a fuel cell powered hydrogen-electric forklift in industrial operations, resulting in promising results in power control and stabilization. Moreover, few studies included actual machine testing focused on excavators, wheel loaders, forklifts, and agricultural tractors [45, 68, 106, 108]. For example, Haghi et al. [45] and Fúnez Guerra et al. [104] concluded that fuel cells reduced emissions and improved cost-efficiency. Additionally, hydrogen maintained the same performance as the conventional diesel engine [68] and reduced fuel consumption by approximately 27% [108]. According to Lourido et al. [107], hydrogen improved efficiency by approximately 29% in dump trucks (Table 4).

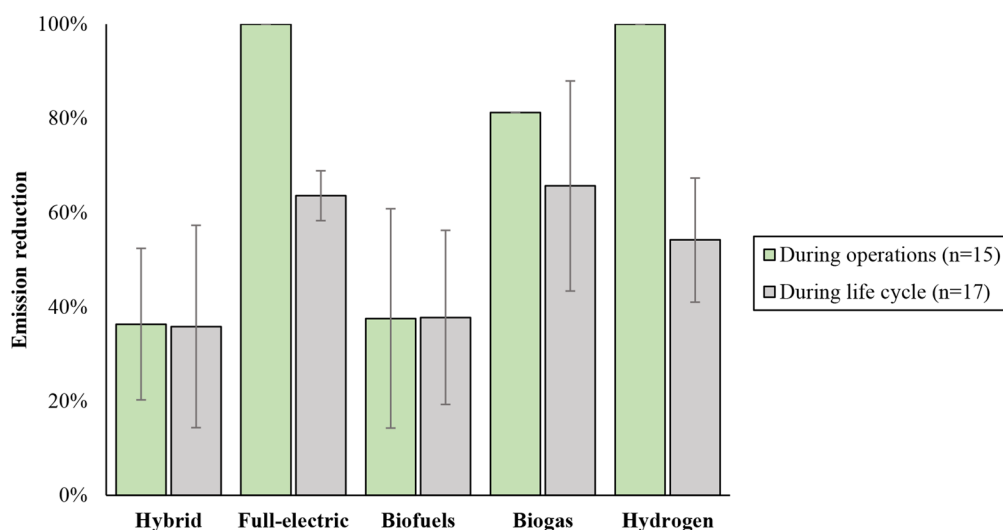
In excavators and wheel loaders, fuel cells reduced hydrogen consumption by approximately 12–17% [106]. However, with a hydrogen combustion engine, lower hydrogen consumption resulted from higher flammability range and higher ignition rate, allowing the engine to operate with less fuel injection [119]. Thus, hydrogen has a high potential to reduce emissions [92]. The limitations are high costs of the fuel cells [48], and the lack of hydrogen production, requiring a solution when accelerating the utilization of hydrogen in heavy NRMM fleet [47]. Moreover, Ahluwalia et al. [106] pointed out that in high-power machinery the required hydrogen storage is relatively large, increasing the weight of the machine.

## Emission Reduction Potential

Although hybrid has been considered the alternative powertrain with the most potential, its emission reducing potential during operations seemed to be the lowest: on average, it was 36% (std 0.16) [24, 25, 70, 74, 120, 121], ranging from 23% [25] to 59% [120]. However, with hybrid, it is also possible to reduce emissions by approximately 36% (std 0.21) during the life cycle [27, 33, 77, 83]. Full-electric powertrain, on the other hand, produces zero local emissions during operations [122], thus its emission reduction potential was 100%. During the life cycle of the machine, including the technology production and maintenance, the average emission reduction potential with full-electric powertrain was 64% (std 0.05), ranging from 58% [31] to 68% [87]. The corresponding estimation by Lagnelöv et al. [123] was 65%. Moreover, battery replacement and other maintenance caused additional emissions during the life cycle [89] (Fig. 4).

With biofuels, Emberger et al. [97] found that the potential was 34% with rapeseed oil, Simikic et al. [124] and Kurniawan et al. [125] reported a slightly lower potential of 18–27% with biodiesel or bioethanol-hydrogen blend. Furthermore, Ettl et al. [116] reported that rapeseed oil reduced CO<sub>2</sub> emissions by 67%, NO<sub>x</sub> emissions by 78%, HC emissions by 88%, and PM emissions by 49%, resulting in an average of 71%. Thus, the average emission reduction potential with biofuels was 38% (std 0.23) during operations (Fig. 4). During the life cycle, biofuels produce approximately 38% (std 0.18) less emissions varying from 14% [53] to 58% [126].

According to New Holland [127], the new biogas-powered tractor produces 81% less emissions on average during



**Fig. 4** Average emission reduction potential during operations and life cycle of each alternative powertrain based on previously reported results. The grey lines describe the standard deviation in each pow-

ertrain group. The observations are based on the analysis of the studies, where emissions of alternative powertrains were compared to diesel/gasoline ( $n=32$ )

operations. Correspondingly, the life cycle emissions of the biogas-powered tractor were reported to be 77–80% lower than in similar diesel-powered tractor [55, 101]. Furthermore, Wisell et al. [81] stated that biogas has the potential to reduce emissions approximately 40% during the life cycle. Hence, the average emission reduction potential during the life cycle with biogas was 66% (std 0.22). Hydrogen, on the other hand, embraces a 100% CO<sub>2</sub> emission reduction during operations as well [128], which was confirmed by U.S. Department of Energy [129] stating that hydrogen powered fuel-cell engines emit only water and air. During the life cycle, the average emission reduction potential with hydrogen was 54% (std 0.13), varying from 44% [130] to 69% [131] (Fig. 4).

**Table 5** Average TRLs with different forestry, industrial, construction, and agricultural machinery. This assessment included 83 different studies, of which 10 studies were used in the determination of TRLs of several powertrains and machine types. Thus, the total number of observations used in this assessment was 97

Machine type/ group	Alternative powertrain/fuel				
	Hybrid (n=39)	Full- electric (n=29)	Bio- fuels (n=11)	Biogas (n=5)	Hydro- gen (n=13)
<b>Technical Readiness Level (average [variation range])</b>					
<b>Forestry machinery (n=17)</b>					
Chippers	6.0	-	-	-	-
Crushers	9.0	-	-	-	-
Forwarders	6.0	-	-	-	-
Harvesters	6.6 [6–8]	-	4.0	-	-
Skidders	6.0 [5–7]	-	-	-	-
Yarders	7.3 [7–8]	-	-	-	-
<b>Industrial machinery (n=30)</b>					
Cranes	-	8.6 [8–9]	-	-	-
Forklifts	7.3 [5–9]	6.7 [6–8]	-	-	5.7 [5–7]
Log stackers	7.0	-	-	-	-
Telehandlers	7.0	8.0	-	-	5.0
Wheel loaders	6.2 [5–7]	6.3 [5–8]	-	-	5.0
<b>Construction machinery (n=27)</b>					
Bulldozer	7.0	-	6.0	-	-
Dump trucks	-	-	-	4.0	5.0 [4–6]
Excavators	6.6 [5–8]	6.6 [5–8]	-	1.0	3.7 [1–5]
<b>Agricultural machinery (n=24)</b>					
Farm tractors	5.3 [5–6]	4.7 [3–6]	6.0 [5–7]	4.0 [3–6]	4.0 [3–5]

### Technology Readiness Levels (TRLs)

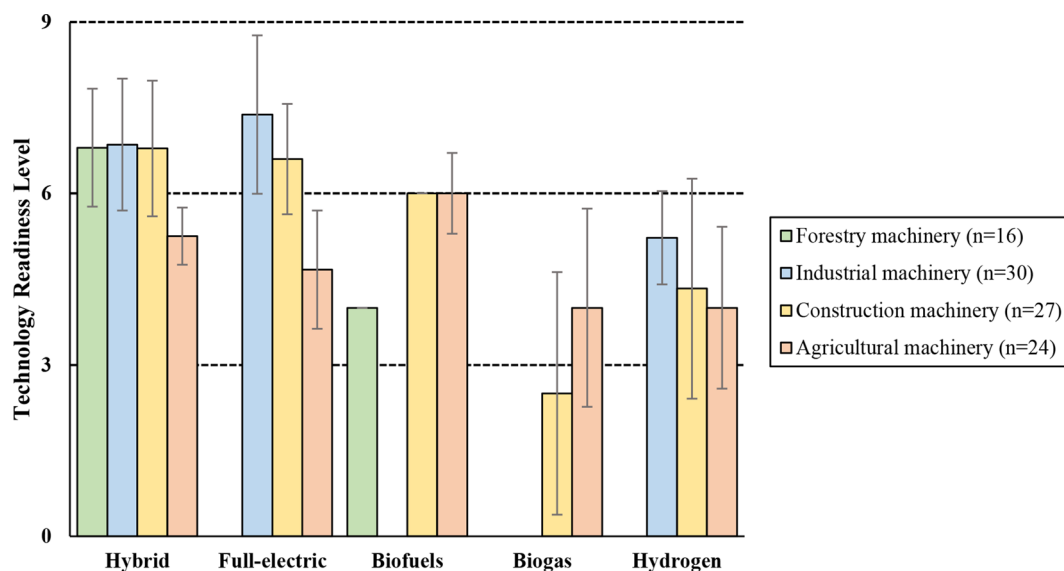
A total of 83 studies were investigated when determining the TRLs of NRMM in this analysis (Table 5). The average TRL in hybrid-powered forest machinery was 6.8, followed by biofuel technology (4.0) (Fig. 5). In industrial machinery, the highest TRL was achieved by full-electric technology with an average TRL of 7.4. However, the TRL of hybrid powertrain was close to full-electric (6.9). Biofuel and biogas technologies have been studied rather little, and consequently we were unable to determine the TRLs. Hydrogen, on the other hand, has been studied more in wheel loaders and forklifts, averaging 5.2 on the TRL scale. In construction machinery, the highest TRLs were achieved with hybrid and full-electric technologies as well (6.6–6.8). The third highest TRL was biofuel technology with an average of 6.0. With biogas and hydrogen, the TRLs of construction machinery were between 1.0 and 5.0. In agricultural machinery, two of the highest TRLs were achieved with biofuels and hybrid solutions (5.3–6.0). The TRL of full-electric agricultural tractors averaged 4.7, while biogas and hydrogen technologies had values of 4.0.

For hybrid solutions, the TRLs of forestry, industrial, and construction machinery averaged 6.8–7.0 (std 1.03–1.19). The TRL of hybrid in agricultural machinery was lower (5.3) with a standard deviation of 0.50. The TRL of full-electric powertrain was 4, but in construction and agricultural machinery TRLs were higher varying between 4.7 and 6.6 (std 0.97–1.03). In industrial machinery, the corresponding TRL was 7.4 (std 1.39), reaching 7. The development of biofuel technology was the highest in agricultural and construction machinery (6.0), while in forestry machinery the corresponding level was 4.0. The highest TRL with biogas solutions was achieved with agricultural machinery (4.0), which was followed by construction machinery (2.5). We were unable to determine the TRL of biofuel and biogas technologies with the industrial machinery. With the hydrogen, the highest TRL was determined to be industrial machinery (5.2) with standard deviation of 0.82, while in construction and agricultural machinery the TRLs were averaging 4.0–4.3 (std 1.41–1.92). Due to the lack of research on full-electric, biogas, and hydrogen powertrains in forest machinery, the assessment of TRLs were excluded from this review (Fig. 5).

### Discussion

#### Data and Methods

In this review, 17 machine types were classified into four machinery segments (Table 3). The classification excluded



**Fig. 5** Average TRLs of forestry, industrial, construction, and agricultural machinery types ( $n=97$ ). The grey lines describe the standard deviation of the TRLs of each powertrain inside the machinery segments

snowmobiles and ATVs, which can be considered as light-weight non-road machines. Furthermore, we excluded feller-bunchers, grinders, and cultivators from this review, because suitable studies with alternative powertrains focused on other machine types in different machinery segments. Thus, this review concentrated on the most common machines that are operated in forestry, construction, industrial, and agricultural environments.

Although the number of studies varied within each segment, we were able to collect valuable information from different machines. For example, with forest machinery, studies included harvesters [30, 54], skidders [26–28], crushers [121], and yarders [69, 70, 120]. Correspondingly, multiple studies included industrial machines, such as wheel loaders [41, 112], cranes [60–62, 88], or a log stacker [85]. Additionally, several studies concentrated on construction machinery, mainly excavators [33, 35], bulldozers [77], and dump trucks [100, 107]. Moreover, for example, Martini et al. [68] and Baker et al. [101] provided information about alternative solutions in agricultural tractors, as well as the potential of alternative powertrains in NRMM in general were also described [93, 109].

Although 64% of the studies originated from Europe, we were able to include global research information from different working conditions. Studies from the past 15 years, particularly during the past 5 years offered the most up-to-date results, which we used to evaluate recent technology development and current challenges (Fig. 1). Although the total number of studies in this review was 115, several studies examined or described more than one alternative powertrain or machine type (cf [33, 41, 45, 48]). This was observed for a total of 20 studies, increasing the number of observations

of different powertrains to 143. However, some of the studies tended to focus on the different aspects of technology evaluation presenting various results. For example, Ge et al. [35], Yu et al. [63], and Radica et al. [132] concentrated on the energy efficiency of NRMM. On the other hand, Pirjola et al. [52], Beligoj et al. [58], and Balcı et al. [128] focused on the emission reduction potential. Moreover, Troncon and Alberti [65] and Lajunen et al. [93] clarified the technology implementation aspects when considering alternative powertrains. Thus, we were unable to involve all the reports in each calculation or assessment.

Assessing the TRLs based on research articles can expose a risk of neglecting the commercial perspective of such rapid technology development. Furthermore, TRL determination through research information can predispose one-sided evaluations, and thus cause deviant results. However, within this review the TRL assessment based on the classification by European Commission [59] was considered a suitable method to highlight the current situation of different technologies in the NRMM fleet. The provided overview specifies successes, challenges, and limitations of each alternative solution, improving the overall knowledge for future development. Therefore, a detailed pathway was combined with the description of TRL levels (Fig. 2). This enabled us to link a single study to a certain technology level, and furthermore form a technology development stage for single machine types or machinery segments.

## Results

The results of this review presented the advantages, disadvantages, and challenges regarding different powertrains. We found that in forestry, industrial, and agricultural machinery segments, these issues are rather similar. For example, with the hybrid solutions, the advantages are lower fuel consumption and emission reduction [24]. The advantages of electrification, on the other hand, include a higher energy efficiency while covering the energy requirement in suitable environment [81]. In industrial machinery, an advantage is also a higher potential to expand the charging network. Nevertheless, usually electrification is achieved with battery technology, which exposes reliability and implementation issues affecting functionality particularly in areas affected by substantially varying weather conditions and low winter temperatures. Moreover, especially in forestry or agricultural operations, the increased weight of the machine can reduce the operating area [82].

The evaluation of feasibility and potential of full-electric powertrains should focus on reliability, costs, and life cycle of batteries [38, 93, 133]. However, the focus has constantly been on lower emissions and reducing fuel consumption [38, 134]. Manufacturing full-electric powertrains is expensive, and the reliability of batteries can be an issue especially in cold conditions. On the other hand, the longer life cycle expectation of an electrified powertrain under a suitable environment indicates requirements for further development with battery technology [48]. Cable powering is one potential option to electrify particularly industrial machinery, as it disables the weight and weather condition challenges. However, cable charging is suitable only for machines that operate stationary or in relatively small area [89]. For instance, in cranes, cable connection is a suitable option to electrify the machines, as those cranes operate within a rather small area [60–62]. Hence, cable charging is limited by the grid connection, and thus cannot be utilized by, for example, forest machinery.

Concerning biofuels, biogas, and hydrogen, we mainly identified lower emissions as an advantage. Moreover, Remmele et al. [134] implies that rapeseed oil and biodiesel are currently the two best biofuel options for NRMM. Hosseini et al. [135] concluded that enriching biofuels with hydrogen will reduce GHG emissions significantly. We also found that hydrogen potentially maintains the same performance compared to diesel engines [68], as well as reducing costs during NRMM life cycle [47]. However, the disadvantages are higher fuel or energy consumption [98], a similar or lower performance in comparison with diesel [54], as well as higher manufacturing and transportation costs [48]. These disadvantages may occur from a lack of knowledge

about biofuels, biogas, and hydrogen, preventing technology generalization.

Although some of the powertrains are so far unknown within certain machinery segments, we were able to determine the emission reduction potential (cf. Figure 4). However, it must be noted that the emission reduction potential can be derived from, for example, fuel consumption by using different coefficients or standards in calculations or by measuring the actual emissions from the machine. Consequently, this causes variation in the results of different studies. Hence, the emission reduction potential assessed in this review illustrates the environmental effects of each powertrain.

A total of six reports clearly expressed the immediate emission reduction potential with the hybrid solution, resulting in an average of 36% [24, 25, 70, 74, 120, 121]. Full-electric and hydrogen powertrains, on the other hand, produce zero local emissions during operations [122, 128, 136], thus the immediate emission reduction potential was determined as 100% for both solutions. However, the emissions generated by the source of the electricity must also be considered when assessing the emission reduction potential of full-electric powertrains during operations. Although nowadays electricity is also produced from fossil-based sources, Helms et al. [137] claims that the share of renewable electricity sources in the energy mix is expected to increase in the future.

During the life cycle of electrified powertrains, we determined that with additional an electric engine alongside diesel or hydraulic hybrid solutions, emissions can be reduced by approximately 36% [27, 33, 78]. With full-electric and hydrogen powertrains, the emissions occur from repair and maintenance work during the life cycle [122], lowering the life cycle emission reduction potential from 100 to 64% with full-electric [33, 89, 123], and to 54% with hydrogen [68, 93, 131]. As Poikela and Ovaskainen [30] mention, the productivity of the electrified machine must be higher than that of conventional diesel-powered machine to also reach the environmental benefits of electrification.

With biofuels, an immediate emission reduction potential of 81% was identified. This was estimated based on four studies (Fig. 4). Notable is the rather large variation from 18% [124] to 71% [116]. However, Simikic et al. [124] studied biodiesel and Ettl et al. [116] tested rapeseed oil in the field with an agricultural tractor. Thus, the results on the emission reduction can be significantly different, although they highlight the emission reduction potential of biofuels in general. As to biogas, Konepörssi [55] stated that biogas-powered tractor lowers PM and CO<sub>2</sub> emissions by 10–99%. Hence, biogas was estimated to have a significant positive effect when considering the life cycle emissions of the machine. Konepörssi [55], Wisell et al. [81], and Baker et

al. [101] reported that the total emission reduction during the life cycle can be approximately 66%, varying from 40 to 80% (Fig. 4). This underlines the importance of further research of biogas as a fuel.

In agricultural machinery, renewable fuels are considered to have higher potential to replace diesel engines than in, for example, forestry machinery due to larger possibilities for local biofuel production. Thus, the hybrid solution was the alternative with the most potential compared to diesel in forestry machinery. Due to the extensive charging network and small operating area, hybrid and full-electric powertrains reach the highest TRL in industrial machinery. However, in an industrial environment, cable charging must be mentioned due to its capability to control and stabilize the power. In construction machinery, alongside hybrid and full-electric powertrains, hydrogen was investigated more comprehensively, increasing the TRL.

A decade ago, electrified NRMM were estimated to become more common [138]. Recently published research by Kalociński [139] forecasted that NRMM hybridization is expected to be rapid, and the share of hybrid-powered machines may increase significantly. A key element in electric NRMM generalization is the availability of electric components [140], as well as the high manufacturing costs and the lack of recharging or storing possibilities [48]. To solve these challenges in electrification, new cooperation and more extensive charging infrastructure are required when promoting NRMM electrification [93]. This requires compact implementation without an increase of the total weight, as well as reliable battery technology [33, 84]. These highlight the current obstacles in generalizing electric NRMM. To overcome these obstacles, more research in various operational environments is required especially in forestry, construction, and agricultural environments.

To generalize renewable fuels in NRMM, the production should be wider [95]. This is also the reason why the development of biofuels is more advanced in agricultural machinery than others; the availability of the fuel is better when moving towards the countryside. The low production challenge also occurs with hydrogen, in addition to high costs [48]. This can be noted in practice; machine testing with hydrogen powertrain has focused on smaller NRMM (i.e., forklifts) [45, 47]. The reason is that powering heavy NRMM by hydrogen is expensive, and the lack of knowledge considering such technology maintains prudence regarding investments. However, in general, renewable fuels have major potential to become a common powertrain in NRMM operations.

## Prospects for Alternative Powertrains

In conclusion, combining the previous findings with the results of this review, each alternative powertrain produced less emissions compared to diesel-powered machines. Thus, there are justified reasons to increasingly focus further research on the implementation and availability of alternative technologies and fuels. Moreover, there is still time to properly investigate alternative solutions, because the new regulations will ignore the fuels used in agricultural or forestry machinery due to the limited charging infrastructure [9].

As for NRMM electrification, the focus of future research should be especially on the battery implementation and reliability. More specifically, forthcoming research should cover new solutions to manufacture compact and energy-efficient batteries, as well as ensuring the functionality during operations. This is because extending the charging network in forestry or the agricultural environment is challenging, making battery technology necessary under those operational environments. Although battery technology has been studied in the past years, reliability issues under extreme conditions still arise [33, 84]. Thus, making the batteries more feasible in various conditions would improve the generalization of the electric NRMM fleet.

In addition, the concept of biofuel and biogas technologies exist, but the current challenges include a low production and the availability of the fuel [57, 95]. Hence, this limitation affects especially forestry and agricultural machinery due to the more dispersed operation area compared to industrial machinery. Thus, further research should concentrate on biofuel and biogas production, which is followed by technology implementation. For hydrogen, upcoming research should focus on improving the profitability of the manufacturing and distribution processes. Additionally, new solutions for reducing the technology costs would accelerate the generalization significantly [136]. After this, the willingness for implementing hydrogen technology into NRMM would be greater and thus, the technology development would take a further step.

## Conclusions

This review provided insights into the development of alternative powertrains by identifying and describing their potential. The results emphasized that, currently, there are various powertrains considered in NRMM operations and with specific advantages albeit challenges. Furthermore, this review evaluated the current technology development stages, indicating the future prevalence of different powertrains. The results of this review indicate that the

electrification of NRMM has the greatest potential for solving global challenges associated with produced emissions while maintaining the performance. Despite the considerably low development level, renewable fuels are undergoing continuous development and are estimated to become more general in the future.

Developing alternative powertrains to achieve the globally set emission reduction objectives can eventually replace diesel engines, if the profitability of manufacturing, implementation, and reliability are improved. While this is still a work in progress, major improvements can be observed. Especially NRMM electrification has faced major interest in the industrial environment, aiming to derive the positive effects of low-emission and energy-efficient operations in forestry and agricultural machinery. Furthermore, we determined that utilizing renewable fuels can lead to more sustainable NRMM operations due to their ability to reduce emissions globally. Moreover, we found that renewable fuels result in a similar performance for NRMM. Additionally, this review corresponds to the development in the transportation sector, where similar challenges regarding sustainability emerge. Hence, based on this review, future research should focus on the improvement of the implementation of alternative technologies as well as the improvement of the manufacturing infrastructure in NRMM operations.

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## Declarations

**Human and Animal Rights and Informed Consent** This article contains no studies including human or animal subjects performed by any of the authors.

**Competing Interests** The authors declare no competing interests.

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