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Electric and hybrid electric non-road mobile machinery – present situation and future trends

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Abstract

Electrification of non-road mobile machinery (NRMM) is a growing trend. This paper highlights the potential of electric and hybrid powertrains in different NRMM sectors and elaborates the factors that may hinder the development. The NRMM sectors, the vehicle types, their operation and duty cycles and market shares are described. Comparison between the typical duty cycles and operation of on-road and off-road vehicles is performed in order to gain insight into the specific features of off-road vehicles. The development of NRMM is subject to various drivers that range from customer needs to fuel and energy prices and rules and legislation. The main results of our study are 1) a review of the present status and analysis of the future trends and potential of electrification and hybridization of NRMM and, 2) propositions for overcoming the challenges that are related to the electrification and hybridization of NRMM.

Keywords: hybrid powertrain; electric powertrain; non-road mobile machinery; hybridization; emissions

1 Introduction

The term non-road mobile machinery (NRMM) encompasses various vehicles from gardening equipment to large mining vehicles. A common factor for all of these vehicles is that they are intended for intensive, often professional use to carry out a specific task or working phase in a specific environment. They are typically operated for several hours per day and an eight-hour work shift is a standard. In some special environments, such as in mines and harbours, the work shifts can be considerable longer, even up to 24 hours per day. Due to their vast amount and intensive use, the impact of NRMM on the worldwide fuel consumption and emissions is remarkable.

NRMM are designed for a certain purpose, i.e. for instance, for moving material. Maximising the work process performance and its efficiency in terms of, e.g. moved material, is usually the main objective and design choices are dictated by this objective. The energy efficiency of the vehicle has not traditionally been that high on the agenda. The increasing fuel and energy costs and particularly, the tightening emission regulations are shaping the landscape for NRMM, too, and stressing the importance of the energy efficiency in all operations. Electrification and hybridization of the vehicle powertrains are considered to be among the most promising means for reducing the energy consumption and local emissions. Application of electric and hybrid technologies also enables improving the vehicle performance in terms of e.g. controllability and operator comfort and provides freedom in the design of the vehicle layout and structure.

Rather many works address the electrification and hybridization of non-road mobile machinery. A special attention has been given, particularly, for the assessment of different topologies and their techno-economic feasibility to mobile machines. Applicability of different hybrid powertrain and energy storage solutions to an underground mining loader was evaluated in [1]. The feasibility of fuel cells with different energy storage systems was analysed in [2]. The fuel efficiency improvements by hybridization of construction equipment were assessed in [3] and a detailed energy efficiency analysis of a hybrid mining loader was carried out in [4]. The research presented in [5] discusses the fuel economy of a series-parallel hybrid electric powertrain in wheel loaders. The mining loaders are interesting targets for electrification because of the challenges that are connected with the use of diesel engines in underground mines. Not only could the electric loaders improve energy efficiency [6], but reduce exhaust and heat emission in mines. Due to the reduced need for ventilation, the cost benefits are estimated to be significant [7]. The fuel cell hybrid systems are also suitable for underground mining vehicles. Their advantage is low heat production, higher energy efficiency than diesel hybrids, and zero emissions in operation [8]. In very high power machine applications, such as heavy duty gantry cranes and mining equipment, supercapacitors are being used for peak load shaving and short term energy buffering e.g. [9] and [10]. The use of internal combustion engines is problematic in indoor or partially indoor applications, such as in pallet transportation in warehouses due to the exhaust gases. Hence it is not a big surprise that forklifts and automatically guided vehicles (AGV) comprise a fair share of the existing battery powered mobile machinery [11]. These machines usually have a traditional lead-acid battery and the limited energy capacity is quite often solved with changeable battery packs. Recently, the utilisation of fuel cell systems has been increasing in indoor forklifts because they do not produce any local emissions and enable continuous use of the machine [12].

This work presents the status of non-road mobile machinery, their application, operation and market and evaluate the development trends, particularly regarding the electrification and hybridization. The presented research is a continuation for the previous work of the authors [13] updated with the recent developments in the field NRMM. The key features of NRMM are summarised in section 2 while sections 3 and 4, concentrate on the electrification and hybridization: the basic principles, architectures and drivers. The section 5 discusses the present technological solutions that are applied in NRMM. Finally, conclusions about the possible future scenarios are summarized.

2 Introduction to non-road mobile machinery

2.1 Applications

NRMM include mainly wheeled or tracked machines that are targeted at specific tasks in off-road conditions. NRMM are typically divided into different categories by their application. The most common machinery types are construction machines or earth-moving machines. Following classification is often used:

- Construction or earth-moving machines: all kinds of loaders, dumpers, excavators, land rollers, bulldozers, etc.
- Transportation of goods or material handling equipment: forklifts, AGVs, mobile cranes, Rubber Tired Gantry (RTG) cranes, straddle carriers, etc.
- Municipal or property maintenance machines: different types of gardening and cleaning machines often targeted also at on-road operations.
- Tractors and agricultural machines: forest machines (forwarders, harvesters, etc.), combine harvesters, field choppers, self-propelled manure spreader, etc.

There is obviously some overlapping between the machine categories. Agricultural tractors are used a lot in property maintenance and, e.g., some loaders are used both in property maintenance and construction. However, it seems that today's trend is specialization and tailoring. Machines are more and more designed for a relatively niche application and consequently, they are becoming increasingly diverse. If the areas of application are broad, so are the differences in the power ratings. The maximum power rating of small loaders and utility vehicles starts from 10 kW while gigantic dumpers have total installed power up to 3 MW. Figure 1 shows typical earth-moving and transportation machines.

Vehicles can be categorised based on their work tasks, too. The work tasks of NRMM vary considerably but in general, three main task types can be distinguished: transportation, manipulation and continuous high power tasks. Transportation tasks include acceleration and deceleration transients and nearly constant load transportation operation. The loading of transported material – either bulk or parcelled – is commonly carried out by the machine itself with an on-board manipulator. The duration, power demand and energy consumption of the manipulative operation is dependent on the machinery and its contribution to the total energy consumption can be significant.

Figure 1: Earth-moving and transportation machines (left to right): Amman Yanmar small dumper C30R-1 (http://us.yanmar.com), Sandvik TH320 underground truck (http://mediabase.sandvik.com), Caterpillar forklift GC20-33N (http://www.rocla.com), Kalmar DRF Reach Stacker (http://www.kalmarind.com).

Non-manipulative transportation machines are typically different kinds of dumpers – often being similar to the standard road trucks. These machines are loaded by another machine and unloading is done by dumping the whole load. Parcel transportation machines and their manipulators are designed based on the parcel. The most typical examples of parcel transportation machines are forklifts, AGVs and container handling machines.

2.2 Market overview

It is rather difficult to get accurate and comprehensive fleet or market information for the different NRMM categories. The market values that are presented here are gathered from several sources. Construction machines/earth moving machines are the largest single group among NRMM and agricultural machines are the second largest group. The worldwide size of the construction machine market (sold new machines) was estimated to exceed 150 BUSD (10^9 US Dollars) in 2014 [14], and it has been forecasted to be a 166 BUSD industry by 2020 [15]. An important growth is expected to happen in Asia Pacific markets as can be seen from Figure 2 that presents the forecasted construction equipment market by 2020 [14]. The agricultural machine market was 93 BUSD industry in 2008, 149 BUSD in 2014, and it is expected to grow over 200 BUSD by 2018 [16].

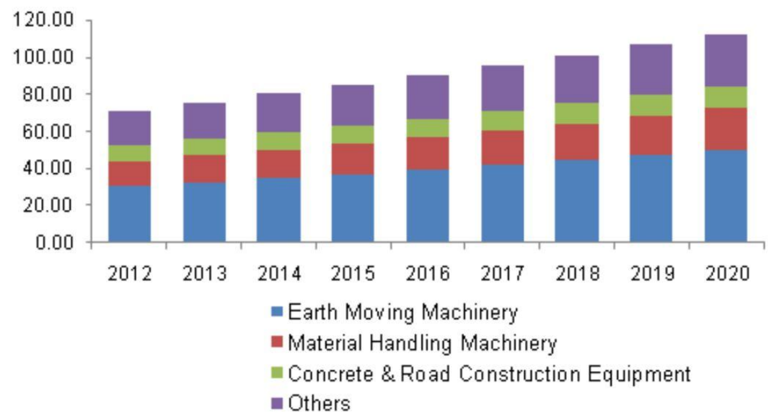

Figure 2: Asia Pacific construction equipment market, by product, 2012-2020, (USD Billion) [14].

2.3 Fuel consumption and emissions

Statistics give an insight into the importance of the fuel consumption among the non-road mobile machinery. A study by European Union [17] indicates that the brake specific fuel consumption (BSFC) of a typical work machine diesel engine is on average 250–300 g/kWh. These values sound quite high as the current advanced diesel engines can have the lowest peak of BSFC under 200 g/kWh. However, the high BSFC values that are given in [17] can be explained by the long lifetime of certain NRMM; some very old and small uncontrolled engines are still in use the BSFC of which can be greater than 300 g/kWh. Accurate evaluation of the fuel consumption of NRMM is challenging due to the lack of general official statistics. However, the rough figures that are shown here underline that there is a tremendous potential to increase the fuel efficiency of the NRMM. Figure 3 presents the Greenhouse gas (GHG) emission shares for NRMM in EU-27 countries. The construction and industry produce a major share of the GHG emissions. The share of the generator sets is also significant. According to [17], the annual GHG emissions from NRMM were around 100 million tons in the European Union countries (EU-27) in 2008.

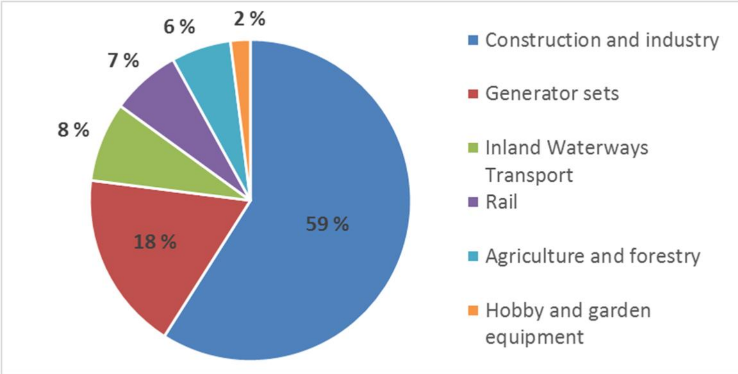

Figure 3: GHG emission shares for NRMM in EU-27 countries [17].

2.4 Machine operation and duty cycles

The duty cycle is the basis for the dimensioning and designing of any vehicle. However, when a hybrid or fully electric machine is developed, the understanding of the duty cycle is particularly important to ensure a proper dimensioning of the system components. Overdimensioning of the key components such as energy storages quickly ruins the economics of otherwise feasible solution.

The potential benefits of a hybrid or electric powertrain are strongly dependent on the duty cycle. There are different types of reference driving cycles for on-road vehicles that can be used for the characterisation of fuel consumption and emissions. The reference driving cycles represent typical operating conditions of a vehicle in some particular area. Duty cycles of non-road mobile machinery differ considerably from an application to another. Some of the duty cycles resemble those of on-road vehicles when others – as the duty cycle of a long haul dumper (LHD) in Figure 4 – have repetitions of exactly the same and very predictable operating pattern for a long time [4]. Another example of a NRMM duty cycle is given in Figure 5 that shows the total power consumption/regeneration of a straddle carrier as a function of time. As can be seen from Figure 5, there is no clear single operation pattern and the total power ranges from -120 kW to 225 kW.

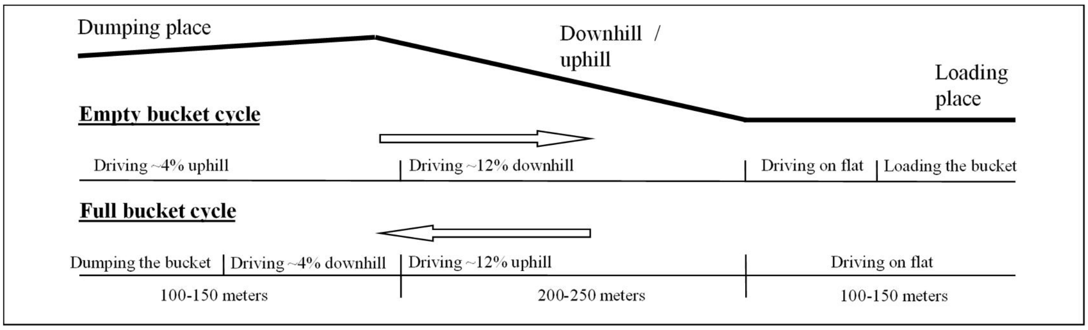

Figure 4: Load-Haul-Dump (LHD) cycle of an underground mining machine.

From the viewpoint of electrification and hybridization, there are operation sequences in both of the presented duty cycles that set hard requirements for the energy storages. When the bucket of the LHD machine is empty, the vehicle is driven downhill to the loading place. The braking power and duration of this transit are considerable. Capturing all the energy that is generated during the transit necessitates a good charging and storing capacity from the energy storage. The uphill drive with a full bucket sets its own requirements for the capacity of the energy storage, too.

The duty cycle of the straddle carrier is a representative example of a power intensive operation. The power demand or available regenerative power fluctuates rapidly. The average power is low in comparison with the highest peak power demands. Such a duty cycle necessitates high power charging and discharging capability from the energy storage. Supercapacitors are usually a natural choice for power intensive operation, i.e. for coping with short-term power needs.

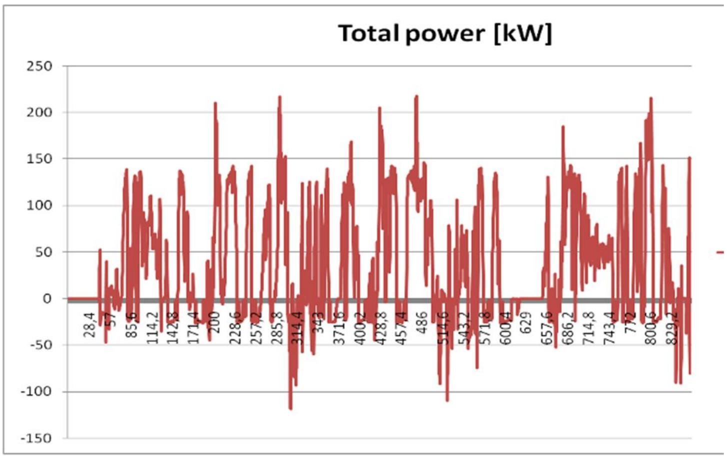

Figure 5: Part of a duty cycle of a straddle carrier.

Operation of a forest harvester presents an extreme example of a duty cycle with frequent but short peak power demands. While cutting and lopping a trunk, a couple of 50 kW hydraulic motors are used sequentially with high frequency. The power varies between 20 and 140 kW, while the peak time is between 1 and 2 seconds and the idle time between the peaks is 0.5–2 seconds. A forest harvester thus performs up to several million peak power sequences during its lifetime. As the average power of the machine is significantly lower than its peak power demand, the overall system energy efficiency could be improved through hybridization. Very recently, a Finnish based company, Logset, announced their powerful hybrid harvester [18].

The duty cycle of construction machines often involves idle periods when the machine is just standing still and waiting for a new task. These idle periods are problematic because the engine has to be kept running to be ready for a quick start and to power all the necessary auxiliary devices. Elimination of the need for these idle periods would yield considerable savings in energy consumption and decrease in emission. These improvements could be achieved though hybridization of the vehicle powertrain.

3 Trends towards hybridization

Average power demand of a non-road mobile machine is often considerably lower than its peak power demand. Hybridization of a vehicle powertrain enables the downsizing of the internal combustion engine and utilization of an on-board energy storage and electric machine drive for responding to peak power demand and exploiting regenerative braking energy. The main objectives in the hybridization of the powertrain are the improvement of the system energy and fuel efficiency and reduction of the emissions. The different aspects of hybridization of NRMM are discussed next.

3.1 Principles of hybridization

Non-road mobile machines do not have any common duty cycles. Instead, their duty cycles are various and dependent on the application and the involved transit and work task operation. One of the main differences between heavy duty on-road vehicles and NRMM is the operation environment. Unlike on-road vehicles NRMMs are in most cases working in a restricted area (e.g. a mine or harbour). As a result, such enablers of electrification and hybridization as high power charging, special fuels or even battery swapping can be organized in a more cost-efficient manner than in on-road conditions. Table 1 presents a comparison between three different vehicular applications in terms of their technical and operation characteristics. The operation of heavy duty on-road vehicles and medium to high power NRMM is highly energy intensive because these vehicles usually have a lot of weight and they need a high peak power/torque to carry out their duty cycle.

The global energy consumption of a vehicle can be divided into three main conversions [19]:

1. the primary energy conversion to fuel for vehicle (well-to-tank),
2. the on-board energy conversion for propulsion (tank-to-wheels) and
3. the propulsion energy conversion to distance travelled (wheels-to-kilometres)

Table 1: Comparison between passenger vehicles, heavy duty on-road vehicles and non-road mobile machinery.

	Passenger vehicle	Heavy duty on-road vehicle	Non-road mobile machinery	Remarks
Operating hours	~250 h/a	5000 h/a	**5000 h/a**	
Power range	30–150 kW	100–400 kW	**10 kW–3 MW**	
Average operating power	20% of max.	40% of max.	**40–80% of max.**	Depends on application and operation
Cycle	City / Highway	City / Highway	**Application specific**	
Speed	0–200 km/h	0–100 km/h	**0–40 km/h**	Many machines do not exceed 20 km/h
Max traction force / max traction force at max speed	5	20	**10–30**	
Manufacturing series	High volume	Medium volume	**Small series (10–1000 / year)**	Agricultural tractors: tens of thousands/year
Power transmission	Mechanical	Mechanical	**Mechanical, hydrostatic, hydrodynamic, electric**	
Energy regeneration	Efficient in city cycle	Efficient in city cycle	**Depending on the application**	
Practical lifetime	~10 years	~8–10 years	**5–20 years**	High variation, depends on the application
Customer willing to pay for green image	Yes	Not really	**Very limited**	

Propulsion is not the only operation that consumes energy in mobile machines. Instead, a certain share of the total energy is consumed during the work task, too. For this reason, in parallel with the second conversion, there is an energy conversion to work done (tank-to-work). This is a very important factor in the operation of NRMM because carrying out the work task can comprise a major part of the total energy consumption of a machine. Efficiency of the second energy conversion (tank-to-wheels and tank-to-work) can be improved through hybridization and, in some cases hybridization also allows improving the efficiency of the first energy conversion. The latter is possible if the operation conditions of the vehicle differ from typical atmospheric conditions. This is the case e.g. with the construction machines that are operated in underground mines where efficient ventilation is needed for running the diesel engines and keeping the air clear enough. The diesel engine run time and related exhaust and heat emissions can be decreased through hybridization and as a result the ventilation power and costs reduced [8].

3.2 Hybrid powertrain architectures

Figure 6 presents the most common automotive hybrid electric powertrain architectures [20, 21] – series, parallel and power split architecture – that all can be used with NRMMs, too. Hybridization can be done in respect of energy sources or powertrain. The first, i.e. the hybridization of the energy sources, refers to series hybrids and the latter to parallel hybrids. The combination of these two is called a series-parallel hybrid (power split), and all the other more advanced hybrid powertrain topologies are called complex hybrids. Fuel cell hybrid powertrain has basically always a series configuration because both of the power sources produce electric power. Differently from the automotive hybrid electric powertrain topologies that are presented in Figure 6, the non-road mobile machines are typically equipped with four-, six- or eight-wheel drives and locks. Two-wheel drives are rarely sufficient for carrying out the demanding duty cycles of non-road mobile machines.

The series hybrid topology is a feasible choice for many mobile machines. It is flexible in terms of placement of the components and there is no mechanical coupling between the traction electric machine and internal combustion engine. Conversion of a diesel-electric powertrain into a series hybrid is, in principle, rather straightforward; only one new key component should be introduced, i.e. the energy storage and associated management and control systems. Most of the existing hybrid mobile machines are based on the series topology.

The parallel hybrid topology is relevant in smaller machines and particularly in such machines that employ a hydrostatic transmission and operate under heavy transient loading conditions. The power split topology is the least attractive to NRMMs because it is rather complicated to design on the part of its mechanical transmission. However, it could be feasible in agricultural tractors. Tractors are frequently operated in continuous high power traction mode. Mechanical transmission has been and still is the most feasible solution for efficient driving under such loading conditions. Additionally, the high manufacturing volumes of tractors make it possible to use more tailored powertrain solutions.

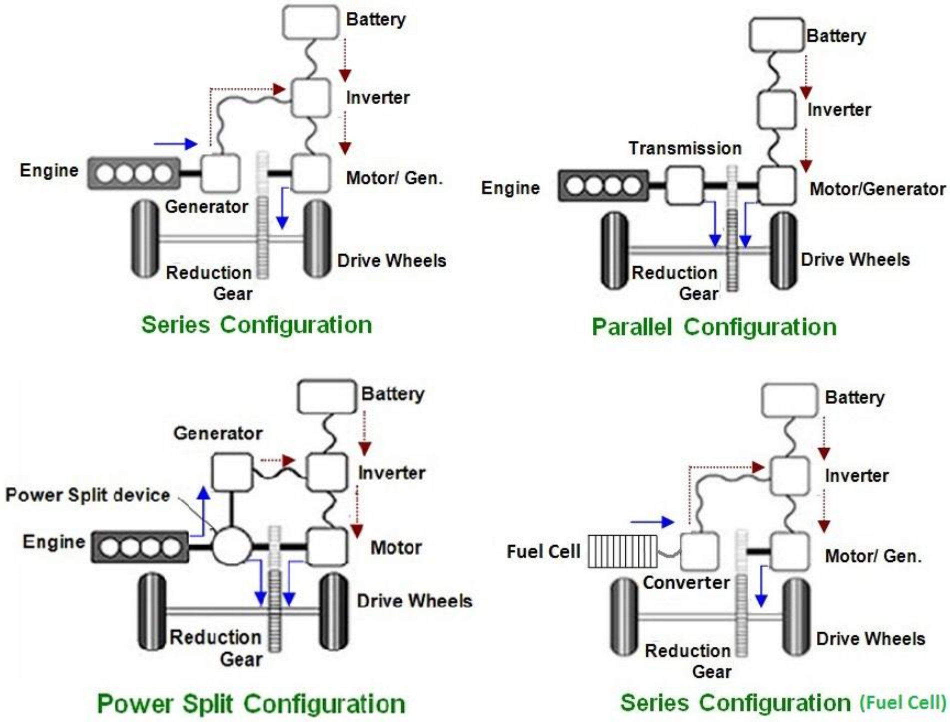

Figure 6: Most common hybrid powertrain topologies.

3.3 Main power sources

The main power sources of hybrid and electric mobile machines can be divided into three categories: 1) internal combustion engines, 2) electrical energy storage (battery or ultracapacitors) and 3) fuel cells. The internal combustion engine includes diesel, gasoline and gas engines. Gas engines are applicable in series hybrids if the machine duty cycle is not heavily transient. Hybridization of the powertrain enables the downscaling of the internal combustion engine and all the engine types can be combined with batteries or supercapacitors. Different principles can be applied to the dimensioning of the electrochemical on-board energy storage and charging of the vehicle from electric grid can be considered, too. Modern lithium based batteries and supercapacitors are developed enough for the use in electrification and hybridization of NRMM and can meet their power and energy capacity requirements [22].

Plug-in vehicles refer to fully electric and rechargeable hybrid vehicles that are either driven by wire or charged from electric grid. Feasibility of pure battery operation depends naturally on the requirements concerning the power rating and storage capacity of the on-board energy storage. In the third option, a fuel cell is used as a primary power source and battery as a secondary. Fuel cell hybrid systems have potential to increase the energy efficiency of non-road mobile machinery. The technology is mature enough but the downside is that the manufacturing costs of fuel cells are still on a quite high level. In short and medium term, it is expected that fuel cell hybrid systems will be adopted in limited, special applications in which the advantages of the fuel cell technology can be exploited in favour of cost-effectiveness [2, 8].

4 Drivers for hybridization and electrification

The drivers towards hybridization and electrification are partly the same for NRMM and for the car industry [23]. The main drivers are associated with better productivity. A hybrid or electric powertrain can improve the energy efficiency and performance of the machinery especially from the control point of view but any significant increase in the production capacity is difficult to realize. In practice, the fuel consumption of an electric or hybrid machine can be approximately 10–50% lower than that of a traditional diesel-mechanical or diesel-hydraulic machine. From the technological and engineering points of view, the hybrid or electric powertrain can offer also the following benefits: 1) continuously variable transmission and actuator control, 2) reduced need for maintenance and 3) flexibility in the mechanical placement of the system components.

The productivity demands can obviously be answered by electrification and hybridization and for some duty cycles the decrease in the fuel consumption can be as large as 50% in comparison with conventional solutions. The challenge with the electric and hybrid machines is that with the current component prices, they are more expensive than traditional diesel-mechanical or diesel-hydraulic machines. Whether the fuel savings that are attained justify the purchase of a more expensive machine depends on the prevailing fuel prices. Green image that is important in consumer market is a plus in the NRMM market, too, but only very few customers – mainly in the municipal machine area – are willing to pay extra from the image. In some niche areas, such as military, additional features (power for electric weapons, silent drive/watch, fuel logistics, and power station function) that are attainable through electrification may also justify higher pricing.

The economic viability of a more electric machine is strongly driven by its operation costs and the business case is usually made through the total cost of ownership. The operation costs include the fuel costs, also electricity for plug-in vehicles, maintenance and e.g. salaries of the operators. The fuel costs are quite significant and it was customary, not very long time ago, to justify the business case of electrification and hybridization by the fuel prices. The present situation, however, is that crude oil and fuel prices have been decreasing for the last couple of years. Although there are other drivers, too, the recent development has had a clear impact on the companies' motivation to advance hybrid and electric solutions. While it is difficult to forecast exactly how the oil price will develop in the future, it can be expected that it will start to increase at some point. Having said that it is also expected that there will probably be a lot of volatility in the oil prices in the future, too.

Other important drivers for electrification and hybridization are the demands and policies to reduce the emissions and related regulations and standards. The emission standards concerning off-road diesel engines and NRMM have been tightening remarkably and this development is going to continue. The current, Stage III/IV, and future, Stage V, European Union (EU) limits for the emissions of variable-speed diesel engines of NRMM according to [24] are tabulated in Table 2. The emission limits of the US EPA Tier regulations go in line with the EU limits. The major change in the proposed emission limits of Stage V is the widening of the scope of regulated engines. Stage V includes also engines in power ranges below 19 kW and above 560 kW. The Stage V requirements are strict and in many cases meeting those necessitates utilisation of particle filters. The change from Stage III/IV to Stage V is not cosmetic and it is estimated that fulling the upcoming regulations involves rather extensive development of the exhaust emission treatment technology. The emission regulations and their tightening trend may, on the other hand, make the hybrid and electric technologies more attractive than ever before and push the machinery manufacturers towards the development of alternative electric powertrain systems.

Table 2: European emission limits for CI engines of NRMM (g/kWh). [24]

	Stage III/IV				**Stage V**			
Power range (kW)	CO	HC	NOx	PM mass	CO	HC	NOx	PM mass
0 < P < 8	No limits				8.0	(HC+NOx ≤ 7.5)		0.4
8 ≤ P < 19	No limits				6.6	(HC+NOx ≤ 7.5)		0.4
19 ≤ P < 37	5.5	(HC+NOx ≤ 7.5)		0.6	5.0	(HC+NOx ≤ 4.7)		0.015
37 ≤ P < 56	5.0	(HC+NOx ≤ 7.5)		0.025	5.0	(HC+NOx ≤ 4.7)		0.015
56 ≤ P < 130	5.0	0.19	0.4	0.025	5.0	0.19	0.4	0.015
130 ≤ P <560	3.5	0.19	0.4	0.025	3.5	0.19	0.4	0.015
P > 560	No limits				3.5	0.19	3.5	0.045

5 Technical solutions of present non-road mobile machinery

Present non-road mobile machines are most commonly powered by energy efficient diesel engines. The power is transmitted to the wheels or auxiliary devices hydraulically, mechanically or electrically. A hydraulic power transmission is currently the de-facto solution in all high force/torque manipulators such as buckets and booms. The reason for this is that there is no better technology available for such application at the moment. In small sized and/or slowly moving (<20 km/h) machines the hydrostatic transmission is also quite often used for traction purposes. The hydraulic transmission provides built-in continuous variable speed transmission and high torque capability. Mechanical transmissions are favoured at higher speeds when it outperforms the hydraulic transmission in efficiency. Mechanical transmission can be realized with a traditional manual clutch and gear box combination. Today, however, most of the machines have a combination of a mechanical gear box and a hydro dynamic torque converter or continuously variable transmission based either on a variator or a variable speed planetary gear controlled by a hydrostatic actuator.

Most of the NRMM that have an electric powertrain are from the smallest and biggest machine classes. Pure battery operation is technically and commercially feasible in low power machines (total power less than 10 kW). The low power battery operated or fully electric machines have a particularly viable market in applications where the environment requires zero emissions and/or low noise level. Indoor forklifts, both human operated and AGVs comprise the largest share of low power battery operated vehicles. Small utility vehicles that are applied to property maintenance and gardening services are also available as battery powered versions. Examples of battery powered vehicles are shown in Figure 7.

Figure 7: Commercial battery powered vehicles, AGV by Rocla (http://www.rocla.com), Electric utility vehicle Gator TE by JohnDeere (http://www.deere.com) and Polaris Ranger EV by Polaris (http://www.polaris.com).

In the mid-power class from 50 to 200 kW, the number of commercial hybrid and electric vehicles is small but when the power increases, increases also the attractiveness of the electric powertrain. The biggest machines are usually driven electrically. Rail machines such as different types of cranes are naturally electric due to the availability of a power supply by cable or trolley but also freely navigating machines such as gigantic dump trucks, straddle carriers and even LHDs are often electrically driven. Big size and high power provides a very good starting point for diesel-electric powertrain. First of all, the energy efficiency is more crucial at high power levels. Moreover, particularly in the megawatt-class, the control of an electric powertrain is much easier than the control of a diesel mechanical system. In (mechanically) big machines there is also more space available for the needed equipment. Traditional power transmission systems do not basically exist in the megawatt range. Figure 8 presents heavy duty machines that are typically equipped with an electric powertrain.

The three machines shown in Figure 8 give a good overview on how different the machines and the motivation for the electrification can be. LHD is supplied by a tether cable. The main motivation for the electrification is zero emission operation which in turn decreases the need of ventilation in underground mines. The use of diesel engines in underground mines necessitates efficient ventilation for maintaining sufficient oxygen level and removing any emissions [7].

Figure 8: Commercial high power, electric driven work machines: Liebherr T282B Dump Truck 2.7 MW(http://www.liebherr.com), Kalmar ESW Straddle Carrier 400 kW (http://www.klamarind.com), and Sandvik long haul dump Toro 2500E 315 kW (http://mediabase.sandvik.com).

In certain mines electric drive-by-wire machines are seen as a cost-efficient alternative despite their limited driving distance and short MTBF (Mean Time Between Failure) of the cable. These cable supplied LHD machines are available in same size/power as the diesel powered models. Dump trucks and straddle carriers are both often diesel-electric. The diesel-electric system saves fuel and reduces emission as the diesel engine can be operated at constant speed and in an optimal operation point. The better controllability, possibility to use a trolley supply and electric braking with regeneration are also important benefits of a diesel-electric powertrain.

Some of the most recent hybrid non-road mobile machines at the market are shown in Figure 9. The hybrid reach stacker of Konecranes that was introduced in 2014 is shown on the left hand side. KESLA hybrid wood chipper is in the middle of the figure, and Logset 12H GTE Hybrid forest harvester on the right hand side. The wood chipper was announced in 2014, and the hybrid harvester in 2016.

Figure 9: Commercial high power, hybrid mobile machines: Konecranes SMV 4531 TB5 HLT hybrid reach stacker (http://www.konecranes.com), KESLA C860 Hybrid wood chipper (http://www.kesla.com), and Logset 12H GTE Hybrid forest harvester (http://www.logset.com).

6 Discussion and conclusions

Electric powertrains have been used in mobile machinery for a long time. However, most of the machines are still based on traditional diesel-mechanical or diesel-hydraulic transmission. The energy efficiency of NRMMs could be improved with electric and hybrid electric solutions. An electric powertrain would generate other benefits such as lower maintenance costs and better controllability and drivability, too.

Due to the intensive and professional use of mobile machinery, the improved energy efficiency would result in a remarkable reduction in the greenhouse gas and other pollutant emissions. The bottlenecks for rapid electrification are partly the same as in the automotive industry. Most pronounced bottleneck is the lack of commercial electric components for mobile machinery and the consequent, significantly higher price of an electric or hybrid powertrain. The focus should be on the development of all the key components, i.e. energy storages, power electronics and electric drives and motors. The market will become attractive to the component manufacturers as soon as there is enough proof for economical sustainability of hybrid and electric powertrains in NRMM. However, there are already application areas such as property maintenance and underground applications where the customer is willing to pay more for the lower emissions rather than of the better fuel efficiency. The reason for this is that in these specific applications polluting is more costly (or even prohibited) than the fuel costs itself. Volatile fuel prices, tightening emission regulations and decreasing price of electric components will speed up the development and market entry and share of different kinds of electric and hybrid electric mobile machinery.

Big technological changes always take time and in the very conventional fields they also face resistance. The recent signs from the market show that hybridization and electrification are gaining more attention after a couple of quiet years; Konecranes introduced their hybrid reach stacker in 2013 and Kalmar a hybrid straddle and shuttle carriers during the same year. Kalmar is planning to enter the market with a fully electric FastCharge carrier during 2016.

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