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Review

Overview of Powertrain Electrification and Future Scenarios for Non-Road Mobile Machinery

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Abstract: Powertrain electrification continues to be a growing trend in vehicular applications. Electric powertrains have numerous advantages over traditional mechanical and hydraulic powertrains but there are still important challenges to overcome for long-term commercial success. This research presents a technological assessment of present and future developments of powertrain electrification in non-road mobile machinery (NRMM). The challenges and opportunities of NRMM electrification are described in detail. The trends and drivers related to technological development such as regulations, policies and market development are analyzed, and technology enablers are highlighted. Future scenarios are formulated based on the prevailing trends and drivers, development of key components, scientific literature and status of the non-road mobile machinery industry. Some recommendations are also given in relation to the development of hybrid and electric powertrains for NRMM. The key findings of this research indicate that the electrification of NRMM is slowly started and the progress is demonstrated by hybridization of some specific, successful mobile machines. In short-term, high component and technology development costs remain the main barrier for higher adoption of electric and hybrid powertrains. In the long-term scenario, many NRMM can operate autonomously and powertrain electrification has become mainstream technology.

Keywords: powertrain electrification; non-road mobile machinery; hybrid powertrain; technology assessment; future forecasting

1. Introduction

Electricity has been used as an energy carrier in vehicular applications since the invention of the automobile. Through history, electric powertrains have been developed for vehicles and mobile machines but their breakthrough on a larger scale has just started to happen. Despite the benefits of electric powertrains, electrification has been slower than expected due to various technological factors, market drivers and policies. Successful developments in power electronics and especially in lithium-based battery technology have overcome most of the technical challenges [1]. Nowadays, electric powertrains provide at least as good performance as conventional powertrains, and they are inherently more energy efficient and emission free in their operation [2]. In this context, powertrain electrification refers to the use of electric power to operate a mobile machine with or without an electrical energy storage. Therefore, it covers full electric, diesel-electric and hybrid powertrains.

In some machine applications, usually in heavy-duty machines, an electric powertrain is the only suitable option due to the high torque demand at wheels and controllability requirements. Powertrain electrification is considered as relevant and competitive option to replace hydrostatic and hydrodynamic powertrains to increase energy efficiency [3]. In mobile machines, electric systems could also improve the maneuverability and increase the control accuracy [4]. For the time being, electric powertrains have not yet been adopted on a large scale in mobile machinery but the recent technological developments strongly indicate that many typical machines can benefit from the use of electricity as traction power and electrification of auxiliary systems [5,6]. There is a worldwide understanding that air pollutant and greenhouse gas (GHG) emissions have to be reduced, which in its part encourages the development and adoption of electric powertrains in all vehicular applications and non-road mobile machines (NRMM). Nowadays, most of the NRMM rely on diesel engine technology as the primary power source but the dominance of the diesel engine is changing along with the stricter emission regulations and new fuel options. The new emission regulations will include all the power levels of engines and limitations to the particle mass and number of particles [7]. These oncoming regulations for Compression Ignition (CI) engines in European Union (EU), called Stage V, are planned to be implemented around 2019–2020. In the United States, similar emission regulations (Tier 4 Final) have been effective since 2015. Because NRMM include a large number of machines, which are intensively used, their worldwide impact on air pollutant and GHG emissions is significant. For example, in 2012 the share of transportation greenhouse gases produced by NRMM in the United States was about 10%, which corresponds to 50% of the emissions produced by the medium and heavy-duty trucks [8]. The air pollutant emission limits have reduced the emission of NRMM but these emissions are still significant in comparison to on-road vehicles [9].

The challenge in evaluation of NRMM is their diversity as they do not form a generic, uniform group of applications nor they have a clearly distinct customer base. To understand complex technological transitions and changes such as powertrain electrification at industrial level, one needs a thorough analysis and systematic evaluation of the underlying phenomena related to the technology itself, future developments, market situation and prevailing policies and regulations. In this paper, a thorough assessment of future technological developments in NRMM is presented focusing on the hybrid and electric powertrains. This research work has been done during the years 2012–2016 as a part of a national research project called Electric Commercial Vehicles (ECV)-Tubridi [10]. The project was carried out in collaboration with Aalto University, Lappeenranta University of Technology, VTT Technical Research Centre of Finland Ltd. and industrial partners. In the sections below, the paper first presents the state-of-the-art for powertrain electrification in NRMM. Second, the present and future drivers of electrification and technological trends are overviewed. Then, the required technology enablers are illustrated following the evaluation of the major challenges for powertrain electrification. After that, future scenarios for powertrain electrification of NRMM are presented. Finally, the key findings are summarized and preferable actions and recommendations are given.

2. State of the Art

2.1. Technology Assessment of Alternative Powertrains

The effects of alternative vehicle technologies have been continuously evaluated in scientific literature. The research focus has been on passenger vehicles [11,12] or transportation in general [13,14]. The investment in hybrid vehicle development was investigated by real option reasoning in [11]. The research results showed the different and sometimes divergent perceptions that car companies can have in the short- and long-term potential of hybrid vehicles. The results also explained the divergence in strategic postures for automotive companies. Dijk and Yarime analyzed the meaning of techno-economic, social and regulatory mechanisms for the emergence of electric engines in the automobile market after 1990 [13]. They concluded that the internal combustion engine have been the most significant development trajectory for automotive engines. It was also mentioned, that the legislative efforts of California's Air Resources Board and hybrid technology development by Toyota activated a development of new innovative solution paths for hybrid electric engines. In [15], the transition towards a more sustainable mobility system was evaluated for fuel cell and hydrogen technology by analyzing the expectations and technology strategies of the major actors of the field.

The evaluation concluded that the strategies are founded on the future expectations and it appears to be crucial for the government strategy to rely on the socio-technical landscape level expectations. A study by Tae-Hyeong Kwon investigated the market barriers and policy solutions in order to increase the market share of Alternative Fuel Vehicles (AFVs) [16]. The results of a system dynamics model indicated that it could be difficult to attain a shift towards alternative fuel vehicles without a policy intervention especially if the vehicle operating costs have any importance. Browne et al. developed a framework to investigate the existing barriers for the large-scale deployment of alternative fuels and vehicles [17]. The research results indicated that there are technical limitations for any alternative fuel and vehicle technology, and many of them suffer from higher costs. As many other studies, they also concluded that the main energy source for vehicular application and transportation is based on fossil fuels in the foreseeable future [18]. There is growing interest towards full electrification of vehicles and recently more studies have been carried out for understanding better the cost structure of electric powertrains in heavy vehicles [19,20]. Based on these studies, the charging infrastructure has an important influence on the vehicle operating performance and lifecycle costs.

2.2. Description of Non-Road Mobile Machinery

Non-road mobile machinery encompasses various machine applications from gardening vehicles to agricultural tractors and from reach trucks to heavy-duty mining vehicles. NRMM are wheeled or tracked mobile machines that are well suitable to operate in off-road conditions. A common aspect for all of these machines is their purpose for intensive use (often professional) to carry out predefined tasks in a specific environment. In professional use, these machines are typically operated for several hours per day and often more than a typical eight-hour work shift. In some environments, such as mines and harbors, the work shifts can be considerably longer, even up to 24 h per day. These machines can be divided into different categories by their primary intended use. The most common machinery types are construction machines or earth-moving machines. The following classification of machine applications has been often used for NRMM [21]:

- *Construction or earth-moving machines*: all kinds of loaders, dumpers, excavators, land rollers, bulldozers, etc.
- *Transportation of goods or material handling equipment*: forklifts, Automated Guided Vehicles (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, snow removal machines, etc.
- *Tractors and agricultural machines*: agricultural tractors, forest machines (forwarders, harvesters, etc.), combine harvesters, field choppers, self-propelled manure spreaders, etc.

There is obviously some overlapping between the categories, e.g., agricultural tractors are also often used in property maintenance. Some loaders are used in both property maintenance and construction. However, it seems that present trend is specialization and tailoring. Therefore, mobile machines are more and more often designed for a relatively narrow segment, and consequently they are becoming increasingly diverse. Figure 1 illustrates some specific machinery applications for agricultural work. Implements powered by an agricultural tractor are common application in agriculture but interest towards self-propelled harvesting machines have been increasing due to the demand for higher productivity.

The maximum power rating of small loaders and utility vehicles starts from 10 kW whereas gigantic mining dumpers can have total installed power up to three mega-watts. Figure 2 presents photos of two typical manipulative machines: a wheel loader and excavator, and a grader. Typically, a mobile machine is designed for a certain purpose (e.g., for moving material) the way that they can carry out their purpose effectively. Therefore, the energy efficiency of the machine has not been a design priority. However, the increasing fuel and energy costs, and particularly the tightening emission regulations, are changing the design objectives for NRMM, and stressing the importance of the energy efficiency in all operations.

Figure 1. Examples of self-propelled agricultural machinery: Vervaet slurry spreader, Dewulf potato harvester, and New Holland TC5050 combine harvester (Photos: Antti Lajunen).

Figure 2. Terex wheel loader, Eurotech mini excavator, and HBM grader (Photos: Antti Lajunen).

Historically, internal combustion engines (ICEs), mostly diesel engines, have dominated the power production in NRMM. Diesel engines have good efficiency among the ICE family, and the emission regulations have not generated technical challenges or increased significantly the cost of the engine technology. Mobile machinery are often operated at low driving speeds when high torque capacity is demanded at the wheels [22]. As hydraulic systems typically offer a good power-to-weight ratio, hydrostatic or hydrodynamic powertrains are therefore well suitable for many machine applications. There is often not a lot of space for powertrain components, which favor for compact and high power-to-weight solutions. Most of the work systems, such as boom or bucket operations, are powered by hydraulic cylinders that are difficult to replace by any corresponding electric system. The major downside of hydraulic systems is their inherently lower energy efficiency in comparison to mechanical or electric systems [23]. In a typical operation of NRMM, hydraulic pumps and motors have substantial idle losses because the flow and pressure in the system have to be maintained even if the machine is not moving or working. Electrification and hybridization are considered as relevant options to replace hydrostatic and hydrodynamic powertrains to increase the energy efficiency, and to improve controllability [3,24].

2.3. Electric and Hybrid Powertrains

Hybridization is probably the most common form of powertrain electrification. Hybridization of on-road vehicles has been successful and various new models are entering the market every year. For the time being, the benefits of powertrain hybridization in NRMM have been recognized but mostly because of the higher development costs, not many machines with a hybrid powertrain are available on the markets. Powertrain hybridization has been successful from the very beginning in some specific applications also from the cost point of view [5]. The major challenge in powertrain electrification relates to the costs of electric components, and the high requirements of component reliability and durability in mobile machinery. Powertrains can be highly complicated and require increased reliability e.g., in military vehicles [25]. In the context of powertrain electrification, scientific research have recently been done increasingly for different types of NRMM. Typically, these research studies focus on specific vehicular applications e.g., on construction machines [5,26], mining vehicles and equipment [22,27,28], port equipment (different types of carriers) [29,30], and agricultural tractors and machinery [31–33].

The development of lithium-based batteries has had a significant impact on the feasibility of electric powertrains [34]. Nowadays, these types of batteries offer adequate energy and power capacity for many machine applications. Often, energy buffering is needed only for short periods on a high power level. Therefore, lithium-titanate battery chemistries are well suitable for high peak power applications as they can accept high level of charging and discharging currents in different conditions [3,35]. Besides electrical batteries, ultracapacitors (also called supercapacitors) are also well suitable energy storages for NRMM because they can offer multiple times higher power–to-weight ratios than batteries [36]. Their specific energy is much lower than those of batteries which limits their use to peak power shaping and short time energy buffering as it has been done e.g., for a large scale mining shovel [27]. Sometimes ultracapacitors are combined with batteries to form a dual-source energy storage unit [3,37]. A battery-ultracapacitor energy storage can have different types of configurations and is well suitable for pulsed current loads [38].

Due to the complex characteristics and limitations of electrical batteries, hybridization can be considered as a way to manage and mitigate the possible technical and economic risks of battery technology. The operation requirements of mobile machines are not easily met by having only an electrical energy storage as energy and power source. Instead, a hybrid powertrain powered by a diesel engine-generator and a lithium-ion battery can often be a much more reasonable solution than a full electric powertrain for many NRMM. Different architectures for hybrid electric powertrains have been well presented in the scientific literature e.g., [24,39,40]. Small mobile machines that operate in very limited areas, such as a construction site or a warehouse, can benefit significantly from full electric powertrain. For instance, small sized forklifts that operate indoors have been electrified for a long time with lead-acid batteries and nowadays with lithium-ion batteries [41]. Figure 3 presents recently developed hybrid mobile machines. A powertrain that has a fuel cell stack as primary energy and power source and a battery as energy storage is also a hybrid powertrain [29]. Fuel cells are still in development phase and first full size fuel cell hybrid vehicles are now entering the markets. The benefits of fuel cells are emission free operation, higher efficiency than diesel engines and low noise operation. High production costs and durability are the major challenges for vehicular fuel cell systems [42,43].

Figure 3. Examples of hybrid mobile machines: Komatsu hybrid excavator (Photo: Antti Lajunen), Venieri hybrid wheel loader (Photo: Antti Lajunen), and Logset 12H GTE Hybrid forest harvester (Photo: Logset http://www.logset.com).

Besides higher development costs, there are some technical weaknesses related to electric powertrains. Electrical components can be large, especially when considering heavy-duty applications [20]. For example, a traction motor typically requires an inverter that also takes quite a lot of space in relation to the motor. The limited specific energy of modern lithium-ion batteries requires compromise solutions between battery capacity, operation availability and charging solution [19]. In addition, safety and thermal management related to the electrical systems are important factors that needs to be taken into account especially for high voltage systems [44]. Because some electrical components use rare-earth metals and some of them may require substantial amount of energy in production, the carbon dioxide emissions of manufacturing electric powertrains are nowadays much higher than for conventional ICE powered mechanical powertrains. The battery system has a major influence on the amount of CO_2 emissions in manufacturing phase [45].

Because of the limited battery specific energy, fast charging solutions are crucial to ensure operation availability of NRMM. Recently, fast and high power charging solutions have been introduced especially for electric city buses [19]. A bus charging station can provide higher than 400 kW charging power which is often delivered through an automatic catenary system. Wireless charging technologies have been developed more rapidly recent years [46] but a robust and reliable wireless charging system could be problematic to establish with NRMM due to the harsh operation conditions and high charging power requirements.

The drivers of powertrain electrification are quite the same for NRMM as they are for the on-road vehicles; fuel efficiency, emissions, and regulations. Hybrid and electric powertrains can offer improvements in energy efficiency and performance of the machinery. Because of numerous different machine applications, the improvements can vary significantly. Practically, the fuel consumption of a hybrid mobile machine can be approximately 10–50% lower than that of a traditional diesel-mechanical or diesel-hydraulic machine [3]. Full electric mobile machinery could save even more energy than hybrid machines. The recent research results indicate that battery electric city buses can reach up to 75% lower energy consumption than diesel buses [47]. Due to the inherent characteristics of electricity and electrical components, hybrid and electric powertrains offer also technical benefits e.g., fully continuously variable transmission (CVT), more precise actuator control, reduced need for maintenance, and flexibility in powertrain design [28].

The major difference between on-road vehicles and NRMM is their duty cycle and operating conditions. The power requirement is often steady for on-road vehicles and transient for NRMM. Therefore, high-power energy storage solutions, such as ultracapacitors and high-energy type lithium-ion batteries, are convenient for NRMM whereas high-energy type storage are more typical for on-road vehicles. The operating conditions of NRMM can be much harder than driving on roads. In harsh conditions, such as in underground mines, more focus has to be given for the system robustness and reliability e.g., in terms of thermal management. The driving speed range causes the major differences between powertrain technical solutions. NRMM are often driven only at slow speeds (less than 40 km/h) and even heavy vehicles are often designed for even up to 100 km/h driving. In heavy on-road vehicles, powertrain hybridization may not provide any more reduction on fuel consumption than e.g., electrification of auxiliary systems [48].

3. Technology Drivers and Trends

3.1. Legislation, Regulations and Policies

The climate strategies of European Union (EU) and individual countries on reduction of carbon dioxide (CO_2) emissions may have an important impact on the design solutions of NRMM. The ambitious EU objective is to reduce greenhouse gas emissions in Europe by 80–95% by the year 2050 compared to the 1990 levels. At present, it is difficult to evaluate the actions and requirements that could be directed at vehicles and mobile machines but solutions that reduce the dependence on fossil fuels will certainly be required. It also has to be recognized that the target level cannot be reached simply by increasing energy efficiency of the conventional technology. The CO_2 emission reduction objectives are complemented with other policies and declarations such as the "White Paper" mapping the path to competitive and resource efficient transportation in Europe [49]. The emission regulations are specific legislative policies that have an impact on technology choices in NRMM. The emission limits for air pollutants carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) are going to be lower in the future EU legislation which will also impose new type of emission limitations [50]. According to the preparation of the EU Stage V emission standards [7], also the small engines (power < 19 kW) and large size engines (power > 560 kW) will be included in the future legislation. Table 1 describes the present European emission limits (Stage III/IV) and future limits (Stage V).

Table 1. European emission limits for CI engines of NRMM (g/kWh).

	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

As a new rule, the particle mass and particle number emissions are included. The direct impact of the new emission limits is the need to use more sophisticated emission control and exhaust gas treatment systems. In the past, the emission standards have been stricter for heavy-duty on-road vehicles than for non-road mobile machinery. Nowadays, new heavy-duty trucks often have to use exhaust gas recirculation (EGR), selective catalyst reduction (SCR) and diesel particle filters (DPF) to reach the present emission limits e.g., EURO VI in Europe [51]. The emission limits of the US EPA Tier regulations go in line with the EU limits [52]. Even though the new regulations have substantial changes, it remains uncertain whether they have a major effect in increasing the interest to adopt hybrid and electric powertrain technologies. The diesel engine technology and its exhaust gas treatment solutions have been developed successfully for on-road heavy-duty engines. It is understood that this development can be exploited for the diesel engines in NRMM.

In a recent European research study [53], it was concluded that market share of electric vehicles in Europe is low and it is not likely to change without significant improvement of technology or public subsidies. The study recommends of coordinated support actions but recognizes that the heterogeneity of regions across Europe also calls for regionally tailored approaches. Unlike on-road vehicles, the operating and societal environments of NRMM are practically similar in all countries so that their operation is less impacted by the local environment.

3.2. Competing Technologies

Although electric and hybrid powertrains hold a great promise and inherent advantages over the traditional mechanical and hydraulic powertrains, they are and will be in competition with conventional technologies. In passenger vehicles, internal combustion engines have been developed more energy efficient to answer to the challenge set by hybrid vehicles. Nowadays, the downsized diesel and gasoline engines have reached low level of consumption, and with turbocharging, they offer a high power density engine even for larger cars. Among NRMM, the diesel technology has also been developed but the future emission standards could require redesigns and more development for the emission control and exhaust gas treatment systems which in turn increases the engine system size and costs. Because of the high energy density and easy and fast delivery of the diesel fuel, it will be hard to replace the diesel engine technology in many mobile machine applications. The present day batteries do not offer energy densities even close to that of diesel fuel. Hydrogen has high energy content and it has been considered as a viable vehicle fuel [54]. However, the hydrogen storage and distribution solutions need to be developed much more to be a real competitor to diesel fuel or electrical energy storages [55]. Even though hydrogen can be produced from many different sources, it is mainly produced from fossil fuels and the production costs are currently quite much higher in comparison to other fuels [56].

Alternative powertrain technologies will be developed in parallel with the conventional technology. Hybrid vehicles have already demonstrated that a combination of conventional and alternative technology can be the best solution particularly when the alternative technologies are still under development. One should not forget new fuel types and sources either which are considered more environmentally friendly than conventional fossil fuels e.g., biofuels. It should be recognized that competition in the market is often a positive trend for the development of new technology as it was stated in a recent research study [57]. The results suggested that there is a positive effect generated by a rivalry situation for LEV (Low Emission Vehicle) development.

As hydraulic systems are being widely used in mobile machinery, and more efforts will be put into developing energy efficient and powerful hydraulic systems and powertrains [58,59]. Digital hydraulics is entering mass markets, which boosts energy efficiency and control accuracy. Figure 4 presents a comparison of the efficiencies between hydraulic and electric components. In the first figure pair, a variable displacement axial piston hydraulic pump is compared to a permanent magnet electric generator, and in the second figure pair, a variable displacement axial piston hydraulic motor is compared to an electric drive with a permanent magnet motor. The presented components have quite similar performance characteristics in terms of motor speed and torque range. Even though the hydraulic components have good efficiency in some operation areas, they lack high efficiency in the high speed and torque area that is quite often used in machinery applications. An electric generator with a reduction gear is very well suitable to be attached to a diesel engine to form an engine-generator unit. An electric drive (inverter and motor) forms a compact drive unit with a high efficiency area.

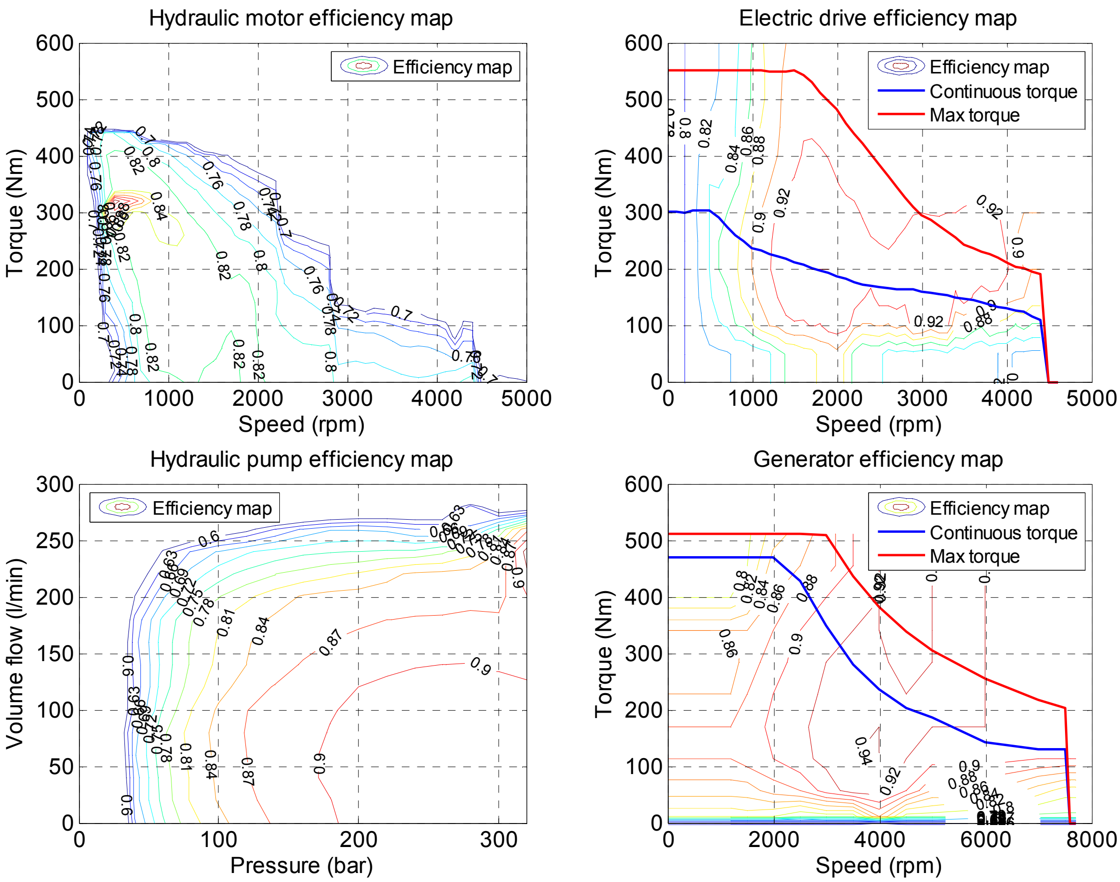

Figure 4. Comparison of the efficiency of a hydraulic pump to an electric generator and a hydraulic motor to an electric drive.

3.3. Opportunities for New Technology

An electric powertrain can be seen as an innovation platform to enhance the performance of conventional technology and offer new, advanced solutions to customers. The driving comfort has been an important feature for passenger vehicles and this has been recognized among mobile machines, too. Electric control systems can enhance the user experience and make previously stressful work much more comfortable. For instance, agricultural tractors equipped with an electric power take-off (PTO) can encourage other manufacturers to design implements for using electric power instead of mechanical or hydraulic power [31,60]. Figure 5 presents examples of DC and AC electric system architectures of agricultural tractors for electrification of implements. The DC architecture is a cost effective solution for the tractor but more expensive for implements whereas the AC architecture is more complex for tractor. With the DC architecture, higher complexity systems for implements can be developed which is harder with the AC architecture. From the control point of view, the AC architecture provides a possibility for a distributed control layout. Electrification of tractors and agricultural machinery was reviewed recently in a research paper [32]. The research concluded that the major advantages of machinery electrification are better torque and speed control, noise reduction, and a more flexible design.

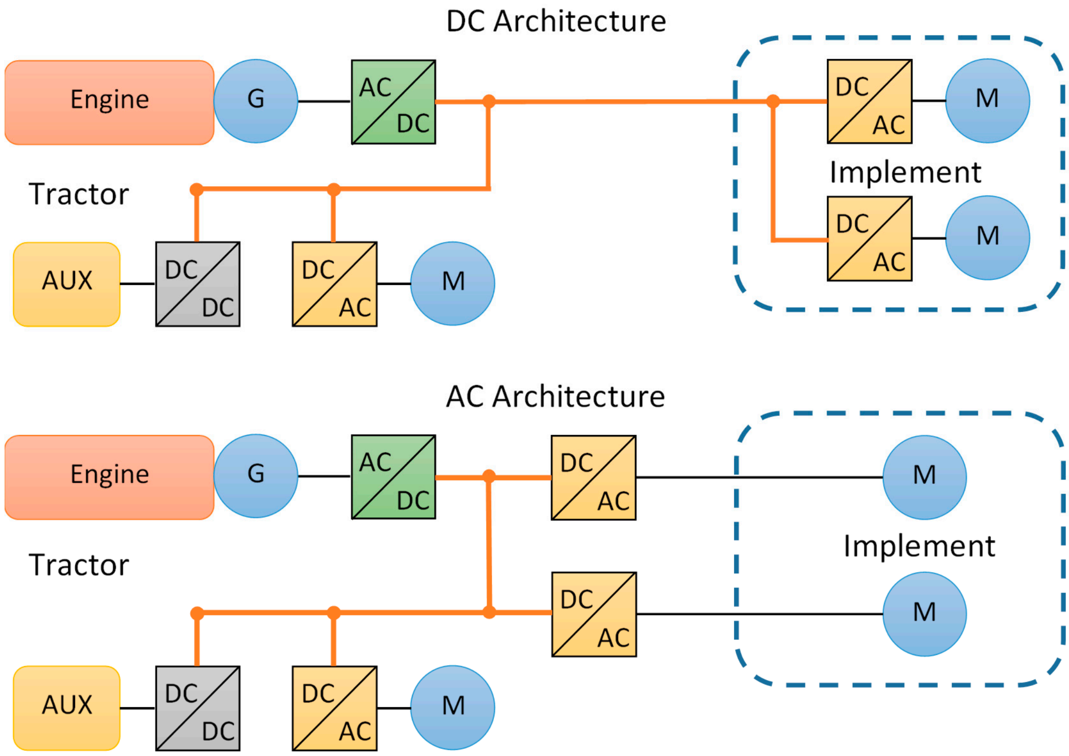

Figure 5. Examples of electric system architectures for agricultural tractors: G = Generator, M = Motor, AUX = Auxiliary devices (Data from [60]).

Nowadays, all machines have already at least one electrical system that is typically the 24 V lead-acid battery-based system. It delivers power for the auxiliary devices such as ventilation, lights, and windshield wipers. Only components with a continuous power demand of less than a few kilowatts can be operated by this low voltage system. Recently, the number of auxiliary devices has generally been increasing. The same challenge has been recognized among passenger vehicles in which the amount of comfort and infotainment auxiliary devices has rapidly increased. Therefore, one possible step is to implement another electric system with higher voltage level than 24 V but still lower than 60 V, which is the limit for high voltage in on-road vehicles and mobile machinery [61]. Higher voltage systems have specific requirements that could unnecessarily increase the system costs. In passenger vehicles, 48 V hybrid system is getting a lot of interest for many reasons. In such a low voltage system, the hybrid system can be integrated to the engine, the power levels are up to 12 kW (maximum current around 250 A) which gives enough freedoms for the engine control to reduce emissions and significant amount of braking energy can be recovered [1,62]. For NRMM, a 48 V system offering more than 10 kW of power would enable the use of more powerful electric auxiliary devices such as engine fans or electric motor powered hydraulic systems. Higher capacity battery could provide auxiliary power during stop and start operation of the engine.

4. Technology Enablers

4.1. Component Development

Electrical energy storages are key components in the success of powertrain electrification of mobile machinery. The technological development of lithium-ion batteries has been very beneficial but the progress has not been as fast as expected [35]. The battery specific power and energy, lifetime and costs are important characteristics for NRMM. Thermal management of lithium-ion batteries is a specific practical challenge because operation in hot and cold temperatures accelerates aging and battery performance is decreased in cold conditions [63,64]. In the shadow of lithium-ion batteries, other more advanced battery chemistries are being developed [65,66]. Some of them hold a lot of promise, such as lithium–sulfur and metal–air batteries, but the development from the concept level chemistries to the actual real size battery system takes a lot of time, even more than ten years [45,67,68]. Figure 6 shows the theoretical and practical energy densities for different battery types. Among these battery technologies, without having the highest theoretical energy density, Li-Ion has the highest practical energy density. The theoretical energy density refers to analytical calculations that are based on material characteristics and can be considered as the maximum potential of the chemistry. The practical energy density refers to measured energy densities from complete battery packs.

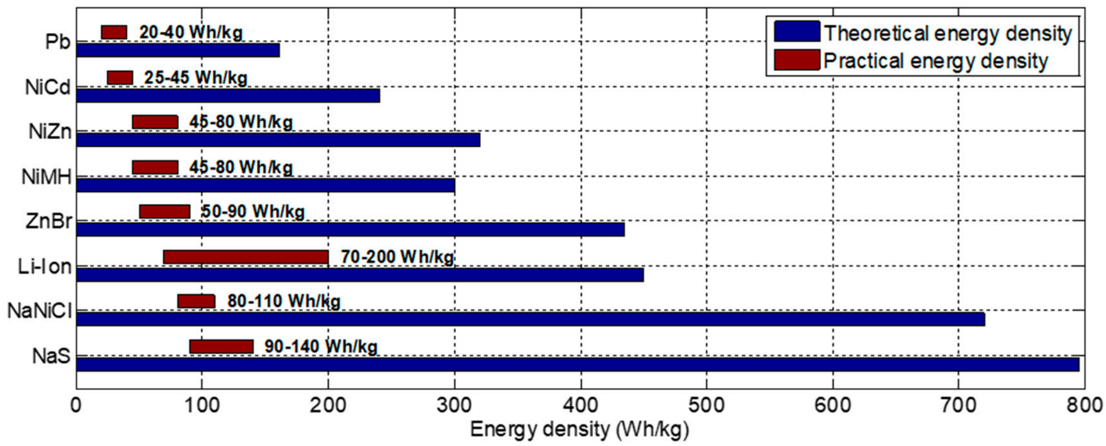

Figure 6. Theoretical and practical energy densities for different battery types (Data from [35,69]).

Even though batteries are often in the spotlight, ultracapacitors have been developed to the level that their usability, feasibility and applicability is approaching that of batteries [70]. However, as long as ultracapacitors have low energy density, they are most suitable for short-term energy buffering in high power applications. Combining ultracapacitors with energy type batteries could sometimes be useful but the cost effectiveness could be hard to reach, and the system can become complex e.g., from the control point of view [37].

Even though electric motors have been used in vehicles and other applications for a long time, there is still a need for development of electric motors especially for the mobile machinery and heavy-duty vehicles [1]. Most of the electric motors used worldwide are designed for stationary use in industrial conditions and hence their specifications do not match those of mobile machines. Again, the compact size, i.e., power-to-weight or torque-to-weight ratio and high energy efficiency over a broad operation range are important characteristics that are not necessarily so relevant in stationary machines. Therefore, sophisticated motor drive design, control and efficient cooling are needed for reducing the weight as much as possible [71]. Mobile machines also require good torque capacity, which can increase the size and costs of the motor. For this reason, it can be more suitable to use electric motor with integrated gearbox for higher torque capacity. In comparison to common industrial applications, the NRMM power electronics is required to have robust protection against vibration, shock and corrosion.

Besides the key components of the electric powertrain (battery, inverter/converter, motor), there are many other smaller size components, such as electric connectors, cables, contactors and fuses, that can increase the system costs and engineering design work. The system integration in electric and hybrid systems plays a very important role in attaining reasonable costs, easy assembly, effortless maintenance and long-term reliability and durability [70]. In this context, the challenge is the availability of reasonably priced components that satisfy the required specifications. Particularly, the components suitable for high voltage systems (>650 V) are usually not off-the-shelf products but specific designs for a particular application without mass production.

4.2. Cost Reductions

The high cost of electric components is often the main challenge for economically successful electrification or hybridization of NRMM. It should be remembered that the first full hybrid passenger vehicle (Toyota Prius) entered markets in 1997 and it took more than ten years to make the car profitable. The mass production was probably the major reason for the reduction of the component and production costs of the Prius. Unlike on-road vehicles, NRMM cannot benefit from the vehicle mass production. Cost reductions of individual components are important but because NRMM are so diverse, the system development and integration costs can be considered even more important. For example, the future cost estimates for lithium-ion batteries in the cell level do not represent well a battery system cost in which the system integration, battery management and cooling system can play a major role. It is worthwhile to note that Toyota was adopting the Prius demonstrated drivetrain technology not only in one lower-segment passenger car model but in licensing it to other brands and sectors as well.

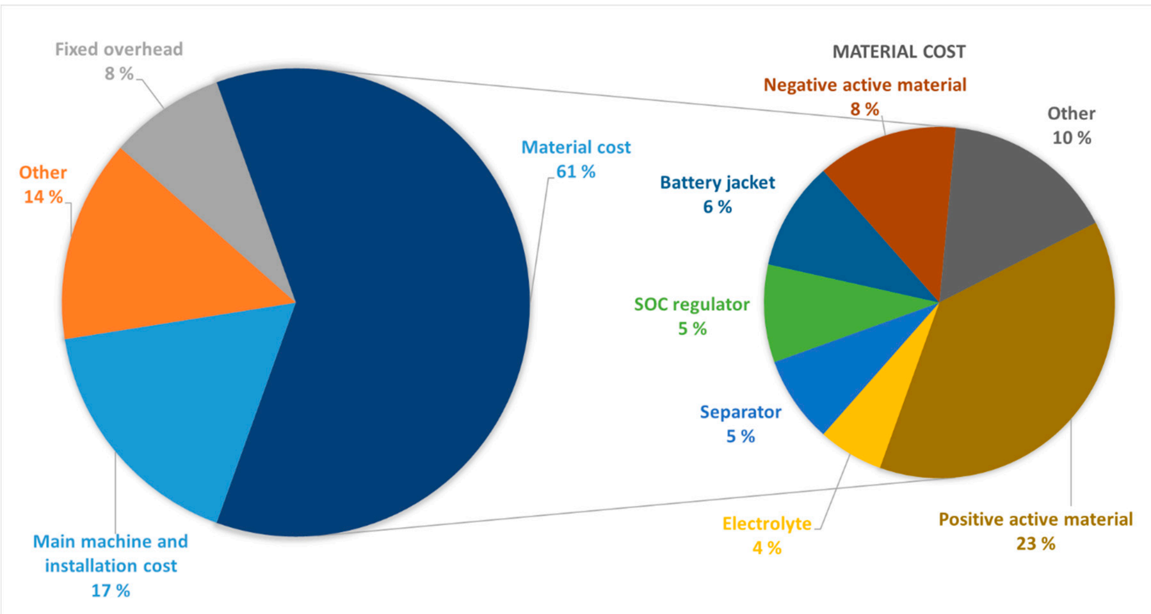

Figure 7. Breakdown of battery pack (high power cell) cost structure (Data from [72]).

The integrated powertrain systems such as engine-generators and traction motor-gear systems can be one solution for the cost reduction. Overall, the cost management has to be extended to the vehicle and business level meaning that the economic benefits of electric and hybrid powertrains are more likely to be generated in the lifecycle context and not only by an individual factor such as a fuel cost or component cost. The costs of lithium-ion batteries have been widely investigated in the recent literature e.g., [72,73]. The costs of battery systems for plug-in hybrid and battery electric vehicles were exhaustively analyzed in [72]. The research results show that the high power cells suitable for plug-in hybrids are twice more expensive in pack-level (\$545 kWh^{-1} vs. \$230 kWh^{-1}) than the high energy type cells for battery electric vehicles. The research also concluded that an annual production volume of 200–300 MWh would quickly reach the economies of scale in battery manufacturing. Figure 7 presents the cost breakdown for a battery pack using high power lithium-ion cells and yearly production of 20,000 according to [72]. It should be noted that the material costs are more than 60% of the total costs.

In a recent report, the global hybrid and electric heavy-duty transit bus market was analyzed [74]. Because transit buses use similar high voltage electric components than NRMM, its market developments are important for evaluating the component costs reductions. Table 2 shows the price forecast presented in [74] for the key components in heavy-duty hybrid and electric powertrains. The cost of controllers is actually expected to rise due to the increasing complexity in the control of integrated systems. For motor, inverter and battery, the cost reduction is forecasted to be around 20–25% during next 15 years.

Table 2. Hybrid and electric powertrain component price forecast [74].

Component/Year	2014	2022	2030
Controller (\$/unit)	900–1000	1000–1100	1200–1300
Motor (\$/kW)	25–30	23–27	20–25
Inverter (\$/kW)	30–35	28–30	24–26
Battery (\$/kWh)	450–500	375–425	330–380

4.3. Technology Hypes

Many new technologies go through a phase of hype when there are great expectations in relation to the current situation. The hype of vehicle electrification, especially electric passenger cars, was getting a lot of boost around 2010. There are positive and negative outcomes from technology hypes. These hypes definitely increase the interest towards technology even among majority of people. They may also encourage governments and other decision makers to think favorable to the adoption of alternative technology, which may lead to specific policies giving benefit for new technologies. Sometimes, a technological hype is a necessity to draw enough attention and get funding for the research and development. Early investors may benefit well from hype with higher returns. As negative outcome, hype is often followed by a disappointment, or at least, the real progress is much slower than expected, and it is only done by incremental steps of innovations. The real growth and dedicated work usually starts after the top of the hype has been reached and expectations are getting more realistic [75]. Different types of models have been created to distinguish technology trends and emergent technologies or to forecast social changes. Recently, it was recognized that the hype cycle of the user, producer or researcher, and the information distributor are different [76].

4.4. System Integration

As hybridization will probably be the first major step for mass electrification of mobile machinery, there is and will be a crucial need for specific integrated subsystems such as diesel-generators and motor-transmissions. Nowadays, diesel-generators are mostly manufactured for stationary use and they do not correspond to the needs in NRMM. A diesel-generator for a mobile machine needs to be compact in size and weight; and controllable as any off- or on-road diesel engine in the present machines. Another integrated system is the combination of the electric motor and gearbox. Because many machines operate only at low driving speeds and require a substantial amount of torque at the wheels, gear reductions have to be used from the electric motor to the wheels. Traditional gearboxes used with diesel engines can be used but these are far from an optimal solution and therefore specific gearboxes are often utilized with electric motors [77]. The design of the gearbox is also different because shifting can be performed even without clutches due to the high accuracy of the motor control [78]. Figure 8 shows a battery system integration which consist of cells, modules and packs. The challenge of the battery system is robust integration of electro-chemical (cell), mechanical (structure and packing), electrical (cables and electronics) and thermodynamic (heating and cooling) systems.

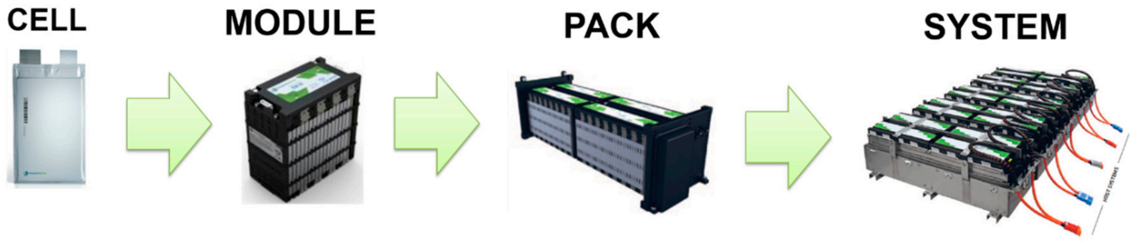

Figure 8. Example of a battery system integration.

4.5. How to Exploit the Benefits?

The hybrid and electric powertrains in passenger vehicles have demonstrated that it is not easy to make economic profit with new technology even if it potentially offers obvious benefits over the presently used technologies. In any case, there are some success stories in automotive field, among heavy vehicles including mobile machinery. The often-recognized success story is the one of Toyota Prius. It was the first full hybrid vehicle that was mass-produced and also designed as a hybrid vehicle from the beginning [79]. However, it took a long time before Toyota could make the model economically profitable. Several models of full electric passenger vehicles have been introduced recently for customers. At present, Nissan Leaf and Tesla Model S are probably the most popular electric vehicles. The main reason for the success of Nissan Leaf is its affordable price and reasonable operating range, over 200 km. Even if Tesla Model S is very highly priced, luxury electric vehicle, it has sold very well. Its advantage is the high operating range, up to 500 km. Overall, the number of hybrid and electric passenger model is increasing rapidly every year and the sales of these vehicles are growing. Figure 9 presents the number of sold hybrid vehicles in passenger vehicle markets from 1999 to 2014 [62].

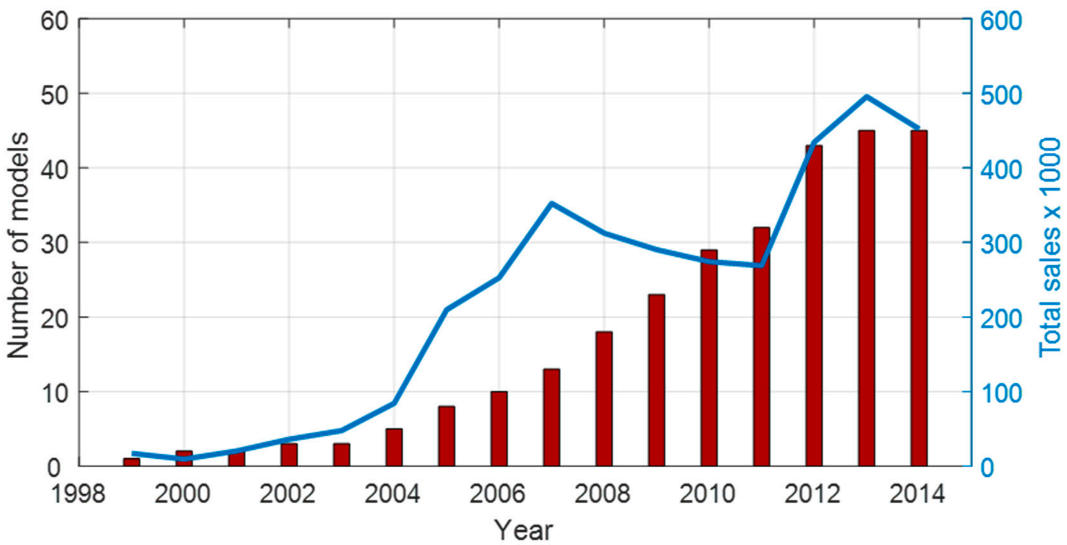

Figure 9. Number of hybrid vehicle models and total sales (Data from [62]).

It seems that both automotive field and NRMM require a certain amount of models with hybrid or electric powertrain for larger breakthrough. The hybrid vehicle sales have been fluctuating in accordance of the world economic situation, thus after 2007 the significant drop of oil price broke the highly increasing trend in hybrid vehicle sales. A new increasing trend in sales started in 2011. The trends from the automotive field also indicate that an individual vehicle success, in highly competitive markets, requires some distinctive feature(s) (e.g., low cost, adequate operating range) that make the model more interesting for customer than the conventional technology.

Among on-road heavy vehicles, hybrid city buses have been in markets about 20 years and they have succeeded to take only a small portion of the global bus markets. The challenge with hybrid buses have been their higher lifecycle costs in comparison to diesel buses [80]. The full electric buses seem to be the success story among on-road heavy-duty vehicles [81,82]. The lithium-ion batteries that can be charged with high power have created the possibilities for high power opportunity charging during operation, which enables a full day operation as well as compact sizing of the battery pack in terms of energy capacity [83]. Even though battery electric buses are currently more expensive than diesel buses, they offer zero emission operation, low energy consumption, reduced noise emissions, and robust powertrain technology. With these benefits, electric buses are becoming more and more popular particularly in China and Europe [84]. However, the implementation of electric bus systems requires intensive collaboration between the local government, transit agencies, energy providers and bus manufacturers especially because of the charging infrastructure [85,86]. The major advantage of electric buses is the emission free operation in city centers and potential to reduce CO_2 emissions [87]. Battery electric buses are considered more cost effective than traditional diesel buses already in near future [47]. Similar step to fully electrified mobile machines without hybridization has also been seen in some newly introduced battery operated mining machines [28,88].

In some mobile machine applications, hybrid systems have already been introduced successfully. There are excavators that regenerate energy from the body movement when swinging [24]. This energy is stored usually in ultracapacitors and then used to rotate the body. A hybrid straddle carrier also exploits the energy regeneration. When a container is lowered, the braking energy is recovered and stored in an electrical energy storage [89]. In NRMM, the operation tasks are often quite short in time and are repeated regularly which creates the possibility to recover e.g., braking energy and temporarily to store it to an electrical energy storage. It is characteristic that the power levels are often quite high which favors the use of ultracapacitors or lithium-titanate batteries.

5. Future Scenarios for Mobile Machinery

5.1. Short and Medium Term

In this context, a short-term period is defined to be less than five years, and the scope of the medium term is up to ten years. Unlike for on-road vehicles, the service life of mobile machinery can be much longer, up to 20 years. Therefore, the medium- and long-term technological changes are considered to have more importance for the development of hybrid and electric powertrains in NRMM. The changes in present market economy can be relatively fast and companies might have to make strategic decisions in short term. Hence, companies need to follow up continuously the technology and market trends. The following list describes the main impacting factors and development themes for short and medium term in NRMM powertrain electrification:

- Air pollutant emission regulations enter to all power classes in Europe (EU Stage V) [7]. This will increase the need for better emission control and advanced exhaust gas treatment systems. This might increase the interest towards hybrid powertrains because the emission control system can be less complex due to freedoms in engine operation.
- Consumption of fossil fuels will increase and no decrease or shortages in crude oil production are foreseen. However, the attitudes towards the use of fossil fuels in vehicles are becoming less favorable. The price of oil will be a subject of speculation due to world politics and unstable situations in some important oil producing regions [90]. Therefore, the fuel price should not be the primary driving force for powertrain electrification.

- The development of electric components for vehicular applications is continuous, the volumes increase and they become more available also for higher voltage and power levels. The electrification of on-road vehicles will be an important factor for the electric component development and for technology cost reductions [73,91,92].
- The development of electric powertrains in already largely electrified machinery sectors (locomotives, forklifts etc.) will continue incrementally. However, this will not necessarily have a major impact on the general development of electric powertrains [41,93]. The benefits of electrification or hybridization need to be justified separately for each NRMM type.
- The increasing use of renewable energy sources (e.g., wind and solar) starts to change the traditional energy production and distribution system (local vs. global energy production). There will be a growing need for local stationary electrical energy storages [94].
- Gradual steps towards higher degree of electrification of NRMM are taken, for instance: auxiliary devices → power assist → full hybrid → full electric. First, hybrid machines are equipped with small batteries, and then, mostly due to the technology cost reductions, higher capacity batteries are used in full hybrid and electric powertrains. There will not be generic powertrain layouts for NRMM but more likely component-level integrated systems (e.g., integrated electric axles) that can be shared between different types of mobile machines.
- Tailored powertrain system solutions and services for mobile machines will enter the market. For instance, similarly as among heavy-duty on-road vehicles (city buses), integrated transmission systems with diesel engine and electric motor(s) are developed and commercialized [95].

5.2. Long Term

The long term is defined as the coming 10 to 30 years. In this long time horizon, it is assumed that the major trend will be the implementation of automation in its different forms in machines e.g., [33,96,97]. Mobile machinery is typically being used in somewhat limited areas and many of them are continuously repeating similar work tasks. Therefore, the operation of many machines can be automated as it has already been partly done e.g., for underground mining loaders [98,99]. Recently, driverless vehicles have been getting a lot of attention, which have increased the development of safety and surveillance systems. It can be observed from automotive field that new advanced driver assistance systems (ADAS) are being integrated to vehicles every year [26,100]. At the beginning of automation process, mobile work machines will require supervision from the operator because there can be complicated environments and tasks that are difficult to fully automate. The following list describes the long-term predictions for the NRMM powertrain electrification:

- Automation is a major driving force and it will support the utilization of hybrid and electric powertrains because electric components and systems are more accurate in terms of control and measuring than hydraulic or mechanical systems.
- Autonomous machines without human operator will promote diversity of sizes and/or power classes of machines [33]. When driver/operator cost becomes less significant, machines can work 24/7 and machines can be smaller [101].
- Demands for energy efficiency and automation are favoring the implementation of full electric drivetrain solutions. We estimate that in year 2035 half of new machines are equipped with some degree of electric powertrain.
- Changes and risks in energy production and distribution (e.g., local vs. global energy production, politics, and worldwide crisis) can favor locally produced, independent energy sources. There will be much more renewable electrical energy available distributed via electric grid [94]. Alternatively, large-scale adoption of electric vehicles will increase the energy demand from the electric grid that might increase electricity costs [102].

- Overall consumption of fossil fuels still increases but oil production may decrease and the use of fossil fuels in vehicles will diminish. Oil price is likely to increase in the long-term future but it will always be a subject to speculation [90].
- Drop-in biofuels play a role in the fuel market; they influence on the price and demand of the fossil fuel components [103].
- Fuel cell technology is starting to be cost competitive and increasing hydrogen production is decreasing the fuel prices [17,104,105].
- The role of the management and exploitation of operational data is important in order to maintain the high performance of the mobile machines. Industrial Internet solutions, connected machines and intelligent software solution are becoming mainstream technology.
- It is very likely to have adopted legislation that limits the use of polluting machines e.g., in cities and residential areas. This type of legislation could be put in force similar way that has been done for passenger vehicles e.g., Zero Emission Vehicle (ZEV) Program in California and low emission zones in many cities worldwide.

6. Discussion and Recommendations

New technology comes with risks and rewards. In today's market economy, strategic decisions for the choice of technology are never easy and the possible risks of new technology have to be somehow managed. In the field of non-road mobile machinery, the conventional technology solutions (diesel engines and hydraulic systems) will be present for a long time because they offer a robust, reliable and well-known option. These technologies also benefit from the vast number of existing component suppliers. In the beginning of electrification, relying on only one technology or only one possible supplier can obviously be risky from the business point of view. It has to be recognized that the powertrain electrification will not happen because the previously developed technologies would somehow become obsolete but because of the benefit that electric and hybrid powertrains will generate for the end user. There are many so called external factors such as regulations and legislation that may favor and support the implementation of alternative technologies. The ambitious goals in reducing GHG emissions and improving air quality, especially in city centers, could result in major changes and great opportunity for hybrid and electric powertrains.

With electrification, manufacturers and machine operators have to adapt to a new kind of market environment. Sometimes patience is acceptable especially in system innovations, where multiple actors need to cooperate and develop technology simultaneously. It is not necessary to be the first one offering innovations but, on the other hand, it can be risky in a longer run not to be prepared for the adoption of new technology. One approach is to look for new partners such as electric utility companies, service companies, and leasing/finance sector and try to have an understanding of the changes brought and offered by the electrification. It should be remembered that lifecycle management of powertrain electrification would be an important factor for the economic success of hybrid and electric powertrains in NRMM. Because fast charging has become a very suitable solution to recharge on-board batteries, the installation and management of the charging infrastructure needs to be taken into account in the lifecycle context.

Successful demonstration machines already act as references and they increase the confidence on powertrain electrification. There are already machinery applications with electric powertrains that have economic market success. However, large-scale adoption of electric and hybrid machinery needs more push from the manufacturers and active participation from the end users. For faster introduction and adoption of electric powertrains, it is crucial to have strong:

➢ understanding about the cost effectiveness of electric powertrains,
➢ collaboration between industry, actors in technology research and development, legislative bodies and end users,
➢ benefit from technology hypes and public funding,

- ➢ clear understanding of own business model, partners and customers' business models, and
- ➢ understanding the relation and causality of technologies such as NRMM electrification, automation, communication, and renewable energy.

Due to the economy driven world politics, the prices of energy and materials are vulnerable and subject to substantial fluctuation e.g., the changes in crude oil price can be rather significant even in short time periods (e.g., between 2014 and 2015). If traditional electric motor and power electronic technology markets will grow fast, the limited resources of raw materials might impose instability to market prices of materials. At present, lithium-ion batteries seem to be the best solution for the on-board energy storage. However, many other battery chemistries may develop to be better than lithium based batteries. This is why the companies need to follow continuously the development of key components and technologies.

The major challenges of the electric and hybrid powertrains are the high component prices and system development costs. Because the production series of NRMM are usually quite small, machines could be tailored in specific purposes, and machine sizes vary significantly, it is practically very hard to express any specific cost estimation for powertrain hybridization or electrification. As the manufacturing series are often quite small, decreasing the costs can be challenging. Besides initial purchase costs, the lifecycle costs and payback time are important factors for the end users of these machines.

Based on the present powertrain technology and market situations, it seems that the success of hybrid and electric powertrains will not be determined by the lower fuel consumption or lower fuel costs but more likely by the better energy efficiency, controllability, reliability and reduction of maintenance costs. Thus, a hybrid or electric powertrain in NRMM has to be justified by the value it generates for the end user, environment and society. Cost management of energy storage systems and other integrated systems will be an important factor for decreasing the higher costs of electrification. The production series for individual type of mobile machinery will remain quite low, and thus, major cost reductions in component level will be challenging to realize without high production volumes. In addition, manufacturers might have to rethink the lifecycle management of NRMM because electrical components, and especially embedded software systems, become obsolete faster than the traditional technology.

Author Contributions: This research work was carried out in collaboration of several research partners and the authors have contributed to the paper based on their research focus and professional competence. A.L. contributed to the analysis of powertrain technologies, technology assessment and legislation. P.S. contributed to the evaluation of mobile machinery in general and future scenarios. L.L. contributed to the evaluation of electrical components and system integration. J.P.-M. contributed to the analysis of electric motors and future developments of electric powertrains. K.T. contributed to the evaluation of mechatronics integration and future scenarios. The paper was written together by all authors.

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References

1. Bilgin, B.; Magne, P.; Malysz, P.; Yang, Y.; Pantelic, V.; Preindl, M.; Korobkine, A.; Jiang, W.; Lawford, M.; Emadi, A. Making the Case for Electrified Transportation. *IEEE Trans. Transp. Electr.* **2015**, *1*, 4–17. [CrossRef]
2. Palencia, J.C.G.; Sakamaki, T.; Araki, M.; Shiga, S. Impact of powertrain electrification, vehicle size reduction and lightweight materials substitution on energy use, CO_2 emissions and cost of a passenger light-duty vehicle fleet. *Energy* **2015**, *93*, 1489–1504. [CrossRef]
3. Lajunen, A.; Suomela, J. Evaluation of Energy Storage System Requirements for Hybrid Mining Loader. *IEEE Trans. Veh. Technol.* **2012**, *61*, 3387–3393. [CrossRef]
4. Abdel-baqi, O.; Nasiri, A.; Miller, P. Dynamic Performance Improvement and Peak Power Limiting Using Ultracapacitor Storage System for Hydraulic Mining Shovels. *IEEE Trans. Ind. Electron.* **2015**, *62*, 3173–3181. [CrossRef]

5. Jo, D.-Y.; Kwak, S. Development of fuel-efficient construction equipment. In Proceedings of the IIEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE & ECCE), Jeju, Korea, 30 May–3 June 2011.
6. Mol, C.; O'Keefe, M.; Brouwer, A.; Suomela, J. Trends and insight in heavy-duty vehicle electrification. *World Electr. Veh. J.* **2009**, *4*, 307–318.
7. European Parliament. *Proposal for a Regulation of the European Parliament and of the Council on Requirements Relating to Emission Limits and Type-Approval for Internal Combustion Engines for Non-Road Mobile Machinery*; Procedure 2014/0268/COD, COM(2014) 581 Final; European Parliament: Brussels, Belgium, 2014.
8. U.S. Environmental Protection Agency (EPA). *Sources of Greenhouse Gas Emissions*; EPA: Washington, DC, USA. Available online: https://www3.epa.gov/climatechange/ghgemissions/sources/transportation.html (accessed on 20 December 2016).
9. Helms, H.; Lambrecht, U. *The Relevance of Emissions from Non-Road Mobile Machinery in Comparison with Road Transport Emissions*; Institute for Energy and Environmental Research: Heidelberg, Germany, 2009.
10. ECV, ECV-Tubridi. Electric Commercial Vehicles. Available online: http://www.ecv.fi/in-english/tp3-tubridi (accessed on 20 December 2016).
11. Avadikyan, A.; Llerena, P. A real options reasoning approach to hybrid vehicle investments. *Technol. Forecast. Soc. Chang.* **2010**, *77*, 649–661. [CrossRef]
12. Moawad, A.; Kim, N.; Shidore, N.; Rousseau, A. *Assessment of Vehicle Sizing, Energy Consumption, and Cost through Large-Scale Simulation of Advanced Vehicle Technologies*; Argonne National Laboratory: Lemont, IL, USA, 2016.
13. Dijk, M.; Yarime, M. The emergence of hybrid-electric cars: Innovation path creation through co-evolution of supply and demand. *Technol. Forecast. Soc. Chang.* **2010**, *77*, 1371–1390. [CrossRef]
14. Van der Wardt, T.J.T.; Farid, A.M. A Hybrid Dynamic System Assessment Methodology for Multi-Modal Transportation-Electrification. *Energies* **2017**, *10*, 653. [CrossRef]
15. Budde, B.; Alkemade, F.; Weber, K.M. Expectations as a key to understanding actor strategies in the field of fuel cell and hydrogen vehicles. *Technol. Forecast. Soc. Chang.* **2012**, *79*, 1072–1083. [CrossRef] [PubMed]
16. Kwon, T.-H. Strategic niche management of alternative fuel vehicles: A system dynamics model of the policy effect. *Technol. Forecast. Soc. Chang.* **2012**, *79*, 1672–1680. [CrossRef]
17. Browne, D.; O'Mahony, M.; Caulfield, B. How should barriers to alternative fuels and vehicles be classified and potential policies to promote innovative technologies be evaluated? *J. Clean. Prod.* **2012**, *35*, 140–151. [CrossRef]
18. Dijk, M.; Wells, P.; Kemp, R. Will the momentum of the electric car last? Testing an hypothesis on disruptive innovation. *Technol. Forecast. Soc. Chang.* **2016**, *105*, 77–88. [CrossRef]
19. Lajunen, A. Lifecycle costs and charging requirements of electric buses with different charging methods. *J. Clean. Prod.* **2018**, *172*, 56–67. [CrossRef]
20. Mareev, I.; Becker, J.; Sauer, D.U. Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation. *Energies* **2018**, *11*, 55. [CrossRef]
21. Lajunen, A.; Suomela, J.; Pippuri, J.; Tammi, K.; Lehmuspelto, T.; Sainio, P. Electric and hybrid electric non-road mobile machinery—Present situation and future trends. In Proceedings of the Electric Vehicle Symposium (EVS29), Montréal, QC, Canada, 19–22 June 2016.
22. Lajunen, A. *Energy Efficiency of Conventional, Hybrid Electric, and Fuel Cell Hybrid Powertrains in Heavy Machinery*; SAE Technical Paper 2015-01-2829; SAE International: Warrendale, PA, USA, 2015; pp. 1–8.
23. Lajunen, A.; Leivo, A.; Lehmuspelto, T. Energy consumption simulations of a conventional and hybrid mining loader. In Proceedings of the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition (EVS25), Shenzhen, China, 5–9 November 2010.
24. Wang, J.; Yang, Z.; Liu, S.; Zhang, Q.; Han, Y. A comprehensive overview of hybrid construction machinery. *Adv. Mech. Eng.* **2016**, *8*, 1–15. [CrossRef]
25. Boulon, L.; Hissel, D.; Bouscayrol, A.; Pape, O.; Pera, M.-C. Simulation Model of a Military HEV with a Highly Redundant Architecture. *IEEE Trans. Veh. Technol.* **2010**, *59*, 2654–2663. [CrossRef]
26. Golestan, K.; Soua, R.; Karray, F.; Kamel, M.S. Situation awareness within the context of connected cars: A comprehensive review and recent trends. *Inf. Fusion* **2016**, *29*, 68–83. [CrossRef]
27. Parkhideh, B.; Mirzaee, H.; Bhattacharya, S. Supplementary Energy Storage and Hybrid Front-End Converters for High-Power Mobile Mining Equipment. *IEEE Trans. Ind. Appl.* **2013**, *49*, 1863–1872. [CrossRef]

28. Paraszczak, J.; Svedlund, E.; Fytas, K.; Laflamme, M. Electrification of Loaders and Trucks—A Step Towards More Sustainable Underground Mining. In Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ'14), Cordoba, Spain, 7–10 April 2014.
29. Liukkonen, M.; Lajunen, A.; Suomela, J. Feasibility study of fuel cell-hybrid powertrains in non-road mobile machineries. *Autom. Constr.* **2013**, *35*, 296–305. [CrossRef]
30. Hegazy, O.; Barrero, R.; van den Bossche, P.; El Baghdadi, M.; Smekens, J.; van Mierlo, J.; Vriens, W.; Bogaerts, B. Modeling, analysis and feasibility study of new drivetrain architectures for off-highway vehicles. *Energy* **2016**, *109*, 1056–1074. [CrossRef]
31. Buning, E.A. Electric drives in agricultural machinery—Approach from the tractor side. *J. Agric. Eng.* **2010**, *47*, 30–35.
32. Moreda, G.P.; Muñoz-García, M.A.; Barreiro, P. High voltage electrification of tractor and agricultural machinery—A review. *Energy Convers. Manag.* **2016**, *115*, 117–131. [CrossRef]
33. Gonzalez-de-Soto, M.; Emmi, L.; Benavides, C.; Garcia, I.; Gonzalez-de-Santos, P. Reducing air pollution with hybrid-powered robotic tractors for precision agriculture. *Biosyst. Eng.* **2016**, *143*, 79–94. [CrossRef]
34. Khaligh, A.; Li, Z. Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art. *IEEE Trans. Veh. Technol.* **2010**, *59*, 2806–2814. [CrossRef]
35. Budde-Meiwes, H.; Drillkens, J.; Lunz, B.; Muennix, J.; Rothgang, S.; Kowal, J.; Sauer, D.U. A review of current automotive battery technology and future prospects. *Proc. Inst. Mech. Eng. Part D J. Autom. Eng.* **2013**, *227*, 761–776. [CrossRef]
36. Rotenberg, D.; Vahidi, A.; Kolmanovsky, I. Ultracapacitor Assisted Powertrains: Modeling, Control, Sizing, and the Impact on Fuel Economy. *IEEE Trans. Control Syst. Technol.* **2011**, *19*, 576–589. [CrossRef]
37. Ostadi, A.; Kazerani, M.; Chen, S.-K. Hybrid Energy Storage System (HESS) in Vehicular Applications: A Review on Interfacing Battery and Ultra-capacitor Units. In Proceedings of the IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 16–19 June 2013.
38. Kuperman, A.; Aharon, I. Battery–ultracapacitor hybrids for pulsed current loads: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 981–992. [CrossRef]
39. Bayindir, K.Ç.; Gözüküçük, M.A.; Teke, A. A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units. *Energy Convers. Manag.* **2011**, *52*, 1305–1313. [CrossRef]
40. Emadi, A. *Advanced Electric Drive Vehicles*; CRC Press: Boca Raton, FL, USA, 2015.
41. Gaines, L.L.; Elgowainy, A.; Wang, M.Q. *Full Fuel-Cycle Comparison of Forklift Propulsion Systems*; Argonne National Laboratory: Lemont, IL, USA, 2008.
42. Wang, J. Barriers of scaling-up fuel cells: Cost, durability and reliability. *Energy* **2015**, *80*, 509–521. [CrossRef]
43. Hua, T.; Ahluwalia, R.; Eudy, L.; Singer, G.; Jermer, B.; Asselin-Miller, N.; Wessel, S.; Patterson, T.; Marcinkoski, J. Status of hydrogen fuel cell electric buses worldwide. *J. Power Sources* **2014**, *269*, 975–993. [CrossRef]
44. Arora, S. Design of a Modular Battery Pack for Electric Vehicles. Ph.D. Thesis, Swinburne University of Technology, Hawthorn, Australia, 2017.
45. Manzetti, S.; Mariasiu, F. Electric vehicle battery technologies: From present state to future systems. *Renew. Sustain. Energy Rev.* **2015**, *51*, 1004–1012. [CrossRef]
46. Patil, D.; McDonough, M.K.; Miller, J.M.; Fahimi, B.; Balsara, P.T. Wireless Power Transfer for Vehicular Applications: Overview and Challenges. *IEEE Trans. Transp. Electr.* **2018**, *4*, 3–37. [CrossRef]
47. Lajunen, A.; Lipman, T. Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy* **2016**, *106*, 329–342. [CrossRef]
48. Bracco, R.; Seccardini, R.; de Somma, M.; Gallardo, G.; Lindgärde, O.; Börjesson, S.; Kessels, J.T.B.A.; Cesari, C.; Fabio, S. CONVENIENT—Complete Vehicle Energy Saving Technologies for Heavy Trucks. *Transp. Res. Procedia* **2016**, *14*, 1041–1050. [CrossRef]
49. European Commission. *Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System*; COM(2011) 144 Final; European Commission: Brussels, Belgium, 2011.
50. Johnson, T.V. Review of Vehicular Emissions Trends. *SAE Int. J. Engines* **2015**, *8*, 1152–1167. [CrossRef]

51. European Parliament. *Regulation (EC) No 595/2009 of the European Parliament and of the Council, on Type-Approval of Motor Vehicles and Engines with Respect to Emissions from Heavy Duty Vehicles (Euro VI) and on Access to Vehicle Repair and Maintenance Information*; European Parliament: Brussels, Belgium, 2009.
52. U.S. Environmental Protection Agency (EPA). *Nonroad Diesel Engines*; EPA: Washington, DC, USA. Available online: https://www3.epa.gov/otaq/nonroad-diesel.htm#info (accessed on 20 December 2016).
53. Auvinen, H.; Järvi, T.; Kloetzke, M.; Kugler, U.; Bühne, J.-A.; Heinl, F.; Kurte, J.; Esser, K. Electromobility Scenarios: Research Findings to Inform Policy. *Transp. Res. Procedia* **2016**, *14*, 2564–2573. [CrossRef]
54. Fayaz, H.; Saidur, R.; Razali, N.; Anuar, F.S.; Saleman, A.R.; Islam, M.R. An overview of hydrogen as a vehicle fuel. *Renew. Sustain. Energy Rev.* **2012**, *16*, 5511–5528. [CrossRef]
55. Paster, M.D.; Ahluwalia, R.K.; Berry, G.; Elgowainy, A.; Lasher, S.; McKenney, K.; Gardiner, M. Hydrogen storage technology options for fuel cell vehicles: Well-to-wheel costs, energy efficiencies, and greenhouse gas emissions. *Int. J. Hydrogen Energy* **2011**, *36*, 14534–14551. [CrossRef]
56. Hwang, J.-J. Sustainability study of hydrogen pathways for fuel cell vehicle applications. *Renew. Sustain. Energy Rev.* **2013**, *19*, 220–229. [CrossRef]
57. Wesseling, J.H.; Faber, J.; Hekkert, M.P. How competitive forces sustain electric vehicle development. *Technol. Forecast. Soc. Chang.* **2014**, *81*, 154–164. [CrossRef]
58. Hui, S.; Lifu, Y.; Junqing, J. Hydraulic/electric synergy system (HESS) design for heavy hybrid vehicles. *Energy* **2010**, *35*, 5328–5335. [CrossRef]
59. Casoli, P.; Riccò, L.; Campanini, F.; Bedotti, A. Hydraulic Hybrid Excavator—Mathematical Model Validation and Energy Analysis. *Energies* **2016**, *9*, 1002. [CrossRef]
60. Pichlmaier, B.; Breu, W.; Szajek, A. Electrification of Tractors. *ATZ offhighway* **2014**, *7*, 78–86. [CrossRef]
61. German Electrical and Electronic Manufacturers' Association (ZVEI). *Voltage Classes for Electric Mobility*; ZVEI: Frankfurt am Main, Germany, 2013.
62. German, J. *Hybrid Vehicles—Technology Development and Cost Reduction*; The International Council on Clean Transportation: Washington, DC, USA, 2015.
63. Jaguemont, J.; Boulon, L.; Venet, P.; Dubé, Y.; Sari, A. Lithium-Ion Battery Aging Experiments at Subzero Temperatures and Model Development for Capacity Fade Estimation. *IEEE Trans. Veh. Technol.* **2016**, *65*, 4328–4343. [CrossRef]
64. Zhang, X.; Kong, X.; Li, G.; Li, J. Thermodynamic assessment of active cooling/heating methods for lithium-ion batteries of electric vehicles in extreme conditions. *Energy* **2014**, *64*, 1092–1101. [CrossRef]
65. Lu, L.; Han, X.; Li, J.; Hua, J.; Ouyang, M. A review on the key issues for lithium-ion battery management in electric vehicles. *J. Power Sources* **2013**, *226*, 272–288. [CrossRef]
66. Campillo, J.; Ghaviha, N.; Zimmerman, N.; Dahlquist, E. Flow batteries use potential in heavy vehicles. In Proceedings of the International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS), Aachen, Germany, 3–5 March 2015.
67. Christensen, J.; Albertus, P.; Sanchez-Carrera, R.S.; Lohmann, T.; Kozinsky, B.; Liedtke, R.; Ahmed, J.; Kojic, A. A Critical Review of Li/Air Batteries. *J. Electrochem. Soc.* **2012**, *159*, R1–R30. [CrossRef]
68. Barghamadi, M.; Kapoor, A.; Wenz, C. A Review on Li-S Batteries as a High Efficiency Rechargeable Lithium Battery. *J. Electrochem. Soc.* **2013**, *160*, A1256–A1263. [CrossRef]
69. Malik, M.; Dincer, I.; Rosen, M.A. Review on use of phase change materials in battery thermal management for electric and hybrid electric vehicles. *Int. J. Energy Res.* **2016**, *40*, 1011–1031. [CrossRef]
70. Burke, A.; Miller, M. The power capability of ultracapacitors and lithium batteries for electric and hybrid vehicle applications. *J. Power Sources* **2011**, *196*, 514–522. [CrossRef]
71. Zeraoulia, M.; Benbouzid, M.E.; Diallo, D. Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study. *IEEE Trans. Veh. Technol.* **2006**, *55*, 1756–1764. [CrossRef]
72. Sakti, A.; Michalek, J.J.; Fuchs, E.R.; Whitacre, J.F. A techno-economic analysis and optimization of Li-ion batteries for light-duty passenger vehicle electrification. *J. Power Sources* **2015**, *273*, 966–980. [CrossRef]
73. Weiss, M.; Patel, M.K.; Junginger, M.; Perujo, A.; Bonnel, P.; van Grootveld, G. On the electrification of road transport - Learning rates and price forecasts for hybrid-electric and battery-electric vehicles. *Energy Policy* **2012**, *48*, 374–393. [CrossRef]
74. Kailasam, C. *Strategic Analysis of Global Hybrid and Electric Heavy-Duty Transit Bus Market*; Frost & Sullivan: New York, NY, USA, 2014.

75. Bakker, S.; Budde, B. Technological Hype and Disappointment—Lessons from the Hydrogen and Fuel Cell Case. In Proceedings of the Electric Vehicle Symposium (EVS26), Los Angeles, CA, USA, 6–9 May 2012.
76. Jun, S.-P. A comparative study of hype cycles among actors within the socio-technical system: With a focus on the case study of hybrid cars. *Technol. Forecast. Soc. Chang.* **2012**, *79*, 1413–1430. [CrossRef]
77. Frandsen, T.V.; Mathe, L.; Berg, N.I.; Holm, R.K.; Matzen, T.N.; Rasmussen, P.O.; Jensen, K.K. Motor Integrated Permanent Magnet Gear in a Battery Electrical Vehicle. *IEEE Trans. Ind. Appl.* **2015**, *51*, 1516–1525. [CrossRef]
78. Yu, C.H.; Tseng, C.Y. Research on gear-change control technology for the clutchless automatic–manual transmission of an electric vehicle. *Proc. Inst. Mech. Eng. Part D J. Autom. Eng.* **2013**, *227*, 1446–1458. [CrossRef]
79. Debnath, S.C. Environmental Regulations Become Restriction or a Cause for Innovation—A Case Study of Toyota Prius and Nissan Leaf. *Procedia Soc. Behav. Sci.* **2015**, *195*, 324–333. [CrossRef]
80. Lajunen, A. Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transp. Res. Part C Emerg. Technol.* **2014**, *38*, 1–15. [CrossRef]
81. Pihlatie, M.; Kukkonen, S.; Halmeaho, T.; Karvonen, V.; Nylund, N.-O. Fully electric city buses—The viable option. In Proceedings of the IEEE International Electric Vehicle Conference (IEVC), Florence, Italy, 17–19 December 2014.
82. Mahmoud, M.; Garnett, R.; Ferguson, M.; Kanaroglou, P. Electric buses: A review of alternative powertrains. *Renew. Sustain. Energy Rev.* **2016**, *62*, 673–684. [CrossRef]
83. Rothgang, S.; Rogge, M.; Becker, J.; Sauer, D.U. Battery Design for Successful Electrification in Public Transport. *Energies* **2015**, *8*, 6715–6737. [CrossRef]
84. Corazza, M.V.; Guida, U.; Musso, A.; Tozz, M. A European vision for more environmentally friendly buses. *Transp. Res. Part D Transp. Environ.* **2015**, *45*, 48–63. [CrossRef]
85. Xylia, M.; Leduc, S.; Patrizio, P.; Kraxner, F.; Silveira, S. Locating charging infrastructure for electric buses in Stockholm. *Transp. Res. Part C Emerg. Technol.* **2017**, *78*, 183–200. [CrossRef]
86. Rogge, M.; Wollny, S.; Sauer, D.U. Fast Charging Battery Buses for the Electrification of Urban Public Transport—A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements. *Energies* **2015**, *8*, 4587–4606. [CrossRef]
87. Lajunen, A.; Tammi, K. Energy consumption and carbon dioxide emission analysis for electric city buses. In Proceedings of the Electric Vehicle Symposium (EVS29), Montréal, QC, Canada, 19–22 June 2016.
88. Jacobs, W.; Hodkiewicz, M.R.; Braunl, T. A cost-benefit analysis of electric loaders to reduce diesel emissions in underground hard rock mines. In Proceedings of the IEEE Industry Applications Society Annual Meeting, Vancouver, BC, Canada, 5–9 October 2014.
89. Kalmar, Hybrid Straddle Carrier. Kalmar. Available online: https://www.kalmarglobal.com/equipment/straddle-carriers/hybrid (accessed on 20 December 2016).
90. Beidas-Strom, S.; Pescatori, A. *Oil Price Volatility and the Role of Speculation*; International Monetary Fund: Washington, DC, USA, 2014.
91. Van Vliet, O.P.; Kruithof, T.; Turkenburg, W.C.; Faaij, A.P. Techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars. *J. Power Sources* **2010**, *19*, 6570–6585. [CrossRef]
92. Yong, J.Y.; Ramachandaramurthy, V.K.; Tan, K.M.; Mithulananthan, N. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. *Renew. Sustain. Energy Rev.* **2015**, *49*, 365–385. [CrossRef]
93. Jaafar, A.; Sareni, B.; Roboam, X. A Systemic Approach Integrating Driving Cycles for the Design of Hybrid Locomotives. *IEEE Trans. Veh. Technol.* **2013**, *62*, 3541–3550. [CrossRef]
94. Lund, P.D.; Lindgren, J.; Mikkola, J.; Salpakari, J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev.* **2015**, *45*, 785–807. [CrossRef]
95. BAE, HybriDrive Propulsion Systems. BAE Systems. Available online: http://www.hybridrive.com (accessed on 20 December 2016).
96. Seo, J.; Lee, S.; Kim, J.; Kim, S.-K. Task planner design for an automated excavation system. *Autom. Constr.* **2011**, *20*, 954–966. [CrossRef]
97. Halbach, E.; Halme, A. Job planning and supervisory control for automated earthmoving using 3D graphical tools. *Autom. Constr.* **2013**, *32*, 145–160. [CrossRef]
98. Gustafson, A. *Automation of Load Haul Dump Machines*; Luleå University of Technology: Luleå, Sweden, 2011.

99. Durrant-Whyte, H.; Pagac, D.; Rogers, B.; Stevens, M.; Nelmes, G. An autonomous straddle carrier for movement of shipping containers. *IEEE Robot. Autom. Mag.* **2007**, *14*, 14–23. [CrossRef]
100. Li, L.; Wen, D.; Zheng, N.-N.; Shen, L.-C. Cognitive Cars: A New Frontier for ADAS Research. *IEEE Trans. Intell. Transp. Syst.* **2012**, *13*, 395–407. [CrossRef]
101. Bechar, A.; Vigneault, C. Agricultural robots for field operations: Concepts and components. *Biosyst. Eng.* **2016**, *149*, 94–111. [CrossRef]
102. Graabak, I.; Wu, Q.; Warland, L.; Liu, Z. Optimal planning of the Nordic transmission system with 100% electric vehicle penetration of passenger cars by 2050. *Energy* **2016**, *107*, 648–660. [CrossRef]
103. Karatzos, S.; McMillan, J.D.; Saddler, J.N. *The Potential and Challenges of Drop-In Biofuels*; A Report by IEA Bioenergy Task 39; International Energy Agency: Paris, France, 2014.
104. Mayer, T.; Kreyenberg, D.; Wind, J.; Braun, F. Feasibility study of 2020 target costs for PEM fuel cells and lithium-ion batteries: A two-factor experience curve approach. *Int. J. Hydrogen Energy* **2012**, *37*, 14463–14474. [CrossRef]
105. James, B.D.; Moton, J.M.; Colella, W.G. *Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Transportation Applications—2013 Update*; Strategic Analysis Inc.: Arlington, VA, USA, 2014.