CONSTRUCTION CLIMATE CHALLENGE

Exploring future energy storage systems for construction machineries

- a sustainability review

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Executive summary

Parts of the goals of the Construction Climate Challenge can be achieved by proper electrification or hybridisation of construction machinery. The energy storage system employed must, however, be specifically optimised for construction machinery as the demands are rather unique compared to other types of hybrid and electric vehicles. In this pre-study we have evaluated the most promising emerging energy storage technologies, both in terms of state-of-the art and development potential, with a target of implementation in 2025. While many of the very fundamentals of the emerging technologies are the same as for the energy storage solutions already available today, our focus has been on how they may differ in crucial details and along the full chain of moving from materials via cells and pack to installation.

The lithium ion battery (LIB) technology is currently the prime alternative to support electrification of vehicles. This technology is, however, still limiting in terms of applications where higher energy densities are desired. Even more severe is the limitation when it comes to high power densities, as LIB based energy storage systems show strong capacity fading at high charge/discharge rates as well as limited cyclability. The LIB technology is also challenged by several sustainability/resource issues – primarily associated with the materials used.

To overcome the above limitations in terms of energy density, cyclability, power outtake, cost, sustainability, etc several different approaches have been proposed. These ‘next generation batteries’ are currently explored at the laboratory scale and may be eventually become emerging energy storage technologies. A range of these concepts have here been benchmarked towards the LIB technology to create both a construction machinery specific overview as well as a more general overview; lithium-sulphur (Li-S) batteries, Na-ion batteries, Mg-batteries, and asymmetric super capacitors.

Fundamentally, the Li-S battery is one of the most promising technologies with a theoretical capacity almost 10 times that of LIBs. Apart from the advantage of high capacity, the precious and expensive metals such as cobalt in the LIB cathodes are replaced by abundant, environmentally managable, and cheap sulphur. By transferring from the Li to the corresponding Na or Mg based technologies other advantages are possible. The Na-ion battery has theoretically a capacity on par with LIBs, while considered to be much cheaper and sustainable, whereas Mg-based batteries promise higher capacities through the use of multivalent ions. The asymmetric super capacitors offer very high power capabilities, but limited energy density.

The task-force of the project has a combined expertise in materials science, environmental sustainability assessment and eco-design, and in machine usage and requirements of energy storage systems. The aim is to review if the current research and development in this field is fit to meet the construction site climate challenges. Our focus has been the fundamental and practical limitations stemming from materials and concepts advancing LIB technology towards more power density oriented solutions. The success of the project has relied on a careful analysis of materials development, materials characterization, and extended efforts

in identifying the market perspectives. We finally present a road map towards market introduction of the selected emerging energy storage solutions, starting from applied research *via* advanced engineering towards high technology readiness levels.

The road map and research agenda included provide directions for both fundamental and application oriented research, while keeping the very practical aspects of the construction machinery demands in mind. This opens for creation of knowledge and competencies valuable for the industry as well as for academia. While targeting the construction machinery specifically, many of the research activities proposed will nevertheless create results general enough to be valuable also for other heavy vehicle applications such as city mobility buses and trucks.

The different emerging energy storage technologies are at various development stages for being of interest in construction machinery applications by 2025. In order to be considered as a suitable technology some main research activities have to be successful. The main conclusion of this pre-study is that research activities aimed at creating a better energy storage for construction site machineries by employing these emerging technologies should be directed towards asymmetric super capacitors and Na-ion batteries.

This conclusion is based on taking the following main advantages into consideration:

- High rate capabilities
- Pack simplicity
- Low environmental impact

From a sustainability perspective the Na-ion battery technology is preferred. This is mainly due to *i*) the availability of Na, *ii*) that no Cu current collectors are needed, and *iii*) an energy efficient electrolyte production. The current main drawback, however, is the use of vanadium based cathode materials and therefore further research activities should aim at replacing this material to further improve the already low environmental impact of the concept.

Regardless of the emerging technology chosen, the charging strategies will always highly affect the lifetime cost, pack installation, and environmental impact of the energy storage. To charge many times during the day is preferred from a weight and volume perspective, but from a cost perspective, both lifetime and environmental damage cost, to charge only a few times per day are preferred; lunch breaks, during the night, etc.

As for charging strategies there are also general routes when the focus is on environmental sustainability and climate perspective: *i*) low carbon intensity in the energy system and *ii*) decreased use of scarce materials. Sodium-ion batteries and asymmetric capacitors seem to have the greatest potential for high sustainability performance. These findings are though highly sensitive to recycling options, the carbon intensity of the energy system, and modifications of production processes.

Background

By employing electrification or hybridisation of construction machinery parts of the goals of the Construction Climate Challenge (CCC) can be achieved with maintained functionality of the machineries at the construction site. The energy storage system must, however, be specifically optimised for construction machinery as the demands are rather unique compared to other types of hybrid and electric vehicles currently being developed. In this pre-study we here look at the most promising emerging energy storage technologies with the time-line of 2025 as a target for implementation. While the fundamentals are the same as for the energy storage solutions available today, we stress how these emerging technologies may differ in crucial details and when moving from materials via cells and pack to installations in construction site machineries.

For any energy storage system there is always the struggle to provide both the best possible energy availability and at the same time the best possible power performance. These very basic facts affect the algorithms for the usage pattern, in terms of possible state of charge and charge rates for a hybrid/electric vehicle, and also severely limit the reduction in fuel consumption possible. In addition, the charging rates possible/recommended crucially affect the cycle-life of the energy storage system and consequently the performance of the vehicle or the stationary power supply systems. Today many energy storage systems are forced to be over-sized to comply with the two main needs of energy and power. Joint solutions, combining a battery, with high energy density, and a super capacitor, with high power density, controlled by a common battery management system (BMS), are of course possible. However, the integration of these two diverse devices is far from straightforward and the complexity in both the system design and the BMS drives cost, increases the risks, and reduces the overall efficiency.

This combination of limitations in energy and power density is particularly challenging for applications at construction sites, both for electrification of construction machineries and for local energy storage at the construction site itself. One can note that similar requirements are also found for applications in hybrid heavy-duty vehicles such as buses and trucks. Apart from complying with the technical criteria of applications, any new technology furthermore has to be sustainable in a life cycle perspective adding demands on abundance and/or recycling of materials.

The lithium ion battery (LIB) technology is currently seen as the prime alternative to support the electrification of vehicles and smart-grid applications. This technology is, however, still limiting in terms of applications where even higher energy densities are desired. Even more severe is the limitation when it comes to power density, as LIB based energy storage systems show strong capacity fading at high charge/discharge rates as well as limited cyclability (of the order of 10^3 cycles). The technology is also challenged by several sustainability/resource issues – primarily associated with the materials used.

To overcome the above limitations (in terms of energy density, cyclability, power outtake, cost, sustainability) of the currently totally dominant LIB technology several different approaches have been proposed, and are explored, on the laboratory scale – 'next generation batteries'. The Lithium-sulphur (Li-S) battery is one of the most promising technologies with a theoretical capacity almost 10 times that of LIBs. Apart from the advantage of high capacity, precious and expensive metals such as cobalt in the cathode are replaced by abundant, environmentally friendly, and cheap sulphur. However, so far this technology is not ready for commercialization due to a too short cycle life and a strong capacity fading at high power outtake. Another interesting approach is to transfer from the Li to the corresponding Na or Mg based technologies. The former has theoretically a capacity on par with LIBs and is considered to be much cheaper and sustainable, whereas Mg based batteries promise higher capacities through the use of multivalent ions (*i.e.* Mg^{2+}).

One particularly interesting approach with the aim to simultaneously in a single device achieve both high power and energy densities is the asymmetric super capacitor concept. By using both battery and super capacitor materials this device has the potential to fill a critical void in the combined energy and power demand chart. This concept is proven, but there is currently a very rapid development globally. By smart choices of materials the robustness and fast-charging features of a super capacitor can be maintained, while at the same time retaining the energy density performance of a battery.

All the concepts described above have the promise to meet the energy storage system requirements at a construction site – given the special combined demands for energy and power, but for each technology there is also a need for improvement – starting from the materials used. Equally important for future implementation is to analyse whether or not the suggested concepts can be truly sustainable from an environmental impact and life-cycle perspective, and if the total cost can be envisioned to make the technology competitive.

In this pre-study we have explored the potential of future energy storage systems for application at construction sites with an emphasis on the machinery. The aim is to review if the current research and development in this field is fit to meet the construction site climate challenges. Our focus has been the fundamental and practical limitations stemming from materials and concepts advancing LIB technology towards more power density oriented solutions. We finally present a road map towards market introduction of the selected emerging energy storage solutions, starting from applied research *via* advanced engineering towards high technology readiness levels.

Objectives and scope of the pre-study

In this project we have addressed the combined energy and power "dilemma" by analysing various emerging energy storage system solutions from a sustainable construction site perspective. The two main overall targets are:

- to find the route for selecting the right energy storage system fulfilling the challenges of the construction site of tomorrow.
- to create a research agenda for these energy storage systems to bring the most promising technology(ies) to realisation.

All results and conclusions are based on construction machineries having different degrees of electrification and charging strategies. More specifically, the targeted types of machines are wheel loaders and articulated haulers. The charging strategies are set to these scenarios:

i) to charge within the cycle while driving, *ii*) at lunch breaks, or *iii*) during night. The energy and power demands for the machines are obtained from vehicle simulations, using real driving conditions, performed and provided to us by Volvo Constructions Equipment (VCE).

Since the materials used in any energy storage system will set the boundary conditions for the performance, different materials will be evaluated in terms of energy storage and power capability, sustainability, potential cost, and in a time-to-market perspective. In particular we explore the use of new materials, *e.g.* application of ionic liquids to the electrolyte to improve the capacity and safety, and the use of nano-structured cathodes based on advanced materials, such as graphene, to boost the power density. The key is to assess how to optimise the materials and concepts, in order to meet the requirements and operational conditions at the energy storage system level. For a construction site, there are challenges to overcome to improve the environment by better energy usage, both for the machines in use and for the site as such.

The task-force of the project has a combined expertise in materials science, environmental sustainability assessment and eco-design, and in machine usage and requirements of energy storage systems. The success of the project relies on a careful analysis of materials development, materials characterization, and extended efforts in identifying the market perspectives.

The road map and research agenda resulting from the pre-study give directions for both fundamental and application oriented research, while keeping the very practical aspects of the machinery demands in mind, and opens for creation of knowledge and competencies valuable for the industry as well as for academia. Many of the research activities proposed will create results valuable also for other vehicle applications such as city mobility buses and trucks.

Towards 2025

The implementation time for new technologies in machinery applications is substantial and thus any emerging technology must be at least at a concept stage during the coming two-three years if a market introduction by 2025 should be possible. In this study, however, as we aim for truly emerging technologies, the aim is an energy storage system solution ready for the concept stage machinery by 2025.

New improved electrochemical active materials are needed to enhance energy storage performance. The materials must, however, meet tough sustainability criteria and result in an as low environmental impact as possible. Furthermore, the energy storage system must be further optimised along with improved production processes; from raw materials to complete cells, including a sustainable production process in all steps. Moreover, the understanding of ageing mechanisms to prolong the life and/or use more of the energy will most likely be the main issue for machinery and energy storage manufacturers to enhance both calendar and cycle life. The production of active materials, cells, and modules/packs should be further improved to reduce the cost, and to increase the robustness, capacity and safety and will also consider recycling issues already in the design stage.

There are some general routes to improve the performance, life, and cost of cells and packs, all summarised in Table 1.

Table 1. Improvement routes of cells and packs.

	Cell level	**Pack level**
Energy	High-voltage/high-capacity materials (electrodes and electrolytes)	Low-weight balance of plant components, Control strategies
Power	Electrode design (*e.g.* 3D design), Utilisation of high-rate electrode materials	Cell-to-cell connections, Control strategies, Thermal management
Life	Understanding of degradation mechanisms	Thermal management, Control strategies
Safety	Electrolyte (salts, solvents and additives), Separators, Electrode coatings	Thermal management, Control strategies, Housing, Electronics, Application integration
Cost	Standardised cell formats, Use of low-cost raw materials and production processes	Modularisation, Standardised electrical components, Selection of optimal cell for specific applications, Simple and robust control system

Emerging battery technologies with new functional materials and/or concepts can also be the route for enhanced performance, especially as the (theoretical) energy density often is very attractive. To be an attractive technology for electric machineries these emerging technologies will, however, also have to show improved performance on the battery pack level and equal or better cost, in combination with long life. Clearly there are limitations with this simple view; the theoretical values are for cells and not for the corresponding pack, and moreover, especially important from an application perspective, the power capabilities are not included. Nevertheless, the theoretical figures regarding the energy density of materials combinations provide some concrete basis for how (large) improvements possibly can be made.

Based on a broad general knowledge within the field, the following energy storage technologies have been considered:

1. Improved Li-ion cells utilising a high-voltage cathode and a silicon-carbon based anode. This combination will give both higher cell voltage and improved cell capacity. The main challenges are the electrolyte stability and the volume changes of the anode during cycling.
2. Na-ion cells; due to the availability of sodium and the potential for cell cost reduction. Unlike the Li-ion cells, in the Na-ion cells the current collectors for both the anode and the cathode are made of aluminium, i.e. no use of copper, which will reduce both cell weight and cost.

3. Magnesium cells; due to the potential of high capacity cells as two electrons are involved in the redox reactions. The main challenges are the stability of the electrolyte and to find a suitable cathode material.
4. Li-sulphur cells based on metallic lithium as the anode and a sulphur-carbon mix as the cathode. The cell capacity and cost are the main drivers, whereas the challenges are the lower voltages and power capabilities of the cell.
5. Asymmetric super capacitors utilising an anode of activated carbon and a metal oxide as cathode. Compared to 'normal' super capacitors, these asymmetric capacitors exhibit higher energy densities, but still have high power capabilities.

These emerging technologies have all been selected with a construction site perspective and 2025 as the time-frame for installation. Properties such as power capability, cost reduction potential, and sustainability, have been the underlying constraints for the selection of technologies. There is a wider scope of emerging energy storage concepts at present to consider in general – for example the Li-air and redox flow technologies. These two concepts with nice theoretical promise would, however, result in too large system installations to be of interest for any construction machineries –due to low power capabilities and low energy densities. This is foremost a consequence of these technologies needs of auxiliary system components: tanks, pumps, air-cleaning facilities, etc, but also due to a lack of proven feasibility to in practice be anywhere near the theoretical promise. If substantial research breakthroughs, changing this picture, are made, these technologies would still be more for the time-frame of 2050 than 2025.

Review of future energy storage technologies

In the following the fundamentals of each of the considered emerging technologies are briefly described and the research trends are summarised. The implication of the basics of the different technologies for machinery installation is subsequently treated. While many of the emerging technologies are studied extensively at an academic level, only limited relevant data are available from practical implementations.

Li-ion

The Li-ion battery technology of today can be further improved by advancing the performance of materials, designs, and processes aiming both at performance and cost. Specific areas of improvements include high voltage cathodes, high-energy anodes, high voltage and non-flammable electrolytes, novel processing technologies, high energy and low cost electrode designs.

The capacity of an active electrode material can be increased by: *i)* increasing the average electrode potential, *ii)* increasing the number of electrons involved in the redox reactions, and *iii)* decreasing the molecular weight per mole electrons exchanged. For the next generation Li-ion batteries mainly the first route is in focus, even if the two latter are being investigated to some extent.

The research and development on advanced cathodes is primarily focused on the Li-Mn rich oxide materials of general formula $xLi_2MnO_3\cdot(1-x)LiMO_2$ (M=Ni, Mn, Co), the 5V spinel materials (*e.g.* $LiMn_{1.5}Ni_{0.5}O_4$), and Ni-rich NMC materials charged to higher voltages. The Li-Mn rich materials have the potential to give cells of rather high energy density, about 300 Wh/kg [1]. To charge cells utilising the 'traditional' NMC to higher voltage levels, for example to 4.6 V instead of 4.2 V, would improve the energy density by about 20%. The durability of such a voltage increase has, however, to be secured. The electrolyte stability and the structural disordering occurring during cycling of the cathode material are issues to be understood. In addition, the use of high-voltage spinel materials is limited by the instability of the electrolyte at these voltage levels. Surface coatings, electrolyte purity, additives to create more stable interfaces, and additive/binder free alternatives are routes forward. Other routes are doping of the NMC materials and to increase the stability of inactive components (like current collector, binder, and conductive additive) at high voltages.

The issues of Li-Mn rich materials are primarily voltage fade, high impedance especially at low state of charge, metal dissolution, and low electrode density. By increasing the voltage level an improved capacity will be achieved. Approaches to enable higher operation voltage include varying the material composition within the particles (for example the outer material being more stable against the electrolyte), coatings, metal substitutions, and electrolyte additives that form a protective coating on the cathode particles.

The main "next generation" anode technologies pursued are alloy based, predominantly silicon or tin based anodes. Silicon based alloys are one of the most interesting anodes concepts in terms of high capacity. The challenge is the large volume expansion during the alloying reactions with lithium. Research efforts in order to improve Si-based anodes include: Cu foam current collectors to enable better utilization of Si nano-particles, Si nano-wires directly deposited on current collectors, a variety of nano-structured and nano-porous Si materials, and a new group of electrically conducting binders for use in Si anodes. All these routes have the potential to achieve materials with more than 1000 mAh/g, based on half-cell experiments. The challenge is to tackle the stability vs. electrolytes and enable higher loadings of active materials to make the electrode structures more relevant to commercial batteries. Other alloy-based anodes are also under development. One example is a Si/graphene composite material developed by Argonne National Lab [2]. Independent tests on full-cell measurements have shown (with advanced cathode and electrolyte materials) 525 Wh/kg and a specific anode capacity of 1250 mAh/g [3].

On an even more exploratory front, research is performed on conversion reaction materials (*e.g.* CoO, Fe_2O_3, and CuF). These materials provide high capacity, often more than 600 mAh/g [4]. However, the issues with these materials are poor kinetics, poor capacity retention on cycling, often due to metal agglomeration, large irreversible capacity losses, and large voltage hysteresis.

Current electrolytes, typically 1M $LiPF_6$ in 1:1 EC/DMC, provide good performance and stability, but only within limited voltage and temperature ranges. The solvents are highly flammable and typically have a high vapour pressure, which causes them to gas at elevated temperatures, building up pressure within cells over time. In addition, the $LiPF_6$ salt is known to react almost instantly with traces of water, often from the cell production, producing HF, which in turn attacks nearly all elements of the cell. This reaction, along with the instability of $LiPF_6$ above ~80°C, leads in part to the challenges of high temperature capability of LIBs.

Work on new electrolytes and additives is focused on one or more of the possible improvement areas of high voltage stability, high temperature stability, low temperature operation, abuse tolerance, lower cost, and possibly longer life through interface stabilisation. Research areas include: flame retardant liquid electrolytes, single ion conductor electrolytes, new salts providing better high temperature stability, and electrolytes that enable much lower operation temperature. However, one of the main challenges is to find electrolytes with improved high voltage stability; an issue for example handled by use of additives incl. ionic liquids.

Sodium-ion

Based on the same basic principles as the Li-ion concept other types of metal-ion (Me-ion) concepts are possible. The Me-ion concepts of relevance depend on the electrochemical capacity and the operating voltages.

Na-ion is one of the most attractive Me-ion candidates and the concept is quite comparable to the Li-ion concept; the voltage levels are in the same range and the energy density is comparable. The principle of cell operation is the same as its Li-ion cousin: sodium ions are shuttled between the cathode and anode through a non-aqueous electrolyte. During charge, sodium ions are extracted from the high voltage positive electrode, with a working potential around or above 3.0 V vs. Na/Na^+, and are inserted into the low voltage negative electrode, whose working potential is ideally lower than 1.0 V vs. Na/Na^+.

Sodium is three times heavier than lithium (23 g/mol and 6.9 g/mol, respectively) and is 0.3 V less electropositive, so relatively high gravimetric and volumetric capacity penalties (ca. 15%) may have to be paid in moving from lithium to sodium batteries. Yet, the 0.3 V difference is based on the metals and not on the 'true' anode materials used. Moreover, the availability of sodium in the Earth's crust is more than 1000 times higher than that of lithium, resulting in a more solid sustainability perspective and long term cost competitiveness for the Na-ion concept. Another advantage of Na-ion cells compared to Li-ion cells is the fact that Na does not form alloys with aluminium, hence aluminium can be used as current collectors for both electrodes, resulting in a lower total weight (and material cost) of the Na-ion cell compared to the Li-ion cell (by avoiding the heavy and expensive copper). A 7% weight reduction of the cell can be expected. If the Na-ion technology is successfully achieved, early estimates predict a 30% cost decrease of the cell materials (incl. the change from Cu to Al current collectors) with respect to Li-ion technology while ensuring sustainability [5]. Such a cost reduction also takes into account the possibility to develop cheaper sodium-based electrolytes as high quality sodium salts are cheaper to produce. An analysis of the electrolytes from both a performance and an environmental aspect has been performed [6].

Even if the Na-ion technology is still immature, it is clear that the Na-ion technology can compete with the Li-ion technology in several aspects; about the same capacity as Li-ion materials with the potential of lower raw material costs. With respect to safety there is no empirical indication, or scientific grounds, to tell whether Na-ion batteries will be safer or not than Li-ion batteries, but preliminary tests suggest that they will be at least as safe as Li-ion batteries. Some recent industrial R&D has been disclosed to some extent, for example by Toyota [7]. Already in 2003 Valence Technologies reported a 3.7 V Na-ion cell using $NaVPO_4F$//hard carbon. One openly distributed industrial report by Sumitomo disclosed the fabrication of $NaFe_{0.4}Mn_{0.3}Ni_{0.3}O_2$//hard carbon coin and laminated cells. Furthermore, they also report about heating and overcharging tests carried out, indicating a better performance than for comparable Li-ion cells, as 200% overcharge did only result in swelling without burst or ignition.

Faradion, a UK-based company developing Na-ion cells, claim an energy density of their 18650-cells to be 126 Wh/kg and 343 Wh/L [8], roughly half of the Li-ion 18650-cells (C//NCA chemistry) produced by Panasonic for Tesla and about 30% more energy density than a 18650-cell made of C//LFP chemistry. Faradion has recently disclosed 3Ah Na-ion pouch cells using hard carbon and a layered oxide cathode (165 mAh/g). These are reported as comparable to Li-ion state of the art.

Magnesium

The rechargeable Mg battery has for a long time been considered as a highly promising technology. A high theoretical capacity is related to the number of electrons involved in the redox reaction, why, despite larger atomic weights of the elements, magnesium and aluminium based concepts can be attractive because of their ability to exchange two and three electrons, respectively, compared to only one electron for lithium and sodium. The practical capacity in turn depends on the amount of ions used reversibly during the charge and discharge processes. The main issue for multivalent concepts is, however, to find durable materials for long-time cycling and at rates practical for applications.

Magnesium possesses several characteristics that rank it as one of the most favourable metal anodes for high energy-density batteries. Its specific volumetric capacity is greater than 3800 mAh/cm^3, higher than that for metallic Li (ca. 2050 mAh/cm^3). Moreover, Mg is a benign and abundant metal in the Earth's crust. Despite its potential reactivity it is stable enough in ambient atmosphere for handling and electrode preparation processes. The first breakthrough was demonstrated in 1990 with the development of a stable electrolyte. A decade later, the next breakthrough was achieved by the development of ethereal electrolytes containing Mg-haloalkyl aluminate complexes [9].

The main challenge of Mg based batteries and for all multivalent concepts, is the cathode. The cathode requires materials that allow both several oxidation state steps and acceptable diffusion rates of the Mg^{2+} cation. The ideal material would be a compound based on transition metals having one reversible redox couple per inserted Mg^{2+}, *i.e.* a two-electron reduction of the transition metal, *e.g.* vanadium, manganese, or titanium. The most promising materials are insertion compounds based on oxides or sulphides, due to their capacity and potential.

The two main routes taken at present to achieve high-energy rechargeable magnesium batteries are: *i)* relying on high capacity/low voltage Mg cathodes and *ii)* utilizing moderate capacity/high voltage Mg ion insertion cathodes. The latter will be limited by the maximum practical intercalation level attainable with Mg ions, which is estimated at 200–300 mAh/g. Several studies have concentrated on the development of cathode materials with higher capacities and voltage using complex electrolytes [10,11]. These cathodes are, however, limited to about 200 mAh/g and a 2 V operation voltage.

The most studied group of materials for the cathode is the Mg-based Chevrel phases $Mg_xMo_6T_8$, where T is S, Se, or a mixture thereof. Many of these materials suffer from low electronic conductivity and blended materials may therefore be used. The Chevrel phase compounds enable rapid Mg^{2+} diffusion rates due to the large amount of vacant sites available in the structure and the diffusion rates can be further enhanced at elevated temperatures. There are only a few other potential Mg cathode materials of interest. The main drawback of them all is a lower reversible capacity, true *e.g.* magnesium cobalt silicates. In some cases, these materials are targeted to operate at higher potentials.

To attain a specific energy comparable to that of Li-ion batteries, further breakthroughs are required for the stability of the electrolyte, and, as mentioned above, for high specific energy cathode materials. The main bottleneck is indeed the absence of suitable electrolytes, which also hinders proper testing of new prospective cathode material.

The first successful magnesium battery prototypes used Mo_6S_8 cathodes and were able to sustain more than 500 cycles at a moderate rate with low capacity fading, but the specific capacity was rather low (ca. 60 mAh/g). At present there are a few companies trying to develop rechargeable Mg batteries as part of their overall R&D efforts in the battery field:

Sony, LG Chem, Honda, and Toyota. The American company Pellion Technologies is the main actor fully devoted to development of high energy-density Mg rechargeable batteries [12].

Lithium-Sulphur

The reaction of elemental sulphur to Li_2S has a theoretical capacity of 1673 mAh/g and in combination with an anode of metallic lithium, Li-S batteries can reach gravimetric and volumetric energy densities of 2500 Wh/kg and 2800 Wh/L, respectively. The cost would be much less than a corresponding conventional Li-ion cell based on the materials cost – sulphur is a very cheap cathode material. In addition sulphur is an abundant element and non-toxic. Undoubtedly, these advantages make Li-S cells an attractive emerging battery technology. The main drawbacks are: the low cell voltage (ca. 2 V), the insulating nature of sulphur, creating a need for complex structured C/S composite cathodes, the polysulfide dissolution, causing active material loss, the low power capabilities, and the rapid capacity fading.

In the charged state sulphur exists in the form of a large molecule, S_8, in the cathode. The conversion to Li_2S is a multi-step reaction. At discharge lithium ions from the anode react with the sulphur based cathode and long-chain lithium polysulphides (Li_2S_x, $4 \leq x \leq 8$) are formed. These intermediate products, generated at the initial stages, are soluble in the commonly used electrolytes. In the subsequent stages of discharging these long-chain polysulphides will turn into insoluble Li_2S_2 and finally form Li_2S.

The composition of the electrolyte changes with voltage and furthermore a redox shuttle mechanism is created. Because of this the theoretical capacity can seldom be obtained in practice. Besides the electrochemical reactions, complicated disproportionation reactions of the poly-sulphides also take place in the electrolyte; all affected by the composition of the electrolyte and the temperature. Two recent reviews of electrolytes and salts for Li-S batteries are found in [13,14].

Lithium-sulphur batteries have been studied since the late 1960s. In spite of tremendous progress there are few reports on Li-S batteries with appreciable capacity performance up to 1000 cycles. There are thus still challenges remaining unsolved. The first is associated to the insulating nature of sulphur and its electrochemical products that only allow ions and electrons to diffuse on their surfaces. Second, polysulphides as discharge intermediate products dissolve into the commonly used organic electrolyte, which reduces the amount of active cathode material. The last major problem for Li-S batteries is the large volume expansion of sulphur, as high as ~80% during cycling. The cathode deteriorates by the internal strain leading to loss of contact between the electrode and current collector and severe capacity fading. To ensure consistent cycling performance of Li-S batteries over several hundreds or thousands of charge/discharge cycles, as required in practical applications, all these three problems need to be solved.

For construction site applications, the high energy density is attractive both in terms of weight and volume. The potential of low-cost is also attractive, while the main drawback is the low voltage output of ca 2 V. Furthermore, the self-discharge rate is high and there is a risk of H_2S evolution – a safety risk. From a safety perspective also the low melting point of S, 115 °C, has to be considered. Moreover, metallic lithium is also attributed with some inherent safety risks. If the cell is charged too fast, lithium dendrites may grow internally and in a worst-case scenario short-circuit the cell. Therefore, charge rate limitations are crucial and often in combination with some stability and protective layers on the metallic surface.

Today there are no known commercial Li-S cell prototypes, but the interest of the technology from vehicle manufacturers can clearly be seen at the European project perspective level. As an example; Renault, VW, and PSA are partners within the FP7 (LISSEN, EUROLIS) and Horizon 2020 (HELIS) projects within which some of us (AM, BS, and PJ) are active.

Asymmetric super capacitors

Super capacitors have been duly investigated for hybrid electric vehicles, especially for heavy-duty applications. The high power density and long durability are the main advantages. The drawbacks are mainly the low energy density and thereby the high cost of a pack. Besides the 'traditional' capacitance, a capacitor can be made of pseudo-capacitance character; asymmetric super capacitors. The energy is achieved by redox reactions, electrosorption on the surface of the electrode by specifically absorbed ions, which result in a reversible faradic charge-transfer at the electrode. Depending on the materials chosen for electrodes and electrolyte, different kinds of high-energy density capacitors can be tailored to suit a variety of applications and needs.

There are two fundamental ways to increase the energy density of a capacitor: by increasing the cell voltage or the capacitance. One way to increase the cell voltage is by changing the type of electrolyte. Another way is to utilise the advantages of asymmetric capacitors employing both faradic and non-faradic processes to increase the capacitance. Coupling a redox material with a high capacitance material results in both higher operational cell voltage and higher cell capacitance. One attractive type of asymmetric super capacitors is made by using activated carbon as one electrode and an insertion electrode of a Li-ion cell as the other, so called Li-ion capacitors. The high operational voltage enables Li-ion capacitors of both high power and high energy density: ca. 5 kW/kg and 20-30 Wh/kg is currently possible.

Some companies have already commercialised Li-ion capacitors, *e.g.* JM Energy, FDK, ATC. Another commercial example of this type of capacitors is developed by Fuji Heavy Industry, using a pre-lithiated carbon anode together with an activated carbon cathode, resulting in a cell of 3.8 V and an energy density of more than 15 Wh/kg [15]. The drawback is a limiting charging rate and the low-temperature performance due to the graphite based insertion anode. Moreover, the process of pre-lithiation of the anode may lead to poor cost-effectiveness or instability of the quality in mass production, why alternative solutions for the anode is a current research topic.

Pros and cons

The advantages and drawbacks of the emerging technologies considered in this pre-study are summarised in a short list below. The benchmark used is the Li-ion technology of today (2015).

Next generation Li-ion:
+ High cell voltage → stable electrolyte needed.
+ Less amount of Co used → reduced cost. Drawback: less interesting for recycling?
+ Minor system changes
- Minor improvements in energy and power density

Na-ion:
+ Abundant and less expensive raw materials. Drawback: less interesting for recycling?
+ Same basic production tools and schemes as for Li-ion
+ Aluminium current collectors for both electrodes → cost and weight reduction. Drawback: less interesting for recycling?
- Likely slightly heavier and larger cells compared to Li-ion of the same capacity
- No or minor improvements in power density.

Mg:
+ High energy density due to two electron redox reaction
- Low cell voltage → more cells needed to meet system voltage requirements
- Costly electrolyte?
- No cell prototypes demonstrated

Li-S:
+ High energy density at cell and pack level
+ Cost reduction: cheap cathode material
- Low cell voltage → more cells needed to meet system voltage requirements
- Poor rate capability → more cells needed to meet power requirements
- Production process of cathode can be complex and overall production processes must be developed
- Safety issues related to metallic Li and melting of sulphur

Asymmetric super capacitors:
+ High rate capabilities
+ High cell voltage
+ Concepts in production
- Low energy density compared to battery technologies → more cells needed to meet energy requirements

Construction site challenge

In this pre-study two representative construction machineries have been used as targets for the evaluation of the emerging technologies: wheel loaders and articulated haulers. In addition, both battery electric (BEV) and plug-in hybrid electric (PHEV) conditions have been evaluated. Moreover, we have considered that the construction machineries can be charged in different periods during the day: at lunch breaks, during the night, or in every working cycle. The energy and power requirements for all machineries and all charging combinations are based on simulations made by Volvo Construction Equipment, using real driving and machinery conditions, and provided to us as input. All machinery and charging strategies are summarised in Table 2.

Table 2. The machinery requirements and charging possibilities used in the pre-study. Data from simulations made by Volvo Construction Equipment.

Machinery type and case	***Energy per cycle (kWh)***	***Average cycle power (kW)***	***Diesel consumption per cycle (L)***	***Charging strategy***	***Charging time (sec)***
BEV – 1a	1	30	0	cycle	30
BEV – 1b	1	30	0	night	57600
BEV – 2a	4.5	56	0	cycle	30
BEV – 2b	4.5	56	0	night	57600
BEV – 2c	4.5	49	0	cycle	100
PHEV – 1a	1.1	36	0.3	cycle	30
PHEV – 1b	0.3	10	0.5	Lunch and night	2400
PHEV – 2a	0.4	8	2.8	Lunch and night	2400
PHEV – 2b	1.2	25	2.5	cycle	30

Based on the data of Table 2, the different emerging technologies have been evaluated in terms of battery size, weight, cost, and environmental impact and sustainability. For each technology different material combinations will, as outlined in Chapter 2, give rise to different energy densities, both gravimetric and volumetric. The electrode and cell designs are, however, the main drivers for energy or power optimised cells. Especially the cell format (cylindrical, prismatic, or pouch) will give rise to large variations in performance, but will also vary widely among different cell suppliers. In this study only the total capacity need and power requirements have been considered in order to make the comparison more generic and foremost not supplier/manufacturing specific.

Based on the research trends overview the machinery implications of the emerging technologies can be treated in some detail with respect to future possibilities and limitations. The energy density is more or less available from researchers and companies developing alternative battery solutions. From a machinery perspective, the power capabilities are, however, even more interesting and unfortunately these data are often not available. Therefore, only plausible indications for different technologies impact on battery pack power for machinery installation will be given. The C-rate is the mainly used reference and the power capabilities are also related to the capacity of the cells. Moreover, if the cell is optimised towards energy or power will highly affect the power capabilities. The fast charging capabilities will at a first approximation follow the same trends.

The input data used for the different emerging technologies are given in Table 3. The data are obtained from small-scale laboratory cells and on literature reviews, as well as on a general knowledge about the improvement capabilities. The cell cost of improved Li-ion cells is based on data reported at by Avicenne and Total Battery Consultant [16,17]. The cell cost for the other emerging technologies are calculated using assumptions about material cost reduction potentials and the trends based on the basic layouts and materials used as more exact costs can only be provided when mass-production is in place.

Table 3. Input data for the emerging technologies used in this pre-study.

Technology	*Cell voltage (V)*	*Capacity cathode (mAh/g)*	*Capacity anode (mAh/g)*	*Average C-rate*	*Weight to size ratio*	*Cell cost per kWh (€)*
Li-ion	4.7	250	900	2	2	45
Na-ion	3.7	125	250	1	2.6	39
Mg	2.0	150	2200	0.5	1.5	40
Li-S	2.0	900	3000	0.1	1.1	27
As. S.C.	3.8	1500	150	5	1.0	45

As seen in Table 3 the large variations in concept and material's properties give rise to quite different performance figures. Even the basic conceptual differences can affect the solutions possible. For instance, the cell voltage will highly affect the number of cells needed for the electric system at the machinery level. In all cases the nominal energy storage system voltage is set to 600 V. The corresponding cell capacity requirements needed to fulfil the machinery demands are given in Table 4. The limiting factors for the different technologies are also given.

Table 4. The required capacity (in Ah) for the different emerging technologies.

Case No.	*Li-ion*	*Na-ion*	*Mg*	*Li-S*	*As. S.C.*	*Limiting factor*
BEV 1a	25	50	100	500	10	Cycle power
BEV 1b	293	293	293	500	293	Cycle energy, cycle power for Li-S
BEV 2a	47	93	186	931	19	Cycle power
BEV 2b	560	560	560	931	560	Cycle energy, cycle power for Li-S
BEV 2c	41	82	164	818	16	Cycle power
PHEV 1a	30	60	120	600	12	Cycle power
PHEV 1b	47	47	47	164	47	Cycle energy, cycle power for Li-S
PHEV 2a	23	23	27	137	23	Cycle energy, cycle power for Li-S and Mg
PHEV 2b	21	41	82	411	8	Cycle power

As can be seen from Table 4, the limiting factor is either the power requirement during operation or the energy required for the cycle. In none of the cases, the charging requirements will determine or limit the battery performance. It might, however, affect the durability of the energy storage system.

Each emerging energy storage technology can be modified and tailored to fit different purposes by altering the anode, cathode, and electrolyte material combination. The number of combinations can be large and all combinations are suitable for construction site applications; they can be too expensive and/or have a negative environmental impact. Moreover, all cell manufacturers use their own 'recipes' with several combinations and additives, especially for the electrolyte. The material combinations used in this pre-study are summarised in Table 5. Furthermore, the composite electrodes, *i.e.* all electrodes except the anodes of Mg and Li-S cells, which are metal foils, are held together and attached to the current collectors by using polyvinylidene difluoride (PVdF) as a binder. Moreover, all the cells are assumed being assembled in aluminium casings.

Table 5. Material combinations for the studied emerging energy storage technologies.

Technology	*Anode*	*Cathode*	*Electrolyte Salt*	*Electrolyte Solvent*	*Current collectors*
Li-ion	Si/C	$Li(NiMnCo)_2O_4$	$LiPF_6$	EC:DEC	Cu/Al
Na-ion	C	$Na_3V_2(PO_4)_2F_6$	$NaPF_6$	EC:DMC	Al/Al
Mg	Mg	$Mg_xMo_6S_8$	$Mg(TFSI)_2$	THF	Mg/Al
Li-S	Li	C/S	LiTFSI	DIOX:DME	Li/Al
As. S.C.	C	MnO_2	LiTFSI	$Pyr_{13}TFSI$	Al/Al

The environmental impact and sustainability performance has been analysed using life cycle assessment (LCA) methodology. We have followed the ISO 14044 standard and the goal and scope of the analysis is summarized in Table 6 below. The model used is based on long-term experiences within the field [18-21].

Table 6. Goal and scope of the LCA study.

Item	**Choice**
Intended application	Development of an R&D roadmap
Reasons for carrying out the study:	Request from CCC
Intended audience	Developers and manufacturers of construction equipment
Results are intended to be used in comparative assertions intended to be disclosed to the public	No
Product system to be studied	Battery packs for use in wheel-loaders and articulated haulers. Diesel motors are used as benchmarks.
Functions of the product system or, in the case of comparative studies, the systems	Energy delivery (capacity and power)
Functional unit	Life time energy delivery for 15 years of service
System boundary	From raw material extractions to recycling

	of battery packs. Energy loss during use was assigned to the life cycle of the battery pack. Electricity production is included.
Allocation procedures	Ecoinvent default
LCIA methodology and types of impacts	EPS v 2015d; Ecoindicator99 and Recipe in sensitivity analysis
Interpretation to be used	Sensitivity analysis
Data requirements	If available, taken from Ecoinvent 3.1. If not, literature data on production methods were used, and Ecoinvent data on raw materials were used, with assumptions of energy requirements and efficiencies of the reactions if they were not available.
Assumptions	95% energy efficiency in use 95% collection efficiency of used packs 90% recovery of Li, Cu, Al, Mo, Mn and Co EU 27 average electricity production
Value choices and optional elements	EPS v2015d has been used for monetary valuation of environmental impacts, i.e. environmental damage costs
Limitations	Several materials lack relevant LCI data, partly because they are not yet produced in large amounts.
Data quality requirements	Data for materials and processes contributing most to the monetary value of environmental impacts or to the added CO_2 emission were especially checked for being of reasonable magnitude.
Type of critical review, if any	None
Type and format of the report required for the study	Written report.

In the following Chapters, the results of the analyses of the different emerging energy storage solutions for the two types of construction machineries will be presented and discussed.

Results

For all emerging technologies the corresponding energy storage system has been evaluated for the two machinery types and the proposed charging strategies taken into account. The properties of interest have been weight and volume, part cost and lifetime cost, and the natural capital cost, in order to find the most optimal solution in a sustainability perspective. All of these are presented in some detail in this chapter. Depending on the most important requirements different system solutions become suitable/available and will be presented in Chapter 5.

Weight and Volume

The weight and volume of the packs for the different emerging technologies have been calculated. The calculations are based on machinery requirements and materials needed to meet the demands. Before moving to the results, it is important to point out that taking the step from cells to a pack requires more components: electronics, bus bars, cooling system, framework, and housing. Therefore, in all calculations, 22.5% extra weight has been added: 12% steel (framework and housing), 8% aluminium (mainly cooling structure), 1% copper (connectors and bus bars), and 1.5% electronics. These data are based on data from Volvo [22], and will most likely differ in detail when designing a specific system, but reflect the additional weight, volume, and natural capital cost of the complete pack.

For the BEV cases (Figure 2 and 3) both weight and volume favour asymmetric super capacitors. The same is true for the PHEV cases (Figure 4 and 5). Depending on charging strategies, during lunch breaks, the Li-ion battery technology can be attractive in terms of weight lunch breaks (Figure 5, case 1b and 2a).

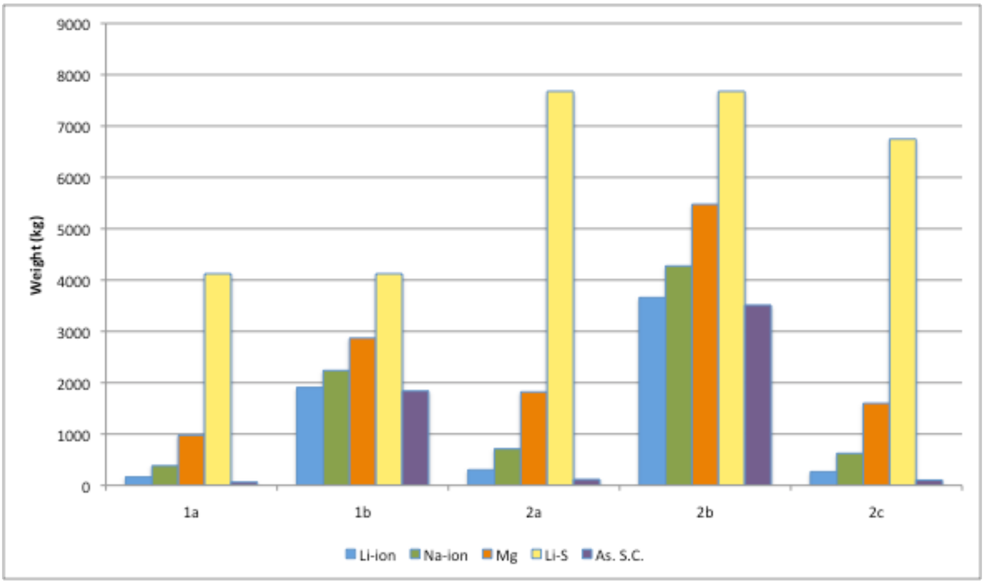

Figure 2. The weight of the battery pack for the BEV cases.

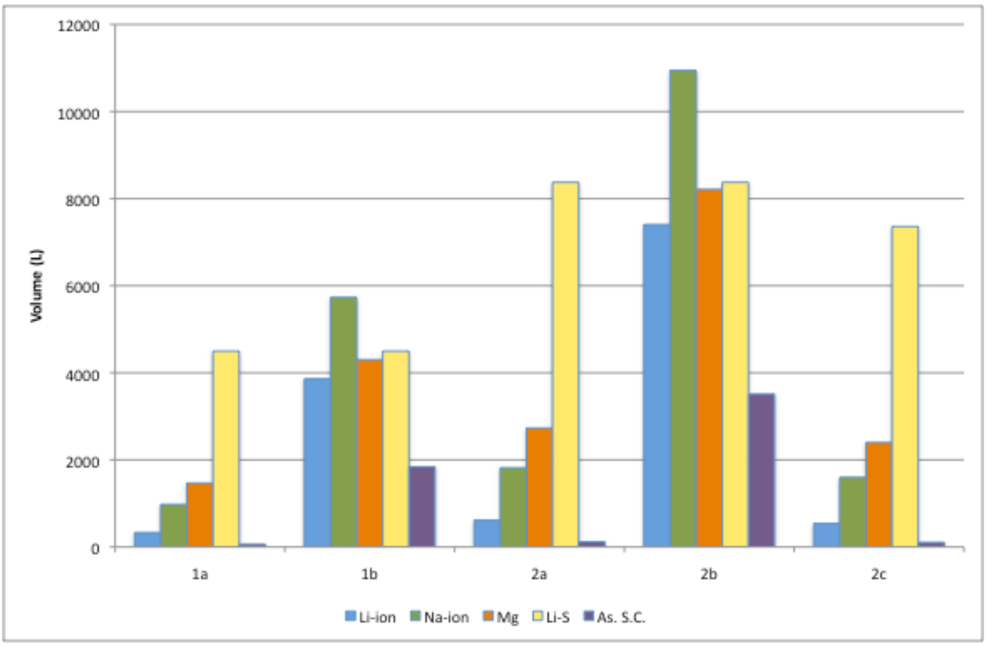

Figure 3. The volume of the battery pack for the BEV cases.

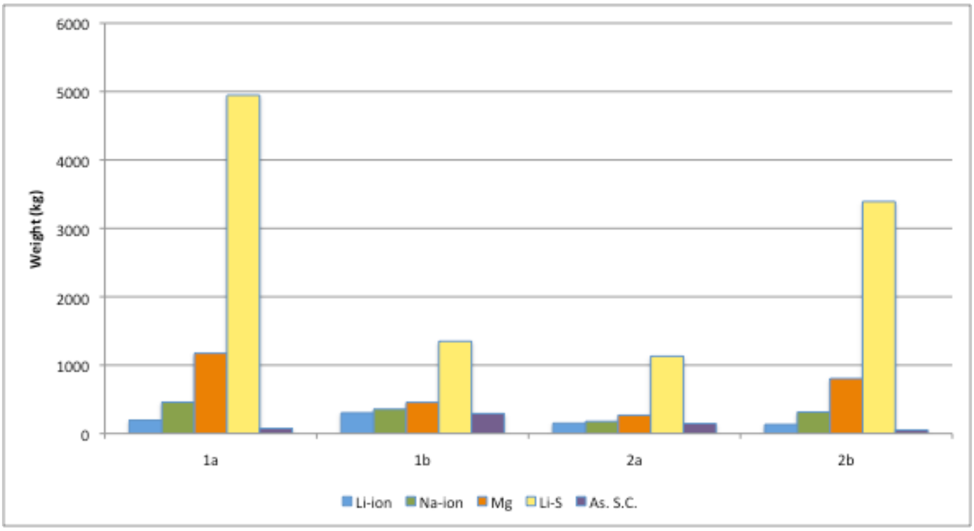

Figure 4. The weight of the battery pack for the PHEV cases.

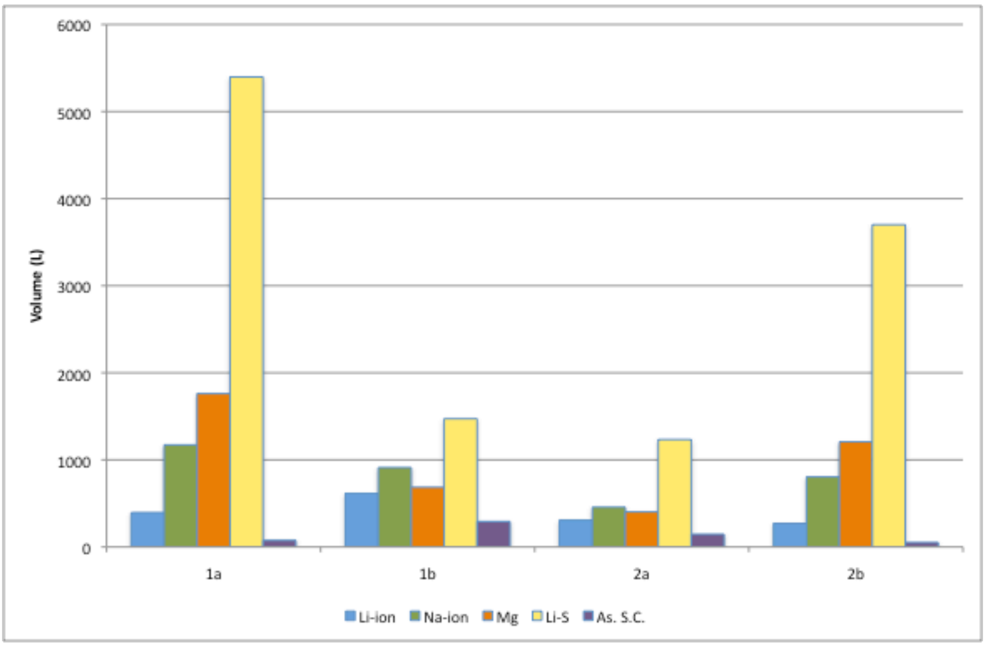

Figure 5. The volume of the battery pack for the PHEV cases.

Part cost and life-time cost

The main trend towards lower cost for the current Li-ion technology is driven by improved production processes, higher production volumes, standardised cell formats and balance of plant components. Hence cost reduction in general cannot be expected to follow any linear trend starting from materials cost. Nevertheless, we here use the same cost reduction trends for all studied emerging technologies as have been proposed for present Li-ion technology. It should be noted that the trends presented are related to cell and production optimisations of the present cell technologies and materials. Cost is related to the size and capacity of the batteries and also the production capabilities.

The cost trends of improved Li-ion cells and battery packs are based on literature data [16,17] and the cost estimations and comparisons in the present study will use the following cell cost split, which is based on Avicenne's data and model [16]:

- 65% of the cell cost refers to material cost
- 40% of the material cost refers to the cathode, 12% to the anode, and 10% to the electrolyte. The remaining 38% refers to current collectors, separators, binder, and cell housing.

Moreover, 75% of the cost of a pack is assumed be related to the cells.

The estimated part cost for the emerging technologies is based on an assessment of a more complete field overview and summarised in Figures 6 and 7. The cost estimates are related to improvements of the present Li-ion technology and also refers to a 2025 time line.

For the two types of machineries, the BEV and the PHEV, the overall most favourable solution in terms of cost are asymmetric super capacitors and next generation Li-ion batteries. However, in case of BEV machineries (Figure 6) and over-night charging (case BEV 1b and 2b) the Na-ion technology is competitive and even better than the asymmetric super capacitors. For the BEV cases, charging within the cycle is though the most attractive charging strategy.

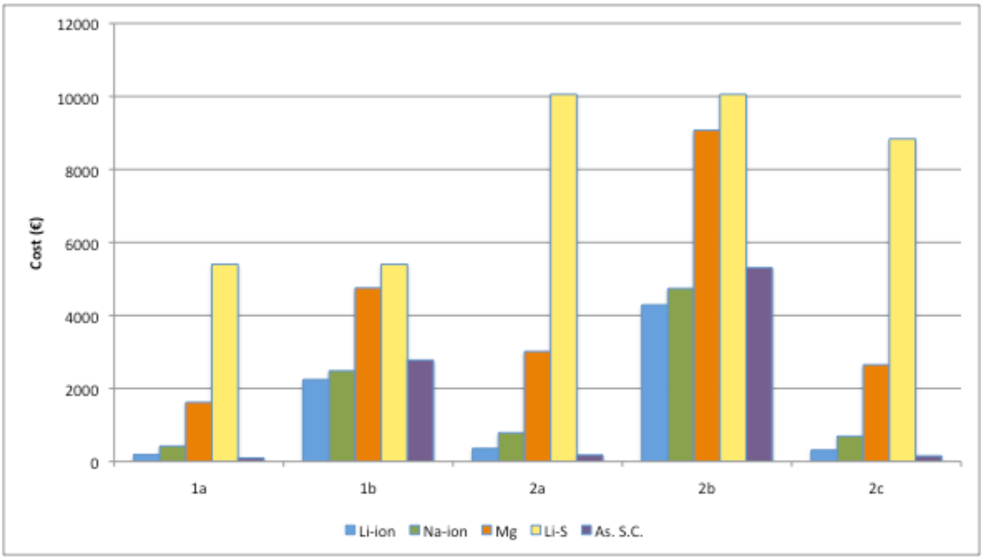

Figure 6. The part cost of the battery pack for the BEV cases.

Also in the case of PHEV machineries (Figure 7) the most cost efficient strategy is to charge within the cycle. For all cases the asymmetric super capacitors are the most attractive. To charge during lunch breaks (case PHEV 1b and 2a) is, however, attractive and in such cases the Li-ion and Na-ion technologies are as competitive as asymmetric super capacitors.

The cost of the complete energy storage pack is highly affected by the material and production cost of the cells. An increase by 10% of the cell cost of asymmetric super capacitors will make the Li-ion technology more cost efficient if the PHEV is charged during lunch breaks. Therefore, the cost estimates should be seen as trends rather than actual costs. Furthermore, if charging during night would be an option for the PHEV cases the Li-ion technology would be the most attractive from a cost perspective.

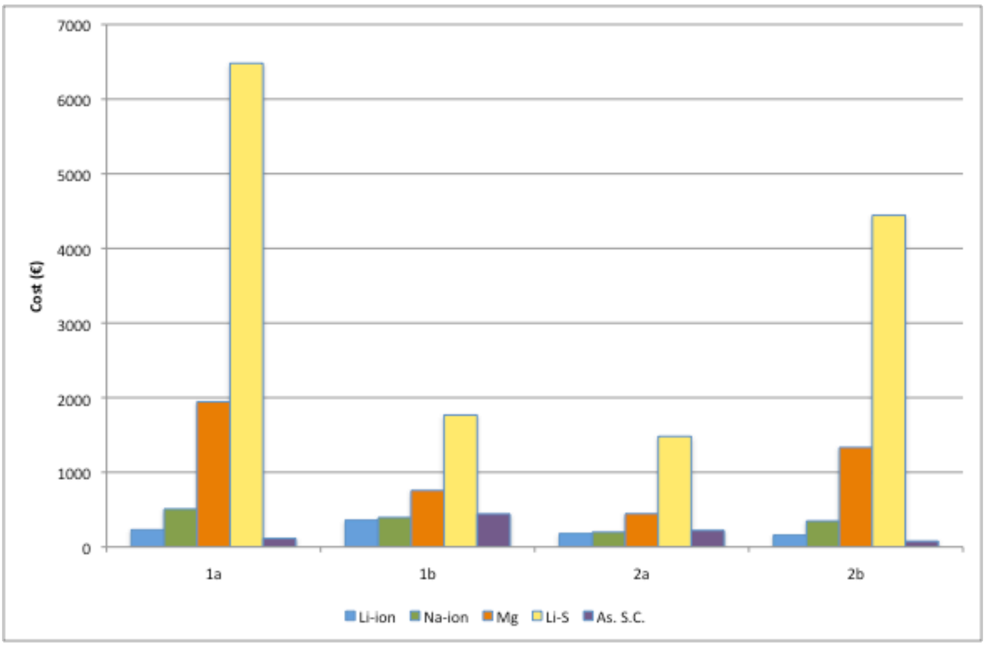

Figure 7. The part cost of the battery pack for the PHEV cases.

For many users the cost of the battery pack over the full lifetime of the machineries is a more relevant cost. As a first approximation the durability for the different kind of cells has been assumed to be 15,000 cycles for power optimised cells and 7,500 cycles for energy optimised cells. The lifetime of the construction machineries has been set to 20 years. Figure 8 shows the lifetime cost for the BEV cases and Figure 9 for the PHEV cases.

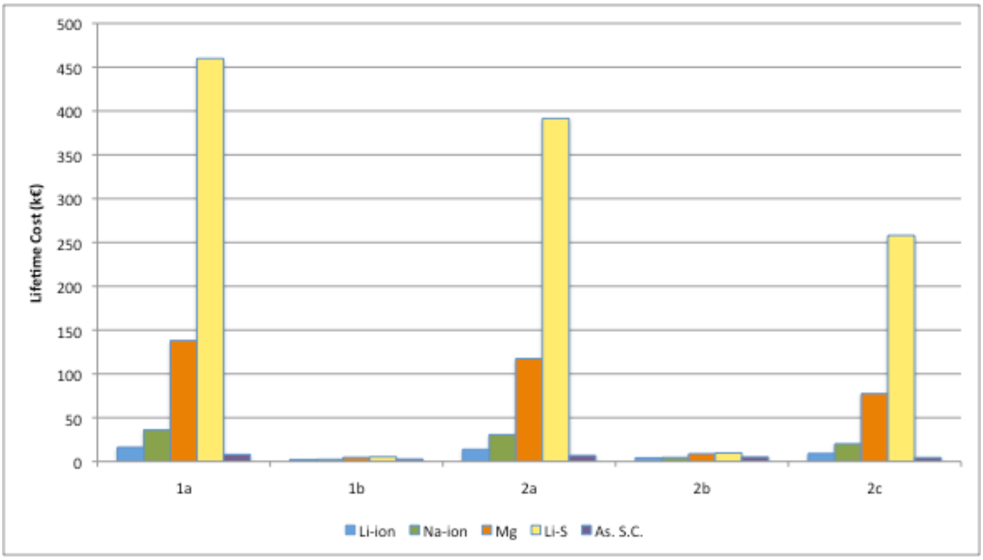

Figure 8. The lifetime cost for the BEV cases.

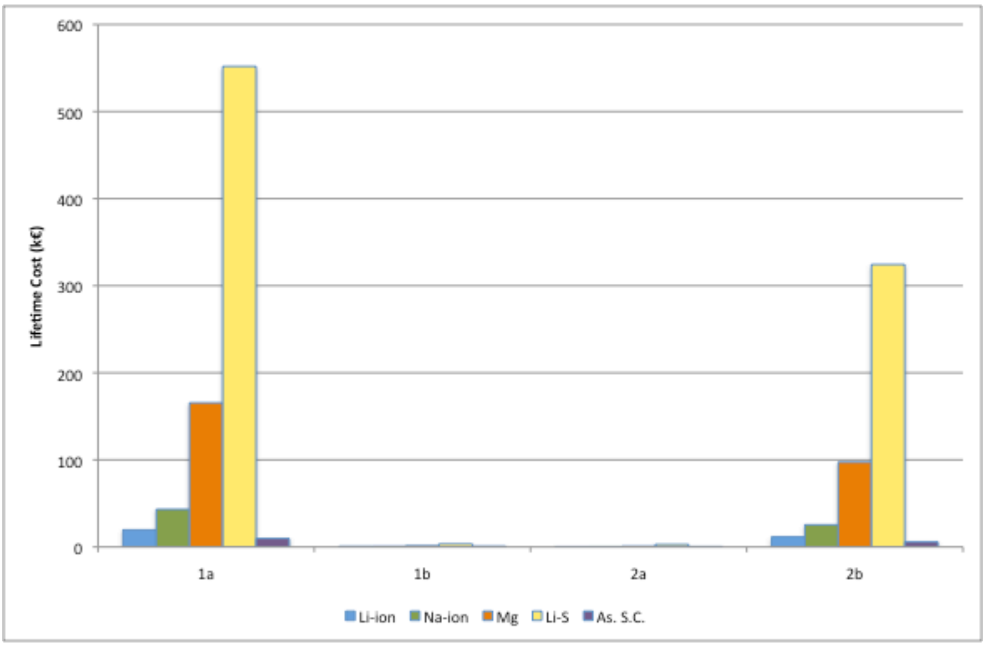

Figure 9. The lifetime cost for the PHEV cases.

For the BEV cases, charging during night (case 1b and 2b) is 2-5 times less costly than the other charging alternatives and the most attractive technology is Li-ion, closely followed by Na-ion and asymmetrical super capacitors.

For the PHEV cases, the asymmetric super capacitors are the most cost effective for all cases, but the most attractive alternative is to charge during the lunch breaks (case 1b and 2a). To charge during each cycle is, however, a remarkable 10-12 times more expensive. The second most attractive solution is to use Li-ion technology and charge during the lunch breaks is then about 30 times less expensive than the asymmetric super capacitor solution.

Environmental and sustainability aspects

For all combinations of machinery and energy storage technology the environmental impact has been calculated in terms of its damage costs to the natural capital and human health. This is made in order to find comparable values to give indications on how the different emerging technologies will influence the environment and to compare the environmental cost with the life-time cost of the packs. The total impact values vary quite significantly, as shown in Figures 10 and 11, mainly because of differences in total CO_2 emissions and use of scarce resources. The highest environmental damage cost for all studied emerging technologies arises from the Mg battery technology, which has an impact tremendously higher than the other. Therefore, the scale is cut in both figures in order to show the variances for the other technologies.

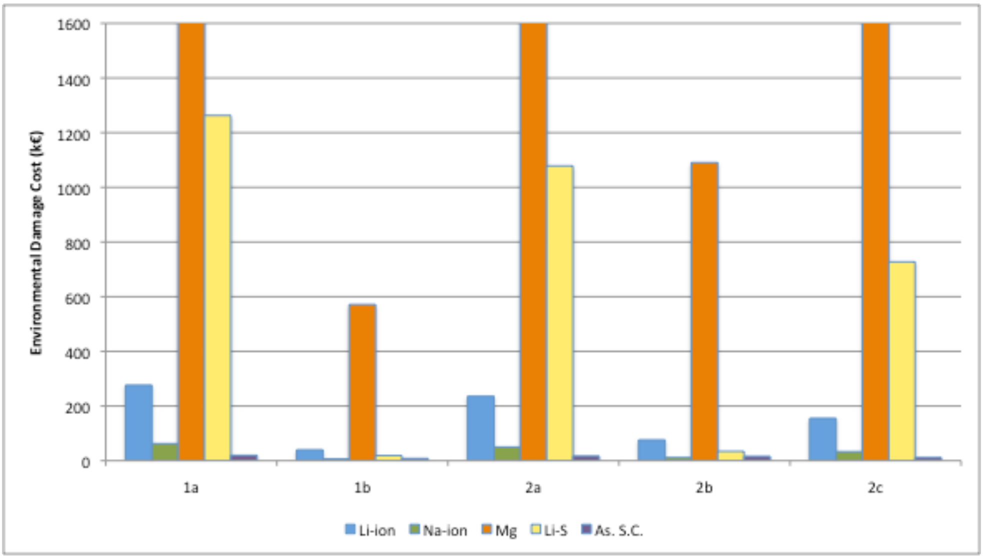

Figure 10. The total environmental damage cost of the pack for the BEV cases. See also Table 7 below.

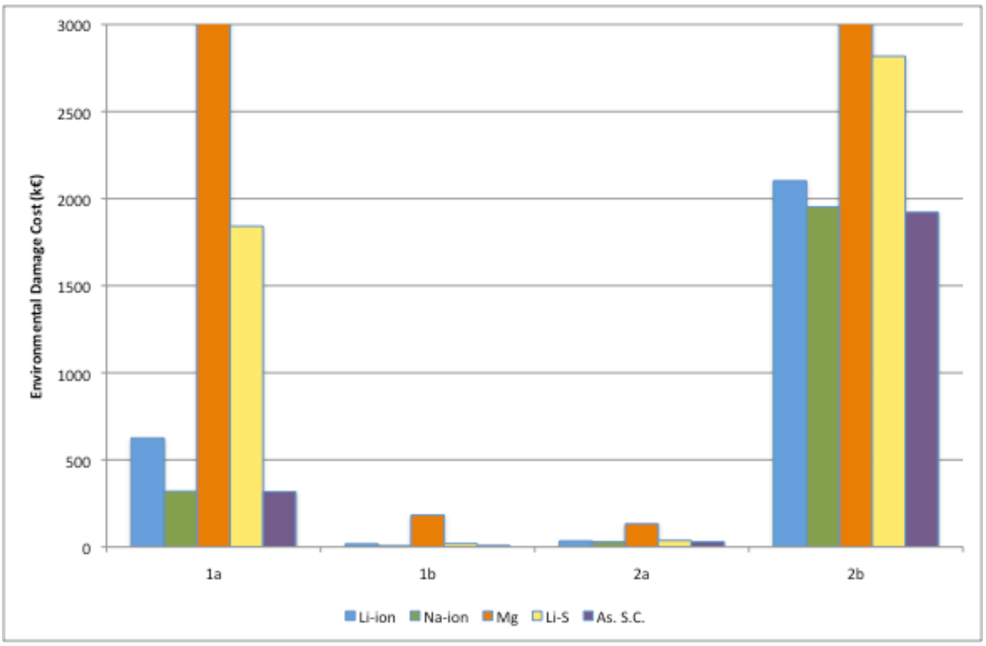

Figure 11. The environmental damage cost of the pack for the PHEV cases including diesel use. See also Table 8 below.

The corresponding costs are given in Tables 8 and 9, respectively. The damage costs for conventional diesel machineries are also shown as benchmark. For cases where there is an improved environmental performance, the numbers are marked in green. For cases where there is no clear improvement, the numbers are marked in orange or red. In an overall perspective, Li-ion and Na-ion technologies, and asymmetric super capacitors seem to be the best alternatives.

Table 7. Lifetime environmental damage cost (€) for BEV packs, including diesel use as benchmark.

Cycle	*Li-ion*	*Na-ion*	*Mg*	*Li-S*	*As. S.C.*	*Diesel*
1a	276519	62548	16511527	1262975	19712	253648
1b	39811	6308	571404	18691	8068	260597
2a	235516	49983	14038443	1078417	16857	521789
2b	76136	11317	1090493	34054	15888	485554
2c	155358	33139	9264294	727398	11197	391342

Table 8. Lifetime environmental damage cost (€) for PHEV packs, including diesel use as benchmark.

cycle	*Li-ion*	*Na-ion*	*Mg*	*Li-S*	*As. S.C.*	*Diesel*
1a	625539	319845	21421774	1841603	317372	572766
1b	17424	6912	182376	18886	7687	86356
2a	34189	28974	132288	37175	29324	68560
2b	2102273	1951697	13552931	2817689	1921455	2168386

If using only CO_2 emissions as the comparison, the environmental damage is as shown in Tables 9 and 10, respectively.

Table 9. Lifetime CO_2 emissions (kg) for BEV packs, including diesel use as benchmark.

Cycle	*Li-ion*	*Na-ion*	*Mg*	*Li-S*	*As. S.C.*	*Diesel*
1a	60254	167652	1258561	4777534	67624	855925
1b	10170	13681	46716	59465	24918	879375
2a	51503	142631	1019859	4069069	57711	1760760
2b	19126	25357	87725	110069	46953	1638485
2c	34252	94376	707454	2683459	38317	1320570

Table 10. Lifetime CO_2 emissions (kg) for PHEV packs, including diesel use as benchmark.

cycle	*Li-ion*	*Na-ion*	*Mg*	*Li-S*	*As. S.C.*	*Diesel*
1a	1453232	1450698	7859786	7113968	1462076	2322597
1b	27889	28937	39715	67425	32448	298289
2a	133662	134191	141198	163003	135956	268479
2b	9010750	9086546	9856233	12338079	9015974	9848430

Overall, for the BEV cases, the lowest impact is found for the Na-ion technology (BEV 1b). The largest contributions to the impact, both for damage cost and for CO_2, come from the manufacturing of Al and from the active cathode material ($Na_3V_2(PO_4)_2F_6$).

The lowest impact for the PHEV cases is for the Li-ion technology (PHEV 1b). The main contribution comes from the production of the Cu foil used as current collector on the anode side.

The raw data on emissions and resources above can be weighted together in different ways compared to the damage costs (Table 7 and 8). When using the Ecoindicator 99 and Recipe methods for weighting of different impacts, a similar priority is achieved. Li-S and Mg will cause high impact, while Li-ion is more favoured. The reason is that both the Recipe and Eco-indicator 99 have a relatively short time perspective on metal and fossil resource depletion (100 to 200 years). In that period resource repletion is less of a problem than when applying longer time perspectives, which may be more of a true sustainability.

Conclusions and future research

The selection of the most optimal energy storage solution will be a trade-off between many different machinery requirements: installation aspects, overall cost performance, markets, usage and charging possibilities, etc., and all needs to have a clear sustainability perspective. As a summary of all requirements and the decisive factors the following conclusions can be made for the BEV and the PHEV machineries:

If **weight** is the most important factor:
- BEV: use asymmetric super capacitors and charge within cycle.
- PHEV: use asymmetric super capacitors and charge within cycle.

Li-ion batteries is the second best alternative, being almost three times as heavy as the asymmetric super capacitors solution for both the BEV and the PHEV cases. To charge the BEV during the night instead of within cycle will increase the weight from 65 kg to about 1900 kg, or from 100 kg to about 3500 kg depending on the energy need per cycle. To charge the PHEV during lunch breaks will increase the weight from 75 kg to about 300 kg, or from 50 kg to 150 kg with a PHEV configuration, using about five to seven times more diesel.

If **volume** is the most important factor:
- BEV: use asymmetric super capacitors and charge within cycle.
- PHEV: use asymmetric super capacitors and charge within cycle.

The Li-ion battery technology is still the second best alternative, being almost five times larger than the asymmetric super capacitors solution. The charging strategies are also important for the volume of the energy storage pack. To charge the BEV during the night instead of within cycle will increase the volume from 65 L to 1900 L, or for the more energy demanding cycle from 100 L to 3500 L. For the PHEV cases, the volume will increase with about 2-4 times: from 75 L to about 300 L, or from 50 L to 150 L with a PHEV configuration, using about five to seven times more diesel.

If **part cost** is the most important factor:
- BEV: use asymmetric super capacitors and charge within cycle.
- PHEV: use asymmetric super capacitors and charge within cycle.

For all studied cases and for both BEV and PHEV, Li-ion batteries are the second most attractive solution in terms of part cost. The costs of the Li-ion battery solutions are, however, double the costs of the asymmetric super capacitor solutions.

If **lifetime cost** is the most important factor:
- BEV: use Li-ion batteries and charge during the night.
- PHEV: use Li-ion batteries and charge during lunch breaks (and night).

The second best Na-ion battery and asymmetric super capacitors solutions would both be ca 25% more expensive. If charging has to be done during the cycle rather than during the night for the BEV, the asymmetric super capacitor is the most attractive solution. The cost will, however, be 2-4 times the combination of Li-ion batteries and charging during the night. For the PHEV case, the same trends are valid: Na-ion batteries and asymmetric super capacitors are both 10-25 % more expensive than the Li-ion battery solution. To charge the PHEV within the cycle rather than during lunch breaks (and night) will be ca. 15 times more expensive. In such a case the most attractive solution is the asymmetric super capacitors.

If **environmental impact** is the most important factor:
In terms of environmental damage cost, for both the BEV and PHEV cases, the use Na-ion battery technology is the most attractive solution combined with charging during the night and/or at lunch breaks. The second best solution is for all cases asymmetric super capacitors, when using the same charging strategies. If only the CO_2 emissions are considered as environmental impact, Li-ion batteries is the preferred solution and Na-ion batteries is the second best.

In all the charging strategies will affect the environmental impact drastically. Machineries based on a PHEV configuration and being charged within each cycle will damage the environment even more than a traditional pure diesel solution. The only exception to this is to use a PHEV configuration based on Na-ion battery technology in combination with a low diesel consuming combustion engine (PHEV case 1a). On the other hand, for BEV machineries there will always be an energy storage solution better than a diesel version.

Research needs and research agenda

The challenges facing all emerging battery technologies, i.e. all technologies beyond the current Li-ion technology, are numerous and include both incremental improvements as well as overcoming hurdles/show-stoppers. Issues also exist at all possible levels for example at the cell level these are in turn related to the cathode, the anode, and the electrolyte – *i.e. all* active parts. Thus the complexity of progress and thus research needed is also vast. The drivers are mainly energy density, availability of raw materials, cost, and utilisation of more than one electron per transition metal. The cost reduction potential once the technologies have been shown to be functional is, however, mainly related to the pack design and components included in the pack except the cells.

As one outcome of this study a number of research activities and actions are proposed for further research and development of the emerging energy storage technologies for CE applications. The activities have been divided into material, cell, pack, and machinery research and are presented briefly below in Tables 11-16 for each of the studied technologies. All activities are additional to the activities needed for the present Li-ion battery technology to emphasize the unique demands, but there are also general research activities that are independent of the specific emerging technology solution.

Table 11. Summary of research activities needed independent of the emerging technology.

Material	***Cell***	***Battery pack***	***Machinery***
Energy efficient production routes with high yields.	SOC window selection and optimisation.	Adaption of thermal management for markets and usage conditions.	Charging strategies and infrastructure.

	Up-scaling for volume production.	Standardised balance-of-plant components to optimise cost reduction.	(Fast-)charging at different temperatures.
		Reduced balance-of-plant components to reduce weight and volume of battery packs.	Uptime, Service and Logistics (spare-parts, battery swapping-solutions, etc.).
			Standardised integration interfaces and monitoring regulations for different regions.
			Definition of figures of merits in order to find optimal solutions.

From an application point of view, many of the proposed actions are related to charging strategies and infrastructure – where many new possibilities are created for a construction site as compared to road vehicles. Therefore, charging strategies in combination with new business models need to be carefully investigated for uptime and logistics optimisation.

Next generation Li-ion batteries

Table 12. Summary of proposed research activities for next generation Li-ion battery technology.

Material	***Cell***	***Pack***	***Machinery***
5 V stable electrolytes.	Design of Si/C anode for high power capabilities.	Sensors for SOC, SOH and updated control.	Installation and modularity.
Cu-free current collectors.		Robust set-up of serial and parallel cell arrangements.	Communication of technology selection.

The next generation Li-ion battery technology differs only slightly from the present mature Li-ion battery technology, but still with some fundamental research needed in order to make the technology ready for the market. Many of the proposed research activities are also applicable for other type of vehicles such as buses and distribution trucks.

Due to the higher cell voltage, 5 V as compared to today's 3.6-4.2 V depending on concept, new constraints develop on the pack level and design in order to have a robust and reliable machinery installation.

In order to give indications about the research potential the cell voltage is compared with the power capabilities of the cell. If the cell voltage can be increased from 4.7 V to 5.0 V, the corresponding weight and volume reductions of the battery pack will be 6-7 % for all studied BEV and PHEV cases. The other research route, to increase the power capabilities from 2C to 5C as the average C-rate, the weight and volume reductions are significant – about 60 % reduction if charged in every cycle and becomes on par with the asymmetric super capacitor solution. On the other hand, if the strategies are to only charge during the night for the BEV cases and during lunch/night for the PHEV, these will not be affected at all by such an increased power capability.

Furthermore, the next generation Li-ion battery technology might rapidly be seen in the eyes of the public and customers as an “old technology” if there are breakthroughs for the Li-S or Mg battery technologies. Therefore, communication on technology selection needs to be understood properly and the competitor’s activities benchmarked.

Na-ion batteries

Table 13. Summary of proposed research activities for the Na-ion battery technology.

Material	***Cell***	***Pack***	***Machinery***
Vanadium-free cathodes.	Optimisation for power and energy.	Temperature control.	Installation for temperature control.
Stable anodes.	Temperature distribution within cell.		
Power capabilities.			

Many of the research activities proposed are related to the materials needed. At the cell level we stress that as the Na-ion battery technology is based on using only Al-based current collectors the temperature distribution within the cell may become an issue as Cu, used in today’s Li-ion batteries, is a better thermal conductor. This may be an issue also at pack and machinery installation levels. As compared to the present Li-ion battery technology, the Na-ion battery technology is foreseen to be slightly more temperature sensitive and a careful machinery installation is required.

If the capacity of the cathode material can be increased by a factor 2, the weight and volume reduction for the all studied BEV and PHEV cases will be only 11 %. Instead, if the power capability can be improved, from 1C to 2C in average, the corresponding BEV pack would be half in weight and size if the charging takes place within the cycle, and the PHEV pack would be only 33 % smaller and about 15 % smaller. If the BEVs and PHEVs are, however, charged during night and/or lunch breaks no reductions are observed.

Mg batteries

Table 14. Summary of proposed research activities for the Mg battery technology.

Material	***Cell***	***Pack***	***Machinery***
Stable electrolytes.	Production processes.	Concept design and selection of cell size.	Availability of cells?
Mo-free cathodes.	Market potential?		Market potential?
Durable two-electron cycling.			

Selection of salt for sustainability and compatibility with other cell components.			

Compared to the Li-ion and Na-ion battery technologies, the Mg battery technology is a rather young technology and no commercial or large-scale prototypes exist. One of the keys for a technology breakthrough is to prove the two-electron reaction. If not, this technology is just an advanced/complicated Li-ion or Na-ion battery technology, *i.e.* only one-electron is transferred.

Another technology breakthrough needed is to find Mo-free cathode materials. The Mo resources in the world are very limited and cannot sustain a large-scale usage as for electric vehicles. Indeed, the extreme environmental impact for this technology is mainly due to the Mo-containing cathode, while else the environmental impact would be of the same order as the Na-ion battery technology. Before any such working cathode material is found, it is not feasible to calculate how and if weight and volume could be reduced by the Mg battery solution.

Furthermore, the driver for Mg batteries in vehicles and machineries would mainly be the passenger car industry. Therefore, development of cells suitable for high power demanding applications will most likely be present only in a long term perspective.

Li-S batteries

Table 15. Summary of proposed research activities for the Li-S battery technology.

Material	***Cell***	***Pack***	***Machinery***
Power capability.	Production process for cathode.	Concept design and selection of cell size.	Availability of cells?
Complex cathode composition and arrangement.	Electrode-electrolyte balancing.		Market potential?
Stability of lithium anode for high rate cycling.	H_2O sensitivity.		
	Power capability.		

One of the current major drawbacks with the Li-S battery technology is the low power capability. Therefore, the design of active materials as well as the cathode needs to be improved. To be attractive not only true for construction machinery reasonable rate capabilities must be reached. As a sensitivity analysis: if a Li-S battery cell could deliver the same capacity at a C-rate of 1C instead of the 0.1C used in this study, the corresponding pack would be 10 times smaller and lighter if the BEVs and PHEVs are charged within the cycle. To charge a BEV only during the night will, however, be unaffected by an increased power capability. On the other hand, charging a PHEV during lunch and night will reduce the weight and volume by 75-85 %. In such a case, the Li-S battery technology will be more attractive than the Li-ion battery technology.

Up to now, with only 10 years left until 2025, there are, however, no major breakthroughs for high power capability for realistic cells and this is mainly due to the stability of the metallic lithium anode. The Li-metal surface must be protected or treated in special ways to prohibit the growth of dendrites and ensure safe operation, an area with a manifold of research activity.

Moreover, the production processes are also essential for mass-production capabilities of the technology. The production process will most likely be even more critical as compared to today’s Li-ion battery cell production in terms of water content.

Just as for the Mg battery technology, the market drivers for Li-S technology must be understood from a construction machinery perspective in order to understand the possibilities for any application optimised cells to be produced/attainable.

Asymmetric super capacitors

Table 16. Summary of proposed research activities for the asymmetric super capacitor technology.

Material	***Cell***	***Pack***	***Machinery***
Material combinations for high energy density with durability.	Production process for cathode.	Less sensitive sensors for temperature, current and voltage.	Adaptation for high-current charging possibilities and consequences for other parts of machinery.
Ionic liquids.	Electrode-electrolyte balancing.		
Material complexity.			

Being the overall most suitable technology for the construction machineries and the usage profiles, a substantial amount of research activities should be directed towards this technology. As asymmetrical super capacitors are still limited in terms of energy density, the material research activities should focus on how to improve the energy density without losing the excellent durability. As a sensitivity analysis: if the capacity of the anode material can be increased by 25 %, only a modest 5% weight and volume reduction will be achieved. Even at a doubled capacity of the anode the reduction will only be 13 %. Therefore, research activities are preferably directed towards altering the electrolyte as the energy density is directly correlated to the square of the cell voltage. One possible route is to change from standard organic solvents to ionic liquids. In order to remain the most attractive energy storage solution for construction machineries from a cost as well as a sustainability perspective improvement in energy density might be needed in the long term.

Conclusions

The different emerging energy storage technologies are at various development stages for being of interest in construction machinery applications by 2025. In order to be considered as a suitable technology some main research activities have to be successful. The main conclusion of this pre-study is that the research activities for construction site machineries should be directed towards the emerging technologies of asymmetric super capacitors and Na-ion batteries.

This conclusion takes the following advantages in consideration:

- High rate capabilities
- Pack simplicity
- Low environmental impact

From a sustainability perspective the Na-ion battery technology is preferred. This is mainly due to the availability of Na, to that no Cu current collectors are needed, and to an energy efficient electrolyte production. The drawback, however, is the current use of vanadium based cathode materials and therefore material research activities can further improve the already low environmental impact of this technology.

The charging strategies will highly affect the lifetime cost, pack installation, and environmental impact. To charge many times during the day is preferred mainly from a weight and volume perspective, but from a cost perspective, both lifetime and environmental damage cost, to charge only a few times per day are preferred; lunch breaks, during the night, etc.

The Li-S and Mg battery technology solutions are not attractive for construction site machineries as long as the power capabilities remain low and at the same time the environmental impact is surprisingly high. If there are research breakthroughs related to the power capability of the Li-S battery technology, this technology will truly be an attractive alternative. The time perspective seeing high-rate Li-S cells are, however, most likely beyond 2025 in general and even more so for construction site machinery applications. For the Mg battery technology Mo-free cathode materials are utmost needed in order to be sustainable. A key question for both technologies is whether the construction machinery market can by the driver of development or if these technologies anyhow might be more suitable for other applications.

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