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Kari Saarentausta

Selection and sizing of electrical energy storage for a hybrid working machine based on the work cycle

Examiners: Professor Pasi Peltoniemi
D.Sc. Paula Immonen

ABSTRACT

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77 pages, 32 figures, and 6 tables

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Keywords: Battery technologies, energy storage, lithium-ion battery, supercapacitor, selection, sizing

The frame of reference for the study is the dimensioning and selection of the electrical energy storage of a hybrid working machine based on the load period (work cycle). The study is part of LUT's e3Power research project funded by Business Finland and compares the power, energy, and temperature values of different electrical energy storage models as well as the space requirements of different electrical energy storage. The research will focus on the specific requirements for electrical energy storage for hybrid working machines for lithium-ion batteries (LFP-, LTO- and NMC-types) and supercapacitors (EDLC-, Pseudo- and Li-C-types) and will develop a selection and sizing procedure for their use as electrical energy storage in hybrid working machines.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT

LUT School of Energy Systems

Sähkötekniikka

Kari Saarentausta

Sähköisen energiavaraston valinta ja mitoitus hybridityökoneeseen kuormitussyklin perusteella

Diplomityö

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Hakusanat: Akkutekniikat, energiavarasto, litium-ioniakku, superkondensaattori, valinta, mitoitus

Tutkimuksen viitekehys on hybridikäyttöisten työkoneiden sähköenergian varastoinnin mitoitus ja valinta kuormitusjakson (työjakson) perusteella. Tutkimus on osa Business Finlandin rahoittamaa LUT:n e3Power-tutkimusprojektia, jossa verrataan erilaisten sähköenergian varastointimallien teho-, energia- ja lämpötila-arvoja sekä asennustilavaatimuksia. Tutkimuksessa keskitytään hybridikäyttöisten työkoneiden asettamiin erityisvaatimuksiin käytettäessä litium-ioni-akkuja (LFP-, LTO- ja NMC-tyyppejä) ja superkondensaattoreita (EDLC-, Pseudo- ja Li-C-tyyppejä) hybridikäyttöisten työkoneiden sähköenergian varastointiin ja kehitetään niille valinta- ja mitoitusmenetelmä.

PREFACE

This Master’s Thesis was done at Lappeenranta-Lahti University of Technology during 2020.

I would especially like to thank Professor Pasi Peltoniemi and D.Sc. Paula Immonen from LUT University, who has guided me to prepare this thesis ready. Warm thanks also to my family and friends, and of course to all my classmates during the master's program.

Kari Saarentausta
December 6, 2020
Vaajakoski

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NOMENCLATURE

Symbols

C	Capacity [Ah, F]
C_{rate}	Defines the relation between current and capacity
DoD	Depth of discharge [%]
E	Energy [Wh]
P	Power [W]
SoC	State of charge [%]
t	Time [s]

Abbreviations

BAT	Battery
CON	Converter
DEH	Diesel-electric hybrid
DHH	Diesel-hydraulic hybrid
EDL	Electric double-layer
EDLC	Electric double-layer capacitor i.e. supercapacitor or ultracapacitor
EG	Electric generator
EM	Electric motor
ESR	Equivalent series resistance
ESS	Energy storage system
FCH	Fuel cell hybrid
HEV	Hybrid electric vehicle
HYDS	Hydraulic system
ICE	Internal combustion engine
INV	Inverter
ISA	Integrated starter/alternator
Li-C	Lithium-ion-capacitor i.e. hybrid capacitor
LiB	Lithium-ion battery i.e. Li-ion battery
LFP ($LiFePO_4$)	Lithium-iron phosphate battery
LTO ($Li_4Ti_5O_{12}$)	Lithium-titanate battery
NMC ($LiNiMnCoO_2$)	Lithium-nickel-manganese-cobalt battery
SC	Supercapacitor
UC	Ultracapacitor i.e. supercapacitor

1 INTRODUCTION

The frame of reference for the study is the dimensioning and selection of the energy storage system (ESS) of a hybrid working machine based on the work cycle (load period. The study is part of LUT's e3Power research project and compares the power, energy, and temperature values of different electrical energy storage models as well as the space requirements of different electrical energy storage. The study will focus on the specific requirements for electrical energy storage for mobile hybrid working machines for Li-ion batteries and supercapacitors and will develop a selection and sizing procedure for their use as energy storage in hybrid working machines.

1.1 Hybridization

Mobile working machines such as dozers, wheel loaders, excavators, tractors, straddle carriers, and harvesters are widely used, and the energy they consume and the emissions they cause are significant. As emission regulations and standards tighten and fuel prices rise, machine builders are increasingly interested in the electrical hybridization. [1], [2] These are also the main lines of hybridization, i.e. reduction of fuel consumption and emissions. [1] - [4] Hybridization is known as a feasible solution for modern vehicles with high fuel efficiency, less energy consumption, and fewer emissions. They are low cost and easy installations regardless of drivetrain configurations. However, the applicability of this methodology with hybrid working machines is still an open topic. [2], [5] Figure 1. shows a development history of hybrid mobile working machines.

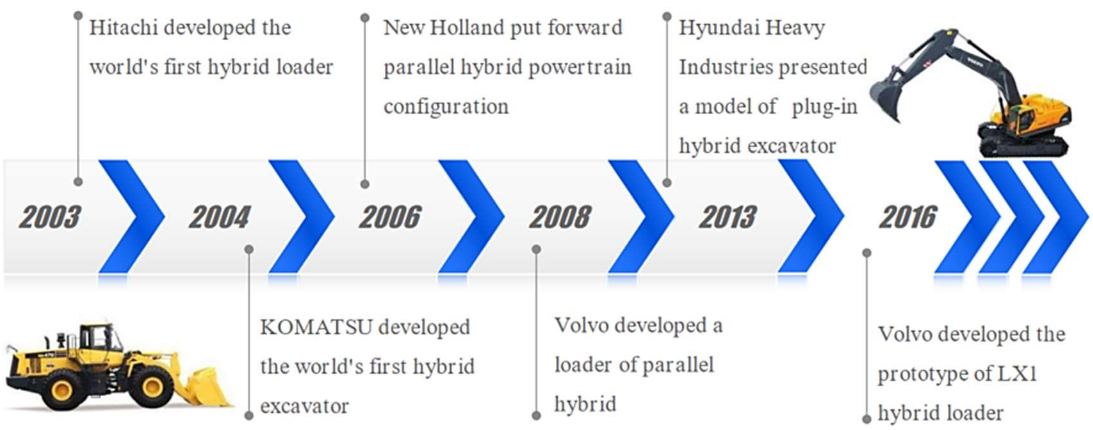

Figure 1. Development history of hybrid working machines. [3]

Mobile working machines can be divided into the forest, mine, farming, building, and terminal working machines by the application field. But their work cycle is much more important than the application field, from the perspective of energy efficiency. Their work cycles can be divided into high constant load cycles, manipulation load cycles, and transport load cycles. High constant load cycles occur in tractors and dozers, that pull or push heavy loads. Manipulation load cycles occur in harvesters and large load variations and transportation load cycles are typical for them also. A load cycle can comprise no-load, acceleration, constant speed, braking, lifting, and lowering cycles. Rotational movements are also possible in excavator load cycles. Load cycles can also be repeatable. [1], [4]

The work cycles of a mobile working machine are often such that hybridization saves a significant amount of fuel. This is because energy recovery allows you to choose a diesel engine with significantly lower energy consumption, and the engine can operate at its best efficiency. [1], [5], [6] An internal combustion engine i.e. diesel engine is mainly needed to move the vehicle and operate the auxiliary systems in passenger cars and buses. In mobile working machines, an internal combustion engine (ICE) is also required to perform various work movements using actuators. [1], [5], [6] A working machine consists of five modules: tool (e.g. boom, arm, bucket, etc.), traction, frame, powertrain, control, and information. [2] Figures 2.a and 2.b. shows the power needed in them as a function of time.

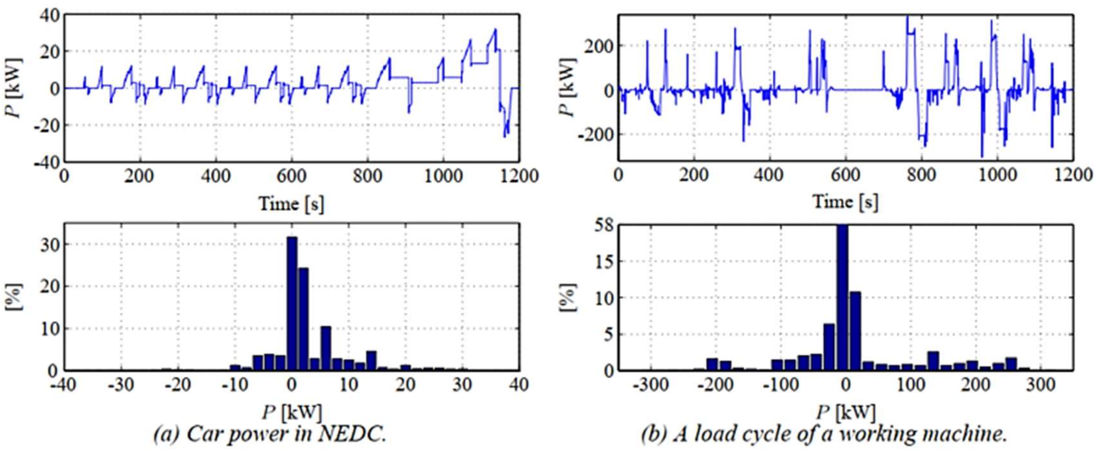

Figure 2. Car and working machine power as a function of time and power distribution. [1]

The largest amount of energy collected in cars is braking energy. In mobile working machines, the actuators produce the maximum energy to be recovered, and the speed and amplitude of the change in load are much higher than in cars. [3] The amount of regenerated energy in mobile working machines is often significant and varies rapidly. However, a mobile working machine can operate without load for more than half of the operating time, in which case the average power is small compared to the peak power. [1], [5] Hence, the energy storage is important for electrical systems, because it allows load balancing and peak shaving, dampens energy oscillations and improves power quality and reliability. [7] When developing a hybrid system, it is necessary to take into differences between cars and working machines, including system topology and components, work cycle, energy management strategy, and reliability. [2], [5]

In the case of a hybrid working machine, it should be select the electric machine (EM) and ICE carefully, to ensure both the machine drivability and working capacity of the actuators. Energy recoverability can be done from the machine braking actions and/or energy of the actuators, which is dissipating as heat in conventional designs. Key components in hybrid working machine design are not limited to only ICE, EM, and power packs. Depending on the degree of hybridization, such key components as the flywheel, hydraulic accumulator, and hydraulic pump/motor, should be taken into the hybrid design, to recover potential and kinetic energy released from the actuators. [2], [5]

Improving the energy efficiency of mobile working machines by hybridization depends on several factors and solutions have to be affordable to the customers. Mobile working machines are used normally for 800-4000 working hours a year, depending on the work shifts and the payback time of hybridization must be less than 3 years. The calendar lifetime of the main components of hybridization has to be at least 10 years and the cyclic lifetime 1 000 000 cycles. The operating temperature of the electrical energy storage is a significant property with mobile working machines and it has to be about -40 - +65 °C. [1]

1.2 Energy storage system (ESS)

Energy storage systems can be categorized in many ways. The most commonly used types of energy storage are classified into electrochemical and battery energy storage, thermal energy storage, thermochemical energy storage, flywheel energy storage, compressed air energy storage, pumping energy storage, magnetic energy storage, chemical, and hydrogen storage. [7], [8] Electrochemical energy sources are based on the conversion of chemical energy into electrical energy. The operation of this chemical process requires at least two reaction pairs and the energy generated is obtained as an electric current at a specified voltage and time. Electrochemical storage technologies are divided into two main branches: electrochemical batteries, and electrochemical capacitors. [8], [9], [10]

This study focuses on the study of electrochemical energy stores. Electrochemical batteries i.e. lithium-ion batteries i.e. Li-ion batteries, and electrochemical capacitors i.e. supercapacitors i.e. ultracapacitors, or combinations thereof can be used in mobile hybrid working machines to store electrical energy. [1] Figure 3. shows a classification of energy storage types, and the types of study focuses.

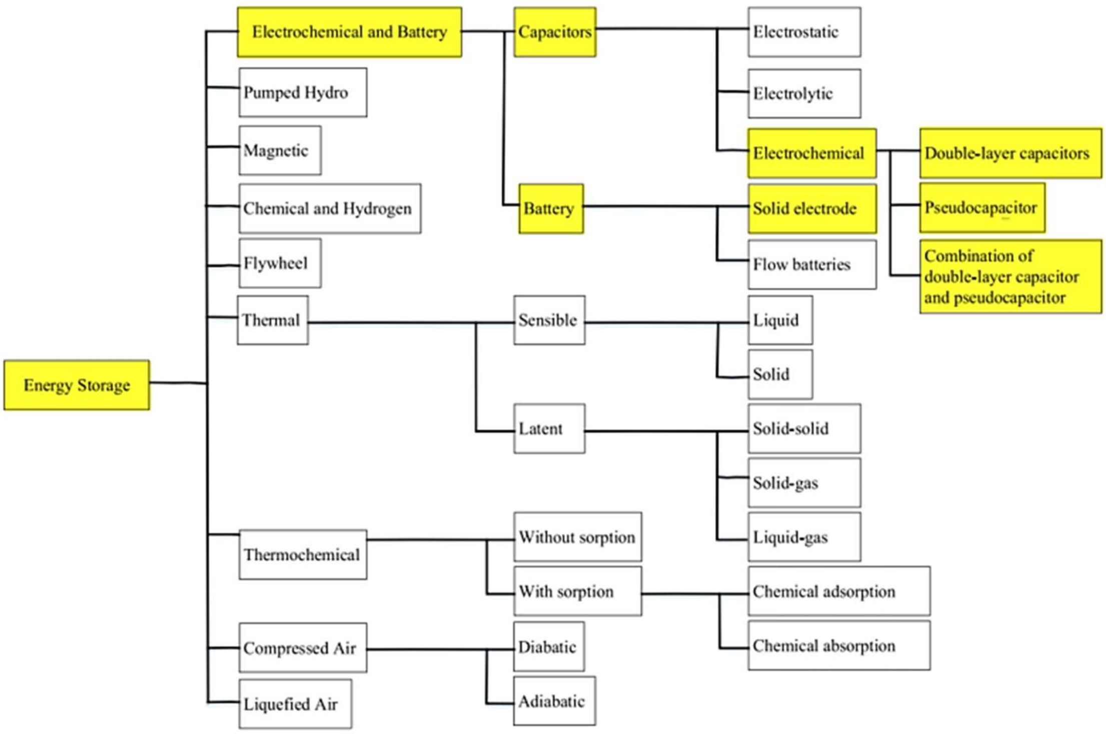

Figure 3. Classification of energy storage types. [7]

1.2.1 Li-ion batteries (LiB)

Of all the metals, the lightest is lithium, which has the highest electrochemical potential and gives the highest specific energy per weight. A Li-ion battery is a type of rechargeable battery, and electrical energy can be stored in it electrochemically. The Li-ion battery uses graphite as the anode, active materials as the cathode, and the electrolyte as the conductor. [11], [12] During charging, ions flow from the cathode to the anode and during discharge, ions flow from the anode to the cathode through the electrolyte. Figure 4. shows the ion flow process in the Li-ion battery. [13]

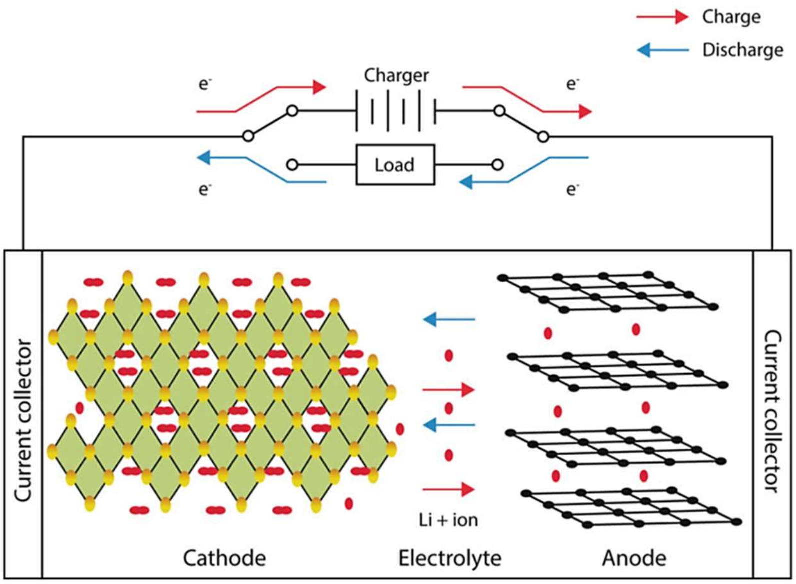

Figure 4. The Ion flow process in the Li-ion battery. [13]

Li-ion battery has high specific energy, high capacity, low shelf-discharge, low internal resistance, long cycle life, and it is a low-maintenance battery type. [11] The Li-ion battery has no memory and does not need regular training (intentional full discharge) to keep it in good condition. The drawback of Li-ion batteries is the need for protection circuits to prevent abuse. Lithium batteries play an increasingly important role in the storage of electricity, due to their high specific energy (energy per kilogram of weight) and energy density (energy per unit volume). [7], [14], [15] Reduced costs, increased specific energy and the absence of toxic material have led to Li-ion being a widely accepted battery solution for applications such as portable applications, heavy industry, and electric powertrains. [11]

Chemistry types of Li-ion batteries (LiB) in the study:

- $LiFePO_4$ (LFP) Lithium-iron-phosphate battery

  The LFP battery consists of a $LiFePO_4$ cathode and a graphite anode. It has a high current rating, a long cycle life, good thermal stability, and better safety if abused. The LFP battery withstands full charge conditions better and high operating voltages, but moderate specific energy than other Li-ion batteries. Cold temperatures reduce performance and LFP battery does not tolerate moisture. It has a higher self-discharge than other Li-ion batteries, which can cause balance problems with aging. LFP battery is often used to replace the lead-acid starter battery in a vehicle and typical uses are electrical energy storage. [16], [17]

- $Li_4Ti_5O_{12}$ (LTO) Lithium-titanate battery

  LTO battery consists of a lithium manganese oxide or NMC cathode and Li_2TiO_3 (titanate) anode. It can be fast-charged and has a high discharge current, 10 times rated capacity i.e. 10C. The cycle life of the LTO battery is higher than regular Li-ion batteries. LTO battery is safe and it has excellent charging and discharging characteristics at low-temperature (80% at -30 °C). The thermal stability of LTO battery under high temperature is better than other Li-ion batteries. The disadvantage of an LTO battery is its high price. Typical uses are electric power trains. [15], [16], [17]

- $LiNiMnCoO_2$ (NMC) Lithium-nickel-manganese-cobalt battery

  NMC battery consists of a nickel-manganese-cobalt anode and graphite anode. This battery type can be tailored to serve as energy cells or power cells. The NMC battery has good overall performance and special energy. It has the lowest self-heating rate and offers high capacity and power. Manufacturers are moving to NMC-mixed Li-ion because the battery can then be built economically and achieve good performance. The three active ingredients of anode: nickel, manganese, and cobalt, can be easily mixed to suit a wide range of applications in automotive and energy storage systems (ESS) that often require cycling. Typical uses are power tools and electric power trains. Figure 5. shows some typical properties of LFP, LTO, and NMC Li-ion batteries. [16], [17]

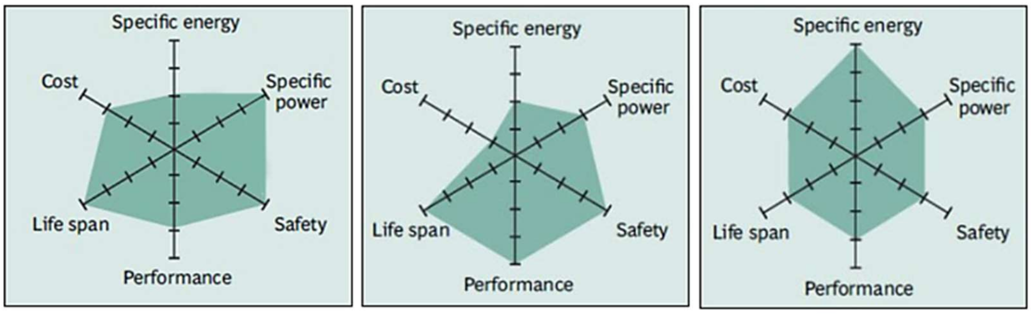

Figure 5. From the left: Typical properties of LFP, LTO, and NMC batteries. [16], [17]

Battery modules are the most popular energy storage system, due to their high energy density, although they are unable to release all stored energy. Additionally, the high initial current demand for electrical machines like motors, cause stress in batteries and reduce their life cycle. [18]

Supercapacitors are excellent enlargement to batteries because they can supply the power demand at the current peaks, reducing by that way the stress on batteries. For that reason, a battery-supercapacitor hybrid energy storage system is a combination, that more energy can be stored and high power densities can be reached through a supercapacitor module. Generally, batteries have a significantly higher energy density, whereas supercapacitors usually have higher power densities. Hence, batteries are for longer energy supply and supercapacitors are for higher power applications. [4], [18]

The combination of battery and supercapacitors is not the same thing as connecting directly together batteries and supercapacitors in series or parallel connection. Hence, a combination of battery and supercapacitor, a hybrid energy storage system needs a control system that manages the energy flow from batteries and supercapacitors. This kind of connection requires DC/DC converters, which are controlling the energy distribution on the output of both devices. These converters are designed to allow free energy flow and protect devices. [18]

1.2.2 Supercapacitors (SC)

Supercapacitor i.e. ultracapacitor (UC) charge and discharge energy electrochemically and it has very high capacitance per unit volume, due to having a porous electrode structure. The supercapacitor stores energy through static charge, which is done by setting the voltage difference between the positive and negative plates to charge the capacitor. The supercapacitor has thousands of times higher capacitance than a conventional electrolytic capacitor and is used for electrical energy storage, where charging and discharging cycles occur at high current and for a short period. [8], [19], [20] Electrochemical capacitors i.e. supercapacitors have a high storage efficiency (> 95%) and they can be recycled hundreds of thousands of times without losing energy storage capacity. They are also sensitive to self-discharge, and therefore their operating voltages must not exceed the potential level at which the electrolyte undergoes chemical reactions. [7], [8], [15] Supercapacitors offering higher power densities, long cycle life, fast charge, and discharge times, wide operating temperature range, and they are also clean and safe for electrochemical energy storage than present rechargeable batteries like Li-ion batteries. [2], [15], [21]

The energy storage mechanism of supercapacitors is based on the accumulation of charge or reversible redox reactions. The energy storage in supercapacitors is done by the same principle as conventional capacitors. However, they are better for quick release and storage of energy than conventional capacitors. Refer to the conventional capacitors, compounded electrodes of supercapacitors having a greater effective surface area than in conventional capacitors leads to better capacitance by a factor of 10 000. [7], [9], [21]

The electrochemical behavior of supercapacitors has a similar configuration to batteries. The supercapacitor consists of an assembly of two electrodes held apart by a separator sank in the electrolyte. The main components of the supercapacitor assembly are; two electrodes, electrolyte solution, separator, and current collector such as the supercapacitor structure shown in Figure 6. The internal resistance, which is limiting all supercapacitors' ideal capacitive and is associated with the power performance of supercapacitors' current collectors and electrodes are called equivalent series resistance (ESR). Designing supercapacitors according to the application, their specific energy and power can vary greatly. This makes supercapacitors flexible in energy storage selections. [7], [9], [21] Supercapacitors are classified according to the charge storage mechanism and the electrode materials used: electric double-layer capacitors (EDLC), electrochemical double-layer capacitors (pseudocapacitors), and hybrid capacitors (Li-C), a combination of the other two types. [7], [9], [19], [21]

"In reality, the EDLC acronym is equally used for two different definitions: (i) Electric Double Layer Capacitor or (ii) Electrochemical Double Layer Capacitor. The former surely represents the more correct operation way for these types of SC, while the latter generates confusion in the attempt to introduce in the same device the concept of "pseudocapacitance", which is typical of SC devices with faradic processes, or to emphasize the fact that the charge reorientation happens at the electrochemical double-layer. This double meaning is currently used in the scientific and technological literature and even in international standards." [19] Figure 6. shows the classification of all capacitors, including different types of supercapacitors.

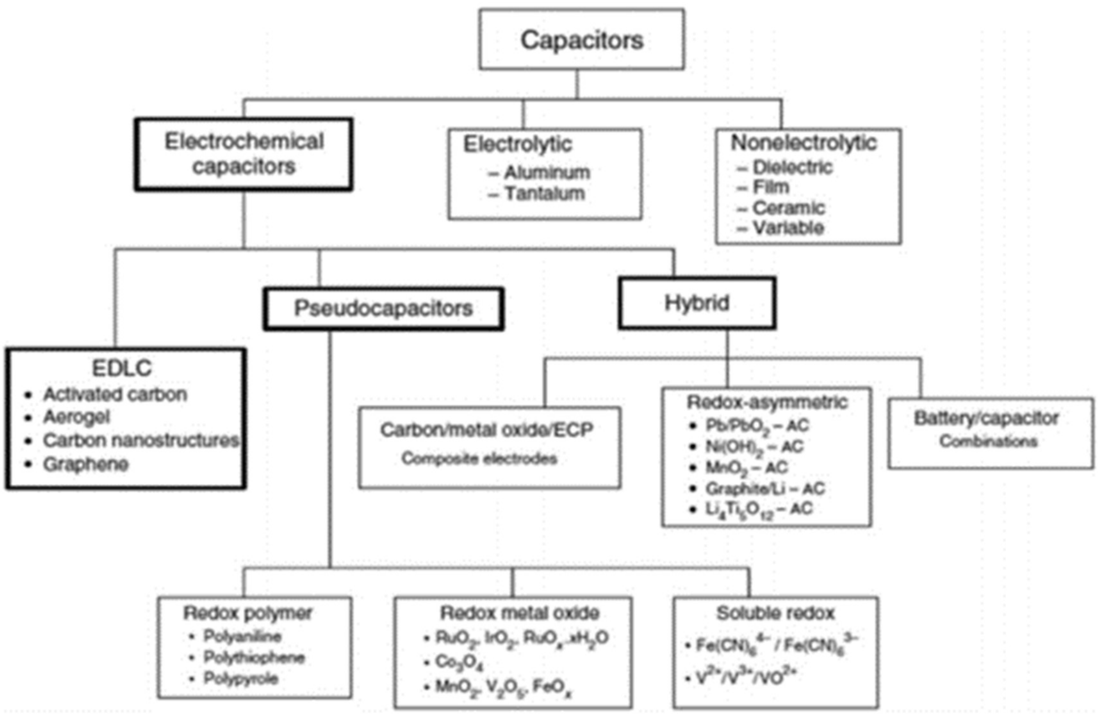

Figure 6. Classification of all capacitors, including supercapacitors. [21]

The types of supercapacitors in the study:

- EDLC type

  The electrode material rapidly attracts solvated ions in the electrolyte, which creates a double-layer acting as two separate capacitors, connected in series by the electrolyte, that remain charged after the circuit is opened. [20] Due to the large interface area of the electrodes, with a similar charge/discharge mechanism as that of the conventional capacitor, the supercapacitor can store more energy based on the EDL capacitance principle. [21] Such materials like carbon, metal oxides, hybrid, and conducting polymers are used for the electrode. Voltage equalization circuits have to be used to balance the voltages between cells. [7] In the normal EDLC supercapacitor, the outcome of energy is depending on electrostatic force among the ions at electrode and electrolyte contact. The selection of the electrode material is essential in determining the electrical properties of the EDLC supercapacitors. The low energy density limits the use of it in electric vehicles and other new energy storage. [21] Figure 7. shows a schematic diagram of an EDLC supercapacitor.

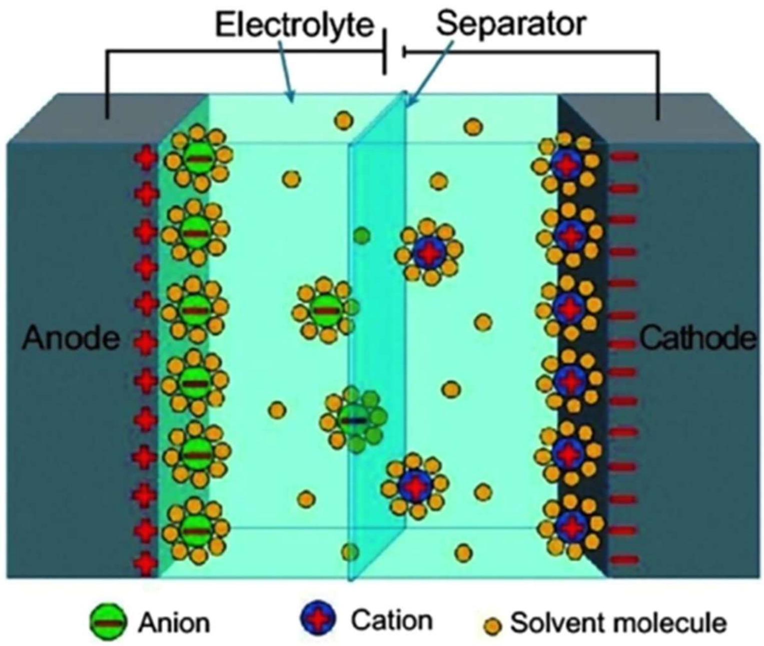

Figure 7. Schematic diagram of an EDLC supercapacitor. [21]

- Pseudocapacitor type

The operation of pseudocapacitors is based on a redox reaction of the faradic charge transfer process on the surface of pseudo-electrodes, where metal oxides are transferred. Electrically conductive polymers are often used as electrochemically active materials. [7], [21] Pseudocapacitance is a completely non-electrostatic property and is forming as a result of electrochemical charge-transfer. It occurs at the electrode surface on which the faradic charge storage mechanism exists. Since this energy storage is based on redox reactions, the pseudocapacitor is a little bit similar to a battery in its behavior. [21]

When a pseudocapacitor equipped with a double-layer it is a supercapacitor. Then the charge moves in two layers with a capacitance related to the potential and amount of acceptable charge. Pseudocapacitance is 10-100 times higher than EDLC capacitance, but it's poor electrical conductivity leads to a lack of cycling stability and low power density. Pseudocapacitance does not exist without double-layer capacitance. The difference between EDL supercapacitor and pseudocapacitor is that the pseudocapacitor combines rapid and reversible redox reactions, that take place amid the active material on electrode and electrolyte interface. The redox reactions are due to the thermodynamic nature of the process. [21] Figure 8. shows a schematic diagram of a pseudocapacitor.

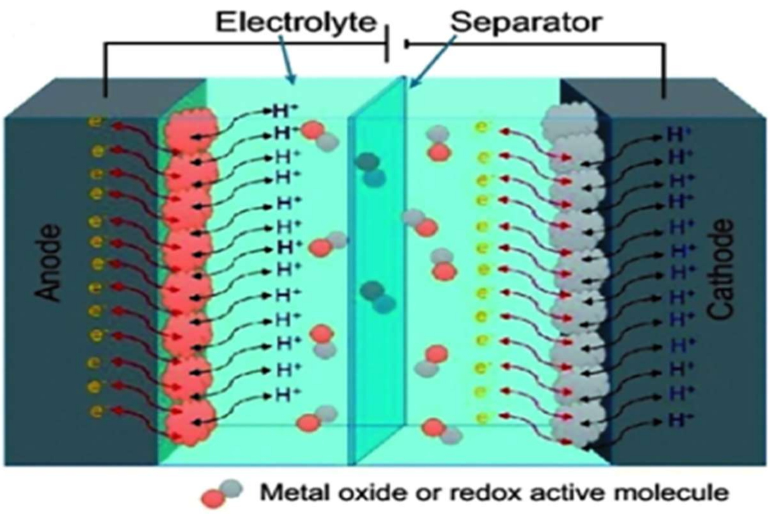

Figure 8. Schematic diagram of a pseudocapacitor. [21]

- Hybrid capacitor (Li-C) type

Commercial versions of hybrid (super)capacitor i.e. lithium-ion-capacitor (Li-C) are an asymmetric combination of EDLC supercapacitor and pseudocapacitor, which acts as a booster in its respective capacitance values. They consist of submerged electrodes within the electrolyte solution kept separate with a separator, which one prevents the short circuits. Compared to an EDLC supercapacitor and pseudocapacitor, a hybrid capacitor produces a higher specific capacitance and energy storage capability. This combination creates a new beginning pollution-free, long-lasting, and proficient energy-storing and is suitable for their utilization in hybrid vehicles and similar sort of power necessity-based devices. However, in comparison to EDLC supercapacitors, hybrid capacitors have lower cyclability. The performance of hybrid capacitors depends on both the electrodes and the electrolyte material. [19], [21]

Hybrid capacitors have been much in the spotlight for their ability to combine the properties of EDLC and pseudocapacitors. They have more improved properties than just combining components. Thus, hybrid supercapacitors have higher energy and power densities than normal EDLC and pseudocapacitors, and this favors their use compared to other energy storage. [21] Figure 9. shows a schematic diagram of a hybrid capacitor.

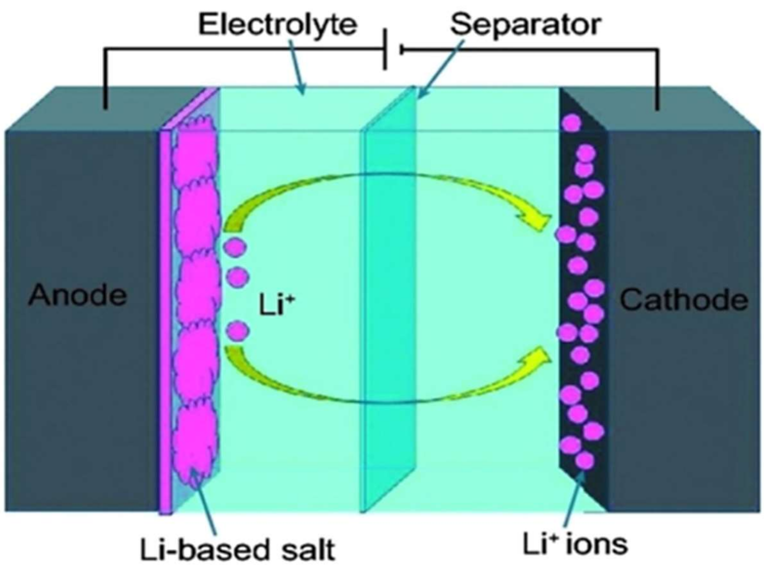

Figure 9. Schematic diagram of a hybrid capacitor. [21]

1.3 Requirements for hybrid power system

1.3.1 Classifications for hybrid power system

The hybrid power system design is based on the configuration of the hybrid working machine, which determines the development and selection of the energy management strategy. Because there are hydraulic actuators in the hybrid working machine, the topology of system configuration is a two-dimensional matrix, which consists of drive train and hydraulics. However, this two-dimensional configuration expression has not any description of the ways and characteristics of energy conversion in the hybrid power system. For that reason, hybrid working machines are classified into three main types: diesel-hydraulic hybrid (DHH), diesel-electric hybrid (DEH), and fuel cell hybrid (FCH). In a hybrid working machine, the energy generating device includes an integrated combustion engine (ICE) and fuel cells, and the energy storage system (ESS) includes batteries, supercapacitors, and hydraulic accumulators. [2], [3]

Based on the configuration, hybrid working machines can be classified into other main three categories: series hybrid, parallel hybrid, and compound hybrid (series-parallel hybrid). [2], [22] The research focuses on DEH-type hybrid working machines. Figure 10. shows energy and configuration based classification of hybrid working machines.

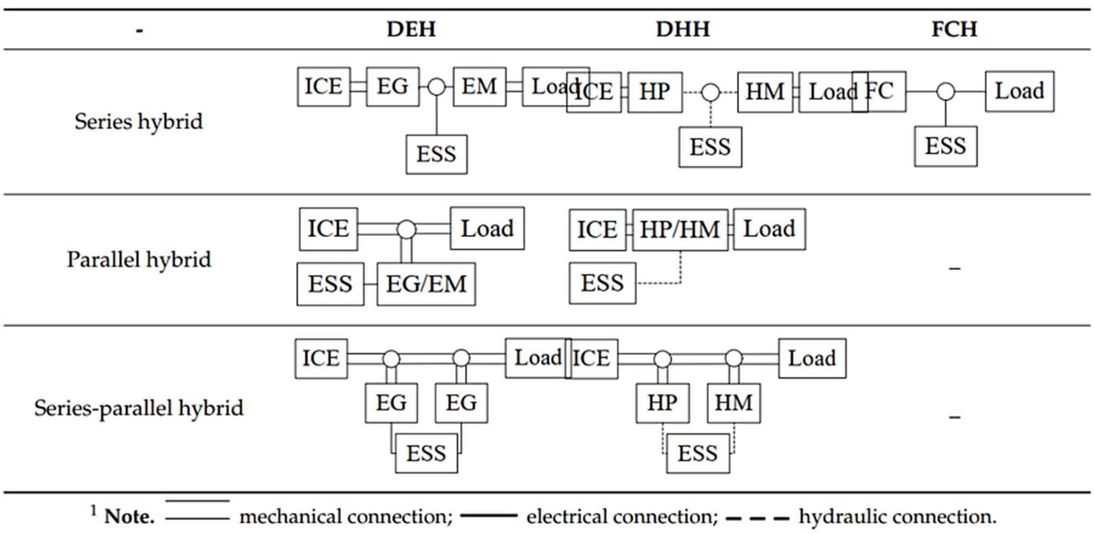

Figure 10. Energy-based classification of hybrid working machines. [3]

Working machines are characterized by lower travel speed, clear periodicity, higher amplitude, and load change rate, complex systems, and structures, as well as more start-stop operations, compared with cars. A large number of actuators are part of the operation process, making the systems, and structures of working machines more complex than those of cars. [2], [3] The International Electrotechnical Commission (IEC) has defined a hybrid electric vehicle (HEV) is a vehicle with two or more forms of energy reserves, which one can be converted into electric energy. [2], [3] DEH has selected a battery or ultracapacitor as ESS, and it's structure consists of ICE, generator, battery and/or supercapacitor, electric motor, and hydraulic actuators. DEH converts the energy of diesel oil to electricity and charges the ESS, and the use of fossil energy is reduced by combining hydraulic and electric energy during operation. Figures 11. - 15. show typical series, parallel, and compound schematic structures i.e. topologies of hybrid working machines. [3]

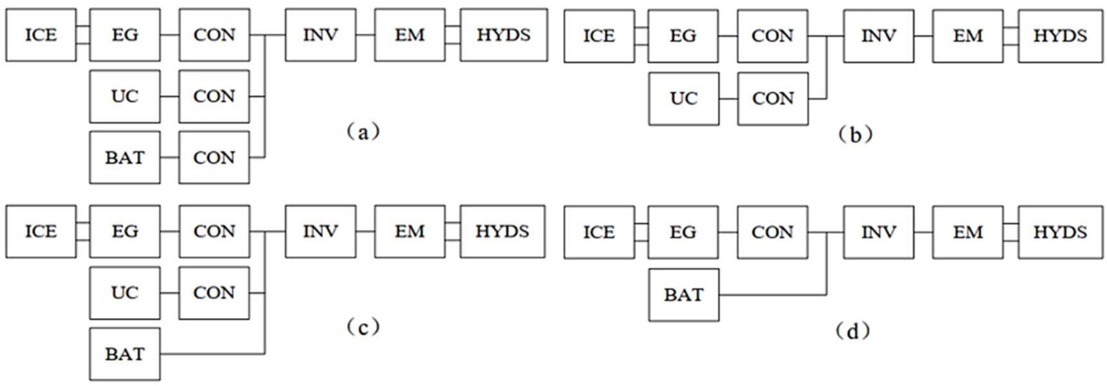

Figure 11. Schematic structures of series hybrid working machine. [3]

Battery (BAT) and supercapacitor (UC) are together in parallel connection with ICE and then in series connection with EM in Figure 11. a) and 11. c). Only supercapacitor or battery is in parallel connection with ICE and then in series connection with EM in Figure 11. b) and 11. d). [3]

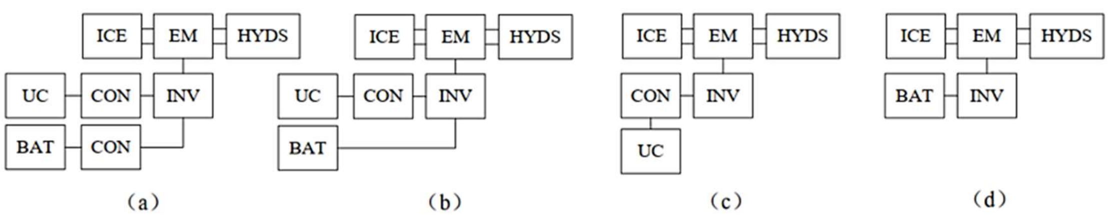

Figure 12. Schematic structures of the parallel hybrid working machine. [3]

Battery (BAT) and supercapacitor (UC) are together in parallel connection and then in parallel connection with EM in Figure 12. a) and 12. b). Only supercapacitor or battery is in parallel connection with EM in Figure 12. c) and 12. d). [3]

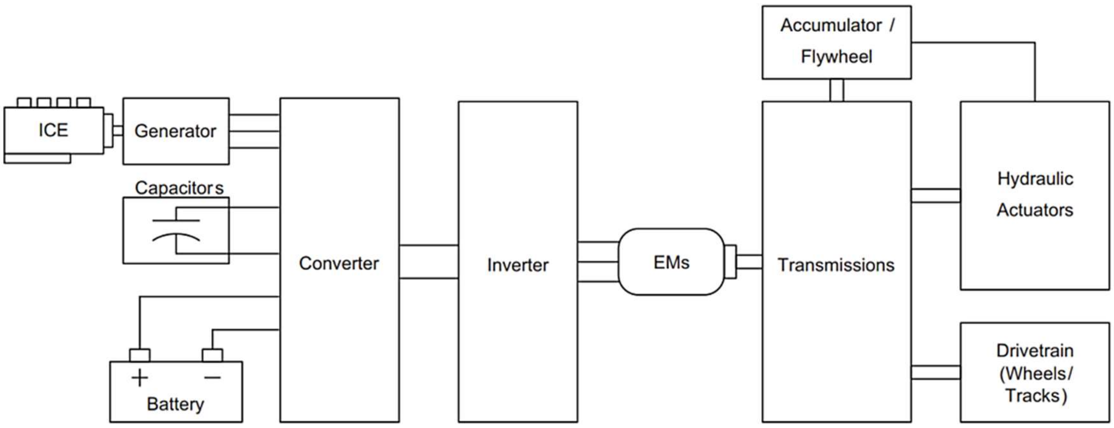

Figure 13. Typical series hybrid configuration for working machines. [2]

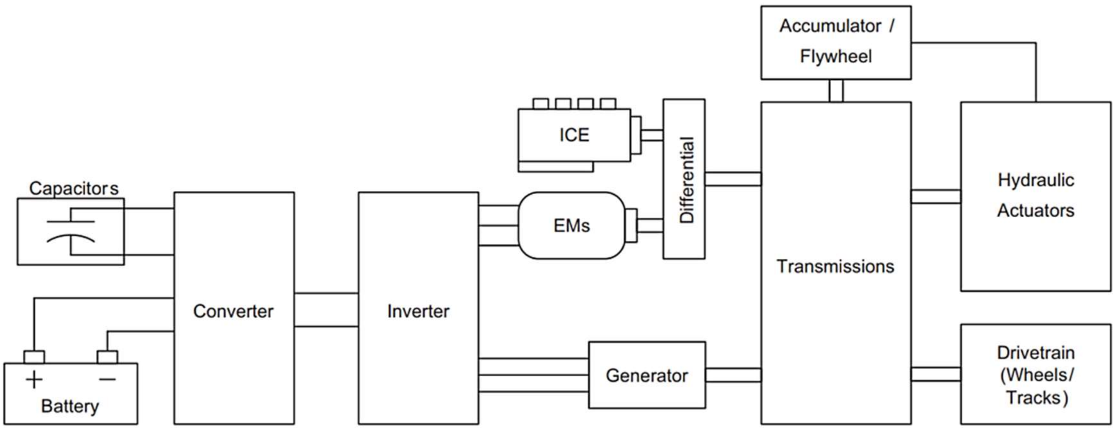

Figure 14. Typical parallel hybrid configuration for working machines. [2]

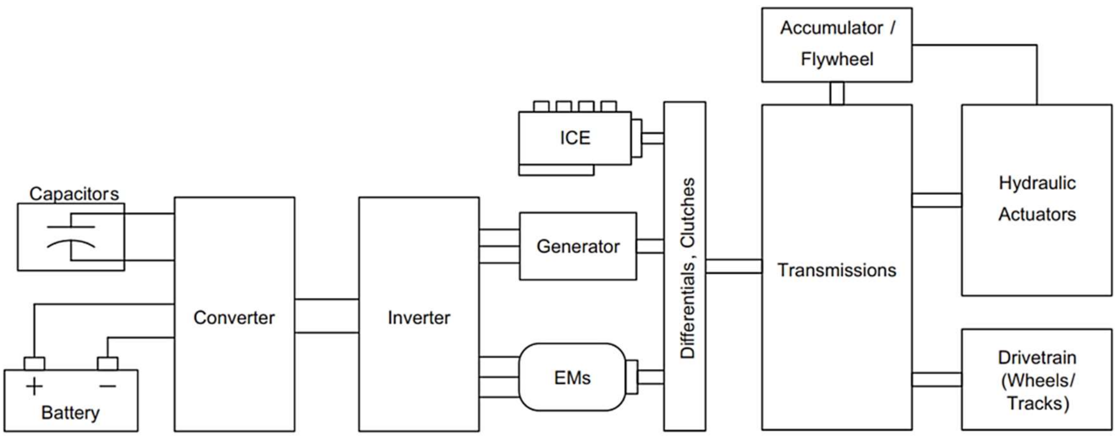

Figure 15. Typical compound hybrid configuration for working machines. [2]

With the degree of hybridization, hybrid electric machines can be categorized into three types: micro-hybrid, mild hybrid, and full hybrid machines. Mild hybridization is the most promising solution for hybrid working machines. Then the integrated starter/alternator (ISA) is combined with an ICE to support the main functions, such as a quick engine start, idle control, stop-start control, power boost control, engine efficiency optimization, and regenerative braking. The electric power rated values of mild hybrid systems are 10-20 kW and 100-200 V. There is a lot of technological challenges with the implementation of mild hybridization in hybrid working machines: machine architectures, energy storage systems, energy management strategies, standards of working profiles, load sensing control, applicability and safety/reliability. [2]

The electrification degree of conventional working machines is usually low, and their design is conservative. Hence, the DEH system needs to add extra X-by-wire systems, electrical components, etc., and make large modifications for the conventional system also. Inverters will cause variation of DC bus voltage and affect by this way itself and motors (loss of torque, an increase of current, low-frequency harmonic distortion of motor power supply, etc.). Furthermore, the energy loss of the inverter and the temperature rise of the motor are the problems with the DEH system. The safety and reliability of batteries, overcurrent, and overvoltage should be ensured. [3]

The extra costs regarding hybridization must be compensated by the benefits of the hybrid system, including:

• by the savings via lower fuel consumption
• by the reduced exhaust via the use of smaller diesel engines
• by the additional functionalities
• by the reduced noise-vibration-harshness
• by the extra potential of electrically auxiliary units. [2]

One of the biggest problems in designing a mild hybrid system is the selection of energy storage systems when the existing technologies enable to operate at a low voltage range 12-64 V. [2]

More and more different types of hybridized working machines are entering the market. Figure 16. shows some examples of modern mobile hybrid working machines: Logset 12H GTE hybrid harvester, Kalmar hybrid straddle carrier, and Huddig Tigon hybrid wheel loader. [23], [24], [25]

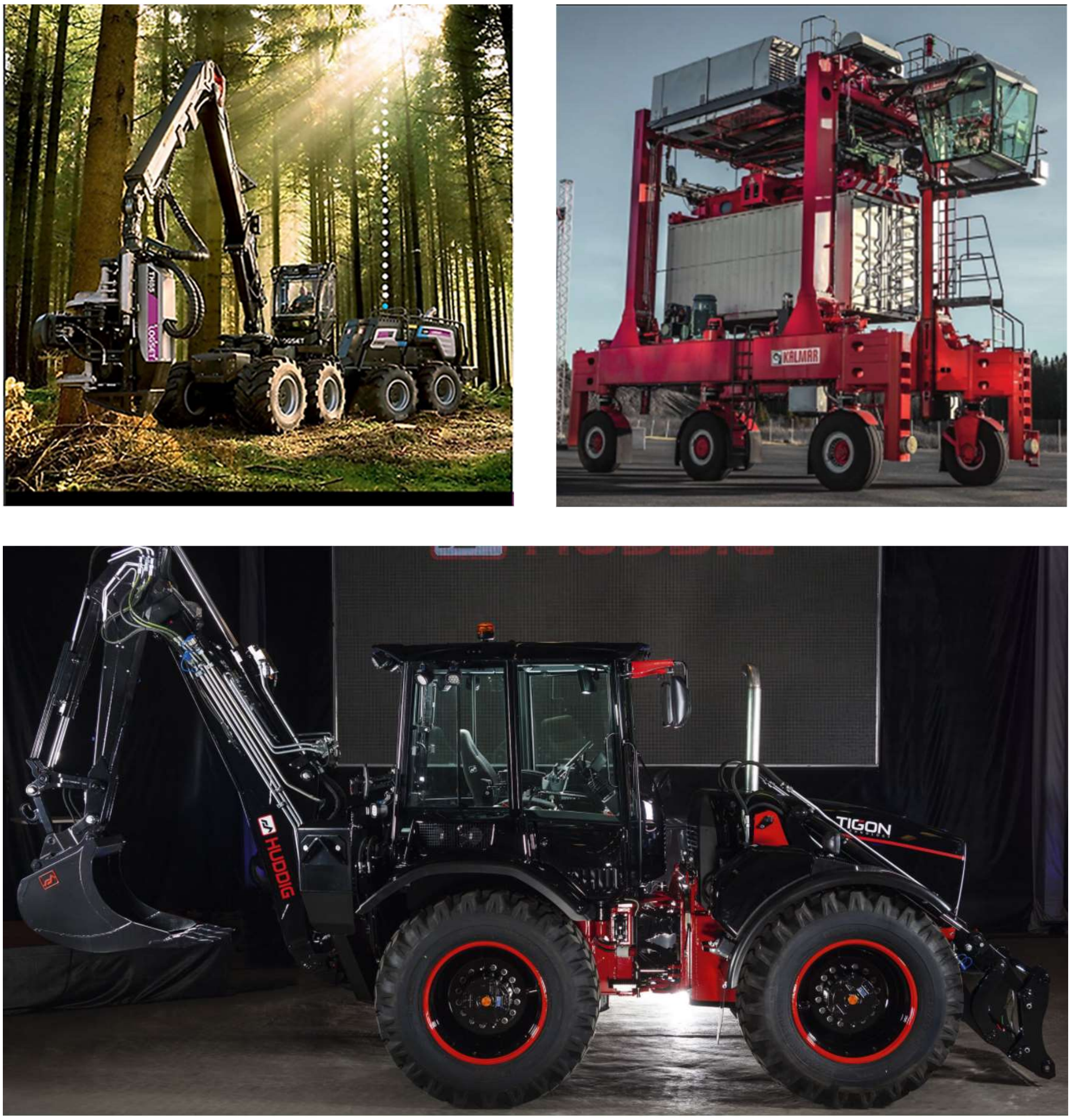

Figure 16. Examples of mobile hybrid working machines. [23], [24], [25]

1.3.2 Requirements for an electrical energy storage system (EESS)

Energy storage systems with higher power density are often used in short-duration applications requiring a fast response, whereas energy storage systems with higher energy density are often used in long-duration applications. [7] The requirements for the energy storage devices used in hybrid vehicles are high power density, fast discharge of power, large cycling capability, high efficiency, easy control, and regenerative capacity. [2], [7], [21]

In this study, electrical energy storage specifications for the hybrid working machines, such as capacity, rated voltage, charging and discharging capacity (C_{rate}), energy and power densities, stored energy, physical dimensions, volume, weight, cyclic life, calendar life, operating temperature, and price depend on the application and are under the study. [1]

The capital costs are informed in terms of cost per unit power output (€/kW) and cost per unit energy stored (€/kWh). When energy is to be stored and discharged €frequently and at a high rate, the cost per unit power output (€/kW) is an important factor when selecting the energy storage system. Whereas, when energy is to be stored for longer durations, the cost per unit energy stored (€/kWh) is an important factor. [7]

When evaluating the characteristics of different types of energy storage, such significant performance parameters are relevant as capacity, energy and power densities, efficiency, calendar and cycle lifetimes, charge/discharge properties, self-discharge, and capital costs, which are making different technologies suitable for certain applications. Hence, storage characteristics of electrochemical energy storage types are often presented in a 'Ragone plot' (e.g. Figure 17.) in terms of specific energy and specific power. They helps identify the potential of each energy storage type and compare them for applications requiring energy storage capacities. [7]

Figure 17. show differences in properties and suitability to working machine applications between Li-ion battery and supercapacitor types. In general, Li-ion batteries have a good energy density and long charge/discharge time, and supercapacitors have a good power density and short charge/discharge time. It can be seen also, that Li-C hybrid supercapacitors have better power density properties than EDLC- and Pseudocapacitors, it is a good solution to meet peak power needs.

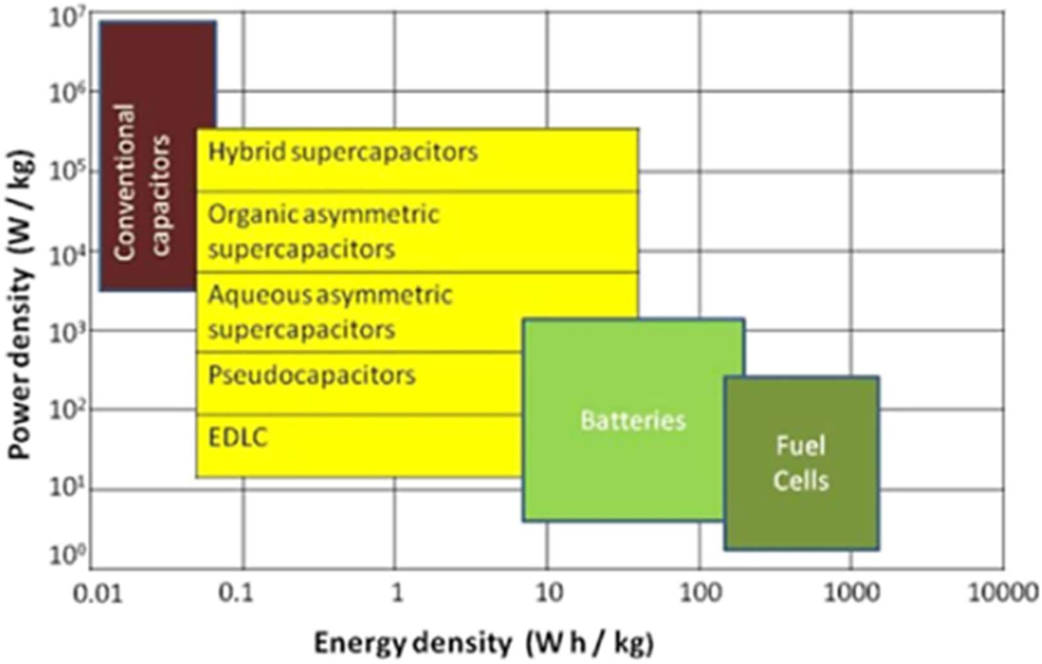

Figure 17. Ragone plot: Power density and energy density of different ESS. [21]

1.4 Research questions

Hybridization is known as a feasible solution for modern vehicles in the automotive industry with high fuel efficiency, less energy consumption, and fewer emissions. They are low cost and easy installations regardless of drivetrain configurations. However, the applicability of this same methodology with working machines is still an open topic. [2]

Some parallel studies have been done over the last ten years. Scientific articles and literature related to the research topic can be found. Additionally, some international standards, directives, and certifications guide the use of Li-ion batteries and supercapacitors for the hybridization of mobile working machines.

The main target of the study:

- The main target of the study is to find out how electrical energy storage is selected and sized for a hybrid working machine.

The scope of the study:

- The study focuses on the suitability of Li-ion batteries and supercapacitors for the electrical energy storage of hybrid working machines.

The main parts of the study are:

- Special requirements for electrical energy storage of hybrid working machines.
- Mapping and comparing the characteristics (including cycle lifetime, calendar lifetime, power density, energy density, C_{rate}, operation temperature, space requirement, and price estimate) of commercially available electrical energy storage batteries and supercapacitors suitable for hybrid working machines. The mapping focuses on supercapacitors.
- Development of a method for the selection and sizing of electrical energy storage (batteries and supercapacitors) for hybrid working machines.
- Development of Matlab-based electrical energy storage selection and sizing tool.

The result of the study is:

- A feasible method and tool for selecting and sizing cost-effective electrical energy storage for hybrid working machines.

The research problem is:

- The selection of suitable electrical energy storage technology for the hybrid working machines, must be taking into account e.g. operation temperature, estimated service life, required power density, energy density, space requirement, and costs.

The research question derived from the research problem is:

- How to select feasible electrical energy storage for a hybrid working machine?

The main hypothesis of the study is:

- The selection and sizing of the electrical energy storage for the hybrid working machine must be based on the measured work cycle (load cycles) and the characteristics corresponding to the operating conditions.

1.5 Research methods

The study focuses on the suitability of Li-ion batteries and supercapacitors for the electrical energy storage of mobile hybrid working machines and is carried out as a theoretical study using a multi-method.

- The study uses case studies of qualitative methods and the wide material used as scientific articles and literature, thesis works, research reports, standards and certificates, and the manufacturer's datasheets for the electrical energy storage and mobile hybrid working machines.
- The study uses also modeling of quantitative methods and computational methods, the results of which are presented in graphical curves and tabulars.

The extensive literature review used Google Scholar, IEEE Xplore Digital Library, SpringerLink, ScienceDirect, and Wiley Online Library search services. The information related to the research topic has also been searched on the websites of various manufacturers and experts in the reports, publications, summaries, application instructions, etc. Standards, directives, and certificates related to the research topic were sought e.g. from the CEN-, CENELEC-, EN-, IEC-, ISO-, REACH, SAE-, and SFS-search services. A mapping of manufacturers, products, and vendors of suitable Li-ion batteries and supercapacitors on the market was done using a Google search service, and the data collected were saved to the separate Excel-file.

2 RESEARCH WORK

2.1 Standards, directives, and certifications

2.1.1 Mapping of used standards, directives, and certifications

Laws, directives, and certificates related to electrical energy storage technology must be taken into account in connection to procurement, installation, operating, service, and repairing equipment related to battery technology. [26] Manufacturers of electrical energy storage (Li-ion batteries and supercapacitors) cite in their datasheets the various standards and certificates according to which their products are manufactured.

- “The Directive on the Liability of Battery Producers in the European Economic Area” (2006/66/EC) obligates battery manufacturers to recycle batteries, which in practice means reimbursing the costs of collecting, treating and recycling used batteries. [26], [27]

- “Electrical Safety Act” (Finlex 1135/2016 and “Electrical Work and Operational Work of Electrical Installations” (Finlex 1435/2016), must be followed concerning electrical work related to the installation and operation with the electrical energy storage system. They describe the requirements set in Finland for electrical work, which is an electrical qualification 1-3. Also, electrical safety training following standards “Operation of electrical installations” The European Standard (EN 50110-1) and “Safety at electrical work” SFS 6002:2015 + A1:2018: en are always required for the installation, maintenance, and repair of live electrical equipment. [26], [28] - [32]
- “Live working - Hand tools for use up to 1000 VAC and 1500 VDC” (IEC 60900), standard sets the requirement for the maintenance hand tools i.e. they must be with a rating of 1 500 VDC and 1 000 VAC. [26], [33]
- “Safety requirements for secondary batteries and battery installations - Part 1: General safety information” (IEC 62485-1) and “Safety requirements for secondary batteries and battery installations - Part 3: Traction batteries” (IEC 62485-3) standards covers industrial electric vehicles and other similar devices, such as automatically controlled vehicles and forklifts. [26], [34], [35]

The requirements of the standards for battery installations include protection against electric shock and emphasizes that batteries above 120 VDC must be protected against both direct and indirect contact. Also, the battery storage lockers must be locked and marked with warning signs. Isolation of live parts from the outer shell and delimitation of live parts utilizing protective housings outside the contact distance is a suitable means of protection against direct contact. [26], [34], [35]

- “Degrees of protection provided by enclosures (IP Code)” (IEC 60529) standard specify if the housing is used as a protection method, and it should be at least IP67 in the case of the working machines. When there is a possibility to indirect contact, the means of protection are again the isolation of live parts, protective earthing, and the automatic separation of live parts from the rest of the system. “Low voltage electrical installations - Part 4-41: Protection for safety - Protection against electric shock” (IEC 60364-4-41) standard specify the additional protections. [26], [31], [34] - [37]

- “Safety of machinery - Electrical equipment of machines - Part 1: General requirements” (IEC 60204-1), standard sets the insulation requirements for the cables and wires to prevent short circuits. This means an insulation resistance of at least 1 MΩ, and an insulation test has done at twice the rated voltage and continuous at least one second. The lower limit of the specific resistance of the batteries is defined as at least 1 MΩ for new and fully charged batteries and used batteries above 120 VDC, at least 500 Ω multiplied by the nominal battery voltage. The insulation resistance has to be measured according to the standard between the battery terminal and the conductive outer shell of the device. Batteries exceeding 120 VDC should be divide so, that that they can be serviced as a maximum of 120 VDC batteries. [26], [38]
- “UN/DOT 38.3 certification” i.e. transportation tests under by the UN (United Nations), the IATA (International Air Transport Association and the DOT (Department of Transportation, USA) are required for each system or subsystem using a Li-ion battery. [26], [39], [40]

In “UN/DOT 38.3 certification” tests, approval is sought for eight special tests:

  - T1 - Altitude simulation
  - T2 - Thermal testing
  - T3 - Vibration testing
  - T4 - Shock testing
  - T5 - External short circuit testing
  - T6 - Impact testing
  - T7 - Overcharge testing
  - T8 - Forced discharge testing

However, it should be noted that although the manufacturer of the battery cells, modules, or pack has completed the tests, a new test is required if structural changes are made to the tested battery pack that changes the characteristics of the battery pack already tested by the manufacturer. In addition to the safe transport of batteries, and the certifications applied for, the familiarization of employees with battery technology and its safe use is essentially important. [26], [39]

When investigating the technical datasheets of Li-ion batteries and supercapacitors suitable for the hybridization of mobile working machines on the market, the following lists can be drawn up:

- List of standards commonly used by Li-ion batteries and supercapacitors manufacturers in all their activities:
    - IEC 61427-1: General requirements and methods of test - Part 1: Photovoltaic off-grid application
    - IEC 60068-2-6: Environmental testing - Part 2-6: Tests - Test Fc: Vibration (Sinusoidal)
    - IEC 60068-2-27: Environmental testing - Part 2-27: Tests - Test Ea and guidance: Shock
    - IEC 60068-3-3: Environmental testing - Part 3-3: Supporting documentation and guidance - Seismic test methods for equipment
    - IEC 60068-3-4: Environmental testing - Part 3-4: Supporting documentation and guidance - Damp heat tests
    - IEC 60529: Degrees of protection provided by enclosures (IP Code)
    - IEC 60950-22: Information technology equipment - Safety - Part 22: Equipment to be installed outdoors
    - IEC 61508: Functional safety of electrical/electronic/programmable electronic safety-related systems - Parts 1-7
    - IEC 62391-1: Fixed electric double-layer capacitors for use in electric and electronic equipment - Part 1: Generic specification
    - ISO 26262-9: Road vehicles - Functional safety - Part 9: Automotive Safety Integrity Level (ASIL) -oriented and safety-oriented analyses
    - ISO 16750-3: Road vehicles - Environmental conditions and testing for electrical and electronic equipment - Part 3: Mechanical loads

  - SAE J2380: Vibration Testing of Electric Vehicle Batteries
  - SAE J2464: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
  - UL 810A: UL Standard for Safety Electrochemical Capacitors

- List of certificates commonly used by Li-ion batteries and supercapacitors manufacturers in all their activities:
  - E-mark and e-mark certifications
  - EuP Directive: Eco-design of Energy Using Products
  - REACH certification: Registration, Evaluation, Authorisation, and Restriction of Chemicals
  - RoHS certification: Restriction of Hazardous Substances
  - UN 38.3 certification: UN Manual of Tests and Criteria - Ensure the safety of lithium batteries during shipping
  - WEEE certification: Waste Electrical & Electronic Equipment

2.1.2 Results of research work

However, more standards, directives, and certificates should be considered, when hybridizing working machines by Li-ion batteries and supercapacitors. This can be seen based on the lists of available IEC and ISO standards. There are more standards about e.g. explosive atmospheres, electrical insulating materials, safety requirements of batteries, degrees of protection provided by enclosures for electrical equipment, etc.

  - IEC 60079: Explosive atmospheres
  - IEC 60085: Electrical insulation - Thermal evaluation and designation
  - IEC 60216-1: Electrical insulating materials - Thermal endurance properties - Part 1: Ageing procedures and evaluation of test results
  - IEC 62133-2: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary lithium cells, and batteries made from them, for use in portable applications - Part 2: Lithium systems

- IEC 62262: Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code)

2.2 Characteristics of electrical energy storage system (EESS)

This is a brief introduction to the battery technology parameters to be studied, before mapping and comparison of the characteristics (C_{rate}, power density, energy density, cycle life, calendar life, operating temperature, space requirement, and price estimate) with electrical energy storage suitable for the hybridization of the working machines.

The properties of the EESS i.e. batteries and supercapacitors are not the same kind, not even with the same chemistries. Some of them have better power properties, and some have better energy properties. The main trade-off with batteries and supercapacitors are between power and energy properties. [41]

The electrical energy storage of the hybrid working machine consists of a high voltage battery and/or supercapacitor pack which consists of individual modules and cells connected in series and parallel. A cell is the smallest component of a battery and generally rated one to six volts. A module consists of several cells connected in series or parallel. A battery pack is then formed by connecting modules together, again in series or parallel. Batteries for hybridization of working machines are secondary battery types, which are rechargeable. [41] Figure 18. shows an electrical energy storage system integration that consists of cells, modules, and packs. The challenges are the robust integration of electrochemical cells, mechanical structures, cables, electronics, and thermodynamic systems. [4]

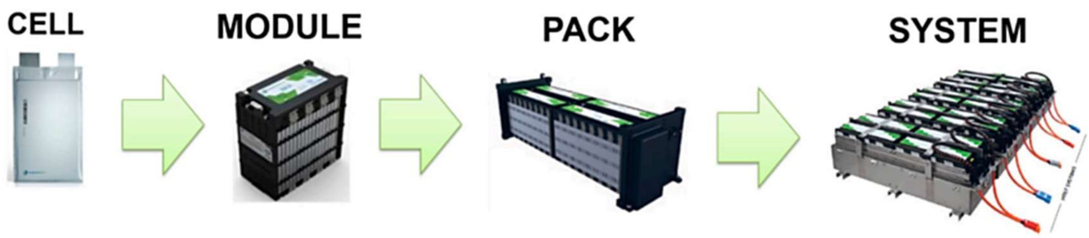

Figure 18. Electrical energy storage system integration. [4]

2.2.1 Charge/Discharge rate [C_{rate}]

The rate at a battery or supercapacitor can be charged or discharged relative to its maximum capacity. The 1C rate means that the discharge current will discharge the full battery in 1 hour. The battery with a capacity of 100 Ah, this equates to a discharge current of 100 A. A 5C rate for the battery with a capacity of 100 Ah would be 500 A, and a C/2 rate would be 50 A. [17], [41], [42]

C_{rate} can be determined as follows:

$$C_{\text{rate}} = \frac{P_{\text{ch}}}{E_{\text{cap}}}$$

where P_{ch} is the total charge power and E_{cap} is the total capacity of the battery. Example in kilowatt-hour-unit: If a battery has a capacity of 75 kWh, then at 1C it would express 75 kW for one hour to completely charge the battery. However, rated capacity in ampere-hour (Ah) is typically used to describe a battery's ability to supply current. For a fixed time period, the higher the C_{rate}, the lower the rated Ah capacity, and vice versa. [17] Figure 19. shows typical charge cycle of battery type electrical energy storage. [17]

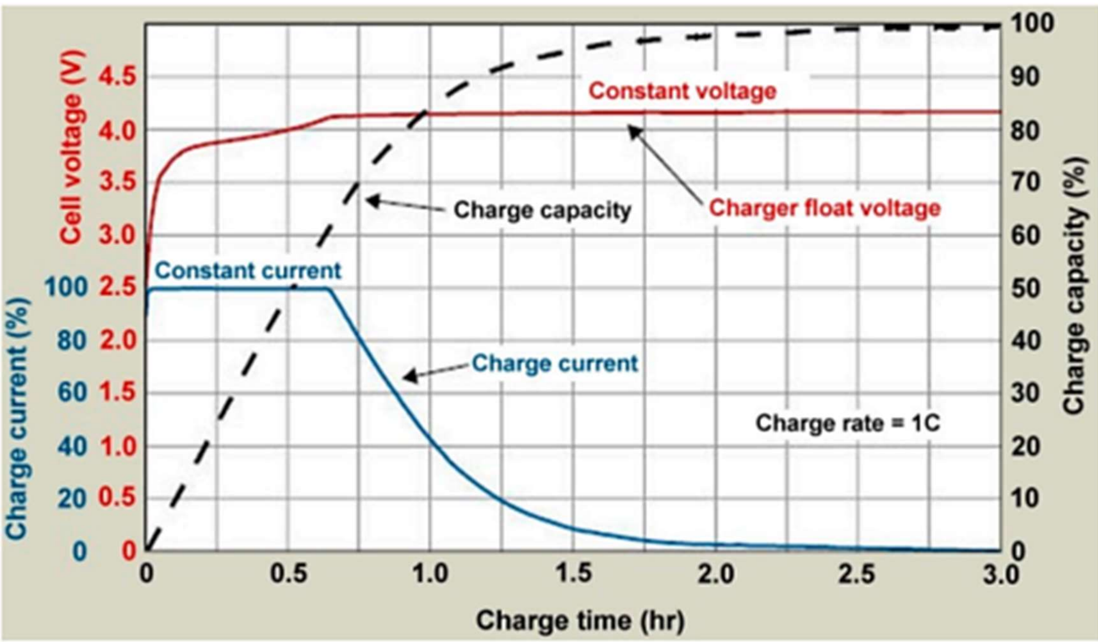

Figure 19. The typical charge cycle of battery type energy storage. [17]

2.2.2 Specific power [W/kg] and Power density [W/l]

The maximum available power per unit mass or volume. [41], [43], [44] It express the ability to store power per mass or volume. With Li-ion batteries, the increase in power density leads to lower energy density and vice versa. [45], [46] When a battery has a high power density, it can produce lot of energy quickly based on its volume, and they can also recharge quickly. Supercapacitors have a higher power density than batteries. They can discharge energy more quickly, but batteries can store more energy. [47]

2.2.3 Specific energy [Wh/kg] and Energy density [Wh/l]

The nominal energy per unit mass or volume. [41], [43], [44], [48] It express the ability to store energy per mass or volume. The battery pack has a lower energy density compared to the single-cell due to the protective housing. [45] Batteries have a higher energy density than supercapacitors, but it does not mean a high power density. They can store more energy, but supercapacitors can discharge energy more quickly. [46], [49] Figure 20. shows the relationship of power density and energy density of different energy storage systems.

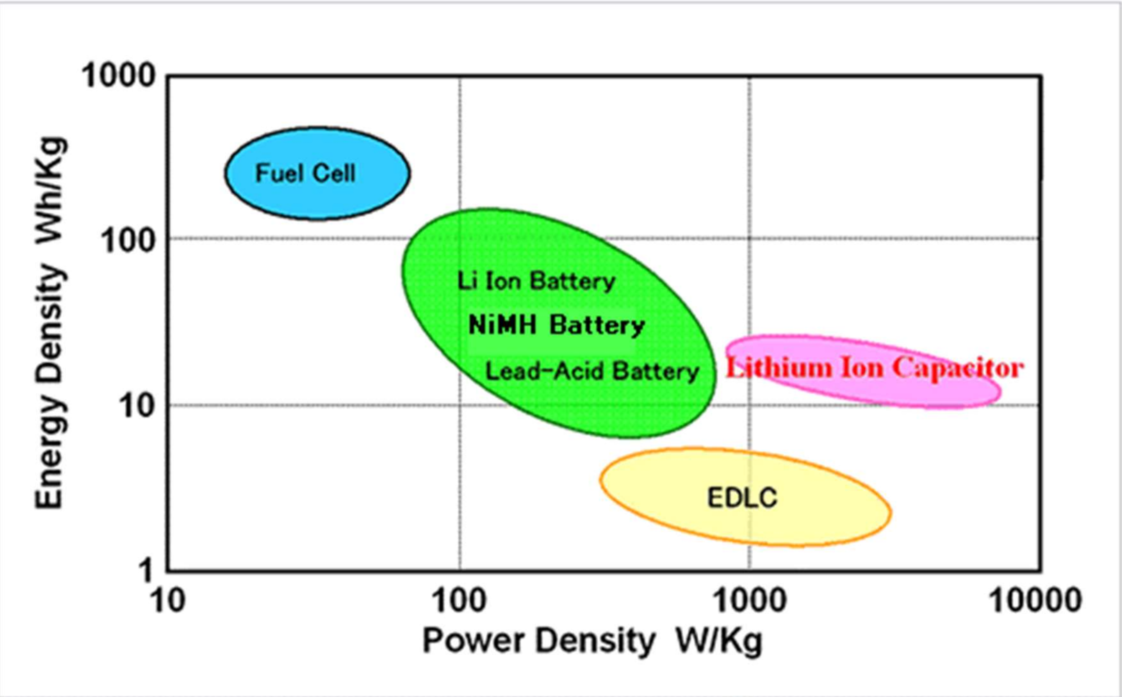

Figure 20. The relationship between power density and energy density of different ESS. [49]

2.2.4 Cycle lifetime [cycle]

The number of discharge-charge cycles of the battery or supercapacitor before they will lose their specific performance criteria. Cycle lifetime is estimated for specific charge and discharge conditions. The operating lifetime of the battery or supercapacitor is affected by the rate and depth of cycles, and also temperature, humidity, and voltage. What a higher DoD (Depth of Discharge), that lower the cycle lifetime. DoD value is typically between 70-80% of the nominal capacity. Most of the batteries prefer lower DoD value, rather than a full discharge. [41], [45], [48], [50], [51], [52]

2.2.5 Calendar lifetime [a]

Calendar lifetime of battery or supercapacitor which starts to expire just from that time it is completely manufactured and they will expire even if they are not used at all. The calendar lifetime varies depending on the types of batteries or supercapacitors. Battery or supercapacitor applications and storage methods affect their calendar lifetime. Low humidity and the right temperature is reducing battery or supercapacitor aging. These factors must be taken into account, especially in the design of the housing. It is important to enclose as tightly as possible to prevent the adverse effects of humidity especially in the case of Li-ion batteries. Battery or supercapacitor overcharges and high currents consume a relatively large amount of their power and thus have a significant effect on their aging. Generally, a limit is used, in which case the capacity of the battery or supercapacitor has decreased to 80% of the original capacity. [26], [45], [48], [50], [51], [52]

2.2.6 Operation temperature [°C]

Operating temperature effects strongly on battery life and performance. Battery manufacturers set their battery performance for the specific operating temperature range. All major manufacturers recommend operating their batteries at 20-25 °C operating temperature range. Higher temperature values are increasing battery performance but decreasing battery calendar lifetime. [53] Operating temperature range affects the performance and durability of supercapacitors, and therefore it has been defined in the datasheets for all supercapacitors. Although operating temperature affects capacitance and internal series resistance, only a few manufacturers provide operating temperature curves. The operating temperature ranges of EDLC, pseudo- and hybrid supercapacitors vary significantly between different manufacturers. [52]

2.2.7 Space requirement [mm, dm^3]

Space requirement informs physical dimensions (LxWxH) in millimeters of battery or supercapacitor. There are several standards which are driven the physical dimensions of batteries according to their chemistries. The shapes of batteries are usually cylindrical, prismatic, and pouch cells. Li-ion batteries are using standard sizing codes: 18650, 26650, 14500, 21700, and 32650. [54]

Most of the supercapacitors on the market have a cylindrical shape, and most of these have 60-mm-diameter cells that have become a standard in the industry. Only the length of the cylindrical housing varying between models of different sizes. However, there are some newer manufacturers which are using an angular shape. The angular or flat shape allows for denser packing in multi-supercapacitor systems. [52]

2.2.8 Price estimate [€, €/kW, €/kWh]

The price estimate is the unit price (€/pcs) inform by the manufacturer or vendor for the battery or supercapacitor. Cost is also one of the features, and an important factor, which must be taken into account when choosing a battery or supercapacitor. The price of the battery or supercapacitor consists of the materials used in the cell, module, or pack and their production process. The materials used in the cathode, such as cobalt and nickel, are expensive metals whose prices fluctuate widely. [45]

2.2.9 Results of research work

A mapping of manufacturers and products on the market of Li-ion batteries and supercapacitors suitable for hybridizing working machines was done using by Google search service. Suitable Li-ion batteries and supercapacitors found from different manufacturer's or vendor's websites were listed in a separate Excel file, that has been used to compile the summary table on the next page. Manufacturers were sought e.g. from these operators' websites: Chinabrands, DirectIndustry, Eletimes, Imarcgroup, ThomasIndustry, Unique Energy Hub, VentureRadar, and from these supplier's websites: CapComp Shop24, DigiKey Electronics, Elfa Distrelec Group, Energy XPRT, Farnell, FindChips, Ineltro AG, infinity-electronic, Richardson RFPD, Rutronik24, and Mouser Electronics. [55] - [70]

The products which characteristics were thought to meet the demanding needs and conditions of hybrid working machines were selected from the Excel list for the summary Table 1. Datasheets from several manufacturers were quite insufficient, especially for supercapacitors. For that reason, the table below has been complemented also with the general values found in the literature and by calculating (with italic font). The summary Table 1. is based on the characteristics of module versions, and the value range for each parameter has formed by considering the lowest and highest values of all selected types.

Manufacturers of Li-ion batteries from whose collections the data were collected were AIMS, Akasol, Alpha-ESS, Altairnano, Ampetus, BattleBorn, BST Power, BYD, DCS, Delta, Dragonfly, East West Life Technology, Enerdell, Enerdrive, Forsee Power, Genz, Hybria, Hyperdrive, Impact, Incell, Kokam, Leclanche, LG Chem, LIAO, LithiumValley, Melsen, Mercedes-Benz, MG, PBES, PowerTech, Pylontech, Relion, Rensea, Saft, Samsung, Sentry, SimpliPhi, SmartBattery, Soltaro, Sony, Spear, Tesvolt, Toshiba, Victron Energy, XALT Energy, YIY, and Zhejiang Xinghai Energy Technology.

Manufacturers of supercapacitors from whose collections the data were collected were AOWEI, Eaton, Electro Standards Laboratories, IOXUS, Jianghai Europe, JM Energy, LS Mtron, Maxwell Technologies, Samwha, Sech SA, Skeleton Technologies, SPSCAP, Tecate Group, Yunasko, and WIMA.

Typical for the supercapacitors are the different trade series names by their manufacturers like BestCap, BoostCap, CAP-XX, DuraBlue, E-Cap, Energy-C, FastCap, Goldcap, Green-Cap, Hy-Cap, PowerCap, PseudoCap, SkelCap, SuperCap, ThinCap, ULTIMO, Ultracapacitor, etc. what is making difficult users identify right type products for their applications.

Also characteristics/properties in the datasheets of manufacturers are not standardized, which means that the comparing between products is very challenging and taking a lot of time. For example, the value of the gravitational power density i.e. specific power [W/kg] has been calculated in many different ways depending on the manufacturer, and the pulse time [s] for the peak (pulse) power current [A] is varying depending on the manufacturer.

Table 1. Characteristics of electrical energy storage module types on the market. [7], [46], [48], [71] - [92]

Energy storage type	**Li-ion batteries**			**Supercapacitors i.e. Ultracapacitors**	
Properties	**LFP $LiFePO_4$**	**LTO $Li_4Ti_5O_{12}$**	**NMC $LiNiMnCoO_2$**	**EDLC or Pseudo cap.**	**Li-C i.e. Hybrid cap.**
Nominal voltage [V]	12 - 307	24 - 55	3.6 - 44	2.5 - 381	12 - 136
Maximum power [kW]	2.6 - 11	4.4 - 12	10 - 12	0.9 - 218	2.9 - 13
Maximum pulse power [kW]	2 - 30	7 - 22	7.6 - 25	7.5 - 458	0.7 - 29
Capacitance [F]	-	-	-	2.5 - 3000	92 - 14 000
Capacity [Ah]	20 - 410	18 - 91	24 - 46	0.1 - 1.3	0.5 - 33
Stored energy [Wh]	640 - 12 800	480 - 4200	288 - 2040	2.6 - 213	5.5 - 1067
Specific power [W/kg]	31 - 281	294 - 806	214 - 546	433 - 6800	960 - 2160
Power density [W/l]	49 - 308	369 - 1682	308 - 893	457 - 10 300	720 - 2160
Specific energy [Wh/kg]	38 - 183	38 - 83	68 - 164	1.4 - 5.6	1.8 - 34
Energy density [Wh/l]	15 - 206	34 - 140	43 - 222	1.3 - 6.3	1.4 - 42
Charge rate [C_{rate}]	0.2C - 3.7C	2C - 20C	0.2C - 5C	20C - 7686C	9C - 1086C
Discharge rate [C_{rate}]	0.2C - 20C	2C - 20C	2.3C - 15C	20C - 7686C	9C - 1086C
Cycle lifetime [Cycles, at DoD 80%]	4000 - 1 000 000	15 000 - 25 000	3000 - 8000	500 000 - 1 000 000	500 000 - 1 000 000
Calendar lifetime [a]	10 - 27	25	5 - 20	10 - 20	10
Operation temperature [°C]	-25 - 80	-50 - 65	-40 - 70	-40 - 65	-40 - 70
Weight [kg]	3.5 - 650	12 - 99	1.9 - 430	0.6 - 85	3 - 19
Volume [dm^3]	0 - 0.468	0 - 0.091	0 - 0.299	0 - 0.114	0 - 0.065
Price [€]	215 - 4966	2525	591 - 1193	539 - 5665	*1032 - 13 548*
Price (CapEx) [€/kW]	526	117	*50*	8.4 - 322	*57 - 664*
Price (CapEx) [€/kWh]	103 - 1726	1741	425 - 621	8791 - 59 816	*20 843*

2.3 Electrical energy storage selection method

The hybridization process of the working machine:

1. Work cycle (load cycles) definition
2. Selection of the hybridization type
    - Series hybrid?
    - Parallel hybrid?
    - Parallel-series hybrid?
3. Dimensioning of
    - Diesel engine
    - Electrical machines
    - Electrical energy storage
4. Calculations of fuel consumption and payback period

The hybridization starts by defining the work cycles and their loads for the main parts of the working machine. The work cycles will be measured from the actual diesel-operated working machine in the normal working environment, and with the basic operations. The work cycles are combined in series and then analyzed with the Rainflow counting methodology. The essential characteristics will be determined at least: the maximum power $P_{\text{load-max}}$, the average power $P_{\text{load-mean}}$, and the maximum energy needed of the system $E_{\text{load-max}}$ of a single action. [1]

The selection of the hybridization type will be based on the analyzed work cycles. In practically, the manufacturer will decide how radical changes they are ready to make to the working machine. A parallel hybrid system can be built with the minimum changes to an existing diesel-operated working machine, but the series hybrid system will be the total rebuilt or a newbuild of the working machine. Dimensioning of the diesel engine, the genset generator, and the electrical energy storage with the best match, is the most challenging task in a hybridization process, for minimizing fuel consumption. After dimensioning, the typical work cycle is calculated again by the several iterative simulations to find the optimum. The payback period of the hybridization is determined in this way, based on the fuel savings during the cycle. [1]

2.3.1 The Rainflow counting cycle method

In this study the Rainflow counting method is used to estimate the needed calendar lifetime, peak power, and stored energy properties of the electrical energy storage to be selected and sized for the ready-made series hybrid working machine. The Rainflow Counting method needs the work cycle of the working machine, and it can be defined by measurements in the authentic environment.

Rainflow counting is a method to determine the number of fatigue cycles present in a load-time history. A fatigue cycle is the loading and unloading of a part. With enough repeated cycles, a part will weaken and eventually fail. [93]

The Rainflow counting is used to pick-up the number of cycles, and their respective range and mean. In real-life, loading is often not cyclic and seems to be random or momentary. When using the Rainflow counting, you can be compare the fatigue damage of one load history to the another load history. The Rainflow counting make it possible to determine the fatigue damage of a given load-time history, and it also reduces the time history of data required to store. By reducing the time data size, the required calculation speed for a analysis is also decreasing, and the amount of computer storage. [93]

The Rainflow counting consists of four main steps, and they are documented in standard ASTM E1049-85(2017) “Standard Practices for Cycle Counting in Fatigue Analysis”:

1. Hysteresis Filtering
   - The first step removes very small cycles from the load-time history which are causing a minimal amount of damage.
2. Peak-Valley Filtering
   - The target of the second step is to keep only data points which are reversals in direction/slope.
3. Discretization
   - The third step is dividing the Y axis into discrete ‘bins’. Each ‘bin’ is a fixed amplitude zone that the measured data points are mapped into.
4. Four Point Counting Method
   - The target of the fourth step is to count the cycles for fatique life.

   This means the amplitude, the number, and the mean of the cycles. [93], [94]

2.3.2 The dimensioning of the electrical energy storage

In the dimensioning of the electrical energy storage are some limiting characteristics, like the voltage, the mass, the volume, the lifetime, and the price. The capacity of the electrical energy storage should not be so high that all the recoverable power could be stored in it. Single high power peaks do not have enough energy so that the power rating of the electrical energy storage should be dimensioned according to such a value. The theoretical optimal dimensioning of the electrical energy storage of hybrid systems is found by simulations. In the simulation procedures, some essential characteristics, like the energy capacity (E_{es}) and power capacity (P_{es}) of the electrical energy storage, and the maximum capacity of the diesel engine (P_{dmax}) are varied. It is noteworthy, that usually it is not possible to test the electrical energy storage also in an actual environment. [1]

In all hybrid systems, the fuel consumption increases when the rated power of the electrical energy storage decreases, and the rated power of the diesel engine increases. Hence, a smaller diesel engine is able to run near to its optimal efficiency, while a larger diesel engine is often running in the non-optimal area. What the higher efficiency the diesel engine has, the smaller is the diesel engine itself, and the higher the rated power of the electrical energy storage. [1]

In the series hybrid system, the diesel engine has to react only by the difference of the power of the load minus the power of the electrical energy storage. The diesel engine must keep suitable the SoC of the electrical energy also. The series hybrid system can be driven so that the diesel engine is running at constant power, and supplying its average power to the system. [1]

In the parallel hybrid system, the efficiency of the diesel engine does not significantly depend on the power of the electrical energy storage. The higher the power of the electrical energy storage is, the slower the diesel engine has to react to the changes in the load, and the better is the energy efficiency. [1]

In the parallel-series hybrid system, the diesel engine has to react only to the changes in the load by the hydraulics. If the power of the electrical energy storage is small, then the difference between the load power and the power of the electrical energy storage must be taken from the diesel engine. The load of the diesel engine has to react to the SoC of the electrical energy storage also. [1]

The power capacity is more important than the energy capacity in the dimensioning. The problem of practice is to find so kind of electrical energy storage, which one has both a high power capacity, and also a high energy capacity. Li-ion batteries use to have high energy capacity and supercapacitors use to have high power capacity. Hence, the normal solution is to select a combination of a small power diesel-engine, and a combination of a Li-ion battery with high energy capacity, and a supercapacitor with high power. [1]

The Li-ion battery modules for which data were used in the case study section were:

- (LFP) - AIMS, USA - LFP12V200AB, 12V 200Ah
- (LFP) - Saft, France - Seanergy 48M (Energy), 46V 82Ah
- (LFP) - Saft, France - Ion'Drive Motive 24V 410Ah
- (LTO) - Altairnano, USA - 24V 70Ah Battery Module
- (LTO) - Hybria, Finland - HE-LTO 24/20, 24V 20Ah
- (LTO) - Toshiba, Japan - Type3-23 2P12S - FM01202CCB01A, 28V 45Ah
- (NMC) - Akasol, Germany - AKAMODULE 46 NANO NMC, 44V 46Ah
- (NMC) - Hybria, Finland - HE-batt 25/80, 25V 80Ah
- (NMC) - Hybria, Finland - HE-batt 50/40, 50V 40Ah
- (NMC) - Hyperdrive, UK - HYP-00-2972, 52V 111Ah
- (NMC) - XALT, USA - XMP 111E, 88V 126Ah

The supercapacitor modules for which data were used in the case study section were:

- (EDLC) - LS Mtron, South Korea - LSUM 129R6C 0062F EA, 130V 1.12Ah 62F
- (EDLC) - Sech, Switzerland - ESS Module M35W-144-0063, 144V 1.25Ah 63F
- (EDLC) - Skeleton, Estonia - SkelMod SMA170V53FAF, 170V 1.12Ah 53F
- (EDLC / Pseudo) - Maxwell, USA - BMOD0063 P125 B08, 125V 1.12Ah 63F
- (Li-C) - JM Energy, Japan - ULTIMO MPA45G275, 36V 1.38Ah 275F
- (Li-C) - AOWEI, China - MUCK24V2870, 24.3V 26.75Ah 14000F

Table 2. Characteristics of Li-ion battery <u>modules</u> of LFP and LTO types. [71] - [74], [95]

Energy storage type	**Li-ion batteries**					
Properties	**LFP**			**LTO**		
Manufacturer / Product	**AIMS**	**Saft**	**Saft**	**Altairnano**	**Hybria**	**Toshiba**
Nominal voltage [V]	12.8	46.2	23.1	24	24	27.6
Maximum power [kW]	2.6	11.1	4.6	12	4.8	4.4
Max. pulse power [kW] *)	4.5	13.9	7.6	21.6	9.6	9.7
Capacitance [F]	-	-	-	-	-	-
Capacity [Ah]	200	82	410	67.4	20	45
Stored energy [Wh]	2560	3800	9471	1450	480	1242
Specific power [W/kg]	91	281	31	806	400	294
Power density [W/l]	83	308	49	1682	369	491
Specific energy [Wh/kg]	91.4	96	62.7	51.8	40	82.8
Energy density [Wh/l]	82.6	106	100.8	108	36.9	138
Maximum charge rate (Peak) [C_{rate}]	1C (1.8C)	1C (3.7C)	0.5C (0.8C)	8.3C (15C)	10C (20C)	3.6C (7.8C)
Maximum discharge rate (Peak) [C_{rate}]	1C (1.8C)	2.9C (3.7C)	0.5C (0.8C)	8.3C (15C)	10C (20C)	3.6C (7.8C)
Cycle lifetime [Cycles, at DoD 80%]	>4000	6000 - 1 000 000	*6000 - 1 000 000*	>25 000	*>4000*	20 000
Calendar lifetime [a]	10	20	*20*	25	*10*	*10*
Operation temperature [°C]	-20 - 65	-25 - 55	-20 - 45	-50 - 65	-40 - 55	-30 - 45
Weight [kg]	28	39.5	151	28	12	15
Volume [m^3]	0.031	0.036	0.094	0.013	0.013	0.009
Price [€]	1345	*1995*	*4972*	2525	*836*	*2162*
Price (CapEx) [€/kW] *)	300	*144*	*652*	117	*87*	*224*
Price (CapEx) [€/kWh]	525	*525*	*525*	1741	*1741*	*1741*

*) Price (CapEx) [€/kW] has calculated by using Max. peak pulse power (kW)

Table 3. Characteristics of Li-ion battery modules of NMC types. [73], [75] - [77]

Energy storage type	Li-ion batteries				
Properties	**NMC**				
Manufacturer / Product	**Akasol**	**Hybria**	**Hybria**	**Hyperdrive**	**XALT**
Nominal voltage [V]	44.4	25	50	51.8	88.3
Maximum power [kW]	11.8	10	10	15.5	26.5
Max. pulse power [kW] *)	25	10	10	15.5	26.5
Capacitance [F]	-	-	-	-	-
Capacity [Ah]	46	80	40	111.4	126
Stored energy [Wh]	2040	2000	2000	5760	11 100
Specific power [W/kg]	674	546	546	420	350
Power density [W/l]	1180	893	780	598	414
Specific energy [Wh/kg]	116.6	109.3	109.3	164	146
Energy density [Wh/l]	204	178.7	156.1	221.5	172
Maximum charge rate (Peak) [C_{rate}]	5C (8C)	1C	1C	1.4C	1C (1.2C)
Maximum discharge rate (Peak) [C_{rate}]	5.8C (12.3C)	5C	5C	2.6C	2.4C (2.4C)
Cycle lifetime [Cycles, at DoD 80%]	>5600	*>4000*	*>4000*	*>4000*	>4000
Calendar lifetime [a]	*10*	*10*	*10*	*10*	*10*
Operation temperature [°C]	-15 - 55	-30 - 55	-30 - 55	-25 - 60	*-30 - 55*
Weight [kg]	17.5	18.3	18.3	37	76
Volume [m^3]	0.010	0.011	0.013	0.026	0.064
Price [€]	*891*	*874*	*874*	*2517*	*4851*
Price (CapEx) [€/kW] *)	*36*	*87*	*87*	*162*	*183*
Price (CapEx) [€/kWh]	*437*	*437*	*437*	*437*	*437*

*) Price (CapEx) [€/kW] has calculated by using Max. peak pulse power (kW)

Table 4. Characteristics of supercapacitor modules of EDLC, Pseudo and Li-C types. [80], [82], [88], [89], [91], [92]

Energy storage type	**Supercapacitors**					
Properties	**EDLC**			**Pseudo**	**Li-C**	
Manufacturer / Products	**LS Mtron**	**Sech**	**Skeleton**	**Maxwell**	**JM Energy**	**AOWEI**
Nominal voltage [V]	129.6	144	170	125	36	24.3
Maximum power [kW]	18.1	25.5	45.9	17.5	2.2	10.9
Max. pulse power [kW] *)	285	374	458	238	18	20.4
Capacitance [F]	62	62.5	53	63	275	14 000
Capacity [Ah]	1.12	1.25	1.25	1.12	1.38	26.75
Stored energy [Wh]	144.6	180	212.7	140	49.5	650
Specific power [W/kg]	2700	6800	433	1700	1620	2072
Power density [W/l]	2250	5440	10300	1609	1620	2072
Specific energy [Wh/kg]	2.6	5.6	3.4	2.3	8.25	34.21
Energy density [Wh/l]	2.19	4.5	3.9	2.09	8.25	34.21
Maximum charge rate (Peak) [C_{rate}]	127C (1994C)	142C (2089C)	214C (2137C)	120C (1629C)	44C (364C)	17C (31C)
Maximum discharge rate (Peak) [C_{rate}]	127C (1994C)	142C (2089C)	214C (2137C)	120C (1629C)	44C (364C)	17C (31C)
Cycle lifetime [Cycles, at DoD 80%]	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	500 000
Calendar lifetime [a]	10	10	10	10	*10*	*10*
Operation temperature [°C]	-40 - 65	-40 - 65	-40 - 65	-40 - 65	-30 - 70	-25 - 55
Weight [kg]	55	32	63	63.4	6	19
Volume [m^3]	0.066	0.040	0.055	0.067	0.006	0.019
Price [€]	*3014*	4235	5500	1840	*1032*	*13 548*
Price (CapEx) [€/kW] *)	*11*	11	12	8	*57*	*664*
Price (CapEx) [€/kWh]	*20 843*	23 528	25 858	13 143	*20 843*	*20 843*

*) Price (CapEx) [€/kW] has calculated by using Max. peak pulse power (kW)

2.4 Summary

Standards, directives, and certificates related to electrical energy storage technology must be taken into account when selecting and sizing Li-ion batteries and supercapacitors. Manufacturers cite in their datasheets the various standards and certificates according to which their products are manufactured. Although the manufacturer of the battery modules and packs has completed the tests, a new test is required if structural changes are made to the tested battery modules and packs. The safe transport of batteries is important.

The battery technology parameters to be studied, before mapping and comparison of the characteristics (C_{rate}, power density, energy density, cycle life, calendar life, operating temperature, space requirement, and price estimate) with electrical energy storage suitable for the hybridization of the working machines. The properties of the batteries and supercapacitors are not the same kind, not even with the same chemistries. The main trade-off with batteries and supercapacitors are between power and energy properties. Characteristics in the datasheets of manufacturers are not standardized, which means that the comparing between products is very challenging.

The electrical energy storage of the hybrid working machine consists of a high voltage battery and/or supercapacitor pack which consists of modules connected in series and/or parallel. Batteries for hybridization of working machines are rechargeable types.

The hybridization starts by defining the work cycles for the main parts of the working machine. The work cycles will be measured from the actual diesel-operated working machine in the normal working environment, and with the basic operations. The work cycles are analyzed with the Rainflow counting methodology. The characteristics will be determined at least: the maximum power $P_{\text{load-max}}$, the average power $P_{\text{load-mean}}$, and the maximum energy needed of the system $E_{\text{load-max}}$ of a single action.

In the dimensioning of the electrical energy storage are some limiting characteristics, like the voltage, the mass, the volume, the lifetime, and the price. The capacity of the electrical energy storage should not be so high that all the recoverable power could be stored in it. High power peaks do not have enough energy so that the electrical energy storage should be dimensioned according to such a value. The theoretical optimal dimensioning of the electrical energy storage of hybrid systems is found by simulations. It is noteworthy, that usually it is not possible to test the electrical energy storage also in an actual environment.

3 CASE STUDY

The case study section developed and tested a selection and sizing method for the electrical energy storage systems and for it a Matlab-based tool. This tool takes into account the selected properties like the maximum power $P_{load-max}$, the average power $P_{load-mean}$, the maximum energy needed of the system $E_{load-max}$, power density, energy density, cycle life, calendar life, C_{rate}, operating temperature, nominal voltage, space requirement, and price estimate. The simulation tests were performed with a real work cycle of the working machine, and for the all selected type of suitable products of Li-ion batteries (LFP-, LTO-, and NMC -types,) and supercapacitors (EDLC-, Pseudo-, and Li-C hybrid -types) on every selected test property. Matlab graphics produced by tested batteries and supercapacitors are printed graphically as research results.

Steps for the selection and sizing of suitable electrical energy storage pack:

1. Find the number of cycles in the work cycle, and their maximum and minimum values of the power, and the maximum energy needed by using Matlab graphs

2. Set the essential selection criteria for the electrical energy storage modules and packs

3. Find the suitable energy storage modules from the manufacturer's datasheets

4. Ensure that the properties of the selected energy storage modules have calculated in the same way

5. Add the needed properties of the selected energy storage modules to the Matlab tool

6. Run the Matlab tool and make a comparison between modules by using Matlab graphs

7. Select the suitable energy storage modules for the pack forming

8. Calculate the needed count of modules in series connection to achieve needed maximum peak pulse power and energy stored values

9. Calculate the other needed values in that count of modules in the series connection

10. Check if the DC/DC converter is needed for the rising of the nominal voltage

11. Check if there is needed some special arrangements e.g. for the operation temperature

12. Make the final comparing and the selection of the electrical energy storage pack.

3.1 Work cycle of working machine

At first, it is needed the work cycle of the original working machine. The work cycle can be defined by measurements in the authentic environment of the working machine. In this case study the work cycle is from the simulated series hybrid working machine.

The Rainflow counting method is used to pick-up the number of cycles, and their respective range and mean. Figures 21. shows the maximum and minimum values of the power, and the energy change value for the electrical energy storage produced by the Matlab application to be selected and sized during the work cycle:
P_{max} = 240 kW (charge), P_{min} = -210 kW (discharge), ΔE_{es} = 0.85 kWh [96]

The minimum electrical energy storage to be selected and sized:

- Peak power [kW]: 240
- Energy stored [kWh]: 0.85

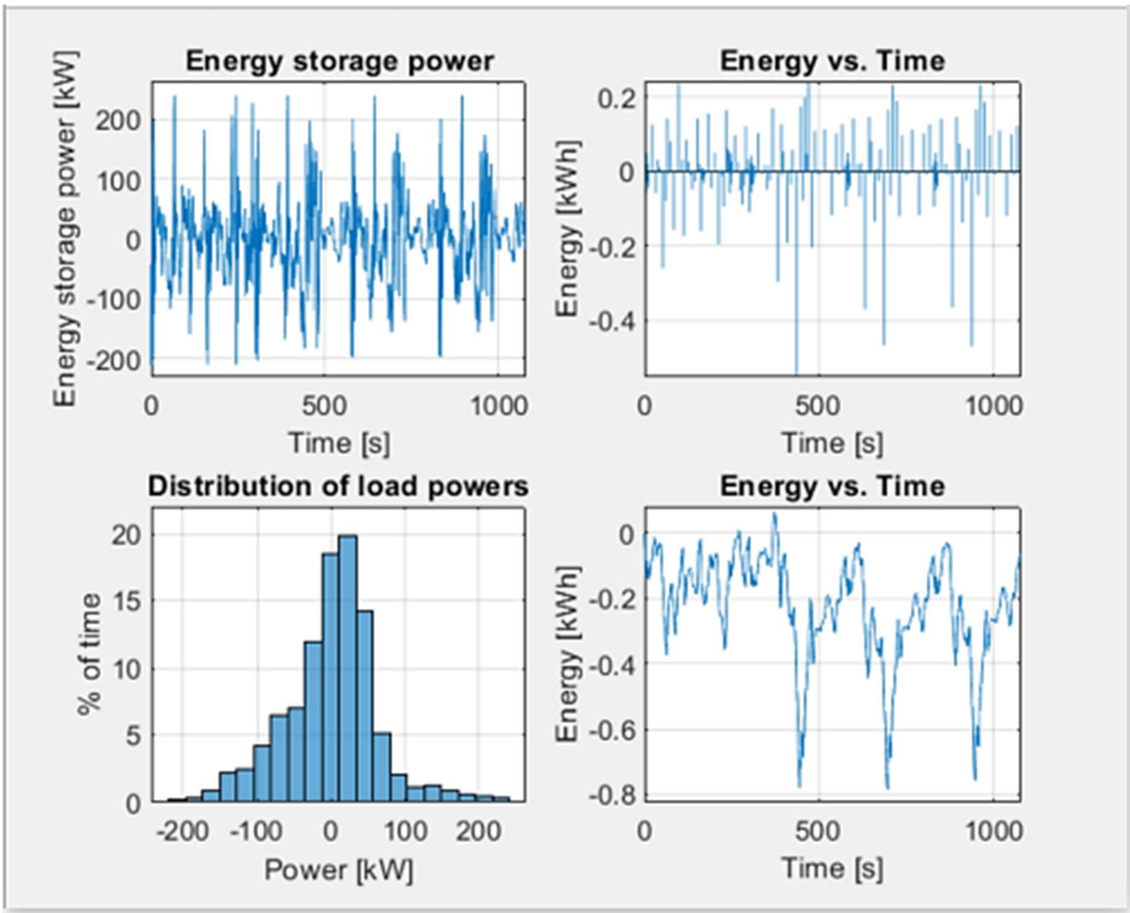

Figure 21. The work cycle (load cycles) of the working machine to be hybridized.

3.2 Selection of electrical energy storage

The selection of suitable electrical energy storage, in this application target, is done by comparing the information of the graphics produced by the Matlab application from the electrical energy storages to be selected with the selection criteria defined according to the application target. In this case, cycle lifetime, calendar lifetime, and operation temperature values are essential at first.

Because the product of Altairnano (for lithium-ion batteries) and the product of Maxwell (for supercapacitors) have been widely used as test cases in scientific articles, they have also been used here in the so-called benchmarking cases in the correct way to calculate for uniforming the essential properties of electrical energy stores. These correct way equations can be found in the Notes section of their datasheets. Furthermore, Maxwell's supercapacitor is classified as a Pseudo capacitor so that it stands out clearly in the graphs.

In addition to the following selection criteria, the initial assumptions for the products under study is e.g. BMS system for monitoring the balance of cell voltages, CAN bus connection, various approvals for enclosure properties, vibration tolerance properties, environmental friendliness, and safety.

The criteria i.e. desired values for the selection and sizing of the electrical energy storage packs in this case are:

- Cycle lifetime [cycle]: 1 000 000
- Calendar lifetime [a]: 10
- Operation temperature [°C]: -40 - 65
- Peak power [kW]: 240
- Minimum energy stored [kWh]: 0.85
- Nominal voltage [V]: 600 - 800
- Space requirement [m^3]: < 0.500
- Price (CapEx) [€]: < 50 000

3.2.1 Cycle lifetime of the electrical energy storage

Cycle lifetime (CL) [cycle] has been estimated between 0 to 10 % DoD. We can form an equation that fits, for example the LTO battery cycle lifetime as follows:

$$CL = 1 * 10^8 \; DoD^{-2}$$

where DoD [%] is the depth of the discharge of the electrical energy storage.

In the cycle lifetime calculation, the battery temperature is assumed to be 35 °C. The temperature of the battery varies in actual operation. Hence, it is important to guarantee the low temperature of the battery. [1] For supercapacitors, the effect of DoD value on calendar lifetime is not as crucial as with Li-ion batteries. Instead, attention should be paid to variations in nominal voltage and operating temperature. [20], [98] Figure 22. shows the cycle life of the different electrical energy storage, and the number of working machine load cycles at specified energy. LTO battery and all supercapacitors have the desired cycle life, but LFP- and NMC-type batteries don't have the desired cycle life.

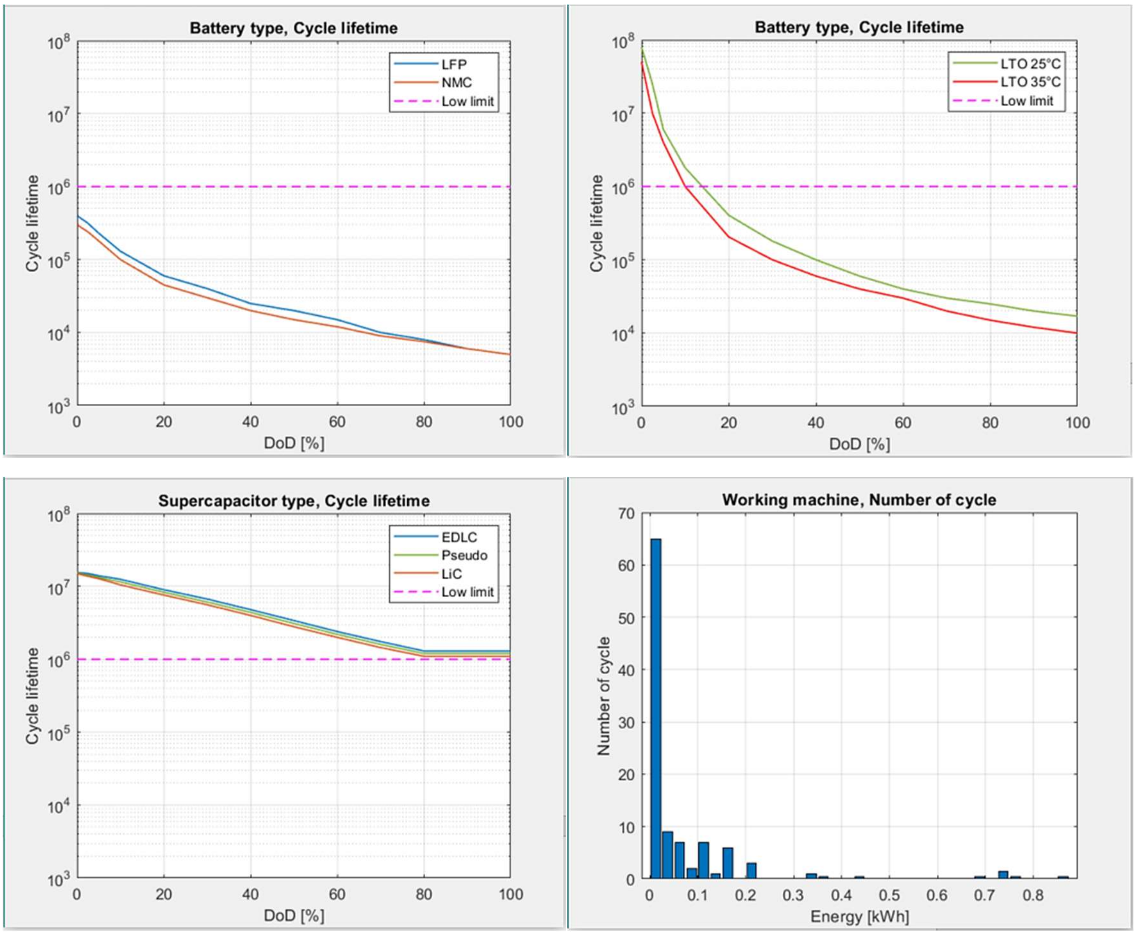

Figure 22. The cycle lifetime of electrical energy storage types, and number of load cycles.

3.2.2 Estimated calendar lifetime of the electrical energy storage

The estimated calendar lifetime (LT) [a] of different electrical energy storage capacities, based on the number of different DoD cycles, and it can be determined as follows:

$$LT = \frac{t_{\text{cycle}}}{\sum_{i=1}^{N} \frac{N_i(DoD)}{CL_\text{i}(DoD)}},$$

where t_{cycle} is the duration time [s] of the load cycle, N_i is the number of cycles with different DoDs [%] during the loading, and CL_i is the cycle lifetime at different DoDs. Please note, this is not a calendar lifetime from the manufacturers' datasheet. Matlab application is calculating this using by cyclic lifetime and number of cycles with different DoDs [%] The desired service lifetime is 10 years, operation hours per year are 4000 h, and the SoC initial value is 85%. [1] Figure 23. shows the estimated calendar lifetime of the electrical energy storage. LTO type battery has desired calendar lifetime (with minimum capacity ~ 7 kWh), and all type of supercapacitors has also (vs. low limits), and they should be selected. LFP- and NMC batteries don't have the needed estimated calendar lifetime and they are not suitable for the selections.

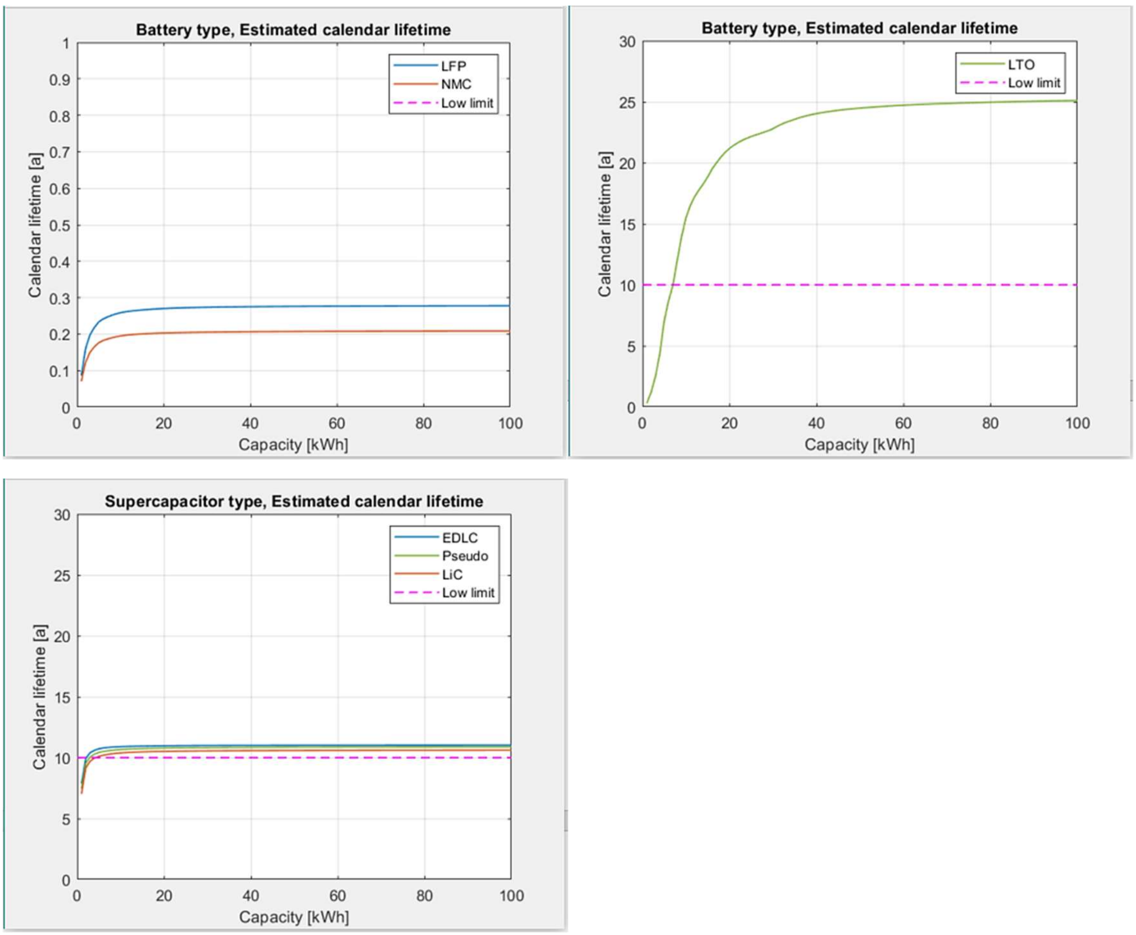

Figure 23. The estimated calendar lifetimes of electrical energy storage types.

3.2.3 Operation temperature of the electrical energy storage

The minimum and the maximum value of the operation temperature [°C] for different electrical energy storages technologies.

Figure 24. shows the operation temperature limits for different electrical energy storages. It can be seen, that all batteries have problems with desired operation temperature range. One of LTO type battery, and EDLC and Pseudo type supercapacitors have the desired operating temperature range (vs. low and high limits), and they should be selected. All NMC type Li-ion batteries and Li-C-type supercapacitors don't have the desired operating temperature range, and they can need special solutions if they are selected.

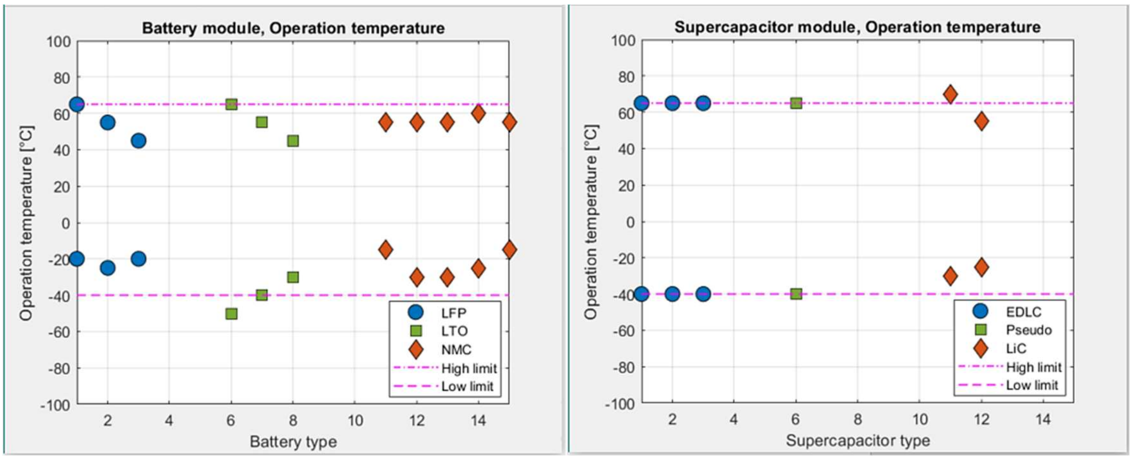

Figure 24. The operation temperature of the electrical energy storage types.

3.2.4 Ragone plots of the electrical energy storage

The continuous and the peak power density (specific power) [W/kg] comparison with the energy density [Wh/kg]. Power density and energy density can be determined as follows:

$$P_{\text{density,cont}} = \frac{I_{\text{cont}} * U_{\text{rated}}}{m}, \quad P_{\text{density,peak}} = \frac{I_{\text{peak}} * U_{\text{rated}}}{m}, \quad E_{\text{density}} = \frac{E_{\text{stored}}}{m}$$

where I_{cont} is the continuous and I_{peak} is the peak current of the charge/discharge. U_{rated} is the rated voltage, m is the mass, and E_{stored} is stored energy of the energy storage. [96]

Figure 25. shows the power density compared with the energy density of the different electrical energy storage. It can be seen, that all LTO and one of NMC type batteries, and all EDLC type supercapacitors have a good peak power density, and they should be selected. Additionally, NMC type batteries and one of Li-C type supercapacitors have a good energy density. LFP type batteries don't have very good power densities, but they have tolerable energy densities. However, the main target with Li-ion batteries is a good power density property, and with supercapacitors s good energy density property.

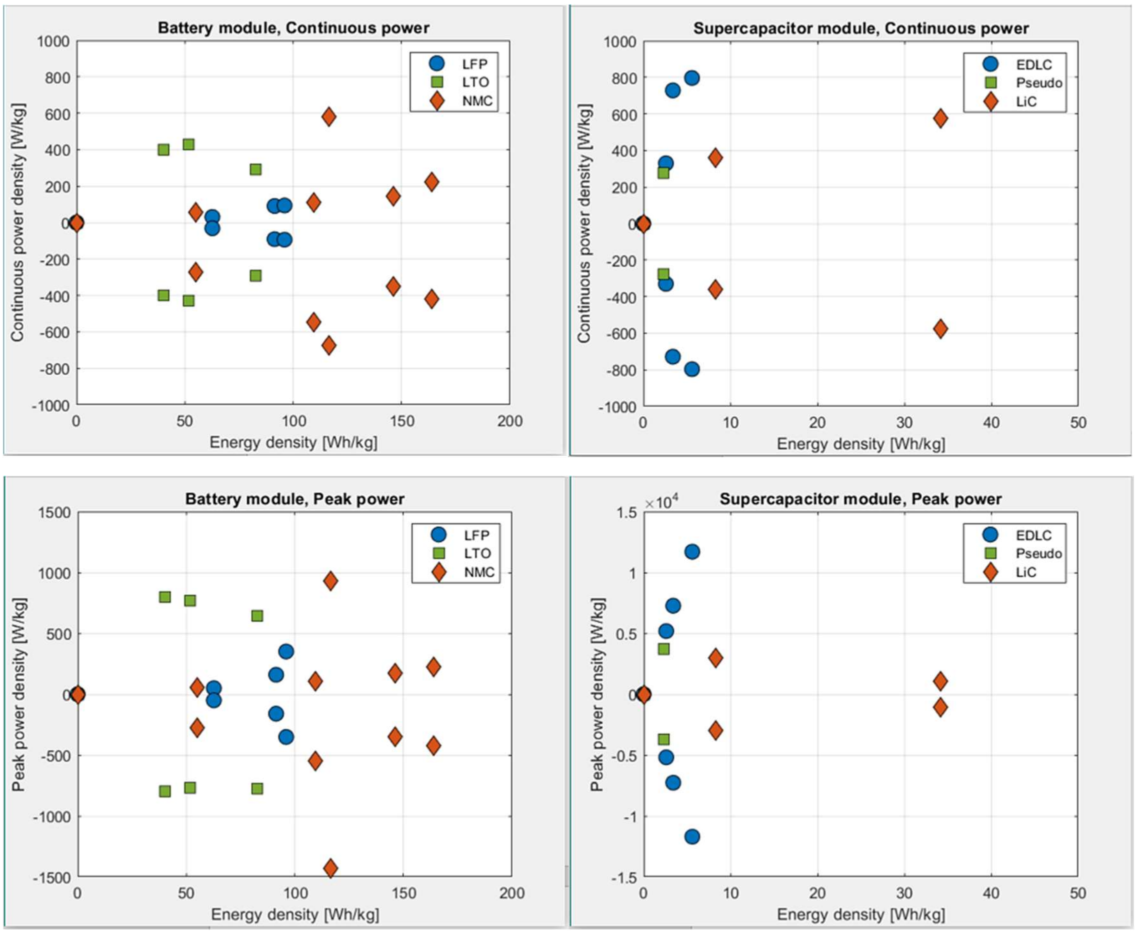

Figure 25. The Ragone plots of the electrical energy storage types.

3.2.5 C_{rate} of the electrical energy storage

The continuous and the peak C_{rate} of the electrical energy storage system and they can be determined as follows:

$$C_{\text{rate,cont}} = \frac{P_{\text{density,cont}}}{E_{\text{density}}}, \quad C_{\text{rate,peak}} = \frac{P_{\text{density,peak}}}{E_{\text{density}}}$$

where $P_{\text{density,cont}}$ is the continuous and $P_{\text{density,peak}}$ is the peak power density [W/kg], and E_{density} is the energy density [Wh/kg] of the electrical energy storage system. [96]

Figure 26. shows the C_{rate} values of the different electrical energy storage.
It can be seen, that LTO and NMC type batteries, as well as EDLC and Pseudo type supercapacitors have a good value of the peak C_{rate} values (vs. desired values), and they should be selected. LFP type batteries and Li-C type supercapacitors don't have a good peak C_{rate} values and this can become a problem depending on the application.

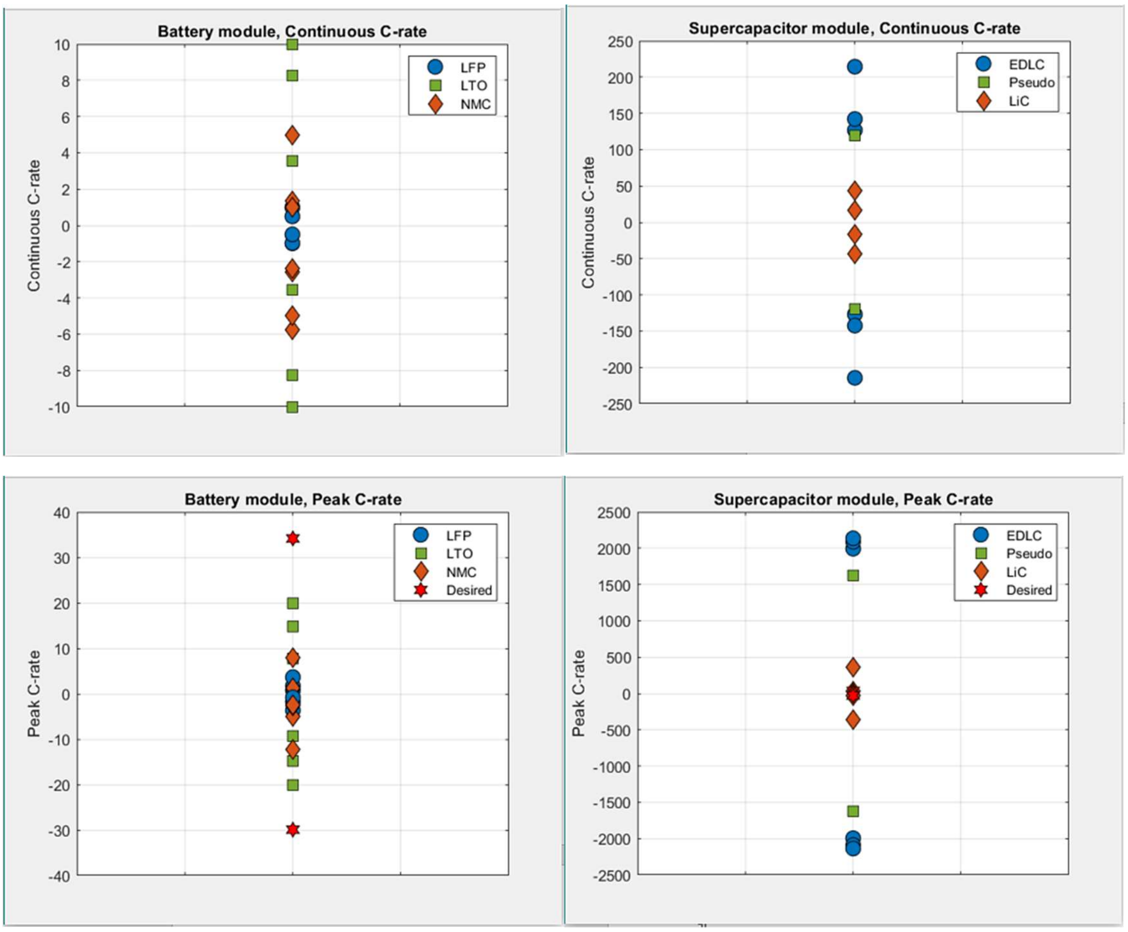

Figure 26. The C_{rate} values of the electrical energy storage types.

3.2.6 Peak power of the electrical energy storage

The maximum peak (pulse) power [kW] of the electrical energy storage system, and it can be determined as follows:

$$P_{\mathrm{peak}} = I_{\mathrm{peak}} * \; U_{\mathrm{rated}} \, ,$$

where I_{peak} is the peak current [A] of the discharge, and U_{rated} is the rated voltage [V].

Figure 27. shows the maximum pulse power of the electrical energy storage. It can be seen, that LTO type #1 and NMC type #1, #4, #5 batteries, and EDLC type #1, #2, #3 and Pseudo type #1 supercapacitors have the desired property (vs. low limits), and they should be selected. Li-C types #1 and #2 have a poor maximum peak power property, but with a large number of modules they can be also selected. Drawback then can be example too big space requirement or a high price estimate i.e. investment costs.

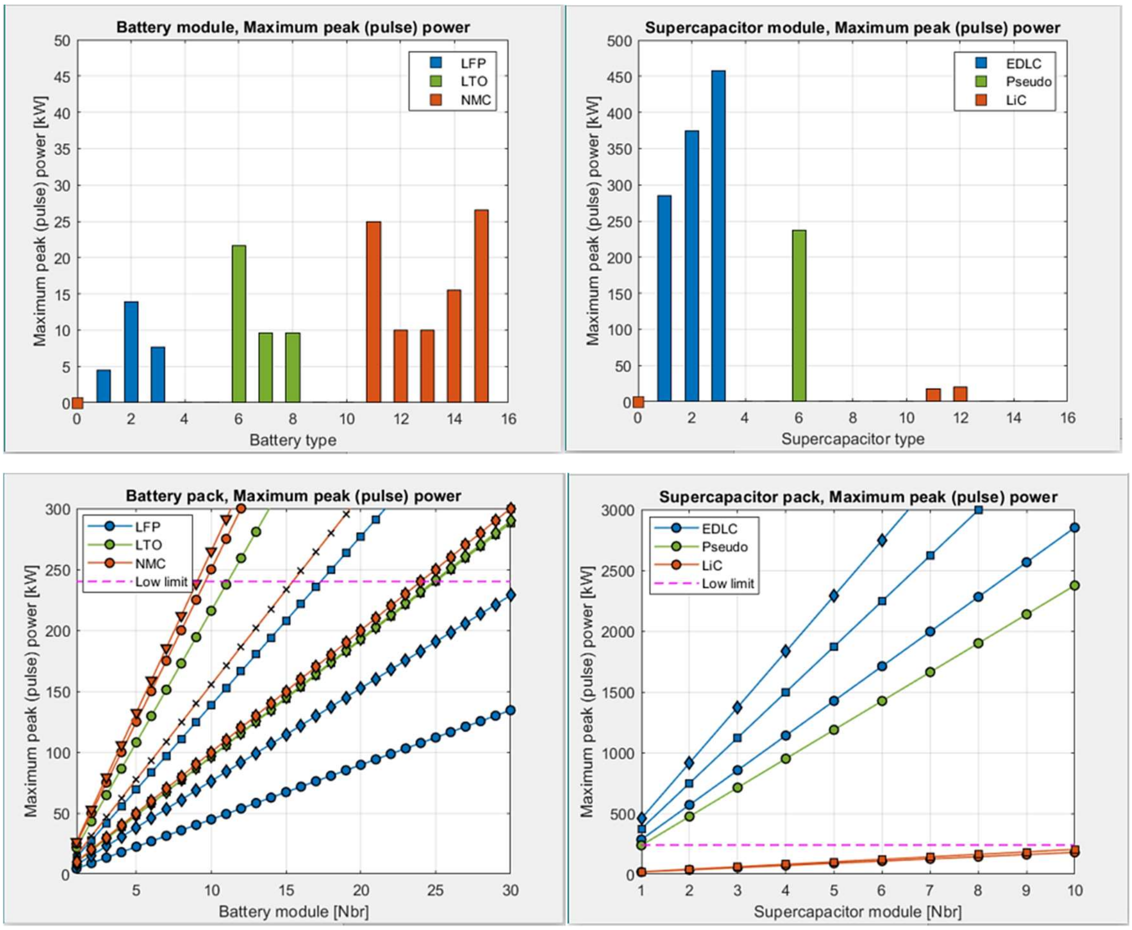

Figure 27. The maximum pulse power of the electrical energy storage types.

Marker symbols on the plot lines: o = type #1, □ = type #2, ◇ = type #3, x = type #4, v = type #5

3.2.7 Energy stored of the electrical energy storage

The energy stored [kWh] of the electrical energy storage system.

With Li-ion battery, it can be determined as follows:

$$E_{\text{stored}} = Capacity * U_{\text{rated}} ,$$

where *Capacity* [Ah] is the capacity, and U_{rated} is the rated voltage [V].

With supercapacitor, it can be determined as follows:

$$E_{\text{stored}} = 0.5 * Capacity * U_{\text{rated}}{}^{2},$$

where *Capacity* [F] is the capacity, and U_{rated} is the rated voltage [V].

Figure 28. shows the energy stored of the electrical energy storage. It can be seen, that all battery types, and all EDLC and Pseudo type and Li-C type #2 supercapacitors have the desired property (vs. low limits), and they should be selected. Li-C type #1 supercapacitor don't have a good energy capacity, but with a large number of modules it can be selected also. Drawback then can be example again too big space requirement.

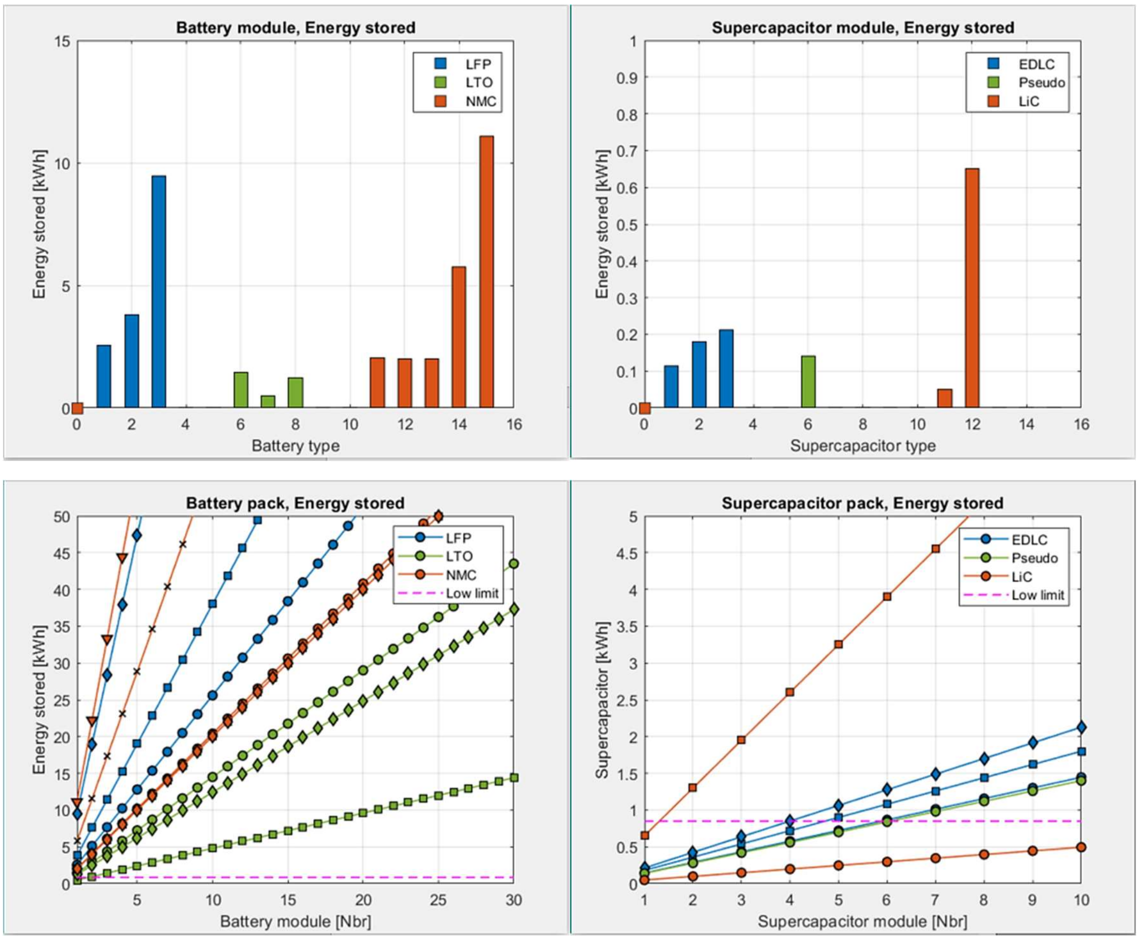

Figure 28. The stored energy of the electrical energy storage types.

Marker symbols on the plot lines: o = type #1, □ = type #2, ◇ = type #3, x = type #4, v = type #5

3.2.8 Nominal voltage of the electrical energy storage

The nominal voltage [V] of the electrical energy storage system. The electrical energy storage pack is connected directly to the DC link of the frequency converter in this study. Hence, the nominal voltage of the electrical energy storage pack has to be such that the direct connection to the DC link is possible.

Figure 29. shows the nominal voltage of the electrical energy storage. It can be seen, that all battery types, and EDLC and Pseudo type supercapacitors have the desired property (vs. low limits), and they should be selected. Li-C types #1 and #2 don't have needed nominal voltage property, but with large number of modules they can be selected also. Drawback then can be example too big space requirement or a high price estimate i.e. investment costs.

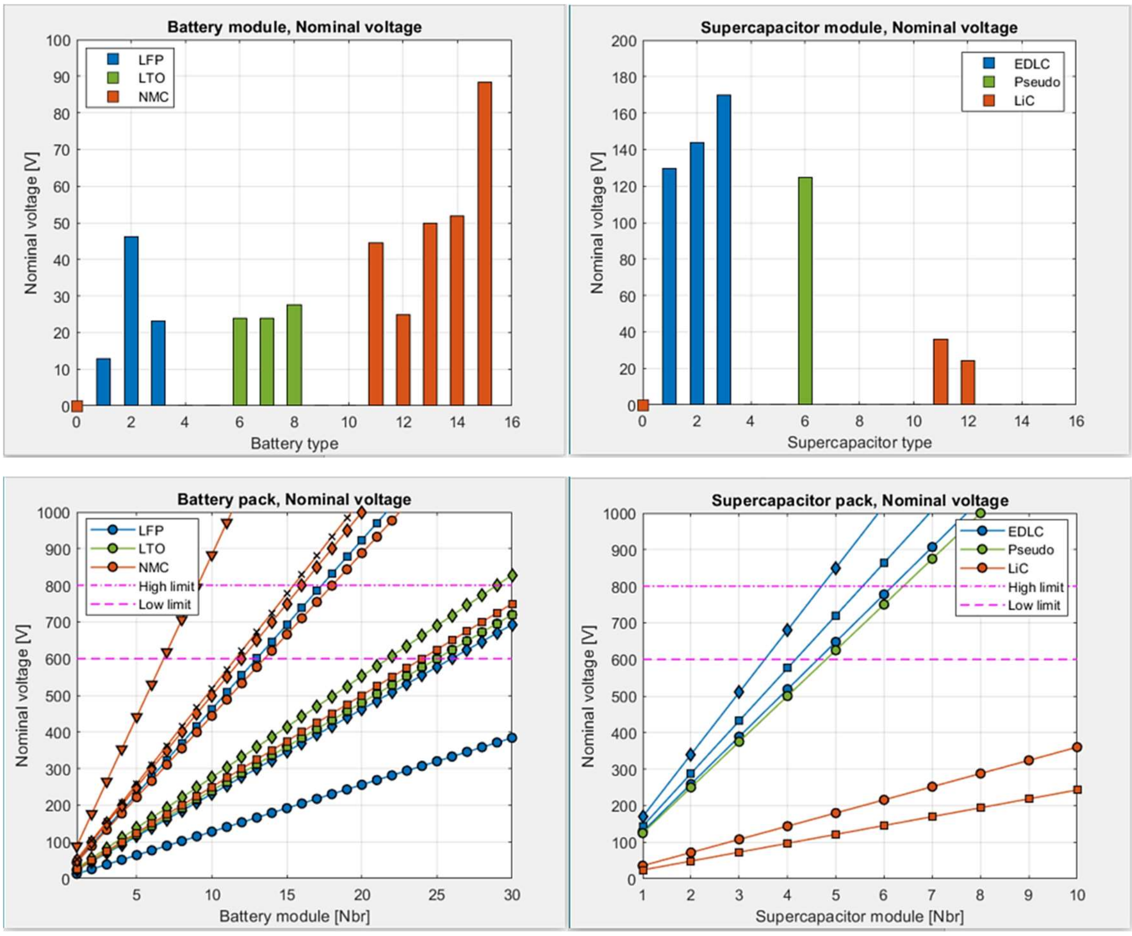

Figure 29. The nominal voltage of the electrical energy storage types.

Marker symbols on the plot lines: o = type #1, □ = type #2, ◇ = type #3, x = type #4, v = type #5

3.2.9 Space requirement of the electrical energy storage

The space requirement [dm^3] of the electrical energy storage system, and it can be determined as follows:

$$Space\ requirement = length * width * height\ ,$$

where length [mm], width [mm] and height [mm] are the physical dimensions of the electrical energy storage system.

The space requirements are defined purely according to the physical dimensions of each type. These graphs do not take into account the cooling space requirements that may be required by different types, and the possible space requirements of DC/DC converters.

Figure 30. shows the space requirement of the different electrical energy storage. It can be seen, that all battery and supercapacitor types have the desired space requirement (vs. high limits), and they should be selected. EDLC type #1 and Pseudo type supercapacitors space requirements of packs are too big with minimum stored energy (0.85 kWh).

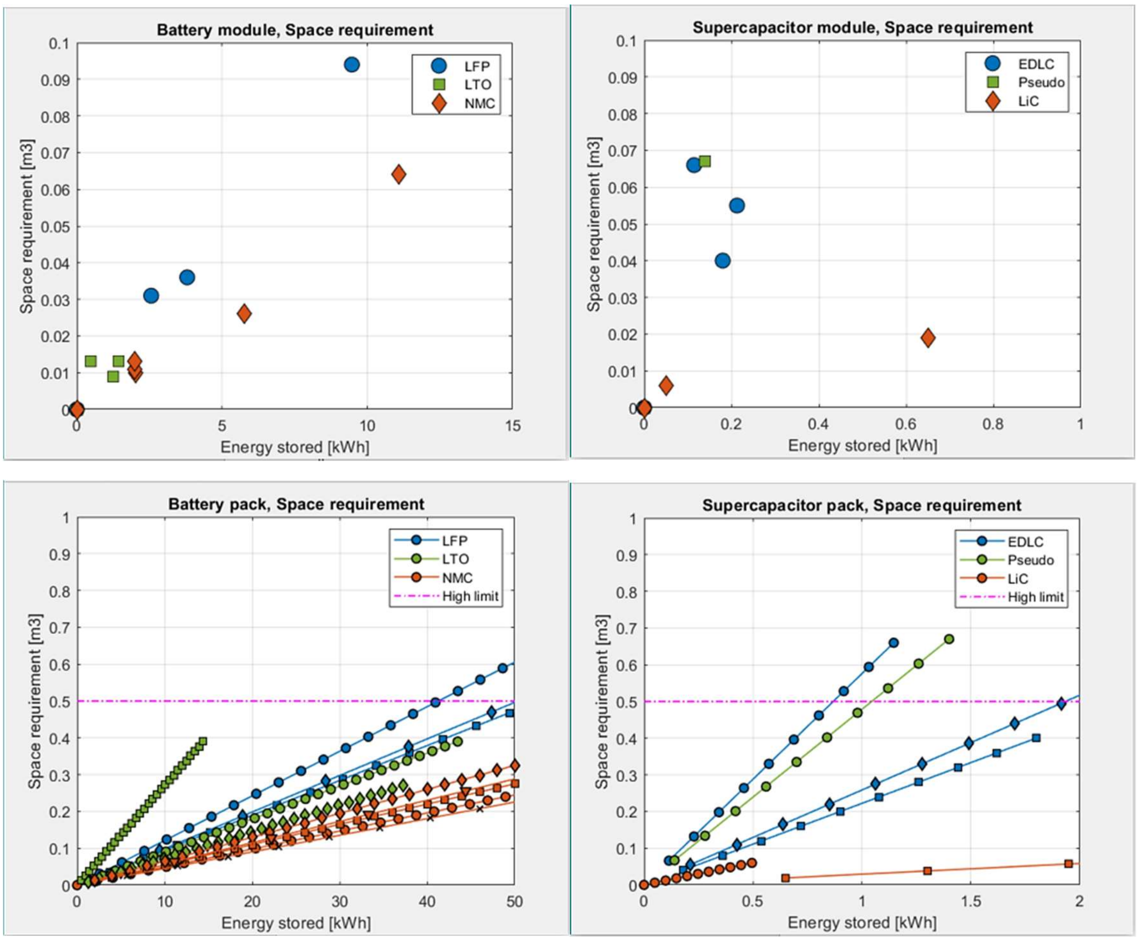

Figure 30. The space requirement of the electrical energy storage types vs. energy stored.

Marker symbols on the plot lines: o = type #1, □ = type #2, ◇ = type #3, x = type #4, v = type #5

3.2.10 Price estimate of the electrical energy storage

The price estimate per stored energy [€/kWh] of the electrical energy storage system, and it can be determined as follows:

$$Price\ estimate = \frac{Price}{E_{\mathrm{stored}}},$$

where the Price [€] is the capital cost and the E_{stored} [kWh] is the capacity of the electrical energy storage system.

Figures 31. and 32. shows the price estimates of the electrical energy storage. It can be seen, that some battery types have problems with a large number of modules. LTO type batteries and almost all supercapacitor types have the desired investment costs (vs. high limits), and they should be selected. Li-C type #2 investment costs can become too high, but Li-C type #1 price estimate is very good with a large number of modules.

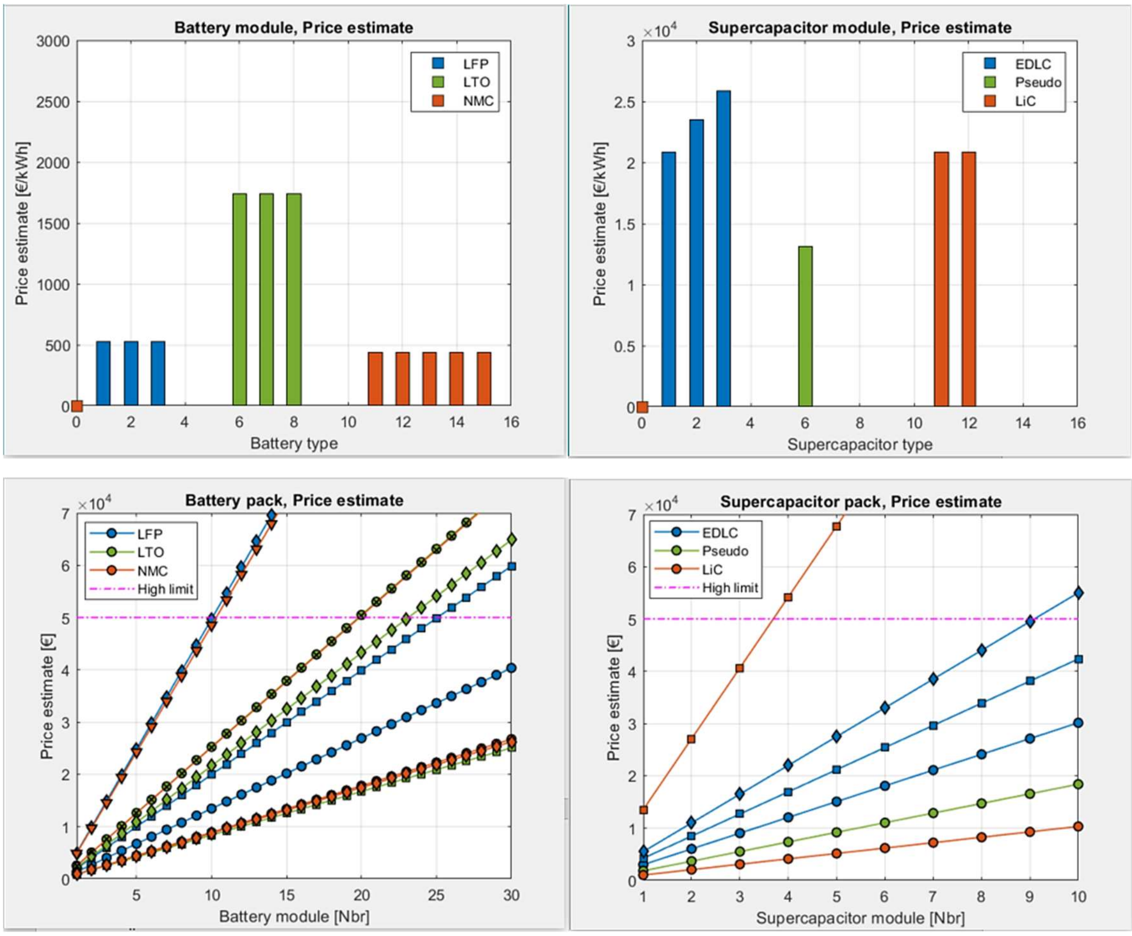

Figure 31. The price estimate of the electrical energy storage types.

Marker symbols on the plot lines: o = type #1, □ = type #2, ◇ = type #3, x = type #4, v = type #5

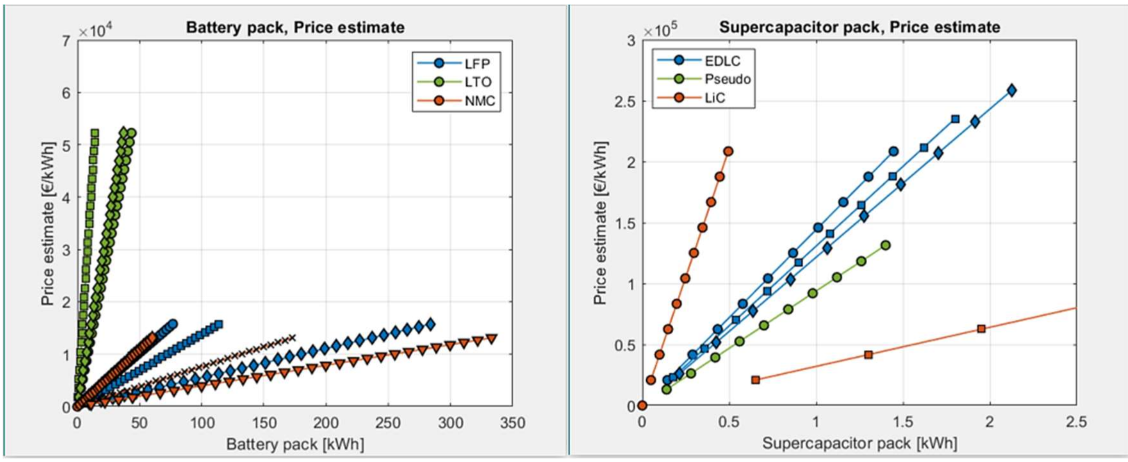

Figure 32. The price estimate of the electrical energy storage types vs. energy stored.

Marker symbols on the plot lines: o = type #1, □ = type #2, ◇ = type #3, x = type #4, v = type #5

3.3 Sizing of electrical energy storage

Table 5. summarizes the graphics produced by the developed Matlab application on the previous pages. Because the basic requirements for hybrid working machines are excellent cycle life, calendar life, and operating temperature, the choice is either the LTO type battery or the EDLC/Pseudo type supercapacitor. In the results on the next pages, there have been calculated five solutions with these types of battery and supercapacitor packs, but also one solution with new type Li-C hybrid supercapacitor for the comparing.

Table 5. Results produced by Matlab application for work cycle of working machine.

Selected energy storage type		**Li-ion battery pack**			**Supercapacitor pack**		
Desired property	**Criteria**	**LFP**	**LTO**	**NMC**	**EDLC**	**Pseudo**	**Li-C**
Cycle lifetime [cycle]	1 000 000		x		x	x	x
Calendar lifetime [a]	10		x		x	x	x
Operation temperature [°C]	-40 - 65		x		x	x	
Power density [W/kg]	-		x	x	x		
Energy density [Wh/kg]	-			x			x
Charge/Discharge peak [C_{rate}]	-		x	x	x	x	
Peak power [kW]	240		x	x	x	x	
Energy stored [kWh]	0.85	x	x	x	x	x	
Nominal voltage [V]	600 - 800	x	x	x	x	x	
Space requirement [m^3]	< 0.500	x	x	x	x	x	x
Price (CapEx) [€]	< 50 000	x	x	x	x	x	x

The sizing continues by the selection of the most suitable commercial products of selected Li-ion battery and supercapacitor types according to the selection criteria in Table 5. After the selection of the modules, they still have to be formed into EESS packages in order to provide the amount of power and energy required by the application.

In this case, the selected modules are connected in series. At first, are calculating the minimum count of the series-connected modules to achieve the needed peak power and the energy stored values. After that, the rated voltage of the application system can also be achieved by using a DC/DC converter. This kind of solution saves installation space and investment costs. The selected and sized EESS packs by this way with the values required are listed on the next pages.

- **Li-ion battery pack, Option #1**

  LTO Hybria 24V 20Ah, 25 pcs of modules, in series

  Cycle lifetime [cycle]: 1 000 000

  Calendar lifetime [a]: 10 at DoD 10%

  Operation temperature [°C] : -40 - 55

  Power density, peak [W/kg]: 800 at ? s pulse

  Energy density [Wh/kg]: 40

  Charge/Discharge, peak [C_{rate}]: 20

  Maximum peak power [kW]: 25 x 9.6 = 240

  Energy stored [kWh]: 25 x 0.48 = 12

  Nominal voltage [V]: 25 x 24 = 600

  Space requirement [m^3]: 25 x 0.013 = 0.325

  Price (CapEx) [€]: 25 x 836 = 20 900

  Price (CapEx) [€/kWh]: 1741

Arguments for the selection:
This device is the cheapest of the LTO batteries studied and the space requirement is reasonable, although as many as 25 pcs of modules need to be connected in series to meet the required power, energy, and voltage needs. The operation temperature range and the peak C_{rate} value are good. The length of the pulse used to measure the peak power density is missing.

- **Li-ion battery pack, Option #2**

  LTO Altairnano 24V 70Ah, 12 pcs of modules, in series, with DC/DC converter

  Cycle lifetime [cycle]: 1 000 000

  Calendar lifetime [a]: 10 at DoD 10%

  Operation temperature [°C] : -50 - 65

  Power density, peak [W/kg]: 771 at 10 s pulse

  Energy density [Wh/kg]: 51.8

  Charge/Discharge, peak [C_{rate}]: 15

  Maximum peak power [kW]: 12 x 21.6 = 259.2

  Energy stored [kWh]: 12 x 1.45 = 17.4

  Nominal voltage [V]: 12 x 24 = 288 *)

  Space requirement [m^3]: 12 x 0.013 = 0.156 *)

  Price (CapEx) [€]: 12 x 2525 = 30 300 *)

  Price (CapEx) [€/kWh]: 1741 *)

  *) Needs DC/DC converter, Danfoss Editron EC-C1200-450 [97]

  Rising of the operating voltage: 288 V => 600 V

  Output voltage: 0 - 850 V

  Output current: 350 A

  Output power: 300 kW

  Dimensions: 244 x 109 x 482 mm

  Add extra costs of DC/DC converter (~ 40 €/kW).

Arguments for the selection:
This device needs only 12 pcs of modules to be connected in series to meet the required power and energy needs, and the space requirement is minor. The drawback is that it needs an extra DC/DC converter to rise up operating voltage to the required 600 V. Which means more cabling and cooling space. The operation temperature range and the peak C_{rate} value are good. The price estimate of the whole system is close to the upper limit of the investment costs.

- **Li-ion battery pack, Option #3**

  LTO Toshiba 27.6V 45Ah, 25 pcs of modules, in series

    Cycle lifetime [cycle]: 1 000 000

    Calendar lifetime [a]: 10 at DoD 10%

    Operation temperature [°C] : -30 - 45

    Power density, peak [W/kg]: 777 at ? s pulse

    Energy density [Wh/kg]: 82.8

    Charge/Discharge, peak [C_{rate}]: 7.8

    Maximum peak power [kW]: 25 x 9.66 = 241.5

    Energy stored [kWh]: 25 x 1.242 = 31.05

    Nominal voltage [V]: 25 x 27.6 = 690

    Space requirement [m^3]: 25 x 0.009 = 0.225

    Price (CapEx) [€]: 25 x 2162 = 54 050

    Price (CapEx) [€/kWh]: 1741

Arguments for the selection:
This device is the most expensive of the LTO batteries studied and the whole system price estimate exceeds the upper limit of the investment costs. The space requirement is minor, although again 25 pcs of modules need to be connected in series to meet the required power, energy, and voltage needs. The operating temperature range and the peak C_{rate} value are worse than the two previous have. The length of the pulse used to measure the peak power density is missing.

- **Supercapacitor pack, Option #1**

  EDLC Pseudo Maxwell 125V 1.12Ah 63F, 6 pcs of modules, in series

  Cycle lifetime [cycle]: 1 000 000

  Calendar lifetime [a]: 10 at 25 °C, 4000 h/a

  Operation temperature [°C] : -40 - 65

  Power density, peak [W/kg]: 3746 at 5 s pulse

  Energy density [Wh/kg]: 2.3

  Charge/Discharge, peak [C_{rate}]: 1629

  Maximum peak power [kW]: 6 x 237.5 = 1425

  Energy stored [kWh]: 6 x 0.14 = 0.84

  Nominal voltage [V]: 6 x 125 = 750

  Space requirement [m^3]: 6 x 0.067 = 0.402

  Price (CapEx) [€]: 6 x 1840 = 11 040

  Price (CapEx) [€/kWh]: 13 143

Arguments for selection:
This device is the cheapest of the EDLC/Pseudo supercapacitors studied and the space requirement is reasonable. Only 6 pcs of modules need to be connected in series to meet the required power, energy, and voltage needs. The operation temperature range and the peak C_{rate} value are good.

- **Supercapacitor pack, Option #2**

  EDLC Skeleton 170V 1.25Ah 53F, 4 pcs of modules, in series

  Cycle lifetime [cycle]: 1 000 000

  Calendar lifetime [a]: 10 at 25 °C, 4000 h/a

  Operation temperature [°C] : -40 - 65

  Power density, peak [W/kg]: 7267 at 1 s pulse

  Energy density [Wh/kg]: 3.4

  Charge/Discharge, peak [C_{rate}]: 2137

  Maximum peak power [kW]: 4 x 457.8 = 1831

  Energy stored [kWh]: 4 x 0.2127 = 0.85

  Nominal voltage [V]: 4 x 170 = 680

  Space requirement [m^3]: 4 x 0.055 = 0.220

  Price (CapEx) [€]: 4 x 5500 = 22 000

  Price (CapEx) [€/kWh]: 25 858

Arguments for selection:
This device investment cost is moderate of the electrical energy storage systems studied and the space requirement is minor. Only 4 pcs of modules need to be connected in series to meet the required power, energy, and voltage needs. The operation temperature range and the peak C_{rate} value are good. The length of the pulse used to measure the peak power density is short.

- **Supercapacitor pack, Option #3**

  Li-C AOWEI 24.3V 26.75Ah 14 000F, 12 pcs of modules, in series

  Cycle lifetime [cycle]: 500 000 **)

  Calendar lifetime [a]: 10 at 25 °C, 4000 h/a

  Operation temperature [°C] : -25 - 55 **)

  Power density, peak [W/kg]: 1074 at 20 s pulse

  Energy density [Wh/kg]: 34.21

  Charge/Discharge, peak [C_{rate}]: 17

  Maximum peak power [kW]: 12 x 20.4 = 244.8

  Energy stored [kWh]: 12 x 0.650 = 7.8

  Nominal voltage [V]: 12 x 24.3 = 291.6 *)

  Space requirement [m^3]: 12 x 0.019 = 0.228 *)

  Price (CapEx) [€]: 12 x 13 548 = 162 576 *)

  Price (CapEx) [€/kWh]: 20 843 *)

  *) Needs DC/DC converter, Danfoss Editron EC-C1200-450 [97]

  Rising of the operating voltage: 291.6 V => 600 V

  Output voltage: 0 - 850 V

  Output current: 350 A

  Output power: 300 kW

  Dimensions: 244 x 109 x 482 mm

  Add extra costs of DC/DC converter (~ 40 €/kW).

  **) Needs special solution for the cycle lifetime and operation temperature

Arguments for the selection:
This device needs only 12 pcs of modules to be connected in series to meet the required power and energy needs, and the space requirement is minor. The drawback is that it needs an extra DC/DC converter to rise up operating voltage to the required 600 V. Which means more cabling and cooling space. The operation temperature range and the cycle lifetime are poor and they must be arrange by a special solution. The price estimate of the whole system is over 3 times the upper limit of the investment costs.

Table 6. summarizes the selections for the electrical energy storage packs. Three solutions have both been calculated for Li-ion battery packs and supercapacitor packs.

Table 6. Selections of the electrical energy storage packs.

Energy storage type		**Li-ion battery pack**			**Supercapacitor pack**		
Desired property	**Criteria**	**LTO**			**EDLC / Pseudo**		**Li-C**
Product option		**#1**	**#2**	**#3**	**#1**	**#2**	**#3**
Product model		Hybria 24V 20Ah	Altairnano 24V 70Ah	Toshiba 27.6V 45Ah	Maxwell 125V 1.12Ah	Skeleton 170V 1.25Ah	AOWEI 24.3V 26.75Ah
Connection type		1p25s	1p12s	1p25s	1p6s	1p4s	1p12s
Cycle lifetime [cycle]	1e6	1e6	1e6	1e6	1e6	1e6	0.5e6 **)
Calendar lifetime [a]	10	10	10	10	10	10	10
Operation temperature [°C]	-40 - 65	-40 -55	-50 - 65	-30 - 45	-40 - 65	-40 - 65	-25 - 55 **)
Power density [W/kg]	-	800 (?s)	771 (10s)	777 (?s)	3746 (5s)	7267 (1s)	1074 (20s)
Energy density [Wh/kg]	-	40	51.8	82.8	2.3	3.4	34.21
Charge/Discharge peak [C_{rate}]	-	20	15	7.8	1629	2137	17
Peak power [kW]	240	240	259.2	241.5	1425	1831	244.8
Energy stored [kWh]	0.85	12	17.4	31.05	0.84	0.85	7.8
Nominal voltage [V]	600 - 800	600	288 *)	690	750	680	291.6 *)
Space requirement [m^3]	< 0.500	0.325	0.156 *)	0.225	0.402	0.220	0.228 *)
Price (CapEx) [€]	< 50 000	20 900	30 300 *)	54 050	11 040	22 000	162 576 *)
Price (CapEx) [€/kWh]		1741	1741 *)	1741	13 143	25 858	20 843 *)

*) Needs DC/DC converter, Danfoss Editron EC-C1200-450 [97]

Rising of the operating voltage: 288 V => 600 V

Output voltage: 0 - 850 V

Output current: 350 A

Output power: 300 kW

Dimensions: 244 x 109 x 482 mm

Add extra costs of DC/DC converter (~ 40 €/kW)

**) Needs special solution for the cycle lifetime and operation temperature

4 CONCLUSIONS

4.1 Selection and sizing of electrical energy storage

The main target of the study was to find out how electrical energy storage is selected and sized for a hybrid working machine, and the study focused on the suitability of Li-ion batteries (LFP-, LTO- and NMC-types) and supercapacitors (EDLC-, Pseudo- and Li-C hybrid capacitor -types) for the hybridization of working machines.

4.1.1 Research work

The literature review was done using several search services. More information has also been searched on the websites of manufacturers and experts. Standards, directives, and certificates related to the research topic were sought also, as well as manufacturers, and vendors of suitable products of Li-ion batteries and supercapacitors on the market.

Characteristics of electrical energy storage for the hybrid working machines, such as capacity, rated voltage, charging and discharging capacity (C_{rate}), energy and power densities, stored energy, physical dimensions, weight, cyclic life, calendar life, operating temperature, and price were under the study.

The study revealed just the same findings as in previous related studies, i.e. the main problems with the objective comparison of different electrical energy storage devices and also their suitability for different applications are related to incomplete characteristics in manufacturers' product catalogs and datasheets. Price information for individual modules is often missing from the websites of manufacturers and product retailers.

It is essential to ensure that the characteristics of all Li-ion batteries and supercapacitors selected for the iteration rounds have been calculated and defined by the same methods in the different manufacturers' datasheets. The datasheets of most manufacturers have a reference to the values of the different properties on a separate "Notes" page where you can find the calculation formula or measurement conditions for the properties.

4.1.2 Case study

This section developed and tested a selection and sizing method for the electrical energy storage systems and for it a Matlab-based application. This tool takes into account the selected properties like the maximum power $P_{\text{load-max}}$, the average power $P_{\text{load-mean}}$, the maximum energy needed of the system $E_{\text{load-max}}$, power and energy densities, cycle life, calendar life, C_{rate}, operating temperature, nominal voltage, space requirement, and price estimate.

The simulation tests were performed with a real work cycle of the working machine and for all selected types of suitable products of Li-ion batteries and supercapacitors on every selected test property. Graphics produced by Matlab application were printed as research results, and they were used for the choice of the modules for calculating the packs of Li-ion batteries and supercapacitors. The choice for calculations was LTO type batteries, EDLC/Pseudo- and Li-C hybrid type supercapacitors for the comparing and final selection of electrical energy storage.

The study proved that selection and sizing of an electrical energy storage system for a hybrid working machine based on the work cycle is the feasible approach to this problem.

4.2 Suggestions for the future work

Next related studies could include a selection and sizing study using work cycles of different types of working machines and different types of hybrid coupling of them.

Research-related standards, directives, and certificates CEN, CENELEC, EN, IEC, ISO, REACH, SAE, and SFS search services should review and list those that are important for the hybridization of work machines.

For supercapacitors, the effect of DoD value on calendar lifetime is not as crucial as with Li-ion batteries. Instead, attention should be paid to variations in nominal voltage and operating temperature. This could be a good thing to explore further as well.

The trend is toward integrated systems consists of batteries and supercapacitors, which are called hybrid devices. In them the electrode of the battery contributes to the energy storage utility while the electrode of the supercapacitor contributes to the power density utility. This kind of solution could be a good solution for mobile hybrid working machines. The related study of hybrid devices could be a good thing also.

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