



ELECTROCHEMICAL ENERGY STORAGES OF MOBILE WORK MACHINES

Juho Leskinen

Master's thesis
December 2015
Automation Technology

TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Automation Technology

JUHO LESKINEN:

Electrochemical Energy Storages of Mobile Work Machines

Master's thesis 51 pages

December 2015

This thesis was conducted to support research and development functions in mobile work machines, or sometimes called non-road mobile machinery, concerning especially electrochemical energy storages in hybrid-electric applications. The scope was in applications where an on-board charging system is present and the machine has the ability to drive fully electrically, thus fulfilling the characteristics expected from a hybrid-electric application.

The work discusses present energy storage technologies and how they are applied in mobile work machines. Electrochemistry, energy control, thermal management and components are examined. The goal of the work was to support future R&D activities and to give predictions of future developments. One of the fundamental parts of the work is the analysis on energy requirement of a work machine under varying load conditions.

The methods of research were literature study and model-based computer simulation. The literature research covered accessible publications on existing solutions in the field of components, systems and control methods applied in energy storages, and on the associated governing phenomena. The simulation covered a development of a principle model of an energy storage system, based on the results of the literature study, able to simulate, to some extent, the behavior of energy storages under different load conditions.

Based on the literature research and application examples, work machines with natural idling in their work cycle are the ideal candidates for hybridization. The nature of operation allows battery powered propulsion and work, but also a possibility to charge the battery with a diesel-generator set during idling.

Hybrid technology is rapidly being adopted in the field of mobile work machine manufacturing, allowing opportunities for increases in fuel saving and efficiency. One of the most promising enablers is lithium-ion based electrochemical energy storage.

The energy storage should be designed based on the respective cycle energy of the machine and on the capacity of the on-board charging system. Also the selection of the chemistry should be thoroughly investigated for applicability to the machine requirements. Safety, lifetime, environmental performance and cost are to be assessed in addition to electrical performance and capacity.

Keywords: battery, energy storage, hybrid, lithium-ion, work machine

CONTENTS

1	INTRODUCTION	6
1.1	Background and motivation	6
1.2	Mobile work machines	7
2	ENERGY REQUIREMENTS IN MOBILE WORK MACHINES	12
2.1	Static load	12
2.2	Dynamic load	13
2.3	Work cycles and identification of energy requirements	13
2.4	Energy balance	15
3	ELECTROCHEMICAL ENERGY STORAGEES	17
3.1	Applied chemistries and their characteristics	17
3.1.1	Lithium iron phosphate (LFP).....	21
3.1.2	Lithium titanate (LTO).....	22
3.1.3	Lithium nickel manganese cobalt oxide (NMC).....	23
3.2	Internal resistance and entropy	25
3.3	Electrical safety.....	26
4	ENERGY MANAGEMENT SYSTEMS	28
4.1	Battery Management System (BMS)	28
4.1.1	Sensors and measurement of electrical quantities.....	29
4.1.2	State of Charge (SoC), lifetime and diagnostics	30
4.2	Power electronics	31
4.2.1	Main contactors	31
4.2.2	Pre-charge and circuit protection	32
4.3	Energy storage discharging	32
4.4	Energy storage charging and balancing	33
5	THERMAL MANAGEMENT	35
5.1	Thermodynamic phenomena.....	35
5.2	Air cooling	38
5.3	Liquid cooling	39
5.4	Phase-change cooling	41
6	APPLICATION EXAMPLES	42
6.1	Volvo L220F Hybrid wheel loader	42
6.2	Mecalac MTX12 Hybrid excavator	43
6.3	Atlas AR-65 Hybrid loader	44
6.4	Huddig Tigon Hybrid loader.....	44
7	FUTURE TECHNOLOGIES	46
8	CONCLUSIONS AND REMARKS	48

REFERENCES.....50

ABBREVIATIONS AND TERMS

AC	Alternating Current
AGV	Automated Guided Vehicle
Ah	ampere-hour (electric capacity)
C	C-rate (defines the relation between current and capacity)
DC	Direct Current
DoD	Depth of Discharge
E	symbol of electric energy
HMI	Human-Machine Interface
HVAC	Heating, Ventilation and Air Conditioning
I	symbol of electric current
L	symbol of electric phase connection
LFP	Lithium Iron Phosphate (battery chemistry)
LTO	Lithium Titanate (battery chemistry)
N	symbol of electric neutral connection
n	cycle lifetime number
NMC	Lithium Nickel Manganese Cobalt Oxide (battery chemistry)
OCV	Open Circuit Voltage
P	symbol of electric power
PCM	Phase-Change Material
Q	symbol of heat transfer
R	symbol of electric resistance
Redox	Chemical reduction-oxidation reaction
RPM	Revolutions Per Minute
S	symbol of thermodynamic entropy
SoC	State of Charge (Battery parameter)
SoH	State of Health (Battery parameter)
t	symbol of time
TCO	Total Cost of Ownership
U	symbol of electric voltage
Wh	watt-hour (electric energy)
Z	symbol of electric impedance

1 INTRODUCTION

1.1 Background and motivation

This thesis was conducted to support research and development functions in mobile work machines, or sometimes called non-road mobile machinery, concerning especially electrochemical energy storages in hybrid-electric applications. The scope is in applications where an on-board charging system is present and the machine has the ability to drive fully electrically, thus fulfilling the characteristics expected from a hybrid-electric application. The on-board system functions as a charging and supporting device for the primary energy storage, producing electrical energy directly to the storage or via a mechanically coupled generator. The electrochemical properties, in the respective field, often indicate implementation of a battery pack consisting of multiple separate modules capable of producing a designed range of DC voltage with a given current. Thus, all the discussed energy storages and associated topics in this thesis are about rechargeable electrochemical batteries, and more specifically lithium-ion batteries.

The background of the work and the thesis was a need for research on present electrochemical energy storages in hybrid-electric mobile work machines. The research scope was on the system level applications and on their applicability for work machines. Ever tightening emission regulations and possibilities in reducing fuel consumption are motivating work machine manufacturers to develop intelligent machines exploiting hybrid-electric technologies. Also the techno-economic aspect has enabled the work machine industry to pursue these technologies in terms of technology maturation and component volume increase, which in turn contribute to decreased overall cost structure, TCO and payback time. This thesis was mandated by one of the R&D departments within Kalmar, which is part of Cargotec, a market leader in container handling machines worldwide.

The work discusses present energy storage technologies and how they are applied in mobile work machines. Electrochemistry, energy control, thermal management and components are examined. The goal of the work was to support future R&D activities within Kalmar and to give predictions of future developments. One of the fundamental

parts of the work is the analysis on energy requirement of a work machine under varying load conditions.

The methods of research were literature study and model-based computer simulation. The literature research covered accessible publications on existing solutions in the field of components, systems and control methods applied in energy storages, and on the associated governing phenomena. The simulation covered a development of a principle model of an energy storage system, based on the results of the literature study, able to simulate, to some extent, the behavior of energy storages under different load conditions.

1.2 Mobile work machines

The variety of mobile work machines is vast and some examples are in place better to illustrate different machines and the different environments they work in. Some of the most well-known industries and environments for work machine applications, and the machine types developed for them, are listed below in the form “Environment/Industry – Machine Type”.

- Forest/Wood – Harvesters, Wheel Loaders, Log Stackers, Forwarders



PICTURE 1. Ponsse ScorpionKing harvester. (Ponsse)

- Agriculture – Tractors, Combine Harvesters



PICTURE 2. Sampo-Rosenlew Comia C10 combine harvester. (Sampo-Rosenlew)

- Underground – Loaders, Haulers, Drill Rigs, Miners, Crushers, Sprayers



PICTURE 3. Sandvik DT821-SC drill rig. (Sandvik Mining and Construction)

- Ports and terminals – Terminal Tractors, Shuttle and Straddle Carriers, Gantries, Cranes, Stackers



PICTURE 4. Kalmar Hybrid Shuttle Carrier. (Kalmar Global)

- Construction – Excavators, Cranes, Drills, Dozers, Loaders, Trucks



PICTURE 5. Volvo EXC EC220E excavator. (Volvo CE)

This is only a small portion of the entire portfolio of available machinery for different work types and environments. The mobility, which defines a given machine as a mobile work machine, is the powertrain and its ability to move the machine, often via rubber tires or caterpillar tracks. Operation and maneuvering is divided into two significant types, manual and automated, which describe the presence of a machine operator manually operating the machine versus the absence of an operator; that is, unmanned, remote controlled. Remote or off-board controlled automatic machines and vehicles are often called AGVs (Automated Guided Vehicle).

The hybrid-electric aspect is already implemented in some of these machine types and many are under research and development. Savings in fuel consumption, lower emissions and overall higher efficiency are the major drivers to push forward on hybridization. The hybrid-electric architecture in work machines can be divided into two distinctive categories: the series-hybrid and the parallel-hybrid. In the series-hybrid configuration a diesel-generator set charges a battery pack, but is not mechanically connected to the machine powertrain. In a parallel-hybrid configuration the diesel-generator set is able to charge the battery pack, but also capable of providing power to the propulsion system through mechanical coupling.

The publicized applications in the field of hybrid-electric work machines are mostly of concepts or prototypes, or outside the scope of this thesis, such as hybrid-electric architectures executed with supercapacitor banks as energy storages. The discussions about lithium-ion technology and applications in this thesis are purely from freely accessible publications.

2 ENERGY REQUIREMENTS IN MOBILE WORK MACHINES

2.1 Static load

As a prerequisite for estimating requirements for an on-board energy storage of a mobile work machine, the machine energy requirements under varying conditions must be investigated.

Let us first investigate the easiest type of load conditions, static load, which is defined as a permanent state affecting energy consumed by static circumstances and the work done to maintain it. For analysis we can assume that a static position is present between transient movement, that is, between dynamic load conditions. We can also assume that the overall power consumption of a machine is constant with a given value under static load. For example, when a machine accelerates to a constant speed, the static condition is preceded by a transient condition due to the change of velocity, which increases power consumption. When the machine has reached the constant speed maintaining it, the power consumption stabilizes to an almost constant value.

As a generalization, we can assume that the energy consumed by a generic work machine in a static state, at zero speed, is mainly of auxiliary components and secondary electric circuits such as radio, HMI, HVAC and other systems keeping the machine ready for actual work. This state of readiness or a waiting period consumes some energy, which is important to realize, but not a governing factor in energy storage design.

The importance of static loads and states at zero speed come in play during longer working cycles of the machine, where those waiting periods are important or even mandatory in terms of available time to recharge the storage. With some work machines, there is some natural waiting time during every work cycle, where the charging strategy can be easier to design, but some machines do not have the luxury of waiting, which poses higher requirements for the design of volume and energy of the storage, machine operation and machine availability.

2.2 Dynamic load

Dynamic load conditions are assumed to be preceded and continued by static conditions, thus representing transient states between permanent states. In mobile work machines, transient states can be continuous during operation and can vary greatly due to different work routines of the machine.

In terms of battery pack characteristics, it has to be able to provide peak power required by the transients, but also able to provide constant power required by static loads.

2.3 Work cycles and identification of energy requirements

After analyzing the two types of load conditions, static and dynamic, the operational work cycles formed by those states, and the energy requirements in those conditions, can be identified. The previously mentioned states together form a cycle which represents the operational cycle of a machine, which can be repeated to form, for example, a complete working shift or any desired timeline of that machine.

A standardized cycle test, which is a norm in the automotive industry, does not exist for work machines due to the already mentioned wide range of operation types and environments. The diagrams below (FIGURE 1.) represent two different types of load cycles of a work machine, where transient and static conditions are present. The leftmost diagram presents electric power (kW) as a function of time (s) with regenerative characteristics indicating a situation where power is regenerated, for instance, by braking with an electric motor. The rightmost diagram presents similar quantities without the regenerative characteristics. It can be also noticed that the regenerative operation produces less variations in the behavior of power in comparison with the operation without regeneration.

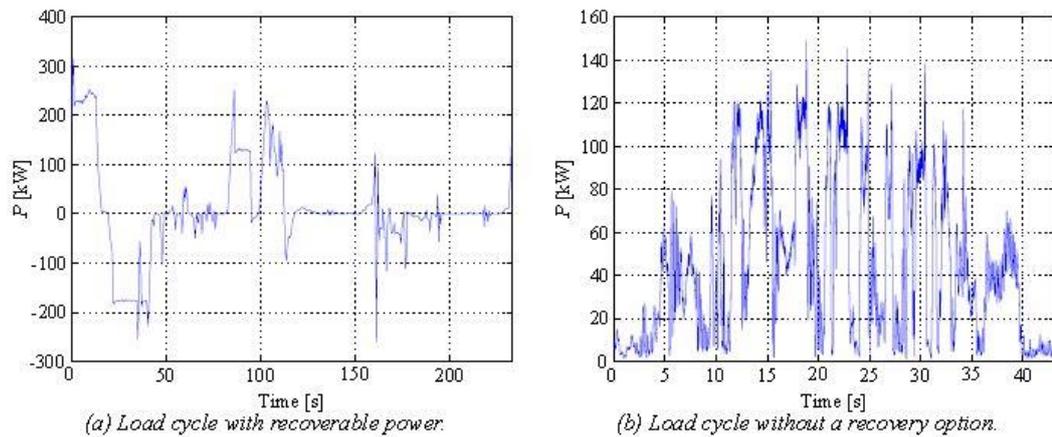


FIGURE 1. An example of an operational cycle, where a) represents a cycle with regenerative power and b) a cycle without regenerative power. (Immonen, 2013)

It is good to investigate the whole cycle, either a single or repeated cycles, to determine the energy requirement posed by the machine operation. There can be many ways of stating the energy required from an energy storage. It can be deduced, for instance, from experimental tests conducted with similar machines, which lack a battery pack, or through mathematical analysis. The overall energy requirements can be divided into separate requirements, on the basis of operation types, for easier analysis. As an example, a theoretical machine is used and its energy demand divided roughly into the following areas:

- Traction
 - Acceleration
 - Maximum speed
 - Deceleration
- Work
 - Drill maneuvering distance
 - Drill maneuvering speed
 - Drilling force
 - Drilling speed
 - Drilling depth
- Hydraulics and cooling
 - Cooling pump
 - Hydraulic pump
- Auxiliaries

- 230 VAC circuitry
- 400 VAC circuitry
- 24 VDC circuitry

All of these form the combined consumption of electrical energy, calculated as the product of electric power and time. Furthermore, the power is calculated as the product of electric current and voltage. A simplified equation is the following:

$$E = UI * t \quad (1),$$

where E represents energy in watt-hours, U voltage in volts, I current in amperes and t time in hours. It has to be kept in mind that some operations allow regenerative power production through electrical braking, which can have a reductive effect to the overall energy required from the storage. The requirement for energy can be simply a request from the machine operator to accelerate to a certain speed, thus being the product of required power to achieve that speed setpoint, and the time it will take to achieve it.

The electric power consumed by all electric components can be summed up to produce the total required power in the machine. Cycle energies can be calculated as a product of average power and time, but will be more precise through time integration of the electric power giving also more illustrative cycle energies when investigating repetitive cycles. After all energies have been summed up, the energy and power requirements have been identified. The result also indicates the required power range from the on-board charging system, and the possible time for operation between charging instances, if fully electric operation is applied.

2.4 Energy balance

Energy balance of a machine illustrates the consumed electric energy throughout different subsystems during specific work or operation, forming the sum of the total energy consumption during a given work cycle. It is especially beneficial to use energy balance analysis to examine where energy is consumed and how much in a specific operation. This contributes, for instance, to further analysis on ways to increase overall energy efficiency.

We can use the previously determined theoretical energy distribution list to create an illustration of energy balance of a work machine. In the table below, the energies are theoretical and are only for illustrative purposes. In order to have the exact figures for the given machine, the respective energies would have to be measured or estimated while in operation. The figures represent percentages (%) of the total energy consumption and generation of a single operational cycle.

TABLE 1. Energy balance of a work machine.

Item	Energy consumption [%]	Energy generation [%]
Traction	45	17
Work	30	
Hydraulics and cooling	15	
Auxiliaries	10	
On-board charging		83
Total	100	100

The energy generation represents regenerative energy from electric traction motors and from the on-board charging system. When examining the figures as kWh, guidelines can be drawn for the energy storage capacity demand and possibilities for different charging strategies.

3 ELECTROCHEMICAL ENERGY STORAGEES

3.1 Applied chemistries and their characteristics

The ability of an electrochemical battery to receive, hold and release electric power is based on reversible chemical reactions between the battery electrodes. Battery chemistry dictates, for example, the discharge and charge cycling: how many cycles can be achieved before significant cell ageing (the ability to release and receive current decreases), how many amperes it can be discharged and charged with, and the nominal cell voltage. These attributes are of course greatly affected by temperature fluctuations inside and around the cell. Especially cell ageing is mostly affected by temperature and cell usage close to and above the rated maximum voltage.

One of the most common chemistries in use for vehicle batteries is lithium iron phosphate (LiFePO_4), commonly referred to as lithium-ion, which has somewhat good characteristics in terms of number of efficient cycles and discharge current. Another, widely applied lithium-ion chemistry, or basically a modified lithium-ion chemistry, is lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$), which has lithium-titanate nanocrystals on the surface of its anode increasing the effective surface area of the anode, and thus giving the possibility of a faster charge carrier movement. The main observed - and some of them often also introduced by battery manufacturers - characteristics of electrochemical energy storages are the following:

- Capacity [Ah]
- Peak and continuous discharge currents [A]
- Peak and continuous charge currents [A]
- Cycle lifetime with 100 % DoD [n]
- Operation temperature range [$^{\circ}\text{C}$]
- Nominal voltage and total voltage range [V]
- Usable energy as a product of capacity and voltage [Wh]
- Recommended SoC range [%]

The C-rate, which is commonly used to describe the charge and discharge currents, is defined as a factor for capacity, thus the current being the product of C-rate and nominal

capacity. For example, if a battery capacity is rated at 40 Ah and the peak charge current at 3 C, the peak charge current in amperes is calculated as $3 * 40 = 120$ (A). The selected chemistry for a specific application is often a compromise between battery characteristics, performance, safety and lifetime. For comparison of different characteristics between different rechargeable batteries, the table below will give the average performance ratings of a few common chemistries.

TABLE 2. Comparison of characteristics between common rechargeable batteries. (Battery University)

Specifications	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/kg)	30–50	45–80	60–120	150–190	100–135	90–120
Internal resistance ¹ (mΩ)	<100 12V pack	100–200 6V pack	200–300 6V pack	150–300 7.2V	25–75 ² per cell	25–50 ² per cell
Cycle life ⁴ (80% discharge)	200–300	1000 ³	300–500 ³	500–1,000	500–1,000	1,000–2,000
Fast-charge time	8–16h	1h typical	2–4h	2–4h	1h or less	1h or less
Overcharge tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge		
Self-discharge/month (room temp)	5%	20% ⁵	30% ⁵	<10% ⁶		
Cell voltage (nominal)	2V	1.2V ⁷	1.2V ⁷	3.6V ⁸	3.8V ⁸	3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75	1.00		2.50 – 3.00		2.80
Peak load current Best result	5C ⁹ 0.2C	20C 1C	5C 0.5C	>3C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C	0 to 45°C		0 to 45°C ¹⁰		
Discharge temperature	–20 to 50°C	–20 to 65°C		–20 to 60°C		
Maintenance requirement	3–6 months ¹¹ (topping chg.)	30–60 days (discharge)	60–90 days (discharge)	Not required		
Safety requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory ¹²		
In use since	Late 1800s	1950	1990	1991	1996	1999

The explanations for the index numbers on the above table (Battery University):

1. Internal resistance of a battery pack varies with milliampere-hour (mAh) rating, wiring and number of cells. Protection circuit of lithium-ion adds about 100mΩ.
2. Based on 18650 cell size. Cell size and design determines internal resistance.
3. Cycle life is based on battery receiving regular maintenance.
4. Cycle life is based on the depth of discharge (DoD). Shallow DoD improves cycle life.
5. Self-discharge is highest immediately after charge. NiCd loses 10% in the first 24 hours, then declines to 10% every 30 days. High temperature increases self-discharge.
6. Internal protection circuits typically consume 3% of the stored energy per month.
7. The traditional voltage is 1.25V; 1.2V is more commonly used.
8. Low internal resistance reduces the voltage drop under load and Li-ion is often rated higher than 3.6V/cell. Cells marked 3.7V and 3.8V are fully compatible with 3.6V.
9. Capable of high current pulses, needs time to recuperate.
10. Do not charge regular Li-ion below freezing. See Charging at High and Low Temperatures.
11. Maintenance may be in the form of equalizing or topping charge to prevent sulfation.
12. Cut-off if less than 2.20V or more than 4.30V for most Li-ion; different voltage settings apply for lithium-iron-phosphate.

Furthermore, the lithium-ion chemistries are often divided into the following “flavors”.

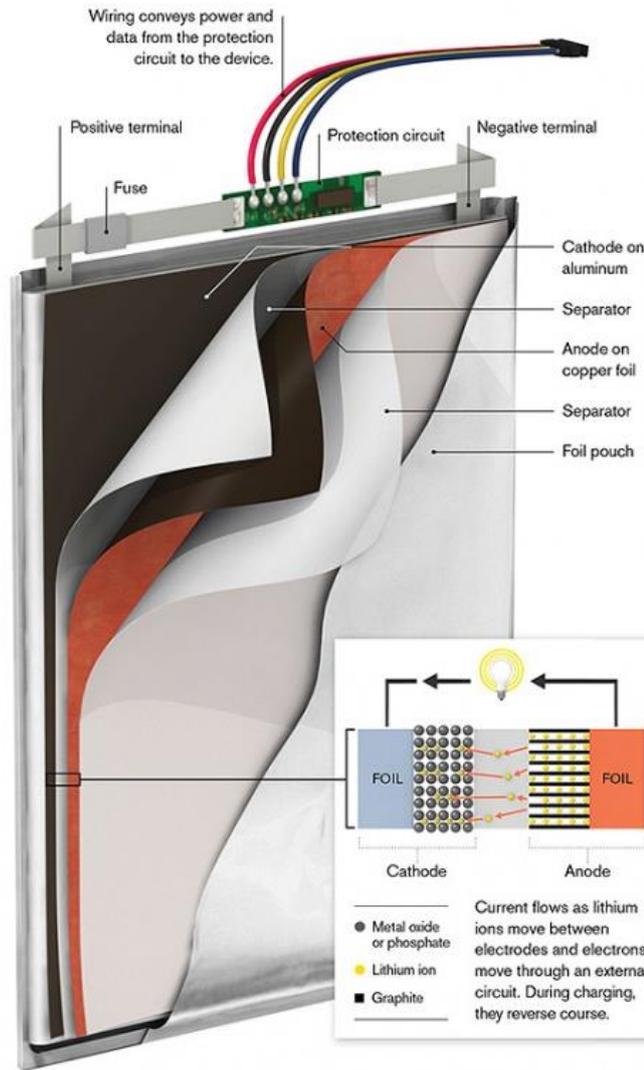
TABLE 3. The most common lithium-ion chemistries and their characteristics. (Battery University)

Chemical name	Material	Abbreviation	Short form	Notes
Lithium Cobalt Oxide ¹ AlsoLithium Cobalate or lithium-ion-cobalt)	LiCoO ₂ (60% Co)	LCO	Li-cobalt	High capacity; for cell phone laptop, camera
Lithium Manganese Oxide ¹ Also Lithium Manganate or lithium-ion-manganese	LiMn ₂ O ₄	LMO	Li-manganese, or spinel	Most safe; lower capacity than Li-cobalt but high specific power and long life. Power tools, e-bikes, EV, medical, hobbyist.
Lithium Iron Phosphate ¹	LiFePO ₄	LFP	Li-phosphate	
Lithium Nickel Manganese Cobalt Oxide ¹ , also lithium-manganese-cobalt-oxide	LiNiMnCoO ₂ (10–20% Co)	NMC	NMC	Gaining importance in electric powertrain and grid storage
Lithium Nickel Cobalt Aluminum Oxide ¹	LiNiCoAlO ₂ 9% Co)	NCA	NCA	
Lithium Titanate ²	Li ₄ Ti ₅ O ₁₂	LTO	Li-titanate	

The explanations for the index numbers on the above table (Battery University):

1. Cathode material
2. Anode material

The mostly applied cell formats in vehicles are cylindrical, pouch and prismatic. The cell format is chosen by the cell manufacturer based, for example, on the chemistry and packaging.



PICTURE 6. The structure of a pouch-type cell. (MIT Technology Review)

The above picture illustrates the mechanical structure and the principle of operation of a pouch-type lithium-ion cell. In addition to vehicle and work machine applications, the slim structure makes the pouch cell very favored in consumer electronics as well.

Some of the most common lithium-ion chemistries applied in mobile vehicles and machinery are discussed a bit further below.

3.1.1 Lithium iron phosphate (LFP)

LFP cells are often referred to as energy cells indicating somewhat low current and high capacity cells, which often also define the application that LFP is used in. The nominal

voltage of a single LFP cell is around 3.3 V with greatly varying capacities affecting also on the cell physical size.

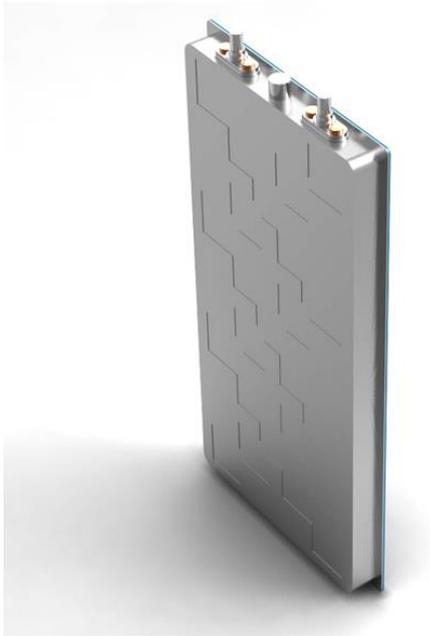


PICTURE 7. A123 Systems cylindrical LFP cell. (A123 Systems)

The above picture illustrates a cylindrical 18650 LFP cell, which has a nominal capacity of 1.1 Ah and a nominal voltage of 3.3 V. The 18650 type indicates the dimensions of the cell: 18 mm in diameter and 65 mm in length. (A123 Systems)

3.1.2 Lithium titanate (LTO)

Where the LFP has weight on the energy attributes, the LTO cells are often referred to as power cells. That indicates a high current and low capacity cells, the latter derived directly from a lower applicable voltage range. The nominal voltage of a single LTO cell is around 2.3 V and the advised voltage range often from 1.7 V till 2.7 V, which indicates a significantly lower capacity than with LFP. LTO has a reputation for safe, long lifetime and wide operable temperature range chemistry.



PICTURE 8. Padre Electronics LTO cell. (Padre Electronics)

The above picture illustrates an LTO cell with a nominal voltage of 2.4 V and a nominal capacity of 20 Ah. (Padre Electronics)

3.1.3 Lithium nickel manganese cobalt oxide (NMC)

NMC is often regarded as a compromise between an energy and a power cell, that is, between LTO and LFP. The nominal cell voltage for an NMC cell is around 3.7 V and capacity changes according to the design of energy vs. power cell. Compared to LTO, the NMC has somewhat the same C-rating, but half the lifetime. The safety of NMC due to its chemical content is often questioned.



PICTURE 9. Xalt Energy NMC cell. (Xalt Energy)

The above picture illustrates an NMC cell with a nominal voltage of 3.7 V and a nominal capacity of 31 Ah. (Xalt Energy)

The figure below (FIGURE 2.) represents an example of a common electrical configuration applicable on both cell and module levels. The vertical connections represent strings of series-connected cells/modules. The horizontal connections between the strings represent parallel connections. The series connection builds up voltage and the parallel connection builds up capacity, both of which are components of energy (Wh) as a product of voltage (V) and capacity (Ah).

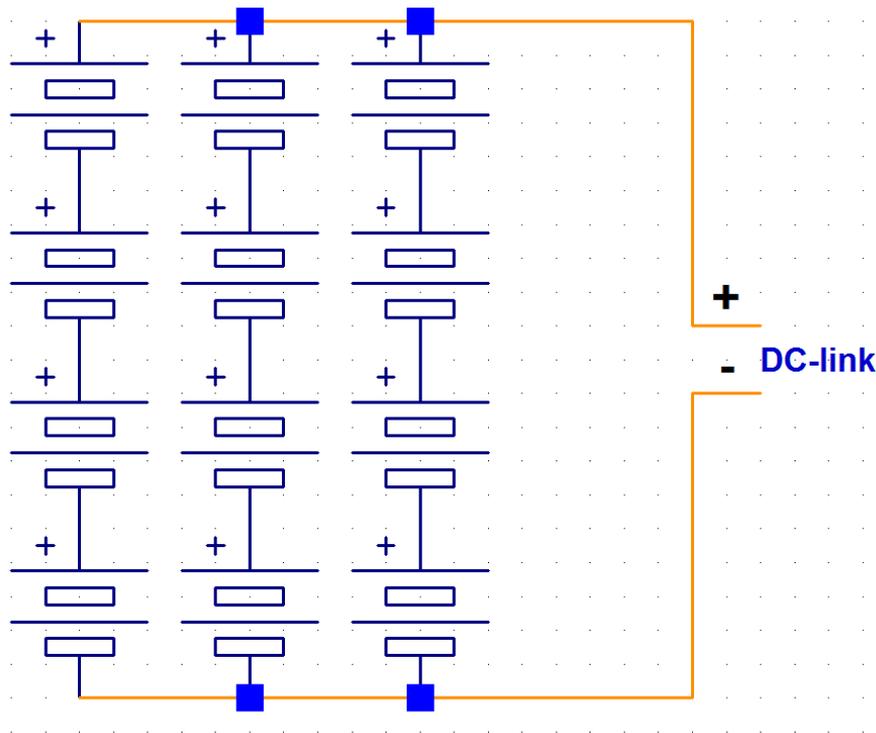


FIGURE 2. Architecture of series- and parallel-connected cells/modules.

3.2 Internal resistance and entropy

The internal resistance of a battery cell and changes in its value are one of the most illustrating indications of the state of health of the cell. The resistance is continuously affected by previously discussed current and temperature, and will experience short and long term variations during cycling and the aging process of the cell's materials. It is also necessary to know the internal resistance of the battery, if the Joule heat generation or I^2R power loss in the battery is investigated. However, a simple measurement with an ohmmeter is not possible because the current generated by the cell itself interferes with the measurement.

To determine the internal resistance, first it is necessary to measure the open circuit voltage (OCV) of the battery. Then a load with a known resistance should be connected across the terminals, propagating a current flow. This will reduce the battery terminal voltage due to the IR voltage drop across the terminals, which also corresponds to the battery's internal resistance. The battery voltage should then be measured again, when the current is flowing. The resistance can be calculated by Ohm's law from the voltage difference between the two measurements and the current, which is flowing through the

external load. The measurements should be done with constant currents and with current pulses to really understand the behavior of the battery chemistry and the changes in the internal resistance.

Another essential characteristic of a battery cell is entropy and the observed changes in it. Entropy in thermodynamics describes the amount of disorder or the possible ways of arrangements of a thermodynamic system. It is defined through the following equation:

$$\Delta S = \pm \int \frac{dQ}{T} \quad (2),$$

where ΔS represents the change of entropy, dQ represents the transfer of heat and T represents the absolute temperature. The \pm before the integral indicates that the heat transfer can be reversible or irreversible, that is, transfer of heat into a system or out from a system.

Resistance and entropy are both fundamental parts of the thermodynamics of a cell, further contributing to cell performance and ageing. These quantities and their influence on cell lifetime and heat generation are discussed in chapters 4.1.2 and 5.1, respectively.

3.3 Electrical safety

Electrochemical energy storages always pose a risk of electric shock and should always be treated as fully charged, despite any indications of a depleted battery. High voltage equipment should not be handled without proper training and understanding of the possible risks involved. While working with batteries, protective gear, such as electrically insulating gloves, and appropriate tools for high voltages should be used at all times.

One should always be aware of the risks of electricity to a human. If a person was be connected to a DC circuit by mistake, the person might not even feel it after the initial transient when being connected to the circuit, due to the fact that DC power has a constant polarity and does not possess natural fluctuating magnetic field characteristics like AC circuits. This makes it possible to think that one is, in fact, not connected to the circuit at all. After a period of exposure, the electric current through the person can inflict harmful or even fatal internal damage.

In case of a short circuit of the battery pack, the short circuit current can increase to several hundreds or even thousands of amperes for a period of time. This also inflicts high temperatures and a risk of fire. It is important to remember that lithium chemistries always possess the possibility of re-ignition even after a successful extinguishing and cooling of the battery.

The safety aspects are also highlighted in regulations concerning lithium-ion cell and battery transportation. Some types of certifications or approvals are often required for transporting batteries with lithium-ion content.

4 ENERGY MANAGEMENT SYSTEMS

4.1 Battery Management System (BMS)

Plain electrochemical battery is usually not intelligent on its own, but requiring monitoring and control. Intelligent control of energy is based on measured quantities and on effects contributing to them and arising from them. The measured parameters of a battery pack usually are at least the following:

- Individual cell voltage
- Individual module temperature
- Module and pack current
- Cooling air or liquid temperature
- Ambient temperature

The previous parameters are applied to calculate or estimate the following parameters and diagnostic states:

- Pack voltage
- Module and pack energy
- State of Charge (SoC)
- State of Health (SoH)
- Operation within predetermined temperature range
- Operation within predetermined current range
- Operation within predetermined voltage range

The calculations and estimations are based on basic electrical formulae and algorithms, but the SoC and especially the SoH are maybe the most arduous and difficult to reliably determine. Based on the real-time results of calculations, the BMS can adjust its parameters, such as current limits, for optimum performance under the experienced conditions.

The figure below (FIGURE 3.) contains a basic architecture of an energy storage system applicable to vehicles and work machines. Starting from upper left corner, the diesel-

generator set provides three-phase (U, V and W) AC power to the rectifier. Assuming that the rectifier is an actively controlled solid-state system, it will provide a controllable DC voltage as an output. The positive and negative terminals (+ and -) of the rectifier output are connected to the main contactors (S1 and S2) of the battery pack (B) and on the positive line, also to the pre-charge contactor (S3) through a pre-charge resistor (R). The DC-link connection is equipped with current transducers (T1 and T2) on both the positive and the negative cabling.

The battery pack (B) can be constructed from series- and/or parallel-connected modules to generate a desired voltage range and capacity. Furthermore, the modules can be constructed from several series- and/or parallel-connected cells.

All of the mentioned components and their role in the energy system are explained in the following chapters.

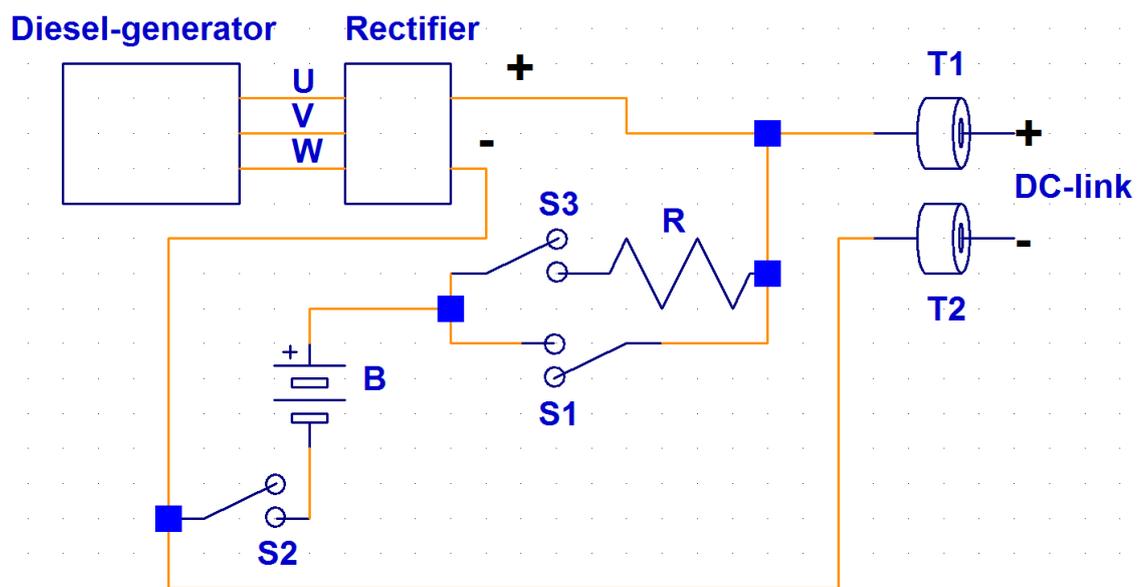


FIGURE 3. Energy storage architecture.

4.1.1 Sensors and measurement of electrical quantities

The key parameters within a battery environment that are to be monitored should meet the requirements posed by the application. The measurement of cell voltage should be

done directly from the cell terminal and added to other cell voltages to give the total pack voltage.

Electric current can be measured with a current transducer, which measures the magnitude and direction of current based on the magnetic field the flow of current generates around itself. The output signal from the transducer is voltage, which can be somewhat universally interpreted by the assigned measurement circuit. Another often applied current measurement technique is shunt measurement, which is based on voltage measurement across a known resistance (shunt resistor) allowing the current to be calculated based on the respective values.

Battery temperatures are often measured with NTC- or PTC-thermistors, which both have many variations, but are based on change in resistance in relation to temperature.

4.1.2 State of Charge (SoC), lifetime and diagnostics

The state of charge and its rate of change as an indication of capacity, along with an estimation of lifetime, are the most governing factors when determining the present and near-future conditions of the storage of an even individual cell.

The SoC can be determined somewhat directly from the individual cell voltages, but can be sometimes affected by a phenomenon called the memory effect. There have been studies for and against the fact that lithium chemistries do not have a memory effect, meaning that you can have incomplete discharge and charge cycles, which do not affect the observable capacity. Incomplete cycling means that the battery is not completely charged or discharged through the full usable SoC range, but with limited use of the battery's capacity. The memory effect has been clearly observed with other battery chemistries, such as nickel cadmium (NiCd) and nickel–metal hydride (NiMH), which exhibit values of a lower capacity than in reality after many low level charge and discharge cycles. They remember a lower voltage level, but still allow the same current to be released. This behavior can have further problematic influence in cases where the “assumed” voltage level falls below an operative voltage range of a device connected to the DC-link, causing the device to experience under-voltage conditions.

End of life (EoL) is often described as the state of a battery when its capacity is decreased below 80 % of the initial rated capacity. Beyond this point, the battery is often considered hazardous and unsafe to use in the operation it was originally designed for. At 80 % of initial capacity, the internal materials of the battery cell often have been degraded in a way which may allow the structure to fail in maintaining its properties or even to experience dangerous short circuit or heating, which can lead to a thermal runaway and fire.

EoL batteries could be proposed to have a second life for example in power grid balancing during voltage and frequency disturbances, propagating from variations in load and power generation. The usage of a battery in some other, less demanding application after its initial purpose could significantly lower the TCO when the available energy is offered to a local power grid company as a frequency/voltage controlled power reserve.

4.2 Power electronics

The electronic components and their intelligent control form the part where the electric power is managed within the energy storage and also between the storage and the DC-link. The power electronics entity has many tasks, such as managing voltage levels, voltage rise time and current upon pre-charging, and preventing electric arcing, if opening a contactor while current is flowing through it. This entity can be thought, not just as an interface between the storage and the DC-link, but also as an enabler for the whole designed capacity of the storage to be exploited.

4.2.1 Main contactors

In the case of a battery pack, which should be capable of safely connecting and disconnecting itself from the main power circuitry, there must be components present enabling that action. Those switching components function as a basis of a relay, but are often called contactors, mainly due to the relatively high connection voltages and flowing currents. In addition to their main task, they may also have an integrated current transducer, which, given that the measurement characteristics are found sufficient, can allow neglecting separate transducers and reduce the overall amount of components.

The two tasks of the main contactors are to connect the battery to the DC-link, often after a successful pre-charge sequence, and to disconnect the battery from the DC-link.

4.2.2 Pre-charge and circuit protection

The main task of a pre-charge circuit is to ensure a controlled galvanic connection between the battery pack and the external DC-link. A direct connection of battery terminals to an external circuitry may inflict hazardous current peaks, especially if the circuitry includes capacitance parallel to the battery. The idea of a pre-charge is to allow only a restricted current through the circuit for a given time before the main contactors are applied. This results in a controlled voltage rise of the DC-link voltage with a relatively low current.

To protect the battery and the cabling against excess currents and short circuits, it is often advised to place fuses or breaker switches between the battery and the DC-link. Depending on design and application, the fuses can react very rapidly to currents exceeding the rated current limits or slowly, allowing currents above rated limits for a given time.

4.3 Energy storage discharging

While an energy storage experiences an external load, which consumes power, the storage is in discharging state. The discharge current is often limited by the characteristics of the battery chemistry and, furthermore, the minimum allowed voltage level to which it can be discharged. In mobile work machines the discharge current, and thus the voltage level, can be very arbitrary above the minimum voltage level. This is directly due to inconsistencies in the usage profile of the battery or in the external loads.

4.4 Energy storage charging and balancing

While an energy storage experiences a voltage higher than its terminal voltage, the ion movement inside the storage is reversed building up charge imbalance between its terminals. Charging methods vary greatly depending on the type of battery chemistry, local distribution grids and legislation. However, we can first make some generalizations of a few charging methods and then discuss tailored solutions for work machine environments. Some environments, such as underground and remote locations, pose very different requirements for charging infrastructure and applicable technology.

Charging methods in the automotive industry, which are also often adopted for work machine applications, currently consist of three main types, all of which are bound to standardization and legislation. The first and the most common type in Europe is single-phase AC, which usually applies three contacts (L, N and PE), voltage level of around 230 VAC and frequency of 50 Hz. This method is sometimes referred to as slow charging requiring an on-board charger rectifying the AC voltage to DC and controlling the charging current. The name slow charging comes from the restricted maximum current of 10 A, or in some cases 16 A depending on the capabilities of the power supply. The on-board chargers are often rated around 3 kW of power and used in overnight charging. The proportionality of charging current magnitude and charging time is evident, but not applicable to the entire range of the state of charge. The capability of current supply cannot always be fully exploited and has to be controlled, especially during balancing, which will be discussed later.

The rest of the three charging methods are three-phase AC and DC fast charging. Three-phase charging usually applies a grid voltage of 400 VAC ($\pm 10\%$) with 50 Hz and usually requires an on-board charger. The charging power can be from around 20 kW to 40 kW depending on the charger architecture. The most interesting method, however, is the direct DC charging indicating that a grid-connected off-board charger is applied, which produces electric power directly to the DC-link or energy storage of a given vehicle. In the method of DC fast charging, the charging power is already in DC form and can have power of over 50 kW (400-600 VDC) and charging current of 100 A or more in passenger vehicle applications, but electric bus charging applies powers of 200-500 kW with currents of 300-600 A, and charging cycles lasting from 15 seconds to a couple of minutes. The power levels and charging times of buses could also be applicable

to the requirements of high power and little time posed by the work machine environments.

The battery's ability to accept current and the speed of charging depend also of the SoC level of the battery pack. The BMS decreases the allowed current on purpose when the SoC level rises close to full charge. That is to prevent cell overvoltage situations and to allow effective cell balancing, which means controlling all of the cell voltages close to the same level. The battery pack usually consists of multiple modules and cells requiring balancing, which is often done near full charge or continuously during the whole charging process. Active balancing means that the cells with a lower voltage are still being charged and the cells which have reached the maximum cell voltage are discharged into the cells of lower charge. Passive balancing often discharges the excess energy into waste heat. The process, whether active or passive, can be usually done directly in the BMS circuitry.

5 THERMAL MANAGEMENT

5.1 Thermodynamic phenomena

It is critical to understand the heat generation mechanisms of a battery in order to evaluate safety parameters and cooling requirements under varying conditions. Internal heat generation of a cell is comprised of two variables, which contribute - together with ambient temperature - to the thermodynamic behaviour of the cell. The following parameters affect directly the temperature of a cell, if all cooling methods are omitted:

- Internal resistance
- Entropy
- Ambient temperature

The internal resistance contributes to irreversible polarization heat, which is always positive, increasing cell temperature while charging and discharging. However, changes in entropy have been shown to have reversible heat characteristics, which can be either positive or negative, decreasing cell temperature during specific conditions of charging. These endothermic and exothermic reactions, during charge and discharge, are generated on lithium intercalation on the cell electrodes. Changes in ambient temperature produce heat transfer between the cell and the surrounding medium, which can have either a cooling or a heating effect depending on the temperature differences between the respective materials and on their ability to transfer heat.

The following figures and analysis is from a thermal characterization of a li-ion cell, specifically of a Panasonic CGR18650HG cell. The characterization was conducted by NASA representatives with a calorimeter in order to investigate the thermal properties of the cell under testing. The cycling conditions were the following:

- Charge current of $C/5$
- Taper charge current of $C/50$
- Discharge current of $C/2$
- Isothermal conditions with a constant temperature of $35\text{ }^{\circ}\text{C}$

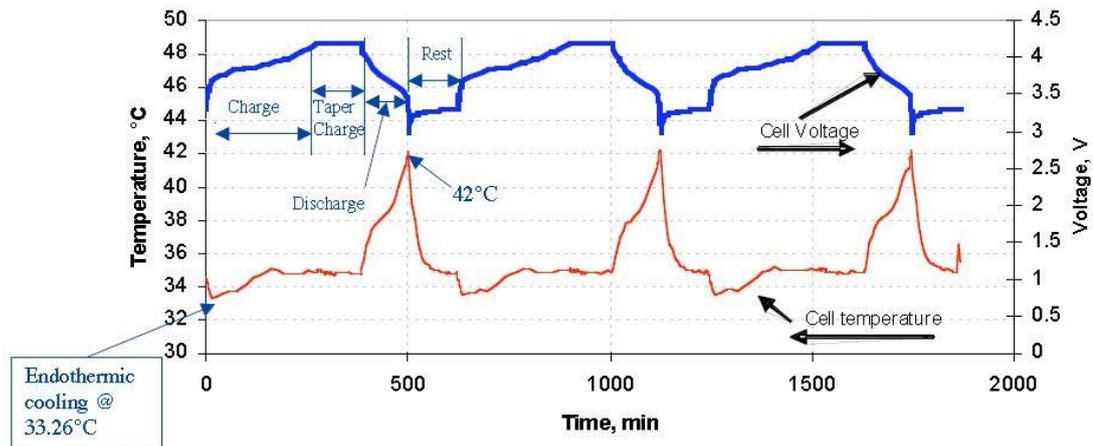


FIGURE 4. Voltage and temperature during charging and discharging cycling. (Britton et al. 2007.)

The figure above (FIGURE 4.) illustrates charging and discharging cycling of the 18650 cell showing the effects of internal resistance and entropy in the form of temperature changes. In the beginning of the first cycle, when charging commences, there is a visible drop in temperature due to change in entropy causing an endothermic effect, which in turn is cooling the cell. Eventually, while charging continues, the temperature begins to rise reaching its peak during cell discharging. This behavior in temperature occurs with every cycle. The ambient temperature during the experiment was kept constant, which allows excluding changes in external temperature and its impacts to heat transfer that would arise from it.

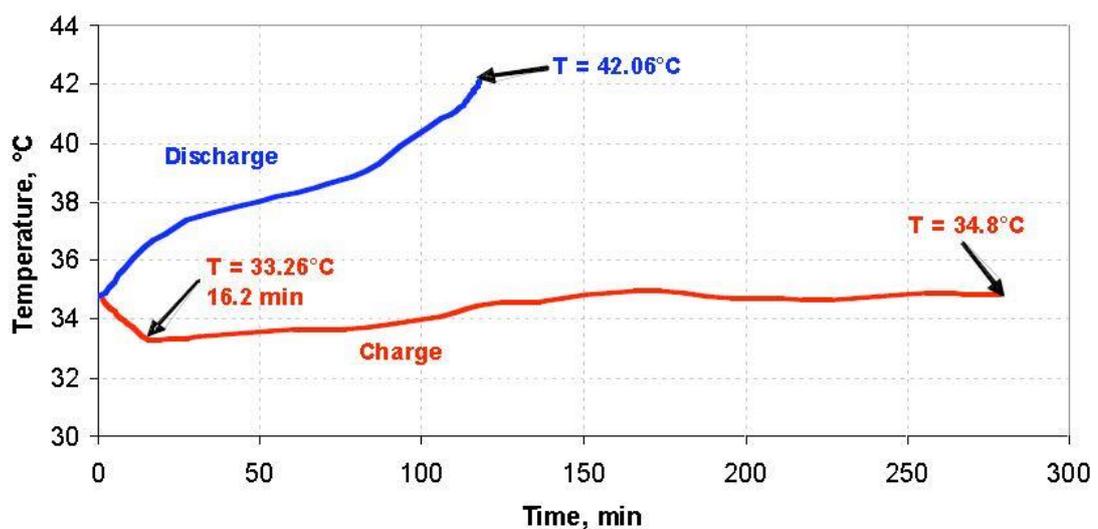


FIGURE 5. Temperature during the first charging/discharging cycle. (Britton et al. 2007)

A closer look at the first charging and discharging cycle (FIGURE 5.) shows detailed temperature curves and further proof of both endothermic and exothermic reactions.

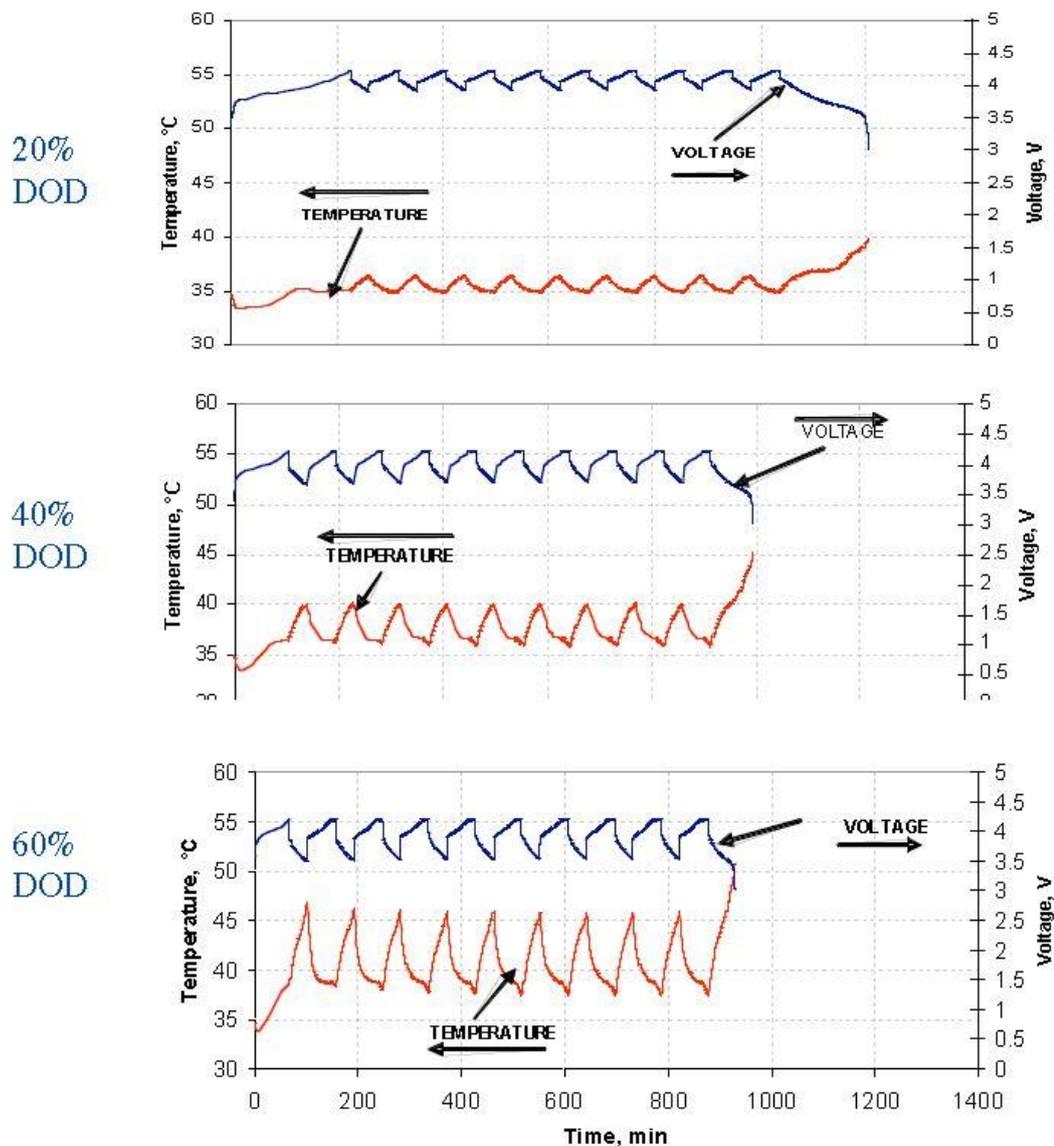


FIGURE 6. Temperature at different DoD levels. (Britton et al. 2007)

The figure above (FIGURE 6.) illustrates the relationship between cell temperature fluctuations and the depth of discharge. It is clear that when the cell is in a state of lower SoC, that is, in a state of higher DoD, the temperature is significantly increasing. From all of the figures, we can deduce that the heat generation of a cell is the sum of irreversible and reversible heat obtaining changing characteristics as a function of DoD. The relationship between the magnitude of current and heat generation has to be remembered, which can contribute to different absolute values of temperature, but the relative behaviour should remain the same.

This behaviour depends also on the type of applied chemistry and electrode. Research has shown that while LiFePO_4 based electrodes exhibit somewhat low changes in entropy, a lithium cobaltate (LiCoO_2) cathode exhibits significantly higher changes in entropy, in comparison. On the other hand, titanate anodes exhibit lower changes in entropy compared to graphite anodes.

Due to internal resistance, the battery cell itself experiences some minor self-discharge over time. If a BMS is powered via the battery, the observed self-discharge is even greater, which may require the battery to be frequently charged in order to prevent depletion.

5.2 Air cooling

The method of air cooling is based on airflow within and through the battery enclosure, absorbing heat from the battery cells and transferring it to the outside air. This method is often the least expensive in terms of components, but requires thorough design of the airflow around the battery cells, ventilation equipment and possibly a pre-cooler for the inlet air.

Air cooling is often adequate for low current battery applications, which do not generate substantial overall heat and do not experience large variations in temperature. Cylindrical cells are probably the best cylinder format for an efficient air cooling due to their shape, which allows possibilities to design a proper airflow between them.

The figure below shows an airflow and cooling simulation made for a battery module comprising of six cylindrical cells. The thermal image shows that the achieved cooling is very effective and works also in between the cells, not just around them.

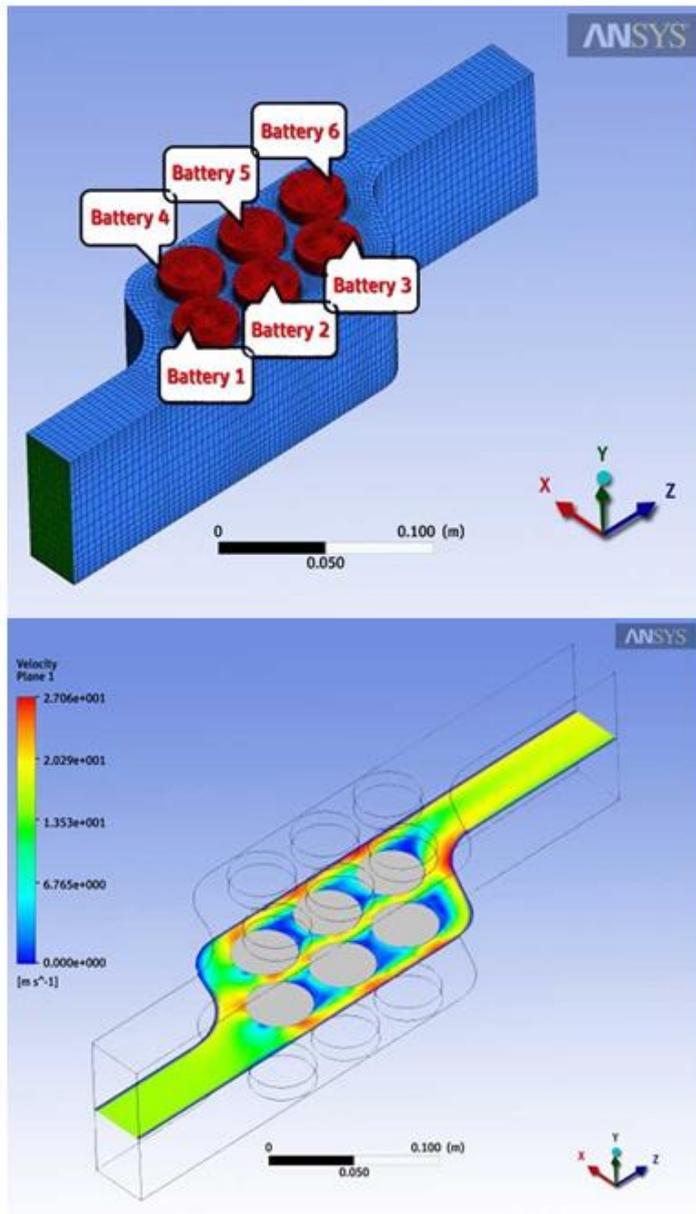


FIGURE 7. Simulation model of an air cooled battery module. (Stanton & Sovani, 2013)

5.3 Liquid cooling

The method of liquid cooling is based on liquid coolant flowing in close proximity to the battery cells absorbing heat and transferring it to the outside air through a heat exchanger. This method often requires a cooling pump, cooling plates, tubes and hoses for the coolant and a liquid-to-air heat exchanger. The system is usually closed and does not require a large reservoir for the coolant.

Liquid cooling is often required in high current battery applications where heat generation and temperature variations are a major factor. The liquid system could also be used to heat the battery cells up to the minimum suggested operating temperature in case of low or freezing ambient temperature.

The figure below illustrates a liquid cooling circuit applied for battery cooling. The pump provides a steady flow of coolant through the battery cooling plates absorbing heat from the modules. Then the coolant flows through a radiator, which dissipates the heat to the surrounding environment possibly enhanced with an airflow.

The figure also includes some optional features, such as an electric heater for heating the liquid flowing into the battery in cold temperatures. There is also a chiller, which is connected to the air conditioning circuit in order to increase the cooling effect of the battery under heavy loads. A controllable 4-way valve is used to choose between different cooling strategies also allowing a free circulation, if cooling is not required. Other liquid cooled components (Inverter) can also be used in the same cooling circuit, as is in the figure as well.

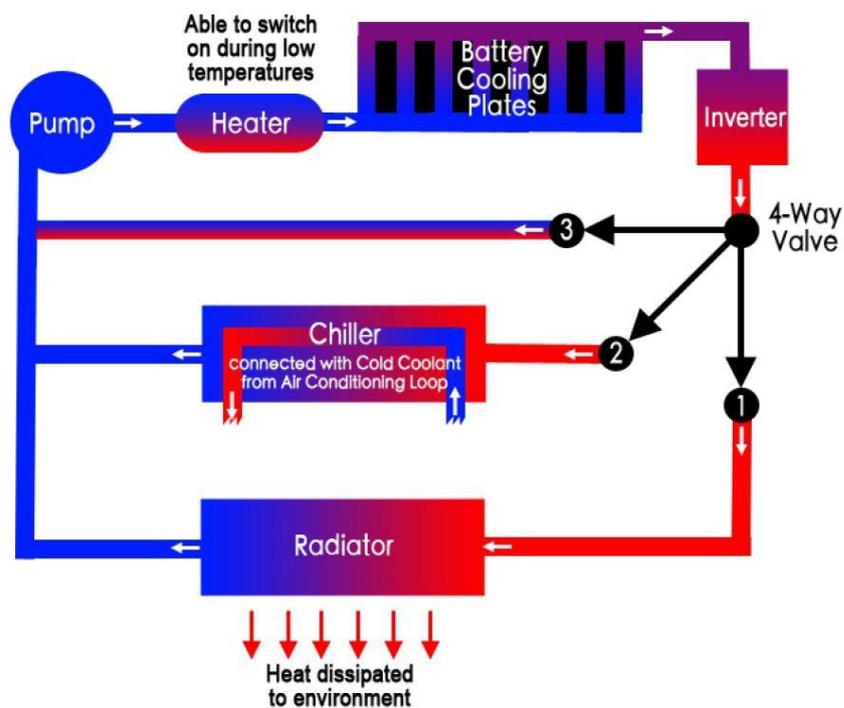


FIGURE 8. Principle of liquid cooling of a battery. (Ho. 2013)

5.4 Phase-change cooling

Another, still mostly in development, method of battery cooling is to surround the cells or modules directly with a phase-change material (PCM). The PCM is purely a passive thermal management solution utilizing a mass capable of absorbing heat and transferring it away from the source by changing its state of matter. It does not only transfer heat away from the source, but also decreases the rate of heat rise in the source by having a formidable volume.

An example of a battery module applying PCM cooling is constructed of cells surrounded by PCM/graphite mix for passive cooling. The porous graphite has been impregnated with wax (PCM), which melts at a predetermined temperature. The graphite provides a low-resistance path for heat transfer to the wax. The battery cells are directly assembled into the PCM/graphite material, which also works as a structural part of the module. (Gi-Heon et al. 2008)

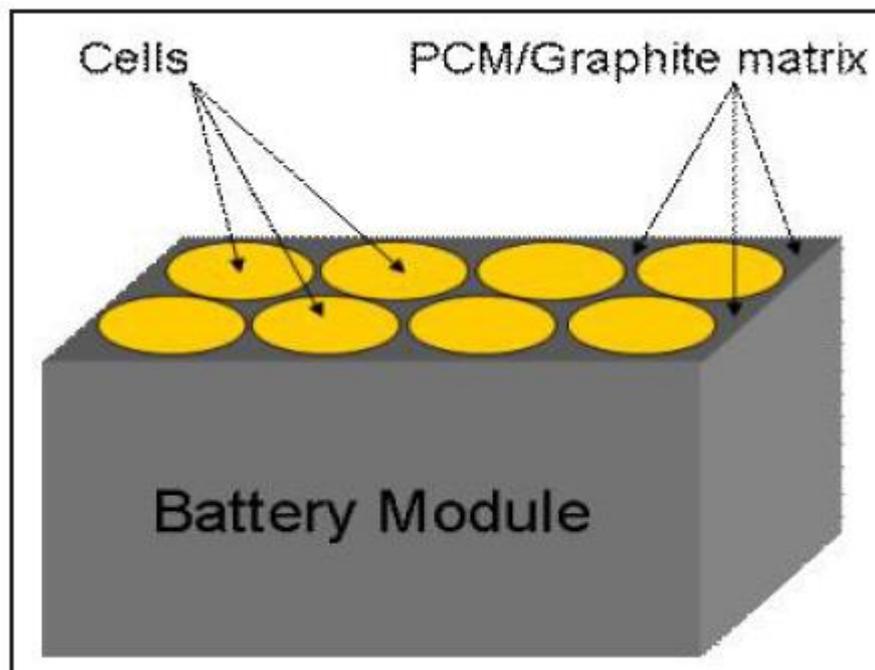


FIGURE 9. Battery module with PCM/graphite cooling method. (Gi-Heon et al. 2008)

The cooling method for a given battery pack can be one of the previously presented or any combination of them. Selection of the correct cooling method is often based directly on the thermal characteristics of the battery and the operation environment.

6 APPLICATION EXAMPLES

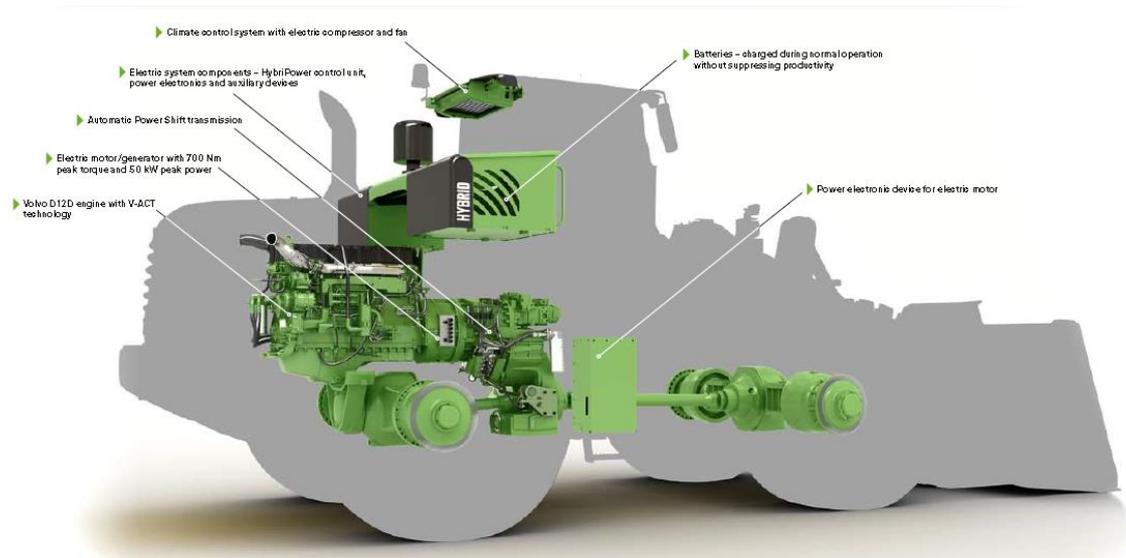
6.1 Volvo L220F Hybrid wheel loader

A hybrid wheel loader developed by Volvo Construction Equipment is fitted with a lithium-ion battery, which is used to power the on-board electrical consumers including the electric traction motor. This allows the diesel engine to be operated at lower RPMs and to use automatic start-stop operation. This capability is said to reduce the overall fuel consumption by around 10 %. (Volvo hybrid loader)



PICTURE 10. Volvo L220F hybrid wheel loader. (Volvo hybrid loader)

Detailed information on the lithium-ion battery has not been disclosed, but only a remark that it is equipped with a battery of hundreds of watts in power (Hybrid Drives for Construction Equipment).



PICTURE 11. Component layout of the L220F hybrid loader. (Volvo hybrid loader)

6.2 Mecalac MTX12 Hybrid excavator

The Mecalac MTX12 hybrid wheeled excavator exhibits a 400 V lithium-ion battery pack providing electric power to the parallel-hybrid configuration. The hybrid system is said to achieve 25 % savings in fuel consumption. (Cummins)



PICTURE 12. Mecalac MTX12 Hybrid. (Cummins)

6.3 Atlas AR-65 Hybrid loader

Atlas Weyhausen has developed a hybrid loader together with Deutz exhibiting a 400 V lithium-ion battery pack. Deutz claims the system to achieve 20-30 % fuel savings, which equals to 1500 € per year in cost (Deutz). The total cost of ownership is determined based on the expected savings in fuel and maintenance, but also on the cost of hybrid components during the lifetime of the machine. These parameters can vary significantly based on the machine operation and environment.



PICTURE 13. Opened rear-end of the Atlas machine showing the electric drive and high voltage cabling. (Deutz)

6.4 Huddig Tigon Hybrid loader

The work machine manufacturer Huddig (based in Sweden) has developed a hybrid loader with a lithium-ion battery providing electric energy for hydraulics and propul-

sion. Huddig claims that the 25 kWh battery contributes to 25 % decrease in fuel consumption. (IVT International Magazine; Huddig)

Huddig calls the hybrid technology Tigon technology and speculates customer payback time to be from two to four years depending on the usage profile. (Huddig)



PICTURE 14. Huddig Tigon hybrid loader. (Huddig)

7 FUTURE TECHNOLOGIES

New battery chemistries and systems are being developed all the time to meet future demands. Based on the presented facts and figures in this thesis, the following steps can be expected.

The requirements for future energy storages:

- High energy density
- High thermal conductivity
- Low internal resistance
- No memory effect
- Deep discharge capability and recoverability
- High cycle life
- Modularity
- Low cost (€/cell, €/kWh)
- Safety and stability
- Recyclability
- Second life applicability

Some of the promising chemistries under R&D, which could meet the energy density demand, are the following:

- Breathing batteries
 - Zinc (Zn) – air
 - Lithium – air
- Lithium – tin (Sn)
- Lithium – silicon (Si)
- Lithium – sulfur (S)

Also the electromechanical structures will experience changes. In addition to the already existing thin film and nanowire structures, solid state structures are being developed. The structure would eliminate the need for separators and liquid electrolyte, increasing ionic conductivity and making it possible to utilize over 90 % of a cell's potential energy density. In other words, it closes the gap between the expected and the potential energy densities.

On the system level, the following predictions or assumptions could be made.

- Battery energy storages will reach gasoline parity within the next 15 years
 - Equal energy density with traditional gasoline
- Auxiliary on-board battery charging systems will increase
 - Photovoltaic and thermoelectric power harvesting
- Storage-to-grid and storage-to-storage systems will emerge
 - Power grid stabilization and inter-machine charging
- Huge improvement in capacity and charge/discharge rates
 - Increased current acceptance and release capabilities through incorporation of nanomaterials and solid-state structure
- Challenges in availability of some raw materials

8 CONCLUSIONS AND REMARKS

Hybrid technology is rapidly being adopted in the field of mobile work machine manufacturing, allowing opportunities for increases in fuel saving and efficiency. From the customer point of view, the TCO can be greatly lowered. One of the most promising enablers is lithium-ion based electrochemical energy storage.

The energy storage should be designed based on the respective cycle energy of the machine and on the capacity of the on-board charging system. Also the selection of the chemistry should be thoroughly investigated for applicability to the machine requirements. Safety, lifetime, environmental performance and cost are to be assessed in addition to electrical performance and capacity.

As a conclusion from the literature study, a simulation model of an energy storage with basic attributes can be put together.

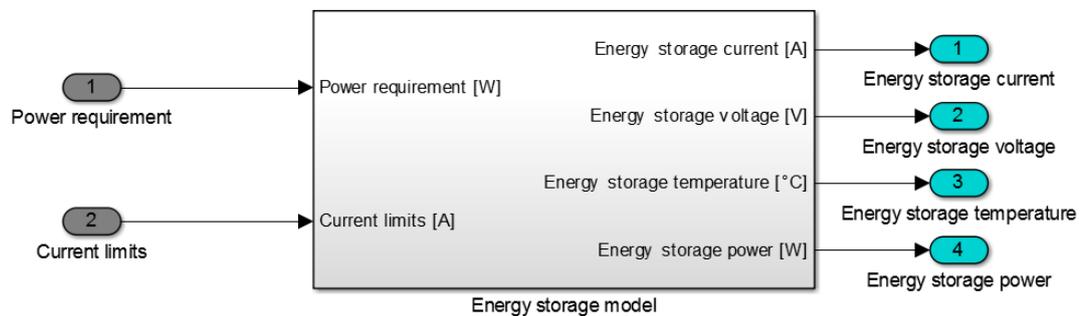


FIGURE 10. An upper level model of an energy storage.

The above model is based on two inputs, a power requirement from the machine and current limitations based on the energy storage manufacturer specified limitations. The limitations are affected by the battery chemistry, temperature and SoC.

Furthermore, the model can be viewed one level deeper showing the path from the inputs to the monitored outputs.

REFERENCES

A123 Systems. <http://www.a123systems.com/lifepo4-battery-cell.htm>

Britton, D., Miller, T. & Bennett, B. 2007. Thermal Characterization Study of Lithium-Ion Cells. National Aeronautics and Space Administration. 10th Electrochemical Power Sources Symposium.

Buchmann, I. 2014. Battery Diagnostics and Monitoring Advancements in Battery Test Technologies. Battery Power Magazine. Webcom Communications Corp. http://www.nxtbook.com/nxtbooks/webcom/batterypower_2014fall/#/0

Buchmann, I. Battery University. Cadex Electronics Inc. www.BatteryUniversity.com

Bullis, K. 2012. Lithium-Ion Battery. MIT Technology Review. <http://www.technologyreview.com/hack/428155/lithium-ion-battery/>

Cummins B3.3 Powers Mecalac 12MTX Hybrid to Gold Award for Innovation. <http://www.constructionequipmentguide.com/Cummins-B33-Powers-Mecalac-12MTX-Hybrid-to-Gold-Award-for-Innovation/12559/>

Deutz and Atlas Weyhausen take up dSpace for hybrid-drive development. <http://articles.sae.org/6715/>

Gi-Heon, K., Gonder, J., Lustbader, J. & Pesaran, A. 2008. Thermal Management of Batteries in Advanced Vehicles Using Phase-Change Materials. The World Electric Vehicle Journal. Volume 2. Issue 2.

Ho, V. 2013. Gcorelab Gets \$482,000 For New Battery Cooling Technology. TechCrunch. <http://techcrunch.com/2013/04/23/gcorelab-gets-482000-for-new-battery-cooling-technology/>

Huddig. <http://www.huddig.com/media/1234/tigon-broschyr-english.pdf>

Immonen, P. 2013. Energy Efficiency of a Diesel-Electric Mobile Working Machine. Doctoral Thesis. Lappeenranta University of Technology. Lappeenranta: Yliopisto-paino.

Kalmar Global. www.kalmarglobal.com

Korane, K. 2009. Hybrid Drives for Construction Equipment. <http://machinedesign.com/sustainable-engineering/hybrid-drives-construction-equipment>

Lajunen, A. 2014. Improving the Energy Efficiency and Operating Performance of Heavy Vehicles by Powertrain Electrification. Doctoral Dissertation. Aalto University. School of Engineering. Helsinki: Unigrafia Oy.

Padre Electronics. <http://www.pdbattery.com/20000-cycles-lto-battery.html>

Ponsse. www.ponsse.com

Put a Tigon in your tank. 2015. IVT International Magazine. June Edition.

Sampo-Rosenlew. www.sampo-rosenlew.fi

Sandvik Mining and Construction. www.miningandconstruction.sandvik.com

Stanton, S. & Sovani, S. 2013. Advanced Numerical Simulation for Hybrid and Electric Vehicles. Electronic Design. <http://electronicdesign.com/power/advanced-numerical-simulation-hybrid-and-electric-vehicles>

Takano, K., Saito, Y., Kanari, K., Nozaki, K., Kato, K., Negishi, A. & Kato, T. 2002. Entropy change in lithium ion cells on charge and discharge. Journal of Applied Electrochemistry. Volume 32. Issue 3. Pages 251-258.

Viswanathan, V., Choi, D., Wang, D., Xu, W., Towne, S., Williford, R., Zhang, J., Liu, J. & Yang, Z. 2010. Effect of entropy change of lithium intercalation in cathodes and anodes on Li-ion battery thermal management. Journal of Power Sources 195 3720–3729.

Volvo CE. www.volvoce.com

Volvo wheel loader.

http://www.volvoce.com/SiteCollectionDocuments/VCE/Documents%20Global/wheel%20loaders/brochureHybridloader_21A1004471_2008-02.pdf

Xalt Energy. <http://www.xaltenergy.com/index.php/solutions/technology/cells.html>