

Battery Technology – Use in Forestry

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Abstract

Technical development and system optimization during the last decades have targeted more efficient, socially acceptable and ecologically sustainable ways to use forestry machines and tools. This is supported by the development of electronics and electrical components, as well as battery technology, without which it is impossible to imagine doing some forestry work in forest areas with no permanent source of electricity. Today, we cannot imagine life without e.g. a cell phone, and also doing business in the forestry sector without a field computer. There are numerous examples in everyday life, but also in industry, where portable devices make life and business much easier, and the basis for the operation of these devices is battery technology. The importance of the development of battery technology is proven by the fact that in 2019 the Nobel Prize in Chemistry went into the hands of scientists who developed a lithium-ion battery - a lightweight, rechargeable and powerful battery that is used today in numerous products from mobile phones to laptops and electric vehicles. This paper will outline the historical development of battery technology and the use of battery powered devices, tools and machines with their advantages and disadvantages in forestry sector.

Keywords: battery characteristics, Li-ion, battery management system, electronic devices, power tools, hybrid machines

1. Introduction

Advanced rechargeable batteries are the enablers of energy in multiple applications such as cordless power tools (for household or professional use), e-mobility transportation (e-bikes, motorcycles, electric-type automobiles), e-communication devices (i-pods, i-pads, PC, mobile phones), and in numerous stationary energy storage applications (Recharge 2018).

According to the Batteries Directive 2006/66/EC, the batteries placed on the market in EU are classified in 3 categories:

- industrial batteries (mainly corresponding to electric mobility and energy storage markets)
- automotive batteries (mainly lead-acid batteries for vehicles starting and lighting)
- portable batteries (neither industrial nor automotive, mainly suitable for portable equipment applications, such as laptop, phones, power tools, cameras and most of alkaline primary cells, etc.).

With the development and innovation of electronic technology, EEE (Electric Electronic Equipment) has been rapidly growing over the past decades. The rea-

son lies in the fact that EEE is widely used in our daily life - from personal to high-technology devices applied in aerospace due to the ability to integrate and interact with a human, which has brought great convenience and epoch-making changes, becoming an indispensable part for almost every person. In general, stable energy sources are mandatory in these devices to guarantee the desired performance (Liang et al. 2019, Barsukov and Qian 2013).

To meet the high requirements of EEE, significant improvements in electrochemical performance of rechargeable batteries have been attained. The rechargeable batteries of EEE have gone through the phase of lead-acid, nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), lithium-ion (Li-ion) batteries, and so on (Fig. 1). Their specific energy and specific power have been substantially improved as time goes on (Liang et al. 2019, Miranda et al. 2015). However, the current battery technology cannot fully catch up with the rapid growth of EEE (Tarascon and Armand 2001). The state-of-the-art technology of rechargeable batteries for EEE has many drawbacks, that is, limited energy storage capacity, short cycle life, and high self-discharge, which have become the constrained bottleneck

for further development of EEE (Chen and Fan 2018). High-power consumption of multifunctional EEE requires energy storage systems with higher energy, smaller volume, lighter weight, and longer operational time. However, it is challenging for current batteries to satisfy the ever-increasing demands of emerging electrical and electronic equipment. Therefore, the rational design and production of new batteries has been a relentlessly pursued goal for the future EEE. Great efforts have been dedicated to improving the electrochemical performances of batteries (Liang et al. 2019).

The rapid progress of EEE is impossible without the progressive improvement of rechargeable battery technologies. Primary batteries have already been used as the main energy source of EEE for a lengthy period. However, the significant strides of rechargeable batteries with higher energy and power density have remarkably changed the situation since the early 21st century. Presently, rechargeable batteries have already been applied in most EEE (Goodenough 2018).

A battery is composed of several electrochemical cells that are connected in series and/or in parallel in order to provide the required voltage and capacity,

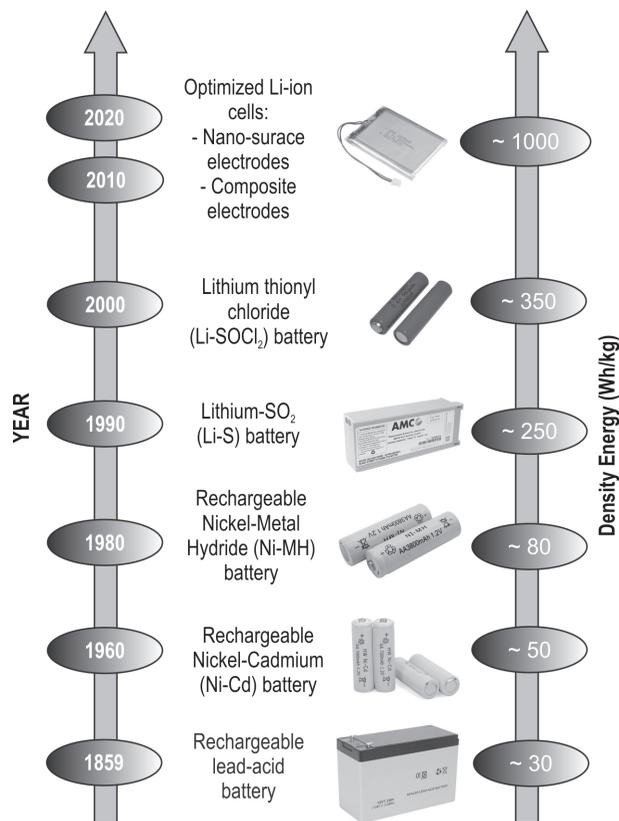


Fig. 1 Historical development of rechargeable batteries (Miranda et al. 2015)

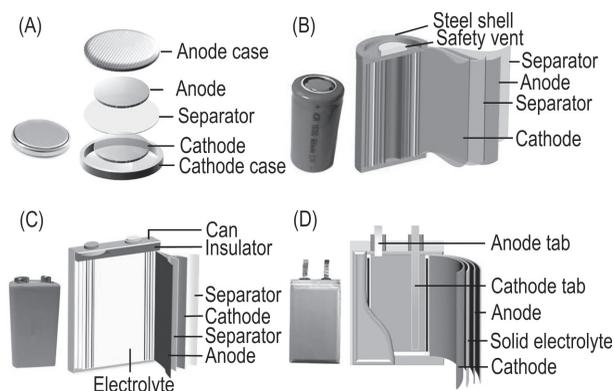


Fig. 2 Schematic illustration of typical rechargeable battery configurations: A - coin, B - cylindrical, C - prismatic and D - pouch shapes (Liang et al. 2019)

respectively. Each cell is composed of a positive and a negative electrode, where the redox reactions take place. The electrodes are separated by an electrolyte, usually a solution containing dissociated salts so as to enable ion transfer between the two electrodes. Once these electrodes are connected externally, the chemical reactions proceed in tandem at both electrodes, liberating electrons and providing the current to be tapped by the user (Dunn et al. 2011, Tarascon and Armand 2001, Goodenough and Kim 2010).

EEE evolved and incorporated several different types of rechargeable batteries, including lead-acid, Ni-Cd, Ni-MH, and Li-ion batteries. These rechargeable batteries often adopt four types of shape, that is, coin, cylindrical, prismatic, and pouch cells (Fig. 2).

Lead-acid and Ni-Cd batteries have been used for a long time. The former can be dated back to 1859, while the latter was first manufactured in 1909. Ni-MH and Li-ion batteries are relatively young. Ni-MH and Li-ion batteries have played critical roles in implementing the wide adoption of EEEs, especially Li-ion batteries.

2. Main Types of Rechargeable Batteries

2.1 Lead-acid Battery

The lead-acid battery was invented by the French physicist Gaston Planté in 1859 as the first commercially successful rechargeable battery. Despite its oldest age, the lead-acid battery has been continuously widely used because of its low cost, low self-discharge rate, high discharge currents, and good low-temperature tolerance. These features make it attractive for applications not only in some EEE but also in solar systems, automobiles, golf cars, forklifts, and other vehicles.

Lead-acid batteries can be made in cylindrical or prismatic configurations (Fig. 2). Its usable capacity decreases when high power is discharged. For this reason, lead-acid batteries have a limited depth of discharge. They have a typical cycle life of approximately 1500 cycles at 80% depth of discharge. They are also toxic for humans and the environment, and have a slow charge rate. In particular, the main drawback of lead-acid batteries is their low gravimetric energy density of about 40 Wh/kg. They have the lowest specific energy storage capacity among Ni-Cd, Ni-MH, and Li-ion batteries, and usually, have a large size and heavy weight. This indicates that lead-acid batteries store the least amount of energy based on the battery weight, which limits their usability in cordless tools and especially in small EEE (May et al. 2018, Liang et al. 2019).

The anodes in each cell of a lead-acid battery are plates or grids of lead containing spongy lead metal, while the cathodes are similar grids containing powdered lead dioxide (PbO₂). The electrolyte is an aqueous solution of sulphuric acid. The nominal cell voltage is relatively high at 2.05 V. Connecting three such cells in series produces a 6 V battery, whereas a typical 12 V car battery contains six cells in series. When treated properly, this type of high-capacity battery can be discharged and recharged many times over (Schmidt-Rohr 2018).

2.2 Nickel-cadmium (Ni-Cd) Battery

The Ni-Cd battery was invented by Waldemar Jungner in 1899, and it offered several advantages over lead-acid battery, such as longer lifetime, attractive low-temperature performance, higher charge-discharge rates, and versatile size ranging from small sealed portable types to large vented cells. The nickel-cadmium battery is a water-based cell with a cadmium anode and a highly oxidized nickel cathode that is usually described as the nickel(III) oxo-hydroxide, NiO(OH). The maximum cell voltage during charge is 1.3 V, and the average cell voltage is 1.2 V (Omar et al. 2014, Liang et al. 2019). Due to these exceptional characteristics, the Ni-Cd battery was once the dominant battery choice for both portable and standby power sources. The widespread manufacture of this type of sealed Ni-Cd batteries began in the 1950s. From then on, the Ni-Cd battery occupied an overwhelming majority of the market as rechargeable batteries in various EEE, including mobile phones, laptops, flashlights, video cameras, and radios up to the 1990s. This type of battery is also used in devices like drills, portable vacuum cleaners, and AM/FM digital tuners. Nevertheless, a major drawback of Ni-Cd batteries is their memory effects, where their maximum energy capac-

ity is gradually lost when they are not fully discharged before recharging or are not used for a while. Hence, Ni-Cd battery was often limited to electronic devices, such as mobile phones, which are frequently recharged after being only partially discharged.

Although Ni-Cd batteries are lightweight, rechargeable, and high capacity, they have certain disadvantages. For example, they tend to lose capacity quickly if not allowed to discharge fully before recharging, they do not store well for long periods when fully charged, and they present significant environmental and disposal problems because of the toxicity of cadmium. Considering that a large number of EEE was disposed every year, the abandoned Ni-Cd batteries also raise significant environmental concerns. Since the 1990s, Ni-Cd batteries have gradually lost their popularity due to the development of Ni-MH and Li-ion battery technologies. Today, Ni-Cd batteries are only used for some specific applications.

2.3 Nickel-metal Hydride (Ni-MH) Battery

The nickel-metal hydride (Ni-MH) battery was patented in 1986 by Stanford Ovshinsky. Commercially available in 1989, Ni-MH battery is an important type of rechargeable battery used in EEE. Nickel-metal hydride batteries are similar to the proven sealed nickel-cadmium battery technology except that a hydrogen-absorbing negative electrode is used instead of the cadmium-based electrode. This eliminates cadmium, a toxic material, while this substitution increases the battery electric capacity (measured in ampere-hours) for a given weight and volume. They both use the same cathode materials and electrolyte, but instead of cadmium, a hydrogen absorbing alloy is used as the anode in Ni-MH battery.

Ni-MH battery has moderate specific energy (70–100 Wh/kg) and relatively high energy density (170–420 Wh/L), significantly better than those of Ni-Cd battery. Other advantages of Ni-MH batteries over Ni-Cd batteries include a reduced »memory effect«, and they are more environmentally-friendly. Ni-MH batteries have longer cycle life than Li-ion batteries. The Ni-MH battery has a wide range of applications from portable products to electric vehicles and potential industrial standby applications, such as uninterruptible power sources (UPS). The flat discharge characteristic, excellent high rate, long cycle life, and abuse tolerance have made Ni-MH the first choice for use in hybrid electric vehicles (HEVs). However, the significant barrier for HEV applications is the high rate of self-discharge, losing 5–20% of its capacity within the first 24 h after fully charging. Ni-MH batteries currently cost about the same as lithium-ion batteries (Revankar 2019).

The average cycle life can reach 500 cycles on a high-capacity Ni-MH battery and almost 3000 cycles on a low-capacity one. The Ni-MH battery also renders fast charge ability. For instance, it can be rapidly charged within 1 hour. Because of all these advantages, Ni-MH batteries soon replaced Ni-Cd batteries in EEE and became the primary power solution in the early 1990s. However, in recent years, the use of Ni-MH batteries has decreased significantly, mainly due to the development of Li-ion batteries and some of their disadvantages (Liang et al. 2019).

2.3 Lithium-ion (Li-ion) Battery

As the most commonly used rechargeable batteries nowadays, Li-ion batteries have brought EEE to a new age since 1991, when the Sony Corporation commercialized the first Li-ion battery. Compared with other commonly used batteries, lithium-ion batteries are characterized by high energy density, high power density, long life and environmental friendliness and thus have found wide application in the area of consumer electronics due to high voltage of about 3.6 V (three times that of typical Ni-based battery), being maintenance free and lightweight, and providing good safety and excellent cycling performance. These advantageous features make Li-ion batteries the best energy storage option for small-sized EEE, such as mobile phones, laptops, digital cameras, and others, which used to be dominated by Ni-MH and Ni-Cd batteries. Meanwhile, Li-ion batteries are also growing in popularity for military, electric vehicle, and aerospace applications (Goodenough 2018, Blomgren 2017, Lu et al. 2013, Yoshino 2012).

With the introduction of new materials and technologies, Li-ion batteries continuously improve their energy density, power density, lifespan, and safety. However, Li-ion batteries are still suffering from some drawbacks. For instance, the higher manufacturing costs result in higher prices when compared with other rechargeable batteries. Although the price is getting lower year-by-year, Li-ion batteries still cost more than other competing batteries. Further, Li-ion batteries require additional protection circuits to limit voltages and currents to ensure safe operations. Besides, Li-ion batteries would lose their capacity and cycle life when stored at temperatures over 30°C for an extended period. Nowadays, battery scientists and engineers are making significant efforts to address the drawbacks of Li-ion batteries (Liang et al. 2019, Dunn et al. 2011).

There are several world-class companies such as Samsung, Panasonic and LG that manufacture the lithium-ion cells (mostly they look like an AA battery – type 18650) that are assembled in the battery pack



Fig. 3 Different shapes of Li-ion battery

that powers a tool. Tool manufacturers do not manufacture their own cells. Cell manufacturers are constantly developing and advancing the technology so they offer a wide variety of latest technology cells for use in every industry that uses Li-ion batteries. Lithium-ion batteries could now be recycled with an efficiency of 97% w/w of the valuable battery active materials (Hanisch et al. 2015).

Current research activities aim at developing new or alternative technologies like lithium-air, lithium sulphur, lithium polymer and solid-state lithium. A significant advancement in one or more of these chemistries could prove disruptive to the industry; however, the extensive testing needed to bring a new chemistry into a vehicle production makes it unlikely that this could occur during the 2020s, as there are no game-changing technologies approaching the consumer market (Thielmann et al. 2015, Blagoeva et al. 2016, Avicenne 2016).

In general, there is a trend to more energy-efficient devices, which means either that the battery weight remains stable and the devices offer more functions, or the weight of the battery decreases (e.g. shift from an AA to an AAA battery, or to button cells, or use of lighter batteries) for the same product functionality. The changes can be very abrupt. A product-centric example of a rapid change of the technical requirements is the shift of portable PC towards thin and »ultraportable« notebooks, in which the traditional battery shape used since the 1990s (based on a standard cylindrical shape Li-ion cell having a diameter of 18 mm) cannot be used anymore. The new battery design requires a maximum thickness of 10 mm or less, and therefore, the use of a new battery technology with a new material composition (Recharge 2018).

Table 1 Characteristics of rechargeable batteries (Liang et al. 2019)

| Characteristics | Battery type | | | |
|--|--------------|-----------|-----------|-----------|
| | Lead-acid | Ni-Cd | Ni-MH | Li-ion |
| Gravimetric energy density, Wh/kg | 30–50 | 40–60 | 60–120 | 170–250 |
| Volumetric energy density, Wh/L | 60–110 | 150–190 | 140–300 | 350–700 |
| Battery voltage, V | 2.0 | 1.2 | 1.2 | 3.7 |
| Cycle life, to 80% of the initial capacity | 300 | 1500 | 1000 | 500–2000 |
| Self-discharge per month, % | 5 | 20 | 30 | <10 |
| Fast charging time, h | 8–16 | 1 | 1–4 | 1 or less |
| In use since | Late 1800s | 1950 | 1990 | 1991 |
| Toxicity | High | High | Low | Low |
| Overcharge tolerance | High | Moderate | Low | Low |
| Operating temperature range, °C | –20 to 60 | –40 to 60 | –20 to 60 | –20 to 60 |

3. Battery Management System – BMS

Automotive lithium-ion batteries have high capacity and large serial-parallel numbers, which, coupled with such problems as safety, durability, uniformity and cost, imposes limitations on a wide application of lithium-ion batteries, especially in vehicles and cordless power tools. Lithium-ion batteries must operate within the safe and reliable operating area, which is restricted by temperature and voltage range. Exceeding the restrictions of these ranges will lead to rapid attenuation of battery performance and even result in safety problems (Lu et al. 2013). To solve these problems, people try to develop new battery systems that could work under very bad conditions. On the other hand, the current commercial lithium-ion batteries must be fitted with a management system, through which they can be controlled and managed effectively; thus every single cell would be working under proper conditions, which means that every cell should be operated within the lithium-ion battery safety operating range (between 1.5 and 4.2 volts, and in temperature range between –20 and 55 °C).

To manage a lot of cells, the battery management system (BMS) has a very important role. When batteries are charged and discharged over time, their discharge capacity fades. To provide continuous and reliable electric power sources for the aforementioned systems and devices, battery prognostics and health

management is required. The system could manage the battery by monitoring the battery, estimating the battery state, protecting the battery, reporting the data, balancing it, etc. The main tasks of the BMS in vehicles and cordless power tools are as follows (Xing et al. 2011, Vezzini 2014, Wang et al. 2019):

- data acquisition
- safety protection
- ability to determine and predict the state of the battery
- ability to control battery charging and discharging
- cell balancing
- thermal management
- delivery of battery status and authentication to a user interface
- communication with all battery components
- prolonged battery life.

The main function of the BMS is to ensure that the battery pack is operated within safe limits and achieves optimal performance over its use life and under a wide range of operating and environmental conditions (Xing et al. 2011).

All Li-ion batteries require a BMS. This is due to the fact that all Li-ion batteries will fail if overcharged, completely discharged or operated outside their safe temperature window. Each Li-ion cell type has its own safe operating area, which makes it necessary to program the BMS accordingly. In low-cost systems, there might be some differences in the requirements or functions for the BMS. Especially for a low number of cells in series (e.g. 12 V systems with four cells in series), some battery system manufacturers propose a simple external under voltage shutoff circuit and a charger with controlled end-of-charge voltage.

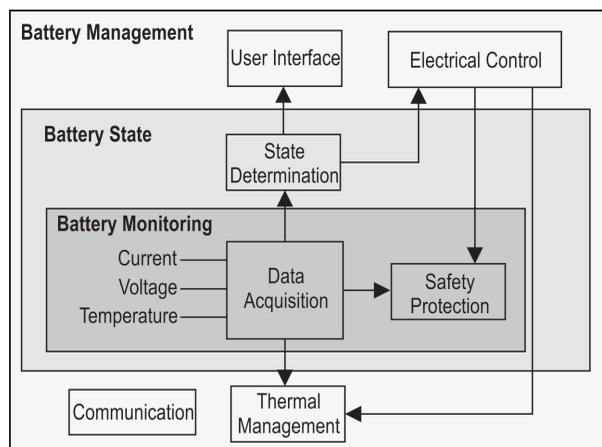


Fig. 4 Illustration of a battery management system – BMS

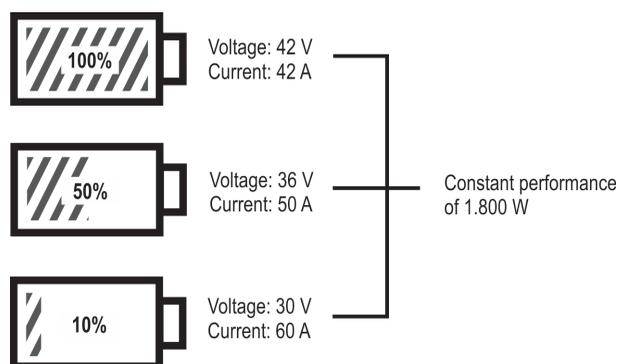


Fig. 5 Constant power supply of cordless power tool as a consequence of battery management system

It is important to determine the battery health status including the state of charge and state of health. State of charge is a short-term parameter to indicate the remaining energy at a given charge–discharge cycle. State of health is a long-term parameter to indicate the remaining charge–discharge cycles, namely remaining useful life (Zhang et al. 2018). As these two basic battery parameters cannot be directly measured, they are estimated and predicted by using other collected measurements, such as current, voltage, temperature, etc. (Wang et al. 2019).

The efficiency of the entire system is particularly important in cordless power tools, which only have a limited amount of energy per battery charge. To get the best possible results over a long period of time, the amount of power the battery actually delivers to the tool you are using is crucial. That is why reputable manufacturers like STIHL, Milwaukee, Bosch, Makita, etc. focus on intelligent engine control, which enables the battery and the cordless power tool to exchange data and actively supply power based on the real need (known as the load). To ensure that the cordless power tool always receives all the power the battery has to offer, the current is automatically increased while the voltage of the battery slowly decreases during use (Fig. 5). On the other hand, if a situation does not call for the battery full power, the current is automatically reduced. For example, battery-powered hedge trimmers work with a higher current when trimming a large hedge than when trimming a small box tree, making optimum use of the energy in the battery and extending the battery life of the charge.

Software is also needed to support Li-ion batteries. The battery in the tool and in the charging station is equipped with software. Different software packages communicate with each other. Each tool manufacturer develops its own software to manage safety issues and

the overall performance of a tool. When a tool requires power, the software manages how fast and how much power is taken from the battery. The software also protects the tool from receiving too much power and it shuts down a battery when there is little power left in a battery (Li-ion batteries may not recharge if they are completely drained). The software ensures that equal amounts of power are taken from each cell in the battery, it keeps batteries in safe condition, and it monitors battery temperature and shuts it down if it gets too hot, as heat degrades batteries over time and is the ultimate enemy. Communication between the software in the battery and the tool is all important too.

4. Battery Technology and (Cordless) Power Tools

More than 30 years ago, the first cordless tools coming on the market were light duty drills and screw drivers mainly driven by Ni-Cd batteries. For heavy duty applications or other uses, the power provided by this technology did not lead to satisfactory work results and machine runtime. In the meantime, Ni-Cd has been completely replaced by Li-ion, providing tools with a much better performance. Li-ion batteries have two to three times the energy density of other battery technologies. Higher energy density translates to smaller battery packs for lighter and more compact hand held tools. As a consequence, today most of the drilling and screw driving is done cordless and corded tools get more and more replaced. Furthermore, in other product groups, such as small angle grinders, jig – and circular saws or small hammer drills, the number of battery driven tools has constantly increased. Today, the development goes one step further. The new generation of battery cells allows enough power storage for tools in heavy duty applications as well. Therefore, all power tool manufacturers strongly extend their offer for cordless tools in all segments. The use of battery driven products becomes more and more common. Professional users prefer to have one battery system for all cordless tools they use. This is partly based on the confidence to a brand and its battery system they have built up over the years. They also want to avoid complexity for their work on jobsite. Battery technology, battery system and a wide range of products working with the same system have become new important elements of the purchase decision. This is a new dimension in the market and, economically and technically, a big challenge for all manufacturers. In 2016, for the first time in history, the market for cordless power tools reached a share of 51% of the total market. Due to further development in Li-ion technology and the extended possibili-

ties to use the progress in technology for power tools, a disproportionately high growth is expected for this segment in the years to come. This could change the power tool market and industry (Recharge 2018, Poje et al. 2018, Pistoia 2009).

Cordless power tools are quiet and are usually lighter than comparable models with a petrol engine. They have no cord and do not generate any exhaust, plus they are low-maintenance and easy to use. Today, most cordless power tools use lithium-ion batteries. That is because the Li-ion batteries offer a host of advantages over other battery types: they have a high energy and power density along with a low weight, no memory effect, a long service life and low self-discharge. As cordless power tools make it possible to work without a cord, they also provide maximum flexibility and freedom of movement.

Tool companies usually tell the manufacturers what qualities they are looking for in a battery – not all tool manufacturers want the same qualities. They want different balances between cell capacity or energy storage, size and weight, power available, run time, and safety. All tool companies maintain their own research labs to extensively test these cutting edge cells and their research helps them make final cell choices. The current state-of-the-art battery cell is rated at approximately 3.6 volts and 4 amp-hours yielding 14.4 watt-hours. When used together in a power tool battery configuration, these cells can provide up to 160 watts (Nasvik 2018).

All modern batteries are equipped with electronic monitoring to prevent deep discharge and overheating or overloading of cells. They have tough, compact housing for optimum protection against mechanical stress. The battery housing comes with a built-in electronic charge level indicator that can be activated simply by pressing a button and displays information such as charge level by using LED indicators.

The power tool and battery market has yet to establish a standard for determining the performance of a battery. Manufacturers are free to choose the metric they want. Many decide to list voltage as the measure of their batteries performance. However, the most meaningful metric is watt (W), which is calculated as voltage (V) multiplied by current in amperes (A): $W = V \times A$. As a result, the combination of voltage and current, rather than a single metric alone, plays a decisive role in the power of a cordless power tool. So, we can find power tools and their batteries with a rated voltage from 12 V (even less) to 80 V (or more).

Lithium-ion battery packs consist of individual cells arranged in rows. Each of these cells has a rated

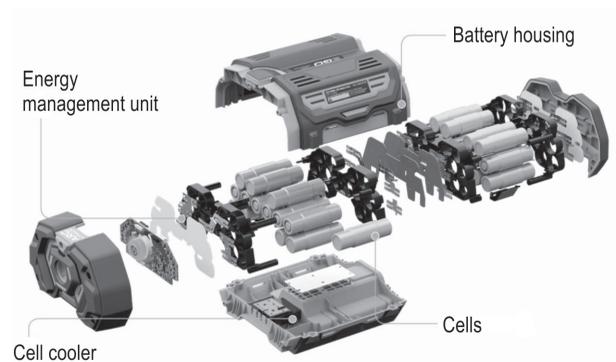


Fig. 6 Basic components of power tool battery pack

voltage of 3.6 V. For example, STIHL 36 V batteries always feature ten cells in a row ($10 \times 3.6 = 36$ V). Therefore, the voltage is the product of the number of round cells in a row.

Today, all remarkable power tool manufacturers are incorporating brushless direct current (BLDC) motors into their power tools due to their robustness, simplicity, large torque to volume ratio and high-efficiency. BLDC motors are also used as computer peripherals, servo control systems, and in hybrid and electrical vehicles (He and Wu 2018). There are several motivations for using BLDC motors. The maximum RPM of a BLDC motor is limited primarily by the construction of the rotor, whereas the RPM of a brushed DC motor is limited primarily by the brushes themselves. In most applications, a transmission with gear reduction is used to reduce the RPM of the motor down to the desired RPM of the application. Consequently, since the BLDC motor can rotate many times faster than a brushed motor, a physically smaller BLDC motor, with a corresponding adjustment to the transmission gear ratio, will produce the same RPM and torque applied to the output of the product. Another obvious advantage is the elimination of brushes that wear out and generate significant electromagnetic interference. For increased operating time, a significant advantage of a BLDC motor is the increase of efficiency, typically 150% or better, over a similar brushed DC motor (Huang et al. 2019, Renesas 2018, Luo et al. 2012).

5. Battery Technology in Forestry

5.1 Cable Yarders and Slack-pulling Carriages

At AustroFOMA 2015, Koller Forsttechnik displayed the first prototype hybrid tower yarder – Koller

K507H-e. A key difference from the classical model (Koller K507H) is electric winches power-driven by a diesel-electric configuration with the ability to capture and store energy in battery packs. The 3-cylinder diesel engine is only 36 kW with fuel consumption of 3–5 litres per hour. During normal operations, the engine runs only about 30% of the working day, and for most tasks it works directly from the battery. For example, during set-up and take-down, the engine does not need to run, and this makes communication among the crew much easier. In uphill yarding, the engine needs to run only when pulling the load, and the battery stores the braking energy from slowing the carriage when returning (Visser 2015).

A range of battery powered slack-pulling carriages is now available on the market in Europe, while battery powered carriages are not new (a battery powered grapple carriage was in operation in the USA in the 1970s!). The Franz Hochleitner Bergwald 5000 is a hybrid carriage, which has a small diesel engine with a 3-litre fuel capacity, and a 48 V Li-ion battery for energy storage that can be used continuously for 10–12 hours before recharging. Konrad Forsttechnik GmbH of Austria made three types of hybrid carriages (1.5, 2 and 4 t of lifting capacity). The battery is common for all hybrid carriages, and its energy is used to operate the skyline and mainline clamps and drive the slack-pulling drive system. While all three units are slightly different, an alternator (or similar) is driven by the carriage sheaves as it moves along the skyline to charge the battery.

Today, it is impossible to work with a cable yarder without radio controlled devices, such as winches, carriage movement, radio-controlled chokers and also communication devices. Radio controlled chokers can increase productivity but also may have come at the cost of a higher workload for the choker-setter. The yarder operator was particularly pleased with the radio controlled choker and noted not only the simplification of his routine but also the additional safety around the landing site (Stampfer et al. 2010). Using radio-controlled applications allow for automation of process and enables both the yarder operator and the choker-setter to control the yarder (Heinimann et al. 2006). All of these devices need a power for their work, and the power comes from batteries. Technical developments and new materials have allowed the operating mechanism to become more robust and the weight of a choker to be significantly reduced. The classic goal of modern ergonomics is to optimize both the system efficiency and working conditions. The heavier weight of portable devices could lead to an increase in physical strain of workers. It is important that the increase



Fig. 7 Radio-controlled choker (<http://ludwigssystem.com>)

in productivity and working safety does not come at the expense of an increase in physical strain of the choker-setter.

5.2 Navigation Devices

There are many papers in the forestry literature dealing with the research of portable GPS, RTK GPS, GLONASS, GNSS devices (Pirti et al. 2010, Hasegawa and Yoshimura 2003, Horcher and Visser 2011, Pandur 2013, Suvinen 2006, Ringdahl et al. 2012, Brach and Zasada 2014). The basis for all portable navigation devices is a rechargeable, high-capacity battery that does not lose energy at very low or high outside temperatures.

5.3 Power Tools

Borz et al. (2019) evaluated the productivity, physical strain, exposure to noise, and postural risk index of workers operating in motor-manual felling of willow short rotation coppice. Using the battery powered chainsaw, all of the above problems would be significantly less, especially the noise and workload of workers because of less weight of battery chainsaw, and absence of combustion engine that could increase the noise level (Poje et al. 2015, Potočnik and Poje 2017).

Tools equipped with two-stroke engines, such as those commonly used in motor-manual operations, expose the workers to other harmful factors such as noise (Taoda et al. 1987), which can result in hearing loss (Fonseca et al. 2015, Tunay and Melemez 2008). In terms of work efficiency, the use of battery chainsaws is comparable to petrol chainsaws and they provide a lower level of energy consumption, and lower exposure of fellers to noise and hand-arm vibrations (Poje

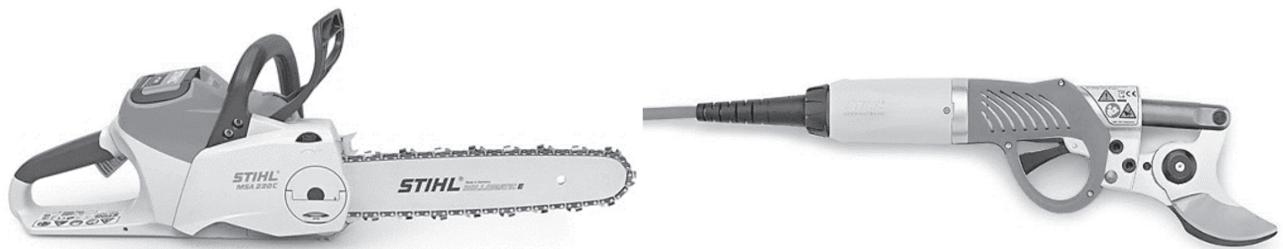


Fig. 8 Battery powered chainsaw and shears (<https://unikomerc-uvoz.hr>)

at al. 2018, Neri et al. 2018, Colantoni et al. 2016). The major problem of battery powered chainsaws is insufficient capacity of the battery and overheating of battery pack due to hard work, and consequently, lower productivity.

Motor-manual harvesting of willow short rotation coppice (WSRC) still represents an affordable option among small scale farmers (Talagai et al. 2017), who lack the ability to purchase expensive purpose-built equipment (Spinelli et al. 2012) and often decide to carry on their harvests manually (Schweier and Becker 2012). While it can return high delivery costs compared to the dedicated equipment (Vanbeveren et al. 2015), in many cases motor-manual harvesting of WSRC is the only available option, which is also sustained by lower labour costs in developing countries.

As an alternative to hand tools in forest cleaning activities, intensive research has been done in Croatian forestry on the application of battery shears (Bačić et al. 2019). It is assumed that substituting manual method with the motor-manual method can have a positive impact on workers' health. Nutto et al. (2013) researched the effect of different types of tools, including a hand saw, pruning shears and battery shears, in eucalyptus pruning on the physical workload of the worker, and concluded that working with battery shears results in the least physical workload. Bačić et al. (2018) also recorded lower average and maximum heart rates during forest cleaning with battery shears in comparison to manual method with a billhook.

5.4 Hybrid Electric Machines

Due to increasing regulatory pressures for lower emissions and a growing demand for machines that cost less to operate, manufacturers started to look for new harvesters with electric and hybrid drives to replace the traditional hydraulic and mechanical driving system (Shen et al. 2017, Silvaş et al. 2012.)

Ponsse and Elforest Technologies have jointly studied 6 and 4 hybrid technology tree harvesters, which are more economical and more efficient than traditional harvesting machines (Elforest 2017).

Machines with efficient (hybrid electric) power sources have been designed (Lindross et al. 2017). Hybrid hydraulic crane system, as a crane innovation, including forwarder cranes, should reduce the fuel consumption during loading and unloading processes by 30% over a conventional load-sensing system and increase the speed for loading and unloading, if the operator can control the higher speed. Especially the high number of movements in narrow thinning will show the biggest improvement. In this way, selective thinning can be more competitive than clear-cutting, supporting sustainable wood production from multi-functional forests, recreational and production forests. Of course, energy saving improves the process of loading and unloading and makes it more economical and more environmentally friendly (Forwarder 2020, 2019). Forwarder with an electric-hybrid transmission, compared to the standard hydrostatic-mechanical transmission, has a lower fuel consumption of 20% to 50% and a lower mass because of a simpler transmission system without a bogie axle. Its mass is 9500 kg, while its carrying capacity is 12,000 kg (Pandur et al. 2019, Löfroth et al. 2007).

The world first full hybrid wood chipper Kesla C 860 H was presented at the FinnMetko forest machinery exhibition on August 28–30th 2014 in Central Finland (INFRES 2015).

Prinz et al. (2017) concluded that fuel consumption as well as the productivity of Kesla C 860 H hybrid chipper was lower compared to conventional chippers – Kesla C 1060 A & Volvo FH 750 and Kesla C 1060 T & Valtra S 280.



Fig. 9 Hybrid wood chipper Kesla C 860 H (<https://www.kesla.fi>)

Construction machines, such as loaders and excavators, equipped with hybrid-electric powertrain with reduced mechanical complexity consume, on average, 25 to 33% less fuel (Shen et al. 2017, Lajunen et al. 2016, Ishida and Higurashi 2015, JohnDeere, 2019).

A Finnish forest machine manufacturer, Logset, produced Logset 12H GTE Hybrid harvester, which is



Fig. 10 Elforest – hybrid forwarder (<http://elforest.se>)



Fig. 11 Hybrid harvester Logset 12H GTE (<https://www.logset.com>)

the first of its kind in forest machinery. It is a significant improvement on the previous diesel engine thanks to the integration of EDITRON, the world's most sophisticated electric drivetrain system, which has been designed, manufactured and delivered by Danfoss Mobile Electrification. The software controls and optimizes each individual component of the hybrid drivetrain, making power distribution in the harvester far more intelligent. Within a microsecond, the hybrid system can deliver up to 510 hp (380 kW) and generate an enormous torque of 2000 Nm. In comparison with the previous diesel machine, the Logset 12H GTE Hybrid harvester is 72% more powerful, with a 54% increase in torque, 27% increase in hydraulic flow, 5% noise reduction and 20–30% lower fuel consumption (Logset 2019).

6. Conclusions

Advanced battery technology provides a combination of technical features progressively enabling new products. For example, the strong improvement of the life duration and the autonomy of the batteries, required by the electric-mobility, will probably allow for the new uses in the future. It can also be seen that the world of power tools and gardening tools is moving fast toward electrification. Forestry work requires a lot of energy where it is not easily accessible. Fossil fuels deliver on that task with great success, however with big drawbacks regarding ecology and energy utilization. Energy autonomy is a key question for implementing battery technology in forestry work. Some power tools and machines can already perform with great efficiency, others must wait for new battery technology to be developed.

There is constant research to find energy sources that perform better than lithium-ion batteries but there appears to be nothing in the immediate future. In the meantime, research is focused on developing Li-ion batteries that are smaller, lighter, and capable of storing more energy. In the long term, solid state technology is being considered.

The power tool industry is constantly introducing tools that require higher levels of power from a battery. In that regard, battery technology does not keep up with the energy requirements of power tools.

Manufacturers continuously develop tools more portable by eliminating power cords, gasoline engines, and compressed air for powering tools. There is a great benefit from these improvements both ecologically and ergonomically. Battery chainsaws are more favourable than gasoline chainsaws in terms of noise

Table 2 SWOT analysis of battery powered tools/devices and hybrid machines in forestry

| STRENGTHS | WEAKNESSES |
|--|--|
| Lower fuel consumption Better ergonomics (less noise, vibration and exhaust emission) Smooth variable continuous power to wheels, drums, hydraulic pump, etc. Environmentally friendly (less GHG and PM emission*) Easier operating (automated or remote operation control) Lower physical workload Less maintenance | Purchase price (30–50% higher than conventional) Battery life Battery price Low energy density of battery Overheating of batteries due to fast discharging (hard workload) Lower cutting speed of battery powered chainsaws |
| OPPORTUNITIES | THREATS |
| Improved battery technology (smaller, lighter batteries with higher energy density) Better efficiency of electric (brushless) motors Shortage of fossil fuels | Increase of battery price Shortage of raw materials for battery production |

* GHG – Greenhouse gas
 PM – particulate matter

emission and energy efficiency, but cannot keep up with professional gasoline chainsaws in terms of cutting speed.

Hybrid drives typically let machinery companies to use smaller diesel engines and operate them at speeds where they are most efficient and run cleaner (with less emission). The key advantage is lower fuel consumption over machines with more conventional powertrains (e.g. up to 25% in case of hybrid machine) – which saves money and lessens environmental impact. Hybrid machines can offer productivity gains and often require less maintenance.

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7. References

Avicenne, 2016: The Rechargeable Battery Market and Main Trends 2015–2025. Presentation by Christophe Pillot at the Batteries congress, September 28th, Nice, France.

Bačić, M., Šušnjar, M., Pandur, Z., Šporčić, M., Landekić, M., 2018: Physical workload while working with hedging bill and battery cutter in tending of pedunculate oak. *Proceedings of the International Symposium Ergonomics – Emphasis on Wellbeing*, Zadar, 59–64.

Bačić, M., Landekić, M., Šušnjar, M., Šporčić, M., Pandur, Z., 2019: Movement analysis of a worker in the forest cleaning activities. *FORMEC 2019 – Exceeding the Vision: Forest Mechanisation of the Future 6–9 October*, Sopron, Hungary, 1–7.

Barsukov, Y., Qian, J., 2013: *Battery Power Management for Portable Devices*. Norwood, MA: Artech House, 259 p.

Blagoeva, D.T., Alves Dias, P., Marmier, A., Pavel, C.C., 2016: Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU. *Wind power, photovoltaic and electric vehicles technologies, time frame: 2015–2030*; EUR 28192 EN. <http://dx.doi.org/10.2790/08169>

Blomgren, G.E., 2017: The development and future of lithium ion batteries. *Journal of The Electrochemical Society* 164(1): A5019-A5025. <https://doi.org/10.1149/2.0251701jes>

Borz, S.A., Talagai, N., Cheța, M., Chiriloiu, D., Gavilanes Montoya, A.V., Castillo Vizuete, D.D., Marcu, M.V., 2019: Physical Strain, Exposure to Noise and Postural Assessment in Motor-Manual Felling of Willow Short Rotation Coppice: Results of a Preliminary Study. *Croatian Journal of Forest Engineering* 40(2): 377–388. <https://doi.org/10.5552/crojfe.2019.550>

Brach, M., Zasada, M., 2014: The Effect of Mounting Height on GNSS Receiver Positioning Accuracy in Forest Conditions. *Croatian Journal of Forest Engineering* 35(2): 245–253.

Bruce Dunn, B., Kamath, H., Tarascon, J.M., 2011: Electrical Energy Storage for the Grid: A Battery of Choices. *Science* 334(6058): 928–935. <https://doi.org/10.1126/science.1212741>

Chen, L., Fan, L.Z., 2018: Dendrite-free Li metal deposition in all-solid state lithium sulphur batteries with polymer-insalt polysiloxane electrolyte. *Energy Storage Materials* 15: 37–45. <https://doi.org/10.1016/j.ensm.2018.03.015>

- Colantoni, A., Mazzocchi, F., Cossio, F., Cecchini, M., Bedini, R., Monarca, D., 2016: Comparisons between battery chainsaws and internal combustion engine chainsaws: performance and safety. *Contemporary Engineering Sciences* 9(27): 1315–1337. <http://dx.doi.org/10.12988/ces.2016.68133>
- Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. <http://data.europa.eu/eli/dir/2006/66/oj>
- Dunn, B., Kamath, H., Tarascon, J.M., 2011: Electrical Energy Storage for the Grid: A Battery of Choices. *Science* 334(6058): 928–935. <https://doi.org/10.1126/science.1212741>
- Elforest, »Ponsse Ergo with Elturbo« 2017: <http://elforest.se/eng/references.html>
- Fonseca, A., Aghazadeh, F., de Hoop, C., Ikuma, L., Al-Qaisi, A., 2015: Effect of noise emitted by forestry equipment on workers' hearing capacity. *International Journal of Industrial Ergonomics* 46: 105–112. <https://doi.org/10.1016/j.ergon.2014.05.001>
- Forwarder 2020, 2019: Sustainable and smart logging. Project funded from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727883. <https://www.forwarder2020-project.eu/innovations/>
- Goodenough, J.B., Kim, Y., 2010: Challenges for rechargeable Li batteries. *Chem. Mater.* 22(3): 587–603. <https://doi.org/10.1021/cm901452z>
- Goodenough J.B., 2018: How we made the Li-ion rechargeable battery. *Nature Electronics* 1(3): 204. <https://doi.org/10.1038/s41928-018-0048-6>
- Hanisch, C., Loellhoeffel, T., Diekmann, J., Markley, K.J., Haselrieder, W., Kwade, A., 2015: Recycling of lithium-ion batteries: a novel method to separate coating and foil of electrodes. *Journal of Cleaner Production* 108(Part A): 301–311. <http://dx.doi.org/10.1016/j.jclepro.2015.08.026>
- Hasegawa, H., Yoshimura, T., 2003: Application of dual frequency GPS receivers for static surveying under tree canopies. *Journal of Forest Research* 8(2): 103–110.
- He, C., Wu, T., 2018: Permanent Magnet Brushless DC Motor and Mechanical Structure Design for the Electric Impact Wrench System. *Energies* 11(6): 1360–1384. <https://doi.org/10.3390/en11061360>
- Horcher, A., Visser, R., 2011: Using On-Board GPS to Identify Training Needs of Helicopter Pilots. *Croatian Journal of Forest Engineering* 32(2): 481–488.
- Huang, C., Lei, F., Han, X., Zhang, Z., 2019: Determination of modelling parameters for a brushless DC motor that satisfies the power performance of an electric vehicle. *Measurement and Control* 52(7–8): 765–774. <https://doi.org/10.1177/0020294019842607>
- INFRES 2015: Prototype of hybrid technology chipper – D 4.6. <https://www.luke.fi/wp-content/uploads/2016/03/D-4.6-Demoreport-hybrid-chipper.pdf>
- Ishida, K., Higurashi, M., 2015: Hybrid wheel loaders incorporating power electronics. *Hitachi Review* 64(7): 398–402.
- John Deere, 2019: 644K Hybrid Wheel Loader. <https://www.deere.ca/en/loaders/wheel-loaders/mid-size-wheel-loaders/644k-hybrid-wheel-loader/>
- Lajunen, A., Suomela, J., Pippuri, J., Tammi, K., Lehmuspelto, T., Sainio, P., 2016: Electric and hybrid electric non-road mobile machinery – present situation and future trends. EVS29 Symposium Montréal, Québec, Canada, June 19–22, 1–12.
- Liang, Y., Zhao, C.Z., Yuan, H., Chen, Y., Zhang, W., Huang, J.Q., Yu, D., Liu, Y., Titirici, M.M., Chueh, Y.L., Yu, H., Zhang, Q., 2019: A review of rechargeable batteries for portable electronic devices. *InfoMat.* 1(1): 6–32. <https://doi.org/10.1002/inf2.12000>
- Lindroos, O., La Hera, P., Häggström, C., 2017: Drivers of Advances in Mechanized Timber Harvesting – a Selective Review of Technological Innovation. *Croatian Journal of Forest Engineering* 38(2): 243–258.
- Löfroth, C., Jönsson, P., Nordén, B., Hofsten, H., 2007: Hybrid forwarder achieves considerable reduction in fuel consumption. *Jan Fryk, Uppsala, Sweden*, 4 p.
- Logset, 2019: The most productive hybrid forest harvester in the world. Electrifying the diesel engine to boost power. <https://www.electrificationstory.com/logset-hybrid-forest-harvester/>
- Lu, L., Han, X., Li, J., Hua, J., Ouyang, M., 2013: A review on the key issues for lithium-ion battery management in electric vehicles. *Journal of Power Sources* 226: 272–288. <https://doi.org/10.1016/j.jpowsour.2012.10.060>
- Luo, H., Cao, J., Wu, Z., Yang, C., Zheng, Y., Zhao, T., 2012: Simulation Research on Brushless DC Motor of Electric Car. 2nd International Conference on Electronic & Mechanical Engineering and Information Technology (EMEIT-2012), Paris, France: 1–4.
- May, G.J., Davidson, A., Monahov, B., 2018: Lead batteries for utility energy storage: A review. *Journal of Energy Storage* 15: 145–157. <https://doi.org/10.1016/j.est.2017.11.008>
- Miranda, D., Costa, C.M., Lanceros-Mendez, S., 2015: Lithium ion rechargeable batteries: State of the art and future needs of microscopic theoretical models and simulations. *Journal of Electroanalytical Chemistry* 739: 97–110. <https://doi.org/10.1016/j.jelechem.2014.12.010>
- Nasvik, J., 2018: Revisiting Power Tool Batteries. <https://www.forconstructionpros.com/concrete/article/21033142/revisiting-power-tool-batteries>
- Neri, F., Laschi, A., Foderi, C., Fabiano, F., Bertuzzi, L., Marchi, E., 2018: Determining Noise and Vibration Exposure in Conifer Cross-Cutting Operations by Using Li-Ion Batteries and Electric Chainsaws. *Forests* 9(8): 501–514. <https://doi.org/10.3390/f9080501>
- Nutto, L., Malinovski, R.A., Brunsmeier, M., Schumacher Sant'Anna, F., 2013: Ergonomic aspects and productivity of different pruning tools for a first pruning lift of *Eucalyptus grandis* Hill ex Maiden. *Silva Fennica* 47(4): 1–14. <https://doi.org/10.14214/sf.1026>

- Omar, N., Firouz, Y., Monem, M.A., Samba, A., Gualous, H., Coosemans, T., Van den Bossche, P., Van Mierlo, J., 2014: Analysis of Nickel-Based Battery Technologies for Hybrid and Electric Vehicles. Reference Module in Chemistry, Molecular Sciences and Chemical Engineering. <https://doi.org/10.1016/B978-0-12-409547-2.10740-1>
- Pandur, Z., 2013: Primjena komercijalnog sustava za praćenje rada strojeva u istraživanju izvoženja drva forvarderom. Disertacija, Šumarski fakultet sveučilišta u Zagrebu, 1–312.
- Pandur, Z., Šušnjar, M., Bačić, M., Đuka, A., Lepoglavec, K., Nevečerel, H., 2019: Fuel consumption comparison of two forwarders in lowland forests of pedunculate oak. *iForest – Biogeosciences and Forestry* 12(1): 125–131. <https://doi.org/10.3832/ifer2872-011>
- Pirti, A., Gümüş, K., Erkaya, H., Hoşbaş, R.G., 2010: Evaluating Repeatability of RTK GPS/GLONASS Near/Under Forest Environment. *Croatian Journal of Forest Engineering* 31(1): 23–33.
- Pistoia, G., 2009: Chapter 3 – portable applications. In: *Battery operated devices and systems*. Elsevier, Amsterdam, 75–161. <https://doi.org/10.1016/b978-0-444-53214-5.00003-0>
- Poje, A., Spinelli, R., Magagnotti, N., Mihelič, M., 2015: Exposure to noise in wood chipping operations under conditions of agro-forestry. *International Journal of Industrial Ergonomics* 50: 151–157. <https://doi.org/10.1016/j.ergon.2015.08.006>
- Potočnik, I., Poje, A., 2017: Forestry ergonomics and occupational safety in high ranking scientific journals from 2005–2016. *Croatian Journal of Forest Engineering* 38(2): 291–310.
- Poje, A., Potočnik, I., Mihelič, M., 2018: Comparison of Electric and Petrol Chainsaws in Terms of Efficiency and Safety When Used in Young Spruce Stands in Small-Scale Private Forests. *Small-scale Forestry* 17: 411–422. <https://doi.org/10.1007/s11842-018-9395-4>
- Prinz, R., Laitila, J., Eliasson, L., Routa, J., Järviö, N., Asikainen, A., 2017: Hybrid Solutions as Measure to Increase Energy Efficiency – A Prototype of Hybrid Technology Chipper. FORMEC 2017 – Innovating the Competitive Edge: From Research to Impact in the Forest Value Chain September 25th – 29th, Braşov, Romania. https://www.formec.org/images/proceedings/2017/B1/B13_Prinz_et_al.pdf
- Recharge, 2018: The Batteries Report 2018. The European Association for Advanced Rechargeable Batteries. <https://www.rechargebatteries.org/wp-content/uploads/2018/05/RECHARGE-The-Batteries-Report-2018-April-18.pdf>
- Renasas, 2018: White Paper – Bridge Drivers for BLDC Motor Applications. Renesas Electronics America Inc. (REA): 1–5. <https://www.renatas.com/eu/en/doc/whitepapers/mosfet-driver/bridge-drivers-for-bldc-motor-applications.pdf>
- Revankar, S.T., 2019: Chemical Energy Storage. Storage and Hybridization of Nuclear Energy. Techno-economic Integration of Renewable and Nuclear Energy: 177–227. <https://doi.org/10.1016/B978-0-12-813975-2.00006-5>
- Ringdhal, O., Hellstrom, T., Wasterlund, I., Lindross, O., 2012: Estimating wheel slip for a forest machine using RTK – DGPS. *Journal of Terramechanics* 49(5): 271–279. <https://doi.org/10.1016/j.jterra.2012.08.003>
- Taoda, K., Watanabe, S., Nishiyama, K., Fukuchi, Y., Miyakita, T., 1987: Survey of noise exposure level on national forestry workers. Department of Preventive Medicine, Shiga University of Medical Science, Otsu, Japan.
- Tarascon, J., Armand, M., 2001: Issues and challenges facing rechargeable lithium batteries. *Nature* 414: 359–367. <https://doi.org/10.1038/35104644>
- Thielmann, A., Sauer, A., Isenmann, R., Wietschel, M., Plötz, P., 2015: Fraunhofer Institute for Systems and Innovation Research ISI (Karlsruhe) (Hrsg.): Product roadmap lithium-ion batteries 2030; Karlsruhe: Fraunhofer ISI, 2012.
- Schmidt-Rohr, K., 2018: How Batteries Store and Release Energy: Explaining Basic Electrochemistry. *Journal of Chemical Education* 95(10): 1801–1810. <https://doi.org/10.1021/acs.jchemed.8b00479>
- Schweier, J., Becker, G., 2012: Motor manual harvest of short rotation coppice in South-West Germany. *Allgemeine Forst und Jagdzeitung* 183(7–8): 159–167.
- Shen R-F., Zhang, X., Zhou, C., 2017: Study on Drive System of Hybrid Tree Harvester. *The Scientific World Journal* 2017: Article ID 8636204. <https://doi.org/10.1155/2017/8636204>
- Silvaş, E., Hofman, T., Steinbuch, M., 2012: Review of optimal design strategies for hybrid electric vehicles. *IFAC Proceedings Volumes* 45(30): 57–64. <https://doi.org/10.3182/20121023-3-FR-4025.00054>
- Spinelli, R., Schweier, J., de Francesco, F., 2012: Harvesting techniques for non-industrial biomass plantations. *Biosystems Engineering* 113(4): 319–324. <https://doi.org/10.1016/j.biosystemseng.2012.09.008>
- Stampfer, K., Leitner, T., Visser, R., 2010: Efficiency and ergonomic benefits of using radio controlled chokers in cable yarding. *Croatian Journal of Forest Engineering* 31(1): 1–9.
- Suvinen, A., 2006: Economic Comparison of the Use of Tyres, Wheel Chains and Bogie Tracks for Timber Extraction. *Croatian Journal of Forest Engineering* 27(2): 81–102.
- Talagai, N., Borz, S.A., Ignea, G., 2017: Performance of brush cutters in felling operations of willow short rotation coppice. *Bioresources* 12(2): 3560–3569.
- Tunay, M., Melemez, K., 2008: Noise induced hearing loss of forest workers in Turkey. *Pakistan Journal of Biology Science* 11(17): 2144–2148. <https://doi.org/10.3923/pjbs.2008.2144.2148>
- Vanbeveren, S.P.P., Schweier, J., Berhongaray, G., Ceulemans, R., 2015: Operational short rotation woody crop plantations: manual or mechanized harvesting? *Biomass and Bioenergy* 72: 8–18. <https://doi.org/10.1016/j.biombioe.2014.11.019>
- Visser, R., 2015: Harvesting technology watch – HTW-016. *Future Forest Research*, November, 1–5. <https://fgr.nz/documents/download/3763>
- Vezzini, A., 2014: Lithium-Ion Battery Management. *Lithium-Ion Batteries – Advances and Applications*: 345–360. <https://doi.org/10.1016/B978-0-444-59513-3.00015-7>

Wang, D., Kong, J.Z., Yang, F., Zhao, Y., Tsui, K.L., 2020: Battery prognostics at different operating conditions. *Measurement* 151: 107182. <https://doi.org/10.1016/j.measurement.2019.107182>

Xing, Y., Ma, E., Tsui, K., Pecht, M., 2011: Battery management systems in electric and hybrid vehicle. *Energies* 4(11): 1840–1857. <https://doi.org/10.3390/en4111840>

Yoshino, A., 2012: The birth of the lithium-ion battery. *Angew. Chem. Int. Ed.* 51(24): 5798–5800. <https://doi.org/10.1002/anie.201105006>

Zhang, Z., Si, X., Hua, C., Lei, Y., 2018: Degradation data analysis and remaining useful life estimation: A review on Wiener-process-based methods. *European Journal of Operational Research* 271(3): 775–796. <https://doi.org/10.1016/j.ejor.2018.02.033>



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