ELECTRICAL VEHICLE STUDY PLATFORM FOR VOCATIONAL EDUCATION

OVERVIEW

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1. INTRODUCTION

1.1. Abbreviations

EV - electric vehicle.
BEV - battery electric vehicle.
HEV - hybrid electric vehicle.
PHEV - plug in hybrid electric vehicle.
E-REX - extended range electric vehicle.
ICE - Internal Combustion Engine.
BMS - battery monitoring system
CAN - Controller Area Network
ECU - electronic control unit
OBD - On-board diagnostics
LBC - lithium battery controller
AC - alternating current
DC - direct current

1.2. Most important units in EV-s

AC - alternating current. Type of electrical current in which the current repeatedly changes direction. AC sources are generators and inverters. Since the mains network is powered by very huge generators locally we can say that the mains network is also an AC power source.

DC - direct current. One-directional flow of electric charge. DC current sources are batteries and solar panels.

Ohm's Law:
U - voltage [V]
I - current [A]
R - resistance [Ω]
P - power [W]

$$I = \frac{U}{R}$$

Power formula

$$P = I * U$$

Losses (copper loss)

$$P = I^2 * R$$

kWh - kilowatt-hour, used as a measurement of electric energy. Capacity of the battery usually falls between 15kWh - 120kWh.

Wire gauge dimensions table

permissible current [A]	5	13	17	22	30	40	54	43	60	101	126	152	195	236
wire size [mm2]	0,3	0,5	0,85	1,25	2	3	5	6	10	25	35	50	70	95

Selection of high current standard electrical cable dimensions [mm^2]:
35, 50, 70, 95, 120, 150

The rule of thumb for selecting cables depending of the current:

Copper wire current < 5A/mm^2

2. HISTORY AND USE CASES

EV-s were quite popular in the 19-th century. But fossil powered vehicles took over in the beginning of 20-th century.

Beginning 1801-1850	First Age 1851-1900	Boom and Bust 1901-1950	Second Age 1951-2000	Third Age 2001-2020
The earliest electric vehicles were invented in Scotland an the USA	Electric vehicles enter the market and start to find broad appeal.	EVs reach historical peaks of production but are then displaced by petrol-engine cars	High oil prices and pollution created a new interest in electric vehicles	Public and private sectors now commit to vehicle electrification
1832-39 Robert Anderson of Scotland built the first prototype electric carriage	1888 GER 1.-st Four wheel EV car	1908 Petrol Ford Model-T comes to mass production	1973 OPEC oil embargo high oil prices interest in EVs	Oil prices reached record high
1834 Thomas Davenport of the USA invented the first DC electric motor in a car that operates on a circular electrified track	1899 FRA 1.-st EV over 100km/h	1912 Kettering invented electric starter motor for petrol cars	1996 California ZEV requirement, GM produced EV1 electric car	2011 Nissan Leaf was launched and it got European car of the year award
	1900 EV-s were best selling road vehicles in USA 28% of the market	By 1935, the number of EVs dropped almost to Zero and ICE vehicles dominated because of cheap petrol	1997 JAP Toyota starts selling Prius world's first commercial hybrid. 18000 were sold that year	2012 Tesla Model S 0-100km/h 2.8sec 500km range starts new EV boom in 21 century March 2020 Tesla has produced 1 000 000 EV-s

The table shows that the private car manufacturing started in the 1830-s with EV-s. By 2020 the history of the car seems to be repeating itself, VW and other big car companies have promised to produce millions of new EV-s. But is it a solution to the personal transport problem? By achieving the goal of self-driving vehicles there will be no need to own personal car because self-driving car can take you to work and then instead of standing the whole day at the parking lot and waste city space for nothing, it can serve other people who need a ride, like a taxi, but fully automated and of course fully electric drive.

2.1. BMW, VW and Daimler-Benz 90's.

VW full EV history can be read from their media site: Charged up for more than 40 years
BMW EV history also: 40 years of electric mobility at the BMW Group. From the BMW 1602 to the BMW i3.

Picture of BMW EV prototypes 1972 - 2013. Source: www.press.bmwgroup.com

3. ELECTRIC BUGGY FOR EDUCATIONAL PURPOSE

The electric buggy is used in vocational schools to teach automotive and electrician students. The purpose of the main design is to create a platform for studying electric vehicle technology. A buggy type of vehicle is fit for this objective because all the parts and systems are visible through the frame construction.

It is designed that there would be minimal risks of electric shock. Low voltage design with 60V. To get reasonable power, a very high current controller is used. Battery is mounted similarly as usual road EV-s and therefore it is possible to practice EV service with a smaller and lighter battery pack then on real electric cars. Battery weight is about 80 kg. Nowadays some cars already have 500 kg battery packs that can be dangerous when handled by students. In addition it is important to take into account the price of a real battery if something goes wrong. Besides, it is not very easy to guarantee the safety of the students with a 400V battery pack. Workshop regulations do not allow unqualified people near real EV when high voltage systems are opened.

When studying is done, it is possible to use a baggy to drive for fun, because it is fully functional.

3.1. Safety

There's electrical safety and physical safety. Physical safety means keeping the battery in a suitable temperature range. Lithium batteries perform best at 20C but some cars heat them up to 50C to get better fast charging speed. Theoretically they say that lithium batteries do not like charging in cold under 0C. But older EV-s had these situations in winter and these worked fine. Nowadays (2020) batteries have liquid heating and cooling systems to keep them in the best temperature region.

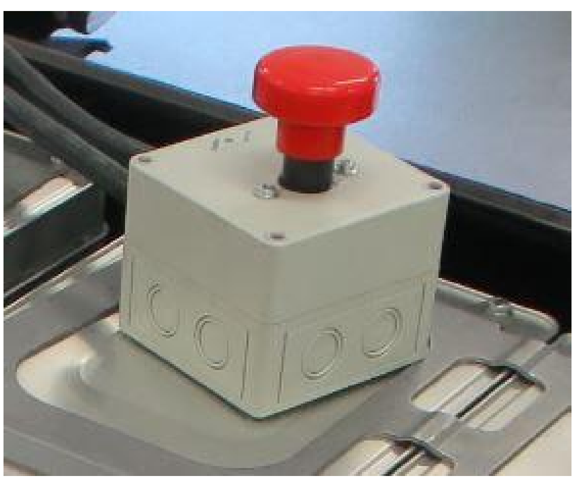
There’s also high voltage risks. For example with big crashes the high voltage orange wires will be revealed. In that case EV control systems will switch high voltage systems off. Further there is a new danger in the car workshop where technicians need to be trained to service and fix these cars. Crash tests are performed to design and create safe cases for the batteries. Same as with petrol cars where there is flammable liquid in the petrol tank. Main problem with battery safety is that a person cannot momentarily switch off the battery cell. In case of situation that there is a problem outside of the battery box then there is no problem.

But when it comes to opening the battery box then there is quite a big danger. Untrained persons are not allowed to make any repairs on EV-s but it will happen sooner or later. Main problem is that batteries will always have their charge. Even when they are discharged they have minimum of 3V per cell this makes 96*3V=288V of DC! It is important not to overcharge or over-discharge batteries. Nowadays 400V EV batteries consist of 96 cells connected serially. Each serial cell voltages are monitored that is the job of BMS

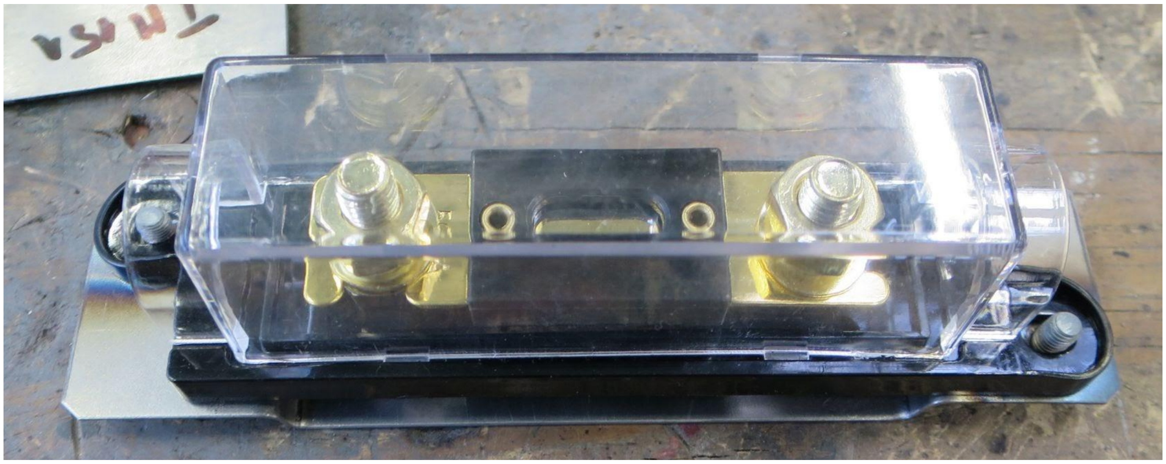
EV battery has 3 means of switching off possibilities:

1. + contactor,
2. - contactor,
3. safety switch,
4. fuse.

Plus contactor and minus contactor capable of switching upto 600A.



Safety switch.



Fuse in fuse holder.

3.2. Motors and Drives

In an ICE vehicle there is not much freedom in designing a place for the engine. In most cars the motor is in the front, nowadays the front wheels are often also the drive wheels. This is not an ideal solution but it's cheaper to manufacture. Some ICE vehicles have a front motor and a rear wheel drive (for example many BMW-s, so they have to transmit the power from the motor to the gearbox and then with a long shaft to the rear axle. It can be even more complex, in the case of four-wheel drive vehicles. One problem with ICE is that it cannot produce any power from standstill. That means that it has to start to rotate in order to get the car moving from standstill, this requires a clutch. Another problem with ICE engines is that they make usable power and torque only in a small band of revolutions, usually 1000 - 6000rpm. Therefore the car requires a gearbox, nowadays even 8 or 9 gears!

The electric motor is free of these problems; it can put out maximum torque from standstill, so no clutch needed. Electric motors for EV-s usually rotate between 0 - 13000rpm, so no need for a gearbox either, this makes the electric cars driveline cheaper to produce, shorter, lighter and four times more efficient (20% vs. 90%). The electric cars use electric motors not engines; the electric motors are much smaller and there is no problem in installing two of them- one on the front axle and other on the rear axle. Then the car is capable of four-wheel drive and the software can decide when it is better or more economical to use front or rear or both motors. Nowadays EV electric motors are one package including the reducer and differential; some even have the power electronics inverter integrated. There have been prototype or hyper cars with one motor for each wheel; this allows to achieve even better control over the car on the road or the racetrack. While cornering, this system can decelerate corner side wheels and accelerate the wheels on the other side to make the vehicle turn better.

3.2.1. Asynchronous and synchronous motors, IGBT-s inverters or controllers.

Electric cars have used brushed DC motors for over a hundred years. 21 century electric cars are all equipped with motors without brushes because the brushes can wear out in about 20 000km. In 2010 Japanese manufacturers Nissan and Mitsubishi started manufacturing or founded a manufacturer of brushless direct current motors (BLDC). American companies have used AC induction motors starting from 1996. GM EV1 and later Tesla Model S. Audi E-tron also uses an AC induction motor. Those two main types of motors both are very reliable. AC induction motors are known for reasonable pricing and outstanding reliability from manufacturing and workshops.

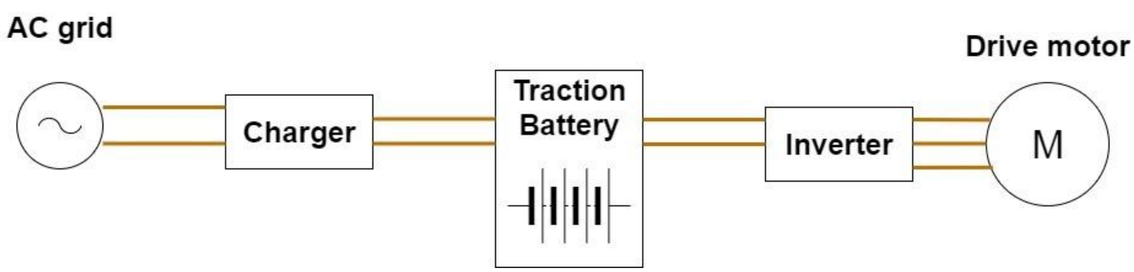
It is the main motor type which allowed for the industrial revolution which got rid of steam machines and led to more efficient and energy saving factories. Some have tried to use bigger AC induction motors from the lathe or drill press on a converted car. But it's not that easy. The author has driven one in Räpina, Dacia Sandero, which on some rpm's made the same noise as the lathe but it drove for more than 100 km on one charge. Unfortunately the car was not as fast as it used to be with a petrol ICE. GM, Tesla and others have designed special AC induction motors for their cars. Those motors are liquid cooled and some have controllers integrated. All of them are attached to a special reducer and differential. Also there are many modifications compared to industrial motors which make them better suited for traction application. Tesla used this type of motor mainly to get 416 hp (310 kW) and 600 Nm of torque. It was needed to outperform most ICE cars in 2012. They did quite well, it was a five door luxury electric car with 5 seats and was faster at 0-100km/h than most supercars. Tesla Model S, with only a rear drive AC motor, did it in 3,2 seconds.

Tesla Model S rear motor.

An AC induction motor is best used for big power and torque but somewhat lacking in efficiency. Brushless Synchronous motors (BLDC) are a bit better at that but are more expensive to manufacture because they need neodymium magnets. As we know, automotive engineers have two choices about drive motors; BMW, Koreans, Japanese manufacturers have chosen brushless synchronous motors, Audi has AC induction motors. Cars with synchronous motors drive further on one charge because of better efficiency. In the year 2020 electrical systems on most electric cars work at 400V. Only one manufacturer, Porsche, uses an 800V electrical system.

Mitsubishi i-MiEV motor Y41 with reducer and differential. 49kW 170 Nm.

Electric motors are very powerful and can achieve high torque, they require three phase AC (Alternating current).
EV-s have batteries as the energy source, but batteries as chemical energy storage devices output only DC direct current. Therefore a device that can convert and invert DC into
3 phase AC is needed. Those devices are called inverters in the car industry, because of their ability to convert AC from DC and at the same time make three phase sine wave current with variable frequency for the motor.



Buggy electric system block diagram.

3.3. Battery

As we all already know the batteries main problem is that they tend to discharge too fast. There's never enough energy. But technology, electronics and machines evolve and use more and more power. Seems like batteries are just a little bit behind in development, but it makes all the difference. Battery converts electrical energy into chemical energy and stores it until a load is connected and it starts to convert stored chemical energy into electricity on its plus and minus terminals.

Batteries used to be measured in amp hours (Ah), it meant how many amperes in one hour you could get from the battery. It's ok to use it on a usual ICE car starter battery because they mainly are 12 Volt batteries.

On electric cars it's always not the case, only BMW is using this unit at the moment (2020) on their EV, BMW i3. Now they offer a 120Ah battery for the car but when they started to sell this model (in 2013) it had half the capacity (60Ah) in the same space! In a few years batteries have become twice as efficient! i3-s 60Ah is 22kWh and 120Ah battery is 42kWh.

To describe batteries on EV-s the unit kWh (kiloWatt per hour) is used. This is a unit for measuring electric energy and it fits much better with cars since they use a lot of energy. Kilowatt hours(1000W = 1kW) are also used to measure home energy consumption. The only difference is that Volts are multiplied with Ah and you get Watt hours.

For example the New 2020 Nissan Leaf is available with a 40kWh or 62kWh battery. The biggest batteries on road cars at the moment of writing are 100kWh (Tesla Model X). But already manufacturers claim that there will be EV pickup trucks with 200kWh batteries and so on.

Nissan Leaf battery without box.

3.4. Battery management

The battery monitoring system (BMS), which Nissan calls LBC (lithium battery controller), takes care of battery “health”. The EV battery has to last for 10 years and to fulfill this expectation there are lots of electronics and clever software. The main parameters are battery voltage and state of charge (SOC). Usually SOC is displayed in percentage %. BMS can be integrated to measure battery current and to control contactors and transmit information to cars ECU-s for displaying or other management. Also when diagnosing the cars battery the BMS has all the data about the battery’s state of health, internal resistances and even cars VIN code. BMS will take care of the battery; in case of discharging, it sends data to ECU-s about cell voltages and the battery’s current, then the computer calculates how many kilometres can be driven and lets the driver know if the driver could reach the desired destination or suggested a charging stop if needed. EV-s were already capable of this ten years ago.
The most dangerous thing for lithium batteries is discharging too deeply, here the BMS will monitor cell voltages and when the first cell hits 3 Volts then the battery is empty and the computer will not let the vehicle be driven further. Usually in EV-s there are one or two warnings before this happens but people sometimes do not take these messages seriously or just want to test the limits and then a flatbed tow truck is needed to get to the nearest charging station. Another dangerous situation for the battery is overcharging, which the BMS has to avoid. There is also a difference within the manufacturers, some cars charge every cell to 4.1 volts, some a little bit more, depending on the used battery chemistry. Some people have tested overcharging lithium batteries, have forgotten batteries charging without BMS and have caused serious battery fires.

The buggy needs a system where the driver would get the information about how far the vehicle can be driven or what is the state of charge. Like a fuel level gauge on a petrol car or a computer which shows how many km are left.

Some of the available affordable systems are:

- “Power watcher” energy meter with an android app (developed in Ukraine).
- “123BMS” Netherlands BMS Windows software.
- “Cycle analyst” electric bike computer.

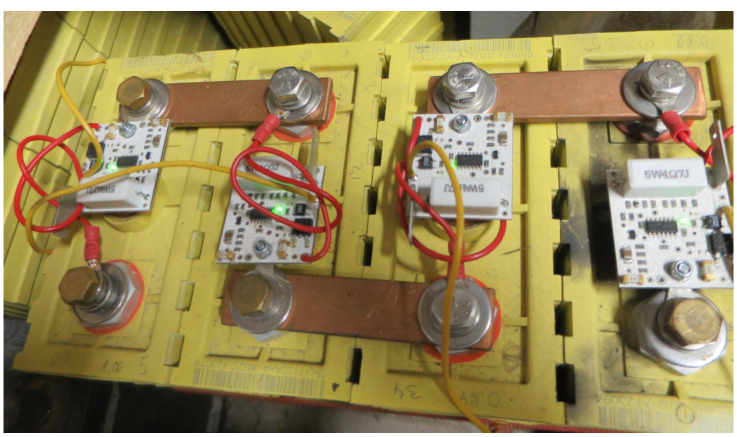
Li-ion batteries need a management and monitoring system. These systems are quite expensive because of the high voltages involved and the complexity needed to ensure reliability. They consist of high quality electronics, very high currents, an automotive environment and special software. The system has to be very reliable otherwise the lithium batteries might catch fire at the end of charging. There have been several DIY battery projects that have had accidents and also some production EV-s have caught fire. When the EV battery is burning it would be extremely difficult to put the fire out, because of the intense heat and anything nearby is in danger too. Emergency services must be called immediately!

Usually Lithium batteries do not start burning when discharging, but more often when overcharging because of a failed BMS or there is a faulty lithium cell. A fire may also start if the electrical system is short circuited or there is mechanical damage to a battery cell; for example something sharp pierces the battery cell and causes the cell layers to short circuit.

For this work the following BMS's were studied:
- BMS123,
- Minibms,
- Nissan Leaf original LBC.

3.4.1. Minibms

This system was made in the USA in the early days of DIY electric cars when big LiFePo4 batteries went into production in China. There were not many systems available that could protect and monitor every cell which were also very expensive at the time. This is the simplest system. The author has used it for over five years on his first small van electric vehicle and his home battery also uses the same system. Although it is robust, reliable and still not very cheap but meant for automotive use and is fully hardware only electronics, no software needed. Therefore you cannot measure battery cell temperatures, separate cell voltages and do diagnostics. But it works and doesn't allow overcharging and it can be set up so that it wouldn't allow deep discharging, which could also cause death to lithium batteries.
If simpler diagnostics are required, without removing the battery from the car, miniBMS would suffice. If the battery is repeatedly fast charged, it could cause overheating problems.
It's a simple system that is not used in production Electric vehicles.



Here are the cell monitoring units on 100Ah Lifepo4 cells. A green LED light means that the cell voltage is normal. When one cell is overcharged, there will be a red LED light and a signal will be sent through yellow wires to the central unit which stops charging. It's a robust, hardware based analog system that the author has used on converted EV's and it has proven itself reliable.

MiniBMS may be used with Yuriy Logvins product "Power Watcher 3" which has app support and provides a nice display for the EV. https://powerwatcher.net/

Power Watcher 3.

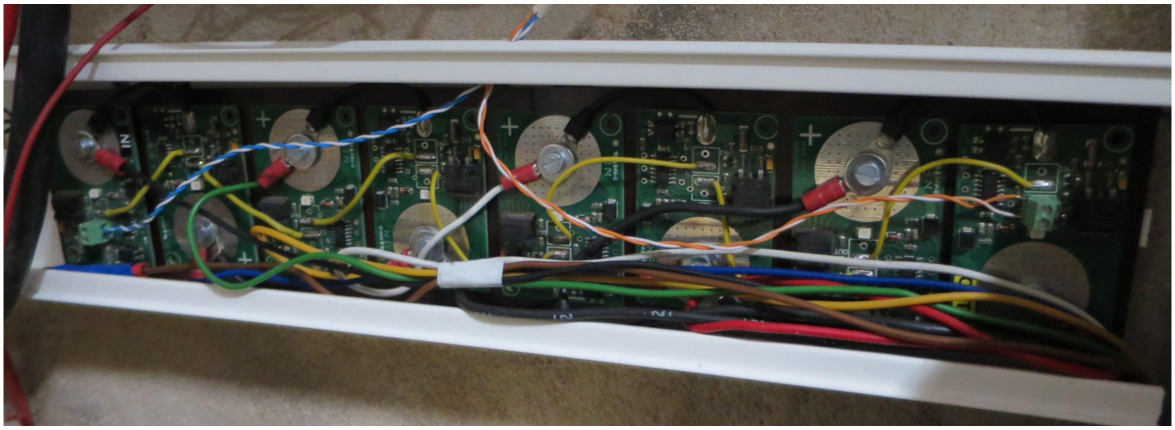
3.4.2. BMS123

This system is made in the Netherlands and is much more advanced, the system is called BMS123. It is programmable and compatible with Windows, nowadays new versions have an Android app. It is meant for use in DIY EV-s and can be used with traditional analog gauges or a Windows computer with a graphical user interface. It's ability to balance the battery cells is quite powerful and adjustable in lots of ways, making it a very flexible system for any lithium battery.

The author had it working for a few years. The main problem was the need for a Windows computer to adjust it and use all it's capabilities. It shows the highest and lowest cell voltages and temperatures, calculates state of charge, is capable of handling 500A and has a Hall effect current sensor like production EV-s. Analog gauges can be connected to display battery current and voltage. Nowadays it has a new version that has app support and it is called "Smart 123 BMS" but it's mainly meant for home storage battery systems.

The upper gauge is a regular ICE vehicle fuel level meter that, in this application, shows the batteries state of charge.
The black box is the 123BMS's main controller.

Here is what the Windows based graphical user interface looks like.



Here are eight cell monitoring units mounted together in one place.

3.4.3. Nissan Leaf original LBC

This is a very sophisticated system made in Japan specially for Nissan cars and batteries. It is robust and reliable, there has been no news of any Nissan battery fire accidents. CAN (Controller Area Network) communication requires a car ECU to work but some have managed to connect it to an arduino board. There is an app called Leaf Spy which displays battery cell voltages on an android device over an OBD(on-board diagnostics) Bluetooth connection. Nissan did not name his system BMS but LBC - lithium battery controller. It is made for Nissans original batteries, 96 Cells in series, it does not work if battery configuration is different. Main difference compared to other BMS systems is that Nissan LBC balances the battery cells all the time but with very little current, as low as 10mA.
This buggy project car has only 20 cells in series, therefore we cannot use Nissan LBC.

3.5. Charging

EV-s are charged from the electric grid. Usually at home at night or at work when the car is parked. It is possible to charge even when on the road using DC fast charging. In 2020 the most powerful chargers were 350kW but at the moment there are not many cars utilizing so much power.
Porsche Taycan was the first but it had to have the battery warm and at the right state of charge to get maximum power, and even then, this power level lasted only for a few minutes. Porsche has claimed that this car can charge to a 100 km range in 5 min.

When charging from the AC grid the car uses an on board charger which converts the AC to DC and to a suitable voltage for the battery. There are some differences in plugs and countries: some use 110V and others 230V but car chargers are universal; their range is 110-230V.
Older cars have the J1772 standard plug on the side of the vehicle and the type2 plug is used in Europe.
There are also differences in DC fast charging connectors.

The first was the Japanese ChaDeMo plug which was rated at 500V 120A and 50kW, then there's the Tesla fast charging connector which differs in the USA and the EU; then there are the German manufacturers' standard: CCS(Combined Charging System) so called Combo plug.
The Combo plug can handle 350kW of power at maximum 800V.

3.5.1. Onboard charger selection.

Available 84V Li-ion chargers that would fit the buggy’s battery pack:

84V 1kW 167€
84V 1,8kW 392€
84V 3,3 kW 670€

power [W]	voltage [V]	charging current [A]	100Ah battery charging time [h]
1000	84	12	8
1800	84	21	5
3300	84	39	3

We chose 1,8kW charger because of the charger size, price, availability and reasonable charging time.

3.5.2. Monitoring instruments

EV-s need a system that calculates energy available in the battery during charging and discharging. Here are a few indicators that would be useful.

1. Battery SOC (state of charge) gauge,
2. Voltmeter,
3. Ammeter.

Electrical instruments left battery SOC gauge right Voltmeter and ammeter.

4. INTEGRATION TO CURRICULUM

4.1. Electrical Vehicle (buggy) curriculum. Full curriculum

Title: Electrical vehicle(buggy) building, 10 EKAP.

Learning outcomes:

- Evaluates, according to the worksheet, the car and its additional equipment technical conditions compliance to regulations, services cars and its additional equipment.
- Envisages a work process for the installation of low-current cables and equipment, based on a given task.
- Understands the working principles of low-current installations and their connections to the laws of physics.
- Installs and connects low-voltage devices and installations (exc. ATS and surveillance signalling) following instructions and requirements, based on a given task.
- Complies with work safety, electrical safety and environmental safety requirements when performing work.
- Prepares the workplace and details for welding work with welding equipment and welds the sample seam and adjusts the operating modes of the welding equipment.
- Manufactures and inspects the part / assembly according to the task (drawing, technological card WPS) and corrects the operating modes of the welding machine.
- Completes the work process and hands over the details according to the instructions.
- Understands and implements occupational safety and environmental requirements in the work process.
- Understand the need to apply knowledge of ergonomics in the work progress.

Evaluation:

- The student describes how EV-s work.
- The student lists the main parts and their functions on EV-s.
- The student performs practical work independently while working individually or in a group.
- Performs work on schedule.
- Finds the right information from working drawings.
- Practical work is performed with good work culture and quality and by following good practice.
- Analysis of the work has been prepared correctly.
- The prerequisite for assessment is that the student has acquired all the skills described in the learning outcomes at the threshold (calculated "A") level.

Topics:

- Construction of alternative energy vehicles, general diagnostics, electrical principles, batteries, motors and control systems, charging, maintenance.
- Electric motors, controllers, batteries, BMS systems, chargers.

- Welding technology and practical welding, use of different electrodes.

Teaching format: lecture, exercises, practical work.

Materials: the teacher's materials

4.2. Curriculum: Car technician. Integrated module

Title: Electric and Hybrid Vehicles, 2 EKAP.

Learning outcomes:

- Evaluates, according to the worksheet, the car and its additional equipment technical conditions compliance to regulations, services cars and its additional equipment.
- Uses the necessary IT tools, databases, technical documentation and professional vocabulary in Estonian and foreign language.

Evaluation:

- The student describes how EV-s work.
- The student lists the main parts and their functions on EV-s.

Topics:

- Construction of alternative energy vehicles, general diagnostics.
- Electrical principles.
- Batteries.
- Motors and control systems.
- Charging.
- Maintenance.

Tasks:

- Using personal protective equipment when working on EV-s.
- Measuring electrical units, voltage, current, resistance.
- Battery diagnosis.
- Battery capacity check.
- Battery replacement.
- Safety switch.
- Battery balancing.
- Changing electrical parts.

Teaching format: lecture, exercises, practical work.

Materials: the teacher's materials

4.3. Curriculum: Electrician. Integrated module

Title: Installation of automation and low voltage equipment, 4 EKAP.

Learning outcomes:

- Envisages a work process for the installation of low-current cables and equipment, based on a given task.
- Understands the working principles of low-current installations and their connections to the laws of physics.

- Installs and connects low-voltage devices and installations (exc. ATS and surveillance signalling) following instructions and requirements, based on a given task.
- Uses correct professional terminology for documenting and communicating in Estonian and English.
- Complies with work, electrical and environmental safety requirements when performing work.
- Analyzes his / her ability to cope with various tasks in the construction of low-voltage installations.

Evaluation:

- The student performs practical work independently while working individually or in a group.
- Performs work on schedule.
- Finds the right information from working drawings.
- Practical work is performed with good work culture and quality and by following good practice.
- Analysis of the work has been prepared correctly.

Topics:

- Electric motors.
- Controllers.
- Batteries.
- BMS systems.
- Chargers.

Tasks:

- The student properly installs electrical, communication and data cables based on the given project and requirements.

Teaching format: lecture, exercises, practical work.

4.4. Curriculum: Welding. Integrated module

Title: Welding, practical work, 4 EKAP.

Learning outcomes:

- Prepares the workplace and details for welding work with welding equipment and welds the sample seam and adjusts the operating modes of the welding equipment.
- Manufactures and inspects the part / assembly according to the task (drawing, technological card WPS) and corrects the operating modes of the welding machine.
- Completes the work process and hands over the details according to the instructions.
- Understands and implements occupational safety and environmental requirements in the work process.
- Understand the need to apply knowledge of ergonomics in the work progress.

Evaluation:

- The prerequisite for assessment is that the student has acquired all the skills described in the learning outcomes at the threshold (calculated "A") level.

Topics:

- Welding technology and practical welding.
- Use of different electrodes.

Tasks:

- Explains from the drawing or technological map the compliance of the task with the work instructions.
- Selects the welding device according to the technology.
- Sets the welding mode of the welding machine according to the task.
- Prepares the details according to the task.
- Welds the sample seam according to the task.
- Adjusts the operating modes of the device according to the result of the sample seam.
- Manufactures the part / assembly according to the task, using angle and butt seams.

Teaching format: lecture, exercises, practical work.

4.4. Extracurricular activities

The buggy will be used for a number of extracurricular activities:

- Racing (extracurricular activities).
- Building new features (extracurricular activities).
- Driving skills (agile driving).