Deliverable D 4.1

Requirements specification

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CO	**Confidential, only for members of the consortium (including the Commission Services)**	
CI	**Classified**	

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Abbreviations and acronyms

AGV	Automatic guided vehicle
BMS	Battery management system
BOL	Begin of life
CAGR	Compound Annual Growth Rate
CHP	Combined heat power
C&I	Commercial & Industrial (applications)
EOL	End of life
EV	Electrical vehicle
IC	Integrated circuit
KPI	Key performance indicators
LCA	Life cycle analysis
Li	Lithium
LIB	Lithium ion battery
MRE	Measuring range end value
PV	Photovoltaic
RES	Residential energy storage systems
ROI	Return on investment
SOA	State of the art
UAV	unmanned aerial vehicle
VMB	VARTA Microbattery
VMI	VARTA Micro Innovation
VS	VARTA Storage

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Executive Summary

Within the ECO2LIB project, high-level, industrial requirements have been defined for both, stationary applications, and high current applications like high-quality vacuum cleaners in close collaboration between the partners. In both cases, the requirements were derived in a top-down approach, starting at system level and proceeding from the module level to the cell level. The use case analysis carried out for this purpose points to future and trendsetting products around 2025.

Besides other important requirements, the energy density and power density, C-rate capabilities, and lifetime expectations have been specified. Based on the requirements for the project cell, a specification for the respective battery packs has also been drawn up.

Gearing these requirements to the practical cell development work will guide the ECO2LIB project to achieve its ambitious goals to continue the success of its previous project SINTBAT. A subsequent and consequent requirement management will therefore be conducted throughout the whole project.

1 Introduction

1.1 Background and selected approach

Energy storage based on Lithium-ion technology has been established for many years in different applications and sectors. The current technical improvements (e.g. in energy density, lifetime, cost per cycle) and the positively changing framework are creating huge market potential for this technology.

The present deliverable contributes to achieve the objectives of task 4.2.The specification of the requirements for the LIB cells especially for stationary applications will be described and fixed as a measure for the project success.

To achieve the objectives of WP4 and of the present deliverable, different use cases were identified and analysed. Among others, the use cases include stationary applications like electricity storage in buildings (homes, commercial and industrial buildings) to increase self-consumption, peak-shaving and grid stability services, and the integration of renewables.

Moreover, non-automotive applications like industrialized robots such as AGVs, home and garden tools and other portable devices will be analysed. Each application will be analysed regarding market opportunities and operation profiles.

1.2 Purpose of the document

This document reports the results produced by the project task to achieve the objective of WP4, which is to specify the necessary requirements for the project cell. The purpose of this report is to identify different non-automotive use cases. Each application has been analyzed regarding market opportunities and operation profiles. At the end of the analysis, a selection with the most promising use cases and cell requirements is created.

1.3 Introduction and classification of USE CASES

The relevance of Li-based battery systems is increasing significantly in many ways and applications.

1. The clear and necessary expansion of renewable energy systems is necessary above all, against the background of reaching the international climate targets. The use of renewable energy sources goes hand in hand with fluctuating availability. Flexibility options are needed. One of these options is storage.
2. Based on the latest Lithium-technologies, further, very promising applications have now been created, for example home and garden devices and robotics.

For all promising applications, sustainability, availability, etc. should be in the foreground. At the beginning, the use cases were differentiated.

We classify the different use cases in the following way:

<u>Stationary applications</u>

- Residential battery storage systems
  - Enhancement of PV self-consumption
- Commercial large storage solutions
  - Enhancement of PV self-consumption

- Peak shaving
- Solar-driven emergency power supply
- Grid services

<u>Non-automotive applications</u>

- High power applications
- Home & garden devices
- Robotics

1.4 Initial approach

The procedure is based on a top-down approach vertical to the value chain. This means that the use cases are primarily analyzed and evaluated, and the KPIs and test definitions are subsequently worked out. At least, the requirements for cells and materials are worked out.

Furthermore, the analysis was divided into various criteria in the form of a table (Table 1) – in order to enable a structured evaluation and subsequently also a weighting in the form of the success chances of different use cases.

Table 1: Example of the Use Cases Excel table to create a first and initial overview / big picture (content will be described later)

General informations @ SYSTEM LEVEL (Battery Systeme + Power Electronic)													
Application	Description	Owner / Operator	motivation owner	adressed territory	driver BC	barriers	market STATUS [units/y in territory]	future market @ 2025ff [units/y in territory]	source	risk probability future market 2025ff	stages product life cycle	Inication market volume [Mio€/y]	comment

electrical framework (future market 2025ff) @ SYSTEM LEVEL (Battery Systeme + Power Electronic)										
min. Power [kW]	max. Power [kW]	min. Capacity [kWh]	max Capacity [kWh]	typical DC-link voltage [V]	typical C charg.	typical C discharge	Over load capability	efficiency relevance	typical no. Cycles	comment

mechanical, enviromental framework (future market 2025ff) @ SYSTEM LEVEL (Battery Systeme + Power Electronic)					price indic. (future market 2025ff) purchase price OWNER (net) [€/kWh]				Others			
min temp [°C]	max temp [°C]	place of install.	vibration	comment	SYSTEM LEVEL	MODULE LEVEL	CELL LEVEL	comments	average Power [kW]	average capcity [kWh]	other	source

2 Use cases (VS)

This section provides an overview of the different stationary and non-automotive use cases that are relevant for the ECO2LIB project.

2.1 Stationary

Stationary applications e.g. residential storage solutions have already been sold and used in Europe in significant quantities. For example in Germany, the gap between the electricity price (0.30 €/kWh as selling price DSO/utility to end customer) and the electricity production cost (less than 0.08 €/kWh by own operating photovoltaic system of 5 kWp) enables operating a decentralized storage system.

Figure 1 (Source: EuPD Research 2020) displays the quantity of residential storage systems installed in Germany depending on the system capacity of:

a) Up to 5 kWh and

b) Between 5 kWh and 10 kWh

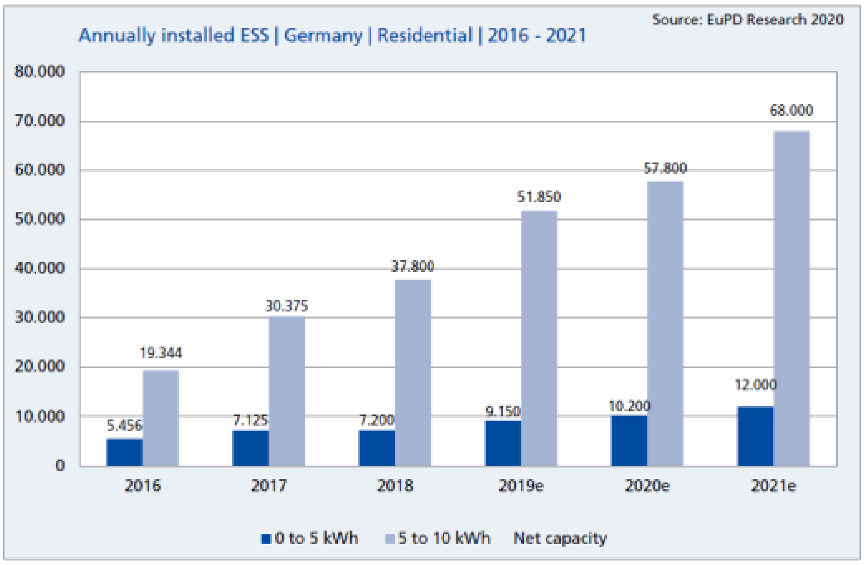


Figure 1: Market development Germany residential storage systems in units per year
(Source: EuPD Research, German Solar & Storage Market Briefing 2020, Saif Islam, 05.03.2020)

In general, significantly more than 50% of sold photovoltaic installations – in residential applications – are already sold together with a storage system.

The diagram illustrates the strong growth seen in the marketplace in the class 5 kWh to 10 kWh and it is expected that this class will have a significant further growth in future. Additionally to the range of 5 kWh to 10 kWh, systems with more than 10 kWh will become very important as well. Reasons for this are e.g. the need and the motivation of end customers to use their own electricity to charge EV (electrical vehicles), which will come into place in the medium term, plus increasing electrification of residential heating systems with the growth in air source heat pumps following the introduction of low NOx legislation.

A further reason to see this growing market is, that in different EU countries, feed-in tariffs and subsidies will end, e.g. Germany after 20 years, starting in 2020.

Market growth will not only be phenomena of high costs that end customers have to pay for electricity. Furthermore also environmental aspects, like public grids with less reliability, different price situations between high and low tariffs or peak shaving application to support a limited grid connection point will affect the growth of residential storage solutions positively.

The following diagram (Figure 2) displays the market size estimation from now to the year 2030. Next to the growth in residential (RES) also very strong growth in commercial and industrial (C&I) is expected. A utility scale indication is also added. All values are based on Bloomberg analyses and on worldwide values.

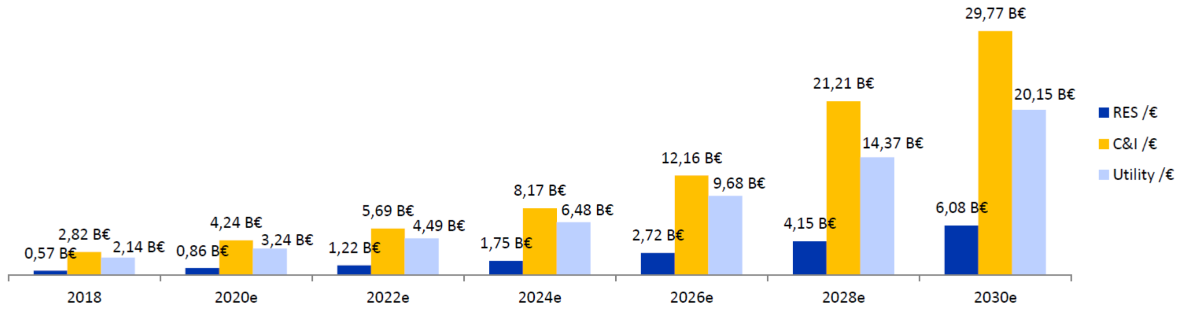


Figure 2: Market development worldwide, divided in residential, commercial and utility applications. The graph has been created by VS for internal purposes and is based on data from the source Bloomberg.

Even soft facts, like increasing the independent (monetary and emotionally) from the DSO/utility company are strong drivers for the purchase decision of residential end customers (Figure 3). One example of a residential installation is shown in the picture beside; VARTA element 12 with 12 kWh usable capacity and 4 kW charging and discharging power (Source: VARTA Storage GmbH).

Beside these reasons for purchasing a storage system, the EuPD research study displays also reasons which are currently barriers for end customers (Figure 3). This information is based on a sampling inspection using interviews with electrical installers in Germany. Beside the monetary aspects, the environmental concerns were also highlighted. In addition, customers' talks have shown that the CO_2 footprint of a product and a sustainable value creation become more and more important and should be a very important KPI within the development of new cell materials.

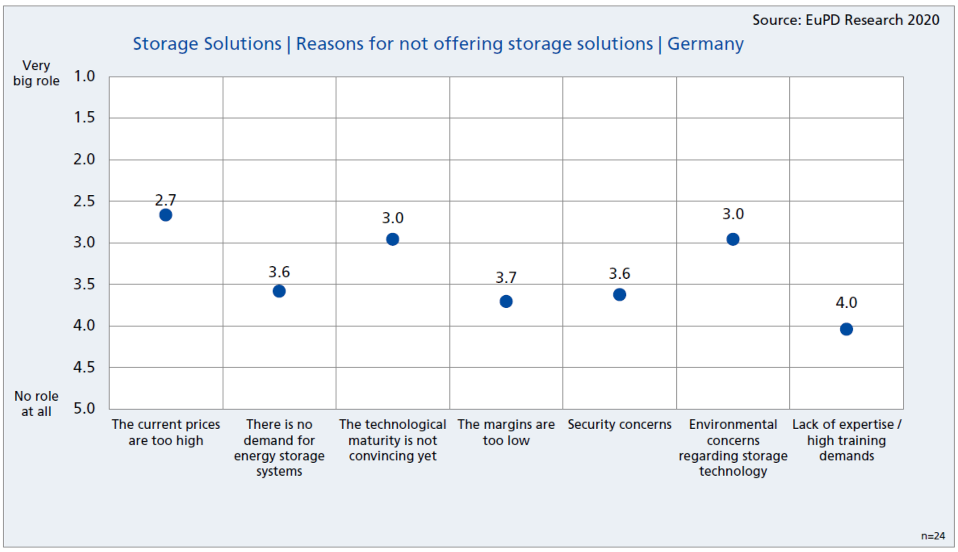


Figure 3: Reason for “not” offering storage systems (Source: EuPD Research, German Solar & Storage Market Briefing 2020, Saif Islam, 05.03.2020)

The VARTA use case analyses are focusing on the most promising market in Europe and especially on European specific requirements on the storage systems. The following functionalities – for residential applications – are addressed:

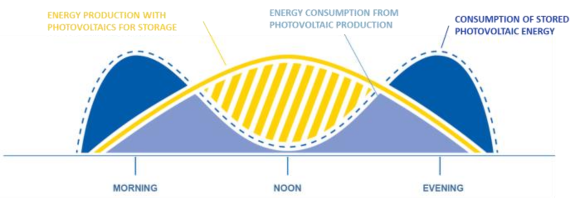
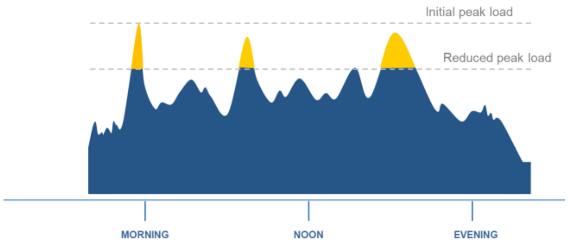
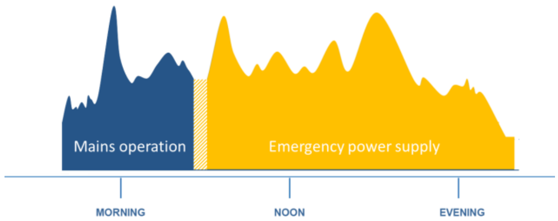
Solar self-consumption optimization Main focus is to use the photovoltaic energy (produced during the daytime) during the night. High relevance: e.g. optimized device efficiency and reaction time	
Peak Shaving Main focus is to reduce the maximum load on the grid-connection point, or cover charging of EVs (Electrical Vehicles). High relevance: e.g. system stability and system availability	
Emergency Power Main focus is to build up an “island grid” after a power outage on the public grid. High relevance: e.g. system stability and high peak power (inrush current) capability	

Figure 4: Functionalities – for residential applications

Beside these functionalities, the interconnection of each decentralized device and the possibility to use the “micro grid” for grid service will create new potentials.

To sum up, it can be said that the market of residential storage is in an early growth period and will have a significant growth in medium term up to long term. In order to ensure this, the price level of the battery has to follow the learning curve and – as well – the ‘sustainability’ of the raw material supply chain has to be ensured.

2.2 Residential Storage System

2.2.1 Electrical parameters

Currently, most residential storage systems have a system voltage of less than 60 VDC (battery modules). Similarly to the development in commercial storage applications, the system voltage will also increase in private applications up to more than 600 VDC. This development allows the system integrator to reduce the overall system cost and as well the ROI time for the customer.

High C rates have not been very important in the past but become more important in the medium term perspective. The reasons for this are very low price levels for PV installations (with the result that the PV installation size is increasing) and the motivation of the end customer to use his storage systems to enable high charging and discharging power values for the upcoming EV (electric vehicle) market or installation in his own household.

Also very important is, and will be, the system efficiency of the device.

At least, all quality issues which will have positive effect on the lifetime (calendar lifetime as well as cycle lifetime) will become highly important. Currently, customers are satisfied with a lifetime limited to 4,000 full cycles per storage system. This will change in future because of the evolution of the system operation, in particular by “stacking” applications together (e.g. solar self-consumption optimization and peak shaving or solar self-consumption optimization together with the parallel use of CHPs). As a result, a lifetime of 6,000 cycles will become necessary.

DC-link voltage (V)	C charge	C discharge	Efficiency	Lifetime
> 650	1	1	High importance	6,000 cycles

2.2.2 Environmental parameters

Systems are installed indoors, thus a temperature range of 5°C to 40°C and very little vibrations will occur.

Min temp	Max temp	Vibration	Place of installation
5°C	40°C	Low	indoor

2.2.3 Market specific parameters

Depending on the residential household (size, persons, connected electrical consumers, etc.), the size of the system will vary a lot. In case of small households, 2 kW systems will be fitted; in larger households, more than 11 kW systems could be installed. As well, the capacity will be different. For example, the decision to operate an EV in future will have a huge impact on choosing the right system capacity.

Min power	Max power	Min capacity	Max capacity	System target price in 2025
2 kW	11 kW	3 kWh	25 kWh	< 500 €/kWh

2.3 Commercial Storage Systems

As shown in the graph "Market development worldwide" in Figure 2, a high growth in the market commercial storage (C&I) is to be expected. Different framework conditions accompany the expected market watch. These include:

- Expiring feed-in commitments (post-feed in market)
  - Generating energy is no longer funded via a secure feed-in tariff
- Roll out EVs (electro mobility)
  - Associated demand for high electrical performance during charging
- CO2 requirements
  - Efficient storage and use of electricity at the point of origin
- Stability of networks with high proportions of fluctuating renewable sources
- Use of storage as an emergency power supply, supported by PV

2.3.1 Electrical parameters

The requirements differ with below in the above-mentioned application cases. In the following, we decided to give the requirement a weight and to list the relevant value in each case.

DC-link voltage (V)	C charg.	C discharge	Efficiency	Lifetime
> 650	1	1.5	High importance	6,000 cycles

2.3.2 Environmental parameters

Systems are installed indoors, thus a temperature range of 5°C to 40°C and very little vibrations will occur.

Min temp	Max temp	Vibration	Place of installation
5°C	40°C	low	indoor

2.3.3 Market specific parameters

Min power	Max power	Min capacity	Max capacity	System target price in 2025
100 kW	500 kW	100 kWh	600 kWh	< 350 €/kWh

2.4 High current applications

High-quality cordless vacuum cleaner

In general, there is a growing demand for battery-powered cleaning equipment. Cordless vacuum cleaners find important applications in households (private persons) and industries. The motivation for using a cordless vacuum cleaner is mainly comfort, flexibility and brand reputation. VS focuses on high-quality applications provided by manufacturers like:

- AEG
- Bosch
- Dyson
- Electrolux
- Grundig
- Miele
- Philips
- Vorwerk

Manufacturers are investing in research and development activities to broaden and offer light-weight, energy-efficient and intelligent applications. Since most important performance factors are determined by the battery, this is the key strategic component in applications like these.

In 2019, Miele presented its first cordless handheld vacuum cleaner "Triflex HX1" at the IFA in Berlin. In order to specify, design and produce the battery and charger for this new product, Miele decided to work with VS. [1]

Figure 5: Cordless vacuum cleaner “Triflex HX1” by Miele [1]

The type of customers for this use case are:

- Private persons and industry

The main drivers of owners are:

- Comfort
- Flexibility
- Brand reputation

Barriers for this use case are:

- Cost
- Runtime

This market is very likely to increase in the future, due to online channels, effective advertising and marketing campaigns. Additional, users mainly decide on low-maintenance and electrical-efficient products, which are why automated cleaning devices, compatible to digital assistances such as Amazon Alexa and Google Home, are also expected to drive the market demand over the forecast period.

The worldwide market for cordless vacuum cleaners is expected to grow at a CAGR of roughly 13.3% over the next five years, reaching 4.25 billion US$ in 2023. [2] Considering this data and an expected market share of 30% for high quality applications (source: internal market knowledge), following market indicators show:

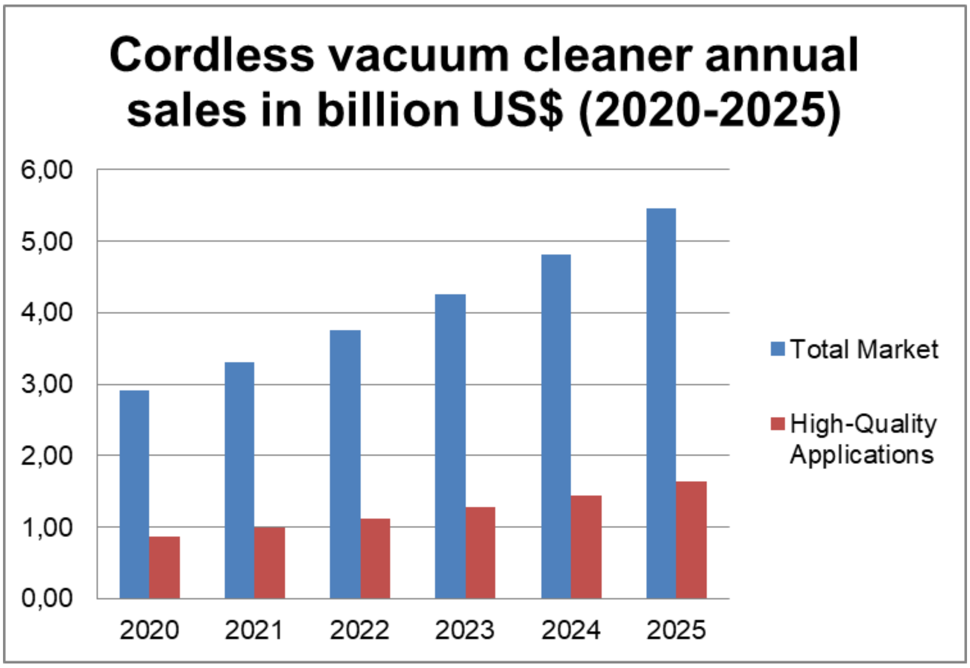


Figure 6: Cordless vacuum cleaner annual sales in billion US$ (2020-2025)

The territorial scope: Worldwide

Current market status for 2020: 0.88 billion US$ per year

Probability of future market 2025: 1.64 billion US$ and approx. 2 million units per year (considering a system target price in 2025 around 750 €)

2.4.1 Electrical parameters

Due to size, usual voltage is limited in a range between 25.2 V and 36.0 V for cordless vacuum cleaners. Following framework is based on current requirements (except capacity) – since, due to handling, size and weight probably won't increase any further. Future developments will focus on cells with higher capacity. A lifetime of 1,000 cycles is foreseen in the future market.

Typical Voltage	Typical C Charge	Typical C Discharge	Efficiency Relevance	Lifetime
25.2 V – 36.0 V	0.5	5*	High	1,000 cycles

*Discharge rate depends on operation mode

2.4.2 Environmental parameters

Systems are mostly installed indoors, therefore narrow temperature range of 5°C to 40°C and little vibrations will occur.

Min. Temp.	Max. Temp.	Place of Installation	Vibration
5°C	40°C	Indoor	Low

2.4.3 Market specific parameters

The system size is application-dependent and can vary from 150 W to 300 W. This market is already growing and the system target price is estimated by 750 € per unit.

Min. Power	Max. Power	Min. Capacity	Max. Capacity	System target price in 2025
150 W*	300 W*	60 Wh*	TBD	>750€

*Depends on battery configuration (here: 7S1P)

2.5 Garden Devices

High-quality cordless lawnmower

The growing demand for quieter and more environmental-friendly garden devices is fuelling the increase of the worldwide electric lawnmower market. Electric lawnmowers are particularly cheaper compared to petrol-powered lawnmowers and have therefore received an expanded preference. VS focuses on high-quality applications provided by manufacturers like:

- AL-KO
- Bosch
- Gardena
- Husqvarna
- Kärcher
- Makita
- Stihl

The type of customers for this use case are:

- Private persons and industry

The main drivers of owners:

- Reduced noise pollution
- Flexibility
- Brand reputation

Barriers for this use case are:

- Cost
- Safety

In terms of performance, the global electric lawnmower market can be divided into corded and battery powered lawnmowers. Demand for battery powered lawnmowers is expected to increase strongly as they do not have a cable that limits their application range. Technological advances are intended to improve battery life, performance and thus increase demand.

The global electric lawn mower market is estimated to generate revenues of around $7 billion by 2024, growing at a CAGR of approximately 8% [3]. Considering this data and an expected market share of each 30% for cordless and within this market high-quality cordless applications (source: internal market knowledge), following market indicators show:

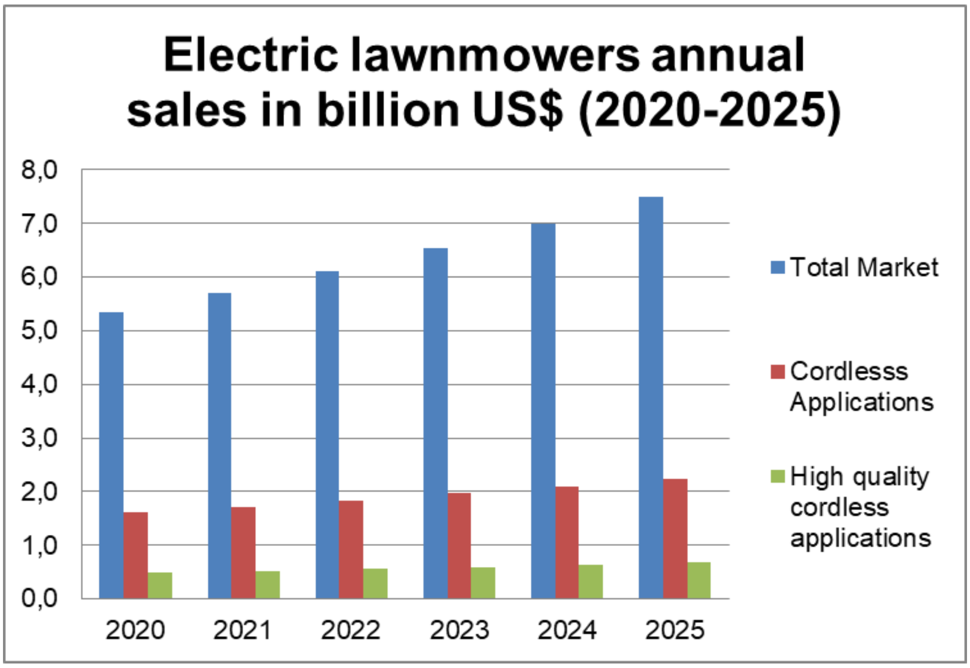


Figure 7: Electric lawnmowers annual sales in billion US$ (2020-2025)

<u>The territorial scope:</u> Worldwide

<u>Current market status for 2020</u>: 480 million US$ per year

<u>Probability of future market 2025:</u> 670 million US$ and approx. 593 thousand units per year (considering a system target price in 2025 around 1,000 €)

2.5.1 Electrical parameters

Due to size, usual voltage is limited in a range between 14.4 V and 25.2 V for electric lawnmowers. Following framework is based on current requirements (except capacity) – since, due to handling, size and weight probably won't increase any further. Future developments will focus on cells with higher capacity. A lifetime of 1,000 cycles is foreseen in the future market.

Typical Voltage	Typical C Charge	Typical C Discharge	Efficiency Relevance	Lifetime
14.4 V – 25.2 V	1	5	High	1,000 cycles

2.5.2 Environmental parameters

Systems are mostly used outdoors, therefore wide temperature range of -20°C to 50°C and high vibrations will occur. The minimum temperature is based on the storage of the battery.

Min. Temp	Max. Temp	Place of Installation	Vibration
-20°C	50°C	Outdoor	High

2.5.3 Market specific parameters

The system size is application-dependent and can vary from 250 W to 400 W. This market is already growing and the system target price is estimated by 1,000 € per unit.

Min. Power	Max. Power	Min. Capacity	Max. Capacity	System target price in 2025
250 W	400 W	100 Wh	TBD	>1,000€

2.6 Agricultural Robotics

Unmanned aerial vehicles (UAVs)

Unmanned aerial vehicles are unpiloted flying robots. Originally designed for military purposes, today they are used in various areas, from surveillance to disaster management, firefighting, border protection, courier services and agriculture.

Within the agricultural use case, UAVs are used in pest control, crop irrigation, animal mustering, geo-fencing and other agriculture-related activities.

Major companies in the agriculture robots market are: [4]

- AGCO Corporation
- AgEagle Aerial Systems
- AgJunction
- Boumatic
- Deere & Company
- DeLaval
- DJI
- Lely
- Topcon
- Trimble

A special requirement for most UAV applications in agriculture is an integrated camera with which pictures can be taken. Images are used, among other things, to identify and control weeds, for soil analysis, animal monitoring, and geo-fencing.

Figure 8: Aerial mustering using an UAV [5]

The type of customers for this use case are:

- Mostly agriculture holdings

The main drivers of owners are:

- Reduced labour costs
- Time savings
- Material savings

Barriers for this use case are:

- Economic efficiency
- Service life

The UN projects that the current world population of 7.6 billion is expected to reach 8.6 billion in 2030 [6]. Considering farms and agriculture companies to cover this population growth, managing thousands of acres of land, the potential for UAVs in agriculture is extensive.

The worldwide market for agricultural robots is expected to grow at a CAGR of roughly 22.8% over the next five years, reaching 20.7 billion US$ in 2025. [4] Considering this data and an expected market share of 20% for UAV applications (source: internal market knowledge), following market indicators show:

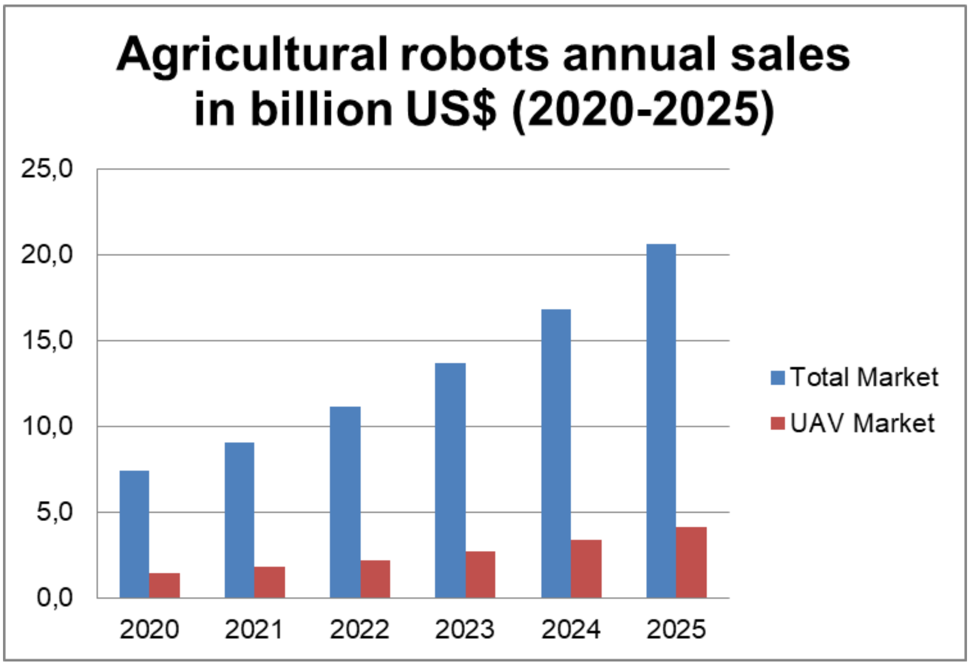


Figure 9: Agricultural robots annual sales in billion US$ (2020-2025)

The territorial scope: Worldwide (currently focus on USA)

Current market status for 2020: 1.5 billion US$ per year

Probability of future market 2025: 4.1 billion US$ and approx. 725 thousand units per year (considering a system target price in 2025 around 5,000 €)

2.6.1 Electrical parameters

In general, there is a trend towards 48V batteries in various applications. Thanks to modular design, these batteries can be used for different sized UAVs (depending on the required load). A lifetime of 500 cycles is foreseen in the future market.

Typical Voltage	Typical C Charge	Typical C Discharge	Efficiency Relevance	Lifetime
48 V (modular)	1	3 (pulse up to 15)	Medium	500 cycles

2.6.2 Environmental parameters

Systems are mostly used outdoors, therefore wide temperature range of -20°C to 50°C and high vibrations will occur. The minimum temperature is based on the storage of the battery.

Min. Temp.	Max. Temp.	Place of Installation	Vibration
-20°C	50°C	Outdoor	High

2.6.3 Market specific parameters

The system size is application-dependent and can vary from 3,000 W to 4,500 W. This market is already growing, and the system target price is estimated by 5,000 € per unit.

Min. Power	Max. Power	Min. Capacity	Max. Capacity	System target price in 2025
3,000 W	4,500 W	1,500 Wh	TBD	>5,000€

2.7 Outcome use cases

From a medium-term perspective, the following analyzed uses cases will have the biggest chance to become a successful application:

- Residential Storage to increase the solar self-consumption rate
- High current applications, e.g. cordless vacuum cleaners

With these two options, two applications are considered, which are very different in their requirements (electrical and mechanical). For both applications, VS would like to contribute the expertise it has already built up and expand it within the framework of the project. The development of the following requirements is focusing on these applications and on their specific needs.

3 Cell requirements (VS, VMB, VMI)

The current portfolio of VARTA Storage ranges from small-scale residential battery storage systems with an energy content of several kWh to commercial storage systems which feature energy contents of up to MWh. Whereas the small-scale systems are normally used in order to increase the self-consumption, the systems in the commercial sector are used for peak-shaving, off grid applications and also for self-consumption. Figure 10 illustrates the current range of VARTA products with their respective energy capacity.

VARTA pulse / pulse neo (3/6) | VARTA element (6/9/12) | VARTA one L & XL (2.8kWh - 13.8kWh) | VARTA flex storage P & E (52 kWh – 750 kWh)

Figure 10: Current system portfolio of VARTA Storage [7]

The first system from VARTA storage was the VARTA One XL which formerly was called Engion Family. This highly modular system features space for up to 30 small-scale battery modules with an energy content of 0.46 kWh each. The smaller version of the VARTA One XL is the VARTA One L. Instead of 30 modules, this system features space for up to just 15 modules. Whereas the maximum energy content for the One XL is 13.8 kWh the One L features up to 6.4 kWh.

In order to attract more customers the more cost-effective VARTA Element was introduced in 2015. This system features four different energy contents ranging from 3.3 to 13 kWh. For this system, two different module sizes (3.3 and 6.5 kWh) are available and both are multiple times larger than the modules for the VARTA One series with 0.46 kWh. Overall cost per kWh on module level are usually higher for smaller battery modules compared to larger ones since cost for housing, connection, thermal management, monitoring and in the end also manufacturing as well as testing emerge multiple times for smaller modules. This is one of the reasons why the costs per kWh of the Element are significantly less compared to those of the VARTA One systems. However, in that context, it also has to be mentioned that the VARTA One systems contain high quality cells with extreme long lifetime. This also adds to the cost.

Defining the stationary requirements in ECO2LIB, the focus is on the latest VS systems in the residential sector, the VARTA Pulse and the VARTA Element. Both systems can be equipped with either small (3.26 kWh, 16.6 l) or large battery modules (6.52 kWh, 28.7 l). Whereas only one small or large module fits into the VARTA Pulse, the VARTA Element can handle up to two modules which allow more system configurations ranging from 3.3 kWh up to 13 kWh.

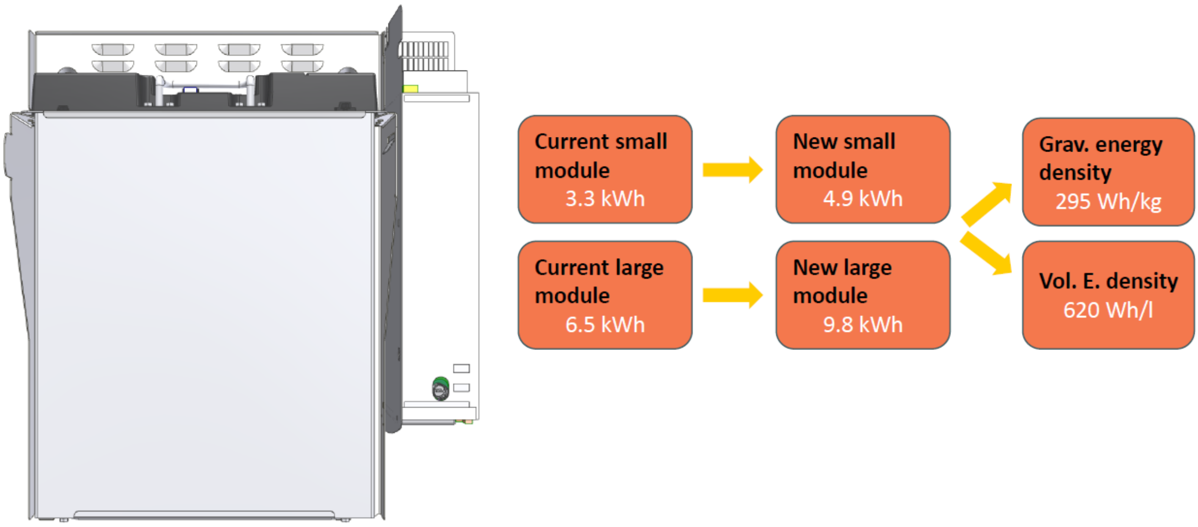


Figure 11: New stationary module concept and derivation of the energy density on cell level

In order to meet the demand of increasing energy content, new versions of the small and the large modules with increased energy content are considered (Figure 11). The dimensions of the housing and the weight should remain unchanged. The new small module has an energy capacity of 4.9 kWh, while the large module has 9.8 kWh, which both represent a very good extension of the existing portfolio. Taking into account the weight and available volume of the battery modules, the gravimetric and volumetric energy density has been calculated to 295 Wh/kg and 620 Wh/l respectively.

From VS experience it is known that the size of the system depends strongly on the respective household profiles. Therefore, for reasons of sustainability and to ensure an optimal operation of the battery it is important to offer very specific energy capacities to the customers. On the other hand, it is to be expected that the demand for energy, e.g. to charge the electric car, will increase in the future. Battery modules with cells with higher energy capacity could therefore extend the existing VS portfolio very well. Table 2 illustrates the expansion of the current portfolio, which makes VARTA pulse and element more adaptable to different conditions and thus more attractive for customers.

Table 2: Possible VARTA system portfolio with ECO2LIB cells and project modules (extensions are marked in orange)

	VARTA pulse	VARTA element
Market	Residential	Residential
System	Li-Ion	Li-Ion
Grid connection	AC 1-ph.	AC 3-ph.
Energy capacity (kWh]	3.3 / 4.9 / 6.5 / 9.8	3.3 / 4.9 /6.5 / 8.2 / 9.8 / 11.4 / 13 / 16.3 / 19.6

Based on the derivations from chapter 2, a wide range of definitions and requirements was compiled in close cooperation between VS, VMB and VMI. The cell design in the project should correspond to the format 21700. Due to the current dominance of the 18650 format on the market, however, the requirements were defined in general terms and not bound to a specific format or size (e.g. capacity). The cell requirements with conditions and notes are listed in Table 3 for both stationary applications and high current applications. Since this area covers many different applications and, accordingly, cell requirements, the requirements for cordless vacuum cleaners are discussed in more detail below.

Table 3: Definitions and requirments for the project cell drawn up in close collaboration between VS, VMB and VMI. Color code: orange – residential, blue – cordless vacuum cleaners, black – applies for both.

	Cell requirements / specifications	**conditions / comments**
Chemistry	NMC622 / polymer electrolyte / Si-based anode	
Application	Residential storage Cordless vacuum cleaner	
Volumetric energy density	> 620 Wh/l	
Power density	> 2000 W/kg	Continuous discharge at I_{max}*U_{max}; 5 - 95% SOC
C-rate capability	Must: 0.5 C / 1 C Optional: 1 C / 1 C Must: 0.5 C / 2 C – 10 C Optional: 2 C / 2 C - 10 C	Continuous Discharge rate depends on operation mode
Fast charging	not much relevance 10 – 80 % SoC in 25 min	 mean C-rate: 1.75 C
DC internal resistance[*1]	< 35 mΩ < 15 mΩ	T = 23°C, 50% SOC, 1C, 10s T = 23°C, 50% SOC, 10A, 10s
Operation limits $T_{min, max}$ $U_{min, max}$	 5°C – 40°C 2.5 V – 4.3 V	 Indoor applications Voltage window can be different; BMS can be adjusted.
Energy deviation BOL, DC internal resistance deviation BOL	< 2% < 2%	
Self-discharge rate	< 1%	100% SOC, 25°C, per month
Energetic charge- and discharge efficiency	0.5 C: ≥ 96% 0.2 C: ≥ 98%	
EOL-criteria (capacity / internal resistance)*	80% of BoL capacity 130% of BoL resistance	Application specific profile 50% SOC, 23°C, 10s, I_{max}
Number of cycles	> 4000[*2] 6000 600[*3]	0.5 C / 0.5 C, 23°C, 80% DoD, EOL-criteria 60% of BOL capacity 0.5 C / 50 W (I_{max} ≈ 18 A), 23°C, 90% DoD, EOL-criteria[*3]

Calendar life	> 15 years > 5 years[*3]	EOL-criteria
Storage conditions	25°C, 90% SoC, 15 years 45°C, 90% SoC, 48 months 60°C, 90% SoC, 18 months	EOL-criteria
Safety (Sandia definition)	Pass ≤ 4 ≤ 4 ≤ 4 ≤ 4 ≤ 4	UN 38.3, UL1642 Overcharge Ext. short circuit Crush Forced discharge Thermal stability test

[*1] SOA for cells on the market in the format 21700
[*2] In order to limit the test duration, intermediate requirements could be: 1000 cycles, 0.5 C, 23°C, 80% DoD, 90% of the initial capacity remaining.
[*3] End of life criteria for cordless vacuum cleaner batteries depend very much on the customer specific requirements. Therefore these specifications represent only one example of a vacuum cleaner for private use and have no general validity.

From the material and cell design point of view, the volume effects of the Si-containing anode must be considered. For the assembled cell, the volume expansion must approach zero at the cell surface. The VS specification for the tolerances for the cell diameter and height is 0.1mm.

The cell requirements in Table 3 show very clearly how different the cell requirements for a long-term application with a high energy cell on the one hand and a high current application on the other hand can be. These differences are particularly noticeable in the operating parameters such as the C rates and the DOD and the EOL criteria in terms of cycles and calendar life expectations.

In summary, a first set of high-level requirements has been derived with a top-down approach for both applications. The entire catalogue of requirements was discussed within the framework of WP4. The requirements were also presented to all partners at the M6 GA online meeting on June 24, 2020.

4 Module requirements (VS, VMB)

In this chapter, the requirements on the ECO2LIB modules are described. For both applications, the four areas of electronics, mechanics, BMS and environment will be discussed. Figure 12 illustrates this approach. It also shows a photo of the research module that was built and tested from VS as part of the predecessor project SINTBAT.

The specified parameters in this chapter will be successively adapted to the progress made in the course of the project.

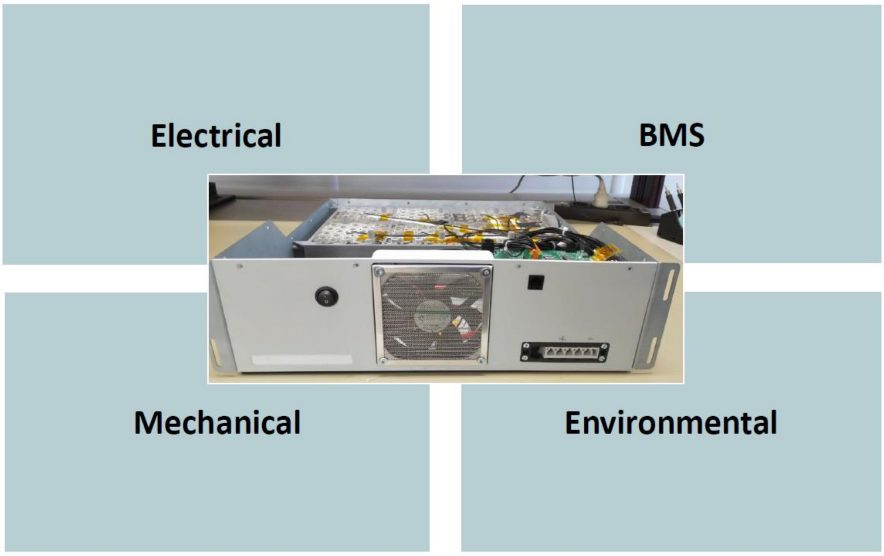


Figure 12: Module requirement areas and photo of the SINTBAT module

4.1 Residential energy storage systems

In energy storage systems from VS, battery modules are implemented and connected with power electronic devices. Within each module, several cells are connected in series and/or in parallel. Especially when a certain capacity is demanded, cells are connected in parallel: the smaller the cell, the higher the number of cells that are usually connected in parallel. Since the cylindrical cells in ECO2LIB feature a rather small capacity – compared to large format cells like pouch cells and prismatic cells – several cells will be connected in parallel in order to reach the intended capacity and energy content of the module.

4.1.1 General requirements

- In the 1st stage, the module needs to be compatible with the VARTA Element. In an optional 2nd stage integration in the VARTA Pulse needs to be envisaged. Here, electrical communication as well as safety interfaces needs to be considered.

- Module format: 19 inch slide-in rails for integration in the VARTA system

- Module design has to consider (touch) protection against hazardous voltage and hazardous energy content in operation, maintenance and assembly.

- Cost-effective assembly must be ensured taking into account the following aspects:
    - Few assembly steps
    - Handy assemblies
    - Few different tools to assemble

  - During assembly the application software has to be uploaded with simple methods. The appropriate interface to the battery management system (BMS) must be accessible

- High quality in mechanical and visual appearance

- Expected lifetime: > 15 years

4.1.2 Battery module specification

- Cell type: 21700, height: 70 ± 0.1 mm, diameter: 21.3 ± 0.1 mm

- Nominal module voltage: 50.4 V

- Max. module voltage range: 35 – 58.8 V
  For the ECO2LIB stationary module, the number of cells connected in series have been fixed to 14. This number results from the requirement that the module voltage should stay below the small safety voltage of 60 V. Considering a maximum cell voltage of 4.2 V, a module voltage of 58.8 V results, which is below that limit. Moreover, this module voltage allows integration into existing storage systems of VS.

- Nom. Energy: 4.9 kWh (small module) – 9.8 kWh (large module)

- Topology: 14s*x*p
  The nominal energy capacity of the module is calculated from the nominal capacity and voltage of the individual cells. For example, a 5.4 Ah cell with a nominal voltage of 3.6 V in a 14s18p configuration gives the required energy capacity of 4.9 kWh for the small ECO2LIB module. As the project progresses, the final module configuration is determined based on the current findings.
  The values given for capacity and nominal voltage are guide values based on experience from the Sintbat project.

- Continuous charge and discharge current: 50 A and 100 A

- Round trip efficiency > 95%

4.1.3 Battery management system

The project modules will be equipped with a BMS for monitoring purposes. Here, VS will use an existing platform from other R&D projects and adapt it according to the needs of the project. The requirements for the BMS are as follows:

- Balancer function: The BMS has to balance the cells when the difference between the minimal and the maximum cell voltage is bigger than 10mV. A passive balancing is followed and the balancing current should be at least 80mA per cell.

- The BMS has to be capable of monitoring the cell voltage:

  - Separate measurement of 14 cell voltages
  - Voltage range: 0 V – 5 V
  - The resolution of the voltage measurement should be 1 mV with a maximum error of 2 mV

- A temperature measurement needs to be included as well
  - Up to 8 cell temperatures should be measurable
  - Temperature range: -30°C to +120°C
  - Resolution of temperature measurement: < 1K
  - The board temperature should be measured as well to identify hot spots – for example under balancing conditions

- A watchdog function which triggers the safety line when a communication fault is detected needs to be implemented.

- Fuel Gauging: It outputs the capacity with the help of the measured current of the current sensor which is the input to the fuel gauge. The capacity is in turn used to calculate the SOC (State of charge).

- Redundant hardware protection mechanisms: Other than the protection with balancing chip, a 2nd level hardware protection needs to be implemented in the BMS. It includes protection against overvoltage, under voltage, overcurrent, and over temperature.

- The current sensor is used to measure the current with a measurement error of ≤ 0.5% MRE (measuring range end value).

- In the BMS, a current fuse which blows when a short circuit occurs, needs to be considered.

- Dry Contact: The dry contact is mandatory to be connected with an external protection mechanism like a relay in order to cut the current flow.

- Communication:

  - Protocol: CAN
  - Data transmission of min./max./average cell voltage, module voltage, module current, temperatures, balancing flags, SOC, SOH, error flags

- State estimation

  - State of Charge (SOC) should be estimated
  - State of Health (SOH) should be estimated

4.1.4 Mechanical requirements

- Dimensions
  - Width: max 500 mm
  - Height: max. 180 mm
  - Depth: max. 500 mm

- Weight: max. 40 kg

- Cooling: Fan

- Mechanical stability has to be ensured (also considering drop tests)

- Deployment of fire-resistant and electrolyte-resistant materials

- Low-resistance and corrosion-resistant contacting

- Power Contacts: Würth M6 bolt

- Dry contact (safety line): Wago terminal

- CAN-Bus in/out: RJ45 jacks

4.1.5 Environmental conditions

It must be possible to store and operate the module under the following ambient conditions:
  - Storage temperature: -20°C to +60°C
  - Humidity: 5 to 95% non-condensing
  - Charge and discharge temperature range: +5°C to +40°C
  - Preferred operating temperature +23 ± 2°C

VARTA plans to provide about 500 cells for the assembling of the ECO2LIB demonstrators, similar to the previous project SINTBAT. Depending on the module configuration (14S*x*P with $x \approx 18$), it would be conceivable that two small modules with 4.9 kWh could be assembled and tested under real conditions in the VARTA systems.

4.2 Cordless vacuum cleaner

In the field of power tools, the requirements are very much customer-specific. Further different sizes and designs of the cleaners (hand-held devices, robots, heavier floor equipment with longer running time) have to be considered.

4.2.1 General requirements

- Module design has to consider (touch) protection against hazardous voltage and hazardous energy content in operation, maintenance and assembly.

- Cost-effective assembly must be ensured taking into account the following aspects:
  - Few assembly steps
  - Handy assemblies
  - Few different tools to assemble
  - During assembly the application software has to be uploaded with simple methods. The appropriate interface to the BMS must be accessible
  - Common parts to be used where possible
  - Reduction of screwing processes, snap fit solutions or similar preferred

- Expected lifetime: > 5 years

4.2.2 Battery pack specification

- Cell type: 21700, height: 70 ± 0.1 mm, diameter: 21.3 ± 0.1 mm

- Topology: 7S1P – 10SXP: depends, for example, on whether the battery is for a hand-held vacuum cleaner or mobile vacuum cleaner on rolls (weight, expected capacity, etc.). The following values are exemplary for a 7S1P topology.

- Nominal pack voltage: 25.9 V

- Pack voltage range: 21 V to 29.4 V

- Nominal energy: minimum 60 Wh

- Power of vacuum cleaner: max. 400 W

4.2.3 Battery Management System

- Balancer function: The BMS has to balance the cells when the difference between the minimal and the maximum cell voltage is bigger than *x* mV (to be defined). A passive balancing is followed and the balancing current should be at least *y* mA (to be defined) per cell.

- The BMS has to be capable of monitoring the cell voltage:

  - Separate measurement of 7 cell voltages
  - Voltage range: 0 V - 5 V
  - The resolution of the voltage measurement should be below 10 mV

- A temperature measurement needs to be included as well
  - Once cell temperature should be measured (via NTC 10k Ohm), ideally close to centre of the pack.
  - Temperature range: -30°C to 120°C
  - Resolution of temperature measurement: < 1K
  - The board temperature should be measured as well.

- Fuel Gauging: It outputs the capacity with the help of the measured voltage over the shunt resistor which is the input to the fuel gauge. The output capacity is in turn used to calculate the SOC.

- Redundant hardware protection mechanisms: Other than the protection with balancing chip, a 2nd hardware protection needs to be implemented in the BMS. It includes protection against overvoltage. Undervoltage, overcurrent, and overtemperature, communication faults, etc. are covered by the protection IC (integrated circuit).

- In the BMS a current fuse which blows when a short circuit is detected, needs to be considered.

- Communication:

  - Protocol: UART, I^2C, SMBUS
    Various possibilities are conceivable here and the customer wishes differ. Therefore this has to be defined in the course of the project.
  - Data transmission of min./max./average cell voltage, module voltage, module current, temperatures, balancing flags, SOC, SOH, error flags

- State estimation

  - State of Charge (SOC) should be estimated
  - State of Health (SOH) should be estimated

- For transportation and longer storage periods a low power mode should be implemented.
- Wish: SOC indicator (4 white or green LEDs), push button
- Data logging for life time (cycles, SOH, errors) and events has to be implemented

4.2.4 Mechanical requirements

- Available space: 120mm x 80mm x 80mm, space to be used as efficiently as possible
- Battery to be replaceable without tools, locking system integrated on vacuum cleaner, design of locking features have to be defined
- Optional: Free-form surfaces on the plastic housing for modern optical appearance
- Max. weight 700 g
- Drop Test criterion must be fulfilled: 3 times drop from a height of 1m at 20°C ± 3K onto a concrete floor (random orientation), 1 time falling down the stairs (20-30 steps). Passing criteria: OCV after test min. 95% of initial OCV, communication ok.
- IP protection class IP3X
- Power and data connector preferably in one standard connector (e.g. Molex, JST, etc.). Charging and discharging via the same connector.
- Min. 400 mating cycles
- Wish: SOC indicator (4 white or green LEDs), push button

4.2.5 Ambient conditions

Ambient conditions for storing and operating the battery pack:

- Storage temperature: -20°C to 60°C
- Humidity: 5% to 95%
- Charge and discharge temperature range: 5°C to 40°C
- Preferred operating temperature 20°C

In this section, the specifications for both battery modules, for residential energy storage and high-quality vacuum cleaners have been created. The comparison shows interesting differences in the requirement profiles for the project cell (see also section 3). In the course of the project the partners will decide together which type of battery pack should be selected for the further work of the work package: module design (task 4.3), assembly and testing (task 4.4).

The first impression from the M6 meeting on June 24, 2020 shows a tendency towards the RES module. This is due to the fact that a thermal analysis and simulation in the large battery module with high life expectancy seems more effective. Also with regard to recycling and the LCA the RES module seems more interesting.

5 Conclusion

In summary, a set of high-level requirements has been derived with a top-down approach for the two most promising use cases analysed, residential energy storage systems and high-quality vacuum cleaners. The requirement catalogue is intended to play the role of orientation for the project and to define the pathway for the development work in order to achieve the ambitious project goals. For this, the elaborated requirements need to be successively compared with the progress of the experimental project work in order to identify potential gaps. The difference between the requirements and the experimental results gives then the chance for adaptions and so improvements to reach the target values.

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