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CHARACTERIZATION OF 2ND LIFE LI-ION BATTERIES FOR USE WITHIN AN EU CONTEXT

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ABSTRACT

Lithium-ion batteries have revolutionized the industry in terms of mobile power applications. Ranging from cell phones to electric vehicles, Li-ion batteries have been at the heart of the energy transition. In this document the consequences of the latest EU directive concerning batteries is reviewed, the potential for creating a business via the use of 2nd life li-ion batteries is discussed and the viability of characterizing a li-ion battery for use in its second life by measuring its internal resistance is investigated. It has been shown that it is indeed possible to create a business model around the latest EU directive by providing guaranteed energy storage for residents, and that a test bench using low cost materials and an Arduino Nano can be used. The calculated internal resistance of 42mΩ has an acceptable 5% error with the theory, and is likely due to hardware limitations such as no filtering being done within the circuit. Future work includes building upon this thesis to create a commercial product to provide SoH estimations for 2nd life batteries for use within an EU context.

ACKNOWLEDGEMENTS

During the writing of this thesis I was diagnosed with Lymphoma and had to pause my studies. I unfortunately had to remain in the Netherlands during my treatment of approximately 1 year where I underwent intense cancer treatment. I would like to acknowledge my professor Francisco Díaz-González for being so supportive for my health and being open to reconnect to having me finish it off. A special thanks to the ISE foundation and everyone involved for allowing my return to the study without much administrative hassle. It was a difficult journey to say the least, and I am glad that it's over and positive for the future and look forward to my professional and personal future.

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LIST OF ACRONYMS

BEV	Battery Electric Vehicle
BTM	Behind-The-Meter
CRM	Critical Raw Material
DBM	Diagnostic Battery Management
DRC	Democratic Republic of Congo
EOL	End Of Life
EPR	Extended Producer Responsibility

ESS	Energy Storage System
EV	Electric Vehicle
EU	European Union
RC	Resistance-Capacitance
SEI	Solid Electrolyte Interface
SOC	State Of Charge
SOLI	State Of Life Indicator
FTM	Front (of)-The-Meter
LMO	Lithium Manganese Oxide
PHEV	Plug-in Hybrid Electric Vehicle
ROI	Return On Investment
UK	United Kingdom

TABLE OF CONTENTS

1 GENERAL INTRODUCTION AND OBJECTIVES

This thesis evaluates the potential to recycle Li-Ion batteries for reuse within the EU. This document is broken down into several chapters. We begin in this chapter with discussing some background information pertaining to Lithium-Ion batteries, and its production value chain and market.

This leads to a set of general objectives

1. Investigate the background information pertaining to Li-Ion batteries
2. Research the potential of a business around 2nd life batteries
   2.1. Review the existing proof of concepts and discuss the barriers to entry
   2.2. Discuss methods of business modelling
   2.3. Show via the Business Model canvas how it is intended to make profits with a hypothetical company
3. Discuss 2nd life batteries and its potential applications
   3.1. Analyze the latest EU directive concerning the extended producer responsibility for 2nd life batteries
   3.2. Shape the problem statement of this thesis as a result of the EU directive
4. Describe the methodology of verifying the problem statements that were discussed
   4.1. Delve into the state of the art characterization techniques and discuss the simulations made
5. Build and validate the test setup
   5.1. Describe the circuit design and show the bill of materials
   5.2. Code the microcontroller to output, measure and calculate various things in parallel
   5.3. Discharge a battery and collect the data to interpret the results
6. Prove the concept that a low cost microcontroller can be used for such a project
   6.1. Discuss potentials for future work

1.1 BACKGROUND VALUE CHAIN OF LI-ION BATTERIES

1.1.1 Li-ion batteries

A Lithium-ion battery is one of the newer types of rechargeable batteries on the market. Found in almost any application today, ranging from smart phones to cars and even aerospace applications such as satellites and aviation [9], this advanced technology gets its name by using Lithium as one of its key components. The first commercial Li-ion battery was made by Sony in 1991 as an R&D project for new batteries with a higher energy density where its initial commercial use was for mobile applications [1] [2].

Li-ion batteries are low maintenance, have no charge memory (where the battery exhibits “remembering” having a small capacity than it actually has) and no particular cycling schedule is required to prolong its life unlike with other batteries. Furthermore, its self-discharge is low and causes little harm when the batteries are disposed of [3]. The typical energy density of Li-ion batteries is about 200Wh/kg, which is good compared to alternative storage types with a lower energy density. One of the drawbacks of Li-ion batteries is its fragility. It requires a protection circuit to limit peak and too low voltage levels to prevent damage, as well as to monitor the cells to prevent excessive temperatures. These protections ensure that 'metallic lithium plating' as a result of overcharging is eliminated [3]. Panasonic has been developing flexible batteries that seem to show promise [4].

1.2 THE VALUE CHAIN OF LI-ION BATTERIES

The typical value chain (without recycling) boils down to what is shown in Figure 1.

Figure 1: Production structure of the Li-ion battery industry [5].

Some companies apply their competencies in more than just one of the fields in this value chain. Tesla for instance produces battery cells to their own specifications including the cathodes, assembles their own battery packs and use those for their own electric vehicles (Tesla EV) [5]. While others of course would focus solely on single cell components. In terms of said industry, battery cell manufacturers include:

Panasonic	Samsung SDI	LG Chem	AESC	GS Yuasa	Li Energy Japan	BYD
Panasonic	SAMSUNG SDI	LG Chem	Automotive Energy Supply Corporation	GS YUASA	LITHIUM ENERGY JAPAN	BYD
Toshiba	Wanxiang					
TOSHIBA	萬向集團 WANXIANG GROUP					

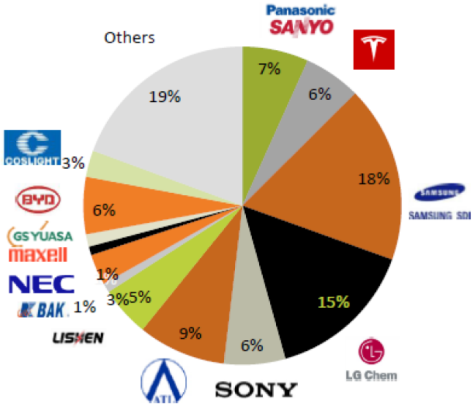
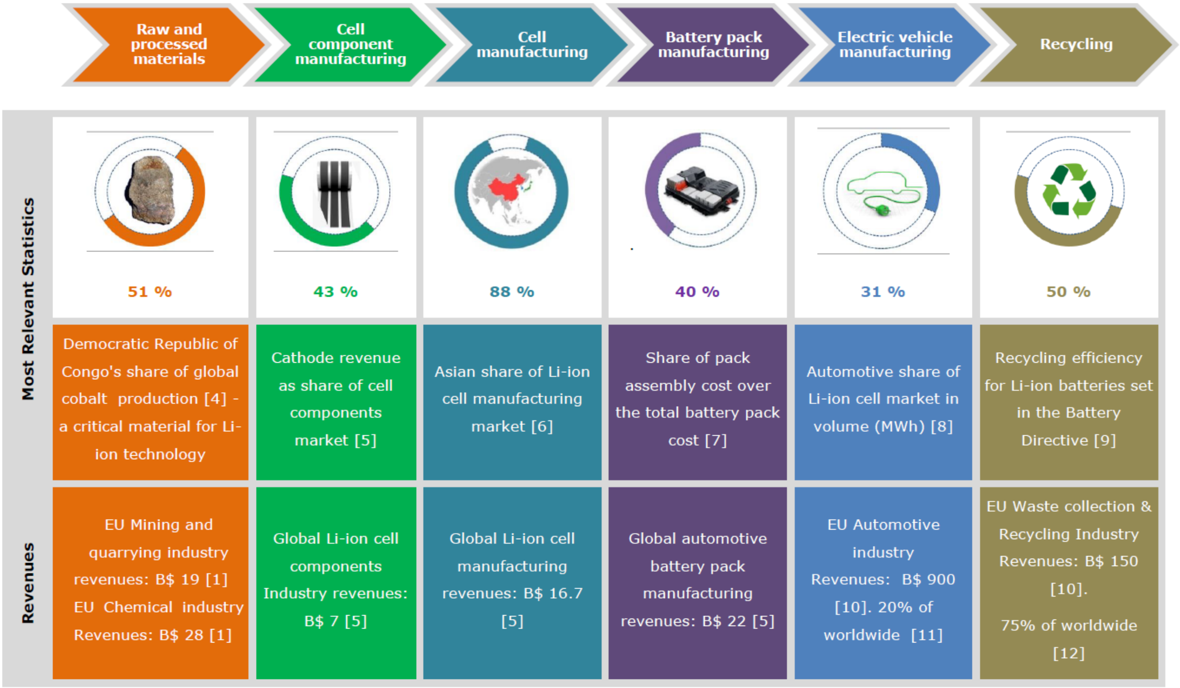


Figure 2: Worldwide Li-Ion battery market: Company market share in 2015 in value ($16.7B) [6]

The automotive lithium-ion battery value chain is shown in Figure 3.



	Raw and processed materials	Cell component manufacturing	Cell manufacturing	Battery pack manufacturing	Electric vehicle manufacturing	Recycling
Most Relevant Statistics	51 %	43 %	88 %	40 %	31 %	50 %
	Democratic Republic of Congo's share of global cobalt production [4] - a critical material for Li-ion technology	Cathode revenue as share of cell components market [5]	Asian share of Li-ion cell manufacturing market [6]	Share of pack assembly cost over the total battery pack cost [7]	Automotive share of Li-ion cell market in volume (MWh) [8]	Recycling efficiency for Li-ion batteries set in the Battery Directive [9]
Revenues	EU Mining and quarrying industry revenues: B$ 19 [1] EU Chemical industry Revenues: B$ 28 [1]	Global Li-ion cell components Industry revenues: B$ 7 [5]	Global Li-ion cell manufacturing revenues: B$ 16.7 [5]	Global automotive battery pack manufacturing revenues: B$ 22 [5]	EU Automotive industry Revenues: B$ 900 [10]. 20% of worldwide [11]	EU Waste collection & Recycling Industry Revenues: B$ 150 [10]. 75% of worldwide [12]

Figure 3: Automotive lithium-ion battery value chain as of 2015 [6]

Here it is seen via the relevant statistics that the DRC and China are important players in the fabrication of Li-ion batteries, with 51% of the cobalt being mined in the DRC and 88% of cell manufacturing occurring in China. This is touched upon again below in this document. It should be noted that these figures are from 2015, and changing market positions between the 6 years of the data and this report would shift the statistics.

1.2.1 Characterization of companies in the battery value chain

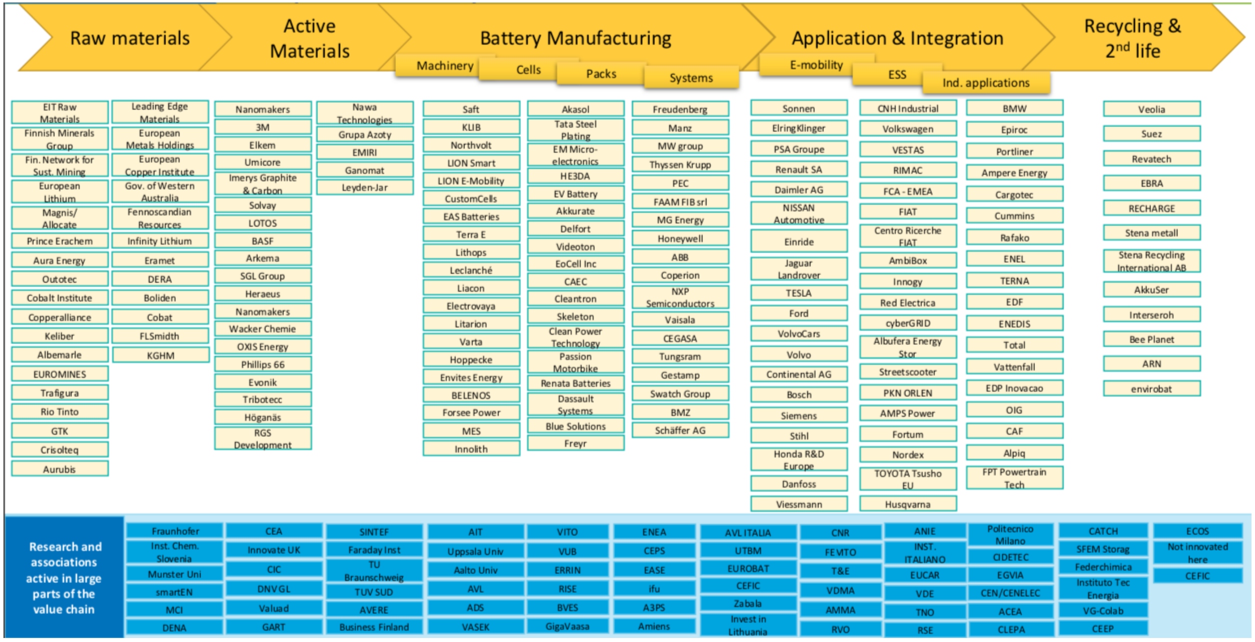


Figure 4: Stakeholders along the supply chain of batteries (Adapted from [7])

Above we can see a vast amount of companies associated within each step of the value chain. This gives a more holistic overview of the companies involved as well as where strategic maneuvers may be needed with them as per a 2nd life battery business model.

1.2.2 Raw materials & Cell component manufacturing

Many materials are used to produce Li-ion batteries. Among them are Cobalt, Carbon, Silicon, Copper and many others. Of these, the first 3 are have high economic importance while also having a high risk of supply and are named "Critical Raw Materials" [6]. Below in Table 1 is a list of the main producers, EU import sources, as well as the substitutability index and end of life recycling rate of the material as of 2015 [6].

Raw material	**Main producers (2014-2015)**	**Main sources of imports into the EU (mainly 2012)**	**Substitutability index**	**End-of-life recycling input rate**
Critical raw materials used in Li-ion batteries				
Cobalt	Democratic Republic of Congo: 51 % China: 6 % Russia: 5 % Canada: 5 % Australia: 5 %	Russia: 96 % (cobalt ores and concentrates) USA: 3 % (cobalt ores and concentrates)	0.71	16 %
Natural graphite	China: 66 % India: 14 % Brazil: 7 %	China: 57 % Brazil: 15 % Norway: 9 %	0.72	0 %
Silicon metal	China: 68 % Russia: 8 % USA: 5 % Norway: 4 %	Norway: 38 % Brazil: 24 % China: 8 % Russia: 7 %	0.81	0 %
Non-critical raw material used in Li-ion batteries				
Lithium	Australia: 41 % Chile: 36 % Argentina: 12 % China: 7 %	n.a.	n.a.	

Table 1: Main producers, source, substitutability & recycling rate of some CRM's [6]. The closer the substitutability index is closer to 1, the is less substitutable that material is.

The list of CRMs is published by The European Commission and is reviewed and updated every 3 years. An overview of the biggest CRMS to the EU are shown below [8].

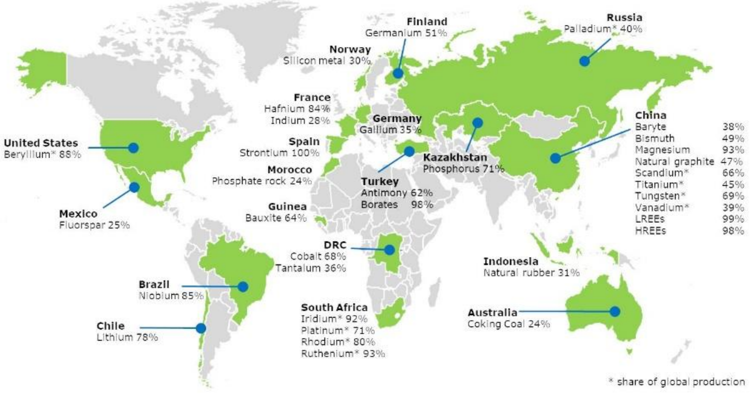


Figure 5: Biggest supplier countries of CRMs to the EU [8]

The report states that at estimated demand rates for raw materials (following the EU’s climate-neutrality scenarios for 2050), the EU would need up to 18x more Lithium and 5x more cobalt in 2030. This increase in demand can lead to supply issues if not addressed properly.

Below is a brief description of some CRMs.

1.2.2.1 Lithium

The 27th most abundant element in the earth’s crust. It is the lightest of all the metals with the greatest electrochemical potential while providing the largest energy density [3].

It is usually extracted from hard rock (spodumene) or brine. The former has most of its reserves in Australia, while the latter have its reserves in Chile, Argentina and China [9].

In general, the supply chain includes refining the lithium into lithium carbonate. This is then purified into other precursors used by the cathode active material & electrolyte manufactures. Lithium carbonate has been used mostly because of the higher cost of producing other compounds like lithium hydroxide. In fact, lithium carbonate is used as a precursor to lithium hydroxide.

As it stands, current reserves allow for the increase in its demand over the next decade even without the recovery of lithium from the recycling of Li-ion batteries. As of 2015, this was feasible, but not economically viable enough to be implemented [6]. By context of the latest EU regulations described in the “Analysis of latest EU directive” section that the increase in recovery rates must more than double, indicates that the focus will shift stronger towards its economic viability.

Lithium production is also geologically influenced as only a few countries hold the majority of the supply as seen in Figure 6 Figure 7. It can be seen that the majority of it is produced in Australia, Chile, Argentina and China.

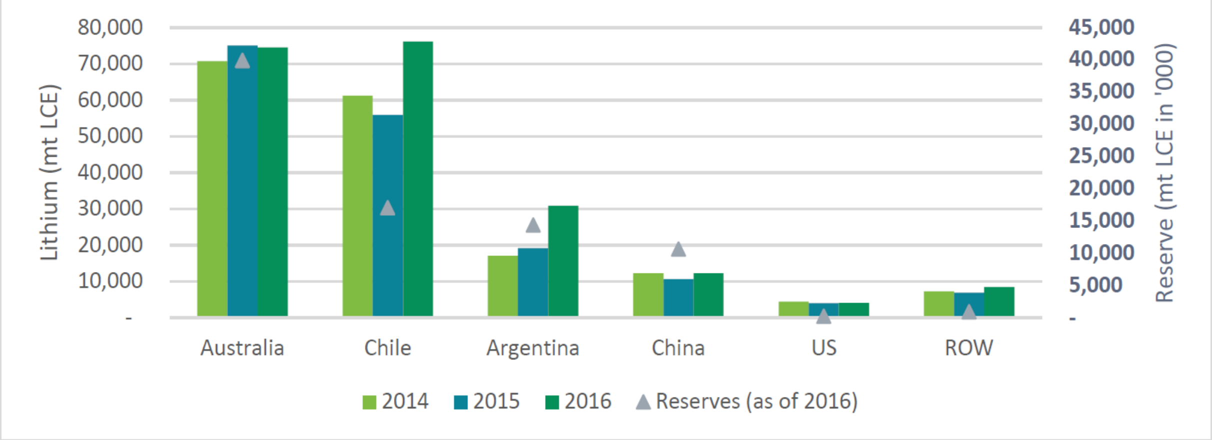


Figure 6:Lithium reserves and mine production [9].

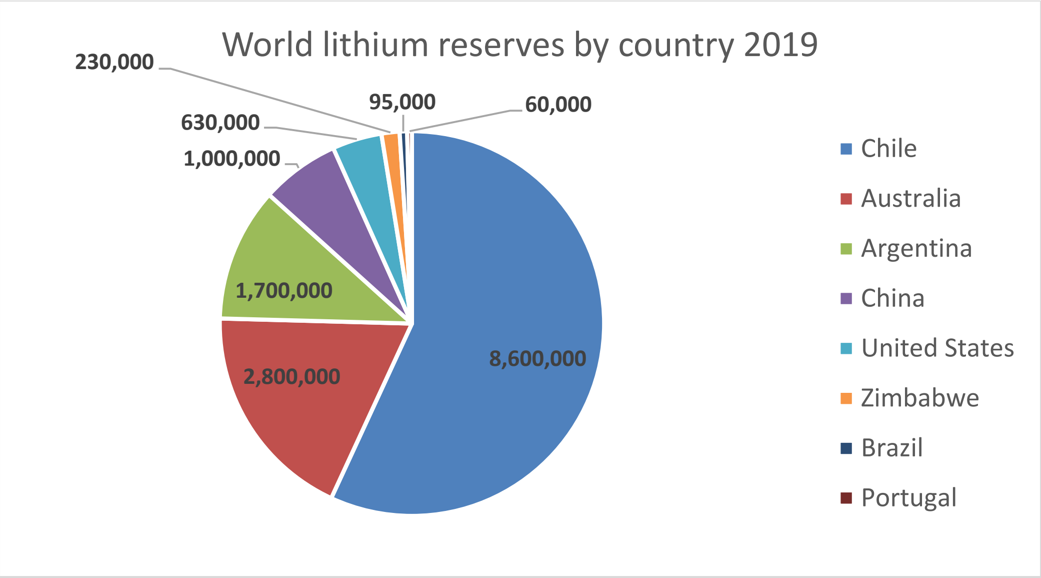


Figure 7: Countries with the largest lithium reserves worldwide as of 2019 [10]

1.2.2.2 Cobalt

Cobalt is a widely used metal and has its biggest share of use in batteries, with an identified terrestrial resource of about 25 million tons [6]. Its demand for Li-ion batteries for EV's increased 191% during the period of 2014 to 2016 [9]. Most deposits of cobalt are in the "Central African Copper belt". This includes The Democratic Republic of Congo (DRC) and Zambia. The DRC led the world in being the mining source for cobalt. It currently stands at 68% of global mined cobalt, with a value upwards of $4.5 billion [9]. The production of cobalt in their respective countries are seen in Figure 8 where it shows that its production is vastly dependent on the DRC.

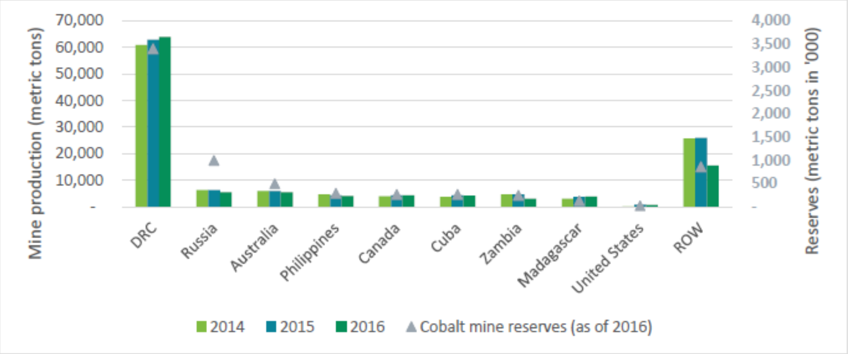


Figure 8: Cobalt reserves and mine production [9].

The specific supply chain for cobalt in Li-ion batteries is shown in Figure 9

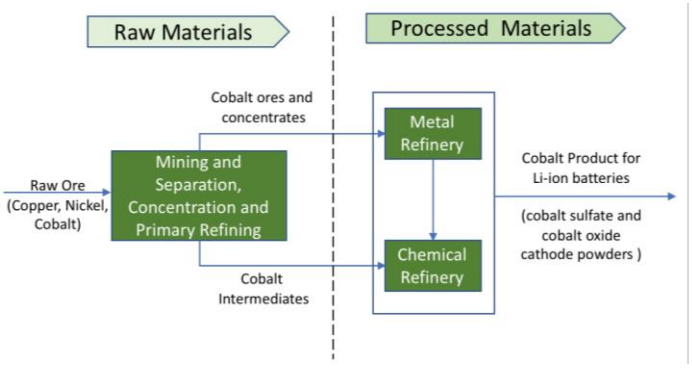


Figure 9:Cobalt supply chain in Li-ion battery manufacturing [9].

It is shown that the cobalt is received from raw ore, separated into cobalt ores and intermediaries, where it is them refined and produced for Li-ion batteries.

The majority of the mines in DRC are owned by Chinese companies. These include [9]:

China Molybdenum	Zheijiang Huayou Cobalt	Jinchuan Group	Shalina Resource	Wanbao Mining	Hanrui Cobalt
CMOC	华友钴业 HUAYOU COBALT	JINCHUAN金川	Shalina	WANBAO MINING	HANRUI COBALT 寒锐钴业

1.2.2.3 *Natural graphite*

Natural graphite shares 4% of its applications as an anode active material in batteries [6]. It's inferred that over 800 million tons of recoverable graphite exist, of which 230,000 tons of natural graphite exist whereas 1190 tons were mined as of 2015 [11].

Historically, 70% of graphite has been mined in China, whereas almost all of the anode material of graphite is processed there [12].

1.2.2.4 *Silicon metal*

Silicon metal and alloys are emerging as anode active materials to be used in Li-ion battery cells. It has a low substitutability index of 0.81 meaning that it's difficult to replace for the use of Li-ion batteries. Its end of life recycling input rate is at 0% as of 2015 [6]. This would indicate that there's a growing scarcity, but Silicon is a very abundant material and so there's not much incentive to use it as a recovered material.

1.2.2.5 *Cadmium*

Social concerns exist with the use of heavy metals such as cadmium as it is classified as a cancerous substance by the European Commission [13]. This is what fueled stricter recycling targets for lead-acid and nickel-cadmium batteries. In the USA, fines up to $10.000 can be given out for violators of these targets [14]. Nonetheless, research is being done to synthesize li-ion batteries with it and it has currently been shown that a cadmium-based coordination polymer can be made to serve as electrode materials for Li-ion batteries; specifically as an anode material [15].

1.2.2.6 *Titanium*

Used as an anode, it is not the most critical material and is ranked as the 9th most abundant earth crust element (with oxygen being the most) [5]. This abundancy makes it suitable to substitute carbon-based anode materials [16]. Development has been limited due to the low transport kinetics and low electric conductivity of Li-ion batteries. It is important to improve the electrochemical properties of anode materials to meet increasing demands of Li-ion batteries. Currently, a lot of research is being done into TiO_2 as an anode material. A synthesized version of TiO_2 has been shown to display high cycling stability and capacity retention [16].

1.2.2.7 Manganese & Nickel

LMO, a cathode precursor, is a common Li-ion type used in various types of electric vehicles, e-bikes, power tools and medical devices and has been one of the cheaper options in comparison to some other battery types [14] [5]. Lithium-Nickel-Manganese-Cobalt-Oxide (NMC) batteries also exhibit desirable characteristics for specific applications, and also dominates in the EV and PHEV markets while at the same time operating in those of the LMO markets. Projections also exist for grid use [5].

Due to its higher thermal stability, LMO's are generally more safer as thermal runaway only occurs around 250°C [5]. Not to mention that LMO's relies on abundant and environmentally friendly materials.

1.2.3 Cell & battery pack manufacturing

Li-ion batteries are typically made either as pouch or cylindrical cells as shown in Figure 10.

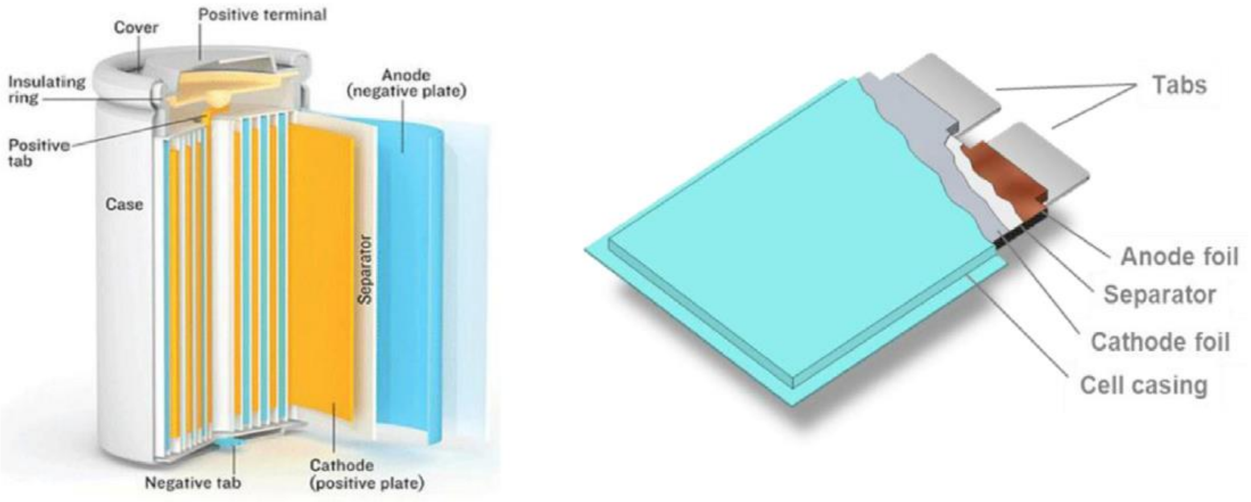


Figure 10: Li-ion battery cell configurations [5]

The pouch has the anode, cathode and separator enclosed within a laminate film, while the cylindrical has these components rolled and encased into a metal enclosure [5].

1.3 MARKET

The total rechargeable battery market worldwide was valued at €73B where €32B (44%) comprised of Li-Ion batteries [17] [18].

Mobility, such as that which is used for vehicles as well as stationary storage has been arising as interesting areas for batteries as well. As can be seen in Figure 11, the majority of battery demand is within the BEV sector. Furthermore, sales for Li-ion battery cells mobility and stationary applications are projected to have an exponential growth, with a valuation between €40 to €65B in 2025 [19] [20], or even $70B is by 2022 [21].

As the world transitions to more solutions away from the traditional use of gasoline, EV's are expected to get a boost from EU regulations that are pushing for further electrification of energy sources and energy efficiency which leads to the projection that EV's will demand up to 95% of Li-ion batteries by 2030, compared to the 55% as of 2020 [17].

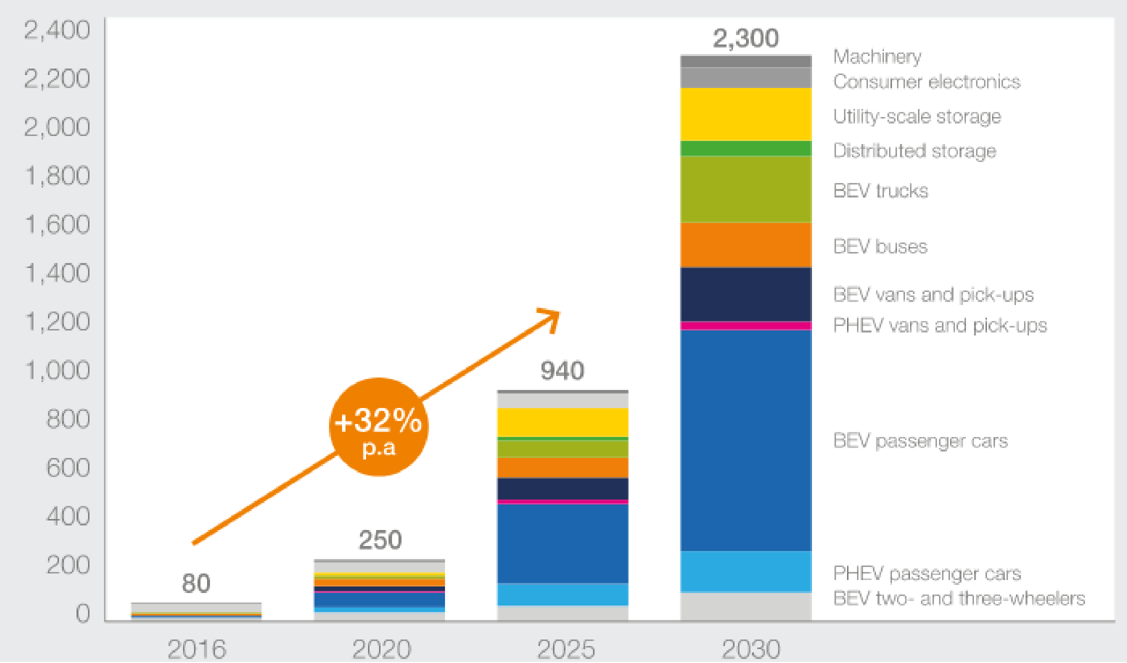


Figure 11: Annual battery demand: electric mobility segments, stationary battery storage, consumer electronics, and machinery [GWh/yr] [22]

There is still a lot of R&I being done in the field of battery chemistry to advance the technology. Chemistries that are most promising often include:

- Lithium metal batteries;
    - With a capacity beyond 10x that of LiC_6 anodes used as of 2015, these need to undergo more research to stabilize the anode in the cells. Other challenges include parasitic reactions in the liquid electrolytes, low cycling efficiency, dendrite formation and dendrite induced short circuits in the batteries [23] [6].
- Solid State Batteries
    - With higher current densities and quicker charging times, there are still challenges in the fundamental understanding of the technology and manufacturing. One of which stem from its high operational temperature requirement (80 °C), another from its rate capability whereas it seems to prevent fast charging and low thermodynamic stability of its inorganic solid electrolytes. [6].
- Lithium-air (Li-air)
    - This uses oxygen from air, and has the potential to yield the highest energy density of any battery technology. Though there is still a significant lack of understanding the technology [6].
- Lithium Sulphur (Li-S) batteries.
    - Being the most promising of the abovementioned, specifically for its low cost and high energy density, fundamental challenges do still exist for the technology.

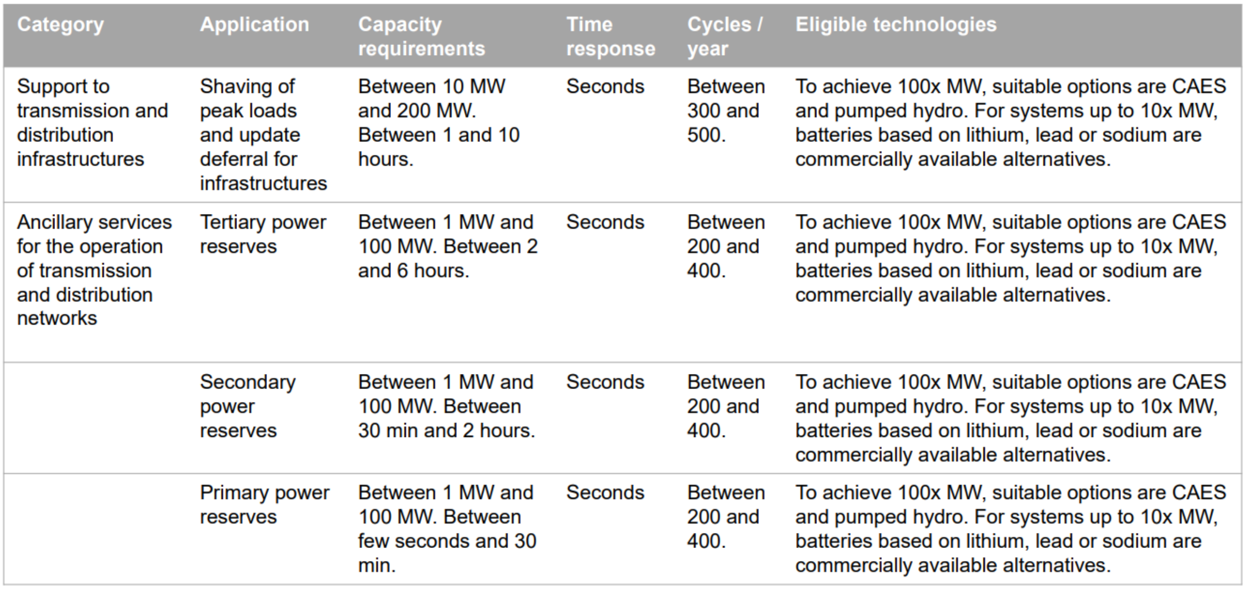
Historically the time it takes from conception to market for new batteries range between 10 to 20 years [19]. As of 2015, there has been no significant manufacturing base for the new technologies, leaving the potential to be there for Europe to take hold, as no significant barrier to entry seems to exist [6].

2 TOWARDS A BUSINESS MODEL FOR 2ND LIFE BATTERIES

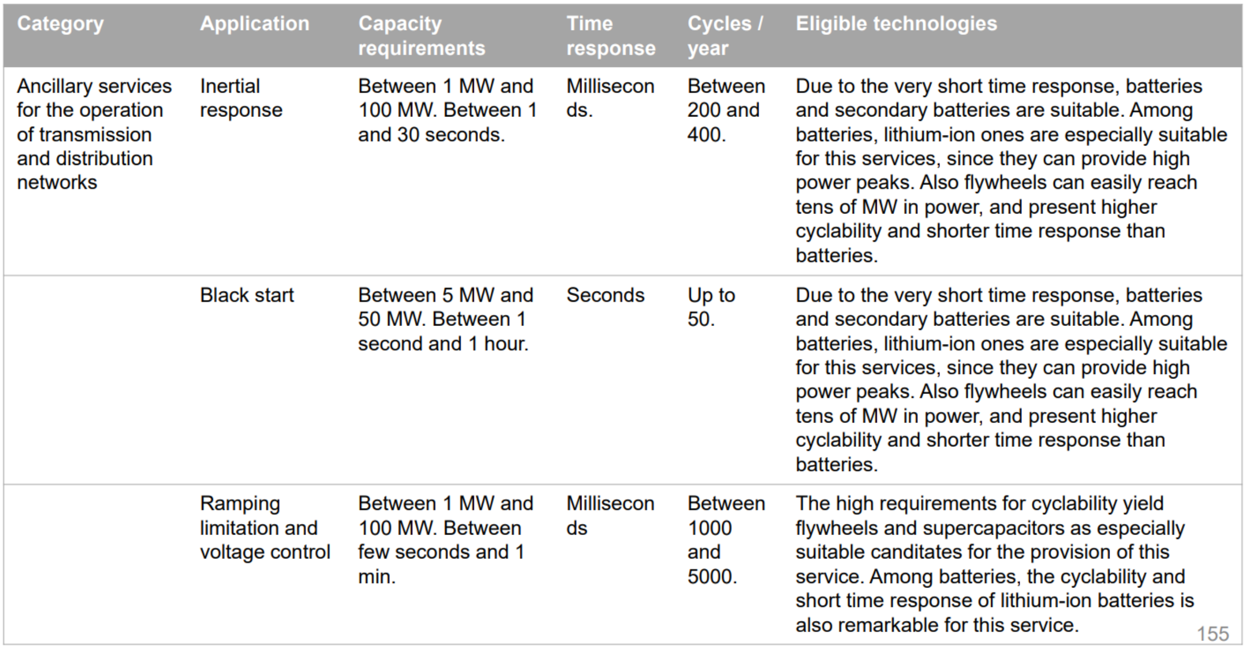
As referenced above, in the upcoming years, the share of electric mobility will dominate the market for the foreseeable future. Therefore, a business model must be defined for 2nd life batteries in the field of mobility or stationary storage, and not in consumer electronics.

2.1 POTENTIAL APPLICATIONS

Various applications for 2nd life batteries exist, and each of them can be turned into viable business models;



Category	Application	Capacity requirements	Time response	Cycles / year	Eligible technologies
Support to transmission and distribution infrastructures	Shaving of peak loads and update deferral for infrastructures	Between 10 MW and 200 MW. Between 1 and 10 hours.	Seconds	Between 300 and 500.	To achieve 100x MW, suitable options are CAES and pumped hydro. For systems up to 10x MW, batteries based on lithium, lead or sodium are commercially available alternatives.
Ancillary services for the operation of transmission and distribution networks	Tertiary power reserves	Between 1 MW and 100 MW. Between 2 and 6 hours.	Seconds	Between 200 and 400.	To achieve 100x MW, suitable options are CAES and pumped hydro. For systems up to 10x MW, batteries based on lithium, lead or sodium are commercially available alternatives.
	Secondary power reserves	Between 1 MW and 100 MW. Between 30 min and 2 hours.	Seconds	Between 200 and 400.	To achieve 100x MW, suitable options are CAES and pumped hydro. For systems up to 10x MW, batteries based on lithium, lead or sodium are commercially available alternatives.
	Primary power reserves	Between 1 MW and 100 MW. Between few seconds and 30 min.	Seconds	Between 200 and 400.	To achieve 100x MW, suitable options are CAES and pumped hydro. For systems up to 10x MW, batteries based on lithium, lead or sodium are commercially available alternatives.



Category	Application	Capacity requirements	Time response	Cycles / year	Eligible technologies
Ancillary services for the operation of transmission and distribution networks	Inertial response	Between 1 MW and 100 MW. Between 1 and 30 seconds.	Milliseconds.	Between 200 and 400.	Due to the very short time response, batteries and secondary batteries are suitable. Among batteries, lithium-ion ones are especially suitable for this services, since they can provide high power peaks. Also flywheels can easily reach tens of MW in power, and present higher cyclability and shorter time response than batteries.
	Black start	Between 5 MW and 50 MW. Between 1 second and 1 hour.	Seconds	Up to 50.	Due to the very short time response, batteries and secondary batteries are suitable. Among batteries, lithium-ion ones are especially suitable for this services, since they can provide high power peaks. Also flywheels can easily reach tens of MW in power, and present higher cyclability and shorter time response than batteries.
	Ramping limitation and voltage control	Between 1 MW and 100 MW. Between few seconds and 1 min.	Milliseconds	Between 1000 and 5000.	The high requirements for cyclability yield flywheels and supercapacitors as especially suitable canditates for the provision of this service. Among batteries, the cyclability and short time response of lithium-ion batteries is also remarkable for this service.

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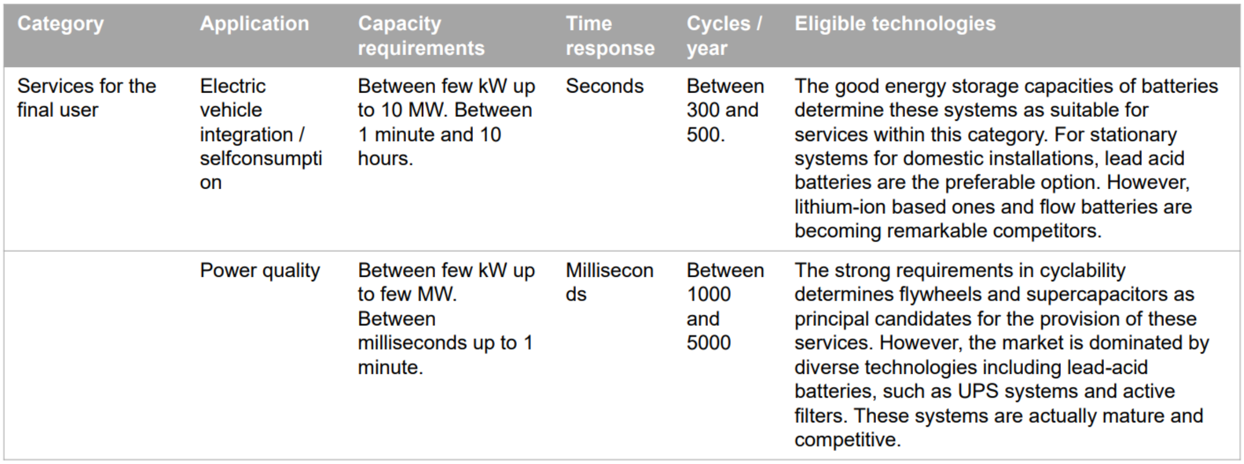


Category	Application	Capacity requirements	Time response	Cycles / year	Eligible technologies
Services for the final user	Electric vehicle integration / selfconsumption	Between few kW up to 10 MW. Between 1 minute and 10 hours.	Seconds	Between 300 and 500.	The good energy storage capacities of batteries determine these systems as suitable for services within this category. For stationary systems for domestic installations, lead acid batteries are the preferable option. However, lithium-ion based ones and flow batteries are becoming remarkable competitors.
	Power quality	Between few kW up to few MW. Between milliseconds up to 1 minute.	Milliseconds	Between 1000 and 5000	The strong requirements in cyclability determines flywheels and supercapacitors as principal candidates for the provision of these services. However, the market is dominated by diverse technologies including lead-acid batteries, such as UPS systems and active filters. These systems are actually mature and competitive.

Table 2: Potential applications with the use of ESS systems [24].

Further application definitions include;

BTM storage

This is where the batteries are used to smooth out the electrical peak demand and ends up reducing electricity costs. The battery is “behind” the meter, meaning that its always charged up for use and the electricity comes through the meter to the battery to the end user [25].

FTM storage

As the name suggests, the ESS is implemented before the electricity goes through the meter to the end user [25]. Used more in terms of utility-scale services, this storage method comprised of frequency regulation, voltage support and storing of excess renewable energy.

Low-power electric vehicles

A form of down-cycling batteries; instead of being used for high demand EVs that require acceleration and range demands, these batteries are instead used to power golf carts or other vehicles like forklifts as they require less power [25].

EV Charging

This is when 2nd life batteries are used to charge virgin batteries at EV charging stations. They help to reduce grid demand from peak hours.

Telecom and data center backups

One of the largest 2nd life application in the world [25], this form allows for backup power for data centers which would need stable power due to their important nature of remaining functional.

2.2 EXISTING PROOF OF CONCEPTS

Figure 12: SUNBATT Container [26]

Figure 13: SUNBATT EV Charging station [26]

SEAT (automotive company) in collaboration with **Endesa** (the electric company) have used 4 PHEV batteries which are installed in a container to provide energy services of about 40 kWh and offer 90kW peak power [27]. This, in partnership with the UPC of Barcelona has led to the SUNBATT; a living lab where the above mentioned batteries are studied and monitored on a micro-grid [26].

This grid consists of;

- A 14kW solar array for energy generation (Generation)
- Electricity distribution grid (Distribution)
- The 4 reused batteries (Storage)
- 3 vehicle charging points (Consumption)

It makes use of an underlying software that optimizes the charging costs for vehicles. If a vehicle needs to be charged at night, then as energy costs are low it will charge from the grid. In contrast if it needs to be charged at peak sunshine during the day when electricity grid prices are high, then it will charge from the batteries or from the PV panels [26]. It also generates information pertaining to CO2 emission reductions, bills and other cost equivalents.

As of now, the technology has demonstrated a viable future for discarded EV batteries. Though, changes within electric vehicle battery manufacturing would need to be done for these batteries to be used effectively in their 2nd life [26].

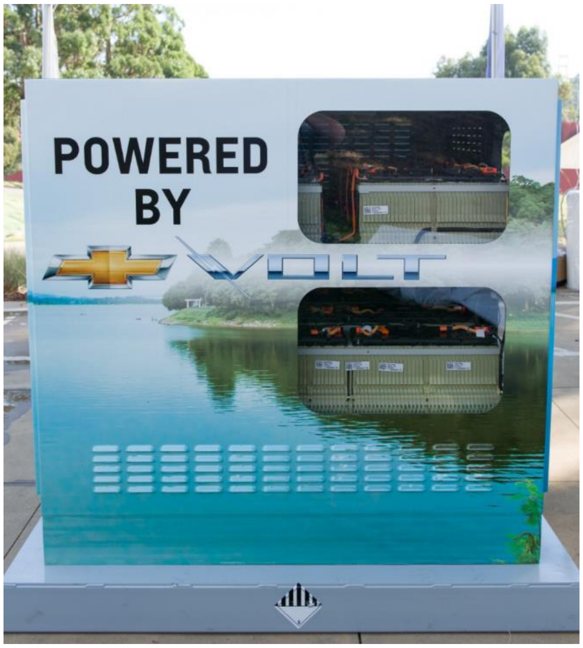


Figure 14: : Image of the storage system by GM and ABB [28]

General motors in collaboration with **ABB** have repackaged 5 used “Chevrolet Volt” batteries into a modular energy storage system that provides uninterrupted power and balances the grid. The prototype is capable of providing 25kW of power and 50kWh of energy for an “off grid” structure used during its showcase [28]

The technology demonstrated that a Chevrolet Volt battery pack could be utilized in collecting energy and delivering supplemental power to homes and businesses. During the latest showcase event, it was able to provide 100% of power for the “off grid” structure.

However, due to the unprofitability of the Chevrolet Volt itself, the production of the car was halted. This of course resulted in GM not pursuing this project further [29].

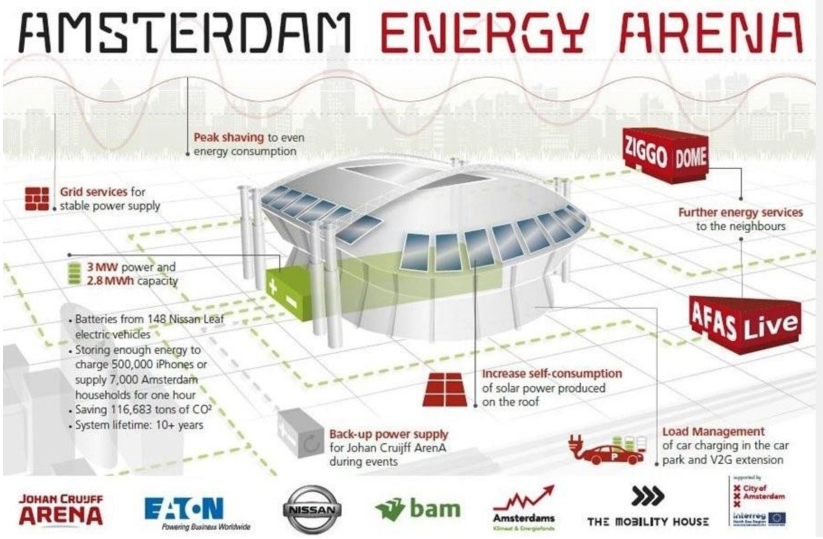


Figure 15: Amsterdam energy arena [30]

Amsterdam Arena uses 148 Nissan LEAF batteries in their 2nd life totaling to 3MW of energy storage for peak shaving during heavy energy use. The batteries are either charged via the grid or via the 4200 solar panels on its roof [30].

Figure 16: Nissan Europe concept art [31]

Nissan's Europe office in France is piloting a container based battery system using 2nd life batteries. Their system comprises of 12 Nissan LEAF batteries, totaling to a capacity of 192kWh [31]. Their aim is to determine the scalability of this system with the tests still ongoing.

2.3 INDUSTRY BARRIERS

ESS's such as batteries will be playing a major role in mediating the intermittent nature of energy produced by renewable energy resources. However, barriers do exist. The main ones are cited below [13]:

2.3.1 Regulatory & Economic barriers

This pertains to the lack of dedicated regulatory practices towards batteries & the high economic costs of the technology. We observe 3 technical properties and regulations associated with grid connected batteries [13]:

2.3.1.1 Energy rating

Aptly named "Time shift applications" where the ESS is used to store large amounts of energy for future use (usually several hours later). Here, the longevity of the energy capacity and the roundtrip efficiency are crucial for this type of application.

Applications include using nuclear base-load power generation towards pumped hydro storage when there's an excess energy production.

One of regulatory problems are at the European level in the current design of grid tariffs [13]. ESSs can be viewed as either energy producing or energy consuming, as a result in some countries the ESSs will need to pay double the tariffs for access to the network (Eg. Norway), while in another there's only a one-way fee for energy consumption (Eg. France or Germany). At the same time, other countries would charge nothing for the consumption/generation of ESSs (eg. Italy, Spain, UK). This lack of a unified EU framework is of course difficult to navigate, and prevents scalability for ESS solutions.

Another issue is the lack of price signals at the final user level [13]. This entails the fact that the real costs of the power systems are not passed to the end user, leading to the potential flexibility of the ESSs is unusable. If, however smart meters and real time pricing schemes were to roll out more effectively, then the use of ESS and other demand side management systems can be employed.

2.3.1.2 Power rating

Used for power balancing, the ESS is used to equalize the production/consumption of power on the order of minutes. It's important to consider the ability for quick changes between the charge & discharge cycles of the battery. Its main use is for secondary and tertiary frequency control. The regulatory barrier here is the minimum bidding requirements for up and down frequency regulation [13]. If this were to be relaxed, it would allow ESS and other flexibility services to get and provide more value (as the barrier for frequency control via them is lower) and can as a result increase competition. Its desirable that there's more market design improvements such that there's more market access for aggregators. This would make it possible for small scale flexibility storage markets to exist at the transmission and distribution network level [13]. Of course, DSO's should be notified if there's going to be a usage of a grid flexibility system to ensure that market schedules are not in conflict with operation constraints. Therefore, TSOs and DSOs will also need to be considered when developing the abovementioned desired framework.

2.3.1.3 Response time

Here, the system is utilized for pulse power for grid services. Therefore, the response time of the ESS is important and is the main technical requirement for this type of application. The provision of current frequency regulation services at the TSO level is an example of how this system is used. The regulatory issues are similar to that of the "Time shift applications"; there's no homogenous rule as to remuneration of primary regulation. Some countries have it mandatory, other countries have it in terms of bilateral contracts.

2.3.1.4 Permits

As a grid connected system: the ESS should be certified in GCC class II or I according to the “DNVGL-SE-0124” [32].

In the case of Microgrid operation, the ESS system should be able to balance generation and consumption: Island mode. It needs to be able to detect (unintentional) islanding in the event of a failure and stop such a situation to comply with the grid code.

It should be able to start itself up to energize the microgrid from a “black start”.

In terms of Lithium cells, IEC 60896 and IEC 62660-1 state that 80% is the EOL capacity, while IEC 6260 and IEC 61960 allow down to 60% remaining capacity to meet the EOL criteria. IEC 6260 applies to large format lithium cells and batteries for use in industrial applications. This would in fact mean that a market could be made for using batteries that are at 80% capacity to be used in this industry. Once adhered to, various product testing and certification headquarters can be contacted and used for attaining the proper permits.

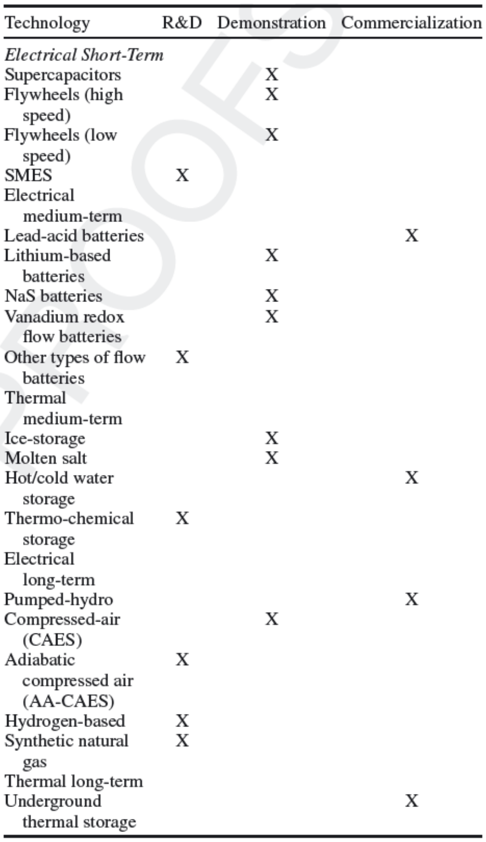
2.3.2 Geopolitical Barriers

Pertaining to the supply chain of raw materials. Rare earth mining as well as the ecological & social impacts are then barriers for ESSs.

2.3.3 Technological barriers

Pertaining to the R&I required towards improving the technology.

As can be seen in the figure below, few of the storage technologies are beyond the demonstration phase and are being commercialized. [13]. It is worth noting, that Lithium-based batteries have seen a surge in recent years where it is currently being commercialized, and Adiabatic Compressed Air is currently in its demonstration phase [18].



Technology	R&D	Demonstration	Commercialization
Electrical Short-Term			
Supercapacitors		X	
Flywheels (high speed)		X	
Flywheels (low speed)		X	
SMES	X		
Electrical medium-term			
Lead-acid batteries			X
Lithium-based batteries		X	
NaS batteries		X	
Vanadium redox flow batteries		X	
Other types of flow batteries	X		
Thermal medium-term			
Ice-storage		X	
Molten salt		X	
Hot/cold water storage			X
Thermo-chemical storage	X		
Electrical long-term			
Pumped-hydro			X
Compressed-air (CAES)		X	
Adiabatic compressed air (AA-CAES)	X		
Hydrogen-based	X		
Synthetic natural gas	X		
Thermal long-term			
Underground thermal storage			X

Figure 17:Classification of storage technologies according to their maturity (2013) [13]

2.4 BUSINESS MODELING METHODS

A distinction must be made between a business model, and a business model framework.
"A ***business model*** *describes the rational of how an organization creates, delivers, and captures value, in economic, social, cultural or other contexts."* [33]
A **business model framework** is used to define value streams for the business model. It involves *"the totality of how a company selects its customers defines and differentiates its offerings, defines the tasks it will perform itself and those it will outsource, configures its resource, goes to market, creates utility for customers, and captures profits".* [33]

The most commonly used frame work is the Business Model Canvas, or the Lean Canvas. The Business Model canvas is a visual representation of 9 main building blocks of a business such that it can create value for its customers.

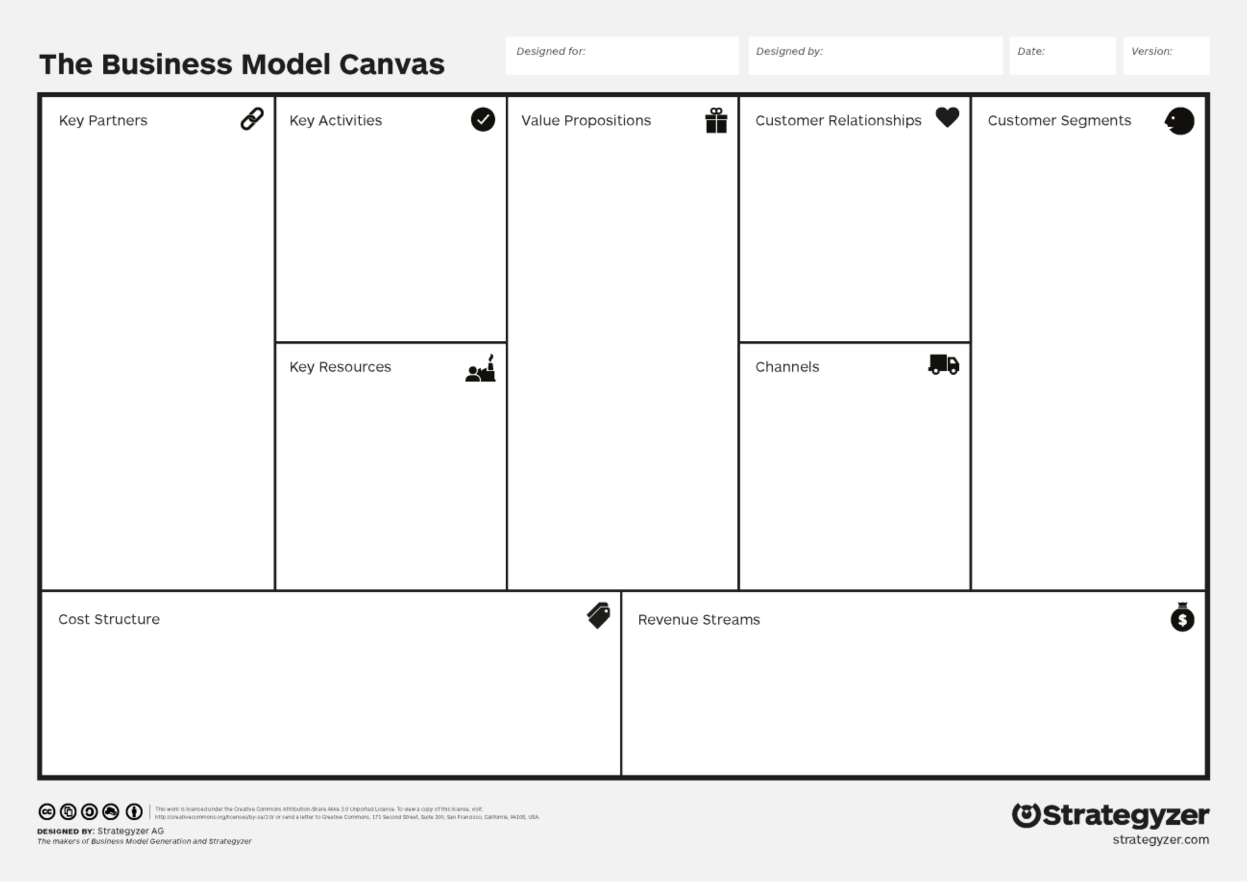


Figure 18: The business Model Canvas [34]

Depending on who is asked, the order of which the canvas is filled out does (not) matter. In this text we will explore the order of which the idea for a business comes first, and after considering the totality of the business, the revenue structure is established. This will be done as follows:

1. Value proposition
2. Customer segments
3. Key partners
4. Key activities
5. Key resources

6. Customer relationships
7. Channels
8. Cost structure
9. Revenue streams
10. (From Lean canvas) High level concept

2.4.1 Application of the business model canvas

Based on the information outlined in this paper, some opportunities can be identified for the use of 2nd life batteries with their specific use cases being.

- Stationary storage for peak shaving of the grid
    - For a city
    - for residential applications.
        - Use for residential PV installations
    - For industrial applications
- Charging stations at bus stops (For cellphones)
- Storage for energy communities
    - For private estates
- Powering water heating systems for hotels
- Refurbishment of the li-ion batteries for 2nd hand electric vehicles.
- The creation of a battery recycling plant in Europe

Stationary storage for energy communities shall be investigated and is indicated in Figure 20.

An energy community comprises of citizens who actively participate in the energy system; a type of organizing collective of citizen actions in the energy system [35]. These would be for instance schools that have PV panels, or windmills installed nearby a village. They can be using small biomass installations or utilize district heating schemes or any combination of the abovementioned and more [35].

2.4.2 Methodology for analysis

Parallel to the writing of this report, a further analysis was being done by the same author on a specific business model case. The economic model used below is adapted from that parallel document from [36].

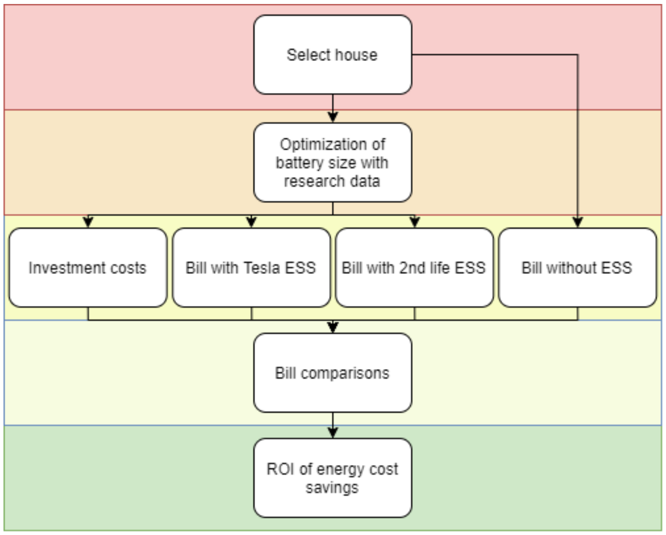


Figure 19: Variable segmentation diagram. Adapted from [36].

- **Select house**
  - Here the residential house is selected. Inputs that are valuable are the energy consumption, the roof solar capacity and the total solar irradiance. Further inputs are
    - Annual energy demand
    - Feed-in-tariff
    - Grid price
- **Optimization of battery size with research data**

  Research papers are used to find information on the typical 2^{nd} life battery power, costs of replacing these batteries, self-discharge rates etc.

- **Investment costs**

  This includes costs of:
  - Storing the battery
  - Operation &maintenance
  - Battery price/kW
  - Ancillary services
  - Installation
- **Bill with Tesla ESS**

  Here, the cost of a Tesla “Power wall” is used with the input parameters of the house.
- **Bill with 2^{nd} life ESS**

  Here, the bill with the use of a 2^{nd} life Li-Ion battery is chosen. Sized according to the input parameters of the house.

- Bill comparisons

  Here, the comparisons of all the costs are made.
- ROI of energy cost savings

  The ROI is calculated by the sum of the investment (C_inv) and battery replacement costs (C_r), divided by the savings gain of having the ESS (G) [36].

$$(C_{inv} + C_r)/G$$

If the ROI is below 7.5 years with a given installation, then it is deemed as a worthwhile investment. This has been found in the parallel report in [36].

2.4.3 The BM Canvas

Key Partners

- *Recycled battery suppliers*
- *Energy community members*
- *Prosumers*
- *Energy auditors*

Key activities

- *R&I*
- *Piloting*
- *Certifications*
- *Implementation*
- *Maintainence*
- *Data aggregation*

Key resources

- *Team (Engineers, Sales etc)*
- *Access to 2nd life batteries*
- *Financial*

Value proposition(s)

Guaranteed energy storage for prosumers

High Level pitch

- *The powerwall for*

Customer relationships

- *Personal B2C*
- *On demand support*

Channels

- *Delivering battery system*
- *Connection to facility/ grid*
- *(Social)Networking*

Customer segments

Prosumers actively connected with their energy community

Cost structure

- Infrastructure costs/ rent (€145/mo [57])
- Battery testing facilities (& equipment)
- Equipment (€1k/y)
- Legal fees (€1.5k)

Revenue streams

- Installation fees
- Insurance fees (for guaranteed operation)
- Pay as discharged

Figure 20: Business Model Canvas

2.4.3.1 Value proposition

The main function of batteries is to provide a means of energy storage. Therefore, guaranteed energy storage via 2nd life batteries for the residence is the foremost value proposition to customers.

2.4.3.2 Customer segments

Many customer segments exist, ranging from TSOs/DSOs, 2nd hand electric vehicles, private enterprise use, data centers, trains, private estates, hotels and more. For the purposes of this report, only the segment of prosumers within energy communities are investigated who use solar PV for their own energy generation.

2.4.3.3 Key partners

The recycled battery suppliers would be needed to receive the discarded Li-ion batteries. They will be the most critical as it's important that there's a reliable supply chain of incoming 2nd life batteries to then be tested, refurbished and then used. The energy community members show merit in terms of networking and having the system implemented without much resistance. Of course, they are the customers and the path to new customers within their domain as well. Prosumers are the abovementioned customers that will be important for retaining the business' financial stability.

Energy auditors both internally and externally shall provide information on the viability of a certain energy community over others and help to objectively benchmark the energy requirements of the solution.

2.4.3.4 Key activities

In the beginning of any project, research must be done. This document serves as an initializing point for this. More concrete information in terms of LCOE, battery sizing and in-house competencies must be known/acquired before entering the market. Furthermore, sourcing and testing the 2nd life batteries are an important activity to determine the expected performance of the battery would be essential. Piloting is a good way to benchmark the solution and validate the potential market acceptance of the idea.

Certifications are required as stated in “Permits” section, as well as compliance with the rules set out in [37] would be necessary. Implementation and maintenance describes the process of integrating the batteries into the facilities for its use. Data is an invaluable asset in today’s world, therefore usage data and battery health will be constantly monitored to ensure that the customer always has a functioning battery system.

2.4.3.5 Key resources

The team’s composition greatly enhances the value of the output it can deliver. Due to the nature of the solution a large amount of money would be needed. This is why a financial investment is necessary to get off the ground. This can be found via investors and grants.

2.4.3.6 Customer relationships

This generic method of maintaining a relationship with a company is through person to person contacts within an organization. To compare with the B2C model here, in order to provide dedicated customer support, it is also assumed that a good relation between the customer and the business is necessary.

2.4.3.7 Channels

This part describes the way the value is brought to the customer, and not the way that customers are communicated with. The actual deliverance and connection of the battery to the grid is necessary, and for valorization and promotion of the customers’ vanity and the business’ success, (Socia)networking is used for value creation. This can range from the use of Facebook (ads, groups, viral memes), Google search, YouTube ads, Instagram, Pinterest and online news websites.

2.4.3.8 Cost structure

The costs described above are generic towards most businesses with the exception of battery testing facilities. These are meant for quality assurance of the ESS’s. The office space is a basic necessity for a company. It is considered to be big enough for about 2-3 years. Post covid-19 though, the question on the need of having actual office spaces is very much prominent. For the sake of simplicity however, it will be assumed that the traditional need will still be there and therefore this cost is taken into account.

In terms of staff, an electrician would be responsible for the installation of all the equipment of the ESS setup at the consumers’ house. The salary shown above is calculated considering a 10€/hour wage for a work week for 48 weeks/year.

This equipment cost is associated with the tools that the electrician would use for installation of the ESS. It is assumed as a safe estimate of the tool requirements for the first year.

The legal fees are approximated according to the costs in different countries of Europe. The legal fees include everything from the cost of registration of the company and all other initial costs before start dealing with customers.

Important employees would include a General director, Finance, Operations, Sales, and Tech managers.

The sum of the total costs would approximate to €132.8k/y year.

2.4.3.9 Revenue streams

Installation fees cover the first time setup and administration of the system. With an installation fee of €3.36k per unit installed (Cheaper than Tesla [38]). Assuming that this would be done in Spain, the price will jump to €5.6k is charged to the client since government would pay 40% of it [39].

Insurance fees are charged to the customer for ensuring that under any circumstances, they will be guaranteed a functioning 2nd life battery. This would be at €50/ 3months. Via simulations performed in [36], every year a minimum of 43 sales must be done to cover costs. The 44th sale would make the company profitable in 1 year. Assuming that there were no sales costs (hardware and installation costs) this would be 36 sales per year. The "pay as discharged" model pertains to having the clients only pay once the battery's capacity is used below a certain percentage (around 60%). Once the customer drains the battery to that level, the price for each kWh after is passed onto the customer. This way, the customer is incentivised to prolong the battery's health, and only use it for peak shaving for a lesser amount of time, while the main source of revenue comes from the operational insurance of the battery.

2.4.4 Results

This document has characterized the various companies that play a role in the creation of Li-Ion batteries, and as a result it is known where the most important materials are found as well as what can be done in terms of using these batteries in their second life.

The analysis performed in [36], written in parallel to this report show that under the assumption of a very lean startup, a profitable business model can be achieved after the sale of approximately five 2^{nd} life batteries with a 7.5-12y ROI. This would be a result of 2 cases. The first where the founders take no salaries, and the more realistic one where they do. In the 2^{nd} case in Figure 21 it can be seen that there is €4.440 deficit in the first year. If the abovementioned sales numbers were to be achieved, a profit of €2480 in the second year can be realized.

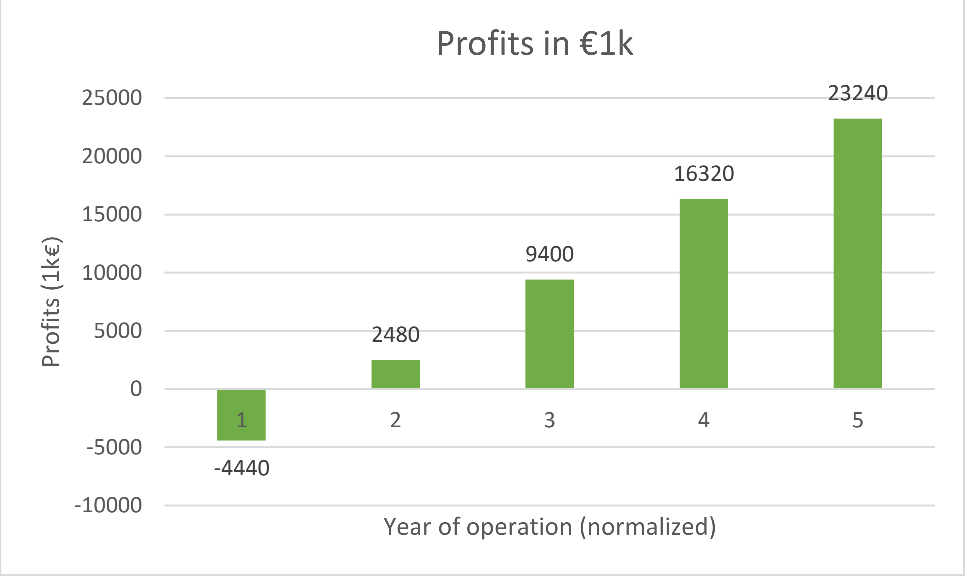


Figure 21: Sales profits of 2nd life business model

This would suggest that that this is a feasible business model with a profitable outlook.

3 CIRCULAR ECONOMY & 2ND LIFE BATTERIES

A circular economy is an economic system in which approach to development is designed such that it benefits environment, society, and businesses as a whole without the continual use of finite resources and is inherently regenerative by design. This is opposed to the linear model of "take-make-use-dispose" that dominates the value chain of materials today [40] [41]. It is estimated that between 112 and 275 GWh per years' worth of energy would be available in 2030 globally from 2nd life batteries [42].

Battery refurbishment began with mobile phones [43]. Up to 90% of returned batteries were easy to be serviced and sold as "b-class" batteries. These batteries show no difference in performance compared to brand new ones and therefore a market of refurbishing batteries was able to flourish. In other fields such as for medical devices or other medical departments, there is a gap between the optimal retention of batteries and the current methods. Without an active battery diagnostics program, irrespective of their condition, batteries are often replaced by the indicated time of expiry. Of course this is good for the battery industry as it allows them to sell more, though because batteries can still function properly after these dates, there's an unnecessary cost incurred by clients (in this example the medical sector) [43].

The life of batteries is mainly dependent on its use and less on time. This therefore already puts "date stamping" at a disadvantage as overused batteries can fail prematurely, and underused batteries to last much longer.

The main indicator of battery health is its capacity, as this also translates to how profitable a refurbished one can be. Between 80-100% is considered good whereas if the capacity is below 80% then it cannot be used for critical applications anymore. Under usage of batteries is quite common and therefore leads to a large waste of battery potential. Concretely, every year approximately 1 million Li-Ion batteries are discarded to be recycled whilst still having up to 80% of their capacity left [43]. These batteries can be used for less demanding services such as stationary storage. This would be anywhere above 50-60% of its capacity. Below which the capacity drops rapidly and may exhibit other issues [43] [44].

A battery's energy storage capacity can be divided into 3 sections.

1. The available energy
    a. This is the energy that can be retrieved instantly
2. Empty zone
    a. This is the portion that can be recharged
3. Unusable "rock content".
    a. This is amount of inactive material that won't contribute to energy provision and is therefore unusable.

Batteries with a reduced capacity charge quicker as there's more unusable rock content. This would be due to many factors such as cell oxidation [44], the growth of the SEI [45] and others.

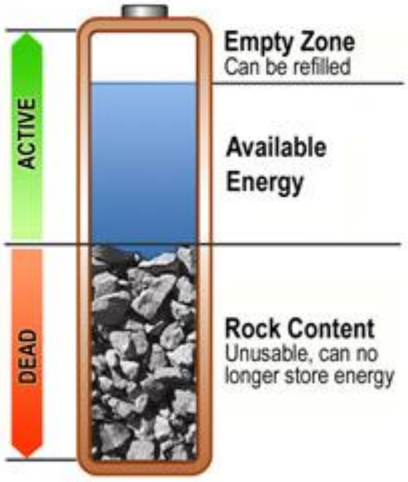


Figure 22: Aging battery illustration [17]

3.1 DEFINITION OF A BATTERY'S "SECOND LIFE"

The operational definition of the battery's second life is defined in this report as; *The use of a battery after being replaced from its primary application, where its state of charge is such that it can be used for a secondary application for an appreciable amount of time before needing to be dismantled and recycled.*

3.2 APPLICATION OF THE CIRCULAR ECONOMY TO BATTERIES

3.2.1 Recycling

When batteries are needed, it must be ensured that they can be manufactured. Towards this end, battery cells are needed which influences demand for raw materials.

At the end of this, a recycling process should be in place to ensure full market acceptance [46].

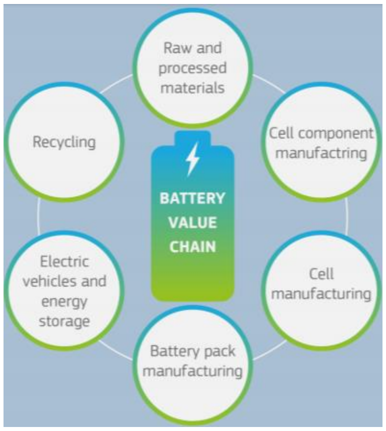


Figure 23: Battery value chain [47]

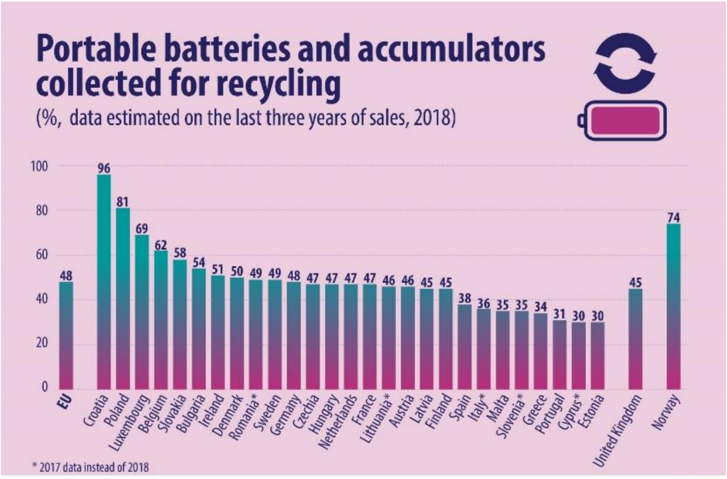
Lithium-ion batteries are rapidly growing in the industry. Due to this, recycling processes and other issues have become quite relevant to the European Union [6]. The benefits of recycling and reuse of batteries may not be as self-evident as it seems and will be further expanded upon in this text.

It is worth noting that the largest environmental impact from batteries is during its manufacturing. The natural gas and electricity required represents 70% of the total kg-CO2 equivalent for the battery's lifetime [13].

Related, there is an increase of producer responsibility. Among other directives, the EU Battery Directive [48] imposes among many others, that all member states collect batteries separately, have them undergo treatment and recycling that complies with regulations, and use economic instruments towards these ends. This introduced the EPR, further expanded upon in the latest regulations in 2020, described in the "Analysis of latest EU directive" section.

Its projected that China will generate 500000 tons of used Li-ion batteries. By 2030, it will be 2M tons per year globally [21]. Most of these batteries may end up in landfills even though Li-ion batteries are recyclable in terms of recovering its materials.

As of 2018, close to 48% of portable batteries sold in the EU were collected for recycling as seen in Figure 24.



ec.europa.eu/eurostat

Figure 24: Portable batteries and accumulators collected for recycling [49]

In contrast to the numbers above, recycling rates of specifically **Li-ion** batteries in the EU and US are around 5% [21] [50].

One of the challenges of battery recycling is the lack of standardization in the process. This is due to the many battery chemistries and formats that exist for the myriad of applications. As such, dismantling and pretreatment of batteries ensue much complexity.

Lithium-ion batteries have been added to the list of pollutants in battery manufacturing [43]. Though the chemistry is only mildly toxic, the sheer volume of Li-Ion batteries that are being produced is of increasing concern.

Large fluctuations on the prices of raw materials used for batteries cast uncertainty on the economics of battery recycling. Specifically, a large drop in Cobalt's price made it more economically viable to make new batteries with the cheaper cobalt than with recycling [21]. As a result the recycling rate for end-of-life cobalt is relatively low at 16% [47].

3.2.2 Benefits

- Reduced dependence on virgin material mining
- Reduced dependence on CRMs like Cobalt
- Materials can make new batteries reducing the manufacturing costs
- Reduction of landfilled material like Cobalt, Nickel Manganese and others which contaminates the soil and ground water [21]
- Reduction of the rate of hazardous waste production from used batteries.

The typical recycling process of Li-ion batteries is shown below:

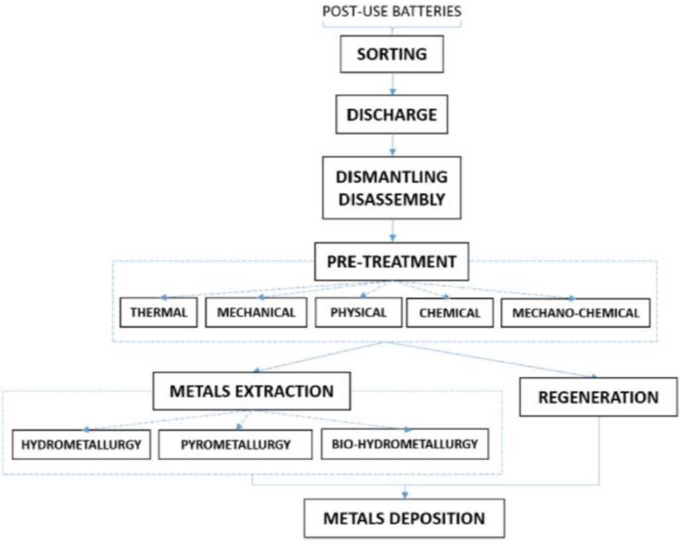


Figure 25: Typical Li-ion battery recycling process [51].

After the sorting, discharging and dismantling of the batteries, they're pretreated through mechanical, thermal, physical, chemical or mechano-chemical processes.

Afterwards the now "enriched" metals fraction is subjected to several solutions towards getting the metals deposition required. On the other side, the regeneration method recycles and directly resynthesizes the powder from the cathodes after a process of "re-lithiation" is done (done via co-precipitation or sol-gel technologies) [51].

The two main recycling processes being the pyro-metallurgy (smelting) and hydrometallurgy [52], as well as bio-hydrometallurgy. Other end of life strategies, include [53]:

- Low value recycling
- Direct physical
- Commingled recycling
- Cryogenic shattering
- Dismantling
- Crushing
- Separating
- Smelting

3.2.3 Costs of recycling

Its estimated that recycling the metals of Li-Ion batteries can save 13% of its cost per kWh. A major driver of the economic value from these metals come from the cathode, representing about 90% of the total value of the battery [51].

Cobalt, Copper, Nickle, steel and aluminum are mostly recycled, while Lithium, Manganese and graphite rarely are. Industrially, recycling recovery profits are at $8900/ton of LCO and NMC chemistries (as they have high cobalt and nickel content, while chemistries like LMO and LFP at $860/ton therefore aren't as attractive as they're approximately 10x less profitable [51].

In this section, the costs of recycling Li-Ion batteries are investigated. Research papers are drawn upon to give an estimate of the generalized recycling costs. Information would be drawn from [51] and likely others.

3.3 ANALYSIS OF LATEST EU DIRECTIVE

In this chapter, some implications and regulations of the latest battery directive by the European Commission [37] will be explored. The regulations shall go into force as of 1 January 2022 and is binding for all member states. From the first battery directive of 2006, the articles 10(3), 12(4), 12(5) continue to apply until 31 December 2023 (besides transmission of data, which will continue until 31 December 2025) as well as article 21(2) will continue to apply until 31 December 2026.

Its notable to mention that at the beginning, its stated that the European Investment bank announced that it expects to increase financing for battery-related research and projects to over €1B as of 2020 [54]. This will of course spur growth and innovation in the field.

The directive aims at addressing 3 interlinked problems related to batteries

1. Lack of incentives to invest in production capacity
    a. This is linked to an insufficient market and playing field due to diverging regulatory frameworks within the internal markets via uneven implementation of the previous batteries directive.
2. Sub optimal recycling systems
    a. As also evident from this report, battery recycling is difficult as they’re not produced in standard ways making it difficult to close the loop. The previous directive was not sufficient to keep up with the newest technological processes and therefore it was not profitable to implement them
3. Social and environmental risks that aren’t already covered within existing EU laws.
    a. This includes;
        i. The lack of transparency on the supply chain of making the batteries
        ii. The hazardous natures of batteries
        iii. “Untapped” potential of the environmental impacts for recycling and offsetting the battery life cycles

In essence these issues are simply due to information failures and market failures. And this seems to be the general guiding principle for the new regulation.

The document includes definitions, requirements, summaries etc.

Article 1 details sustainability requirements, safety and labelling of batteries in the market. Whereas the 4 main categories are now;

- **Portable batteries**
- **Automotive batteries**
- **Electric vehicle batteries**
- **Industrial batteries**

Article 2 contains definitions, *Article 3, 4, 5* are more procedural in terms of defining the principles of free movement of the battery market within the EU, specifics within the requirements, and the designation of a competent authority to deal with the end-of life phase of batteries.
Article 6 pertains to the restrictions on hazardous substances.

This report will not contain an exhaustive description on every rule however some notable ones will be mentioned below:

Article 7 states that batteries with a capacity of 2 kWh shall have documentation on its carbon footprint. This includes information about the producer, geographic location of the manufacturing, the carbon footprint in kg of CO2 equivalent, verification statements and a publicly accessible version of the study towards the carbon footprint declaration results.

This would immediately provide a market for startups to do this exact verification and CO2 calculations as a service for battery producers, and gives a monetary incentive for sustainability analysis in the market. Three main requirements are to be complied with;

- Carbon footprint declaration (As of 1 July 2024)
- Performance classes (As of 1 January 2026)
- Maximum life cycle carbon footprint thresholds (1 January 2026)

Article 8 states that as of 1 January 2027, industrial and EV batteries containing cobalt, lead, nickel or lithium as their active materials shall contain information on how much of said materials have been recovered. Furthermore, there are imposed minimum requirements of the recovered materials in the batteries. The limits are as of 1 January 2030 and change as of 1 January 2035. The minimum share of recovered materials are:

- 12% recovered Cobalt, then raises to 20%
- 85% recovered Lead and stays at 85%
- 4% recovered Lithium, then raises to 10%
- 4% recovered Nickel, then raises to 12%

Article 12 states that stationary battery ESS's must operate safely and include evidence of being successfully tested for defined safety parameters, for which state-of-the-art testing methods should be used.

Article 13 and 14 states the mandatory access to information that is relevant to the battery, and that industrial a vehicle BMS's store information and data needed for determining the state of health and expected lifetimes of the batteries (Also touched upon in **Article 59**). The access to this information has to be available for the purchaser or of a third party evaluating the battery. This is directly in line with the transparency goals of battery production.

The more interesting new provisions that have been implemented are the following articles pertaining to the end-of-life management of batteries.

Article 47, 48 and 49 mandates that battery producers are obliged to "ensure the attainment of the waste management obligations" in line with extended producer responsibility. This means that producers individually or through a "producer responsibility organization" must ensure that all waste portable batteries be collected. This is done irrespective of the battery's nature, brand or origin. Furthermore, they must also establish a network of collection points to receive these EOL batteries, *free of charge to the end-user*. The producers are also obliged to provide for any practical arrangements necessary to collect and transport these batteries from the collection points such that they can be further treated. The same rules apply to all automotive and industrial batteries.

These articles may be one of the most consequential in the field of recycling batteries, as this immediately puts the responsibility of closing the chain back to the producers. The market for collection, testing and repurposing batteries can be better served with such new laws to spur further improvements of recycling.

It’s also good to note that **Article 55** puts the new collection rates of portable batteries to be 65% by 2025 and 70% by 2030. Based on the chart in Figure 24, these targets seem achievable if trends in recycling continue to improve.

A relatively new concept that’s been introduced by the Global Batteries Alliance is the battery passport. It’s a unique electronic record for each individual battery placed on the market. This would entail all information pertaining to the battery as stated in articles above and must be accessible online as per **Article 65**. This passport would enable second life operators to make better decisions towards planning how these batteries can be used. It will facilitate the enforcement of the obligations in the mandate and be useful for market intelligence and other potential business activities towards battery track & tracing.

The reader of this document is advised to read the full text of the regulation by the European Commission [37], where all 79 articles are defined in depth.

It would seem that the latest regulations do in fact add some more force towards producers with a good amount of business models that can be found through intelligently working with the new rules.

Enforcement of these new regulations seem to be up to the member states, as penalties of infringing these rules are not explicitly stated in the new regulation document.

3.4 PROBLEM STATEMENT

As a result of the analysis done before it is apparent that there will be a shift in the markets as per the EU directives. New companies will need to comply as well as existing ones will need to shift their business models around. Particular note will be on articles 12 through 14, 47 through 49, and article 65. In short;

Batteries will be subject to;

- A battery passport
- Recovery by the producers
- A mandatory test for their SoH

This would lead to initiatives for having used batteries be reintroduced into the market as many times as possible to get the biggest return on investment for producing them. However, an important metric is knowing how well the battery will perform after being used from its primary application and it can be inferred that there must be a need for doing these types of tests. Therefore, these initiatives must be equipped with proper methods of battery characterization.

Therefore, in this thesis the general objective is to research the applicability of making a testing device that can eventually feed into battery models to evaluate their SoH using its internal resistance to add value to the abovementioned companies.

Its valuable to have a customizable test that can feed into battery models. With the results of these battery models, the battery can be properly parametrized. Either with a simple battery model or one containing a series resistance and RC block.

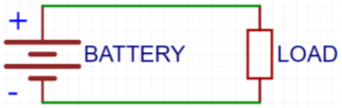


Figure 26: Simple battery model

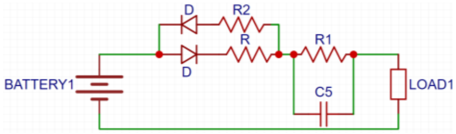


Figure 27: More complicated battery model

4 METHODOLOGY

This section will describe how the overarching methods of executing the R&D of this test bench project as well as a replication in detail as to how each step has been achieved. Below is a block scheme of how it has been done.

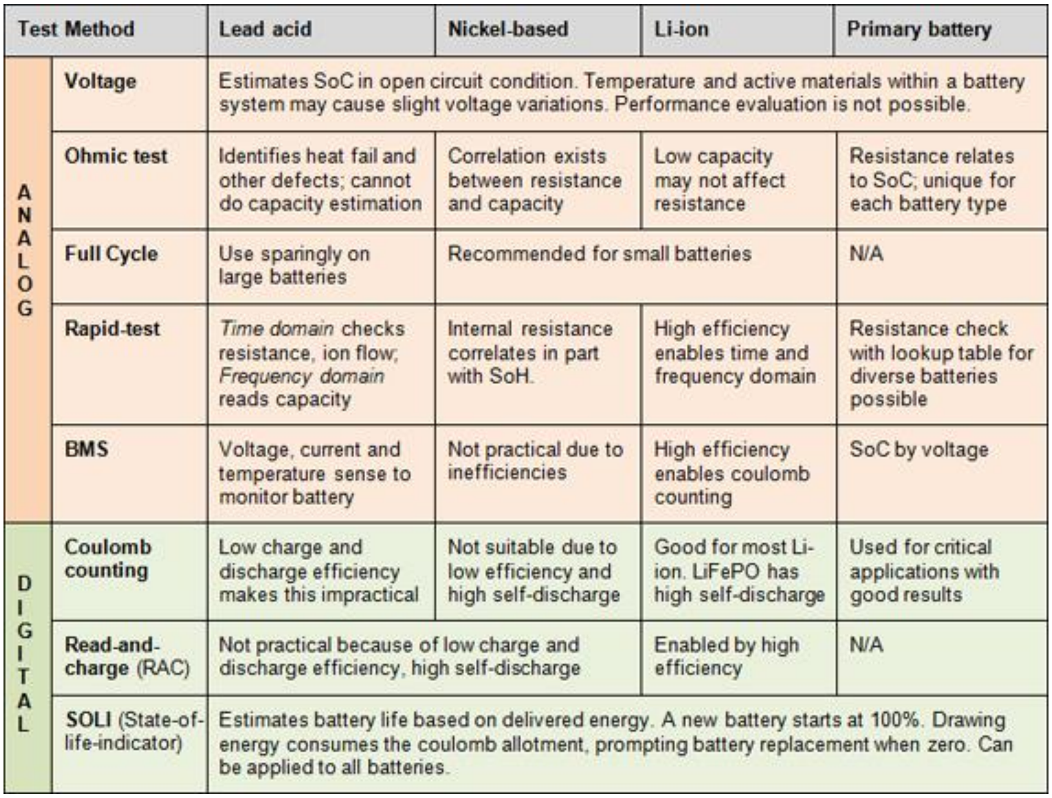
- Setting of objectives
- Investigate most cost effective methods of building the test bench
- Design & simulate the testing circuit to create certain expectations
- Order the components
- Program the microcontroller according to the specified goals
- Plan & execute the test
- Collect the data and analyze the results
- Describe practical limitations
- Validate the hypothesis
- Correlate the data with the known parameters of a Li-ion battery

4.1 STATE OF THE ART CHARACTERIZATION METHODS

Battery testing methods can be done by measuring the internal resistance via an *AC impedance* method, or coulomb counting or Electrochemical Impedance Spectroscopy (EIS) [55]. The term for characterizing batteries is within the field of DBM

Current meters are able to detect the current by using a special ink that passes through it while multi-meters use resistors. Li-ion batteries cannot be measured this way, as the drop in voltage determines if its functional or not, contrary to the drop in current.

The testing methods for common battery chemistries can be seen below.



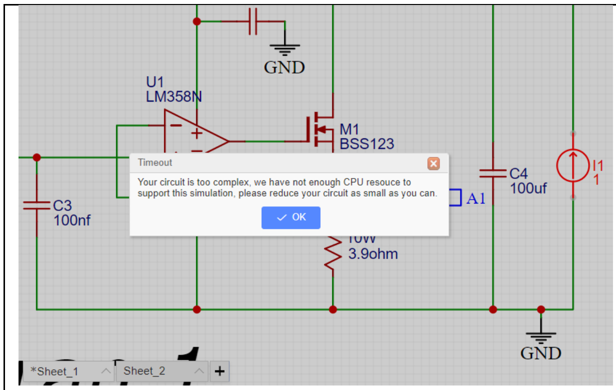
	Test Method	Lead acid	Nickel-based	Li-ion	Primary battery
ANALOG	**Voltage**	Estimates SoC in open circuit condition. Temperature and active materials within a battery system may cause slight voltage variations. Performance evaluation is not possible.			
	Ohmic test	Identifies heat fail and other defects; cannot do capacity estimation	Correlation exists between resistance and capacity	Low capacity may not affect resistance	Resistance relates to SoC; unique for each battery type
	Full Cycle	Use sparingly on large batteries	Recommended for small batteries		N/A
	Rapid-test	*Time domain* checks resistance, ion flow; *Frequency domain* reads capacity	Internal resistance correlates in part with SoH.	High efficiency enables time and frequency domain	Resistance check with lookup table for diverse batteries possible
	BMS	Voltage, current and temperature sense to monitor battery	Not practical due to inefficiencies	High efficiency enables coulomb counting	SoC by voltage
DIGITAL	**Coulomb counting**	Low charge and discharge efficiency makes this impractical	Not suitable due to low efficiency and high self-discharge	Good for most Li-ion. LiFePO has high self-discharge	Used for critical applications with good results
	Read-and-charge (RAC)	Not practical because of low charge and discharge efficiency, high self-discharge		Enabled by high efficiency	N/A
	SOLI (State-of-life-indicator)	Estimates battery life based on delivered energy. A new battery starts at 100%. Drawing energy consumes the coulomb allotment, prompting battery replacement when zero. Can be applied to all batteries.			

Figure 28: Battery test methods [55]

4.2 SIMULATION

4.2.1 Initial mistakes

Initially, I attempted to build the simulation in EasyEDA. I used a current source to simulate the behavior of the battery and an oscilloscope to measure the discharge voltage and current. My first attempt was with the use of an RC filter at the input control signal. This simulation proved unsuccessful as can be seen in the error message in Figure 29.



Timeout

Your circuit is too complex, we have not enough CPU resouce to support this simulation, please reduce your circuit as small as you can.

Figure 29: Simulation timeout error

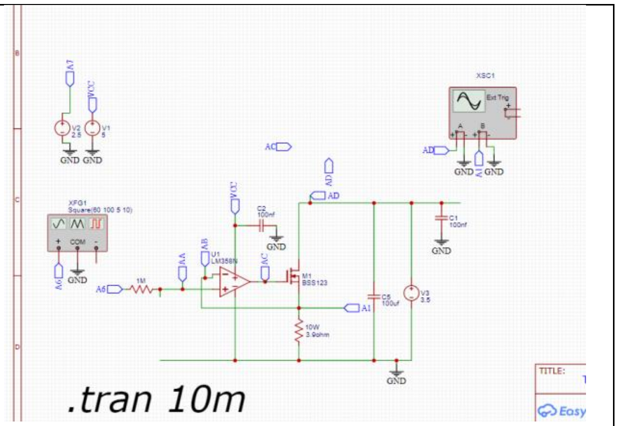


Figure 30: Circuit used for simulation

Upon removing the RC filter, the simulation was able to run. In Figure 30, the wave generator (left) and oscilloscope can be seen (right). Furthermore, additional unconnected “net ports” can be seen. These connect different parts of the circuit together without the need for very long and complex wiring. A7 is used for connecting a 2.5V voltage source to a desired part in the circuit (here unused). VCC provides the 5V DC to the MOSFET. A6 is the control signal, which receives its signal from the wave generator and passes it to the non-inverting output of the op-amp.

It had seemed that AD will always measure the battery voltage no matter what. I wanted to measure the voltage at which is over the resistor; A1 which is always at 1V meaning that I = 1/3.9. AA and AB were **not** equal, though they should be and adding a capacitor did not change that, nor removing the resistor, nor halving the duty cycle, nor changing the C5 value. It turned out that I was using the wrong MOSFET representation entirely.

4.2.2 Correct simulation

By using the simulation tool from Falstad [56], it is possible to quickly and easily create a simulation circuit. This circuit includes a 3.7V voltage source (the 18650 Li-ion battery), a N-Type MOSFET, 3.9Ω resistor, op-amp, ground leads and a square wave generator. This mimics the 490Hz generated by an Arduino Nano's analog pins that generates via PWM its voltage.

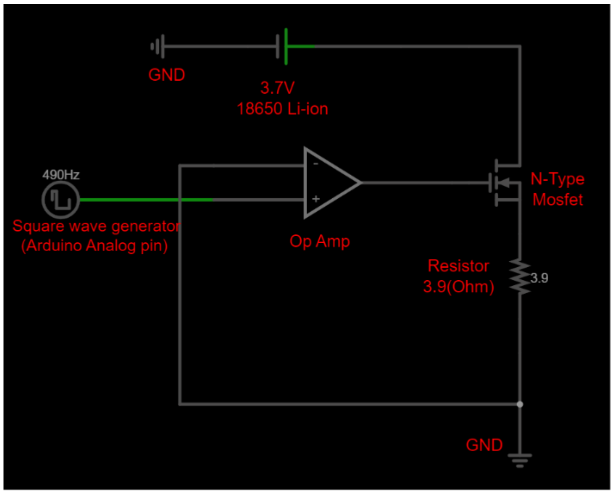


Figure 31: Simulation circtuit for discharging the battery

Via the tool, it is also possible to plot the voltage and current characteristic over time as well as view the average voltage and current.
Given an input source where the op-amp provides a full gate voltage to allow the switch to be open, with the duty cycle at 20%, the max discharge current can be seen as 946.554mA, with the average being 185.597mA. The max discharge voltage being 3.692 where the average voltage is 796.211 mV.

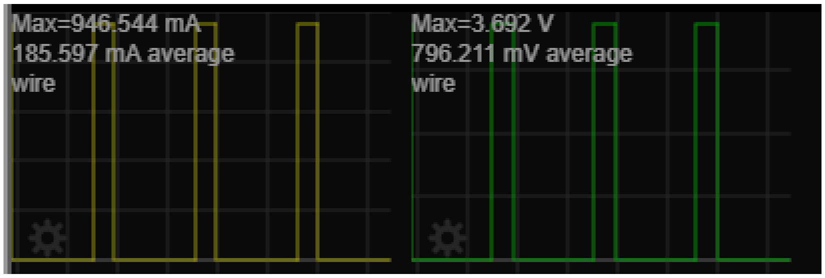


Figure 32: Theoretical results for discharge currents and voltages

Below is a table indicating what the simulated discharge should be. This is assuming that the battery voltage does not decay however. And a practical experiment will need to be done to verify the correlation between the simulation and the result.

Duty cycle	Discharge voltage (mV avg)	Discharge current (mA avg)	Discharge time (expected)
10	370.0963	92.799	34.48313
20	741.924	185.597	17.24166
30	1.104	278.396	11.49442
40	1.475	371.194	8.620829
50	1.846	463.992	6.896671
60	2.217	575.351	5.561822
70	2.588	668.149	4.789351
80	2.95	755.4	4.236166
90	3.321	853	3.751465
100	3.692	946.544	3.38072

Table 3: Simulated discharge currents and voltages

If we want to measure the internal resistance of the battery, we can easily put an Ω meter on both ends and be done with it. That would be a first approximation. A secondary approximation would be to measure the voltage drop over it while a certain current is being drawn. This is what the entire circuit does. We draw a certain amount of current over time, we will also know the voltage drop of the battery over this time, so we can always calculate the total resistance of the circuit. We can measure via the simulation that there is a voltage difference of 8e-3 Ω over the MOSFET. This will also need to be measured over time. This will be done by taking the discrepancy of the voltage calculated by the measured current multiplied by the discharging resistance. If the calculated voltage does not match with the measured voltage, then the difference can be attributed to the MOSFET.

During the measurement, the voltage drop over the discharge resistor will be continuously measured. This way the with the given resistance, we can always calculate the current flowing through the circuit. This therefore allows us to know the internal resistance of the battery during its discharge cycle, as we always know the battery voltage at any given time.
In short it is measured:

- Battery voltage over time (t)
- Voltage drop over discharge resistor over time

Then I will calculate the current I over time, which will lead to the internal resistance over time.

5 BUILDING THE TEST SETUP

Here we describe step for step how the test bench is built up. For this report an 18650 Li-ion battery is selected for testing. This is to prove the concept that it is possible for making such a test bench whereas recommendations will be given on how to scale with larger batteries. The core components needed for the electronic circuit is investigated and described in the Circuit design section as well as their limitations. The principal tool for controlling the discharge process is an Arduino Nano.

We first need to describe the internal structure on how to build up a multi-meter using an Arduino Nano. A method for just a simple Ω meter can be found in [57] and [58]. A voltage meter is done by using the analog input as the positive pole and the ground as a negative pole on the Arduino. The Analog input values will need to be normalized to represent a voltage between 0 and 5V. If higher voltages are to be read, it must first be fed through a voltage divider that steps the voltage down to 5V where the normalization and recalculation of the voltage can be done within the code.
The testing circuit will be built up as an adaptation to [59] , [60], and [61].

My setup includes:

- Different code for running the different tests
- Different discharge load resistor (10W, 3.9Ω)
- The use of an SD card logger for the data
- Buzzer
- Integrated charging circuit

5.1 CIRCUIT DESIGN

Here, we describe the components used within the circuit. In the figure below, the circuit diagram can be seen. The components and their functions are described below. Luckily, all of the components can be purchased online and the setup can be done with some programming know-how and circuit design.

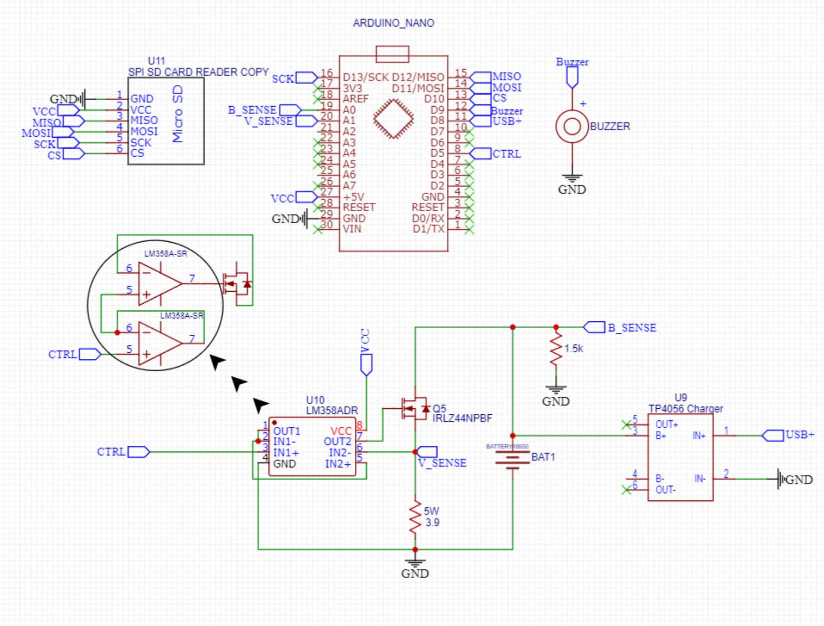


Figure 33: Circuit diagram for the battery tester

A photo of the physical circuit design can be found in Figure 42 in the Appendix.

18650 Li-ion battery

This will be the battery that I will be testing. A typical acceptable internal resistance of a good 18650 battery cell is about 35mΩ [62]. Typical battery cells have a voltage of 3.67V. The cell that will be used for this thesis will be 3200mAh, with a max discharge current of 10A, with a minimum cutoff voltage of 2.5V.

Battery holder

This holds the li-ion battery in place where the + and – terminals are connected according to the circuit's design.

TP4056 Li-ion charger

This is to charge the li-ion battery to then run the test. This is a cheap and easy to use board with little need for instructions. It can also be used with an Arduino to have a control signal sent to charge/discharge a battery.

Arduino Nano

This is the board that will be doing the computations. These are microcontrollers that allow for a wide range of uses in the field of electronics. It can be used to measure and control sensors, actuators, internet protocols, do calculations, and almost anything in between. I've experience with using and coding Arduino microcontrollers including the Arduino Mega2560, Arduino Due, ESP32 Cam, and Nano. The Nano is the cheapest version available and due to this project not needing many external devices, there's not many pins required. This is the main factor for using this board compared to the others like a Mega2560, as there would be a larger board for little benefit.

Breadboard

This will first be used to validate the circuit. It is possible to a physical PCB from Easy EDA, EDA being **E**lectronic **D**esign **A**utomation. Where all the pins and connectors are soldered and a market-ready product can in fact be made.

Mosfet (IRLZ44NPBF)

This is to send the signal to begin discharging or not (x)

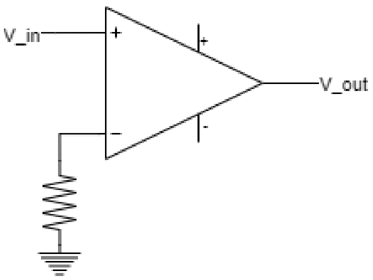
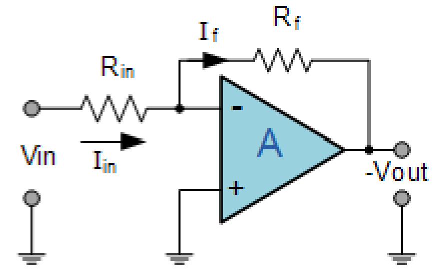
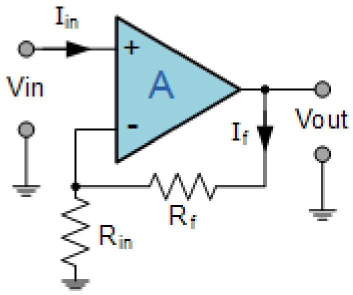
OpAmp LM358 (MRIN)

Operational Amplifiers (Op-Amps) allow for boosting a signal of well over 100.000x. [63].
Their construction is that of a 3 terminal device, with 1 output and 2 inputs. These are not including the power connections which would have a positive and negative pole. There are 3 main characteristics attributable to op-amps.

1. Infinite input impedance; This means that there will be no current that flows through either of its 2 inputs.
2. Zero input offset voltage; this means that between its 2 input voltages, there will be no difference.
3. Zero output impedance; this means that there will be no current that flows out from its output.

When the op amp is in an open loop state; there's no feedback to its input and the gain will be as high as possible. Closing this open loop by adding a resistive or reactive component between the output and the input allows for greater control of the aforementioned gain.

Normally, there are two ways an Op-Amp is connected in a closed loop as shown in the figures Figure 34: Open loop op amp configuration.

Open Loop	*Inverting Op-amp*	*Non-inverting Op-amp*
 *Figure 34: Open loop op amp configuration*	 *Figure 35: Inverting op amp configuration [63]*	 *Figure 36: Non-inverting Op-amp [63]*

In the inverting mode, the feedback voltage allows for an overall gain (A) of the signal as;

$$A = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_{in}}$$

For the non-inverting mode, the feedback voltage results in an overall reduction of the amplification as;

$$A = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

By way of the formulas it can be seen that by varying the resistances, the gain can be adjusted. It can also be seen that by connecting the output directly to the negative input terminal with the signal also going into the negative terminal, the amplification is equal to 1. This is a called a voltage follower circuit and is characteristic of the current circuit design that is used.

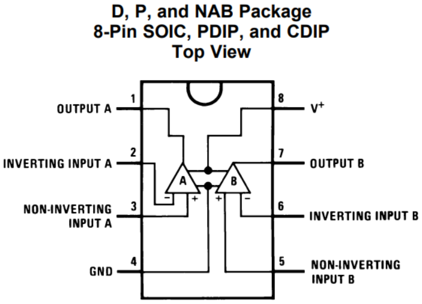


Figure 37: Circuit design of Op amp used in the report

Heatsink

Heatsinks are used to transfer heat from a particular heat generating source to the surrounding environment. Often air or a liquid. In this case, it is used in combination with the MOSFET to dissipate its heat and avoid over temperatures of the MOSFET.

SD Card data logger

This is used to save the measurement data from the Arduino for data analysis.

Buzzer

This is used simply as a warning device in case the voltage of the battery drops too low than desired

10W, 3.9Ω power resistor

This low resistance allows for a large range of current to be used to discharge the battery. Current through the load is calculated from the voltage drop across the resistor, and the load resistance as $I = \frac{V}{R}$. Since the resistance is fixed and the voltage can be varied by the changing the output voltage of the Arduino, the discharge current is also variable allowing to choose between a low discharge current or high discharge current by simply varying the voltage output on the Arduino (via its PWM).

5.2 BILL OF MATERIALS

Where	Item	Cost	Link
Conrad	18650 Li-ion battery	11.55	[64]
	Heatsink	0.5	[65]
	Buzzer	0.62	[66]
	Shipping	6.95	
Reichelt	Mosfets (IRLZ44NPBF) (x2)	1.34	[67]
	LM358 OpAmp (MRIN) (x2)	0.51	[68]
	Shipping	6.95	

BitsAndPartsNL	TP4056 Li-ion charger	1.75	[69]
	Shipping	2.50	
Elektronicawereld	10W, 3.9Ω power resistor (x2)	0.50	[70]
	Shipping	3.95	
Otronic	Li ion battery holder	0.99	[71]
	Shipping	1.10	
Vanallesenmeer	Sd card data logger	2.20	[72]
	Shipping	2	
	Arduino nano	21.49	[73]
	Breadboard	4.81	[74]
	1M resistor,	0.13	[75]
Total		65.89	

5.3 DESCRIPTION OF THE CODE

The blog diagram is shown below:

During operation, the Arduino is constantly:

- Measuring the instantaneous battery voltage
- Measuring the instantaneous discharge voltage
- Calculates the instant current
- Calculates the instantaneous internal resistance

Via these measurements with the discharge voltage and a known resistance, the instant current is calculated by:

$$I_i = V_d/R$$

Where R = 3.9 Ω, V_d=Discharge voltage.

The battery voltage difference is calculated by taking the measured voltage minus the previously measured battery voltage. At the beginning, this previously measured voltage is set to 0. This is now divided by the instant current to calculate the internal resistance.$R_i = \frac{B_i - B_{i-1}}{I_i}$

Where:

R_i=Internal resistance,
B_i=Instant battery voltage,
B_{i-1}= is the instant battery voltage at the previous time-step. At t=0, it is equal to 0.
I_i=Instantaneous current at time-step i.

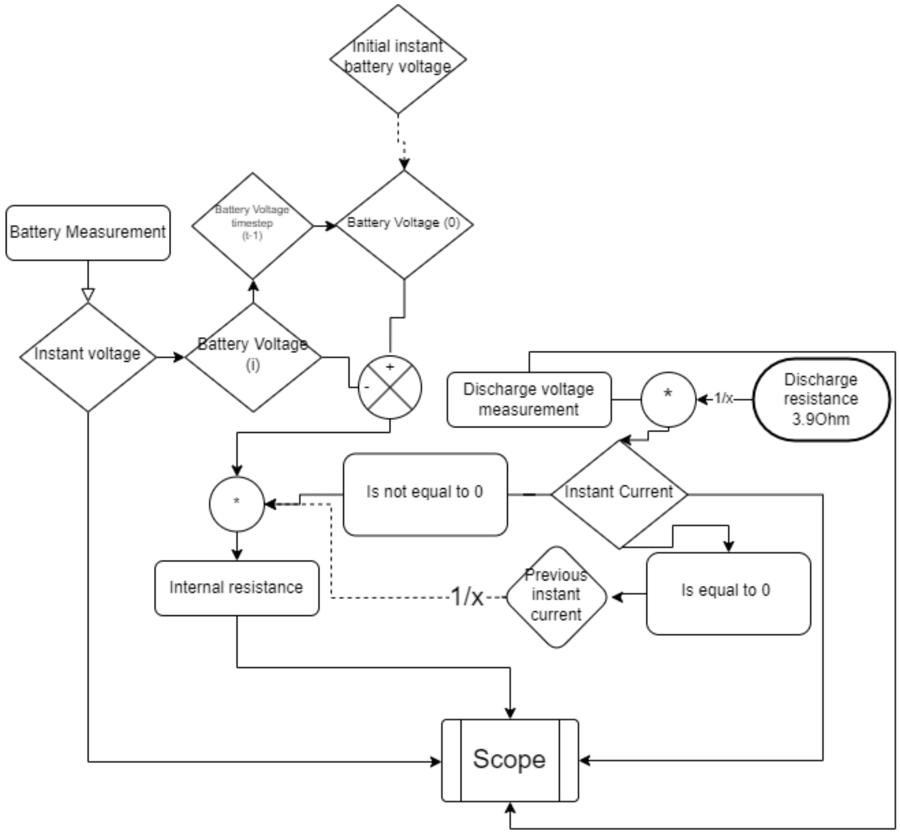


Figure 38: Block diagram of Arduino code

5.4 TESTING PROCEDURE & DATA COLLECTION

The battery test is done as follows:

1. Connect the circuit board as seen below
2. Charge the lithium ion battery to a specific voltage. This was chosen to be 3.6V
3. Let the battery relax for 5 minutes,
4. Discharge the battery with a duty cycle of 10 for 30 minutes and save the output of the discharge to the SD card
    a. This in fact can be one with a separate program called PuTTY which allows for saving the serial output of the Arduino. This is easier in case its desired to save the files directly to the host PC than to have it saved on an SD card and then copied to a PC.
5. Repeat step 2 and step 3
6. Discharge the battery with a duty cycle of 80 for 30 minutes and save the output of the discharge.
7. Compare the results of the duty cycle of 10 to the duty cycle of 80 to get the internal resistance.

The results of this test can be seen below.

5.5 RESULTS

Internal resistance calculation based off the results from the Arduino

$$R = \frac{\Delta B_{volt}}{\Delta I_{inst}}$$

Where ΔB_{volt} is the difference between battery voltage at time t with a specified discharge duty cycle and a battery voltage at a different discharge duty cycle.

The results below were attained by charging the battery to 3.6V and then discharging at a duty cycle at 10%, then at a duty cycle of 80%.

4 select times at the first 11 seconds of the measurement were taken between the two discharge duty cycles. These times are specifically chosen as they are when the PWM signal of the Arduino is high in both cases at the same time. Measuring at different time intervals would cause an inaccurate measurement of the internal resistance.

T(ms)	I (80%)	I (10%)	B_v (8%)	B_v (10%)	Internal resistance (Ω)
2550	0.2145	0.06137	3.64863	3.65799	0.061124535
4217	0.252	0.05808	3.64863	3.65799	0.048267327
8742	0.27211	0.04842	3.64863	3.65331	0.020921811
11607	0.28098	0.0439	3.64863	3.65799	0.039480344
Average Internal Resistance					**0.042449**

Table 4: Testing results

According to the specification of the datasheet, the internal AC impedance should be ≤ 40mΩ while my results show that it is 42mΩ.

Once plotted however, it would seem that there's a large discrepancy between the internal resistance calculations for the duty cycles. Whereas the average internal resistance at a duty cycle of 10 shows approximately 7mΩ, the average for the high duty cycle shows an average of about 0.55Ω.
This is not due to a fault within the code of the microcontroller, but due to noise that is presented with a high discharge current of the battery. The battery at time-step *t* can be very different at *t+1* due to the fact that at *t+1* the battery is being discharged. Thus the calculation of the internal resistance using a large voltage difference will indeed give a large internal resistance, as between the approximate 3ms between each time-step, the battery is strongly stressed and relaxed causing this jump.

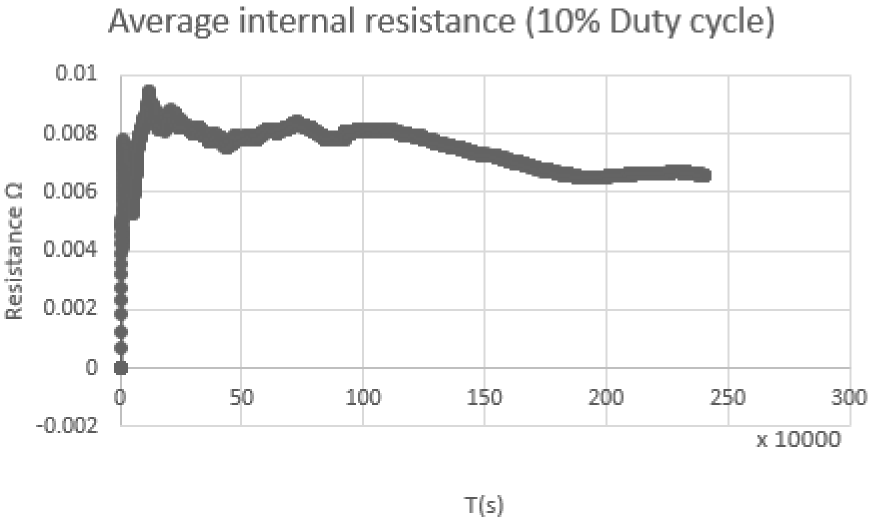


Figure 39: Internal resistance plot for 10% duty cycle

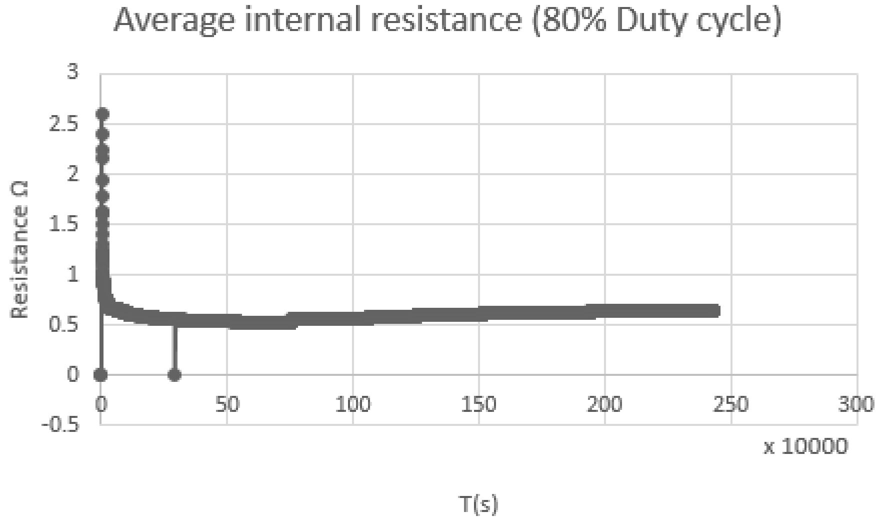


Figure 40: Internal resistance for an 80% duty cycle

This would mean that in fact the circuit itself would need a high-pass filter to get rid of these high frequency components within it for a better measurement, further discussed in the Conclusion.

6 CONCLUSION

Based on the work done on the thesis, the results match with the theory with a 5% error.

Based off of objective 2.3 I've been able to show that it is possible to come to a business model that can profitably provide flexible energy services for prosumers from 2nd life batteries. Being an entrepreneur myself, the reality and the theory might not always match perfectly and unforeseen circumstances can in fact arise. However, given the strong need for a solution to test batteries and the law coming into effect, there is the potential for such a venture to take place.

Every step of objectives 5 has been successfully carried out without major setbacks. Based on the results of objective 6, I have been able to prove that creating a device to measure the internal resistance of a Li-ion battery at low cost in fact possible.

6.1 FUTURE WORK

Though it has been shown that a test bench can be made, it is only a first step along the value chain for the business model, as it would need to use a 2nd life battery for guaranteed energy storage for residents. Additional topics to be covered in the future would be:

6.1.1 Additional filtering components to the circuit

This would be extending the circuit with passive components to create an LC low-pass filter. I propose a hypothetical circuit would such as in Figure 41. It will take the right calculations to determine the optimal values for the capacitance and inductance to smooth out the high frequencies, but due to time constraints in the thesis it was not possible to do so and source the components in time.

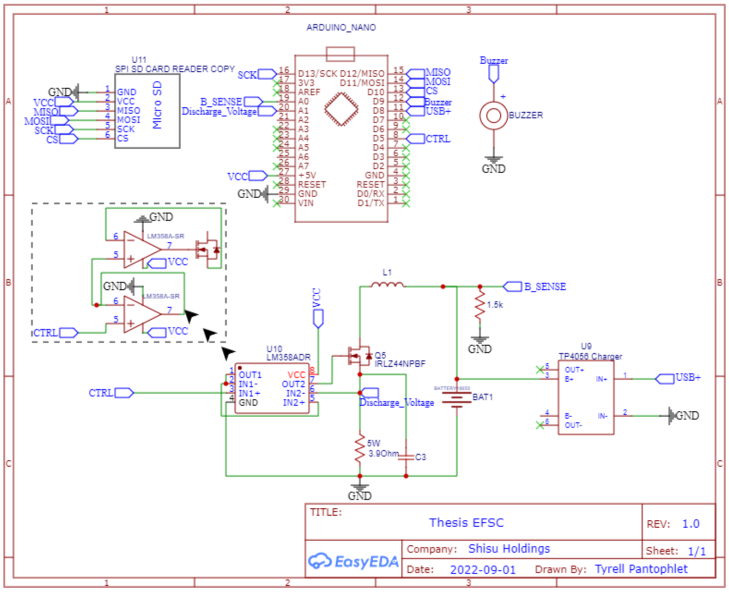


Figure 41: Proposed future schematic with LC filter

6.1.2 Changing discharge resistance

By using different discharge resistances, it is possible to get a larger range curves for the internal resistance of the battery. This can only provide more information for use in SoH models.

6.1.3 Feeding internal resistance parameters into SoH models

It would be interesting to see to what degree the values of the internal resistance provide an accurate estimation of SoH of Li-ion batteries and what parameters would be needed to change for better conclusions

6.1.4 Extending the circuit to work with larger batteries.

This can be done by using a voltage divider that steps the battery voltage down to about 5V where the Arduino Nano can read it while keeping the discharge circuit the same.

6.1.5 Translating the test setup to a finalized commercial circuit

Once it is shown that all the steps towards providing an accurate SoH estimation can be done via the internal resistance test, it can be a commercial product that can directly be given to battery producers that must receive their batteries.

7 APPENDIX

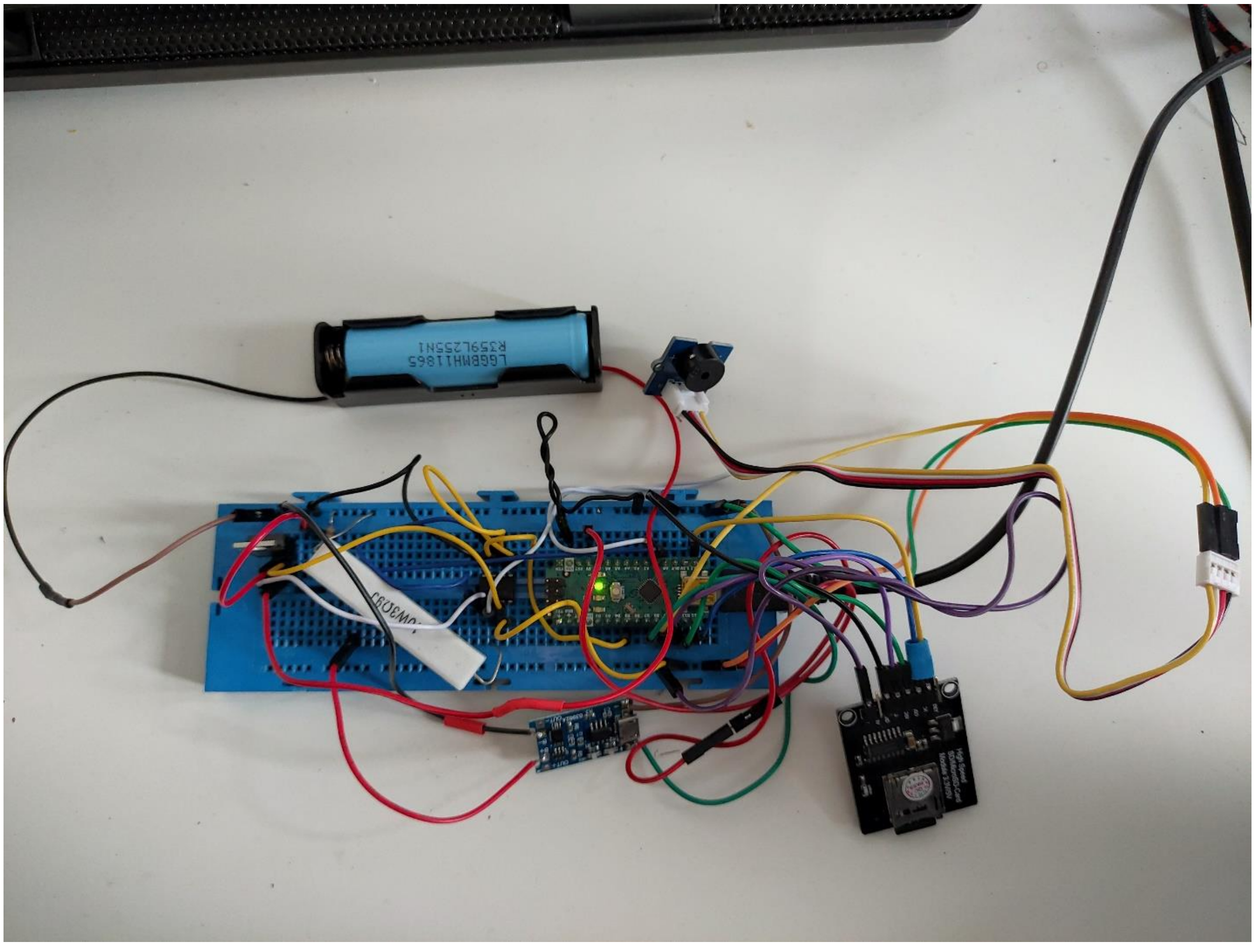


Figure 42: Physical circuit of test bench with Li-ion battery

8 REFERENCES

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