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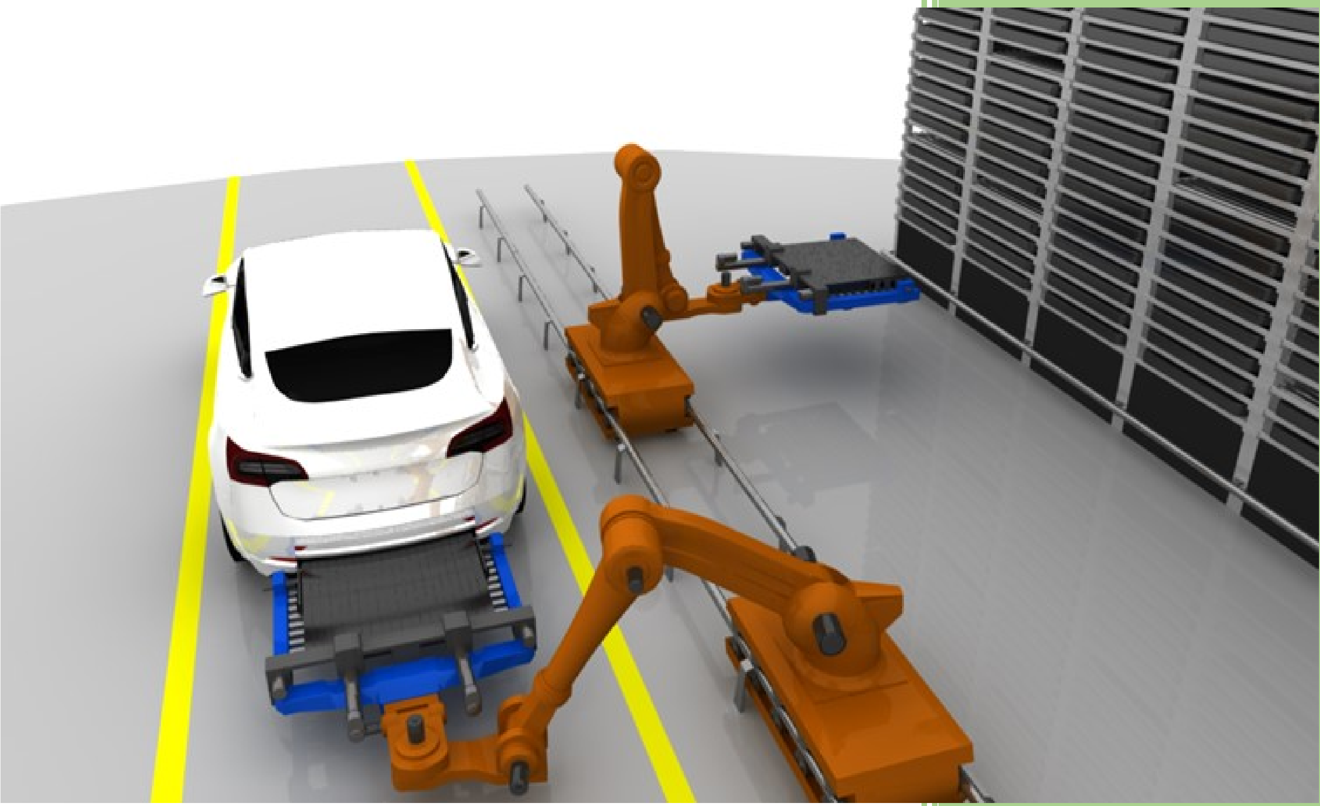
RETHINKING BATTERY SWAPPING: A view for the future of Automobility



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The purpose of this technical report is to promote the idea of battery swapping as a method for extending the operating range of electric vehicles, to present an innovative method and the relevant system for implementing the battery swapping process, as well as to investigate the feasibility of the proposed concept.

This document contains the approach of the author at the time of issue and does not offer any warranty or guarantee regarding the accuracy of the figures, calculations, estimates or projections contained in this technical report.

A patent process is currently in progress for the presented battery swapping system and method. An animated video of the relevant system can be viewed in the YouTube link: https://youtu.be/cPFsTPwTIwg

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ABBREVIATIONS

EVs	Electric vehicles
ICEVs	Internal combustion engine vehicles
WTW	Well-To-Wheel efficiency
WTT	Well-to-Tank efficiency
TTW	Tank-to-Wheel efficiency
AAA	American Automobile Association
BNEF	Bloomberg New Energy Finance
IRENA	International Renewable Energy Agency
MIT	Massachusetts Institute of Technology
BSS	Battery Swapping Station
UHV	Ultra-high voltage
BMS	Battery management system
V2G	Vehicle to grid
LIB	Lithium-ion Battery
NMC	Nickel manganese cobalt oxide
LFP	lithium-iron phosphate

EXECUTIVE SUMMARY

Over the last decade the electric vehicles market continues to grow, creating a great potential for the future of the relevant automotive sector. These vehicles, under certain conditions have a significant impact on reducing greenhouse gas emissions and air pollution, leading many governments and organizations to support their adoption with a wide array of policies and initiatives. However, in order to reach their full potential, electric vehicles must account for a larger share of sales, as well as to be powered by an energy mix with high penetration of renewable energy sources.

Although many barriers have been overcome, there is still a long way to go before electric vehicles become the main choice of typical consumers. Falling battery costs and continued government support help to overcome the barrier of high initial cost, while the increased availability of a variety of vehicle models, makes the purchase of an electric vehicle more attractive for prospective vehicle owners. Nevertheless, despite government subsidies, initiatives and frameworks, electric vehicles ownership cost is still significantly higher than the cost of comparable conventional vehicles.

Another barrier that seems to have been overcome is the limited range. The range of electric vehicles is constantly increasing during the recent years, as they can drive further than ever before, with some models available in the market reaching or exceeding the range of 300 miles (480 km). However, still, they fall far short of the range that a conventional vehicle can achieve. The price for longer driving distance autonomy is the increase in the weight of the electric vehicles with consequent increase in production costs, the need for more raw materials, longer battery charging times, inefficient operation, etc.

Many analysts estimate that given the current energy mix, the environmental benefits provided by electric vehicles do not justify the cost of government subsidies and the costs of upgrading the power distribution infrastructure and expanding the public chargers network. Consequently, the increased penetration of renewable power sources in the energy mix is a prerequisite for obtaining undoubted benefits from the transition to the era of electric vehicles.

However, to further increase the renewables penetration, large-scaled flexibility mechanisms such as energy storage systems need to be developed. Battery storage installations will play an important role in the development and expansion of a network powered by renewable energy sources. The amount of storage capacity that will be required is enormous.

The penetration of electric vehicles worldwide combined with the increased demand for energy storage installations is likely to be accompanied by increased demand for raw materials widely used in the manufacture of lithium-ion batteries. Other social and ecological issues related to the raw materials mining are likely to arise. Furthermore, the additional electricity demand due to the high shares of electric vehicles assumed for the future will have serious implications to the electrical network power quality and infrastructure.

Battery swapping, a method where the discharged battery packs of electric vehicles can be swapped with fully charged ones, provides significant benefits that facilitate the overcoming of significant barriers that slow down the adoption of electric vehicles, such as high cost of ownership, large battery recharging time and limited driving range. At the same time, the battery swapping stations, the facilities where the battery swapping takes place, can also operate as energy storage installations, providing grid ancillary services and thus facilitating the renewable power sources penetration.

However, problematic issues such as material and equipment standardization, reliability and acceptance of the swapping model by the consumers, are some of the main reasons that have so far contributed to the fact that this concept has almost been abandoned in Europe and the U.S.

Based on this point of view, the purpose of the following technical report is to promote the idea of battery swapping as a method for extending the range of electric vehicles, by proposing a concept where vehicles will be equipped with a permanent battery for covering short driving ranges, while when needed they will be able to use swappable batteries to increase driving ranges.

Furthermore, this paper proposes a method and the relevant equipment for implementing the battery swapping process, investigates the feasibility of the proposed concept and proposes associated policies, which would facilitate the widespread application of the method.

I. INTRODUCTION

The transport sector is one of the main sources of greenhouse gas emissions, producing about 24% of global CO_2 emissions [1]. Light duty vehicles are responsible for producing 15% of these emissions [2]. The burning of fossil fuels causes the accumulation of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) into the atmosphere and thus listed as one of the main factors leading to climate change.

For a growing number of policymakers around the world, decarbonizing the transport sector by increasing the number of electric vehicles (EVs) has become a strategy of immediate priority towards the target of meeting stringent emissions levels. In this way, several governments provide subsidies and initiatives for EVs production and marketing. Moreover, many governments have announced future bans on internal combustion engine vehicles (ICEVs).

Consequently, although EVs currently represent a small part of the transport market, they are expected to experience significant and rapid growth over the coming decades. It is estimated that the global EV fleet will grow from approximately 3 million vehicles in 2017, to about 95–105 million EVs by 2030 and 585–823 million EVs by 2050. At this level of market penetration, EVs would constitute one-third to one-half of the overall light duty vehicles fleet by 2050 [3].

At the same time, a debate about the future of cars, EVs or ICEVs, is in progress in the last decade, where EVs enthusiasts and skeptics suggest their justified or not arguments:

EV Enthusiasts

- There is no need for gas station refueling, as required for ICVEs. EVs can charge wherever there is an appropriate electrical socket, either at home, at work or in public places.
- EVs are much more energy efficient than ICEVs. Regenerative braking increases further the vehicles efficiency.
- EVs charging cost is significantly lower compared to fossil fuel costs for ICEVs.
- The use of EVs reduces dependence on imported fuel oil.
- EVs have zero tailpipe carbon emissions and lifetime carbon emissions that are considerably less than those of ICEVs. Furthermore, they reduce local air pollution, especially in cities, as they do not emit any harmful exhaust emissions.
- EVs reduce noise pollution as they are much quieter than ICEVs.
- The cost keeps decreasing. Nowadays, automakers provide a wide variety of EV models, and thus there is an EV to suit almost in every budget. In any case, the fuel cost savings, tax credits and state incentives can help to offset the increased upfront purchase price.
- EVs need less maintenance and servicing is much simpler since they are fully electric and no longer use lube oil to lubricate the engine. Furthermore, they have fewer moving engine parts and consequently they are more reliable than ICEVs.
- Their driving range is constantly increasing. EVs can drive further than ever before.
- EVs offer an improved driving experience and safety. The electric motor provides instant torque, which ensures high and responsive acceleration. The small size of

the electric motor allows designs with larger crumple zones while their lower center of gravity makes them less likely to roll over, improving handling, comfort and safety.

- Electric motors are smaller than combustion engines allowing for more storage volume. Some electric vehicles have a trunk both in the front and the back.

- EVs are safer, as fires that may occur in ICVEs combustion engines are far more common.

- Regenerative braking can greatly reduce the need to use friction brakes, particularly in urban areas and consequently reduces the brake dust that is created when brakes are applied, minimizing the non-exhaust particulate matter (PM) emissions.

- The vehicle to grid (V2G) technology allows EVs to return part of the energy stored in their batteries to the electric grid, in order to be used during high electrical demand hours.

- The batteries which are retired from EVs can have a second life, since they can be used in stationary storage applications, reducing the amount of new batteries required in the future for this purpose.

EV Skeptics

- Nowadays the efficiency of ICEVs has significantly increased reaching up to 40% with 50% considered to be the practical limit [4].

- Taxation makes fossil fuels more expensive than electricity. Currently, EVs charging costs are lower than fossil fuel costs for ICEVs. This is because the energy mix includes cheaper but heavily polluting or hazardous electricity power sources, such as natural gas, coal, or nuclear. In the future, increased penetration of expensive renewables will increase charging costs. Nevertheless, in many cases the fast charging costs, especially in the U.S., are near or even above the equivalent per-mile cost of driving an ICVE [5].

- EVs pollute proportionally to their charging energy mix, which in most cases include fossil fuels, while they shift the air pollution towards the electricity power plants installation areas.

- The EVs cost of ownership, even after subtracting the government subsidies, is still higher than that of comparable ICVEs. The home charging equipment adds extra costs. Furthermore, EVs have bigger resale value declining because of the uncertainty over battery longevity.

- EVs have long charging times. Fully recharging the battery pack with a Level 1 or Level 2 charger can take up to 15 hours and even the newest technology of chargers with rated capacities in the level of 350 kW, still needs 20–30 minutes to charge up to 80%. Moreover, fast charging causes battery degradation.

- EVs on average have a shorter diving range than ICVEs. Longer range means bigger batteries, increased vehicles weight, more cost and inefficient operation.

- Manufacturing of EVs requires more energy than manufacturing of ICVEs. Consequently, EVs create more carbon emissions than ICVEs during their production. Furthermore, the carbon emissions from EVs disposing and recycling are bigger due to the energy-intensive process for battery recycling and disposing.

- EVs expose passengers in dangerous magnetic fields, while there is an increased potential to expose passengers and first responders to dangerous voltage in the event of a collision, due to damage that may occur to the electrical insulation and power isolation systems.

- The replacement cost of batteries, which are quite expensive, should be considered as part of the maintenance costs of EVs. Battery replacement is required after 8 to 10 years because of degradation.

- Batteries suffer from reduced performance in extreme low or high ambient temperatures. Regional temperature and weather conditions may affect further the longevity of the battery.

- EVs could create a significant environmental problem due to the accumulation of battery waste. The cost of batteries recycling is bigger than the value of the recovered materials [6].

- EVs need rare earths overly dependent on imports. With the increasing demand for rare earths, dependency on imported oil from Middle East could be replaced by dependency on lithium from South America, cobalt from Democratic Republic of Congo and graphite from China.

- The use of heavy metals in the manufacture of batteries provides significantly more toxicity to human health than manufacturing ICEVs. It is estimated that one ton of rare earth produces 75 tons of acidic waste [7].

- Electric vehicles cause range anxiety to the drivers. This is the fear that battery will run out of power before reaching your destination.

- Road abrasion and tire wear that are caused by the friction between the tire thread and road surface is directly proportional to the weight of the car. As EVs are heavier than ICVEs, they produce more non-exhaust emissions, while accelerate the wear and tear of the road surface.

- EVs consume energy even when they are parked and fully charged. This is necessary in order to keep the battery and the cabin temperature ready for the next drive, when ambient temperature is at extreme peaks either hot or cold.

- Fossil fuel taxation is an important source of incomes for the government. EV users pay lower taxes and consequently changes to the tax system may be required.

- The increased energy demand for charging EVs batteries will impose large-scale investments in the electrical power generation, transition and distribution system. These investments must be paid by all energy consumers while their environmental footprint is also significant.

The main question in the debate about the future of cars is whether EVs truly offer measurable environmental benefits with respect to global warming potential and, if so, at what cost. In order to address this question, many total lifecycle economic cost and environmental impact analyses of EVs versus ICEVs have been performed. However, the findings of these analyses vary widely, reaching in many cases in completely contradictive conclusions, while researchers have been criticized or even accused by opponents of deliberately applying bad or dirty mathematics.

The results of the analyses are strongly dependent on the input assumptions that determine the amount of energy consumed per kilometer, the source of the electricity used for batteries charging and input assumptions regarding the size and lifetime of the battery and the vehicle itself. Additionally, the uncertain amount of energy consumed during battery production process can also have a strong impact on the results.

The input assumption with the most significant role in vehicles lifetime analyses is efficiency. The overall efficiency of EVs and ICVEs can be used as a benchmark for estimating the environmental impacts, in terms of use, for the two different types of vehicles.

II. EFFICIENCY COUNTS

The efficiency index measures the amount of energy in fuel that is converted into kinetic energy and makes, eventually, the vehicle to move. The difference in efficiency between EVs and ICVEs has implications with respect to the running costs and the environmental benefits accordingly. The better the efficiency of the vehicle, the lower will be the CO_2 emissions for given driving distance.

The total energy chain efficiency, also known as Well-To-Wheel (WTW) efficiency, is a combination of the Well-to-Tank (WTT) and the Tank-to-Wheel (TTW) efficiencies [8]. These terms can be used proportionally for describing the energy chain efficiency for both EVs and ICVEs.

The WTT cycle efficiency of ICVEs results from an analysis of the petroleum-based fuel pathway and includes all steps from crude oil recovery to final finished fuel. Respectively, the WTT cycle efficiency analysis for EVs includes all steps of electric energy production, including power plants fuels recovery and preparation, up to the power socket for vehicles charging.

TTW efficiency analysis for ICVEs and EVs includes actual combustion of fuel and respectively electric energy consumption for motive power.

Depending on where an EV is used, its efficiency and consequently its environmental impact relates to the local power system energy mix. A rough estimation of the overall WTW efficiency of a typical EV driven in Germany is attempted herein below, considering the energy mix shown in Figure 1. Germany's choice for this analysis was due to the relatively high share of renewables in the country's energy mix.

The following data was taken into account in the relevant assessment, which relate to efficiency and energy losses at the various stages of electric energy production, transmission and distribution. The data gathered applies mainly to the German power system:

- Hard coal and lignite fired power plants average efficiency 36% [9].
- Estimation of coal and lignite mining and transportation energy losses 8% [10].
- Natural gas power plants (combine and open cycle power plants rated above 50 MW) average efficiency 46% [11].
- Estimation of natural gas drilling and recovery, processing, compression and transportation energy losses 6% [12].
- Estimation of nuclear fuels recovery (uranium mining and transportation, fuel preparation, spend fuel disposal, etc.) energy losses 6%.

- Estimation of biomass fuels recovery (farming, transportation, handling, preparation, byproducts disposal, etc.) energy losses 10%.
- Average line loss for the power transmission and distribution system 4% [13].
- Efficiency of nuclear and biomass power plants, wind, solar and hydro-power 100%.

Considering the above data and the energy mix as shown in Figure 1, the WTT efficiency of EVs in Germany is estimated at 65%.

The TTW efficiency of an EV typically is between 60% and 73% [14]. This range value has been obtained taking into account the energy losses of the battery during its charging and discharging, the inverter and charger losses, the cabling and motor losses, the auxiliary systems consumption, as well as the mechanical transmission losses. In comparison, the TTW efficiency of ICVEs ranges only between 12% and 30%. However, the most efficient ICVEs today have reached the level of 40% [15].

Considering an average EV TTW efficiency of about 66%, then the overall WTW efficiency of a typical EV in Germany is estimated at 43%.

As far as ICVEs is concerned, considering an average TTW efficiency of about 21% and crude oil extracting, transportation, refine and fuels distribution energy losses 8% [17], then their overall WTW efficiency is estimated at 19%.

Consequently, in terms of vehicle use, the electric powertrain (43%) in Germany is significantly more energy efficient compared to the liquid fuels one (19%).

If, however, the relevant estimation takes into account the TTW efficiency values of the most technologically advanced vehicles, which is currently 40% for ICVEs and 73% for EVs, then the overall WTW efficiency is estimated at 37% for ICVEs and 47% for EVs.

Even under this approach and in terms of use, EVs still have approximately 10% better WTW efficiency than ICVEs. However, for the assessment of vehicles lifetime CO_2 emissions, the energy losses for vehicles manufacturing, recycling and disposal must also be taken into account. EVs produce significantly more carbon emissions than ICVEs (Figure 2) during their construction, while the carbon emissions from their disposal and recycling are also higher.

The question to be answered, then, is regarding how many years of operation are required in order for the higher manufacturing emissions of EVs to be recovered by emissions savings due to an advantage of about 10% in the WTW efficiency of vehicles.

In this respect, the overall carbon footprint of EVs does not clearly prevail that of technologically advanced ICVEs, even in Germany, where renewables penetration is rather high, approaching 30% of the total energy production.

Even if we accept that the total life-cycle emissions of EVs are lower than those of ICVEs, the difference is not that significant so as to provide countable and indisputable environmental benefits that justify the huge investments imposed by the increased penetration of EVs, such as upgrading the power generation, transmission and distribution system and the development of an extensive network of public chargers, as well as to justify the cost of government subsidies for the promotion of EVs.

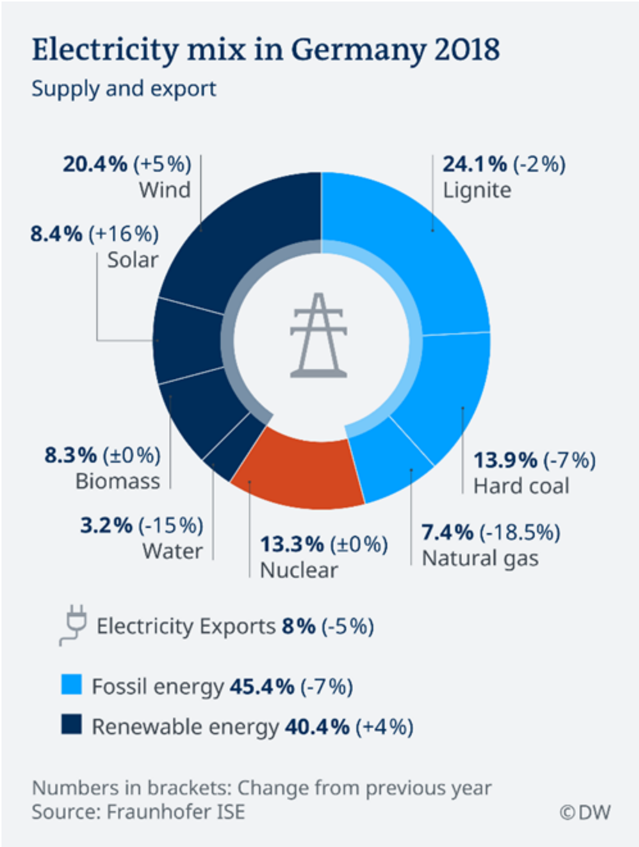

Figure 1: Energy mix in Germany 2018. *Sourced from [16]*

Moreover, the environmental footprint of the huge investments required to increase power generation, to upgrade power network facilities, to develop an extensive network of public chargers, to upgrade domestic and work-place electrical installations, including the heavy industrial investments required for raw materials mining and processing, as well as for traction batteries production, is a significant and difficult estimation and for this reason it has not been examined so far by any life-cycle emissions study conducted.

If, however, a similar EVs overall WTW efficiency estimation is attempted for Norway, the findings will be completely different. The energy mix of this country contains 95% renewable power sources. With this energy mix, the overall WTW efficiency of EVs is estimated at 67%, which is significantly higher than the WTW efficiency (37%) of the most technologically advanced ICVEs. This difference in efficiency between EVs and

ICVEs is really a game changer in the effort to drastically reduce greenhouse gas emissions in the transport sector.

Therefore, for EVs to reach their full potential, the electricity generation must shift from coal and natural gas to low-carbon renewable sources. The penetration of renewables must exceed the level of 30%-40%, currently achieved in some countries, reaching levels well above these figures.

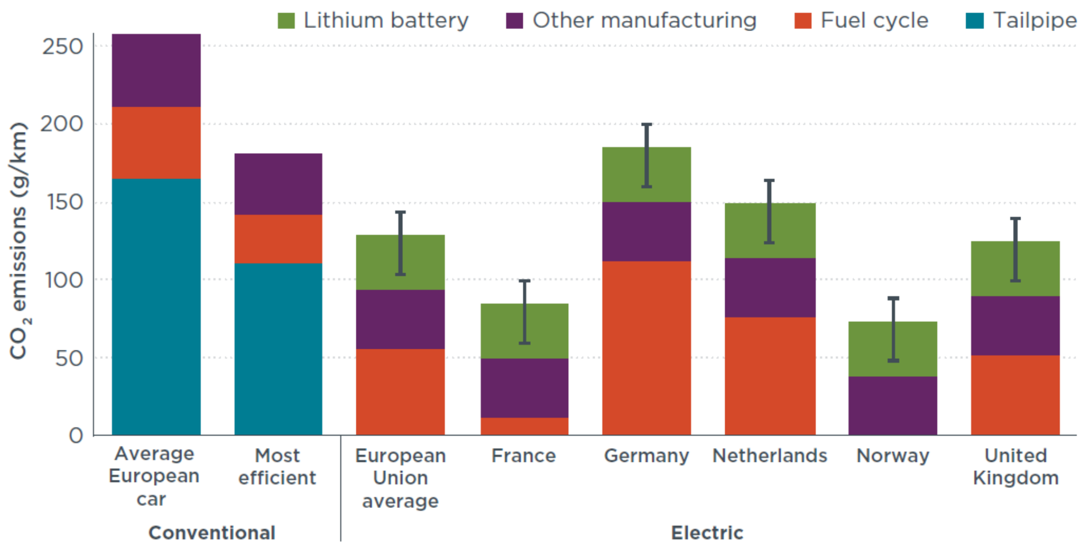

Figure 2: Life-cycle emissions (over 150,000 km) of electric and conventional vehicles in Europe in 2015. *Sourced from [18]*

This conclusion is also admissible by the automakers. Polestar, the Swedish EV manufacturer, have announced that the higher manufacturing emissions of the EV model Polestar 2 can be recovered by emissions savings only after driving a maximum of 112,000 km (69,500 miles), compared to the corresponding ICVE model. That number is calculated based on the global power mix and it drops down to 50,000 km (31,000 miles) when power is obtained from renewable sources [95].

Grid de-carbonization also offers a significant opportunity to reduce the greenhouse gases associated with the manufacturing of traction batteries and energy-intensive metals such as aluminium, which are widely used in EVs construction.

III. THE RENEWABLES

The energy produced by renewable power sources is variable and uncertain, as the wind does not blow continuously while nighttime and clouds limit solar. Unlike conventional electric power generators, such as those used in coal, nuclear and natural gas power plants, the output of renewables cannot be dispatched when it is required. Dispatchable are the generation sources which their power output can be precisely controlled to meet demand changes, both upward and downward. Thus, the intermittent nature of renewables has a significant impact on the flexibility of the power system. The term flexibility means the ability of the power system to constantly keep power production and demand in balance, responding to potential changes in either power production or demand.

Another consequence of the increased penetration of renewables is the uncertainty introduced in the stability of the power system [19], which refers to the ability of the system to overcome disturbances and retrieve a state of operating balance. The main challenge facing a power system with high penetration of renewables is the replacement of conventional synchronous generators by nonsynchronous ones. In conventional power plants, turbines and generators with large rotating mass store kinetic energy in their rotating mass. The mechanical inertia that is stored in these machines resists to the change of their rotational speed and inherently counteracts to sudden frequency variations [20], resulting from an imbalance in power generation and the load. Moreover, inertia provides energy, when needed, to operate the protection devices within the network. Consequently, inertia is a critical parameter in the stability of the power system and any reduction in system inertia increases the possibility of blackouts.

On the contrary, renewable generation units such as wind generators, are provided with power electronic converters that disconnect the generator from the grid, while solar panels have no rotating masses at all, providing no inertia to the system. As a result, the increasing penetration of converter connected generation and the consequent replacement of conventional power plants will lead to a decreasing amount of system inertia, negatively affecting the stability of the power system. For the above reasons, according to studies and depending on the nature of the network, the maximum power generation of variable renewables cannot exceed about 55-60% of the total demand, without risking system stability [21].

Furthermore, in order for renewables to be able to supply reliably a power system, a massive overbuilding of capacity of solar and wind power plants is required. This implies that a significantly larger wind or solar capacity would be required in order to provide the same amount of electricity to the grid as that provided by the existing conventional base load units [21]. However, during a favorable period for renewable power energy production (e.g. windy or sunny periods), the excess of power production must be curtailed and inevitably energy to be lost.

Curtailment is the forced reduction of renewables power generation and occurs when excess supply of power cannot be consumed within a market nor exported to neighboring markets. Additionally, when for reasons of system stability, minimum requirements are set for the share of conventional generation, the level of required curtailment increases even more. The risk of curtailment is an important barrier for further deployment of renewable power sources, as it introduces uncertainty about future revenues for project developers [22].

In order to be possible to increase further the renewables penetration, various mechanisms and technical solutions can be applied to address the issues of power system flexibility, stability and energy curtailment. The new controllers provided in solar and wind power plants are able to participate in frequency response, when a large disturbance happens, applying to the power system the so-called "virtual inertia" or else "synthetic inertia". Retiring thermal plant generators could also be converted into synchronous condensers, which are able to provide reactive power and inertia.

There is also a number of flexibility mechanisms that help address renewables intermittency issues, such as flexible dispatchable generators (e.g. gas turbines or hydroelectric generators), curtailment, forecast models, grid extensions, energy storage and demand response. Not all of these flexibility mechanisms are equivalent or even directly comparable. Significant errors may occur to the forecasts, while flexible generation and curtailment each provide flexibility in a single direction upward or downward. Flexible generators can be used only "upward", producing additional power, while curtailment on the other hand can provide only "downward" control.

However, there are mechanisms that can provide flexibility in both directions by absorbing the excess of energy or providing more energy when it is required. These flexibility mechanisms are the grid extensions, also known as super-grids and the energy storage systems. Demand response, or else "smart grid" can also play a similar role by shifting the load demand to adjacent hours so that it coincides with renewables generation. These three flexibility mechanisms further reduce curtailment and consequently the energy that otherwise would be wasted.

The Super-Grids

A super-grid is a high capacity network of alternating current (AC) or direct current (DC) transmission lines, operating at ultra-high voltage (UHV) that overlays over the existing grid, interconnecting different power systems and transferring large amounts of energy over long distances. This interconnection allows for greater integration of renewables and power exchanges among countries with varying climate and seasonal needs, as well as expands the size of power markets reducing electricity costs for consumers.

Stability is a major concern of super-grids, where a problem in any one part can bring cascading failures across the entire system. Once a failure happens along one of the UHV transmission lines because of any natural, technical, or human incident, widespread power outage and power surplus will co-exist, causing immense damage to the interconnected regions resulting in a nationwide power outage [23].

Another drawback of the super-grids is the high initial cost that consists a challenge for developers, as further to the transmission lines complex and costly converter stations are needed, where the technology of DC is applied. Consequently, funding will invariably be a significant obstacle. Furthermore, the power losses of long-distance UHV transmission systems is also significant.

Perhaps geopolitics is the most problematic issue, especially since super grids would almost invariably cross-national boundaries [24]. The implementation of such projects would take a great deal of cooperation, confidence, political stability and reliability between all countries involved, across the planning and construction phases of the relevant projects.

Furthermore, objections for environmental or social issues may add additional barriers to the extent development of super-grids.

The Smart-Grids

Smart grid is an automated, widely distributed energy distribution network, consisting of a combination of a conventional distribution network and a two-way communication network for sensing, monitoring and dispersion of information on energy consumptions. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enables the near-instantaneous balance of supply and demand at the device level, reacting automatically without the need of human intervention [25]. It offers consumers the choice to adjust consumption by responding to electricity price changes and consequently to improve efficiency, reliability, economics and sustainability of the power system, to reduce the peak loading by shifting demand in time and to facilitate the integration of a greater percentage of renewable energy sources.

Disadvantage of the smart grids is the high cost due to required replacement of analog meters by more sophisticated electronic meters, as well as the risk of privacy and cybersecurity.

However, the time span that can be bridged by shifting demand is rather limited (a few hours) compared to other flexibility mechanisms (e.g. energy storage). This is the main reason that smart grids will not prevail over the other flexibility mechanisms and most probably will operate supplementary to them in order to improve efficiency of the electrical system.

The Energy Storage

The energy storage systems are able to take up a certain amount of energy in a controlled manner, to contain this energy over a period of time relevant in the specific context and to release it over a period of time in a controlled manner [26]. Energy storage allows for the temporal shifting of wind and solar power from times when it might otherwise be curtailed to times when the power output of renewables is lower than current demand, while at the same time provides the necessary system support, including inertia, as well as frequency and voltage control. Energy storage can also become a practical alternative to new-build electricity generation or network reinforcement.

Consequently, energy storage will be a key component in transforming electricity supply systems to accommodate renewable energy technologies.

The energy storage systems, depending on the storage technology used, can be classified as mechanical (pumped hydro, flywheel, compressed air, gravity systems), electrochemical (batteries), chemical (hydrogen production, biofuels), electrical (super-capacitors, super-conducting magnetics) or thermal systems. Each system has its own performance characteristics in terms of life cycle, discharge time, discharge loss, energy density, wattage rating, etc., that makes it optimally suitable for certain grid services. Large-scale technologies, such as pumped hydro and compressed air energy storage, are capable of long discharge times and high capacity. In contrast, various electrochemical batteries and flywheels are more suitable for lower power applications or for shorter discharge times.

The two different technologies that offer a feasible solution for the required demand in energy storage capacity and are being discussed widely right now are the pumped hydro electrical storage and the battery storage.

Pumped hydro storage is currently the dominant system with 99% of the total installed bulk storage power capacity globally [27]. It is an established and mature technology with extensive operational experience, very low self-discharge, reasonable round-trip efficiency, large volume storage (bulk storage), low energy installation costs, good start/stop flexibility (10 to 15 minutes of reaction time), long life and low costs of storage.

However, disadvantages of this technology such as geographic restrictions, since a suitable site with large land use is needed, low energy density, high initial investment costs, lengthy project construction periods, long time to recover investment, restricted geological implementations, environmental impacts, necessity for construction of power transmission lines, etc., it is expected to limit the future development of pumped hydro.

On the other hand batteries are suitable for installation in both large-scale and small-scale energy storage systems, while they can be placed at every level of the grid (generation, transmission, distribution and domestic use by consumers). In comparison to pumped hydro storage, battery storage technologies are more cost-effective at releasing small amounts of energy over a short time at high power, due to their ability to dispatch stored energy in milliseconds, while they provide similar to pumped hydro balancing and ancillary services.

Battery storage systems are quicker to implement than pumped hydro, as they can be modularly deployed close to the demand or generation centers and have very low maintenance and operating costs. Consequently, batteries are ideal for implementing distributed energy storage, which is more valuable, as it is located closer to the point of consumption.

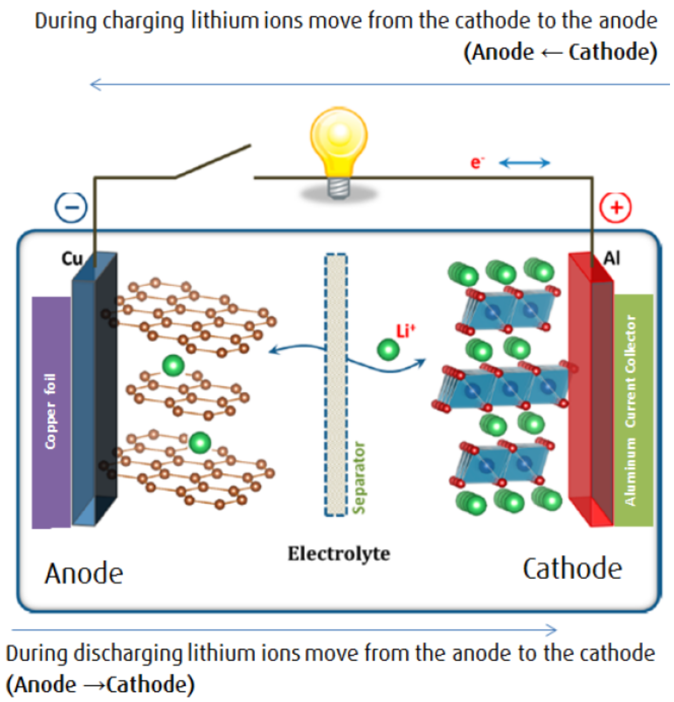

Figure 3: LIB operation principle. *Sourced from [29]*

Concluding this chapter, it is noted that probably none of the above-mentioned flexibility mechanisms, which are required to increase the penetration of renewables, will prevail over the others, but rather they will have a symbiotic relationship in order to optimize operation and increase the efficiency of future power systems. Batteries will undoubtedly play a significant role in the development and expansion of a network powered by renewable sources, as the technology develops and the costs are falling. Consequently, the demand for batteries for stationary energy storage installations is likely to significantly increase in the near future.

IV. LITHIUM-ION BATTERIES BASICS

Lithium-ion batteries (LIB) are currently the most popular type of rechargeable batteries for automotive and for energy storage applications. The choice of LIB is justified by their long lifespan, the high energy density and efficiency, the low weight, as well as their compactness and maintenance-free design. Furthermore, LIBs are highly scalable and they can be adapted to practically any voltage, power and energy requirement. The main failure concerns for these batteries are heat dissipation, thermal runaway events, low-temperature charging conditions, mechanical stress consequences in vehicles' environment and the effects of cell aging.

South Korean, Chinese and Japanese companies are currently the leading established producers of LIBs.

LIB Chemistry and Performance Parameters

The fundamental building block of any LIB is the cell. Cells package a cathode (positive electrode), an anode (negative electrode) and an electrolyte solution. Between the two electrodes there is a separator, which acts as an insulator between the two oppositely charged electrodes.

The anode loses electrons and ions during the discharge of the cell. The anodes in LIB cells are typically carbon-based materials. Commonly used forms include graphene, graphite and carbon black.

The cathode receives electrons and ions during discharge of the cell. The active material of the cathode in a LIB cell is made from a combination of a lithium metal oxide or lithium metal phosphate, a polymer binder and conductive filler. Cathode chemistries most commonly used in automotive applications are the following [28]:

- **Lithium manganese oxide (LMO**) – Used in Nissan Leaf, Chevy Volt, BMW i3.
- **Lithium iron phosphate (LFP)** – Used in hybrids, plug-in hybrids, BYD electric bus.
- **Lithium nickel manganese cobalt oxide (NMC)** – Used in Chevy Bolt.
- **Lithium nickel cobalt aluminum oxide (NCA)** – Used in Tesla Models S, X and 3.
- **Lithium titanate (LTO)** – Used in Mitsubishi MiEVs, Proterra Electric bus.

The separator is a polymer based, microporous, electrically insulating material. The separator prevents internal short circuiting and overheating between the anode and cathode by providing a physical, non-electrically conductive barrier, while also provides a path for ionic transport.

The electrolyte solution is the physical medium that allows ionic transport between the electrodes during charging and discharging of a cell. Electrolytes in LIB may either be a liquid or a gel.

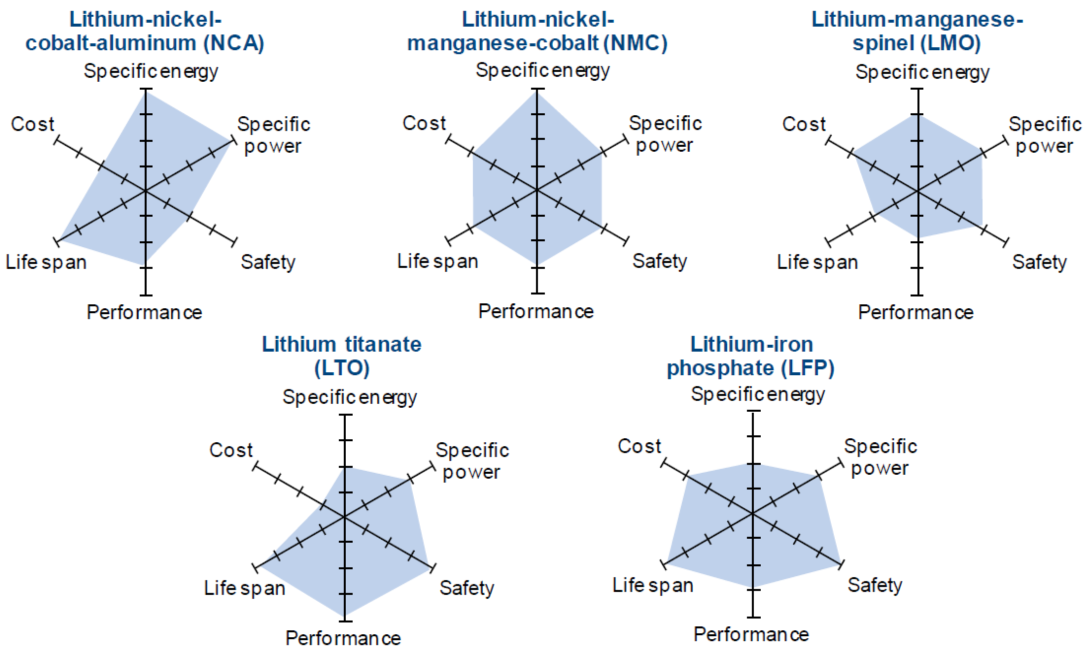

Figure 4: Relative comparisons of LIB performance parameters. *Sourced from [31]*

Currently, NMC chemistry is the most popular in the light-duty vehicle sector due to its high energy density, which allows for longer vehicle range, as well as due to its capability for fast charging. However, NMC batteries have a high cost per kWh because of their reliance on cobalt.

The main LIB performance parameters are the following:

- **Specific Energy (Wh/kg):** The capacity of storing energy per kilogram of weight.
- **Specific Power (W/kg):** The maximum available power that battery can deliver per kilogram of mass.
- **Life span:** The number of charging-discharging cycles the battery can repeat before being degraded under a certain level or else the number of years that a battery can be expected to remain useful.

- **Safety:** Low thermal stability refers to the exothermic release of oxygen when a lithium metal oxide cathode is heated above a certain point, resulting in a thermal runaway reaction that can lead to fire [29].

- **Performance:** The expectation that battery can operate properly in extreme ambient temperature conditions.

The Batteries Structure

The way that cell elements are packaged account for the difference in appearances of battery cells. There are currently three different battery cell formats (Figure 5) [28]:

- **Cylindrical cells.** In these cells cathode and anode layers are rolled into a cylinder. TESLA uses this type of cell that currently sources from Panasonic.

- **Pouch cells.** Pouch cells are provided with flexible polymer coated aluminium packaging. GM and Nissan use pouch cells in the Volt, Bolt and Leaf EV models. GM sources its cells from LG Chem, while Nissan sources from Automotive Energy Supply Corp (AESC).

- **Prismatic cells.** These cells are constructed in a wound or flat plate configuration and are provided within a rigid can. The VW e-Golf and BMW i3 EV models uses this arrangement, sourcing the cells from Samsung.

Cells are built up to battery modules and those modules are built up to battery packs (Figure 6). A typical module consists of an array of cells, sensors, protective safety devices, structures and mounts, cooling elements, etc. Battery packs integrate modules and other control, structure, as well as safety design elements.

Batteries Failure Mechanisms

The main parameters controlling LIB performance are temperature and operating voltage. For each battery chemistry, there is a range of temperatures and operating voltage in which electrochemistry is dominated by intercalation mechanisms. Outside this range, undesirable reactions may occur which can lead to overheating and/or internal electrical shorts circuits.

LIBs contain or can produce, via decomposition reactions initiated by failure mechanisms, chemicals that can pose significant flammability, asphyxiation, material compatibility, or toxicity hazards. These hazardous conditions could be realized when the integrity of a battery casing is compromised, causing the release of volatile, flammable and toxic chemicals from the battery [31]. The following types of situations may initiate failures in LIB cells:

Cell overcharge or discharge. When a cell is overcharged, exothermic reactions may be initiated that have the potential to start a thermal runaway process. During these reactions Li-ions that constitute the physical makeup of the cathode are transferred from the cathode to the anode and accumulate on the anode, removing lithium from the cathode that becoming chemically unstable. Another exothermic reaction caused by overcharging is an increase of the resistance of the cathode material that consequently generates heat. Overcharging can also cause plating of lithium onto the anode that can lead to short circuit. LIB cells must not be fully discharged. After many cycles of complete discharge, metallic dendrites can grow between the electrodes and through the separator that may create an internal short circuit [31].

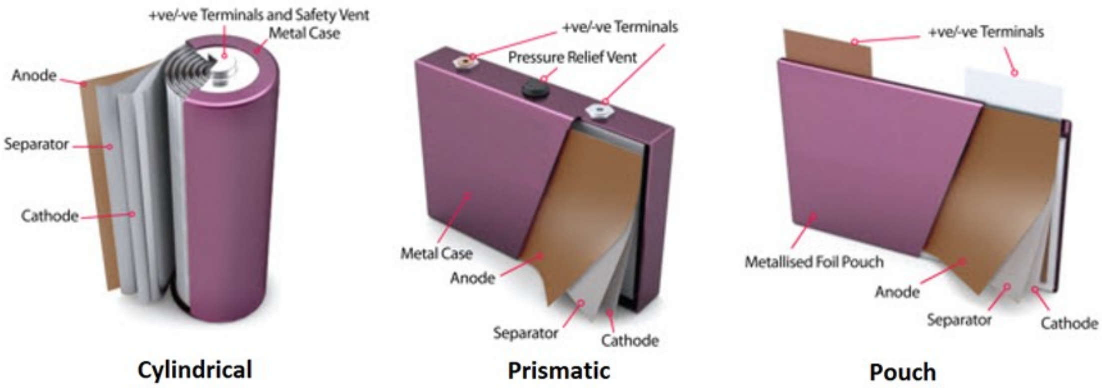

Figure 5: LIB cell formats. *Sourced from [30]*

Recharging at low temperature. Recharging of battery at a low temperature may cause plating of lithium onto the anode forming dendrites and possibly creating an internal short circuit.

Storing or operating the battery at high temperatures. When a LIB is stored or operates in high-temperature environments, there is an increased risk of failure resulting from the vaporization of the electrolyte which consequently increases the pressure inside the cell [31].

Internal short circuit. Internal cell short circuits result in excessive flow of electrons within the cell that consequently increase heating and contribute to thermal runaway. Several different initiating events may lead to an internal short circuit such as incorrect charging, cell internal component failures and undesirable reactions [31].

External mechanical stress. External events such as mechanical stress can damage internal components, increasing the likelihood of failure inducing thermal runaway events.

External short circuit. An external short circuit can lead to over-temperature and overpressure of a cell, thereby causing cell to vent, releasing the flammable electrolyte and possibly creating toxic gases, or rupturing the cell.

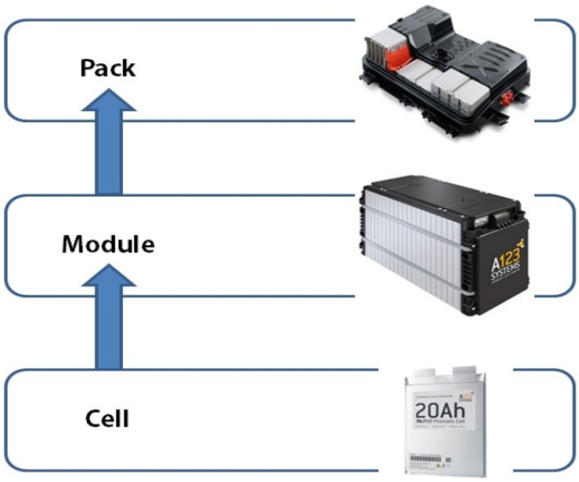

Figure 6: EV battery cell, module and pack. *Sourced from [93]*

Thermal Runaway. The heat accumulated inside the cell caused by any of the failure mechanisms mentioned above must be dissipated in the environment. Failure to dissipate heat at a rate higher than the rate of heat generation in the cell could initiate the thermal runaway procedure. During this procedure, the electrolyte combusts because of the high internal temperature and the pressure in the cell rapidly increases until it bursts and vents the electrolyte. The rapid rise in temperature propagates domino effect to nearby cells leading to smoke propagation, fire and even explosions. The key parameters to controlling thermal runaway are limiting the rate of heat generation and ensuring that the rate of heat removal exceeds the rate of heat generation. This procedure is called thermal management.

Cooling and Thermal Management

Thermal management involves the methods and devices as required for charge and discharge management, as well as methods for dissipating the heat imparted to the cell. Thermal management operates at the module level and includes temperature monitoring, cooling the battery when it operates at high loads and heating the battery when it is plugged during cold weather conditions. The battery pack can have air, liquid, or refrigerant cooling. The control system that is responsible for battery thermal management is called battery management system (BMS).

The BMS is designed to provide cell voltage balance, control and consistent performance over the lifecycle of the battery. The BMS is a circuit board with an integrated microprocessor that monitors, records and actually transmits signals for charging and discharging individual battery cells or cell strings to maintain voltage balance and system performance. It ensures that the battery does not get overheated in order to prevent thermal runaway and manage the temperature of the system.

Temperature is a primary factor in regard to the performance and life cycle of the battery. LIBs should ideally operate between 50°F to 95°F (10^{o}C and 35^{o}C) for optimal life and performance. Using air as a heat transfer medium is a cheap and simple method for battery cooling. However, air cooling is very inefficient in comparison to liquid cooling. Some of the limiting factors of air cooling in EVs are the limited flow rate of cooling air, noise, inhomogeneous temperature distribution within batteries, dependence on vehicle cabin air temperature and safety concerns due to the emission of toxic gases from the battery packs [32].

Liquid thermal management is a much more efficient method for cooling LIBs, but it is more costly and complex to implement. In liquid cooling, a cooling plate can be placed on the surface of the battery and a liquid cooling or heating refrigerant can be passed through tubes onto the plate to draw heat from the battery cells.

Batteries Performance

In order to maintain efficiency, battery packs must be kept within a certain temperature range. Depending on the ambient air temperature, some of the available power may be required to heat or cool the battery, as well as the vehicles interior. Aggressive driving will result in higher rates of heat generation, consequently increasing battery cooling demands.

At low temperatures LIBs are less efficient due to increased heat generation. As temperature decreases, diffusion, conductivity and reaction rates decrease. This leads to increased voltage perturbation and heat generation which means a waste of useful energy and consequently reduced driving range [33]. To avoid this and in order to improve the performance, the battery thermal management system consumes energy to heat the battery via resistive heating or, recently via heat pumps. Consequently, extreme weather conditions reduce the range of the EVs.

The American Automobile Association (AAA) determined after testing that the driving range of five major EVs decrease on average 5% (HVAC OFF) and 17% (HVAC ON) in extreme ambient heat (35°C/95°F) and 12% (HVAC OFF) and 41% (HVAC ON) in temperatures below freezing (-7°C/20°F) [33]. In cold weather, EVs drivers report a 40-60% decrease in range [29].

Norwegian Automobile Federation (NAF) performed a range test in 20 EVs in winter conditions. The findings of the tests showed that in colder climate EVs lose, on average, 18,5% of their range compared to their Worldwide Harmonized Light Vehicle Test Procedure (WLTP) range. Another finding of the tests was the fact that EVs charge more slowly in cold temperatures [34].

Tests at the Argonne National Laboratory's Advanced Powertrain Research Facility found that heating the cabin at ambient temperature of about 20°F (-6°C) caused a 20-59% reduction in range compared to no heating. This reduction in range can be improved tremendously by cabin preconditioning such as pre-heating or pre-cooling when the battery is still plugged in to a charging station [29].

Aging and Degradation

In general, LIBs have a finite duration of effective operation, often specified by the manufacturers. Most automakers warranty their traction batteries for 8 years or a 100,000-mile (160,000km) drive limit. However, there are a number of very complex degradation factors that can easily reduce that duration. Typically, the end-of-life criterion for LIBs is 80% residual capacity from its nominal capacity or a 30% increase in internal resistance [29].

Aging mechanisms of LIB are complex and involve charge levels, charging speed, depth of discharge, as well as ambient and operating temperatures. Battery failures that lead to sub-optimal performance and degradation can often be associated with aging mechanisms within the cell. The cathode and the anode age differently and the majority of aging in the system takes place at the interface of the separator, the electrolyte and the cathode or anode [31].

High temperatures tend to amplify typical aging mechanisms, such as transition metal dissolution and increased resistance, causing degradation during batteries lifetime [29]. Charging repeatedly in cold weather significantly reduces the lifespan of the battery, as well.

Manufacturers tend to specify an operating temperature range between -4°F to 140°F (-20°C and 60°C). However, the scientific consensus is that the optimal temperature range is between 50°F to 95°F (10°C and 35°C) and a lot of studies have shown that temperatures outside of that range have serious deleterious impacts on the battery [29].

Continually charging the battery to 100% and discharging to zero accelerates also aging effects. Manufacturers often advise maintaining a partial charge of about 80-90% and not letting the battery discharge lower than 10%-20%. Furthermore, a high current load can damage the graphite anode and cause structural disordering in the cathode.

Repeated fast battery charging reduces expected battery lifespan, leading to anode damages, increases the structural disordering of the cathode and consequently leading to battery degradation [29].

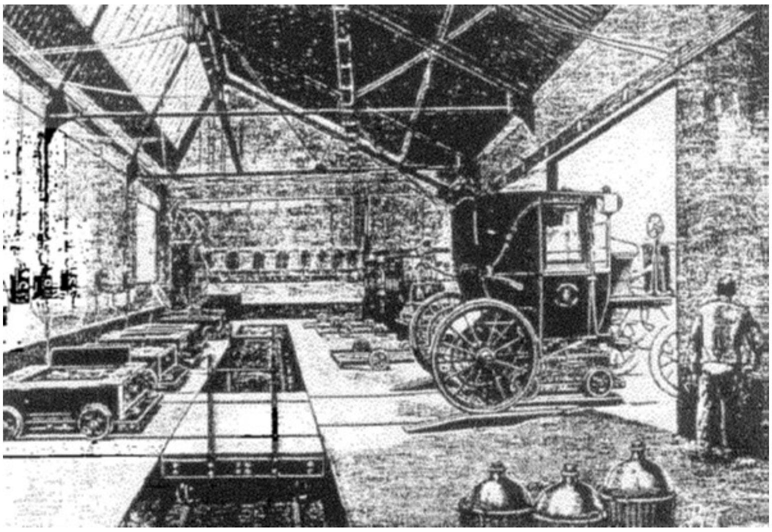

Figure 7: Battery swapping and charging station, Paris, 1899. *Sourced from [35]*

Even if the battery is not being charged, parasitic side reactions within the cell lead to degradation of the battery [29]. Self-discharge is also an issue. Storing the vehicle in hot environment or at temperatures below freezing, increase self-discharge rates.

V. BATTERY SWAPPING

Battery swapping is a procedure where the discharged battery pack of an EV can be swapped with a fully charged one. The installation where a battery swapping can be realized is called Battery Swapping Station (BSS). In modern BSSs, the whole process can be performed by a robotic automated system, in time comparable to ICVEs refueling. This concept envisions a network of BSSs that hold an inventory of fully charged batteries.

The concept of an exchangeable battery service was first proposed in the late 19th century. The necessity to overcome the problem of the limited range and long recharge time was addressed soon after the first electric vehicles appeared on the roads of

Europe and America. Figure 7 depicts a French electromobile hack of 1899, refueling at a charging station in Paris. The battery pack on this vehicle was suspended underneath the vehicle and was removed and replaced with a charged battery using a lateral trolley system.

Battery Swapping Methods

The current battery swapping methods, applied in vehicles that have already been presented in the market, are based on two main techniques. In the first one, called chassis type battery swapping, the unloading and loading of battery packs is achieved from the bottom of the vehicle, while in the second one withdrawable battery packs are unloaded and loaded mainly from the side or the rear of the vehicle.

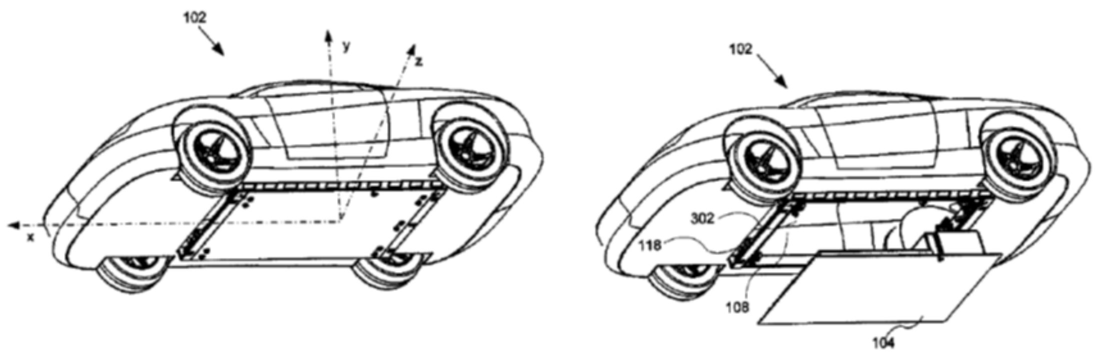

Figure 8: BETTER PLACE chassis type battery swapping method. *Sourced from [38]*

BETTER PLACE, an Israeli company, was the first modern commercial deployment of the battery swapping concept. BETTER PLACE launched its first BSS in Israel, in 2011 and up to the end of 2012, there were 17 battery swapping stations fully operational in Denmark. The Renault Fluence Z.E. was the first EV enabled with swappable battery technology available for the BETTER PLACE BSS network. The vehicle was designed for a chassis type battery swapping technique, using an air-cooled battery pack (Figure 8). A special frame structure was attached to the chassis to mount the swappable battery pack under the vehicle. The suspension of the battery in this frame was achieved with dedicated latches.

The main disadvantage of this method is the increased weight of the vehicle due to the battery mounting frame, as well as the fact that said frame causes differentiations to the vehicles' standardized manufacturing procedures, affecting construction time and costs. Also, disadvantage is the necessity to place the vehicle on dedicated ramps with complicated and expensive underground equipment (Figure 9) and the fact that the battery packs are exposed to dirt and to potential damage when vehicles run over obstacles.

Finally, after raising roughly $800 million, BETTER PLACE went bankrupt in 2013. The company's financial difficulties were caused by the high investment required to develop the swapping infrastructure, as each BSS was initially projected to cost $500k but ended up with a price tag of roughly $2 million [36].

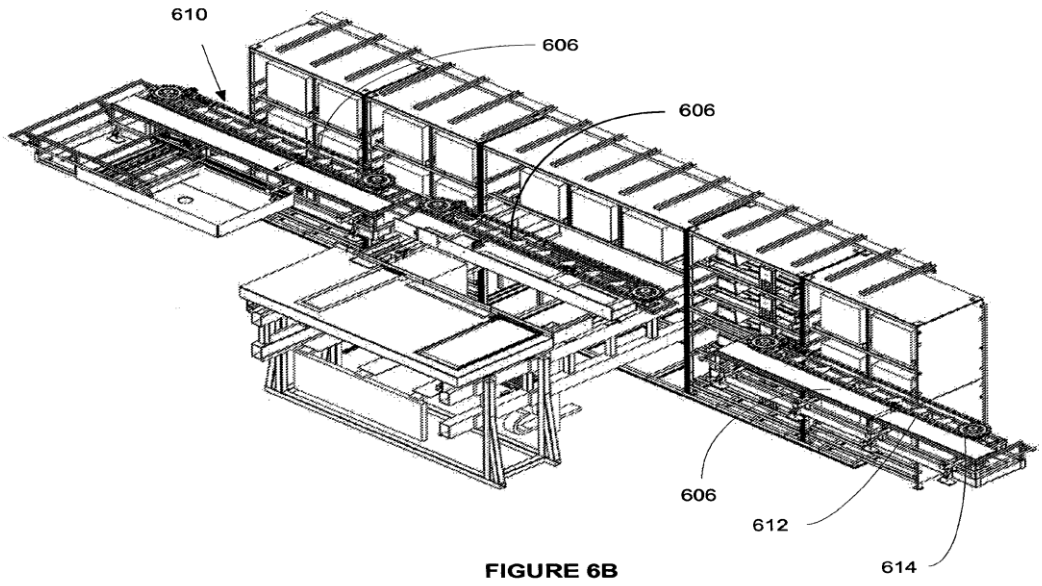

Figure 9: BETTER PLACE battery swapping station infrastructure. *Sourced from [38]*

Moreover, the market penetration was significantly lower than that predicted by the management. The failure of the company to convince automakers to allow their car batteries to be swapped out was another major hurdle that could not be overcome. BETTER PLACE only offered one car model from Renault when it launched in Israel. Fewer than 1,000 Renault Fluence Z.E. cars had been deployed in Israel and only around 400 units in Denmark.

In the same year as BETTER PLACE's bankruptcy, TESLA MOTORS presented its own battery swapping technology. The system of TESLA was able to remove and replace the drained battery pack of a Model S with a fully charged one, in about 90 seconds. The company opened only one pilot BSS in California, in 2015, while in the same year abandoned to build a network of BSSs due to lack of interest from customers and the decision to extend the superchargers network.

The swapping method applied by TESLA was based on the chassis type battery swapping technique. The mounting of the battery pack to the vehicle's chassis was realized in a manner that the battery pack participates to the rigidity of the vehicle.

Disadvantage of this method is the increased weight of the battery pack, as it includes a number of rigid frame structures, as well as the large number of bolts needed for fastening the battery pack to the chassis, making the swapping process rather complicated.

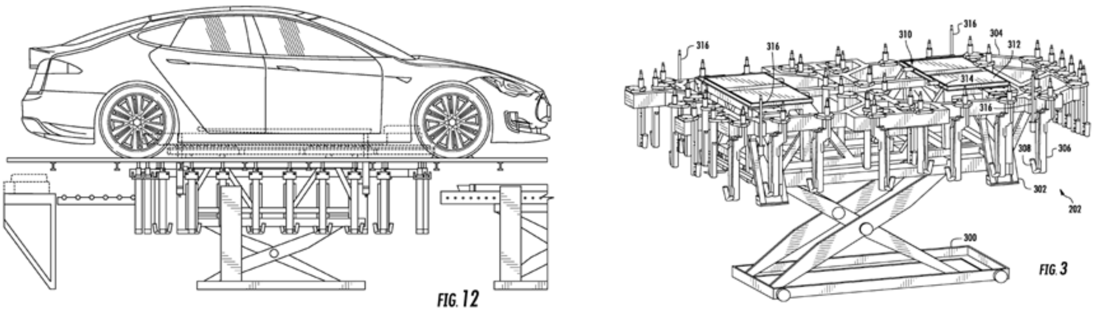

Figure 10: TESLA chassis type battery swapping method and equipment. *Sourced from [40]*

Furthermore, as TESLA established a battery swapping for its Model S, which has a liquid-cooled pack, the fast disconnection and reconnection of the coolant pipes was a rather challenging procedure.

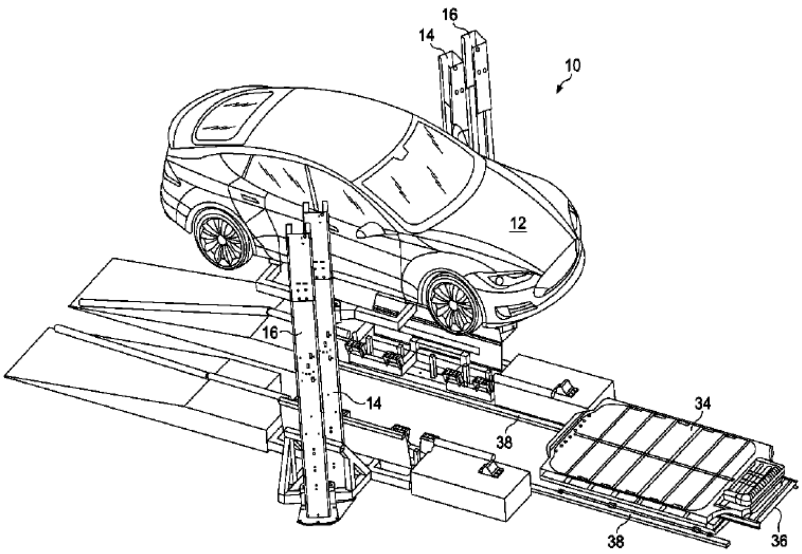

Figure 11: TESLA battery swapping method by lifting the vehicle. *Sourced from [39]*

As with the BETTER PLACE swapping system, the TESLA system needs to place the vehicle in dedicated ramps with underground equipment (Figure 10). However, in 2017 the company patented another battery swapping method that is based on lifting the vehicle technique (Figure 11).

One of the main inhibitory factors for the wider acceptance of battery swapping is the lack of common battery standards across multiple EV manufacturers. Battery packs need to be of the same size and shape. That's an issue that has been arranged in China, as the government is making efforts to establish common industry-wide standards for the procedure [37], so as to make the swapping process uniform across any car, any battery and any facility. In China, most people live in large apartment buildings and owning of an EV means the need to rely on public charging infrastructure. Thus, battery swapping is highly desirable for the Chinese EV owners.

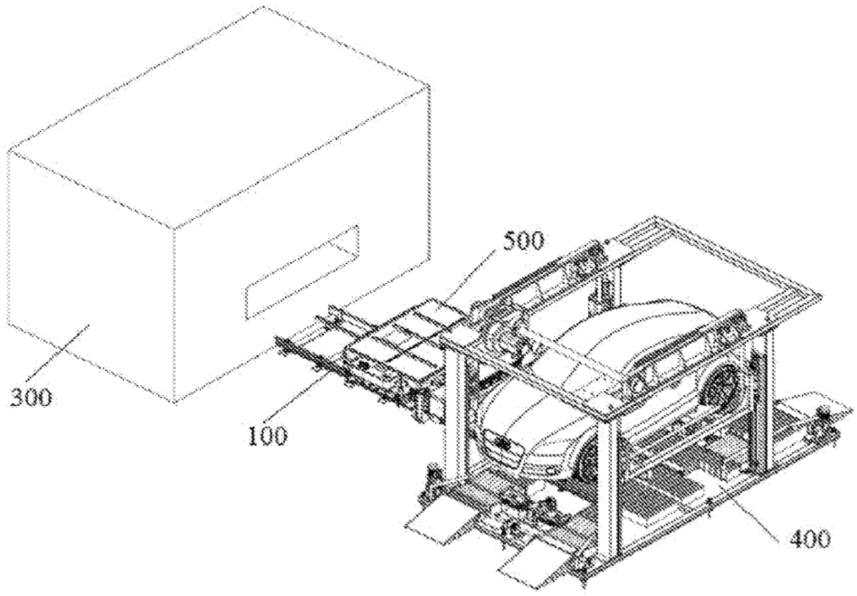

Figure 12: NIO battery swapping station infrastructure. *Sourced from [41]*

Currently one of the few large-scale battery swapping projects is being realized by the Chinese EV manufacturer NIO, who has begun building a network of BSSs to serve its customers. NIO has developed a chassis type swapping system, similar to that of BETTER PLACE, as a special frame structure, attached to the chassis, is used to mount the swappable battery pack under the vehicle. However, instead of taking up the vehicle on a ramp or using underground equipment, the company applies a swapping technique based on lifting the vehicle so that the area underneath is accessible by the special battery swapping robot (Figure 12). With this method, a battery pack in the BSSs of NIO can be replaced automatically in about 3 minutes.

Another Chinese company that manufactures EVs adequate to use swappable batteries, is BJEV that in 2019 handed over 800 EV taxis equipped with chassis type swappable batteries to Beijing-based taxi companies.

POWER SWAP, a Swedish startup, proposes a different method for battery swapping. The company has introduced a robotic device which replaces a number of withdrawable battery packs from the side of the vehicle, where special compartments for batteries installation are provided (Figure 13). The whole procedure is implemented automatically within 3 minutes.

This swapping method overcomes many of the drawbacks of the chassis type swapping techniques, while battery packs with higher level of standardization can be used. It is not necessary to place the vehicle on ramps with complicated underground equipment or to lift it so that the area underneath is accessible by the battery swapping equipment. The concept was created with the goal of using the already well-established infrastructure of the fuels filling stations.

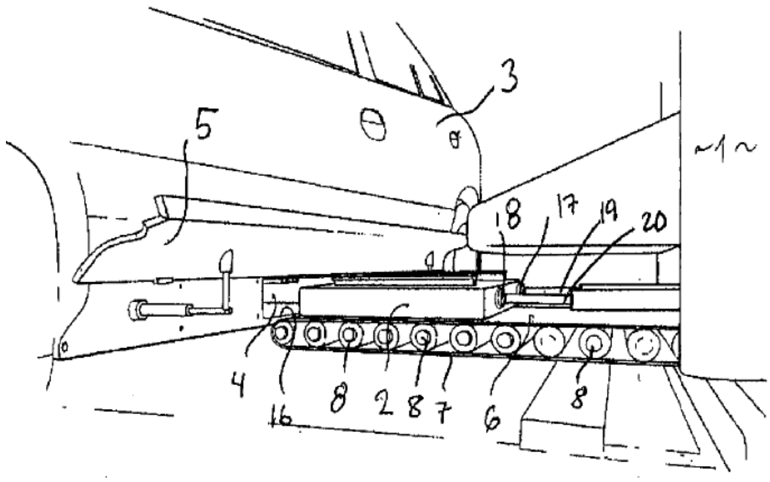

Figure 13: POWER SWAP battery swapping method and equipment. *Sourced from [42]*

However, a serious drawback of this swapping method is the necessity to differentiate the design of the vehicle side beams in order to arrange the opening for inserting the battery pack into their installation compartments. The vehicle is likely to be quite tall, to house not only the battery pack compartments, but also the required structure for keeping the vehicle rigid. This design differentiation implies significant impacts to the standardized practices that automotive industry applies nowadays in vehicles design and manufacturing, thereby increasing manufacturing costs.

BATTSWAPP, another European star-up, also proposes a battery swapping method based on the chassis type technique. The company has a working prototype swapping station for light commercial vehicles in Slovakia, where a battery swapping is completed in less than one minute.

Advantages of Battery Swapping

Battery swapping provides significant benefits for vehicle owners, BSS owners and for the power grid:

For vehicle owners

- A major barrier to the adoption of EVs is the high cost of ownership, which is directly connected to the cost of the battery. Battery swapping helps to reduce the sticker price of EVs to even lower levels than ICVEs. That is because consumers can purchase the car without the battery.

- Saves time for drivers, as battery swapping is as fast as ICVE refueling.

- Permits longer trip distance without the feeling of range anxiety, by accessing the battery swapping procedure in the BSSs.

- Increases operating life of the vehicle, while retains much of its value as a secondhand vehicle.

For BSS owners

- The BSS infrastructure can be established faster and with lower costs compared to a large network of public chargers. This is due to the fact that the EVs need enough space to be parked for several hours and be charged, especially in densely populated urban areas. Since each vehicle spends only a few minutes at the BSS, the land requirement per vehicle in the fleet is much less than the other charging options. Consequently, the cost of real estate is reduced, as there is no need to access large parking spaces [43].

- Fast charging increase battery degradation. Charging of the swappable battery packs in the BSS can be realized with an advanced control charging strategy, in temperature-controlled conditions that slow down degradation, extending the useful life of batteries.

- The BSS owner can charge the batteries in a time-scheduled manner, on the basis of electricity prices, minimizing charging costs.

- Battery storage capacity provides a great opportunity for the BSS owner to maximize his profit by participating in the electricity markets, offering grid ancillary services.

For the Power Grid

- The charging behavior of the EV owners is stochastic and unpredictable. The uncontrolled nature of the charging energy demand could have significant impacts on the power system, such as increasing peak load and network instability. Moreover, fast charging of EVs at 50 kW and up can lead to unsustainable load spikes on the distribution grid, especially at peak-load periods. The BSS approach, however, offers a controlled charging ability by scheduling the batteries charging time, as it is able to postpone the charging of the batteries to off-peak hours or to reduce the load demand by increasing the charging time. By controlling the charging time of the batteries, the potential peak demand or network overloading can be flattened [43].

- An extended network of BSS can offer to the grid an increased level of distributed storage capacity facilitating the renewables penetration and providing grid ancillary services such as voltage control and frequency regulation, so maintaining grid stability and flexibility.

- BSSs, as energy storage facilities, can delay or entirely avoid utility investments in transmission and distribution system upgrades that are necessary to meet load and supply growth on specific regions of the grid.

Disadvantages of Battery Swapping

However, battery swapping suffers from serious drawbacks which are the reasons why this concept has been almost abandoned in Europe and the U.S.:

- Standardization of battery packs across vehicles, meaning interchangeable battery packs that can be used from EVs made of various manufacturers, is very difficult to implement due to different design considerations of EV manufacturers. The battery pack is integrated into the vehicle's chassis and consequently consists a core part of the vehicles' physical structure strength, affecting stability, rigidity and safety. Consequently, it is difficult for each EV manufacturer to share similar battery architecture. Companies like TESLA or NIO that make the car and the BSS did not have to face the challenge of standardization. However, it is absolutely ineffective for each EV manufacturer to have dedicated BSSs, exclusively for its vehicles.

- To swap a battery from a vehicle, the design must allow certain considerations in the structure that ensures easy connection and disconnection of the battery pack to the vehicle's frame. This feature will eventually limit the freedom to design the vehicle and customize it to an undeniable limit [44].

- The operational life of a vehicle usually exceeds 10 years, which could mean as many as 1,000 swaps for a high-mileage vehicle. That involves engineering of new types of mountings, fasteners, seals, connectors, etc., which have to be developed [100]. Furthermore, a challenging task is the swapping procedure to cope with the effects of vibrations, dirt, dust, water and generally the overall stress on the framework and structure of a vehicle, over its whole operational life. In addition, another challenge while removing the battery is to disconnect it from the cooling system without spilling its contents.

- Consumers acceptance of the BSS model mainly relates to their anxiety of not owning the battery at the time of purchase of the EV. The idea of leasing part of the car and swapping that out at regular intervals, potentially is not attractive for the majority of consumers. This is because in industrialized western communities, based on a culture having developed over a century, the car is something that carries great personal attachment. Cars not only fulfill instrumental transportation functions, but they also hold significant symbolic and affective meaning for their owners. Thus, decisions about car ownership do not merely reflect rational economic choices but often they are as much about aesthetic, emotional and sensory values people associate with cars, such as freedom and independence, social status, prestige and excitement [3].

VI. BATTERY SWAPPING AS A RANGE EXTENDER

The concept of battery swapping offers the potential to overcome most of the drawbacks that make EVs less attractive to typical consumers, by addressing issues such as vehicles high cost of ownership, long battery charging time and range anxiety. However, the relevant concept suffers from certain disadvantages that prevent its widespread acceptance.

Therefore, a new approach is needed to address the disadvantages of the currently applied battery swapping methods, while at the same time reaping all the benefits of the relevant concept. This new approach presented in this paper is based on the idea of battery swapping as a method for extending the range of vehicles.

According to a study published by the AAA, the Americans drive, on average, 29.2 miles (47 km) per day [45]. Other studies have shown that the typical daily drive cycle for the average consumers is approximately 40 miles (64 km) for the 95% of their drive cycles [32], while in most European countries, daily average passenger vehicle driving distance is 40-80 km [99].

These driving distances correspond to battery capacity of approximately 15 to 20 kWh. Consequently, a permanent on the vehicle battery pack rated between 20 kWh and 40 kWh, depending on the size of the vehicle, is considered sufficient for covering the daily drive cycle or even more, of most drivers.

Therefore, EVs could be equipped with a permanent battery pack, which will provide the power to cover short driving distances, while they could use swappable batteries to extend their range, when needed.

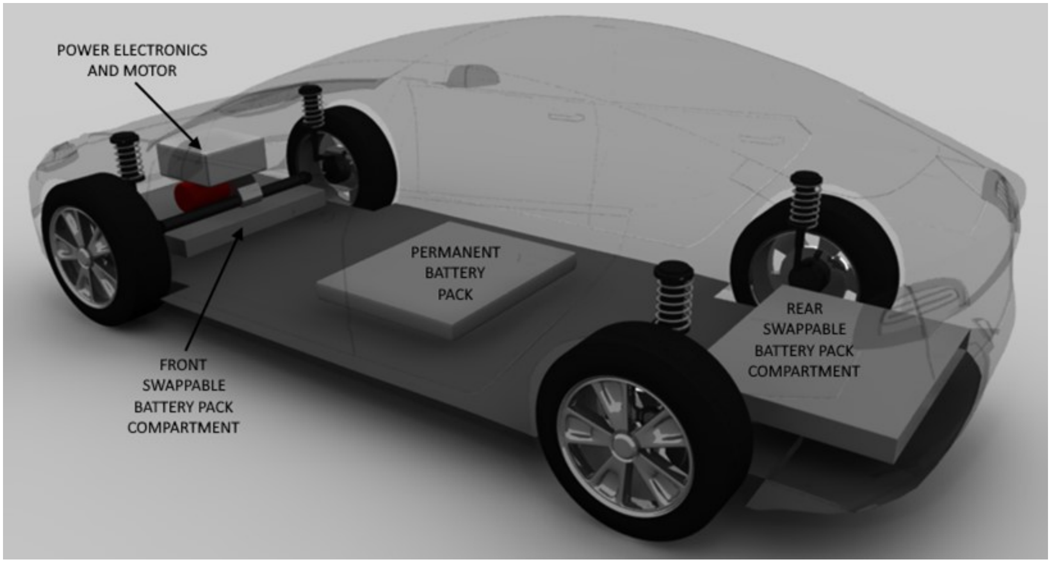

Figure 14: Battery equipment arrangement in a front-wheel drive vehicle with power electronics and motor in common block

To apply the relevant concept, on the front and rear EVs need to be equipped with dedicated compartments, suitable for the installation of swappable, standardized and flat shaped battery packs, of the withdrawable type. These swappable battery packs will offer EV drivers the ability to be served by an extensive network of BSSs that needs also to be developed.

The swappable battery installation compartments will further protect batteries from mechanical stress, keeping batteries and contacts clean of dirt, reducing the risk of short-circuits due to high resistance contact.

The proposed battery arrangement facilitates the use of the area under the frame for the installation of the vehicle's permanent battery pack. Due to the high level of standardization, a number of 4 to 6 different types of battery packs could serve the full range of EV models.

Figures 14, 15 and 16, illustrate indicative arrangements of the permanent battery pack and the swappable battery packs compartments in exemplary vehicles.

Figure 14 illustrates an indicative arrangement of the swappable battery pack compartments and the permanent battery pack in a front-wheel drive vehicle with the power electronics and the motor installed in a common block. The permanent battery pack is located in the middle of the chassis, close to the center of gravity of the vehicle, while the swappable battery packs compartments are located on the front and rear. The installation position of these compartments allows the application of a draw-out swapping method, facilitating the use of battery packs with a high level of standardization.

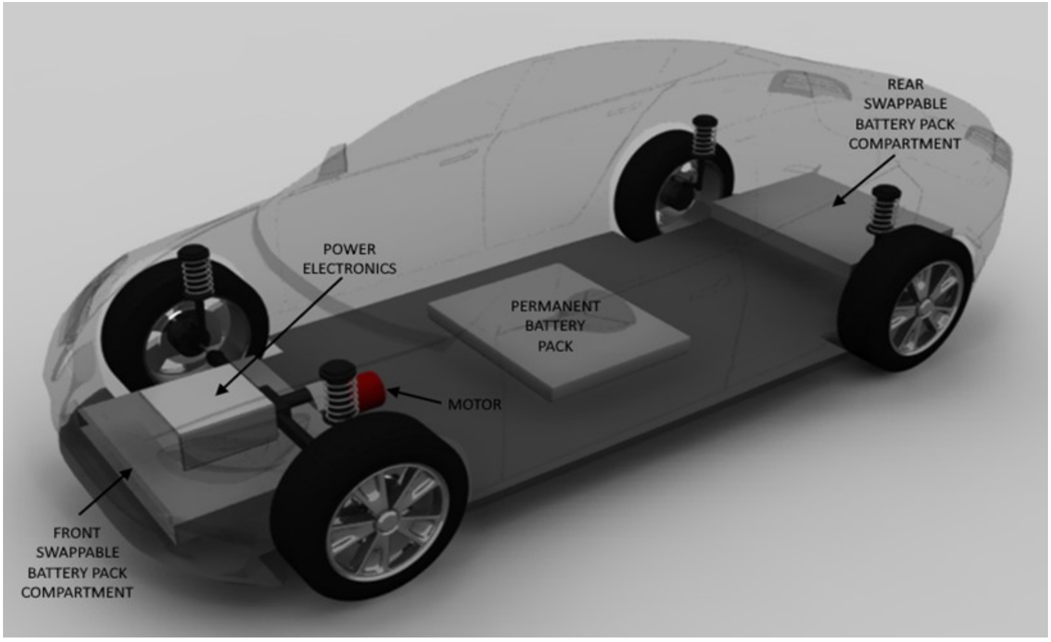

Figure 15: Battery equipment arrangement in a front-wheel drive vehicle with the motor separated from the power electronics

By installing a battery in the front, the vehicle will be understeered, as it will be front heavy and the front will break out in the corners. The same problem will occur if the battery is installed on the rear, making the vehicle to be oversteered. By installing two swappable batteries of similar weight, one at the front and the other at the rear, the driving behavior of the vehicle is neutralized.

Both swappable batteries will be installed low in the frame so that the vehicle does not plunge during braking and acceleration and does not roll in the corners.

In front-wheel drive vehicles, if due to space limitations it is not possible to arrange the power electronics and motor in a common block, the electric motor could be separated from the power electronics and be installed in the area occupied by the transmission system in conventional vehicles. Figure 15 illustrates an indicative view of this arrangement.

Finally, Figure 16 illustrates an indicative arrangement of the swappable battery pack compartments and the permanent battery pack in a rear-wheel drive vehicle, with the power electronics and the motor installed in a common block, similar to that applied in TESLA EV models.

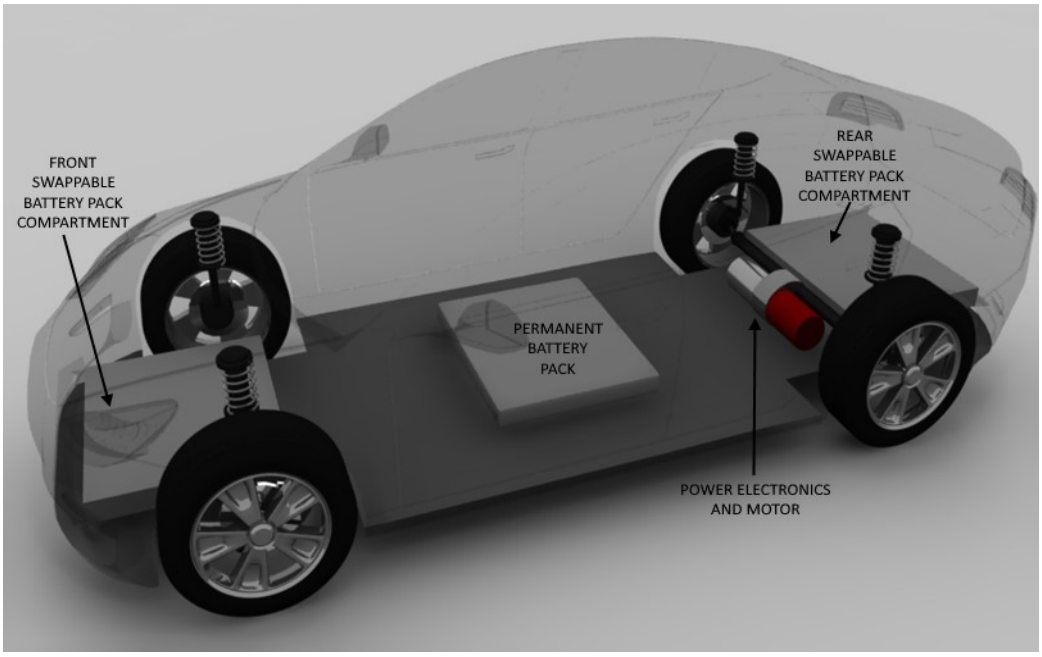

Figure 16: Battery equipment arrangement in a rear-wheel drive vehicle

The installation of three separate battery packs in a vehicle (two swappable and one permanent), facilitates the application of various operating modes. Indicatively, the following can be mentioned:

- The regenerative breaking will charge only the permanent battery pack.
- In cases of excessive power demand, e.g. during acceleration, more than one battery pack will contribute the required power.
- If one battery overheats or fails, it will be isolated and the EV will continue to run, powered by the other two batteries.
- Prior to delivering the swappable batteries to the BSS, their residual energy can be transfused to the permanent one.

The proposed implementation, in conjunction with the development of an extended network of BSSs, addresses in the best way a lot of problematic issues related to the production and use of EVs, as well as issues related to the high penetration of renewables to the power systems, such as:

The Energy Storage Issue

The amount of storage required to achieve high renewables penetration will be enormous. According to studies, high levels of renewables penetration will rely on the development of demand response and energy storage facilities with power capacities of at least 65% of peak demand [46] and energy capacities large enough to accommodate seasonal energy storage. Bloomberg New Energy Finance (BNEF) estimates that battery energy storage installations around the world will multiply exponentially, from a modest 9GW/17GWh deployed as of 2018 to 1,095GW/2,850GWh by 2040 [47].

Accordingly, the International Renewable Energy Agency (IRENA) predicts that a total storage capacity of up to 420GWh (Figure 17) will be installed by 2030 [48].

Many analysts estimate that the extensive penetration of EVs can provide solutions to the issue of energy storage, using mechanisms like the vehicle to grid (V2G) technology or the use of second life battery packs in stationary storage applications. However, said mechanisms need to overcome a number of serious challenges in order to become reliable alternatives to newly manufactured stationary battery systems.

The Vehicle to Grid (V2G) perspective

V2G is a technology that enables a bidirectional flow of energy between EVs and the power grid, allowing vehicles to return part of the energy stored in their batteries to the grid in order to be used when the power demand is high. For the implementation of the system it is required a bidirectional power connection between EVs and the grid, communication capability to control charging and discharging of the EVs and precision metering to audit services provided to the grid [49]. In order to be developed a true V2G market for EVs, several important issues need to be addressed:

- The frequent battery charging and discharging cycles related with the V2G services, causes degradation, affecting battery lifespan. Manufacturers need to allow V2G use under their warranties. Battery degradation also affects V2G business case, as the payment offered to consumers will need to be high enough to compensate for potential battery degradation [49].

- Currently, EV batteries are best suited for shorter-term storage and are suitable for the frequency regulation market. A V2G system, compared to other electricity market participants, has a more limited energy production capacity and the cost per unit of energy is comparatively higher [49]. Future storage markets may require long-term storage of days to weeks.

- Vehicles must be equipped with the capability to allow two-way flows of energy between the vehicle and the grid. The bidirectional AC/DC chargers increase the cost of EVs.

- Regulatory frameworks and EV charging infrastructure are not designed for mobile power resources.

- Essential hardware and software infrastructures that would be needed to enable V2G are generally lacking. These infrastructures includes communication technologies and algorithms for real-time data exchange, advanced metering so EV owners can be paid for making their vehicles available and standard interfaces between vehicle and grid [50].

- Communications and management for a large network of charging points, vehicles and customer information entails security and privacy concerns. Providing routine maintenance, ensuring data integrity and monitoring cyber security may have significant costs [51].

- In order V2G to be a dispatchable power source, a minimum EV plugged-in time will be needed by utilities and aggregators. This requires specific contractual arrangements between vehicle owners and aggregators [52].

While the above-mentioned technical and economic barriers pose substantial challenges, the most significant challenge for V2G development is that unlike the other technologies, the large-scale development of V2G systems depends almost entirely on the willingness of consumers to adopt a V2G-capable EV and participate in the system. The social acceptance of V2G technologies is a paramount concern for the successful diffusion of V2G [53]. Issues like the potential battery degradation could affect consumer's willingness to participate to V2G systems.

Furthermore, EV owners will probably not be willing to enter into binding contracts with aggregators regarding the minimum plugged-in time, as this leads to occasional loss of vehicle use. Especially, during periods of extreme weather conditions or social unpleasant situations, EV owners will prefer to have their vehicles charged and ready for use, instead of making profit participating in the V2G system. During these periods, the energy requirements of the power system increase significantly.

Thus, although V2G is likely to play a significant role in the future energy storage market, it is unrealistic to assume that this technology will dominate this market against the growing competition of the stationary battery storage systems.

EV batteries Second Life perspective

EV batteries are retired from vehicle use when they no longer meet the high standard performance thresholds for that application and either recycled or can have a second life in stationary applications. Typically, a LIB that has less than 80% state-of-health, is considered at the end of its life but still offers significant storage capacity.

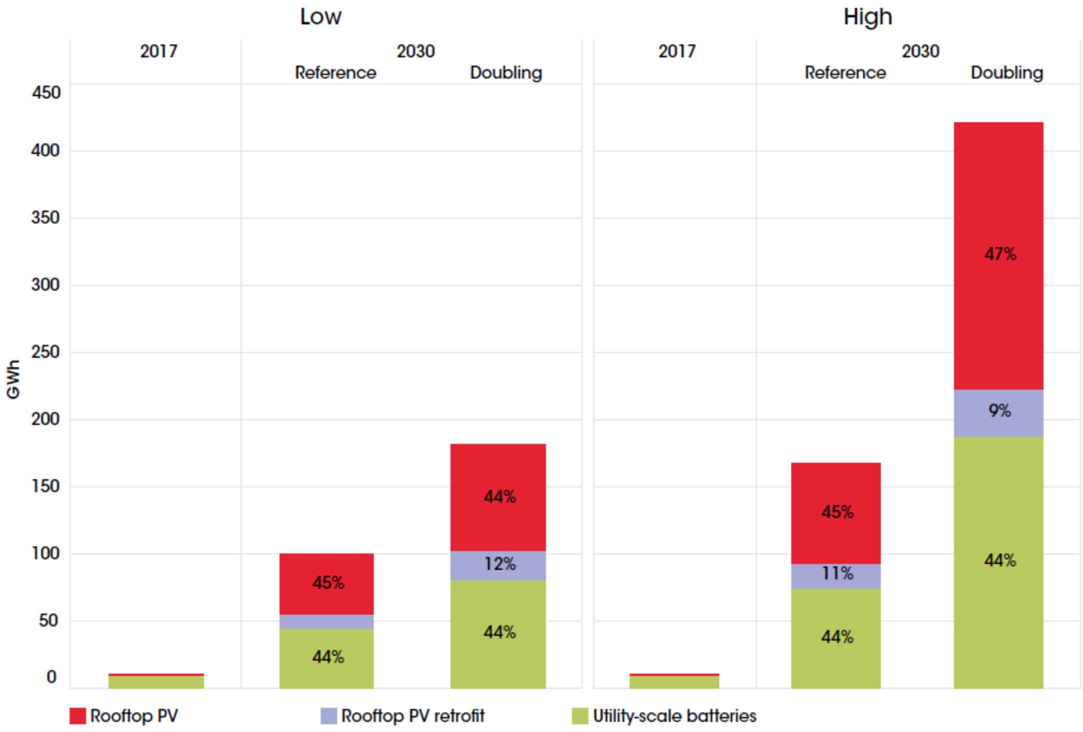

Figure 17: Battery electricity storage energy capacity growth in stationary applications by sector, 2017-2030, according to IRENA. *Sourced from [48]*

The thousands of batteries that will be coming out of EVs in the coming years could be reconditioned and repurposed, providing a large number of inexpensive batteries that can be used in stationary storage applications, reducing the amount of new batteries required in the future for this purpose. The repurposing process of batteries would consist of partial pack disassembly and module separation, components testing and grouping and reassembling components in order to make a second-life battery. Another option is the testing and utilization in stationary applications of the whole EV battery packs without to be disassembled [54].

A research issued by the Massachusetts Institute of Technology (MIT) concludes that repurposing of EV batteries for stationary energy storage applications can be profitable, provided some basic assumptions are met [55]. Various economic and technical challenges, as follows may impact viability of second life battery market:

- From an economic standpoint the sourcing and transportation of used battery packs to dedicated facilities, their disassembling, quality testing and repackaging, is rather uneconomical. It is difficult to ensure that there is enough value left in these batteries to justify the remanufacturing cost. Small cells like the cylindrical ones further increase this cost. Actual remanufacturing costs lies between 25-50€/kWh and is highly dependent on the type and state of the battery, the scale effects and the remanufacturing process [56].

- Safety concerns need to be addressed before mass deployment of second-life cells in order to ensure safety.

- Second life batteries may have poor performance, while their degradation rate is likely to be faster than that of newer batteries. Consequently, guarantee issues regarding second life battery quality or performance need also to be addressed.

- Availability of battery first life data is also a main concern. These data are important especially when the whole battery pack is utilized.

- The competition from new batteries constitutes a major challenge for second life batteries, which makes it crucial to establish the market and infrastructure for second-life batteries in the near term. As new batteries become cheaper, the cost differential between used and new diminishes, given that the rate of decline in remanufacturing cost is expected to lag the rate of decline in new manufacturing cost [57].

- If not all second battery packs utilized in a functioning energy storage system are of the same type, then different types of batteries packs have to be combined together. The various control systems need to work together properly to deal with variations in the battery packs and their voltages. Moreover, battery packs with much poorer performance than others in the same installation can drag the performance of the whole system down [55].

- A large number of battery-pack designs are available on the market that vary in size, electrode chemistry and format (cylindrical, prismatic and pouch). This increases refurbishing complexity due to lack of standardization and fragmentation of volume [57].

Although solvable, all the challenges described above require resources and thus impact the business case for a second-life system and its competitiveness to stationary energy storage systems consisting of newly manufactured batteries.

BSSs as energy storage facilities

There is no doubt that V2G and EV batteries second life will play a role in developing the battery-based energy storage capacity required to increase the renewables penetration. However, due to challenges that could affect the viability of these mechanisms, it is unrealistic to assume that they will dominate the future battery-based energy storage market. Therefore, it is inevitable that enormous energy storage installations consisting of newly manufactured batteries will be required to be developed.

Instead of developing these energy storage installations, an extensive network of BSSs could provide the required storage capacity required for the penetration of renewable energy sources.

BSSs can provide significant techno-economic benefits compared to stationary battery-based or other type of energy storage installations:

- Further to battery swapping services for vehicles, the BSSs can offer grid ancillary services. This wide range of services ensures the financial viability of BSS projects.

- As EVs adoption continues to expand, more and more inner-city refueling stations will be retired as drivers charge at home or at work. Medium and small size BSSs can be developed on the retired refueling stations real estate. In this way, part of the refueling stations shrinking market will be replaced by BSSs.

- BSSs as energy storage installations reap all the benefits of distributed energy storage systems, such as increased efficiency, as they will be located close to energy consumers, consumption shifting away from high demand hours, fast backup power after a blackout, synergy with distributed generation, etc. [58].

- BSSs are more efficient than stationary battery storage installations in managing the energy used to power EVs. This is due to the fact that the power losses during a charging-discharging cycle of the stationary batteries are saved when the energy is used to charge swappable EV batteries. Using batteries for charging batteries is rather inefficient.

- Some battery chemistries are not as affected by cold temperatures compared to others. For example, a battery that contains lithium titanium anode is the best cold weather performer [29]. However, optimization of the battery performance based on the weather conditions of each country is not practical. Currently, typical EV batteries are designed for warm weather and not for the low temperatures of many climates. But this is not necessarily the case of the swappable batteries used in BSSs, the performance of which could be optimized for different ambient temperatures. Thus, batteries that have been optimized for warm temperature could participate in the swapping procedure during the summer, while during the same period those that have been optimized for lower temperature could remain in the BSS controlled environment, providing ancillary grid services and vice versa during the winter.

- When the swappable batteries no longer meet the high standard performance thresholds for powering EVs, they can provide second life ancillary services to the grid within the BSSs. Therefore, it will not be necessary for thousands of batteries to be collected, transported and remanufactured, which is inefficient and uneconomical.

The Raw Materials Issue

The penetration of EVs worldwide combined with the increased demand for energy storage installations for renewables integration is likely to have important implications on the cost of batteries, due to the increased demand for raw materials extensively used on LIBs construction. Consequently, the supply risk of these materials is considered to a continuous investigation by various analyses, in an effort to forecast the future behavior of the relevant market. These raw materials mainly include nickel, cobalt, lithium, copper, graphite and manganese, which are not in infinite supply in nature and are also much sought after for other industrial applications.

The supply risk of a number of other elements used in battery cathodes or anodes such as tin, silicon, magnesium and germanium should be also analyzed, as the demand for some of them could grow rapidly if they become the materials of choice in the next generations of batteries.

A such analysis by MIT researchers indicates that without proper planning there could be short-term bottlenecks of some of the materials required in EV battery manufacturing. This analysis showed that while nickel and manganese are not likely to be impacted, a temporary shortage could be appeared in cobalt and lithium production, causing price increases, as sourcing of raw materials is mainly driven by prices [59].

Despite forecasts, the fact is that the mining for raw materials is often accompanied by social and ecological issues. The working conditions in the mines are extremely health hazardous in many raw material-rich countries around the world and wages are low. It is not uncommon for conflicts to arise between mining companies and the local population over water consumption and environmental pollution resulting from mining and processing of the raw materials.

Many analysts estimate that batteries' recycling has the potential to provide a large portion of the raw materials required. In general, recycling is a capital-intensive business and the value of the recovered materials is usually not enough to cover recyclers' expenses [60]. The variety of materials used in battery cathodes creates a challenge for recycling. To handle mixed cathode chemistry, current recycling processes require expensive organic reagents for solvent extraction to separate cobalt, nickel and manganese. There is an urgent need to develop cost-effective methods for recycling batteries on an industrial scale in order for recycling to become an economically viable practice [3].

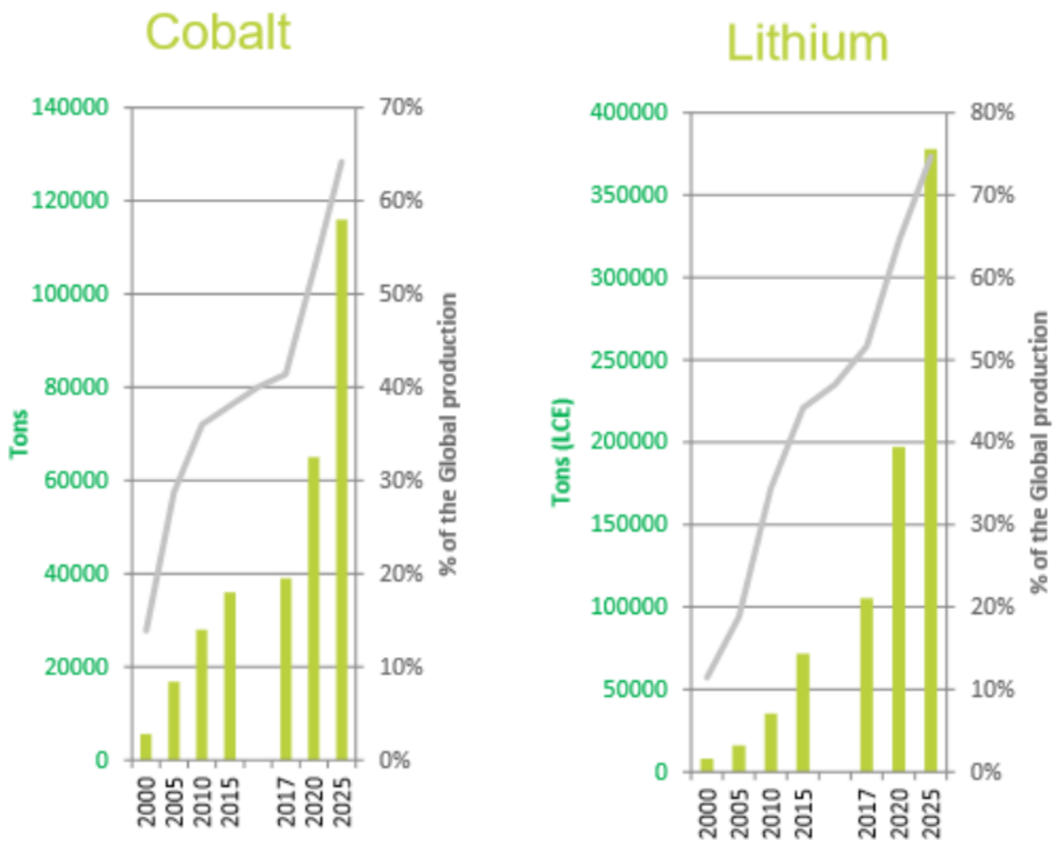

Figure 18: Increase of metals will be needed for rechargeable batteries. *Sourced from [98]*

The Lithium

Lithium is an essential element for EV batteries. It is extracted either by crushing igneous rocks which are mined especially in Australia or from lithium-bearing brine deposits in salt lakes mainly in Chile and Argentina [61].

The majority of the world's lithium refining facilities are in China, enhancing China's dominant power in the lithium-ion battery value chain [62].

The production of lithium can have significant environmental and social impacts as pollution and water shortages tend to accompany the mining process. Chemicals and high temperatures are used to separate lithium from the rocks, demanding significant amounts of energy, while for the lithium obtained from brines chemicals and large quantities of water are required for its purification.

Battery manufacturers are going to need more mines to support their production and they will have to build them quickly, while in many cases mining must be realized in environmentally sensitive areas. According to BNEF, by 2030, Tianqi Lithium, SQM, Albemarle and FMC, the companies that dominate the business, will have to supply enough lithium to feed the equivalent of 35 plants the size of a TESLA Gigafactory. Mining companies have promised to add 20 lithium production sites to the 16 currently operating, but the concern remains that they will not be finished in time to satisfy rising demand [63].

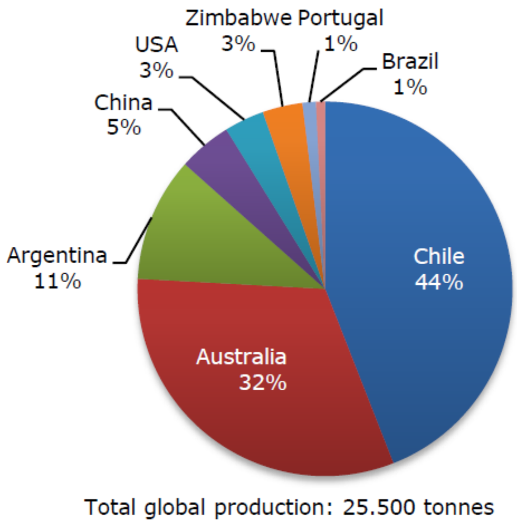

Figure 19: Global production of lithium average 2010-2014. *Sourced from [98]*

Furthermore, a history of price manipulations in the past, like the one in 2015 that almost tripled the prices of lithium to more than $20,000 a ton [64], maintain a significant uncertainty for the future price of this metal.

The Cobalt

Most cathodes of lithium-ion batteries contain cobalt. Cobalt is typically a byproduct of copper and nickel mining activity. Two-thirds of the material production comes from the Democratic Republic of Congo, which is considered as a country with particularly high risk due to the uncertain political, economic and social conditions of the country, which has a history of violent conflicts and corruption. The mining there is often associated with child labour and illegal small-scale mining. This production system, as well as the political instability is the reason for strong price fluctuations and doubts about the sustainability of the supply of said material.

Cobalt is likely to become more expensive in coming years, as several barriers can limit production from mining activities, making supply forecasts complex and largely uncertain. These factors include reserves depletion or unforeseeable production stoppages at active mines, high costs of production and economic and socio-environmental determinants. However, the main issue that will probably affect future cobalt production is the ability to the initiation of new mining activities so as to adapt to the continuously increasing demand [65].

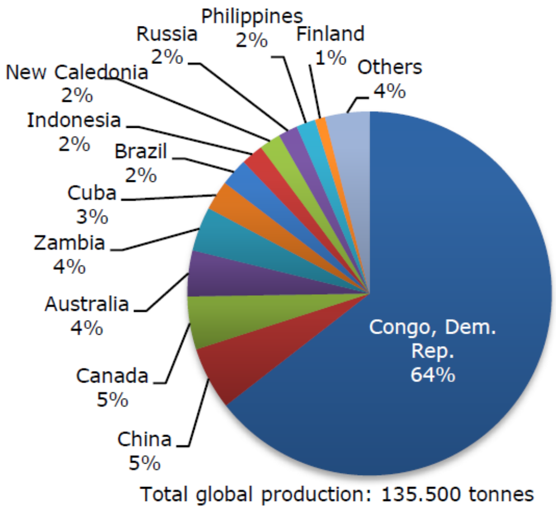

Figure 20: Global cobalt mine production average of 2010–2014. *Sourced from [98]*

According to estimations, the need for larger rechargeable batteries for expanding 5G mobile phones technology is expected to significantly boost demand for cobalt over coming years and potentially pit the sector against electric vehicle makers. This is because larger batteries are required in 5G phones because they need more power compared to 4G phones [96].

Regarding natural graphite, which is another critical element of the anode, China remains the main supplier.

BSSs and raw materials optimization

An extensive BSS network in synergy with EVs that use swappable batteries to extend their range can contribute to the optimization and rationalization of the production of battery raw materials, leading to lower material requirements for the following reasons:

- BSSs that operate as energy storage installations share the same swappable batteries with EVs. These batteries can provide ancillary grid services when they do not provide power for vehicles operation and vice versa. Increasing the utilization factor of the relevant equipment reduces the required number of batteries and therefore the need for more raw materials.

- The permanent onboard batteries of the EVs which use swappable batteries to extend their range are smaller than regular, thus requiring fewer raw materials.
- The swappable batteries can provide their second life services within the BSSs, extending in this way their useful life and therefore minimizing the requirements for new batteries for energy storage applications.
- After the end of the useful life of the swappable batteries, the BSSs can operate as gathering centers for batteries recycling, thus increasing the efficiency of the recycling process and raw materials recovery.

The Grid Impacts Issue

Most of the electricity systems worldwide were developed decades ago in a manner that ensures sufficient power generation and network capacity to meet peak periods of power demand. The power demand in each network varies substantially over a day, forming peaks and valleys. The additional electricity demand due to the high shares of EVs expected in the future will have serious implications to the power quality and the network infrastructure, while also creating the necessity for additional electricity generation. Studies have shown that the electric system with EV loads is lesser stable compared to a system without this type of loads, considering the system dynamics following a three-phase system fault. Furthermore, the network power losses increase significantly as a result of the increased network power flow caused by the large EV penetration [66].

Power quality degradation, infrastructure stress and additional electricity generation, are some of the challenges that the electricity systems have to deal with.

Power quality degradation

The EV charging loads have nonlinear characteristics which are different than the general industrial or domestic loads, while they consume large quantities of power in short time period causing voltage instability in the power system [67].

The EV charger characteristics, being nonlinear, give raise high frequency components of current and voltage, known as harmonics. Harmonics distort the voltage and current waveforms, reducing the power quality. Harmonics also causes stress to power system equipment, like the distribution transformers, which are influenced by the heat generated by the harmonic currents.

Network infrastructure stress

The new peak load during the night will shorten the normal cool-down period of power distribution equipment like cables and transformers. This fact in combination with the additional heat generated by the EV charging loads could lead to increased aging rate of the insulation of the relevant equipment. The impact of the thermal limit violations to the network infrastructure will be more severe in regions with higher ambient temperature. To provide maximum power for simultaneous operation of a large number of EV battery chargers in one location would probably require upgrading the power distribution infrastructure.

Additional electricity generation

Questions like how much electricity will be required, what type of generation will be used to cover the additional energy demand and how the charging peaks will be managed have to find sufficient answers. If all light-duty vehicles in the U.S. were replaced with EVs, they would require about 1,000 Terawatt hours (TWh) of additional electricity per year, or an increase of about one-quarter of the current electricity demand [68].

Additional electrical generation will be required in the European Union to meet the extra energy demand arising from an 80% share of electric vehicles in 2050. The share of Europe's total electricity consumption from electric vehicles will increase from approximately 0.03% in 2014 to around 4-5% by 2030 and 9.5% by 2050 [69].

A problem for every solution

Currently, most people usually charge their vehicles every evening after return home, during peak times, when demand is already at its highest value. If this behavior continuous in the future and due to the high shares of EVs expected, the electrical system will face significant challenges. The energy utilities plan to deal with this situation in various ways, but mainly hope to influence charging behavior by applying time-of-use tariffs [70], encouraging users to charge at times of low electricity demand and consequently to shift the EVs load to fill the valleys and reduce peaks, creating a more uniform load profile across the entire system. This flexible charging, known also as smart charging, could help optimizing the use of grid resources, minimizing the necessity of investing in new peak generation capacity and upgrading the power transmission and distribution infrastructures.

However, such an approach could be successful depending on the choices that EV users will make. Probably, many users will continue to charge their vehicles during time periods of the day which are the most convenient for them, instead of allowing utilities to manipulate their charging behavior.

The most convenient charging period for users is usually during the night. In power systems with high level of renewables penetration this period will not necessarily coincide with the low energy price periods of the day. This is due the fact that in power systems that lack conventional base load units, the energy for charging EVs during the night will derive mainly from storage or interconnections, as wind speed tends to decrease at night [71] and the solar production is zero. This kind of energy will consequently have a higher tariff.

In other words, in power systems with a high level of renewables penetration the periods of low energy prices during the day will follow the volatility of the renewable energy generation, in a stochastic manner and EV users' charging behavior will probably be difficult to adjust to these periods.

The grid must be capable of delivering the required power to its users even on the most congested days. Users during periods of extreme weather conditions or social unpleasant situations will prefer to have their vehicles charged and ready for use. It is rather unrealistic to think that in cases where flexible charging fails to prevent constraint issues, curtailment of EV charging could be applied in order to avoid domestic outages.

Therefore, a power system stability model based on the influence of users charging behavior in certain conditions may be insufficient for the proper operation of the electrical system. Even though such a model can contribute to the efficient operation of the power system, it will not be sufficient to ensure its stability.

From this point of view, investing in new peak generation capacity, in energy storage systems and in large scale upgrading of the power transmission and distribution infrastructures is rather unavoidable.

The domestic electrical installations must be upgraded, as well. With the capacity of EV batteries constantly increasing and given the long charging times achieved by Level 1 chargers, users are more likely to select high power Level 2 chargers for home installation, adding of about 22 kW power consumption in the domestic electrical installation, which is equivalent to the typical demand of three houses. The adoption of chargers with shorter changing duration will push the existing distribution network to its limits.

The impact of fast charging

The main questions regarding the impact of fast charging on the electric grid are related to the number of EVs and the time that they rely on fast charging and whether the electric grid requires upgrades at the installation locations of the fast charging equipment.

Having multiple fast chargers at one site is important in giving confidence to drivers that a charger will be available upon or soon after arrival. A typical Electrify America highway installation with two 350 kW chargers and four 150 kW chargers has a nominal rating of 1,200 kW, representing 5%–10% of the maximum load of a distribution line in the U.S. An additional load of 1,200 kW would likely require an upgraded or a new transformer in the distribution line [5].

Electrify America has a minimum of four and a maximum of 10 chargers per site. Ionity in Europe specifies two to 12 fast chargers per site. In both cases, the power consumption of this number of chargers in a typical parking area is similar to that of a small factory.

The operation of fast chargers of this size causes significant demand peaks that stress the network, causing voltage instability. Distribution systems are the most likely to need upgrades, especially if fast charging occurs at high demand periods of the day.

The BSSs as grid stability tools

As mentioned above, power quality degradation and network infrastructure stress are the main impacts on the grid due to high shares of EVs, while additional power generation will be required. These impacts can be mitigated by the proposed configuration of EVs equipped with a smaller than regular permanent battery pack, in combination with the operation of BSSs as energy storage facilities, providing also a number of additional benefits:

- The smaller capacity of the permanent battery significantly reduces the load that EV charging requires from the grid, putting less stress to the relevant infrastructure, while reducing charging peaks as charging is realized with lower current. Therefore, the upgrades and investments in the distribution system that are necessary to meet load and supply growth on specific regions of the grid can be delayed or entirely avoided.

- The smaller capacity of the permanent battery does not impose significant upgrades to the domestic electrical installation, in order to meet the load demand of the high-power Level 2 chargers, which nowadays is necessary to be installed at homes, as the capacity of EV batteries continuously increase.

- The BSSs will be mainly connected to the robust medium voltage distribution network. This helps to divert load from the vulnerable low voltage grid to the more stable medium voltage one. Moreover, battery charging in installations powered by the medium voltage level is 2-3% more efficient compared to charging in the low voltage distribution network. This is due to the load losses that are lower in the medium voltage distribution system.

- BSSs that operate as energy storage facilities can provide ancillary services that have the potential to improve power quality by preventing voltage instability.

- The impact of harmonics distortion on the grid can be minimized, firstly due to the smaller chargers that are required to charge the EVs permanent batteries and secondly due to the dedicated harmonics filtering equipment that can be installed in the BSSs.

- Battery charging in the BSSs can be scheduled at off-peak hours. By controlling the charging time of the swappable batteries, the potential peak demand or network overloading can be avoided.

The EVs Price Issue

To reach their full potential EVs must account for a larger share of vehicle sales, penetrating massively to medium and low-income households [72]. EV enthusiasts, who can be characterized as “early adopters”, have very different motivations and behaviors compared to the general population, while tend to be environmentally conscious. Typical consumers will not purchase EVs unless they provide superior economic value benefits to comparable ICVEs. For the average car buyer, the potential fuel savings of an EV do not justify its premium price over ICVEs. Consequently, a significant reduction in prices is required in order to make EVs attractive to typical consumers, while at the same time the development of a secondhand market for EVs, which does not involve the risk of the battery replacement, is also required [72].

The price of EVs is directly connected to battery pack cost, which currently corresponds to 25-55% of the entire cost of the vehicle [74]. Larger batteries which are currently used by car manufacturers in order to increase range do not facilitate cost reduction.

Understanding current and future pricing of batteries is a complex task. While there are many market analyses on battery pricing, the underlying assumptions and specific components included in such price forecasts vary widely. The data is so varied that it calls into question any valid guidance for the future of battery pack pricing [97].

There are estimates based on industry expert assessments, concluding that in order for EVs prices to become competitive with ICVE ones, on an unsubsidized basis, EV battery packs need to fall to a cost of $100/kWh. Currently, battery prices, which were above $1,100/kWh in 2010, have fallen to $156/kWh in 2019. By 2023, average prices will be close to $100/kWh, according to a BNEF forecast [75].

The key determinant of BNEF forecast is the relationship between price and volume. From the observed historical values, it calculates a learning rate of around 18%. This means that for every doubling of cumulative volume, it is observed an 18% reduction in price. Based on this observation and the battery demand forecast, it is expected the price of an average battery pack to be around $94/kWh by 2024 and $62/kWh by 2030 (Figure 21) [73].

It is expected that cost improvements will come from economies of scale. Giga-factories and vertical integration including the direct source of raw materials will likely drive costs.

According to BNEF, the sensitivity of battery pack prices to the raw material prices is much lower than commonly understood. A price sensitivity study conducted by them (Figure 22) concludes that a 50% increase in lithium prices would for instance increase the battery pack price of NMC 811 battery by less than 4%. Similarly, a doubling of cobalt prices would result in a 3% increase in the overall battery pack price [73].

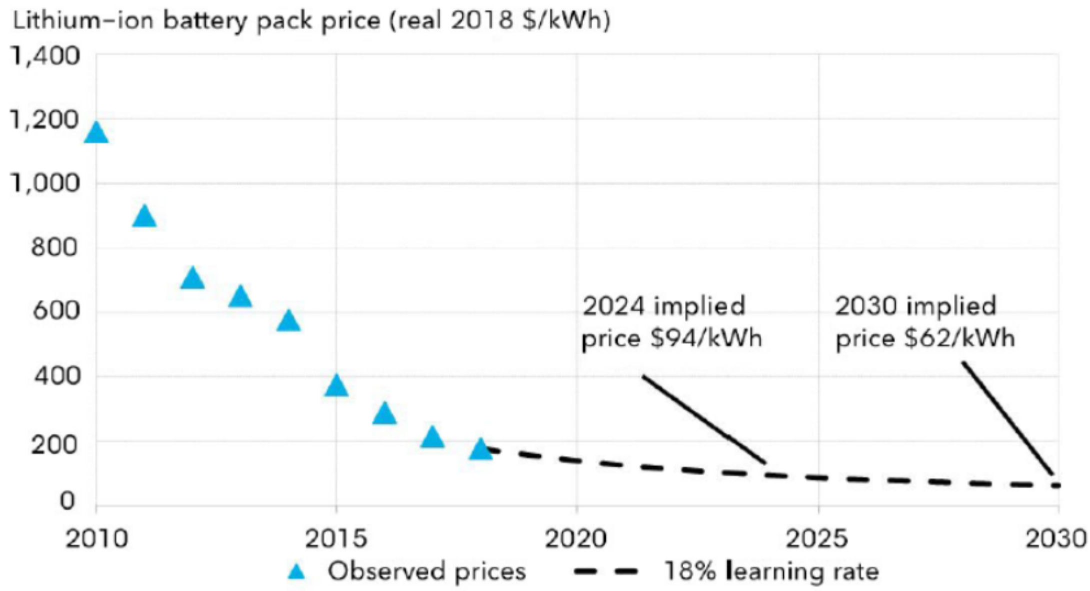

Figure 21: LIBs price outlook according to BNEF forecast. *Sourced from [73]*

In the opposite side, the report "Insights into future mobility, November 2019" from the MIT Energy Initiative concludes that such projections might be too optimistic since the conventional learning curve model implies the potential for unlimited cost reductions [3].

Figure 23 depicts MIT price projection for NMC-based batteries with battery prices approach $124/kWh in 2030, suggesting a price range between $93/kWh and $140/kWh. Therefore, this analysis, suggests that a price target of $100/kWh for widespread EV adoption is very unlikely to be achieved by 2030 [3].

For example, the price of lithium-ion battery packs is expected to drop to $124/kWh by about 2030. Even with this cost reduction, an EV with 200 miles (322 km) of range will remain much more expensive than a comparable ICVE in 2030.

Reaching the $100/kWh threshold by 2030, according to the MIT Energy Initiative report, would require material prices to stay roughly the same as in 2016. However, significant uncertainty remains about the steady-state price of cobalt in the future as demand and supply continue to increase.

In this report the MIT Energy Initiative warns that EVs may never reach the same sticker price with ICVEs as long as they rely on LIBs. The report finds that the steady decline in the cost of LIBs, is likely to slow in the next few years, as they approach limits set by the cost of raw materials.

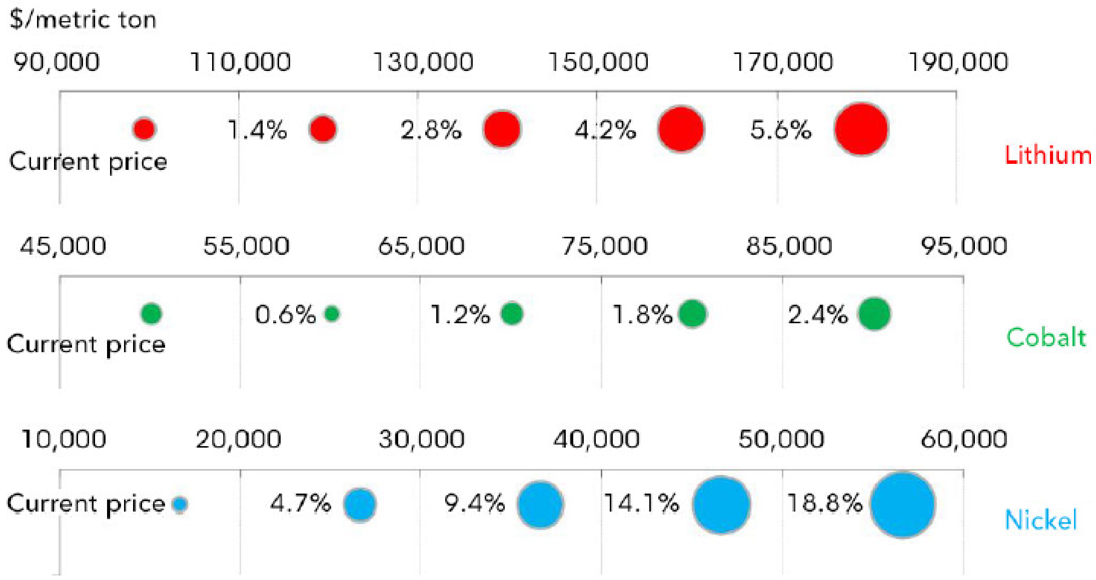

Figure 22: Price sensitivity of NMC 811 battery pack to changes in commodity prices based on prices of February 2019, according to BNEF. *Sourced from [73]*

The findings sharply contradict those of other researches, which have concluded that EVs could achieve price parity with the ICVEs ones in the next five years. The lingering price difference predicted by the MIT report could stunt the transition to lower-emission vehicles, requiring governments to extend subsides or enact stricter mandates to achieve the same adoption of EVs [76].

Another issue that makes EVs less attractive to typical consumers is the fact that they have bigger resale value declining because of the uncertainty over battery longevity that involves the risk of battery replacement. Automakers warranty their EV traction batteries for at least 8 years or 100,000 miles (161,000 km), but after that period, battery replacement is expected to cost from $2,500 to over $10,000, depending on the vehicle [33]. This consumer belief that their property will lose value at a faster rate than usual, causes difficulties to the development of a secondhand market for EVs.

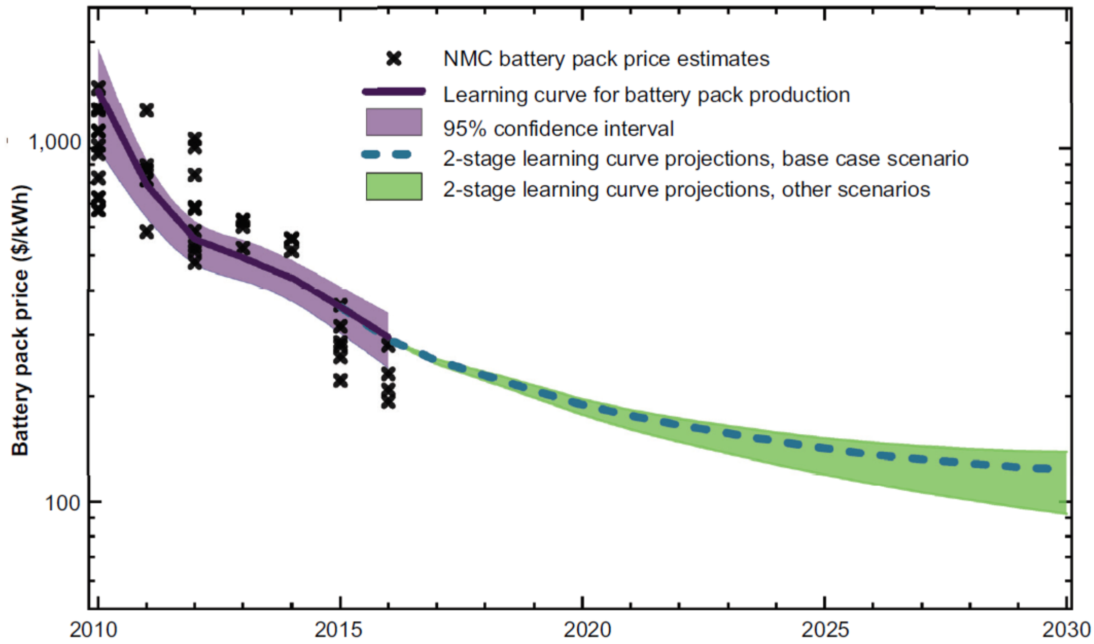

Figure 23: Past and projected price trajectory for lithium-ion NMC battery packs, according to MIT. *Sourced from [3]*

The smaller the battery, the lower the price

The proposed EVs configuration, which foresees vehicles to be equipped with a smaller than regular permanent battery, while using swappable batteries to extend range, addresses price issues in the best possible way, making EVs attractive to all socio-economic classes:

- A smaller than regular permanent battery pack leads to a reduction in EVs manufacturing costs and therefore a reduction in upfront purchase prices, making vehicles cost comparable to ICVEs. If the rate of decline in the price of batteries is also considered, in a few years such a vehicle will have a lower price than a conventional one. Furthermore, as the permanent battery will be lighter, the vehicle frame does not need to be reinforced to carry a heavy battery and therefore the manufacturing cost will be further reduced.

- A vehicle that is equipped with a permanent battery while at the same time can use swappable batteries to extend its range, is fully functional even after the permanent battery has been degraded in state-of-health levels lower than 80%. Consequently, and due to this operating time extension, vehicles retain much of their value, facilitating growth of secondhand market.

- As the size of the permanent battery pack is smaller than regular, the cost of its replacement is more affordable.

- Currently, due to their increased manufacturing costs, EVs are much less profitable, compared to similar ICVEs. As a result, automakers are reluctant to introduce a wide range of new EV models. By providing vehicles equipped with a smaller battery pack, the manufacturing cost reduces and consequently the profit margin for automakers can be increased proportionally.

- Warranty expenses and recycling costs are lower for smaller batteries, further reducing the EV costs.

The EVs Range Issue

To address the issue of range anxiety, EV manufacturers provide vehicles equipped with batteries of increased energy density. For increasing the battery capacity, more cells are required that tend to increase vehicle weight disproportionately, since an increase in the capacity of batteries does not result in a proportional increase in the range of the vehicle [77]. The heavier the vehicle, the more battery capacity it requires to achieve the established range and performance goals, especially in areas with sloppy terrain. Moreover, the thermal management system of the vehicle must be reinforced so as to handle the increased battery thermal load.

Further to the reduction of efficiency, which means the increase of the operational costs, the increased weight affects negatively the dynamic, accelerating and braking characteristics of the vehicle, while the tires, as well as the road surface wear out faster, increasing non-exhaust particulate emissions [78]. Heavier vehicles produce more particulate emissions from non-regenerative braking, as well.

EVs were found to be, on average, 24% heavier than equivalent ICEVs [79]. The batteries weight of some EV models reach up to 1/3 of the basic weight of the vehicle. EVs need certain structural features and reinforced chassis to accommodate the weight of the heavy batteries and these features may add extra weight to the vehicles [80]. Furthermore, in many EV models the battery packs are involved in the chassis rigidity and therefore the packs include a number of rigid frame structures that further increase the total weight of the vehicle.

Automakers, in an effort to compensate the increased weight, use lightweight premium materials in vehicles body construction, such as aluminium or titanium, a practice that increases manufacturing costs. Moreover, as the production of aluminium is highly energy-intensive, carbon emissions related to vehicles production also increase.

The increased energy consumption for battery manufacturing, which in most cases is comparable to the energy required to manufacture the vehicle itself, is another issue that also needs to be considered. The larger the battery, the more energy is required to manufacture it.

According to studies, typical daily drive cycle for the average consumers is approximately 40 miles (64 km), for 95% [33] of their drive cycles. The state of charge of larger batteries may often be higher, as drivers are used to fully charging their vehicles each night, despite the needed range of usage the following day. A state of higher charge than necessary leads to faster battery degradation [81].

To avoid degradation, charging strategies must be applied, which means that BMS should charge the battery for the desired distance and permit full charging only when user needs the full range. However, this type of operation is not practical, as presupposes that users should program daily their moving patterns, making the EV driving experience rather complicated.

The benefits of lightweight vehicles

Further to lower upfront purchase price, EVs with reduced size of battery offer a wide range of advantages. The disadvantage of limited range of these vehicles can be offset by their ability to use swappable batteries to extend their range:

- Vehicles in a typical daily driving cycle will operate without being loaded with the swappable batteries. Consequently, the operation with reduced weight increases vehicle efficiency. Studies have shown that a 10% reduction of the weight of a passenger car can lead to reduction in energy demand by 6-7% [64].

- The capacity of the permanent battery will be significantly lower than that of a typical battery currently used by EVs. Because of this, an air-cooling system could be used for battery thermal management, which is a simple and cost-effective method. Thus, by avoiding a liquid thermal management system, which is more expensive and complex to implement, the manufacturing costs of EVs, as well as their maintenance costs are further reduced.

- The suspension system and the brakes overwork less, as the vehicle does not need to carry continuously the total battery weight. That means lower maintenance costs for these systems. Furthermore, lightweight vehicles have better acceleration, shorter braking distance, while their tires do not wear out fast.

- The road wear due to friction between the tire thread and road surface is directly proportional to the weight of the vehicles. Lightweight vehicles cause less road surface wear and tear. Furthermore, lighter vehicles produce less non-exhaust particulate emissions, caused by road abrasion, tire wear and non-regenerative braking.

- Size and charging of the permanent battery can be optimized to a minimal range in order to prolong battery lifetime.

The Standardization Issue

Standardization is the process of implementing and developing technical standards based on the consensus of different parties that include firms, users, interest groups, standards organizations and governments [82]. The purpose of standardization is to ensure safety for consumer and manufacturer by applying certain strategies to mitigate the risks, to increase product competitiveness and to reduce trade barriers. Vehicle design and manufacturing can reap significant benefits from the standardization of the battery packs such as low production costs, faster and easier vehicle development and manufacturing, final product quality assurance, simplification of repair and maintenance, favorable conditions for mass production, etc.

According to a published study in 2017, it was noted that the amount of EVs sold would produce 250,000 metric tons of battery wastes [83]. The treatment of this amount of wastes is complicated, as various types of chemistries are used, while the batteries are packed in a range of different shapes and sizes. Standardization can offer less variation in the battery packs size and shape, making the removal and recycling of the batteries cheaper and less dangerous, as the recycling process could be realized under automated conditions. Moreover, standardization makes the batteries second life repurposing process safer and easier.

However, despite the benefits, applying standardization in traction batteries is a rather complicated issue. The main reason is the fact that EV manufacturers consider the design, engineering and control practices of their battery packs as core technology and important intellectual property and they are not willing to use the same battery pack size, shape and capacity as their competitors. Currently, automakers develop customized battery packs for each individual vehicle model. This procedure is not only time consuming but also creates additional risks, as each EV model is profitable with large production runs.

The proposed EV design, which foresees the application of a smaller than regular permanent battery and the use of swappable batteries to extend the range, presupposes the application of standardized batteries, thus reaping all benefits of standardization.

The standardization of the swappable batteries removes the barriers raised by customization, giving to many battery manufacturers, and especially those supplying batteries for industrial electric vehicles, the opportunity to enter the EV traction batteries market, further increasing competition in the supply of the relevant equipment.

Moreover, as permanent batteries will be smaller than regular, standardization could easily be applied to these batteries as well. Due to their smaller dimensions, car designers could easily integrate standardized battery packs into the design of the vehicle's chassis, instead of applying customized ones, further reducing the vehicle manufacturing costs.

Finally, due to standardization of the swappable batteries, each BSS can also operate as a gathering center for the batteries to be recycled, further increasing the efficiency of the relevant procedure.

The EV Batteries Charging Issue

EV charging equipment is differentiated by power level, where power-level designations range from ‘’Level 1’’ for low power, to ‘’Level 2’’ for medium power and fast chargers for high power. Most of EVs charging will take place at home and usually during the night. Although regular home charging remains one of the main advantages of EVs, it does not fulfill every charging need and a mix of workplace charging, public charging and fast charging is needed.

Charging of an EV can be more challenging for EV owners that do not have access to overnight charging. People who live in properties that do not have dedicated off-street parking, like users without their own garages or parking spaces or residents of multi-unit dwellings, need to park their cars on the street and they would have to find public charging points in their neighborhood, to rely on workplace charging, or to use fast chargers.

Overnight charging with public chargers also entails security concerns, while another problematic issue about on-street parking is the fact that when the vehicle is immobilized in extreme cold temperatures for several days without the charge cord being connected, it may not start. The vehicle will need to be plugged in to allow the battery to be warmed up sufficiently.

Access to plugs at home and the ability to add a charger differs by country and by region. In the U.K., for instance, only 48% of households and 55% of car-owning households have access to a garage [5] while in London, only 48% of vehicle drivers have off-street parking [84]. In U.S., less than half of vehicles have an off-street parking space at an owner-occupied residence where charging infrastructure can be installed [85].

Without reliable access to charging infrastructure, EVs will not be purchased even if their cost is affordable. Therefore, increasing the number of public chargers, including fast charging installations, especially in cities, is a precondition for the growth of the EVs market. However, it is unrealistic to consider that there will be available a public charging point per each EV parked on the street, as the development cost for such a charging network will be enormous. For this reason, a lot of studies are being conducted with great uncertainty in their results, trying to determine the appropriate number of charging stations that are necessary to support a given number of vehicles, as far as the coverage and the capacity is concerned.

Apart from the increased costs that would be required for the development of an extensive network of public chargers, the maintenance cost of this network is not negligible, while damages from vandalisms and thefts should also be taken into consideration.

Enabling long journeys is also an important function of charging infrastructure in order to provide consumers with confidence that they can travel anywhere they wish at any given time of the day. Having an adequate number of chargers at one site is essential since it reassures drivers that a charger will be available upon or soon after arrival, since frequently charging stations are overwhelmed during peak hours or out of order due to malfunction, making charging more annoying and unreliable. This problem is most common when people travel in masses to popular destinations on weekends or during the holidays. It is more likely that images of EVs waiting for hours in long lines to charge will be quite common in the near future.

Respectively, the extensive installations of chargers in destinations that receive a large number of visitors seasonally, such as holiday destinations, are rather unprofitable for their operators.

Most public charging stations today are of Level 2, rated to deliver 3,6 kW to 22 kW of power. With this type of charger, a typical EV equipped with a 60kWh battery requires five to twelve hours to charge. Consequently, EV owners have to wait much longer to charge their vehicle compared to filling up an ICVE tank.

Fast charging may be a solution for decreasing charging time. Fast chargers ensure a charging state at the level of 80% in about thirty minutes, while when vehicles become available that can fully utilize the extra high-power of fast chargers having an output of 350 kW, these vehicles may be capable of charging up to 80% in about ten minutes.

Currently, no vehicle on the market can accept 350 kW and technological progress must be made in battery cooling or chemistry to fully utilize a 350kW charger. However, these batteries would be much more expensive than the batteries that power today's EVs.

Charging to 80% is unlikely to fall below ten minutes as this requires technology improvements that could enable higher charging speeds such as alternative anode chemistries, more complex cell management to ensure even charging, higher pack voltage and improved liquid battery cooling [5].

In practice, actual fast charging rates can be significantly lower than the maximum rate of the charger, as in many cases battery protection circuits will limit the current and therefore the battery pack will not accept the higher power available by a fast charger. Charging rates depend on the battery's initial state of charge, the ambient temperature, the battery temperature and other factors.

If fast charging of a battery is too often, the BMS may lower the charging current and increase the charging time so as to adjust to the battery conditions in order to maintain safety and to assure battery life extension. Charging a battery with too much power can cause lithium plating and dendrite formation around the anode, reducing capacity permanently, can cause cells to age at different rates, as well as can cause battery pack overheating [5].

Another issue that negatively affects fast charging time is the increased workload of the chargers during peak hours. In many charging stations with multiple fast chargers located at one site, when all chargers are occupied, it is most likely that they are not able to operate at full power simultaneously. The power is shared in such a way so that the total power absorbed from the distribution network does not exceed a threshold and consequently the charging time is increased [5].

BSSs instead of numerous public battery chargers

Instead of developing and maintaining a huge network of public battery chargers, a less extensive network of BSSs, similar to that of refueling stations could be developed, providing significant benefits to EVs charging issues:

- The BSS model can make EVs popular among potential customers who cannot charge at home and have to find public charging points in their living areas. The swappable battery packs delivered from BSSs could be used not only to move the EVs but also to charge the vehicles' permanent batteries overnight. Even degraded swappable batteries can be used for this service, during their second life period of operation. The energy of two degraded batteries is enough to charge the permanent one, as well as to keep the cabin warm and ready for use regardless of the vehicles overnight parking location.

- The battery swapping procedure can be realized in time as fast as refueling an ICVE, saving time for drivers and permitting longer trip distances without the feeling of range anxiety. Furthermore, the permanent batteries of the vehicles can charge faster, as they will be of smaller size than regular ones.

- As the permanent batteries of the vehicles will be smaller than regular, there is no need for installing expensive high-power Level 2 chargers at home or at workplaces. Accordingly, upgrade of the domestic electrical installation to withstand the operation of such chargers will be not necessary.

- The BSS model reduce the need to install a large number of fast chargers, while the smaller size of the permanent batteries does not make it necessary to increase the power output of the fast chargers.

- The development of a charging station with an appropriate number of charging positions requires a large parking area. However, as the battery swapping at the BSSs is realized very fast (up to 3 minutes), less real estate is required for a BSS deployment.

The Subsidies Issue

Because of their costly batteries EVs are significantly more expensive than ICVEs. Thus, in order to accelerate the use of EVs, as a way to reduce local air pollution and carbon emissions, many countries provide tax incentives and subsidies.

However, subsidy skeptics argue that the policies promoting EVs likely do not produce benefits of reduced air pollution and carbon emissions greater than their costs. Furthermore, they raise concerns about fairness and equity of these policies, claiming that subsidies allow wealthy EV users to reap the benefits, while socializing the costs to everyone else [86], especially to lower-income people who cannot afford to buy even subsidized EVs or live in their own homes, taking advantage of residential chargers.

Publicly available demographics show that most EV users are wealthier than the average [87], they frequently belong to multicar households, using the EV as a second car and they live in single-family buildings. Lower-income households may be less likely to buy any type of new car and when they do, they will probably continue to prefer ICVEs because of their lower upfront purchase price. Consequently, from an environmental, social and economic perspective, it would be more beneficial to subsidize the purchase of super-efficient, modestly priced ICVEs by middle and lower-income people for replacing their old cars [86], which in many cases are older than 15 years.

Another issue is the fact that electric utilities must upgrade their distribution infrastructure to accommodate additional EV charging and offer discounts for the equipment needed to charge EVs at home or at work. The costs of this infrastructure upgrade and the charging equipment subsidized programs will be allocated among all electricity customers, using standard cost-allocation procedures without singling out EV users. Again, subsidizing of the residential charging systems benefits higher-income consumers, as these systems are primarily installed in single-family buildings by homeowners with above-average incomes [86].

For these reasons, policymakers at all levels should take into consideration these criticisms when developing policies to address climate change, local air pollution and alternative vehicle policies. Policy benefits must justify their costs, while policies must serve distributive justice goals [88].

The proposed configuration relates to vehicles equipped with battery packs smaller than regular. This design reduces EVs manufacturing costs, making this type of vehicles comparable to ICVEs in terms of upfront purchase prices. Therefore, subsidies are not necessary to accelerate EVs penetration in the market.

Instead, the money currently spent on EVs subsidies could be used for the development of the BSS network. This policy will benefit all people, whether they are EV users or not, as the operation of the BSSs as distributed energy storage installations will be beneficial for all electricity consumers.

BSSs as energy storage installations also have the potential to postpone large scale upgrading of the power distribution infrastructure imposed by EVs penetration, the costs of which would be allocated among all electricity customers.

Another advantage of EVs equipped with smaller than regular battery packs is the fact that it is not necessary to install high-power Level 2 equipment for EV charging at home or at work and therefore to subsidy the cost of this type of equipment from the electric utilities.

Figure 24: Vehicle immersion in a container with water. *Sourced from [91]*

The Safety Issue

The fire risk associated with batteries has become a major safety concern in the design of EVs. Thermal runaway that can occur as a result of faulty operation or traffic accidents, is the main cause of fire in EV batteries. Thermal runaway may be accompanied by fire, jet flames, release of toxic gases and explosion. LIB fires are difficult to extinguish, while they require large quantities of suppressant and may reignite [89]. Consequently, as the size and energy density of EV batteries continue to increase nowadays, fire-safety issues become even more challenging.

Post-crash handling of damaged EVs is also an important issue because of the risk of fire reignition several hours after first extinguishment [90]. The vehicles need to be moved to dedicated areas, where the risk for battery pack reignition will be continuously estimated for several days.

Some fire brigade authorities use to immerse EVs in containers with water, after first extinguishment, in order to prevent fire reignition (Figure 24).

Battery swapping and fire safety

Installing swappable batteries on the front and rear of EVs may raise safety concerns, since due to their specific installation position and in the event of a collision, the batteries are more likely to be mechanically abused. However, this possibility can be significantly reduced by properly designing the vehicle crash management system. Front and rear bumpers, as well as reinforced battery compartments can provide additional mechanical protection to the swappable battery packs.

In the event of a collision, the main reason that can cause the battery to ignite is the chain reaction that follows the thermal runway of a cell, as a result of a short circuit. The transmission of fire to the cabin can be significantly slowed down by enclosing the battery compartments with fireproof material. A build-in fire suppression system could also be provided, flooding the battery compartments with suppression agent.

It is also noted that for most of the driving cycle, EVs will run powered by their permanent battery, without using the swappable ones. Therefore, most accidents are more likely to occur when vehicles do not carry swappable batteries.

Moreover, the proposed EV design provides significant advantages as far as fire safety issues are concerned:

- Sectionalizing the total battery capacity of the vehicle into three discrete and fully separated compartments drastically increases the possibility of limiting any potential fire to only one of the three compartments, the most related to the specific part of the vehicle that has been affected by the collision. This means that the fire load will be significantly lower compared to that involving the complete battery of a typical EV. Lower fire load means more time for passengers to get out of the vehicle safely, as well as less extinguishing time and effort by the firefighters.

- The smaller than regular permanent battery can be easily installed inside the most stiffened and reinforced compartment of the chassis, eliminating the risk of battery pack rupture during a collision. Furthermore, due to the smaller size and energy density of this battery the fire load is significantly lower compared to that of typical EV batteries.

- Chemistries with low inherent safety risks, like the lithium-iron phosphate (LFP) can be selected for the swappable batteries' construction. The LFP battery is cheap, as it contains less or no cobalt and nickel, it has a long lifespan and it is safer, as it has very high thermal stability. Typically, the LFP battery cell ignition temperature is between 350 °C to 500 °C, which is much higher than 200 °C that is valid for other battery chemistries [89]. Consequently, from a fire and heat generation perspective, LFP is the preferred option [90]. The main disadvantage of LFP batteries is the lower performance, as this chemistry has the lowest energy density compared to other chemistries. However, this disadvantage can be offset by the flexibility provided by the swapping procedure.

- The compartments for the installation of the swappable batteries facilitate the application of a build-in fire suppression system that will be activated automatically in the event of a collision, or fire detection. The heat dissipation achieved by the suppression agent, while flooding the battery compartments can cool down the temperature of the battery, stopping or slowing down the thermal runaway chain reaction. Alternatively, the suppression agent could be injected directly inside the battery air cooling ducts, extinguishing the fire directly inside the battery packs.

- The design of EVs that allows the use of swappable batteries facilitates the development of standardized post-crash handling procedures in damaged vehicles, as firefighters will be able to remove the batteries and separate them from the vehicles. Removing the swappable batteries from the vehicle after a collision event, facilitates the development of effective methods for their neutralization.

VII. THE BATTERY SWAPPING SYSTEM AND METHOD

The proposed EV design, which foresees the use of swappable batteries, mounted on the front and rear, requires the use of specialized equipment that will perform the relevant battery swapping process in a fully automatic manner. An exemplary battery swapping system with the corresponding method is described herein below:

The System

The proposed system includes at least one battery swapping device, which performs the whole battery swapping process. An exemplary embodiment of the device is illustrated in Figure 25. The device includes a movable platform which is displaceable along guide rails which are fixed on the ground. This platform includes, at opposite sides a number of guide roller wheels for engaging to the guide rails.

The scope of the guide roller wheels is, in synergy with the guide rails, to guide the swapping device along its operating field, parallel to the vehicles service area, as well as to stabilize and prevent device overturning, as its center of gravity shifts during the battery swapping procedure.

The movable platform further includes a number of electrically propelled wheels, installed in physical contact with the ground. These wheels are used for propelling the platform and consequently the battery swapping device, in both ways along the guide rails.

The battery swapping device also includes an industrial type, multi-axis, robotic arm manipulator, suitable for handling heavy loads. This manipulator is pivotally coupled to the upper side of the movable platform.

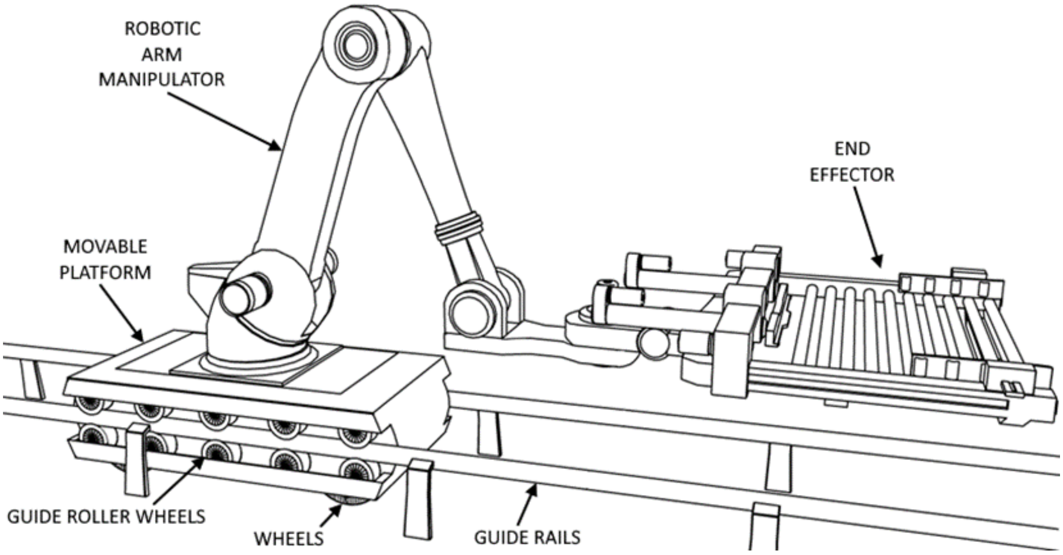

Figure 25: Battery swapping device

An end effector (Figure 26) is operably coupled to the last section of the robotic arm manipulator for handling the swappable battery packs. This end effector includes a metallic frame and a number of conveyor rollers, coupled to the frame, forming a transportation pallet. The scope of the conveyor rollers is to facilitate unloading and loading of the battery packs in the end effector and reduce battery wear and tear.

A rolling bar is operably coupled on the upper side of the end effector frame. The rolling bar is linearly displaceable along the battery loading/unloading direction and it is used for unloading and loading the battery packs in the end effector.

A mechanism for engaging with the battery packs is operably coupled to the rolling bar. The scope of this mechanism is to insert and extract the swappable battery packs from the respective battery storage compartments. This mechanism is linearly displaceable, relative to the rolling bar, along the battery loading/unloading direction.

The mechanism for engaging with the battery packs is an electromagnetic bar. Alternatively, a suction cup connected to a vacuum pump, or a gripper could be used.

The end effector further includes a pair of adjustable side battery support lugs. These lugs are automatically adjusted to fit the dimensions of the standardized battery pack that is going to be handled. The purpose of the lugs is to ensure that the battery pack will be loaded or unloaded, remaining exactly in the center of the end effector, as well as to stabilize the battery pack in the end effector, providing lateral support so as to prevent battery pack displacement during the relevant transportation procedure.

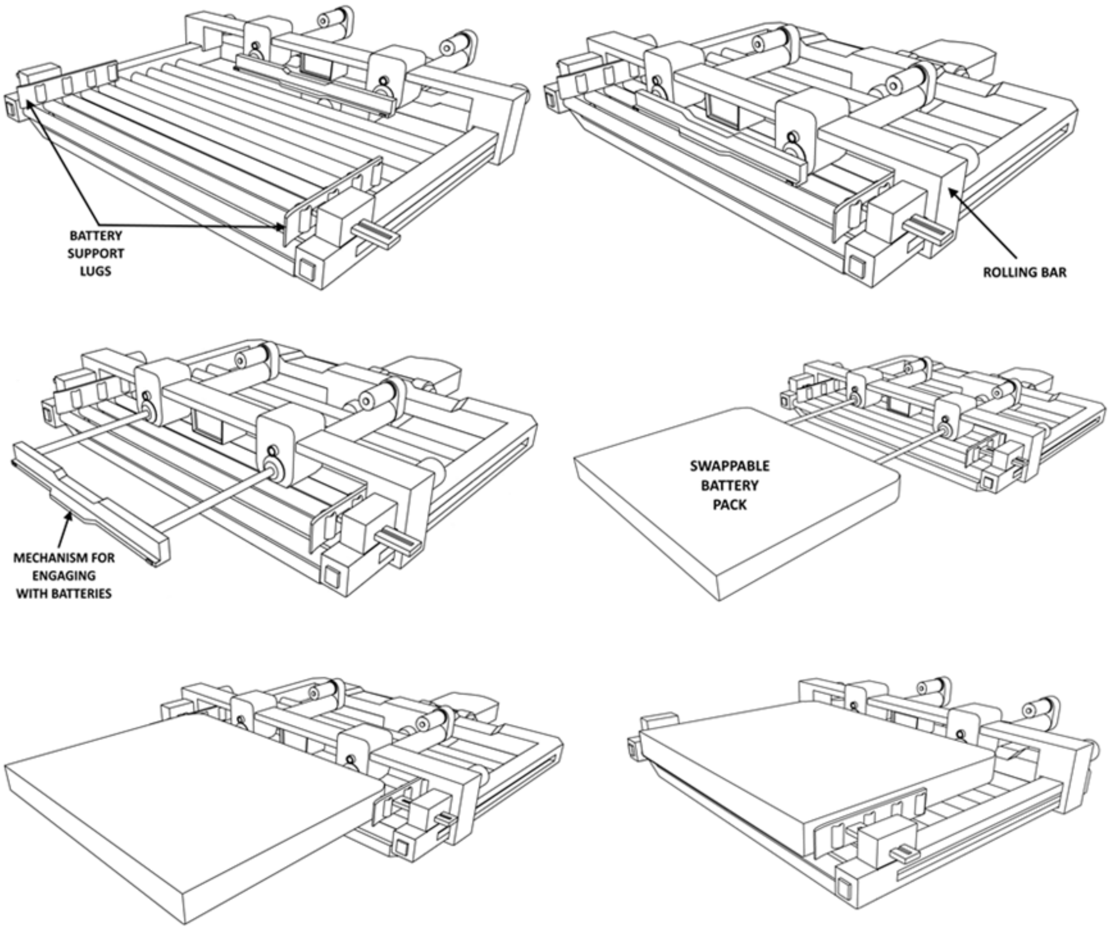

Figure 26: Loading of a battery pack on the end effector of a battery swapping device

Each battery swapping device also includes a plurality of onboard sensors which provide information to the device control system about the detection of the position of the battery storage compartments, about the detection and identification of the battery packs inside the battery storage compartments, about the alignment of the end effector to the battery storage compartments and about the detection of potential obstacles in the operating field of the devise.

These onboard sensors could adopt the technological leverages form state of the art cameras, laser rangefinder devices, laser scanners, proximity sensors, radar devices, limit switches, torque switches or combinations thereof.

All electrical systems and drives installed in each battery swapping device are powered by onboard rechargeable batteries. Charging of batteries will be realized at dedicated docking areas. Battery charging may be realized also wireless at the docking areas or along the whole operating field of the devices.

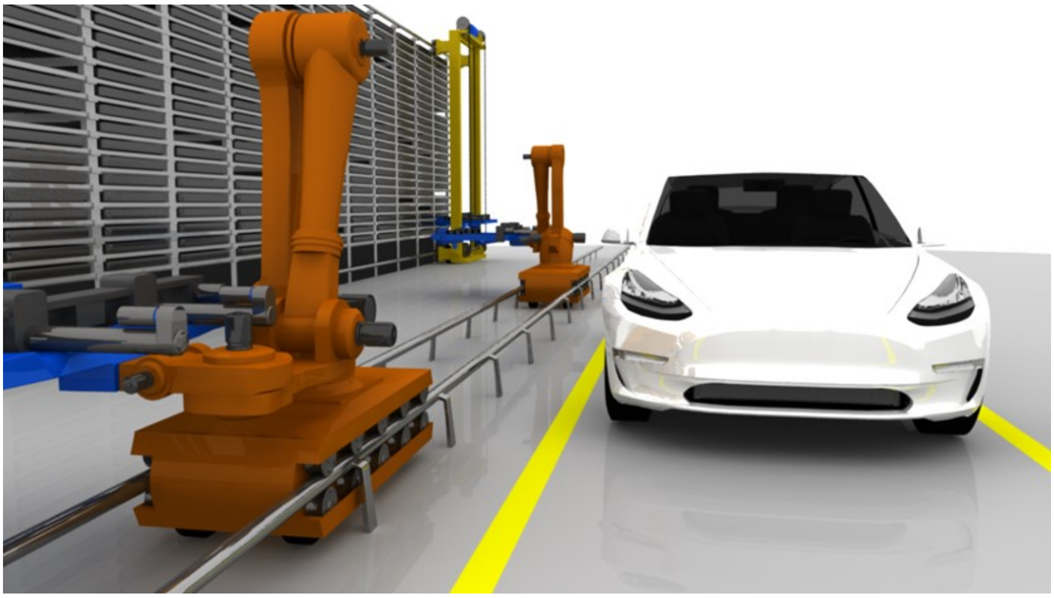

Figure 27: A vehicle in the service area of a BSS

Instead of batteries, the battery swapping devices could be powered by cables arranged on a chain cable carrier, as already used by industrial linear motion tracks for robotics positioning (seventh-axis). However, the proposed design, which foresees the swapping devices to be powered through rechargeable batteries, creates a friendlier and less industrialized environment for the BSS users.

The Method

The main part of the relevant battery swapping procedure is the insertion and extraction of the battery packs from vehicles or BSS battery rack storage compartments, using the end effector of the battery swapping device. Figure 26 illustrates the various phases of a typical battery pack loading procedure on the end effector.

During this procedure, a battery pack can be delivered from a vehicle battery storage compartment or from a BSS battery rack storage compartment, after the end effector has been properly aligned with the corresponding compartment. Unloading a battery pack from the end effector and inserting it into the respective battery storage compartment is realized following the opposite procedure.

Figures 27 to 33 illustrate a typical battery swapping procedure in a BSS, applying the proposed system and method. In this exemplary illustration of the method two battery swapping devices are shown.

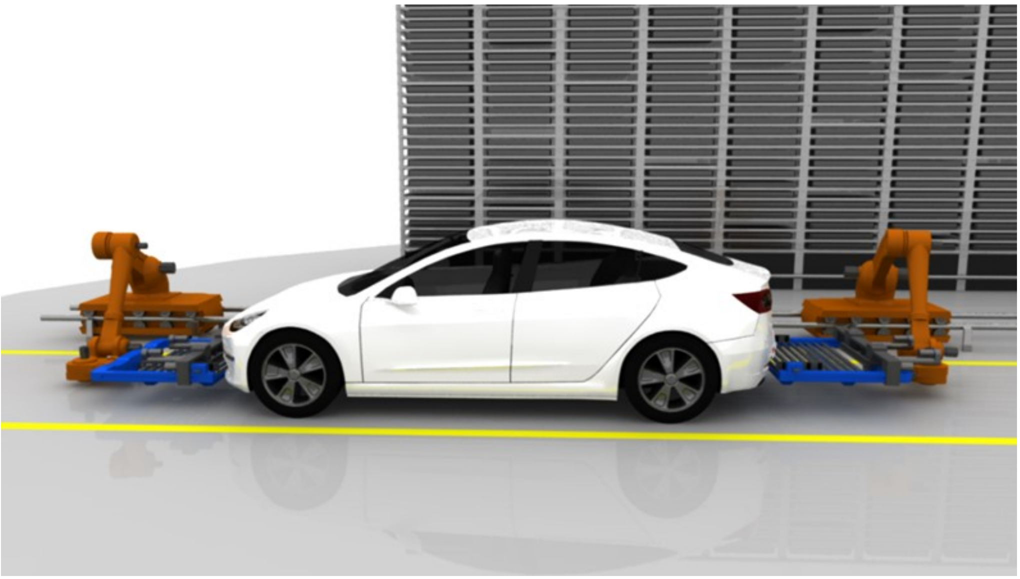

Figure 28: The battery swapping devices taking position at the rear and front of the vehicle

Generally, a BSS can be of the modular design, developed over-ground. Its components can be assembled, arranged and operate in different configurations according to the specific requirements on a case-by-case basis.

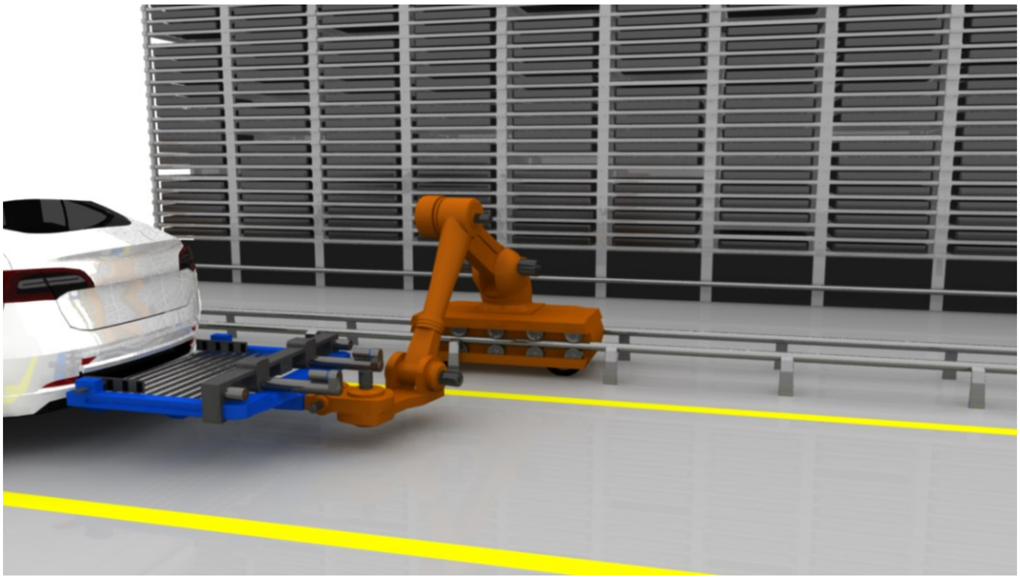

Figure 29: A battery swapping device taking position at the rear of the vehicle

The battery racks and the vehicles service area can be installed inside a building with entrances and exits for the vehicles or can be hosted under a shelter. A BSS may include various systems, installations and equipment such as battery racks equipped with compartments for battery packs charging and storage, battery charging equipment and the relevant electrical installation, HVAC for temperature control of the batteries, fire and dangerous gases detection system, etc.

The BSS will also include a vehicles service area. This service area may be a corridor bordered by other areas of the BSS with colored lane markings. Other methods may also be used to delimit the vehicles service area such as guides, or barriers.

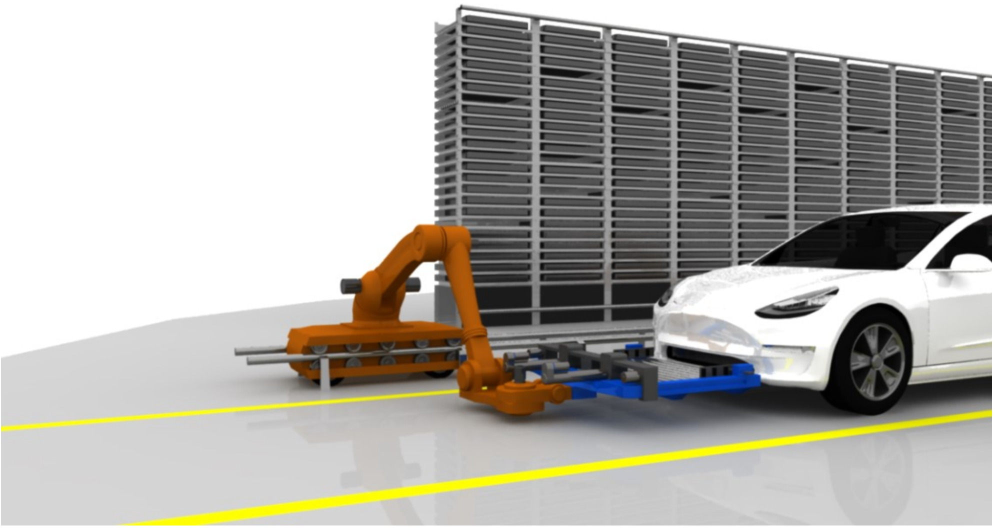

Figure 30: A battery swapping device taking position at the front of the vehicle

The first phase of a typical battery swapping process is shown in Figure 27, where a vehicle has parked in the service area, while the covers of the respective vehicle battery storage compartments are opened.

The next phase of the swapping process is shown in Figures 28, 29 and 30, where the battery swapping devices have been propelled along the guide rails, taking up position near the respective battery storage compartments, at the front and rear of the vehicle.

The following step of the process is shown in Figures 31 and 32, where the discharged battery packs have been removed from the vehicle storage compartments and loaded on the end effector of each battery swapping device. This loading procedure can be performed according to the way shown in Figure 26.

The final phase of the battery swapping procedure is shown in Figure 33, where the battery swapping devices, with the discharged battery packs loaded on their end effectors, are propelled along the guide rails, taking up position opposite to the battery rack, where empty battery storage compartments are available and ready to receive the discharged battery packs.

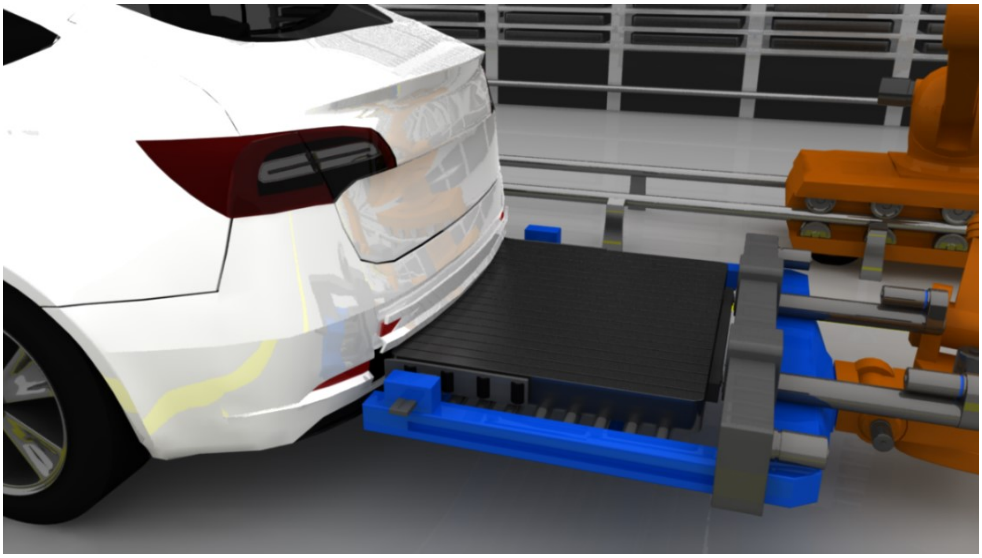

Figure 31: Battery pack extraction/insertion at the rear of the vehicle

The unloading of the discharged battery packs from the end effector of each battery swapping device to the selected battery rack storage compartment, is carried out following the procedure opposite to that shown in Figure 26.

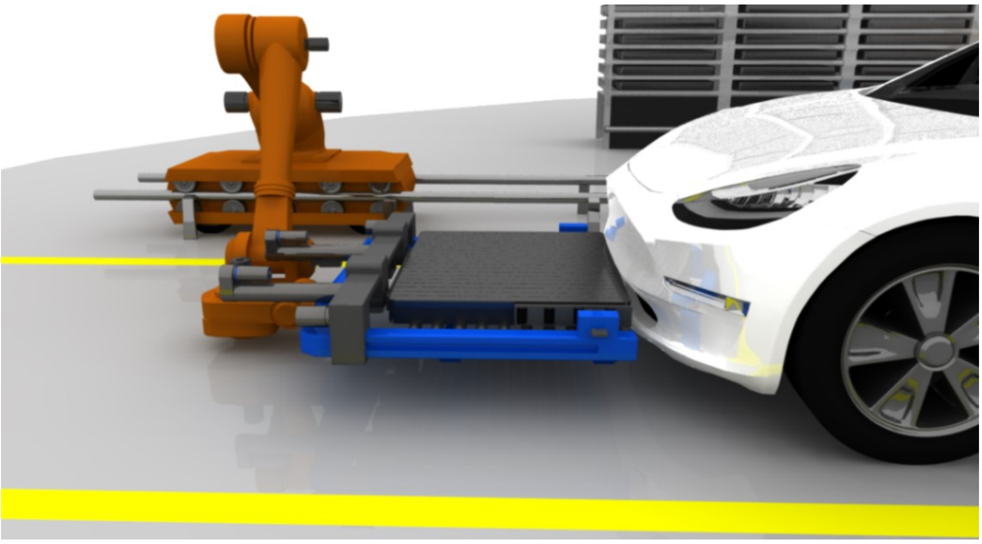

Figure 32: Battery pack extraction/insertion at the front of the vehicle

The process of loading the charged battery packs, delivered from the BSS battery rack storage compartments, to the vehicle battery storage compartments is performed following the procedure opposite to that shown in Figures 27 to 33.

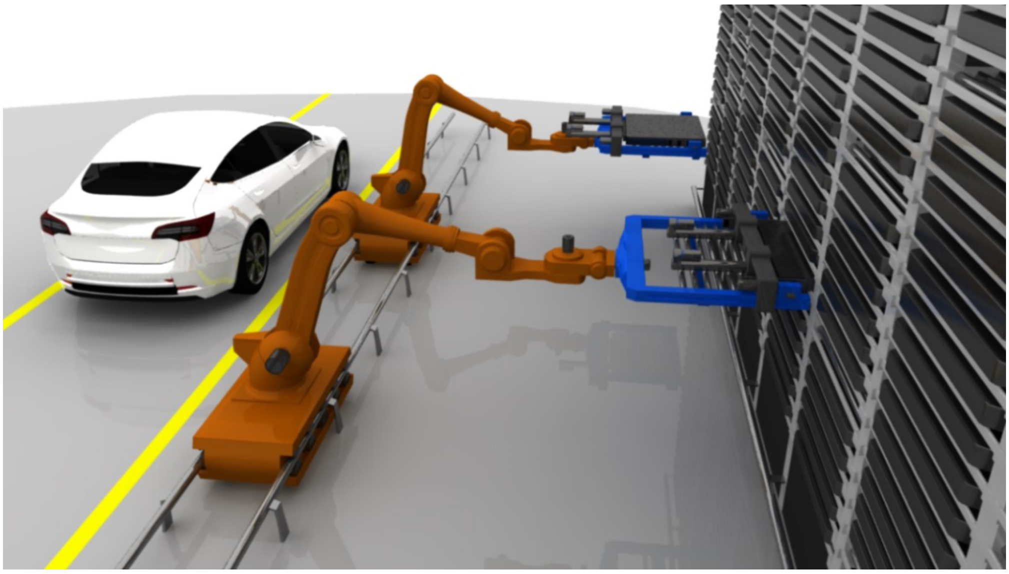

Figure 33: Unloading/loading of battery packs on BSS battery rack

The proposed battery swapping system and method provide significant benefits compared to other swapping methods currently in use, due to the following reasons:

- The entire swapping process takes place above ground. Therefore, it is not necessary to place the vehicle on a ramp, to use underground equipment, or to lift the vehicle, in order for the area underneath to be approachable by the battery swapping robot, methods which increase complexity and cost of the BSS infrastructure.

- The entire battery swapping procedure is carried out by a simple device, ensuring a high level of reliability.

- Any defective swapping device can be easily replaced by a spare one. Moreover, any system malfunction does not trap the vehicle within the service area.

- More than one battery swapping device can be used in each BSS vehicles service area. Consequently, more than one vehicle can be serviced simultaneously in the same service area.

- Battery swapping devices could be designed to operate also outside the guide rails, thus providing battery transporting services between the various BSS facilities.

- The battery swapping device research and development cost, as well as its manufacturing cost will be low, as the robotic arm manipulator, which is the main component of the device, is an established mechanism, widely used nowadays in many industries.

- No special maneuvers are required for vehicle to take position within the BSS vehicles service area. Drivers simply need to park within the service area aisle and the battery swapping device will automatically locate and approach the vehicle. Furthermore, it is not necessary for the driver to get out of the vehicle during the swapping process.

- The end effector is designed to handle the full range of the standardized batteries without the need to adapt special tools for each type of battery.

VIII. THE CHALLENGES

Perhaps the biggest challenge facing the proposed implementation is the willingness of automakers to consent and invest in developing vehicles that are specifically suited to operate with standardized swappable battery packs. The success of such an effort presupposes the participation, at least in the system's start up and launching, of a critical number of automakers, who will define the technical details and establish the terms of standardization of such an implementation.

Nowadays, this level of cooperation between the automakers seems quite difficult, especially after a series of failed attempts in the past, in various other sectors of industry.

However, the success of such an endeavor does not depend solely on the intentions of automakers, as the role of policymakers is equally important. Policy so far has focused only on reducing CO_2 exhaust emissions. Therefore, future policy should focus on encouraging the reduction of the weight of all vehicles. This could be achieved by implementing policy measures such as the CO_2 based bonus-malus taxation, also on the weight of vehicles or their production environmental footprint [92], or both and consequently, putting pressure on automakers to cooperate so as to establish the necessary terms of standardization.

Other challenges of the proposed implementation that also need to be addressed are the following:

- There are doubts about viability of BSS business models after the unsuccessful attempts of BETTER PLACE and TESLA. The viability of this model depends entirely on the acceptance of the end users. The majority of consumers are particularly negative about a swapping model based on the replacement of traction battery, as the idea of leasing part of the car and swapping that out at regular intervals is not attractive. However, the proposed implementation, which foresees the use of swappable batteries for range extension, is a completely different model with significant benefits for users, while best addressing consumers anxiety of not owning the battery at the time of purchase of the EV.

- The investment cost of the BSS infrastructure and especially the cost of the standardized swappable battery packs, is significant. However, the modularity of the BSS infrastructure allows the developed of small to medium-sized facilities. The financial viability and fast repayment of the investment is ensured, as BSS will provide battery swapping services to vehicles and ancillary services to the network. In addition, BSS owners could receive the subsidies currently being spent on EVs promotion.

- Consumers may be not be interested in vehicles equipped with smaller than regular batteries. This could be the norm for higher income consumers, who will prefer EVs with long range batteries. However, the majority of medium and lower income consumers will prefer vehicles with a lower upfront purchase price. This also applies to consumers who do not have access to home chargers. Polices that ban the increased weight or the EV construction environmental footprint [92] will facilitate adoption by the consumers of this type of vehicles and the relevant BSS business model.

- Issues related to the method of payment of the offered battery swapping services should also be clarified. The market already has several leasing tools that can be used for this field of application, while new ones can be developed. The billing can be calculated based on the distance travelled by the vehicle, energy consumption, batteries usage time, or combinations thereof.

- The accumulation of large number of battery packs in the BSSs is another issue that also needs to be addressed. EV owners can participate in the transportation of battery packs that have accumulated in one BSS to other BSSs where there is a need for batteries. This can be realized by providing incentives to drivers, such as free battery swaps or payment.

- The quality of the swappable batteries is also an issue. It will be a challenge to ensure that the battery packs delivered can provide EVs the required amount of energy. However, the state of health and charge of battery packs will be monitored by the BSS control system in order to ensure that only batteries with accepted level of degradation and properly charged will be delivered to EVs.

- Liability insurance issues related to vehicle damage or passenger injures due to battery swapping equipment or swappable battery packs failures should also be considered [94]. The standardization of the swappable batteries, as well as the high level of automation of the proposed swapping process, facilitate the reduction of failure incidents and the identification of related incident responsibilities.

CONCLUSIONS

In order for EVs to reach their full potential, the electrical power generation must shift from fossil fuels to renewable sources. The penetration of renewables at the level of 30%-40%, as is currently the case in some countries, is not sufficient to achieve measurable environmental benefits that would justify the investment costs required to upgrade the electricity system and the cost of government subsidies for EVs promotion.

The penetration of renewable energy sources in the energy mix must be well above the level of 30%-40% in order to achieve real environmental benefits and, therefore, to justify the cost of transitioning from the ICVEs era to that of the EVs.

Electrical grid de-carbonization also offers a significant opportunity to reduce the greenhouse gas emissions related to the production of batteries and energy-intensive metals, such as aluminium, which are widely used for EVs construction.

In order to further increase the renewables penetration, flexibility mechanisms such as super grids, energy storage and smart grids must be developed. Most likely, none of said mechanisms will prevail over the others, but rather they will have a symbiotic relationship in order to optimize operation and increase efficiency of the future power systems. Batteries will undoubtedly play a significant role in the development and expansion of a network powered by renewable sources, as technology develops and costs fall.

Consequently, increased demand for traction batteries and batteries for stationary energy storage applications is likely to be accompanied by increased demand for raw materials widely used in the manufacture of lithium-ion batteries. In addition to the impact on battery costs that can be caused by the growing demand for raw materials, other social and ecological issues related to the mining of the materials may also arise.

In any case, the production of raw materials needed for batteries manufacturing must be rationalized and optimized. Therefore, instead of developing an extensive network of stationary battery-based energy storage installations, the necessary energy storage capacity to facilitate the penetration of renewables can be achieved by increasing the utilization factor of the traction batteries.

Vehicle to Grid (V2G), a technology that enables a bidirectional flow of energy between electric vehicles and the power grid allowing vehicles to return part of the energy stored in their batteries to the electrical grid can be applied so to increase the utilization factor of the traction batteries. However, the social acceptance of V2G technology is a paramount concern for its successful diffusion to the EV users. The large-scale development of this technology depends almost entirely on the willingness of the EV users to participate in the system.

Another way to increase the utilization factor of traction batteries, is the wide application of battery swapping. Battery swapping is a procedure where the discharged battery pack of an electric vehicle can be replaced with a fully charged one. In this way, the traction batteries can provide energy storage services at the battery swapping stations when not in use for vehicles power supply.

Battery swapping can also best address other problematic issues related to the usage of electric vehicles, such as high upfront purchase price, limited range, increased battery charging time, etc.

However, serious drawbacks such as standardization and reliability issues, as well as reduced consumers acceptance of the swapping model, are some of the main reasons that prevent the widespread use of this procedure.

Therefore, a new approach to the issue of battery swapping is needed, which will better address the disadvantages of the swapping methods currently in use, while at the same time reaping all the benefits of the relevant concept. This new approach is based on the idea of applying battery swapping as a method for extending the range of vehicles.

To implement this, electric vehicles could be equipped with a permanent battery, suitable for covering short driving ranges, while at the same time they will be able to use swappable batteries to extend their range. For this reason, the vehicles could be equipped with dedicated storage compartments located at the front and rear, suitable for the installation of standardized, swappable battery packs.

The compartments arrangement at the front and rear of the vehicle facilitates the area under the chassis to be used for the installation of the permanent battery pack. This design allows the construction of efficient, lightweight and cost effective vehicles.

The relevant battery swapping procedure can be performed in a fully automatic way, through simple and reliable battery swapping equipment.

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