POLITECNICO DI TORINO

Master of Science in ICT for Smart Societies

DEVELOPMENT OF KEY PERFORMANCE INDICATORS FRAMEWORK FOR BATTERY SWAP SYSTEM

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Abstract

Electric vehicles have been on the market for years as agencies of transition to a sustainable transport system. However, due to its characteristics, electric vehicle marketing is slow in terms of limited range, long charging time, and high initial cost. Therefore, there is a need to swap batteries overtime to support a larger number of electric vehicles. In order to simulate electric mobility and increase electrical vehicle adoption rate, the aim of this thesis is to provide a key performance indicators framework to help the Municipalities have better insight in the appropriate key performance indicators of the battery swap charging infrastructure as an incentivizing effective decision-making tool.

In order to define the framework, at the first step, I have extracted available key performance indicators (KPIs) by properly reviewing literature in the battery swap field, and second, to better evaluate the impact of each KPI, I have sorted the relevant KPIs based on the relative frequency and at the final step, the classification of KPIs has been done based on the company hierarchical level and their relevant domain of impact including economic, social and environmental effect.

Through the list of ranked KPIs, throughput, user satisfaction, and charging strategies have a great impact on the performance of battery swap charging infrastructure that policymakers should consider for optimizing and adopting electric vehicles purposes.

Introduction

Vehicles are essential for today's fast-paced lifestyle, but a rise in the number of vehicles has resulted in the many serious environmental and management issues. Furthermore, because they are propelled by nonrenewable energy sources there is a need to build better public transit alternatives in the future, as well as an effective vehicle management section. Dependence on fossil fuels makes them unsustainable because a large portion of them has been depleted, and generating them again would take thousands of years, making transportation unsustainable as well. The idea is revolutionizing the entire car industry, which can be realized by the use of EVs Because of the above and other causes, EVs are indeed the need of the hour. The advancement of EV technology must occur in parallel with the advancement of vehicle charging technology.

The backbone of the EVs is the charging infrastructure. Plug-in electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and battery EVs (BEV) are remarkable in a variety of ways, including reduced dependency on fossil fuels, cost savings, emission-free, clean driving, noise reduction, and low maintenance. The advancement of EV technology is being hailed as a source of optimism in the electric vehicle industry. Despite the promising evidence, there are some questions about such innovative concepts for those stakeholders who need to envision before investing in electric fleet rollouts. The social hindrance which arise in existing EV owners due to scarcity in the availability of recharging stations, extended charging delay, intimidation by the underlying utility grid, and, most importantly, the inherent EV range anxiety (EVRA) issue. The Conductive EV charging, Inductive charging and Battery swapping system are among the noticeable charging techniques. The battery swapping system, i.e. the third one, has yet to be implemented as a commercially viable option, despite rapid development in the fields of conductive charging and wireless (inductive) charging. Among all of them, battery swapping appears to be a viable alternative in the current situation. The swapping of the EV battery has one major advantage: faster EV recharging. The job is simple: the car driver simply drives to a battery swap station (BSS), parks in a designated location, has the battery swapped automatically, and then drives back after paying. Tesla has been in the market for over three years, and the whole process takes less than two minutes, making it faster than refueling an internal combustion engine car. In addition, the range offered by such services is like the holy grail of electric mobility. It aligns EVs' flexibility and usability with that of combustion vehicles.

The commercial adoption of electric vehicles is the point of contention. While modern Li batteries used in EVs are powerful enough to satisfy the majority of users on a variety of trips (fast/slow, long/short drive, etc.), only a small percentage of total journeys surpass the available range, posing a barrier to widespread adoption. To get EV adoption going at the desired pace, the disastrous electric vehicle's range anxiety syndrome must be resolved. The deployment of dense and reliable charging infrastructure, which allows consumers to recharge their vehicles at regular intervals, is one viable option. However, preliminary research into specific infrastructures already in place in developing countries (Japan, Germany, Canada, North America, and so on) reveals that certain unavoidable pitfalls remain. Which must be dealt with and resolved. These issues could appear as a lack of charge point reliability, delays caused by queuing at such charge points, security and management problems, and so on. To help alleviate the EVRA and queuing at stations issues, such architectures require easy accessibility. Furthermore, the EV crowd needs an aggregation agent that configures the vehicle fleet on the front end and controls the loads on the smart grid on the back end, with the aim of ensuring the infrastructure's smooth operation. To shape load on the underlying power system caused by a large EV fleet, efficient dynamic energy management mechanisms are needed. Several studies have looked at the multifaceted dimensions of an optimal BSS implementation, taking into account consumers, the BSS owner, and smart grids. The configuration of a BSS, such as the number of batteries, chargers, staff, and other agencies, must be determined ahead of time and is based on the fleet that the BSS must operate. Since each end's resource is restricted, whether it's the BSS owner's investment cost, the operating cost of an EV, or the grid system's burden, there should be a multi-objective optimization framework that ensures all of these are met.

Municipalities and service providers are struggling to optimize the roll-out of additional charging points and how to optimize the usage of charging points in this phase of electrical mobility adoption. This is because the stakeholders (such as municipalities, charging point operators, utilities) of the Charging infrastructure have little insight into the detailed performance of the charging infrastructure and limited insight into the possible measures (as well as and their effect) to manage the effectiveness of the charging infrastructure. Municipalities are committed to stimulating clean air by installing charging infrastructure but need to do so in a cost-effective way to justify their municipal investment. Similarly, at the expense of parking spaces, the municipality needs to balance the placement of charging infrastructure and limit citizens' complaints about under- or over-used charging points. In the meantime, the municipalities aim to promote a constructive business case for charging infrastructure, to ensure that the energy grid can handle the added demand, and to balance adequate access to charging points without dramatically raising the parking burden.

There are a variety of issues for communities that need to be managed to some degree by various stakeholders in the charging infrastructure chain. This research examines the most critical key performance indicators (KPIs) that policymakers can use to monitor and optimize the efficacy of BSS charging infrastructure. [1].

1.2 EV adoption challenges

Logistics and transportation (L&T) operations are an important part of global economies and a major contributor to modern societies' social and economic growth. The L&T industry's prevalence is due to its consistent growth and effect on regional Gross Domestic Product (GDP). In response to the rise of globalization and commercial interchanges among countries, road L&T activities involving motorized vehicles have increased significantly. In regions such as Europe and the United States, transportation consumes a large portion of the oil, and road transport emits a significant portion of the CO2 generated by overall transportation operation. Furthermore, in countries like the United States, the transportation sector accounts for roughly 28% of overall greenhouse gas (GHG) emissions. One option for resolving this issue is the use of less polluting modes of transportation such as plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs), as part of an effort to enhance urban air quality, modern cities promote fleets of vehicles to embrace alternative technologies, such as EVs. Several factors are encouraging the adoption of these technologies, including: (i) financial incentives for businesses to minimize their carbon footprint; (ii) the high uncertainty of oil-based products and the long-term cost risk associated with reliance on oil-based energy sources; and (iii) the high variability of oil-based products and long-term cost risk associated with reliance on oil-based energy sources. (iii) Government incentives to lower procurement costs; and (iv) developments in renewable energy technology (such as electric vehicles), which have the potential to provide more environmentally friendly options at a price that is beginning to be affordable.

The use of electric vehicles should be a top priority for reducing primary energy consumption from both an environmental and an energy perspective.

While the advantages of electric vehicles in terms of efficiency and flexibility in energy usage are of greater concern, the EV technology is currently afflicted by a number of flaws, which can be summarized as follows:

(i) the low energy capacity of batteries in comparison to ICEV fuel; (ii) the long recharge times of EV batteries in comparison to the relatively quick method of refueling a tank of ICEVs; and (iii) the lack of public and/or private EV battery charging stations. EVs struggled in the past due to exorbitant battery costs and limited driving ranges. The scope of these issues has been significantly reduced as electric vehicles have become one of the most important research fields in the automotive industry.

Although the cost of replacing traditional ICEVs with EVs is currently unprofitable in most operating scenarios, the availability of increasingly long-lasting batteries, rising fuel costs, and lower EV purchasing costs are likely to change the picture.

There are several challenges associated with the introduction of electric vehicles (EVs) into L&T operations, which include the following dimensions: environmental, strategic and planning, and operational.

Environmental Consequences of Using Electric Vehicles (EVs)

Transportation operations have side effects (externalities) such as noise emissions, air pollution, and traffic congestion, which are seldom included in existing city planning strategies. Given that the transportation sector consumes more than a quarter of all global energy and that generating energy raises air pollution, these externalities must be weighed in order to ensure the global transportation sector's long-term viability.

Noise, air pollution, infrastructure wear, flow congestion, traffic collisions, and other causes of external costs must be included in a full overview of the issue of externalities in transportation. Nonetheless, since traffic causes noise and air pollution, the majority of environmental studies are focused on these issues.

Nowadays, there is widespread consensus that these negative externalities must be considered when developing transportation policies and logistics strategies. The European Union, for example, has established an infrastructure-use taxation scheme based on the principle of "user and polluter pays". The importance of reducing the environmental effects of freight transportation activities explains the need for new technology to regulate various forms of contaminating emissions.

Strategic and Planning Issues concerning the Use of EVs

Unlike conventional vehicles, EVs need regular refueling due to the short travel distance of their batteries and their restricted driving range. As a result, consumers must determine how many miles they can travel before recharging. This, without a doubt, limits their utility as transportation vehicles. As a result, providing the requisite recharging stations and integrating them into the transportation network are critical issues to address. The following are the key issues to be determined:

The number and type of refueling stations to be established. Location of charging stations and optimal capacity of these stations. Furthermore, businesses must analyze the effect of EVs in their fleets in order to determine the best size and combination of vehicles to use. As a result, the size and composition of the fleet is a significant factor to consider. The following subsections are devoted to analyzing and explaining the effects of some of these variables in the L&T arena.

Different Kinds of Recharging Stations

As more EVs are introduced to the market, the demand for public refueling stations is increasing. When the batteries of an electric vehicle run out, there are two options: recharge them or replace them. There are two types of charging stations: fast charging and slow charging.

A fast refueling station can recharge an electric vehicle in less than five minutes [22], but this type of charging can greatly reduce battery life. A slow charging station, on the other hand, takes longer to recharge an electric vehicle. Vehicles must wait from 2 to 8 hours to completely charge their batteries at Level 1 or 2 (110–240 V) in slow recharging stations.

It takes about 20–40 minutes to completely charge a battery at a Level 3 (480 V) recharge station. As a result, the amount of time it takes to charge an electric vehicle has been a major factor in public acceptance. As suggested by Li [23], one big solution might be to remove the nearly drained current battery and substitute it with a fully charged one. The procedure is known as battery swapping. The speed is the primary advantage of the swapping model. The entire process could be completed in under 10 minutes, which is comparable to traditional vehicles and much faster than some fast recharging stations. Other notable characteristics of battery swap stations include:

- Depleted batteries can be charged overnight when the cost of charging is low.
- Providing grid-support services by centralized charging and discharging.
- Drivers' ability to restart their journeys in minutes with a fully charged battery.

The slow-charging of batteries to prolong their life, and the cost savings of EVs by having operators provide batteries. A battery swapping model could be preferable to a battery recharging model because the former not only increases vehicle productivity but also reduces charging costs. Because of the limited range of batteries and the essence of battery swapping, optimizing the distribution network with a battery swapping infrastructure may be a key component of any green L&T strategy. On the one hand, EV owners anticipate a shorter charging period, similar to that of refueling their current vehicles. Quick charging stations are favored because of this requirement, but this type of charging will shorten the battery's life. Furthermore, since EV users have a stochastic charging profile, implementing centralized charging/discharging power in plug-in mode is extremely difficult. Some incentive strategies may be suggested to avoid unregulated charging, which could result in a substantial increase in peak load and negatively affect power system protection. In light of the aforementioned difficulties, an alternative approach focused on a battery swap station has gotten a lot of attention in recent years. The lack of unified battery specifications for different EVs, however, is an issue for battery swap stations.

Recharging Station Location

As previously mentioned, one of the most important issues to solve in order for EVs to succeed is determining the location of charging stations. As a result, it's critical to devise strategies for reducing the costs of building alternative infrastructure. This "station position problem" can be thought of as a subset of the Facility Location Problem (FLP). The most important concerns that facility planners have are the number of charging stations, the location of these charging stations and the types of these facilities in terms of product range, scale, and other design features.

Capacity of Recharging Stations

The size and capability of electric vehicle charging stations has an effect on transportation planning. Typically, the capacity of these stations is small, and within a given period of time, a station, particularly a recharging station, cannot serve more than its capacity. As a result, only a limited number of vehicles can be charged at the same time. Changing the departure times of a logistic company's vehicles can necessitate different recharging times. Furthermore, travelers who begin their journeys at different times can arrive at different times at a station. If a station is filled at the time indicated for vehicles to arrive, the vehicles must wait in lines. The recharge time, station capacity, and waiting time are all significant issues that have been largely ignored in the literature on EV station location. There are only a few works in the literature that address any of these concerns, therefore, it is critical to develop a strategic plan for constructing recharging stations while keeping overall costs to a minimum. Station construction costs, waiting time costs, and refueling costs are all included in these overall costs. When a vehicle arrives at a battery swapping station, it asks for a fully charged battery pallet to replace the almost empty batteries it already has. A fully charged battery pallet from the station storage or a pallet that is just finishing its charging could both satisfy the request. If the request is granted, the vehicle may drop off a completely or partially used pallet.

If the station has any unused battery pallet chargers, the spent battery pallet is placed on one of them and the recharging process begins; otherwise, it is placed in a queue before a battery pallet charger becomes available. If, on the other hand, the station does not have a fully charged battery, the vehicle can leave and go to another station. It could also wait for a battery to charge fully, which could take some time. If required, the vehicle may also take a new battery that is only partially charged and use it to drive to another battery swap station along its path. In this situation, the vehicle would be forced to stop sooner than expected, which has an impact on route planning, as some stops at stations were predicted, but the vehicle is unexpectedly forced to conduct other not covered stops. The size and cost of the station will vary depending on the number of battery pallet chargers the station has and the number of battery pallets it keeps on hand. The number of charged battery pallets available at any given time is determined by the size of the station, the inventory of pallets on hand, and the current demand for charged pallets. Since the driver may not have to pay for a battery swap, the station incurs an indirect expense from the unavailability of charged pallets when an EV arrives for an exchange, and there could be a loss of goodwill from the unserved consumer. In designing the battery swapping infrastructure, models to quantify overall direct and indirect costs for potential decisions on station sizing and inventory keeping would be extremely useful.

Economic Issues of EVs adoption

The scarcity of refueling stations is a significant impediment to the success of electric vehicles. The establishment of facilities to allow recharging is a pressing issue due to the limited range of batteries. The need for infrastructure services such as battery swapping and recharging is determined by two crucial factors: regular driving distance and battery range. Economic considerations are very critical in deciding the number and location of stations due to the high capital costs involved in infrastructure investment. To serve EV trips economically and efficiently, studies must work to provide a theoretical basis for station deployment, such as with a facility position model. Location problems, in general, are problems involving the allocation of spatial resources to one or more service facilities serving a spatially dispersed collection of demands. The aim is to locate facilities in order to achieve a spatially based goal, such as reducing average travel time or reducing the gap between demands and facilities.

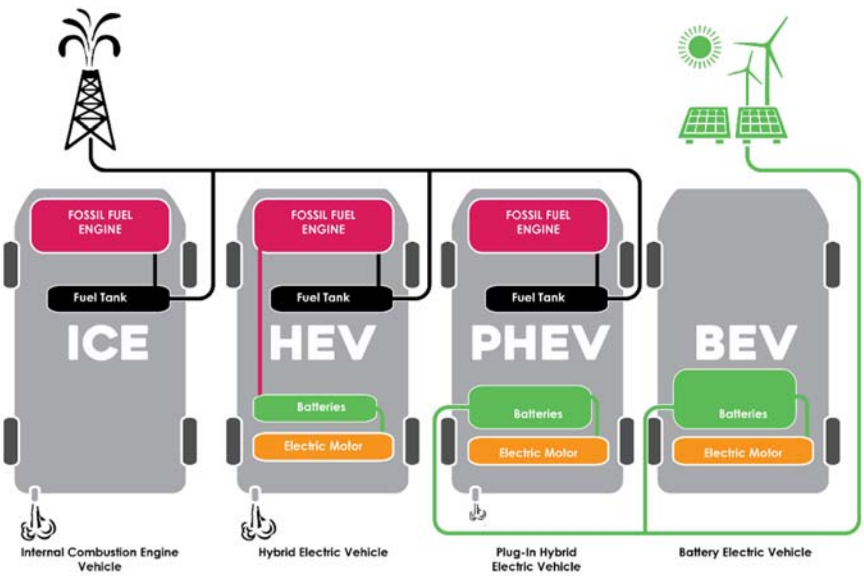
1.3 Current Market of Electric Vehicles

Greenhouse gases and other particles are the main problems we face with the use of internal combustion engine (ICE) vehicles. For this reason, and since natural oil and gas reserves are bound to deplete, albeit, in the long term, governments across the globe are taking action to minimize the emissions caused by vehicles. In densely populated countries like Japan and Singapore, the government discourages the use of personal vehicles. These countries have made excellent public transport available to the central areas of the country and imposed heavy taxes on personal vehicles, or banned personal vehicles from entering the central parts of their key cities. Other governments aim to lower the emissions per vehicle. They have issued new emission standards for the vehicles and require companies to meet the goal by the given time. In recent years, we have seen many governments encouraging their citizens to buy and use EVs as their main driver. Countries have put up tax breaks upon buying an EV, they are offering subsidies, helping companies build free charging stations for EVs, have waived off taxes on the import of electric vehicles, offered limited access to the dense parts of the cities only to EVs and much more. These policies are working and recent times have seen rapid growth in the global market share of EVs.

The figure above shows the rapid growth of EV share in the global market. It is projected by various studies that by 2040, EVs will make a quarter of the global vehicles market share and more than half of the new sales of vehicles. It is, therefore, critical to understanding the problems faced by the users of electric vehicles in adopting EVs as their main drivers so that personal vehicles can also join in the quest towards zero emissions and a booming economy.

Zero Emissions

Before we go into the detail of the charging problem, let's look at the main types of EVs available in the market right now and their emission rates.



The figure above shows the main types of vehicles available in the market.

- ICE

  Internal Combustion Engine vehicles run directly on fossil fuel and do not have an electric motor in them. They have served a critical role in the progress of the world but they are also one of the major causes of environmental degradation. Any extended use of them is unsustainable, environmentally and economically speaking.

- HEV

Hybrid Electric Vehicles mainly run on fossil fuel but the extra energy, such as while idling and braking is used to charge an internal battery that can power an internal electric motor. These vehicles can cover very small distances on battery but extended distances need fossil fuel usage. Studies have shown that HEVs can produce 25%-30% fewer emissions than ICE vehicles.

- PHEV

Plug-in Hybrid Electric Vehicles run on the same principle as HEVs, with the extra option to charge the internal battery with external electric power. With the encouraging use of these vehicles, we can see as much as 50% fewer emissions in city areas and around 30% fewer emissions over extended distances.

- BEV

Battery Electric Vehicles are our main area of interest. They completely run on the battery and have no combustion engine amounting to zero emissions to the environment. In the paper, we will use the terms EV and BEV interchangeably. The only downside of using BEVs over any other kind of vehicle is that you lose the backup option of a combustion engine and high charge times can be a problem for critical situations.

1.4 Charging options of electric vehicles

In this section we review possible charging methods for electric vehicles. There are three main approaches for charging electric vehicles:

Wired Charging

Wired charging is the most basic and intuitive way of charging an EV. The vehicle is connected to a power terminal with a wire that charges the battery pack inside the vehicle using AC or DC, depending on if the rectifier circuit is in the power terminal or the car. In the wired method, the battery is charged at different rates. While the most widely available option, wired charging can take 10 hours to just under an hour to fully charging a discharged battery, depending on the wired charging technology being used and the size of the battery. Better than nothing, but it doesn't compare with the alternate gasoline solutions which can fill the tank in under ten minutes.

Induction Charging

In induction charging, the power terminal charges the battery pack inside an EV with the help of radio waves. The power circuit is usually embedded in the ground at the parking spot of the car. This method is the most convenient; for people who park their cars in the same spot every day because the wireless charging method cannot be used in charging stations since it is magnitudes slower than the wired method. The circuitry used for generating radio waves and then converting them back into power makes the device a bit complex, fragile and expensive. This charging method has its place but it is not the method we will be looking for in a system that requires high capacity batteries to be charged as fast as possible.

Battery Swapping

The final method and the only one feasible for EVs used for transportation of goods and don't have hours every day to fill their batteries is the battery swapping. The EV pulls into a battery swap station; an automated system unplugs the battery from the vehicle and sends it to a charging terminal to be charged optimally, and fixes the EV with a fully charged battery. All of this is done within 5 minutes, the same time it takes to fill a tank with fossil fuel. With the cost efficiency reaching that of ICE vehicles and zero emissions, that is a pretty big improvement over the currently available options.

BATTERY

"Wired" charging using a plug	Battery swapping	Induction charging
Plugging in to a charging station using a cable and plug	Replacing a battery for a fully charged one at a special swapping station	Battery in the car is charged by wireless induction charging
4-8 hrs (slow) 20-30 min (fast)	5 min	~2-8 hrs[2]
▪ PHEV ▪ BEV suitable for plug-in charging	▪ Special BEVs suitable for battery swapping	▪ Special BEVs suitable for induction charging
▪ Renault Zoe (BEV)	▪ Special model of Renault Fluence	▪ N/A (few pilot cars)
Limited availability: >20,000 (slow) >1,000 (fast)	Very limited ~50 stations	Not available (few pilots in progress)

1.5 Structure of battery swapping system

A Battery Switching Station, or BSS, is a physical location, similar in size to a gas station, where EVs' flat batteries can be replaced with fully charged ones automatically. The battery swapping system has many advantage over other charging method for both electric vehicles users and for the whole community.

The removal of driving range restrictions, the transition of battery ownership and costs to BSS companies, and the rapidity of service are the most important considerations from the user's perspective, since BSS eliminate the key source of delay, which is the time taken for the battery to charge.

The creation of a BSS network could be useful to the community in two ways. For instance, BSS are advocates of EV penetration in the industry, which helps in the transition to an oil-free economy. Second, the BSS is likely to become a Smart Grid component, using spare batteries as energy storage devices and engaging in disaster recovery programs.

1.6 Components and Operation of the BSS

This section discusses how a BSS system operates in depth, based on the operating model devised by Better Place, an American-Israeli startup that developed the first modern commercial BSS network between 2009 and 2013.

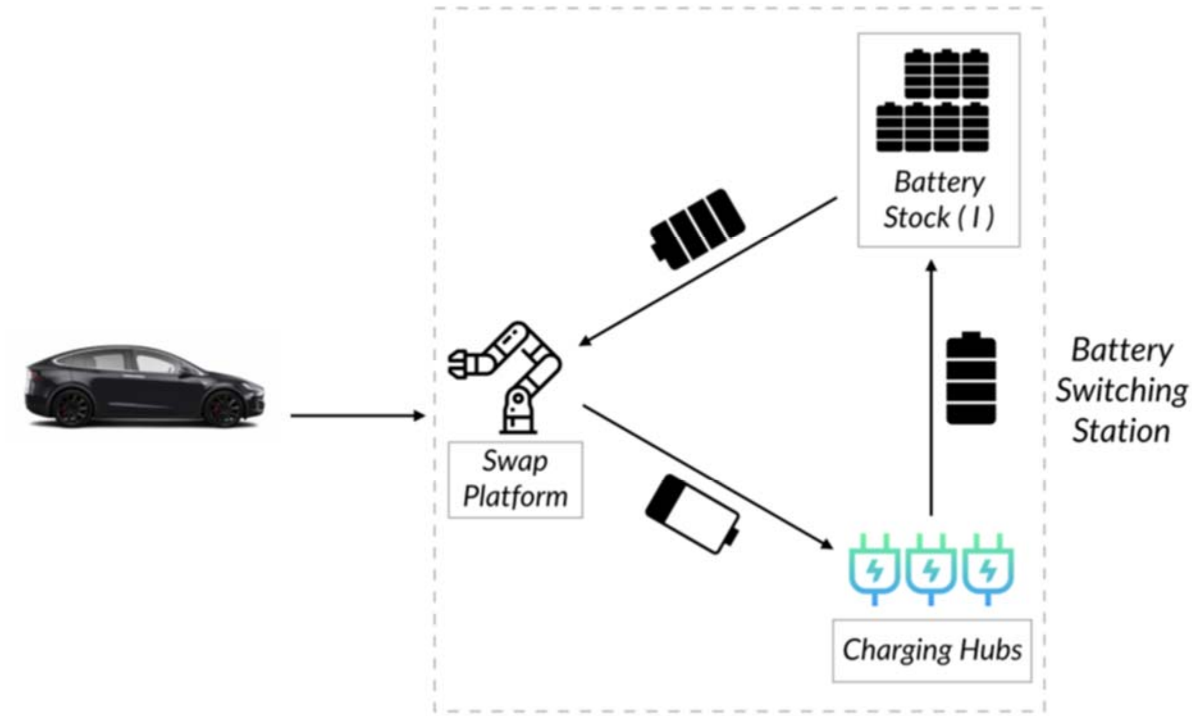
The BSS is made up of different technical components which are listed below:

Swap platforms: Swap Platforms can handle one electric vehicle at a time and are fitted with a robotic arm that performs battery replacements automatically and efficiently, generally in under three minutes.

Batteries Stock: The BSS has a limited number of fully charged batteries on hand, ready to be distributed to EVs who request a battery swap. The BSS is a closed-loop process since each full battery is unconditionally replaced with a depleted one.

Charging Hubs: After a battery exchange in the swapping platform, the drained battery is plugged into a charging hub, where it undergoes a time-consuming charging method. The actual charging time is calculated by two factors: battery capacity and hub power, as shown in the graph below: Battery Energy (kWh) /Hub Power = Charging Time (kW).

EV: The BSS system's clients are the electric vehicles. They finally come to the switching station as their driving range is about to run out and request a swap.



Operation of the Battery Switching Station Model

The BSS only has a limited supply of batteries. EVs come to the BSS with the purpose of demanding a battery. If at least one battery swapping platform is accessible, EVs enter one at a time and begin the process, which takes a specific amount of time.

The EV leaves the BSS once a new battery has been properly installed, and the depleted battery is transferred to a charging phase. In certain cases, this process does not start right away, but it can be delayed until a later date, eliminating the need to import electricity from the centralized power plan and thereby reducing grid peak-load.

The Benefits and Drawbacks of Using a BSS

As mentioned at the outset of this section, BSS has the potential to benefit both individual EV users and the entire community.

From the user's viewpoint, there are two key explanations why EV adoption is usually slow. The first is known as range anxiety, and it refers to the concern that the vehicle would run out of power before arriving at its destination.

The second explanation is the high cost of buying and maintaining the battery, which is typically the most important commercial price differential between EVs and diesel or petrol vehicles. A battery for a mid-size electric car with a capacity of 16 kWh to 24 kWh, for example, will cost up to 14.000 euro [24].

In the case of typical plug-in EVs, such as PHEV or PEV, these two limiting factors are valid. Their range is limited by the amount of travel distance that their battery can provide for each charge, and once they run out of power, recharging takes a long time, depending on the battery capacity and charging power available at the facility. Furthermore, since the battery is sold with the vehicle, the EV owner is also responsible for the battery and its future maintenance costs.

The widespread use of battery switching stations, on the other hand, might be able to address the previous limitations.

It is actually possible to expand the range of EVs by creating a proper network of BSS, since BSS can replace a flat battery with a complete one in a matter of minutes, which is a negligible delay.

The distinction of car and battery ownership is the second advantage. The BSS firm owns all of the batteries, allowing consumers to save money on battery sales, warranties, and maintenance, which is a big factor pushing more people to embrace electric mobility. While the EV users pass some of the risk associated with battery maintenance to the BSS firm, it is also appropriate for the firm to charge the clients for this risk transfer. The switching service would then have a specific fee, which will most likely be higher than the cost of simply charging the device, as in a traditional plug-in facility. However, due to scale economies, the BSS business can handle this risk at a low cost [24]. As a result, the additional cost to customers is kept low, ensuring that the BSS continues to be a viable option.

In addition to the previously stated benefits, the BSS provides a third significant benefit: the ability to The inherent versatility of BSS, owing to the fact that the batteries are the company's property, aids in avoiding peak-loads of electricity by deferring charging to less busy hours. Plan and schedule battery charging Acting as an aggregator, according to the grid's specifications.

There are some limitations of using a mobility system that is based on battery switching stations. For instance, a universal battery standard must be developed in order for batteries to be interchangeable. This means that various electric car manufacturers should build EV models so that the battery is not permanently connected to the vehicle and can be easily removed.

Environmental concerns, especially carbon emissions and oil dependency, are also significant disadvantages. BSS are actually encouraging the adoption of electric vehicles, pushing more and more people to purchase electric cars instead of traditional ICE cars, due to the cost savings of electric cars linked to battery ownership.

On the one side, this results in a decrease in total oil dependency. On the other hand, if energy is generated by fossil-fueled power plants, as it is in many countries, this change leads to a rise in electricity use, which, in turn, raises carbon emissions. Furthermore, a network of BSS decreases range anxiety by substantially expanding the EV's travel range, which in turn allows users to drive more and consume more electricity.

Several countries have adopted policies aimed at lowering CO2 emissions while also restricting oil dependence. For both political and economic purposes, a country's dependence on fossil fuels must be reduced.

Since most crude oil is concentrated in some areas of the world, a transportation system dependent on oil is susceptible to geopolitical contingencies and supply disruptions. A reduction in the amount of carbon dioxide emitted into the atmosphere is therefore important to tackle global warming, which has the potential to cause disastrous consequences.

1.7 Case Studies of BSS in real-life businesses

This section provides three case studies of real-life businesses that have had, or still have, a fully operating network of battery switching stations in recent years.

Better Place

The first company worth mentioning is Better Place, which was founded in October 2007 in Palo Alto, California, by multimillionaire Israeli entrepreneur Shai Agassi, primarily with private investments. In December 2008, the company opened its first operational switching station near Tel Aviv, Israel. Between 2008 and 2009, Better Place ran a campaign to install BSS networks in a variety of countries, mainly on "islands" like Denmark, Australia, Hawaii, and the San Francisco Bay. Due to its rarely-crossed borders, Israel can be called a transportation island.

In September 2012, the company had 21 operational BSS open in Israel [25] and 17 operational BSS open in Denmark [26], which was enough to cover the entire country's service. Renault-Nissan was the first car company to sign a contract for the use of switching stations. Better Place would have provided the charging infrastructure in exchange for Renault producing the cars, according to the agreement. The Fluence Z.E. is a prototype electric vehicle with a swappable battery.

The battery packs mounted underneath the Fluence Z.E. were designed to be replaced automatically by a robotic claw in less than two minutes, using the same technology used to load bombs on F-16 jet fighter aircraft [25] [27].

Such battery packs were projected to provide EVs with a range of 160 kilometers and a life span of 2000 recharge cycles over an eight-year period [25].

Following that, Better Place stations started to embrace a range of battery types from various EVs, as long as the battery pack could be removed from underneath the vehicle [25].Better Place ran a business model focused on a monthly subscription that covered battery pack leasing, swapping and charging prices, the expense of either generating or buying renewable energy, and eventually benefit [25].

Customers would have had to pay for a new consumable, the electric mile. This per-mile charge was about 8c in 2010, and it was predicted to drop exponentially due to technical advances that would have lowered the cost of batteries.

Shai Agassi, the company's CEO, highlighted the value of achieving EV affordability, with a commercial price of at least $5.000 less than the average price of traditional vehicles.

Most people would have been enticed to turn to an EV if this had been the case. The secret to achieving this result was lowering the costs associated with battery maintenance; as a result, any battery problem would have been completely addressed by Better Place.

The firm has made major efforts to convince governments to follow universal standards. However, global adoption of standards like the SAEJ1772 took place just a few years ago. [25]

Better Place was also ahead of the curve when it came to allowing the Smart Grid. According to a simulation conducted by Israel's largest utility in 2009, the country would have invested about $1 billion on new power plants by 2020 if all cars were electric. [26]

The organization overcame this problem by proposing a smart grid control software solution. The switching stations were then to be operated by dedicated software that could schedule the recharging of thousands of electric vehicle batteries outside of peak demand hours, avoiding grid overload [25].

Furthermore, according to Shai Agassi, all of the electricity required to power the BSS should have come from solar or wind farms. Despite this vision, countries such as Israel depend on fossil fuels for bulk electricity generation, rendering the renewable energy initiative extremely difficult to introduce in the near term [25] [28].

Better Place ran into considerable financial difficulties in early 2013 as a result of unsustainable initial investments in too many countries. The company had invested around $850 million in private capital, mostly for the establishment of BSS infrastructures, and the initial outlook for EV market penetration was far too ambitious.

In Israel, less than 1000 Renault Fluence Z.E.s were deployed, compared to an estimated 100.000, and about 400 were sold in Denmark [25] [26] [28]. The company filed for bankruptcy in May 2013 as a result of these concerns.

Tesla Motors

Tesla Motors is a well-known electric vehicle manufacturer that is currently leading the market for quick charging technology. Elon Musk, the company's founder and CEO, introduced a proprietary battery switching service in 2013, in addition to the Superchargers, to extend the charging options for Tesla owners [29], who could then choose between fast and free charging.

Tesla then updated its Model S to allow for fast battery swapping, demonstrating at a demonstration event how a Model S battery could be replaced in 90 seconds, less than half the time it takes to fill a gas tank [29].

Since a large number of Model S were used to make this round trip on a regular basis, Tesla announced a proposal to deploy the first BSS between Los Angeles and San Francisco. However, due to a lack of demand in the only existing pilot facility at Harris Ranch, CA, where only five people tried out the service, the project of a nationwide BSS network was abandoned two years later [29].

The cost of the battery swap, which was about $80 versus the free fast charging alternative provided by Superchargers, was most likely a deciding factor.

NIO

Nio, a Chinese EV startup formed in 2014, is the most recent and, in fact, the only one still running switching stations. The Shanghai-based firm specializes in the production of electric autonomous vehicles and has been providing battery swapping services to its customers since May 2018. [30]

The first BSS, dubbed "Power Swap Station," was built in Shenzhen, Guangdong province, and offered a 3-minute swap service for only the ES8 model. The stations are constructed in a compact modular format, with a volume of approximately three parking spaces, allowing for service scalability [31]. Furthermore, the battery swap facilities are supported by NIO Cloud, an IoT-based technology that allows customers to arrange and schedule battery swap appointments from their phones. [31]

Initially, each battery swap cost 180 yuan (roughly e20), but since August 2018, company leader Lihong Qin has announced that ES8 owners will receive 12 free battery swaps per year at any BSS in China [32], [33]. So far, Nio has constructed 80 BSS in China's major cities and along the G4 Expressway that connects them [32] [33]. Over the next two years, the company plans to develop over 1.000 BSS across China.

In light of these three real-world examples, it's obvious that battery swap is still an emerging technology with tremendous potential, but it's not yet market-ready. Better Place was probably a bit ahead of its time, and Tesla has largely overlooked it in favor of Superchargers. Now, Nio is seizing opportunities in the market and working hard to make BSS a reality.

1.8 Advantage of battery swap station

In this section, we investigate the benefits of a battery swap system from different perspectives, including the EV owner, the station owner, and the power system.

Figure 1. Interactions of BSS with EV owners, station owners, and power systems [2].

Power system perspective

- Providing of controlled charging strategy for better scheduling battery charging time.
- Postponing the charging of batteries to the nighttime or off-peak periods to avoid overloading.

- By applying a smart charging schedule, there is no need to upgrade the grid infrastructure to avoid overloading in high-demand hours.

EV Owner Perspective

- Reduction in the price of electric vehicles.

- Minimum charging time as battery replacement can be done within few minutes in BSS.

- Quick battery swapping provides a long-range driving opportunity for drivers.

- As BSS is responsible for maintains and state of health (SOH) of batteries, the drivers don't worry about the lifetime of batteries.

Station Owner Perspective

- Minimizing the cost of electricity by planning the method of battery charging.
- Raising its profitability (*Better profit margins*) through involvement in electricity markets and the provision of services for demand response.

- Reducing real estate prices, as large parking spaces do not need to be accessed.

1.9 Challenge of battery swap stations

Battery design issues

The main challenge facing battery swapping technology is the design of batteries. The battery pack must be specifically built so that it can be conveniently and efficiently removed from the vehicle and quickly re-attached. Battery interchangeability is another essential attribute. The existence of Interchangeable battery packs is a must in battery swapping, but achieving this objective is not easy, as using all standard battery pack formats will restrict the creativity of the manufacturer. [3].

Infrastructure

The battery swapping infrastructure is more complex and costly than charging. First of all, all battery swapping stations are expected to charge their battery packs, so that they impose the same demand on the grid as they do at the charging stations, with the only difference being that demand can be regulated. Second, to be able to supply customers in need of a sufficient number of batteries, they must have several battery packs that exceed a certain percentage of the daily demand for each station. The cost of setting up a battery swapping network versus a car charging system is also much higher [3].

Battery Degradation

As the battery's performance deteriorates over time, so does the range that can be achieved with each charge. Due to deterioration, we will find batteries with different energy storage capacities in the swapping station in a battery swap situation, despite the fact that all cars will be using the same battery pack format and power. Most people, logically, would choose newer battery packs when swapping because they have a longer range and need less trips to the swapping station. Low capacity packs mean that EV range will be decreased compared to newer packs, so consumers will be disappointed if their current battery pack is replaced with a lower performance pack, since they will get less mileage out of their car.[35]

Battery Ownership

The battery is owned by the car owner: In this situation, the owner would need to buy an extra battery pack that can be used as a backup battery if the vehicle's battery is discharged.

The battery is not owned by the car owner: This situation has some benefits over the previous one. Since the driver does not own the battery, the EV price is more affordable, and unlike the battery-owning case, if a battery is swapped, the driver does not need to return to regain it. This gives you a lot of options. However, there is a big drawback: since the battery is not owned, each time a battery is swapped, the car owner will pay a lease on the battery in addition to the electricity. This lease may be set in stone (with a monthly value) or renewed with each battery swap.[35]

1.10 Negative effects of large scale integration of EVs into the power grid

Despite all of the benefits mentioned in the previous section, large-scale integration of EVs into the existing power system which pose a number of challenges. Analyzing potential negative impacts and developing specific solutions are crucial to not only the secure and efficient operation of the power system, but also the long-term growth of EVs.

Increased peak load demand

The effect of EV charging on grid peak load demand has been studied in a number of ways. According to study, uncoordinated charging combined with a high EV penetration ratio will result in peak demands exceeding the capacity of the generating system on average days.

Smart charging and time-of-use (TOU) tariff plans will significantly reduce peak demand, so the optimization of EV charging and discharging behaviors is focused on provided variations in electricity spot rates, consumer preferences, and driving habits, avoiding the need for additional generation capacity expansion.

Power quality problems

For a reliable power supply, a stable power grid is important. Since the characteristics of electric vehicle charging loads differ from those of conventional household or industrial loads, the effects of EV charging loads on grid power quality have been thoroughly investigated in many studies. The effect of charging on the grid is typically defined in terms of changes in the system's power quality. The irregular charging behavior of EV users will have a number of negative consequences for the system, including overvoltage in the distribution network, deterioration in power quality, increased line damage, distribution transformer downturn, increased distortion, and higher fault current. few of these important effects are explored in depth here.

Discrepancies in voltage

The extent of EV interconnection in residential areas of distribution networks is expected to increase in the future, but their related degree of penetration and corresponding connection spots remain unclear. Residential areas will have single-phase loads, which will necessitate the installation of EV chargers. The voltage imbalance in the three-phase distribution system can result as a consequence of this. The random charging method of an electric vehicle frees the owner from any restrictions, which increases the risk of a higher node voltage offset, which is detrimental to the distribution network. Another research suggested a delicacy analysis of the same phenomenon, as well as a stochastic evaluation to determine the charging and discharging positions of the batteries and the corresponding penetration. According to the findings of the report, voltage imbalance is more prevalent in the distribution portion of the system.

Harmonic Distortion

Gmez and Morcos [34] looked into the effects of EV charger harmonic distortion on the distribution system, especially on transformers. According to the base load, ambient temperature, and time, the proposed method can be used to calculate the optimum charging time. This research also found that uncoordinated direct charge can shorten the life of a transformer, especially in high-temperature and high-load scenarios. The effects of harmonic distortion on electrical equipment can be disastrous. Unwanted distortion in power systems can result in higher temperatures in neutral conductors and distribution transformers due to increased current. Higher frequency harmonics cause additional core loss in motors, causing the motor core to overheat. Since these higher order harmonics oscillate at the same frequencies as the transmit frequency, they can interfere with communication transmission lines Increased temperatures and intrusion, if left unchecked, can drastically reduce the life of electronic equipment and harm power systems.

Section 2 Review of Performance measurement systems

Municipalities play an important role in the rollout of public charging infrastructure and the adoption of electric vehicles. As they have little insight into the relevant key performance indicators of the charging infrastructure, we need a set of KPIs to support effective decision-making. This work aims to contribute to providing a more thorough understanding of relevant key performance indicators for Battery swapping charging infrastructure. The aim of this work is the definition of a KPI evaluation framework for battery swap stations. The framework definition is done through three steps: the first step is the identification of available KPIs based on a literature review, the second step is the sorting of KPIs based on the frequency of use in scientific research papers, and finally, the classification of KPIs based both on their impact domain (economic, social or environmental) and on the company hierarchical levels (strategical, tactical and operational) in which they are used. These steps are described in the following paragraphs [4], [1].

2.1 Review of Performance Measurement Systems

Performance Measurement System (PMS) is a management control tool to improve the organization's performance. PMS creates a significant connection between organizations thanks to measurement within the organization system directly associated with the organization strategy. A well-developed and systematic PMS implementation allows the enterprise to build and improvise the business environment to enhance the process of decision-making. Therefore, there are multi-comprehensive approaches of PMS that have been applied both quantitatively and qualitatively are significant to measure, predict and evaluate current and future organization performance [5].

In this section, the most popular PMSs are introduced.

Theory of Constraints (TOC)

The Theory of Constraints is a methodology for identifying the most important limiting factor or constraint that stands in the way of achieving the goal of the organization and then systematically improving that constraint until it is not the limiting factor anymore.

TOC seeks to supply precise and sustained focus on improving the present constraint until it does not limit throughput, then the focus moves to the subsequent constraint. The underlying power of TOC is its ability to get a tremendously strong focus towards a certain goal (profit) and to remove the constraint to achieving more of that goal. [5], [6].

Strategic Measurement and Reporting Technique (SMART) Performance Pyramid

In 1991, Cross and Lynch developed the Strategic Assessment and Reporting Technique performance pyramid. This pyramid model consists of four levels that illustrate the connection between organizational strategy, strategic business unit, and activity. The first stage is a description of the overall corporate vision that will then be converted into the goals of each business unit. The second stage demonstrates short-term profitability goals and long-term growth and market share objectives. Company operating systems that consist of customer loyalty, flexibility, and efficiency are the third category. The fourth level is the business unit, which consists of four main performance metrics that will then be used in the department (quality, distribution, cycle time, and waste). A structured model that considers stakeholder satisfaction, such as customer satisfaction, quality, and distribution, is the SMART success pyramid. It also tests the activities of the operation, such as efficiency and lead time. The SMART performance pyramid's primary strength is the correlation between corporate goals and the organizational performance indicator (Kurien, &Qureshi, 2011) [5].

Balanced Scorecard (BSC)

Another integrated assessment mechanism for the performance measurement of a complex organization is the Balanced Scorecard (BSC) developed by Kaplan and Norton (1992).This method is an improvement over the other indicator systems from several points of views:

- A direct connection between indicators and strategy is given by the BSC approach.

- It has a simple set of metrics that are useful in strategic planning and management, with a standard framework.

- It focuses on assessing strategic progress driven by mission and vision. (e.g., Micheli and Kennerley, 2005; Vila et al., 2010; Voelker et. al, 2001).

BSCs have considered four major performance attributes for performance measurement, including learning and innovation, internal process, customer, and financial focus (e.g., Chung et al., 2011; Gomes and Liddle, 2009; Wilson et al., 2003) [7].

2.2 Methodology

The main goal of this work is to find out the main set of performance Indicators for battery swapping systems.

To represent and organize a complex system from a different point of view, Anthony's Pyramid structure have been applied to performance Indicators we gained from the literature review [4], [21].
Then indicating three dimensions of performance: economic, environmental and social for each KPIs [8].

Economic Measures

Economic variables ought to be the variables that deal with the financial and economic growth measures along with enhanced revenue to maintain the financial viability of the EV transport sector and support social and environmental sustainability initiatives. Economic Measures include income or expenditures, taxes, business climate factors, employment [7]. Specific examples include:

- Organization income
- Establishment sizes
- Percentage of firms in each sector

Environmental Measures

Environmental variables should describe natural resource measurements and reflect on possible impacts on their viability. It could incorporate air and water quality, energy consumption, natural resources, and waste management Specific examples include:

- Fossil fuel consumption
- Electricity consumption
- Impact on local air quality and ecology

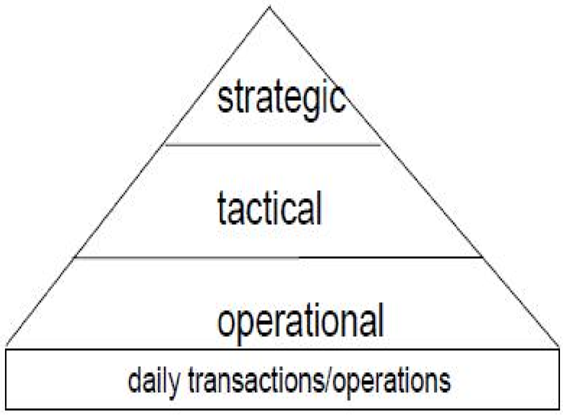
Social Measures

Social variables refer to the social dimensions of a community or region and could include measurements of accessibility, affordability, comfort, safety, security, equity and access to social resources, quality of life, and social capital [7]. Specific examples include:

- Accessibility, connectivity, and travel time
- Level of service and comfort
- Safety enhancement

The Decision Making Problem Level

The Anthony triangle (also known as Anthony's triangle) is a management model. The triangle represents management structure in a hierarchical fashion, with many operational decisions at the bottom, some tactical decisions in the middle, and a few but crucial strategic decisions at the top. The higher an item is in the triangle, the broader its reach and the less precise it becomes.



The assessment operation is organized to help decision-makers. However, to assist them, we would like to understand the decision-making "horizon". Three levels of decision-making concerns have been identified by Ansoff (Ansoff, Anthony, 1965; Stratagor, 1993): the strategic, tactical, and operational levels [9].

<u>The strategic level</u>

The process of strategic planning includes agreeing on and implementing strategic plans in order to achieve strategic goals (or goals). The strategic plans are normally created by top management. There are usually long-term decisions or initiatives that will have ramifications for the next five years or more. Long-term or strategic planning requires a great deal of ambiguity and uncertainty.

The following are some of the strategic operations planning decisions:

1. Technology decisions: suitable technology, infrastructure, process selection, and degree of automation

1. Capacity choices: quantity, timing, and type
2. 3. Facility selection: size, location, and specialization

Planning at the strategic level is concerned with decisions that will have long term effect. These choices are crucial to the organization's success and improved performance. These decisions have an effect on the company's competitive position and help to position the company's operations strategy.

1. Strategic planning aids in achieving objectives in the most efficient manner possible.
2. It aids in the attainment of competitive advantages and the development of competencies.
3. It aids in the development of strengths and the elimination of weaknesses in order to maximize available opportunities.
4. It directs the growth and development of a company.
5. Strategic planning sets the basis for tactical and operational priorities.
6. Strategic decisions must be made with limited information and in an unpredictable and risky atmosphere.
7. Risk is often correlated with strategic level planning, and it is used in certain futuristic assumptions.

Decisions are aimed at planning actions. Decision-making has a national or international effect in this case, so it is largely affected by political and legislative aspects. At this stage, while there seems to be an abundance of knowledge available, it remains imprecise and difficult to sort through. To allow a sufficiently broad margin of maneuver for the decision-making process, assessment conclusions need to be descriptive and not explanatory. (Mintzberg, 1994) [9].

The tactical level

Tactical planning is mainly done at the middle management level, and it includes resource acquisitions and allocations in order to meet organizational goals. When opposed to strategic planning, tactical strategies span shorter time periods and are associated with less uncertainty and therefore lower risk.

Tactical planning is primarily concerned with determining how the organization's resources can be used to achieve the organization's strategic objectives. When compared to strategic planning, tactical planning requires less complexity and therefore lower risk. The majority of the data needed for planning is generated internally.

The following are examples of tactical planning decisions:

1. Identifying metrics for determining organizational performance and productivity.
2. Making plans to make better use of available resources.
3. Make plans for equipment and manpower.
4. Making plans for the modernization and automation of the facilities.
5. Unique technologies and tools to increase the quality or productivity of production.
6. Fixing performance parameters and producing data to compare actual and planned performance, as well as taking measures to close the gap between planned and actual performance, are the main priorities.

7. Makes arrangements to make the best use of available resources.

The decisions in the tactical level are affected to a lower degree by political and legislative aspects that affect the strategic level but also include social and economic dimensions. This is the stage at which public decision-makers most frequently turn to tests to legitimize the actions taken [9].

The operational level

Decisions on operational planning are made at the lowest levels of management, and they are routine decisions. These plans are made to lay out the steps that must be taken in order to achieve operational objectives. These are for a specific period, such as a year. These plans have little or very little uncertainty, and the information required is internal.

These plans lay out the steps that must be taken in order to meet operational objectives. These plans are deterministic in the sense that there is very little ambiguity involved. The proposals are formulated in terms of quantifiable acts.

Decisions in the operational level take on a more analytical and targeted dimension. Knowledge is always more specialized, more accurate, more homogeneous than at previous levels. The analysis of risk at this stage is carried out to implement regulatory measures [9].

By using the combination of these two methods we classify the KPIs for the Battery swap system.

2.3 Weight system definition

From the 214 papers examined, a total of 23 unique indicators were extracted. To evaluate the impact of any indicator, we define three metrics: the relative frequency, the weighted frequency, and the global frequency [4].

To calculate the relative frequency, we divide the indicator occurrences by total outcomes. The relative frequency f_θ^r of a generic indicator θ can be calculated as follows:

$$f_\theta^r = \frac{f_\theta^a}{K}$$

Where $f_\theta{}^a$ the absolute frequency of the generic indicator θ and K is representing the total number of examined papers.

To take account of the paper citations in which the indicator is present, we define a weighted frequency. The weighted frequency f_θ^w of a generic indicator θ is calculated as

$$f_\theta^w = \frac{\sum_{k=1}^{K} C_K B_k^\theta}{\sum_{k=1}^{k} C_K}$$

Where Ck is the number of citations for the k-th paper and $B_K{}^i$ is a Boolean variable that is equal to 1 if the i-th indicator is present in the k-th paper, otherwise it is equal to 0. Finally, a global frequency index is calculated as a mean between the previous frequencies. In order to compare the two different values, normalization is applied, obtaining two normalized frequencies $f_\theta{}^r$ and on which the global index is calculated. To normalize value, we divided by the maximum value, this method satisfies all requirements for a correct normalization of positive indices. Therefore, the global frequency index Gθ of a generic indicator θ is calculated [4]. as follows: $G_\theta=(f_\theta{}^r + f_\theta{}^w)/2$

KPIs	Relative frequency	Weighted frequency	Global frequency	
Throughput	%74.45	%76.96	%100	Tactical
Cycle Time	%15.32	12.42%	%18.36	Tactical
Service Time	%31.02	%30.03	%40.34	Tactical
Frequency Regulation	%2.19	%1.63	%2.53	Tactical
V2G Service	%10.95	%11.69	%14.94	Tactical
Battery Capacity	%13.50	%11.27	%16.38	Tactical
Battery Degradation	%9.85	%5.53	%20.41	Tactical
Profitability	%25.18	%23.38	%32.09	Strategy
Reactive power control	%1.82	%0.52	%1.56	Tactical
Optimal Location	%20.80	%22.99	%28.89	Strategy
Operational Cost	%35.40	%41.78	%50.92	Strategy
BSS Size	%24.82	%21.82	%30.84	Operational
BSS Capacity	%20.44	%25.99	%30.61	Operational
Daily Swapping demand	%14.23	%10.89	%16.63	Operational
IOT enabled energy management system	%2.55	%2.75	%3.5	Tactical
Battery Cost	%10.58	%5.95	%10.97	Strategy
Rental fees	%2.19	%0.97	%2.1	Strategy
Charging Strategy	%39.05	%40.67	%52.65	Strategy
QoS/user satisfaction	%40.14	%45.47	%56.5	Strategy
Impact on grid	%10.58	%6.54	%11.35	Tactical
Incentives	%5.11	%1.35	%4.31	Strategy
Reliability	%2.92	%0.835	%2.5	Strategy
Mobility	%0.73	%0.52	%0.83	Strategy

KPI Identification

The 23 selected indicators are categorized into three clusters following the TBL structure: economic, environmental, and social. Inside the three clusters, other sub categorization was made depending on the nature of KPIs. For each KPI, the relative frequency, the weighted frequency, the global index, and the hierarchy level are reported, the hierarchy level is in each table, the KPIs and their relative frequency are listed in above table.

Economic KPIs

The indicators of this cluster refer to the economic value of the system. In particular, they indicate the performances of the Battery swap system that directly influences the costs and the profit of the system. Inside this group we subcategorized the indicators in 6 separated sub clusters:

- Generic Performances Indicators
- Time-related Performances Indicators
- Cost related Performance Indicators
- Battery related Performance Indicators
- Grid related Performance Indicators
- ICT related Performance Indicators

Economic KPIs sub clusters	**KPIs**
Generic Performance Indicators	Throughput
Time Related Performance Indicators	Cycle-time Service time
Battery related Performance Indicators	Battery capacity Battery degradation Battery charging strategy Battery cost
Cost related performance Indicators	Profitability Optimal location of BSS Operational cost Rental fees BSS size BSS capacity
Grid related performance Indicators	Frequency regulation V2Grid/Battery 2Grid service Reactive power control Daily Battery swapping demand Impact on Grid
ICT related performance Indicators	IOT enabled energy management system

Social KPIs

The indicators of this cluster refer to the social impact of the system. In particularly, they indicate the performances of the Battery swap system that directly influences the society. Inside this group we subcategorized the indicators in 2 separated sub clusters:

Customer based performance Indicators Includes:

- Customer satisfaction
- Persuasion strategy/Incentives

System based performance Indicators

- Mobility
- Reliability

3.1 Definition of KPIs

Throughput

Throughput is a measure of a process or operation's comparative effectiveness, represents the rate of production, and thus quantifies how quickly an operation is processed.

Cycle time

Cycle time involves process time from the beginning to the end of the process, during which a unit is acted upon to get it closer to output and delay time, during which a unit of work is spent waiting for the next step to be taken.

Service time

Service time in the queuing system is defined as the time taken to satisfy a customer. The reciprocal average service time is called the average rate of service and is defined as the number of clients served over a fixed period of time.

Battery degradation

Under particular driving conditions, battery degradation occurs progressively over time and affects EV electricity by reducing driving range due to reduced power, battery degradation often reduces charging/discharge efficiency due to increased resistance, which requires battery replacement when the capacity is lowered to the battery degradation limit.

Generally, EV battery degradation undergoes two processes: one is the loss of cycling capacity due to the growth of the internal solid-electrolyte interphase (SEI) layer, electrode structure degradation and cyclable lithium loss during the charge/discharge process of the battery, as mainly determined by the number of charge/discharge cycles of the battery;

The other case is the loss of calendar capacity due to self-discharge of batteries and side reactions during the duration of energy storage, as defined primarily by the state of charge, aging time, and environment temperature.

Battery capacity

Battery capacity is the maximum amount of energy that, under such specified conditions, can be extracted from the battery. However, the battery's actual energy storage capacities can differ considerably from the "nominal" rating capacity, as the battery capacity depends heavily on the battery's age and past history, the battery's charging or discharge regimes, and the temperature.

Impact of Charging and Discharging Rate on Capacity:

The rated battery capacity is affected by the speeds of charging/discharging. If the battery is discharged very quickly (that is, the discharge current is high), the amount of energy that can be drawn from the battery is reduced and the capacity of the battery is lowered.

Alternately, if the battery is discharged using a low current at a very slow rate, more energy can be extracted from the battery and the capacity of the battery is higher. The charging/discharging rate should also be included in the battery power. Providing the battery capacity as a function of the time it takes to completely discharge the battery is a common way of specifying battery capacity. Therefore, as the driving range is directly related to battery capacity, it might be anticipated that vehicles with greater battery capacity would pursue fewer charging stations than those with smaller battery capacity.

Battery charging strategy

It is necessary to establish a charging strategy for the economic functioning of battery swap stations. Focuses on the impact on the vehicle and the battery, which explores the creation of an optimized charging strategy, taking into account factors such as the state of health (SOH) of the battery, cost-optimized charging and evaluating the charging and discharging behavior of the battery packs.

The lithium-ion battery, when compared to other battery technologies, has the following advantages: high energy density, long cycle life and low self-discharge. Because of these advantages, lithium ion batteries are commonly used in electronic devices. However, because of the slow charging speed and uncertain impacts on battery life, Li-ion battery charging has become a bottleneck in their use. Li-ion battery charging optimization has become a critical and difficult task.

A large number of researchers have developed a number of enhancements to address these issues, including state of charge (SOC) estimation and state of healthy (SOH) estimation as well as optimum charge.

Optimal location planning

Optimal location planning is one of the critical considerations that directly affect the costs of an operation as well as QOS and its ability to support clients. Location planning is Strategic, long-term, and non-repetitive. Therefore careful location planning prevents continuous operating problems in the future.

Battery Swapping station's capacity

One of the significant key indicators is the capacity of the battery swapping station. That addresses questions such as how many batteries should be placed in BSS or how different charging modes should be used to charge empty batteries to provide adequate service at minimum cost (fast charging vs. normal charging). Appropriate battery-swapping station capacity planning often prevents future grid failures and provides a charging service with the highest standard of service efficiency (QoS).

Battery swapping stations size/ infrastructure

The infrastructure planning problem is a critical issue. On the one side, drivers are hesitant to buy EVs until the recharging infrastructure coverage is fairly comprehensive and charging service providers, on the other hand, are not interested in investing significantly in infrastructure unless strong demand would be seen. Infrastructure planners are trying to start rolling out their network of recharging facilities to solve this problem before the vehicles are expected to be produced. Planners must also make rational investment decisions on when and how to deploy the infrastructure long before the actual subscription rates are detected. Because of the need to deploy a full infrastructure network, before observing the real demand, the planner has to make strategic network design decisions. Factors influencing swapping demand, such as the rate of adoption of EVs, the market share of EVs and the driving habits of EV users, are not exactly known at this point which makes planning infrastructure challenging [11].

QoS, user satisfaction

The QoS metric is the ratio of fulfilled EV swapping requests over the total requests [20]. The user satisfaction factor includes four main factors:

- Using cost, hardware facilities in BSS stations, BSS station availability, service experience.
- Using cost metrics include time cost of waiting time and charging cost.

Waiting time cost refers to time consumption that when the electric vehicle that wants to swap its depleted battery arrives at BSS station, is in a state of occupation, then the vehicle needs to wait throughout the battery changing process to be done.

The charging cost is determined by the amount of electricity charging and the price of electricity. Hardware facilities in BSS:

A BSS station's hardware facilities include the number of charging piles, the ratio of charging pile failure, the degree of charge pile aging, the grid power supply capability. Charging station availability involves layout density of the charging station, fuel private parking fee, opening hours of the charging station. Service attitude, after-sales resolution capability, and the accuracy of the app response are the secondary measures of service experience. [18]

Incentives/persuasion strategy

System operators of battery swap stations have discovered major differences in the stations' battery utilization rates. Many studies looks for successful persuasive design techniques that persuade users to select the less visited stations in order to minimize battery idle time in the less visited stations. The phenomenon has a variety of drawbacks. Battery usage rates are low at less-frequented stations, resulting in idle costs that can be avoided. Users also complain about not being able to find a fully charged battery at the busier stations. Resulting in a low degree of customer satisfaction. Examples of persuasive strategies for users in order to choose less visited stations include:

Authority: A system that makes use of authority roles would have greater persuasion capacity. For example, systems may provide specialist advice on using less used batteries for sustainability goals.

Discount: The level of a discount will increase the appeal of a deal and increase the probability of a purchase. Users who visit less-frequented stations, for example, can earn a discount.

Tunneling: By using the framework to direct users through a method or experience, you can convince them along the way. For example, based on the user's previous history and daily schedule, systems can lead them to change the battery.

Financial incentives:

Because of the high cost of electric vehicles, customers can not afford to purchase EVs, therefore, financial supports like tax reduction, direct subsidy policies during purchasing, lower electricity prices or free parking with the use of EVs can be helpful.

Technology incentives:

The long-term growth of EVs depends on the advancement of key fundamental technologies. Many nations, therefore, have great attention to the R&D of appropriate EV technology. This includes batteries, light-weighting technology for vehicles, and sophisticated climate control technology.

Charging infrastructure incentives:

Charging infrastructure has a significant effect on the adaptation of the market share of EVs and electric vehicles. Support for charging infrastructure, however, faces the 'chicken-and-egg' dilemma in that utilities would not invest in infrastructure until large-scale EV adoption happens, and if there was inadequate charging infrastructure, people would not prefer EVs.

Investment in public charging facilities should also be considered by both sides in order to properly understand the implementation of EVs from the government perspective [11].

Battery cost

In the infrastructure planning process, BSS requires a large stock of costly batteries and takes the risk of their significant degradation, which leads to a much higher capital cost compared to EV charging stations.

On the other hand, batteries from different EV brands vary in physical parameters, such as form, size and power, due to the lack of standardization, because batteries from different EV brands are not interchangeable. A BSS needs to maintain several types of batteries to provide facilities for all types of EVs. This incompatibility of the batteries greatly increases capital costs and operating difficulties. Thus, before planning the BSS infrastructure, it is of great importance to consider the effects of the number of batteries and chargers on the charging process of BSSs. Optimal charging operations and strategies thus minimize the running expense of the BSS and have a beneficial effect on battery life.

Battery leasing /rental fee

The idea of battery leasing has been suggested in order to minimize the initial cost of electric vehicles for consumers, as batteries are the most costly part of an electric vehicle.

A corporate company owns and finances the batteries in the battery leasing operation and rents them to clients. Customers can, therefore, only purchase the vehicle shell directly, thus agreeing to pay the battery rental fees.

Such a service could broaden the potential pool of users for EVs and increase the market share of electric vehicles. In the public transport system, battery leasing facilities are also useful; there are obvious advantages of managing the battery swap station with the battery lease mode.

Such a solution not only frees up investment and maintenance concerns for electric city buses but also reduces exhaust emissions and operating costs. The coordinated charging strategy, referring to the battery swap station, helps battery management, increases battery life, and decreases overall operational costs.

The coordinated charging plan in the battery warehouse allows the power grid and the local distribution system to fill the valley with electricity consumption during off-peak time and improve economic operations. Therefore, the battery swap station will effectively promote the development of electric city buses in the public transport industry by introducing the battery lease mode [12], [13].

Mobility

Mobile battery swapping vans are presented as a new solution to offering a battery swapping service for EVs within a short period of time. A battery swapping van will hold tens of fully charged batteries and travel to an EV within a short time to swap a battery and try to meet the needs of EV users, from the point of view of EV users, The presence of a battery swapping van helps them to fully get rid of the old-refueling mode. In order to acquire their energy replenishment, they do not have to search for a charging station or battery-swapping station but simply call a battery-swapping service anytime and anywhere. They just need to send their SOC and speed, direction, and position information. Then, with a battery swapping van, they can get a fast and effective battery swapping service and have no need to worry about SOC of their battery whether the current battery SOC is adequate or whether enough battery swapping stations are available on their travel routes, etc. This principle of battery swap availability has a great influence on QOS and user satisfaction.

IOT enabled energy management system

With the application of the battery swapping system, through the connected vehicle's technology, drivers can quickly find the nearest battery swap station and don't have to queue in the station. Planning a rational route through the technology of connected cars, provide a quick and energy saving way to get the service at battery swap stations. This technology not only reduces traffic congestion and provide traffic flow control, but it can also distribute the resources of the electrical changing station fairly to ensure that everybody can experience the most convenient and efficient service.

For BSS with multi-energy, a smart energy management system (EMS) is needed for cost-effective operation. Charging demand forecasting and BSS optimal charging scheduling modules make up the proposed BSS-EMS. The results show that as compared to uncontrolled charging due to charging load forecasting, the proposed multi-objective optimal charging model will save up to 40% on both charging cost and load variance.

Reliability

Reliability is an indication of how long a system runs without failing. It is commonly expressed as the average time between failures (MTBF). It can also be expressed in terms of the likelihood of not failing. A battery swap control system is studied in most papers to ensure an automated, effective and reliable battery swap process, which greatly improves the efficiency and reliability of the station, and provides a guarantee for the popularization and application of electric vehicles, in order to facilitate the efficient and reliable operation of electric vehicle battery swapping.

The general requirement of battery swap control is to manage all the steps in the process and automatically control the robotic equipment to substitute batteries for electric vehicles with efficiency and security assurance. To avoid any conflict, the control system should check restricted conditions according to safety rules and the status of all relevant items. For example, the batteries can be harmed if the transmission equipment positions the battery in a location that has been occupied. Such a dispute can be avoided by the control system.

Operational cost

The purpose of the construction of the charging station or battery exchange station for electric vehicles is to promote the application of electric vehicles and solve global warming; hence the construction of the charging station must be low construction cost, low operation cost, and energy-saving. The operational cost of BSS depends largely on the infrastructure cost, number of initial batteries to be purchased and deposited at battery swap stations, the cost of battery maintenance, and the cost of electricity.

Infrastructure cost could be:

Cost of installing an air conditioning unit to keep the temperature at a comfortable level (25°C) for optimum battery life.

The cost of setting up the information technology systems that will be used to operate the swap station.

The cost of materials for infrastructure construction.

Profitability

Due to low expected revenues, high capital expenses and high operational and maintenance costs, the operation of the charging infrastructure is not really very profitable. [14]. In view of this, several studies have concentrated on optimal scheduling of charges and pricing strategies to increase the efficiency of charging station operations. The use of an EV charging station operating mechanism, which jointly optimizes pricing, charging scheduling and demand control, maximizes a charging station's average revenue. Most of these methods aim to minimize consumer waiting time as the profit refers to the difference between income and a penalty equal to the average waiting time. The waiting time penalty represents the impatience of the EV owners to wait in the queue for an unnecessarily long period, which damages the charging station's credibility and decreases its long-term revenue [14].

V2G service

An electric vehicle (EV) is able to both recharge its battery and feed energy back into the grid is fitted with the right hardware and software. This feature is referred to as vehicle-to-grid (V2G) and is an important facilitator for supporting the continuous flow of electricity so that supply meets demand continuously, thus ensuring stability and safety in the electricity grid. [15]

The benefits of V2G service includes:

- Applying V2G service reduces the total ownership costs
- Energy market parties can optimize their balance
- Car manufacturers can sell value-added vehicles.
- Operators of the network will maximize investment and stabilize the grid

EVs have the ability to stabilize the grid by controlling the overall load on the grid with the development of smart grid technologies, either by increasing or decreasing the charging power as required. This simply means that to prevent a load peak on the grid, a customer (e.g. an EV) decreases its power demand for a limited period of time. Later, the EV will continue to recharge its battery when the total pressure on the grid is lower. This way, tiny variations of the charging power of each EV, together with millions of other grid-connected devices, help to mitigate the minor grid disruptions that are constantly occurring. V2G-enabled EVs have the potential to execute and control reactive power compensation. An active and reactive power balance is required for a reliable and stable grid operation. Reactive power affects the power quality, reduces system losses, increases the transmission of power and reduces the drops in grid voltage. [19].

Frequency regulation

Regulation of frequency is The Primary Frequency Regulation (PFR) is a service acquired by transmission system operators (TSOs) to ensure that generation and consumption are balanced.

Maintaining a balance between supply and demand, reducing peak load, and reducing losses is important. Due to their quick response time as well as low energy commitments, V2G-enabled EVs are a popular option to provide this service.

V2G is still an on-development technology with a major interest in implementing this technology in the future EV industry, sponsored by several V2G Technologies R&D activities.

Demonstrating that EVs are capable of providing power system services and that EV owners can earn additional revenue for the provision of services is a way of encouraging, first, the industry to manufacture V2G-compatible EVs; and, second, the use of more EVs because, in addition to generating additional revenue, they are a 'green' transportation choice that helps to achieve environmental goals.

The assessment of the attainable economic benefit for EV owners from participating in PFR markets is therefore critical. One of the most common ancillary services procured by TSOs responsible for grid stability is frequency control. The main goal of frequency control is to maintain a balance between consumption and generation of electricity in order to provide a high-quality power supply. The frequency increases in case of over-production, and down control is required. In comparison, the frequency decreases in the event of overconsumption, and up-regulation is needed. Thus, by containing and recovering the frequency to its nominal value, frequency control deals with frequency deviations. This service has commonly been provided by power plants and generator units. Other sources are currently being used to provide PFR, such as renewable energy units, energy storage systems (e.g. stationary batteries (BES) and EVs) (through pilot demonstrations for the case of EVs). EVs act as generation or consumption devices, charging or discharging their batteries according to the frequency signal, to engage in the frequency regulation industry [16], [17].

Reactive power control

Voltage regulation is crucial in an electrical power system for proper functioning of electrical power equipment, preventing damage such as overheating of generators and motors, reducing transmission losses, and preserving the system's ability to withstand and avoid voltage collapse.

Voltage control and reactive-power management are two facets of a single operation that support transmission network stability while also facilitating commercial transactions. Voltage is regulated in an alternating-current (AC) power system by controlling reactive power generation and absorption. There are three reasons why reactive power and voltage control is always needed.

- At first point, all customer and power-system equipment are configured to work within a voltage range, typically within 5% of the nominal voltage. Many types of equipment perform poorly at low voltages; induction motors can overheat and be disabled, and some electronic equipment won't work. High voltages can harm equipment and reduce its lifespan.

- Reactive power, on the other hand, uses up transmission and generation resources. Reactive-power flows must be minimized to optimize the amount of real power that can be transmitted through a congested transmission interface. Reactive-power generation, likewise, can restrict a generator's real-power capability.

- Third, real-power losses occur as reactive power is moved through the transmission system. To compensate for these losses, both capacity and energy must be provided.

The voltage must be maintained in order to transmit active power (watts) via transmission lines, so reactive power (VARS) is needed. To transform the flow of electrons into useful work, motor loads and other loads need reactive power.

When there is insufficient reactive power, the voltage decreases, rendering it difficult to push the power needed by loads through the lines.

Impact of BSS/EVs on grid

The effect of electric vehicles (EVs) as an emerging electrical load on the power grid has recently gotten a lot of attention. The potential challenge for power grids is that widespread adoption of electric vehicles (EVs) could result in extreme surges in demand during peak hours, endangering the stability and security of existing power grids The interconnection of EVs in the distribution grid necessitates a thorough examination of a number of issues, including the grid's impact, how EVs can charge/discharge, and the limits of this process, as well as the benefit or not of the Distribution System Operator (DSO) in such circumstances.

Furthermore, when the operation of a small distribution power system is focused on, for example, the economic optimization of its Distributed Energy Resources (DER), it is critical to understand where and how many EVs will connect, when it would be best to connect and under what rules they can charge/discharge, and which charging technology is the best.

Battery swapping stations are an essential source of energy for electric vehicles, and it is important to investigate a coordinated control strategy to effectively smooth load fluctuations in order to accept large-scale EVs. Taking into account the station's and power grid's bidirectional power flow, many control strategies have been developed to smooth the load profile. These methods can successfully reduce the peak valley difference, with a faster convergence rate and higher convergence accuracy. Energy exchange mode can supply energy for large scale EVs with a smoother load profile than one way charging mode, which is important for the swapping station.

As more large-scale EVs join the power grid, the power load will increase considerably. The charging behavior of electric vehicles is random and intermittent, and the grid effect of large-scale EVs will gradually appear as follows: The charging time of electric vehicles may be concentrated, resulting in a local load peak and dramatic fluctuations in power grid load. To effectively smooth the load profile, coordinated charging is required. Furthermore, it may be able to provide the grid with flexible services such as load shifting, balancing power, and frequency response.

The battery swap station (BSS) is an important charging infrastructure that can both charge and discharge batteries to the grid. When a BSS discharges to the grid, however, the grid's power distribution is irreversibly affected; in other words, the BSS affects the grid's fault features. Control strategies of charge and discharge machines in a BSS are provided to protect distribution system when battery swap stations discharging to the grid.

Daily battery swapping demand

The load demand of the BSS is stochastic due to the randomness of battery swapping and charging patterns. The charging load characteristics of BSS must be investigated in order to guide coordinated battery charging and mitigate the effect of disorderly charging behaviors on the distribution network. Four variables are critical in the uncontrolled swapping and charging scenario: 1) the number of EVs for battery swapping on an hourly basis; 2) the charging start time; 3) the distance traveled; and 4) the time it takes to charge. Taking these considerations into account, methods are presented to estimate the BSS's uncontrolled energy consumption. As a result, it is necessary to forecast EV charging loads and create a realistic charging model in order to minimize the negative impact on the power grid and make use of V2G energy storage benefits, which can reduce the variability and uncertainty of power output and improve power grid management.

4. Conclusion

In this work, a methodical and quantitative approach is used for identifying the KPIs in EV Battery swapping stations with the aim to help the experts of this sector to have a list of useable measures to optimize battery swap station's operation.

These results have been obtained by reading 214 related scientific articles in this field and categorized in two main groups, economic and social and corresponding technical, strategy and operational levels and the For future improvement, it is possible to consider a wide range of related articles for extracting KPIs or we can obtain relevant KPIs by analyzing the objectives of the stakeholders and policymakers in EV charging infrastructures and then map these objectives in KPIs. Particularly in complex systems like electric mobility, there are a large number of stakeholders with different interests and perspectives; therefore, it can be another starting point for identifying relevant KPIs.

In addition, since EV is a burgeoning market, car and battery manufacturers need to agree on a unified standard modular battery design. EV manufacturers currently have their own battery designs and despite extensive R&D budgets at the company level, policy measures at the standard level are lacking at the moment. EV industry now needs to create standards at consortium level on a priority basis. To this end, a single standard battery pack for two wheelers and tri-wheelers is needed that is sufficient for their daily needs. Multiple battery packs can then be used for cars, vans and buses as per their usage requirements.

Features like on-demand battery pack addition and battery swap through mobile delivery will also get a boost from such an endeavor while simultaneously overcoming consumer's range anxiety for long distance travel. Standard modular designs will also simplify the battery swap related hardware. With an add-on based battery pack design where each battery pack can simply be attached/detached from the vehicle shell will avoid the current complex battery swapping procedures.

Similarly, to encourage EV uptake and subsequent optimum utilization of BSS infrastructure, extensive studies on battery performance/degradation characteristics are needed based on local climatic conditions such as extreme heat (desert) and cold (subarctic) environments. Battery performance shows a major degradation under hotter climates and hence proper cooling mechanism for optimum battery storage is another overhead that needs to be taken into account when planning a BSS site in such environments.

Since current BSS design mostly rely on limited pilots projects and future forecasts, parallels can be drawn from the evolution of conventional fuel stations for conventional ICE based vehicles. To this end, ensuring proper social integration using ancillary services facilities (food marts, car wash) can improve service experience (‘invisible’ service time) as well as provide a solution towards the ‘chicken-and-egg' dilemma for BSS operators.

Similarly, clear guidelines and incentives across the board are required for efficient uptake of mutually beneficial services like V2G, Frequency control, Load management. For this, BSS operators, utility companies and governmental planning departments need to take concrete steps towards policy design at the municipal and national level.

In order to ensure a smooth roll out from a BSS operator perspective, initially focus should be on fleet based customers (taxi companies, bus companies, municipalities etc.) where the battery size, load demand and swap hardware can be easily optimized across a few standard vehicle types. A mixed need based charging strategy (fast/slow) is required as a work around the constraints like service time as well as to maintain a minimum level of QoS (fast charging for premium members lane).

BSS operators will have to optimize their business model around the other obvious choice of fast chargers (volume of customers served, cost of electricity, cost of chargers). With recent technological advancements, state of the art fast chargers still take between 20 to 30 minutes to fully charge a battery. Even if future technology ultimately makes fast charging a better option, BSS operators can still remain part of the battery energy mix of solution's as has been the case of ICE based vehicles in the last few decades.

In the end, to ensure profitability which remains the core goal for any business venture updated pricing model can be adopted where customers pay per mile like the traditional ICE based vehicles instead of paying for a fully charged battery. This kind of payment scenarios has recently shown itself to be a profitable business model as per the case of the nascent startup BSS Company Ample.

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