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Review of recent trends in charging infrastructure planning for electric vehicles

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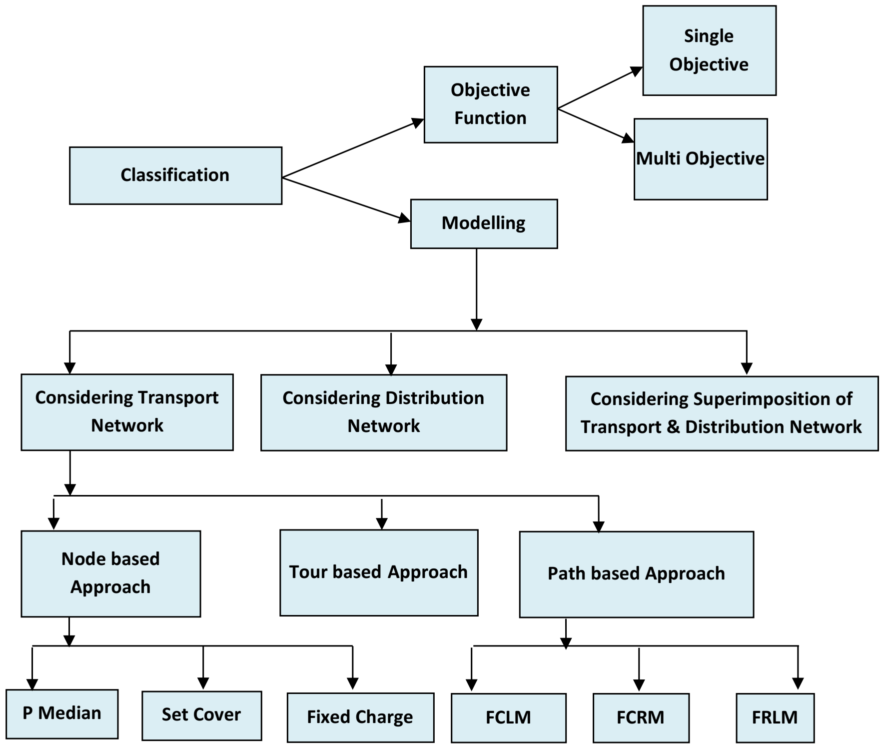
Abstract

The exhaustive nature of fossil fuels and environmental concerns associated with greenhouse gases are the major causes of the paradigm shift from conventional vehicles to Electric Vehicles (EVs). The electrification of the transportation sector and the increasing popularity of the EVs have driven scientists and researchers to delve into charging stations. Underdeveloped charging infrastructure, optimal placement of charging stations, charge scheduling in the charging stations are the major

concerns for the large-scale deployment of EVs. Even few questions related to EVs, such as the vehicle price and driving range, can be partially solved with a well-developed charging infrastructure. Existing old infrastructure may bring severe limitations in the realisation of the optimal placement of charging stations as EVs have not existed when the road and grid infrastructure have been developed. For the past few years, the studies associated with the optimal placement and sizing of EV charging stations have drawn the consideration of the researchers. The researchers have used different approaches, objective functions and applied different optimization algorithms while dealing with the problem of charging station placement. The complex and dynamic nature of the problem has led researchers to apply different optimization algorithms for the solution of the problem. In this particular review study, the research works bearing on the charging infrastructure planning for the EVs are considered. Thus, this review work will endow the research community with the latest developments and research findings in the paradigm of charging infrastructure planning for EVs.

Schematic Overview of classification of charging infrastructure planning problem



Introduction

The ever-escalating energy demand, the exhaustive nature of fossil fuels, CO_2 emissions are the major threats of the 21st century. Moreover, it has been predicted that the oil consumption of the transport sector will rise to 54% by 2035.[i] Further, it is reported that in the year 2015, CO_2 emission from road transport increased mainly because of 4.1% increase in diesel consumption.[i] Studies indicate that the transportation sector is one of the major agents of CO_2 emission.[93, 94, 16] As a measure to reduce the greenhouse gas contributions of the transportation sector, the 21st century has witnessed the replacement of conventional Internal Combustion Engine (ICE) driven vehicles with Electric Vehicles (EVs). EVs have potential to reduce CO_2 contributions of the transportation sector in case the majority of the electric power used in EVs originate from the renewable sources or nuclear power plants. This has motivated many countries to promote the use of EVs for public and private transportation. Low noise, minimal maintenance, and lower operating cost are some of the additional benefits achieved by the use of EVs.[87, 45, 36] The drivetrain of EVs is equipped with the provision to use any renewable energy source for transport whereas conventional engines need liquid or gaseous fuels.[ii] The replacement of conventional vehicles by EVs will reduce the heat emission by a considerable amount aiding to tackle the serious concern of global warming. [iii]

The beginning of the 21st century is characterized by the growth of EVs; however, there are still many factors inhibiting the large-scale use of EVs. Limitations in battery technology, inadequate charging infrastructure, lack of public charging stations, improper placement of charging stations, uncoordinated charging in the charging stations are some of the key factors inhibiting the growth of EVs .[65, 84] It is suggested that a well-planned and incentivized exploitation of charging stations would lead to an improved living environment, along with an increased adoption of the EVs.[iv] Establishment of charging stations mean an increase in the load demand of the utility grid, which accounts for increased peak demand and decreased reserve margin. Improper placement of charging stations in the distribution network may result in voltage fluctuations, power loss, and power quality related problems.[1, 46, v, vi, vii] Also, the location of charging station must be optimized considering the route choice behaviour of EV drivers and charging demand of the EVs computed based on the driving range of the EV.[38] The road and grid infrastructure have existed for decades before the EV boom. The challenge in the charging station placement is to take into account and merge the strong points of the power grid with the significant hubs of the transport network. This area has witnessed extensive research activity in the past few years. The different aspects and issues related to charging infrastructures like charging standards, topologies of fast charging stations and optimization techniques for charging station placement have been reviewed in many research works.[13, 27, 26, 79, 2, 12, 49, 76] However, the aforementioned literature lack intensive analysis of charging infrastructure planning and do not analyze the different modelling approaches, decision variables, objective functions and constraints associated with the serious problem of charging infrastructure planning in quantitative as well as qualitative way. In this paper, we aim to review the recent trends in charging infrastructure planning of EVs from its origin until early 2016. In addition to collecting the existing literature together; we briefly discuss various modelling approaches and objective functions used in the relevant literature.

The main content of the paper is to give a review of different approaches adopted by researchers for the optimal placement of charging stations and the solution techniques utilized for finding the optimal solution. The major contributions are summarized as follows-

1. This work presents the scenario of charging infrastructure development across selected countries,. An overview and importance of home charging is also presented in the work.
2. This paper also provides a deep insight of the complex and dynamic nature of the optimal placement of charging station problem, thereby considering the demand, logistics, and supply aspects related to the problem.
3. An overview and comparative analysis of different modelling approaches of charging station placement problem adopted by researchers is provided.
4. The different objective functions and constraints of the charging station placement problem are also discussed along with a brief understanding of the optimization algorithms adopted for the solution of this placement problem.

The paper starts with an attempt to provide scenario of the charging infrastructure planning across selected countries, importance of home charging and then presents a general overview and brief classification of the problem. The modelling approaches and the objective functions presented in different charging system studies are discussed in the work. Finally, the work concludes by identifying the future direction of work possible in this paradigm.

SCENARIO OF CHARGING INFRASTRUCTURE PLANNING IN SELECTED COUNTRIES

Sustainable development of charging infrastructure concerns researchers across the World. Globally, a number of research projects like 'Electric Vehicles in a Distributed and Integrated Market using Sustainable Energy and Open Networks (EDISON)' [xxi],' Electric Vehicle Charging Station Implementation Plans for the Upstate New York I-90 Corridors' [xxii], The Green e Motion Project'[xxiii] analyzed different aspects of charging infrastructure planning . There is diversity in road and grid structure, economic and social conditions of different countries. Therefore, miscellaneous strategies for charging infrastructure planning are adopted by different countries. In this context, the scenario of charging infrastructure planning in eight countries of the three major continents Asia, Europe, and North America is reported in the present work. The status of charging infrastructure planning is reported for Asian countries like China, Japan which are the leading Asian countries in transportation electrification as well as for a country like India where the EV market is not yet fully developed. The scenario of charging infrastructure planning is reported for European countries like Norway, Denmark, and UK as well as North American countries like USA and Canada. Thus, an attempt has been made in the present work to present the global scenario of charging infrastructure planning by accumulating samples of charging infrastructure planning from developing and developed countries, car manufacturing countries, car importing country, countries with high and scarce population density. Table 1 represents the Plugged In Electric Vehicle (PEV) stock and Plugged In Electric Vehicle (PEV) market share of total new car sales in the eight selected countries. Figure 1 illustrates the status of the charging infrastructure development in the eight aforementioned nations.

Table 1| Light-duty EV stock and PEV market share of total new car sales in the eight selected countries as of December 2015 [xxv, xx]

Country	PEV stock			PEV market share			Sales since
	2015	2014	2013	2015	2014	2013	
China	258,328	83,198	28,619	0.84%	0.23%	0.08%	2008
Japan	126,420	108,248	74124	-------	1.06%	0.85%	2009
Norway	84,401	43,442	20486	22.39%	13.84%	5.60%	2003
Denmark	8100	---------	--------	---------	0.88%	0.29%	--------
UK	53,524	24,500	9982	1.1%	0.59%	0.16%	2003
USA	410,000	291,332	172,000	0.66%	0.72%	0.62%	2008
India	6020	4020	3130	0%	0%	0.1%	--------
Canada	17,058	10,658	5,596	0.35%	0.27%	0.18%	2011

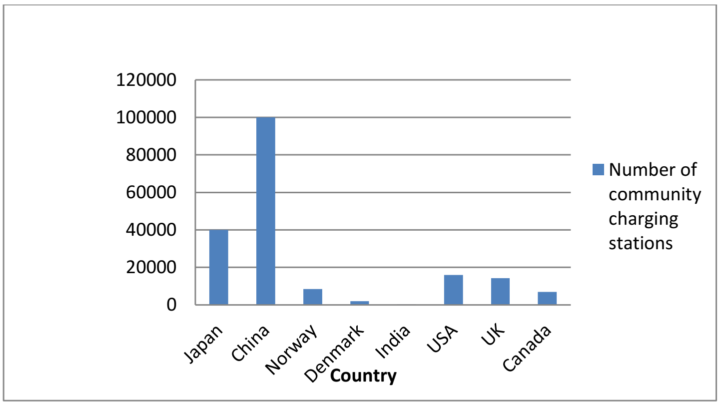


FIGURE 1 |Status of charging infrastructure development in five countries till 2016 (Ref ix-xiii, xix)

Japan

Japan is not only having a good EV market but is also continuously investing a considerable amount of money for the establishment of charging stations. Table 1 reports that PEV market share of total new car sales in Japan in the year 2014 was 1.06% which was even more than China.

The major milestones in the history of charging infrastructure development in Japan are-[xiv]

1. In the year 2009, eight cities were selected as EV town for the development of EV charging infrastructure.

2. Due to the increasing penetration of EVs in the market, the charging demand increased even more. In the year 2010, ten more cities were selected as EV town for the development of EV charging infrastructure.

3. In the year 2011-2012, priority was given on the identification of major issues related to the development of charging infrastructure and billing model for charging service.

4. In the year 2013 emphasis was laid on finding solutions for the issues related to the charging station development identified in the year 2011-2012.

The locations where charging stations are mostly placed in Japan are industries having enough space, gas stations, and retailer stores. [xiv] Four gas station companies ENEOS, Idemitsu, COSMO, and Shell are investing in charging station development in Japan. [xiv] Apart from them some parking service providers like Japan Parking, Parking Laboratory, Le Perc are also investing for charging station development in Japan. [xiv]

Despite having a considerable number of charging stations in Japan, there are still some barriers towards the development of sustainable charging infrastructure in Japan. Some of the major hindrances towards establishment of charging infrastructure in Japan are listed below-[xiv]

1. Permission for the establishment of charging station.

2. Inadequate space for the establishment of charging station.

3. Inexistence of a proper billing model resulting in customer dissatisfaction.

4. Stress on the power grid.

5. Information Security.

China

The charging infrastructure development in China has experienced many barriers because of political conflict between government agencies and property management companies.[102] Despite such barriers the status of charging infrastructure development in China is praiseworthy as depicted in Figure 1. Table 1 clearly indicates that the EV market in China is also developing with a PEV market share of total new car sales of 0.84% in the year 2015.The major milestones in the history of charging infrastructure development in China are-[102]

1. A demonstration program named 'Ten Cities & Thousand Units' was launched by the Chinese government in the year 2008. In most of the participating cities, charging station was established before 2011. Later, in 2012 the number of participating cities was extended to twenty-five.

2. On May 15, 2014, the Beijing Municipal Commission of Development and Reform, Beijing Municipal Science & Technology Commission, and Beijing Municipal Commission of Economy and Information Technology collectively issued a set of administrative rules of the construction of Charging Facility for EVs in Beijing named as the 'Charging Administrative Rule'.

4. Further, on July 1, 2014, keeping in mind the difficulty of charging piles within community districts, the Beijing Municipal Commission of Housing and Urban-Rural Development and Beijing Municipal Commission of Development and Reform issued notification of promoting the construction of Charging Facility in residential areas for New Energy Vehicles. The notification was named as the 'Charging Facility Notification'.

Some of the major hindrance towards establishment of charging infrastructure in China are summarized below- [102]

1. Erection of charging piles in the residential areas was opposed by property management companies because of security reasons. The main reason for this opposition was the fire security associated with charging EVs in the residential areas.

2. It is pointed out by Hao Huang, minister of Shanghai Fire Research Institute that the existing fire codes and fire prevention regulations for the construction of electric vehicle charging infrastructure are inadequate and must be revised.

3. Kaiming Ni, President and CEO of Volkswagen China, also remarked that the construction of EV charging infrastructure in parking lots is unsafe.

4. Students and parents of Meiyuan Primary School in Shenzhen boycotted a charging station because of safety issues.
5. Majority of the residents in first-tier cities in China reside in buildings without garage. Thus, charging stations can only be installed in parking lots. And many older blocks have no fixed parking lots. As a result of this an additional cost will be incurred for the construction of the parking lots.

India

The transition from ICE driven vehicles to EVs is still in its nascent stage in India. EVs made up only 0.1% of the total number of vehicles sold in India. [xxiv, xxv] The current market of EVs in India is bleak. However, there are Electric Rickshaws in many small towns and villages in India. These Electric Rickshaws are meant for smaller commute and are generally charged at home. Despite having a bleak EV market many companies are planning to invest in charging station development because of the following reasons-

1. India unveiled the ambitious 'National Electric Mobility Mission Plan (NEMMP) 2020' in 2013 to address the issues of National energy security, vehicular pollution, and growth of domestic manufacturing capabilities. Reiterating its commitment to the Paris Agreement, the Government of India has plans to make a major shift to electric vehicles by 2030.
2. Lack of charging infrastructure is one of the barriers which hinder Indian public from buying EVs. Thus, development of sustainable charging infrastructure is essential to boost the EV market in India.

Thus, the charging infrastructure development is about to begin in India. The major milestones in the history of charging infrastructure development in India are-[xvii]

1. Government has planned to set up 206 community charging stations.
2. Allocation of 20 crore rupees (2.7 million Euros) for establishment of charging station in the year 2016-2017.
3. NTPC is looking at setting up of charging stations at a subsidized rate of 1 lakh rupees (1300 Euros).
4. TATA Power Delhi is planning to invest 100 crore rupees (13 million Euros) for establishment of 1000 charging stations across Delhi.
5. SUN mobility, Hero Future Energies plans to introduce battery-swapping stations having facility of solar-based charging for depleted batteries.
6. Ola has invested 50 crore rupees (6.7 million Euros) for EV and charging infrastructure in Nagpur.

Although there are several initiatives for development of charging infrastructure in India in the recent years, however, the journey of development of sustainable charging infrastructure is not barrier-free. Some of the major hindrances are listed below-

1. No market for EVs.
2. Less government initiatives compared to other developed countries.

3. Complex structure of the power grid.

Norway

The history of EV deployment in Norway is successful and praiseworthy. Table 1 report that PEV market share of total new car sales in Norway in the year 2015 was 22.39%. The development of different types of charging infrastructure in Norway from 2011 to 2016 is depicted in Figure 2. Tesla Superchargers are the latest and most advanced charging technology having the capability of charging 20 times faster than most common charging stations. [xv] In Norway, Tesla Superchargers are located at roadside restaurants, shopping centers, cafes, etc. The customers generally stop at these locations for either eating or shopping and the EVs are charged during that time, thereby saving additional time of charging. The Combined Charging System (CCS) as well as Chademo also provides fast charging service, however the performance of these chargers are slow in comparison to Tesla Superchargers.

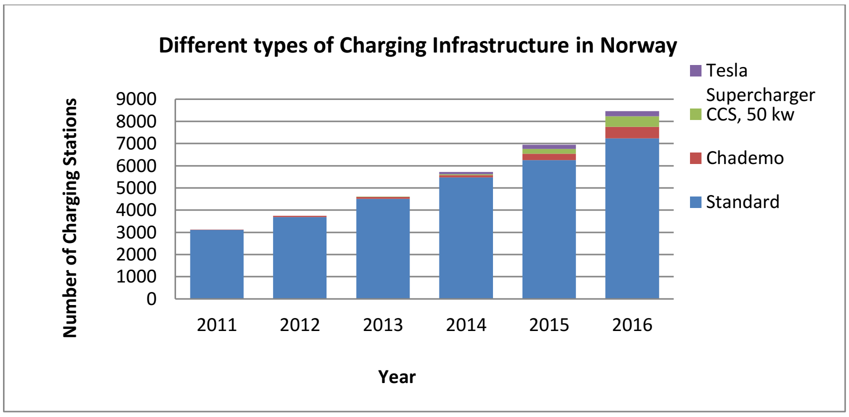


FIGURE 2 | Different types of charging infrastructure in Norway from 2011 to 2016 (Ref xv)

Despite such a praiseworthy development of charging infrastructure in Norway, there are still some issues hindering the development of charging infrastructure in Norway. These issues are listed below- [79]

1. Existence of legal barriers due to protest from conventional fossil fuels companies.

2. Inadequate pricing model for charging service.

Denmark

Denmark attempted to compete with Norway in the field of charging station establishment. [xxiv, xxv] The total number of community charging stations in Denmark is only 2030. Thus, its progress is bleak as compared to Norway. Denmark is one of the pioneering nations to promote battery-swapping stations. In the year 2009, Better Place partnered with Denmark's leading energy company; Dong Energy to promote EV sale and to develop sustainable EV charging infrastructure. The country generates 20% of its electric power from wind energy. Better Place and Dong made an attempt to take advantage of the existing power grid and electric vehicle batteries to harness and store the abundance of wind-generated power and distribute it appropriately for transportation electrification. [xvi] Despite having a solid business model, Better Place failed and became bankrupt in the year 2013. This unexpected failure of Better Place is still a mystery. A company named E.ON acquired 770 stations strong charging network from Better Place after it went bankrupt in 2013. [xvi] The major hindrances towards the establishment of charging infrastructure in Denmark are - [xvi]

1. Failure of Better Place.
2. Lack of government incentives.
3. Lack of social awareness.

UK

The UK is one of the leading nations in the field of transportation electrification and the government of the UK also operates a number of programs to develop sustainable charging infrastructure. Table 1 report that PEV market share of total new car sales in the UK in the year 2015 was as high as 1.1%. The major milestones in the history of charging infrastructure development in the UK are-[xxvi]

1. Highways England has planned to set up charging infrastructure every 20 miles along the major road network. They believe that this plan will reduce the driving range anxiety associated with EVs.
2. The electricity provider Ecotricity has already installed at least one fast charger in each of the United Kingdom's Motorway Service Areas.
3. The Go Ultra Low Cities scheme of the UK government is expected to fund 750 charging stations.
4. The Transport for London and various private-sector partners in London has created the Source London network. The association plans to set up 4,500 charge points by 2018.

   Despite having a good charging infrastructure in the UK, the people of the UK still feel there is requirement of additional charge points to reduce driving range anxiety associated with EVs.[xxvii] Based on a survey the probable locations for establishment of more charge points are predicted as supermarkets, shopping malls, car parking, airports, petrol filling stations, restaurants, train, and tube stations.

USA

The secret of continually rising EV usage in the USA is the presence of a praiseworthy charging infrastructure in USA. The government of the USA is also actively involved in the development of charging infrastructure across the country. The major milestones in the history of charging infrastructure development in the USA are-[xxvi]

1. Much of the initial investment in charging infrastructure in the United States came from the American Recovery and Reinvestment Act of 2009. To serve the early growth of EVs from 2010 to 2013 federal funding was provided through the EV Project and the U.S. Department of Transportation's Transportation Investment Generating Economic Recovery program.
2. One of the milestones in the history of charging infrastructure development in the USA consists of electric power utilities providing mutual benefits to all ratepayers through their investments in charging stations development.
3. Volkswagen will invest approximately $2 billion in charging infrastructure development to support clean transportation across the USA for a 10-year period commencing in 2017 as a part of the settlement of the Volkswagen diesel scandal.
4. The settlement scheme of Volkswagen also establishes an Environmental Mitigation Trust. The Trust allocates funds to the states and allows them to use up to 15% of their allocation for EV charging infrastructure development.

   Despite such a praiseworthy development of charging infrastructure in the USA, there are still some issues hindering the development of charging infrastructure in the USA. These issues are listed below. [xxviii]

   1. Non uniform and inadequate pricing model for the charging service
   2. In some cases, the utilities find it difficult to convince the regulators regarding the profitability of investment in charging infrastructure development. The regulators do not understand the complex cost-benefit analysis associated with charging infrastructure planning.

Canada

The Canadian government has taken a lot of initiatives for the development of sustainable charging infrastructure. The major milestones in the history of charging infrastructure development in Canada are[xxvi]

1. The government is working to write a national zero-emission vehicle strategy and has already committed $182.5 million for electric vehicle charging infrastructure through 2017.
2. The Electric Circuit network, operated by public utility Hydro Québec, includes almost 1,000 stations as of July 2017.

The government also provides support for charging at private homes, workplaces, and multi-unit dwellings, and is working with neighboring U.S. states to create cross-border fast charging corridors.

Investors in Charging Infrastructure Planning

There are many small and big companies providing charging service across the World. A list of major charging service providers are reported in Table 2.

Table 2| Charging Service Providers[xviii]

Country	Provider	Region	Number of chargers	Status
China	North China Grid	Beijing Outskirts	100	Functional from 2010
	State Grid Corporation	Zhejiang	7200	Under construction in 2011
Japan	Better Place and Nisan	Throughout Japan	--------	---------
UK	Elektromotive	Throughout England especially in North East England, Scotland	807	---------
	Zero Carbon World	Throughout England	166	Functional from 2010
	Siemens	London	1300	Functional from 2011
	Ecotricity	Throughout England	397	Functional from 2011
USA	Tesla	California	15	Functional from 2010
	Portland G. Electric	Portland	20	Functional from 2008
	SemaConnect	California, Seattle, Texas, Florida, Georgia, Hawaii		Functional from 2010
	Charge Point	California, Washington State, Boston, New York, Florida, San Antonio	1753	Functional from 2011
	EATON	South Carolina	100	Functional from 2010
	EV Project	San Diego, Seattle, Houston, Tennessee	1210	Functional from 2012
	JNS Power	Chicago	350	Functional from 2011
	Better Place	Hawaii	140/200	Functional from 2011

Country	Provider	Region	Number of chargers	Status
Canada	Sun Country Highway	Throughout Canada	1000	Functional from 2012
	The Electric Circuit	Quebec	253	Functional from 2012
	BC Hydro	British Columbia	30	Functional from 2011
	City of Vancouver	Vancouver	78	Functional from 2011
Denmark	Clever	Throughout Denmark	More than 500	Functional from 2012
	E.on	Throughout Denmark	700	Functional from 2012
	Better Place	Copenhagen	700	Functional from 2012
Norway	Move About	Oslo	More than 50	Planned in 2013
India	Ola	Nagpur	-------	Functional from 2017
	TATA Power	Delhi	-------	Planned in 2017

Home Charging

The present work mainly centers on the public charging infrastructure. However, the role of home charging cannot be neglected for public acceptance of EVs. The early adopters of EVs mostly carried out the charging activities at their homes.[xxvi] Home charging is considered to be an easily accessible option for the EV drivers as the drivers don't have to search for public charging stations and wait there for the charging activity to be completed. In general most of the EVs come with Level 1 or Level 2 charging equipment.[xxvi] However, procuring and installing more advanced Level 2 charging equipment with higher charging power and additional features like internet connectivity or timers add additional costs for the EV drivers. [xxvi] After carefully reviewing the existing literature related to home charging the challenges of home charging , the emerging best practices across the World to promote home charging, challenges of home charging and their possible solutions are highlighted in this section.

Home charging is a popular option among the EV drivers residing in single-family houses, row houses or other smaller building types having access to parking and charging facilities on their own land. For example, in Norway 94-95% of BEV and PHEV owners, charge their vehicles at home in their garage, carport or parking space. [xxxi] Also polls have shown that more than half of homeowners in the USA have access to home charging.[xxx] Even Utilities in some parts of the United States also offer incentives, up to several hundred dollars, for development of home charging stations.[xxvi] Likewise, the United Kingdom's Office for Low Emission Vehicles also pays up to 75% of the hardware and installation costs (up to £500) for Level 2 home charging station. [xxvi] In European countries the provision of EV charging is now included in the building regulations. Under a draft EU directive expected to come into effect by 2019, every new or refurbished house in Europe will need to be equipped with an electric vehicle recharging point.[xxix] In many European and North American countries governments work with residents and property owners to install charging infrastructure in shared parking facilities and promote home charging in multi-unit dwellings like flats. Thus, it is observed that in European and North American countries government has taken necessary initiatives to promote home charging. [xxvi] The energy company E.ON has just launched in 2018 a new pilot project in Denmark to try to utilize home chargers installed around the country at EV owners' homes. On the other hand the status of home charging is not fully developed in Asian countries. Home charging is a common practice among the EV drivers residing in their own houses even in the Asian countries. For example, the Electric rickshaws in the towns and rural areas of India are charged at home. However, if the EV owners live in a building block or larger condominium it is substantially more difficult to arrange electricity and car together. In China there is a lot of controversy regarding home charging. A section of people in China do not promote home charging because of safety issues.[102] Moreover, there is lack of government incentives in the Asian countries to promote home charging unlike the European and North American countries.

Some of the challenges of home charging and their possible solutions are listed in Table 3.

Table 3| Challenges of home charging and their solutions

Challenge	Solution
Cost	Introduction of government incentives to promote home charging Earning revenue by V2G scheme
Lack of dedicated home charging point in multi-unit dwellings	Collaboration of government with property owners to establish dedicated home charging point in multi-unit dwellings
Safety issues	Retrofitting existing wiring
No Power for charging	Use of locally available renewable resources like solar energy to charge EVs
Transformer Loss of life	Co-ordinated charging
Damaged charging point	Co-ordinated charging

GENERAL OVERVIEW OF CHARGING INFRASTRUCTURE PLANNING PROBLEM

Charging station placement problem is concerned with finding the optimal location of the charging stations in the transport network in such a way that the operating parameters of the distribution network are least affected. A generalized mathematical formulation of the problem is given by (1) to (4).

$$Min(Z) = f(p, u_{fast}, u_{slow}) \tag{1}$$

where Z is the objective function, p, u_{fast}, u_{slow} are the decision variable vectors. p represents the locations of charging stations. p can be the nodes of distribution/ transport /superimposed transport and distribution network depending upon the modelling approach explained in the next section. u_{fast} and u_{slow} represent the number of fast and slow charging stations placed at p respectively. Z can include the cost, EV flow, distance, power loss, voltage deviation, net benefit etc. When the placement problem is modelled considering only transport network, Z can be cost, EV flow or distance. When the placement problem is modelled considering only distribution network, Z can be cost, power loss, net benefit or voltage deviation. If the placement problem is modelled considering superimposition of transport and distribution network then all the aforementioned objective functions can be considered together.

Subject to

$$u_{fast}^{\min} \le u_{fast} \le u_{fast}^{\max} \;\; and \;\; u_{slow}^{\min} \le u_{slow} \le u_{slow}^{\max} \tag{2}$$

$$g_j(p, u_{fast}, u_{slow}) = 0 \tag{3}$$

j=1, 2...........m

$$h_k(p, u_{fast}, u_{slow}) \le 0 \tag{4}$$

k=1, 2..............p

Constraint given by (2) includes the upper and lower limit of charging stations to be placed. In equation (2) $u_{fast}^{\min}$ and $u_{fast}^{\max}$ represent the maximum and minimum number of fast charging stations that can be placed at position *p* respectively. Similarly, $u_{slow}^{\min}$ and $u_{slow}^{\max}$ represent the maximum and minimum number of slow charging stations that can be placed at position *p* respectively. Equality constraint given by (3) can include power balance equation, charging demand balance etc. When the placement problem is modelled considering only transport network, then the equality constraint can include charging demand balance. When the placement problem is modelled considering only distribution network, then power balance equation can be considered as an equality constraint. And when the problem is modelled considering superimposition of transport and distribution network, then both charging demand balance and power balance equation can be considered as equality constraint. Inequality constraint given by (4) can include voltage limit, current limit, budget limit etc if the problem is modelled considering only distribution network. When the problem is modelled considering only transport network then inequality constraint can be the budget limit. If superimposition of transport and distribution network is considered while modelling the problem then all the aforementioned inequality constraints can be considered together.

The optimal placement of charging station is a multi-dimensional, complex problem involving the interaction of both distribution and transportation network. Researchers have adopted different strategies to deal with this problem. Even many research organizations like ebusplan [viii] are engaged in developing software for this planning problem. The classification of charging infrastructure planning problem is illustrated in Figure 3.

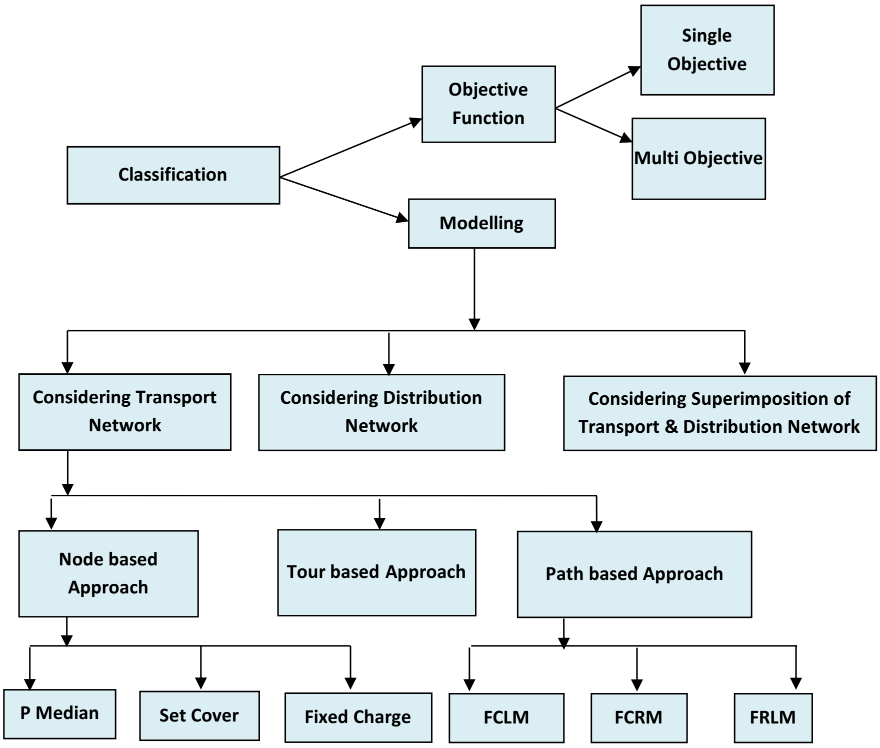


FIGURE 3|Schematic Overview of Classification of Charging Infrastructure Planning Problem

The different classification of charging infrastructure planning problem is exemplified in the next section.

MODELLING OF CHARGING INFRASTRUCTURE PLANNING PROBLEM

The research works investigating and dealing with the charging infrastructure planning problem can be broadly classified into three categories based on modelling approach as illustrated in Figure 3.The three subdivisions are as follows-

1. Optimal placement of charging station considering only transportation network
2. Optimal placement of charging station considering only distribution network
3. Optimal placement of charging station considering superposition of transport and distribution network

The modelling approach considering only transport network is further sub-divided into node, tour and path based approach as explained in the diagram. The third approach (Considering superimposition of transport and distribution network) actually considers both transport and distribution network. Thus, we can say that the modelling approach 1 and 2 can be considered at the same time (modelling approach 3 is actually a combination of modelling approach 1 and 2). However, considering the three approaches at the same time may not be feasible and is not noticed in the existing research works. The detailed elaboration of these three modelling approaches is presented in the following sub-section.

Optimal Placement of Charging Station Considering only Transport Network

A considerable number of research works, consider only the transportation network while determining the candidate locations of re-fueling or charging stations of alternate vehicles. In this modelling approach, the main concern is the optimal placement of charging stations in the road network. A framework of this modelling approach is illustrated in Figure 4. The objective functions and constraints present in Figure 4 are elaborated later in the preceding section.

1. The optimal location of charging station in the transportation network depends on the spatial units to be served and is further subdivided into three units. These units are nodes, paths, or arcs (used as synonym of round trip or tour). Based on the spatial units to be served this approach is subdivided into the following categories-1. Node based Approach 2. Path based Approach 3. Tour based Approach. Though the main aim of all the aforementioned approaches is same, the modelling of the placement problem is different in all the approaches.

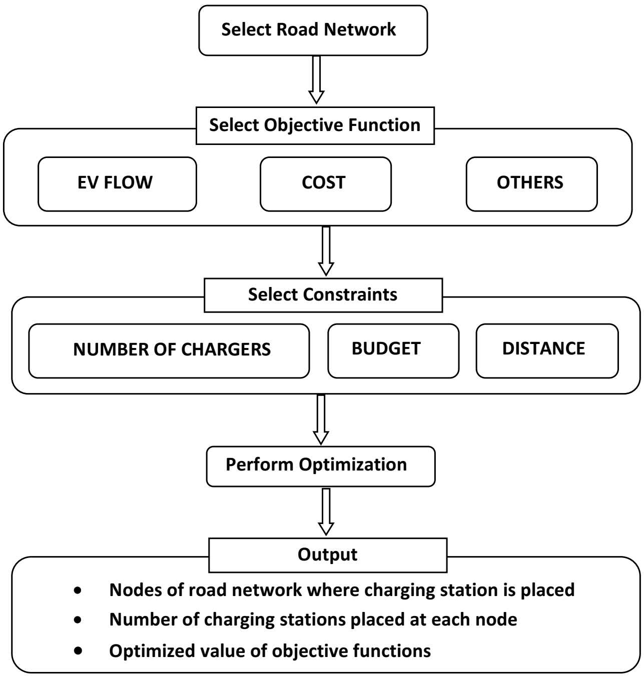


FIGURE 4| Framework for Charging Infrastructure Planning Model Considering only Transport Network

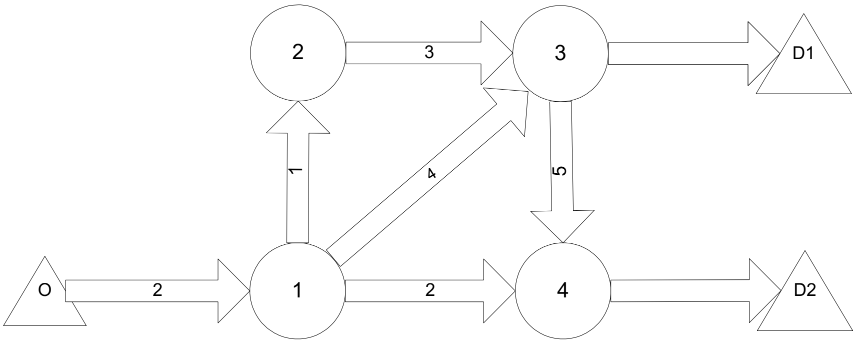


FIGURE 5| Ideal transportation network

Figure 5 represents an ideal transportation network. The circles represent nodes and the arrowheads represent paths. O represents the origin or start point of the journey, D1 and D2 represent destination. The journey from origin to destination by any one route or path is a tour.

Node based Approach

Nodes are considered as the most commonly covered spatial units in the transportation network. In the transportation network, nodes are defined as the point of intersection of the geographic zones as shown in Figure 5. [99] In Node based approach the placement problem is modeled as a simple facility location problem in which facilities need to be allocated at the nodes to fulfill the demand at the nodes. Thus, we can say that the charging station placement problem considering Node based approach has similar structure to that of police station location problem or hydrogen station location problem.

The p median model developed by Hakimi [37] in 1964 is one of the most appealing nodal based methods adopted by researchers. The P median model is a graph-theoretic approach of location allocation problem that locates *p* facilities and allocates demand nodes *i* to facilities *j* to minimize the total distance travelled by consumers to facilities. In Ref 37 the approach was used for optimal location of police stations in highways. Latter, P median based approach is adopted by many researchers for modelling of the hydrogen station placement problem.[68, 69, 62] Futher, a group of researchers utilized the P median model for optimal allocation of charging stations. [28] The results of Ref 28 established the efficacy of P median model in solving charging station placement problem.

Other node based approaches include the set cover model developed by Toregas [88] in 1970. The Location Set Covering Problem involves finding the lowest number of facilities and their locations in such a way that each and every demand is covered by at least one facility. The set cover based approach is used by many researchers for determining the optimal location of recharging or refuelling stations in the transportation network. [95, 35] Wang et al. [95] proposed a hybrid model based on the Set Covering approach with a multi-objective function of cost minimization as well as maximum population coverage. Gopalkrishnan et al. [35] selected an optimal subset from a given set of candidate location of charging stations, illustrating the efficacy of the set cover model in finding the optimal locations of the charging stations.

Another node based approach attracting the interest of the researchers is the fixed charge model developed by Belinski [10] in 1965.The fixed charge based modelling involves nonlinear modelling of the network and gives upper and lower bound of the optimal value of the objective function. The fixed charge based approach is utilized for finding the optimal location of charging station in the transportation network by a number of modern researchers. [8, 9]

One of the advantages of the node based method is the minimal data requirement. It requires only road network data and the population data. Random type of commuting is ignored in the node based approaches. In most of the node based approaches assumption is made that the users make the only single trip from home or workplace to the utility. As a result the node based approach suffers from the inherent shortcoming of incapability of representation of more complex trip patterns.

Path based Approach

Path based approaches are typically flow capturing models aiming at the maximization the passing vehicle flows by allocating one or more unit along the path. Path based approaches are concerned with maximizing the vehicle flows along the paths and not the aggregated nodal vehicle flow. Flow Capturing Location Model (FCLM) introduced by Hodgson [42] in 1990 and Flow Capturing Refuelling Model (FCRM) introduced by Kuby and Lim [55] in 2005 are path based approaches adopted by modern researchers for optimal placement of charging station problem. FCLM has its origin in Maximal Covering Location Model (MCLM). [20] However, FCLM takes cannibalization into account which makes it superior to MCLM.FCLM takes into account variety of trips of the user from the workplace or home to other destinations like shopping malls. FCLM is based on capturing the traffic flow and requires the record of detailed origin destination flow data, unlike the nodal based approaches. Flow capturing approach is utilized to find the optimal location of charging stations in the transportation network in. [101, 22, 58] Wu et al. [101] used a stochastic flow capturing based approach taking into account the uncertainty in the EV flows. Zambrano et al. [22] applied an advanced FCLM model for optimal location of charging station in the city of Barcelona with the aim of maximizing profitability and public service. Lin et al. [58] utilized FCLM model to intercept the largest charging demand.

Flow Refuelling Location Model (FRLM) introduced by Kuby and Lim [55] in 2005 mimics FCLM with the additional assumption that a single facility may not be able to capture the entire vehicle flow. FRLM just like its predecessor FCLM is based on the demand arising due to vehicle flow along paths and not the aggregated nodal vehicle flow. The FRLM is a path-based demand model determining p stations to maximize the number of trips on their shortest paths. Upchurch et al. [98] discussed the superiority of FRLM over p median based nodal approach for optimal location of alternative fuel vehicle charging station problem. Tran et al. [89] reviewed the literature related to optimal placement of recharging stations considering flow based approaches. Further, in 2012 Kim and Kuby introduced a novel approach named FRLM with deviation taking into account the deviation from the shortest path on the way to refuel or recharge.[54] FRLM based approach is utilized for determination of the optimal location of charging station in the transportation network in many research works.[3, 108, 18,107]

Tour based Approach

The tour based approach is a realistic approach of representation of the charging station placement problem as it has the capability to represent real time situations like round trip and random trip. The tour based approach requires a significant amount of travel data, travel route, and driving behaviour of the EV users. The tour based approach gives a realistic flavour and a much strategic representation of the problem. Andrews et al.[4] proposed a scheme for finding the optimal location of charging stations based on tour data of the vehicles. Gonzaleb et al. [34] modelled the daily spatial and temporal behaviour of EVs by considering the daily tour data of the vehicles.

Table 4|Review and classification of research works related to optimal placement of charging stations considering only transportation network

Author	Year	Diligence	Modelling
Wang et al.[95]	2010	Locating passenger vehicle refuelling stations	Set Covering based nodal approach
Ge et al. [29]	2011	The Planning of Electric Vehicle Charging Station Based on Grid Partition Method	Nodal based approach
JIA et al. [51]	2012	Optimal Siting and Sizing of Electric Vehicle Charging Stations	Tour based Approach
Kim et al. [54]	2012	The Deviation Flow Refuelling Location Model for Optimizing a Network of Refuelling Stations	FRLM with deviation
Andrews et al. [4]	2012	Modelling and Optimization for Electric Vehicle Charging Infrastructure	Tour based approach
Zambrano et al. [22]	2013	Optimal location of fast charging stations in Barcelona: A Flow-Capturing approach	FCLM based approach
Author	Year	Diligence	Modelling

Miyagaya et al. [62]	2013	Distribution of Deviation Distance to Alternative Fuel Stations	P median based nodal approach
Wang et al. [96]	2013	Locating multiple types of recharging stations for battery-powered electric vehicle transport	Set covering and MCLP based approach
Cai et al. [17]	2014	Siting public electric vehicle charging stations in Beijing using big-data informed travel patterns of the taxi fleet	Tour based Approach
Gonzaleb et al. [34]	2014	Determining electric vehicle charging point locations considering drivers' daily activities	Tour based approach
Gavranovic et al. [28]	2014	Optimizing the electric charge station network of EŞARJ	P median based approach
Gimenez et al. [31]	2014	Optimal location of battery electric vehicle charging stations in urban areas: A new approach	MCLM based approach
Baouche et al. [8]	2014	Electric Vehicle Charging Stations Allocation Model	Fixed charge model
Baouche et al. [9]	2014	Efficient Allocation of Electric Vehicles Charging Stations: Optimization Model and Application to a Dense Urban Network	Fixed charge model
You et al. [107]	2014	A hybrid heuristic approach to the problem of the location of vehicle charging stations	FRLM based approach
Lu et al. [60]	2015	A location-sizing model for electric vehicle charging station deployment based on queuing theory	FRLM based approach
He et al. [40]	2015	Deploying public charging stations for electric vehicles on urban road networks	Tour based approach
Chung et al. [19]	2015	Multi-period planning for electric car charging station location-A case of Korean Expressways	Modified FRLM Based approach
Hosseini et al. [44]	2015	Selecting Optimal Location for Electric Recharging Stations with Queue	FRLM based approach
Author	Year	Diligence	Modelling

Author	Year	Diligence	Modelling
Lin et al. [58]	2015	The Flow Capturing Location Model and Algorithm of Electric Vehicle Charging Stations	FCLM based approach
Ahn et al. [3]	2015	An Analytical Planning Model to Estimate the Optimal Density of Charging Stations for Electric Vehicles	FRLM based approach
Wang et al. [97]	2016	Electric Vehicle Charging Station Placement for Urban Public Bus Systems	Tour based approach
Nahrstedt et al. [67]	2016	Placement of Energy Sources for Electric Transportation in Smart Cities	FRLM based approach
Zhu et al. [111]	2016	Charging station location problem of plug-in electric vehicles	Modified FRLM
Arslan et al. [5]	2016	A Benders decomposition approach for the charging station location problem with plug-in hybrid electric vehicles	FRLM based approach
Asamer et al. [6]	2016	Optimizing charging station locations for urban taxi providers	MCLP based approach
He et al. [41]	2016	Incorporating institutional and spatial factors in the selection of the optimal locations of public electric vehicle charging facilities: A case study of Beijing, China	P median and MCLP based approach
Davidov et al. [23]	2016	Planning of electric vehicle infrastructure based on charging reliability and quality of service	Set covering based approach
Tu et al. [90]	2016	Optimizing the locations of electric taxi charging stations: A spatial–temporal demand coverage approach	spatial–temporal demand coverage approach
Kuby et al. [43]	2016	A threshold covering flow based location model to build a critical mass of alternative fuel stations	FRLM based approach
Gopalakrishnan et al. [35]	2016	Demand Prediction and Placement Optimization for Electric Vehicle Charging Stations	Tour based approach
Wu et al. [101]	2016	A Stochastic Flow-Capturing Model to Optimize the Location of Fast-Charging Stations with Uncertain Electric Vehicle Flows	FCLM based approach

Zhao et al. [108]	2016	Optimal Siting of Charging Stations for Electric Vehicles Based on Fuzzy Delphi and Hybrid Multi-Criteria Decision Making Approaches from an Extended Sustainability Perspective	FRLM based approach

Table 4 represents an overview of the recent advancements in the paradigm of optimal placement of charging stations considering only transport network.

Optimal Placement of Charging Station Considering only Distribution Network

Appropriate placement of charging stations is necessary to reduce the adverse effects on the power grid. Improper placement of charging station is a threat to the power system security and reliability. Voltage stability, reliability, power losses are some of the key issues to be addressed while selecting the optimal locations of charging station in the distribution network. Staats et al. [85] gave an analysis of the effect of EV charging station on the harmonic voltage of the distribution system based on statistical data. Nyns et al. [21] reported the impact of placement of charging station in the distribution network in a very lucid manner. Schneider et al. [81] gave an overview of the impact of Plugged In Hybrid Vehicles (PHEV) on Pacific Northwest distribution systems. The authors assume the reasons for PHEV focus are the following - ICE serves as a backup when the battery is empty, the power grid is less affected by the use of PHEV, and it is a good option for developing countries. All the aforementioned research works unanimously conclude that the improper placement of the EV charging stations in the distribution network is detrimental to the power grid. The operating parameters of the distribution network must be given due consideration while planning charging infrastructure for EVs. In this modelling approach, the main concern is the optimal placement of charging stations in the distribution network. A framework of this modelling approach is illustrated in Figure 6. The objective functions and constraints present in Figure 6 are elaborated in the preceding section.

Hu et al. [47] gave a scheme for distribution network expansion planning and optimal siting and sizing of EV charging stations. They carried out the simulations on an 18 node test system. They modelled the problem as a multi-stage planning problem with three stages of 1 year, 1 year, and 2 years respectively. At the end of planning period, they proposed the construction of 8 new lines and replacement of 3 existing lines of the distribution network. Liu et al. [59] provided the optimal location of charging stations in IEEE 123 node test feeder. They also provided a scheme for network loss minimization as well as voltage profile improvement. This planning model yielded 5 candidate locations of EV charging stations with an overall investment of 1.3 million USD. Yan et al. [104] provided the optimal location of charging station in IEEE 33 bus system considering the investment cost minimization as objective function and energy loss as the constraint condition. Zheng et al. [110] presented a framework for battery charging/ swapping station in the distribution network considering life-cycle cost (LCC).In order to meet the demand of increased power requirement during charging, they also proposed a scheme of reinforcement of the distribution network. They verified the proposed method on modified IEEE 15 bus system as well as 43 bus radial distribution network. The results of this research work established that the construction of battery swapping stations is economically more beneficial as compared to fast charging stations. Prasomthong et al. [75] provided the optimal placement of vehicle to grid (V2G) enabled charging station in a 9 bus radial network. They also considered the net benefit earned from vehicle to grid (V2G) scheme in their problem formulation. V2G is a scheme allowing EVs to earn revenue by returning power to the grid. Mohsenzadeh et al. [63] provided candidate place of EV charging stations in IEEE 33 bus test network considering net installation cost, penalty cost for unreliability as well as power loss as the objective function and voltage limit as a constraint. The authors computed the optimal locations of charging stations for two scenarios of with and without distance constraint. The simulation results of this work demonstrate that charging station placement without considering the distance constraint is economically more beneficial. However, negligence of distance constraint may become a shortcoming of the modelling approach and the approach may not be applied in the real-world environment. Khalkhali et al. [53] presented a novel methodology for optimal placement of V2G enabled charging station in the distribution network considering economic benefits as well as voltage profile improvement. Their planning model was validated on a 9 bus test network. The active power loss reduction and voltage profile improvement in the presence of V2G enabled charging stations is established by the results of this work. Mohsenzadeh et al. [64] presented a novel methodology for optimal planning of parking lots in distribution network considering power loss and voltage profile. Pazouki et al. [72] presented a scheme for efficient planning of Plugged In Electric Vehicle (PEV) charging stations and Distributed generation (DG) considering financial, technical and environmental effects. They carried out the simulation study on IEEE 33 bus radial distribution network. Pazouki et al. [73] presented a unique scheme for optimal allocation of charging stations and capacitors in the distribution network for improving voltage profile and reduction of power loss. Martins et al. [61] presented a new time series based approach for optimal allocation of EV charging stations in the urban network. They also considered the hourly load variation neglected in most of the studies. Shojaabadi et al. [82] presented a novel approach for PHEV charging stations considering demand response program as well as uncertainty. The optimal planning was performed considering the rate of customers' participation in demand response programs (DRPs) and the presence of some uncertainties associated with the load values and electricity market price. Sachan et al. [80] presented a methodology for optimal placement of centralized EV charging station in IEEE 34 distribution network considering a 24 hour period variable load demand. Shojaabadi et al. [83] presented a new strategic approach for the simultaneous planning of PHEV charging stations and wind power generation station in distribution network considering uncertainties in load demand and wind speed. Pan et al. [70] provided a planning scheme for the centralized charging station in IEEE 123 bus test network.

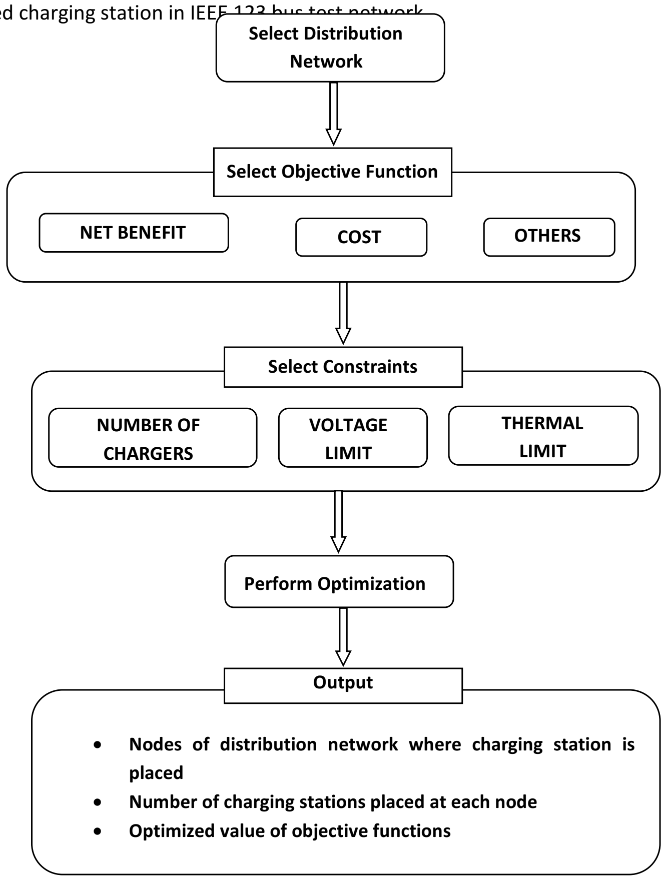


FIGURE 6|Framework for Charging Infrastructure Planning Model Considering only Distribution Network

Optimal Placement of Charging Station Considering superposition of transport and Distribution Network

Optimal placement of charging station is a non-convex non combinatorial problem involving the interaction of both transport and distribution network. Candidate places for charging station must be based on both transport and distribution network. However, the number of research works considering both transport and distribution network for planning of charging station is yet rare. The framework for this modelling approach is same as Figure 6 with the inclusion of additional objective functions and constraints from Figure 4 and considering a superimposed road and distribution network.

Pazouki et al. [71] reported optimal placement of charging station in IEEE 33 test network considering traffic constraint. Wang et al. [98] presented a novel methodology for the traffic-constrained multi-objective planning of EV charging stations considering superposition of IEEE 33 bus radial network and 25 node road network. Yao et al. [106] provided a multi-objective planning methodology for optimal planning of charging station in coupled 23 node distribution and 25 node transport network as well as 54 node distribution and 25 node transport network. Islam et al. [50] presented optimal allocation of charging station in a superimposed network comprising of 14 bus test network and the road network of Bangi, Malaysia. Leeprechanon et al. [56] provided the optimal location of EV charging stations in a superimposed network of IEEE 69 bus test system and the residential network of Tianjin. Zhang et al. [109] presented solved the optimal placement of charging station problem in a coupled network of 9 node transport and 14 node distribution network. Xiang et al. [103] solved this complicated placement problem in a coupled network of IEEE 33 bus radial network and 18 node road network. In the Joint Research Centre (JRC) project report an efficient methodology for placement of EV charging station is proposed taking into account both the road and distribution network of Bolzano/Bozen (city road network) and Alto Adige/Südtirol (rural and highway network).[xxxii]

OBJECTIVE FUNCTIONS AND CONSTRAINTS

Researchers have considered different objective functions for formulating the charging infrastructure planning problem as reported in Table 7. Costs, power loss, EV flow, waiting time are some of the key factors requiring attention while defining the objective function for the optimal placement of charging station problem. A brief elaboration of some of the commonly used objective functions as well as different constraints considered in case of the charging infrastructure planning problem is elaborated below.

Objective Functions

A general overview of different objective functions taken into account while formulating the charging infrastructure planning problem is presented in this sub-section.

Cost

Cost is considered as an objective function in many research works as illustrated in Table 5. The cost function can be sub-divided as shown in Figure 7. The installation cost is the one time investment associated with setting up the charging stations which are further sub-divided into Land cost, Construction cost, Charger cost and Labour Cost as shown in Figure 7. [29, 51] Operating cost is the annual cost of electricity required for providing charging service. Access cost is defined as the additional cost incurred by the EV drivers while travelling from the point of charging demand to the point of charging station. [3] Penalty cost implies the revenue paid by the utility for violation of the safe limits of some distribution network parameters like power loss. [59] Waiting time cost is the cost incurred because of waiting in the charging station due to unavailability of vacant charging spots.

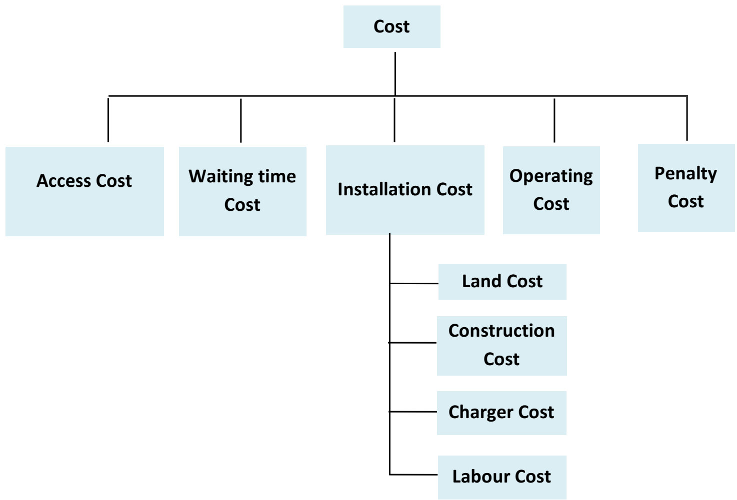


FIGURE 7| Sub-divisions of Cost function

Net Benefit

Charging stations have the capability of acting as the coupling point between EVs and the power grid. And The EVs can supply additional power to the grid via charging stations by the V2G scheme. Net benefit is considered as an objective function for the planning of V2G enabled charging stations.[53, 82] The further sub-divisions of this objective function are as in Figure 8.

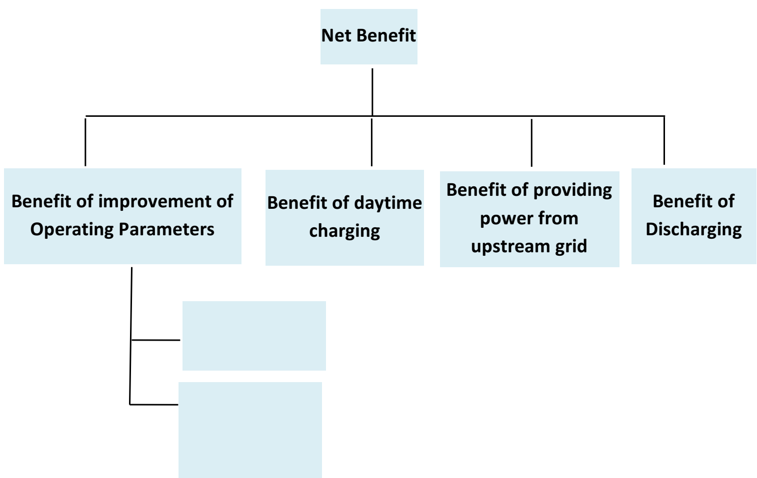


FIGURE 8|Subdivisions of Net Benefit function

Benefit of Discharging is the monetary profit earned by the charging stations by buying power from the EV owners instead of the grid at a cheaper price during peak load hours. [53, 82] By discharging, EVs are supporting the grid by acting as temporary energy storages (V2G scheme).

It is beneficial to charge EVs during the night due to low load demand and lower price of electricity during the night. However, with the increasing number of EVs in the market accompanied by increasing charging demand daytime charging is becoming essential. The charging stations are earning revenue by proving daytime charging facility at a comparatively higher price. [53, 82]

Benefit of providing power from upstream grid is the revenue earned by charging stations by proving power to the grid during peak load hours. [53, 82]

Benefit of reliability and voltage profile improvement refers to revenue earned by the charging stations because of improvement in reliability indices and voltage profile by the implementation of the V2G scheme. [53, 82]

EV flow

The charging stations must be placed in such a way that they can provide charging service to maximum number of EVs. Thus, the maximization of EV flow must be considered while planning charging stations. [106] The objective function is as in (5)

$$Max\ f = \sum_{v \in V} f_v y_v \tag{5}$$

where *V* is the set of non- zero flow paths, f_v is the rate of traffic flow. And,

$$y_v = \begin{cases} 1 & \text{if atleast one facility is located on path v} \\ 0 & \text{otherwise} \end{cases}$$

In many research works, EV flow is referred to as charging coverage or population coverage.

Others

Apart from the aforementioned objective functions mentioned in the previous sub-sections power loss, distance, covered trip, power supply moment balance index are also considered as objective functions while dealing with the charging infrastructure planning problems.

Placement of charging station increases the load of the existing network. An increase in load will further cause increase in power loss. Thus, charging stations must be placed in the distribution network in such a way that the increase in power loss is minimized.[61]

The location of charging station must be optimized keeping in mind the route choice of EV drivers and point of charging demand. Thus, the distance of EV charging station from the point of charging demand must be minimized formulating the charging station placement problem.[9, 4]

A commercial EV must be able to complete maximum number of trips to earn profit. Thus EV charging stations must be placed in such a way that the time wasted for EV charging is minimized, thereby maximizing the number of covered trips of the EV driver.[6]

The power supply moment balance is an index expressing the deviation as well as the dispersion degree of power supply .[70] A better value of this index implies less power supply fluctuation, reduced power loss, and enhanced stability of the system. Thus, minimization of power supply moment balance index must be taken into account while formulating charging infrastructure planning problem.

Constraints

The charging infrastructure planning problem is carried out subject to a number of equality as well as inequality constraint as elaborated in Figure 9.

Equality constraints like power flow equation as in (6), (7), and charging demand balance equation as in (8) must be satisfied.

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{N_D} V_j Y_{ij} \cos(\delta_i - \delta_{j-} \theta_{ij}) = 0 \tag{6}$$

$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{N_D} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{7}$$

where P_{gi}- Active power generation of i^{th} bus

P_{di} - Active power demand of i^{th} bus

Q_{gi}- Reactive power generation of i^{th} bus

Q_{di}- Reactive power demand of i^{th} bus

V_j- Voltage of j^{th} bus

Y_{ij}- Magnitude of $(i,j)^{th}$ term of bus admittance matrix

θ_{ij} - Angle of Y_{ij}

δ_i - Voltage angle of i^{th} bus

δ_j - Voltage angle of j^{th} bus

$$P_{CS}^{i} - P^{i} = 0 \tag{8}$$

where P_{CS}^{i} is the charging demand of i^{th} charging station

P^{i} is the capacity of i^{th} charging station

The limits such as the voltage of each bus, current flow, or thermal limit of each bus must be satisfied after the placement of charging stations in the distribution network. The minimum and maximum number of charging stations to be placed must also be assigned. Also, the charging stations must not be placed too close to each other. The distances between the charging stations are taken into account by the distance constraint.

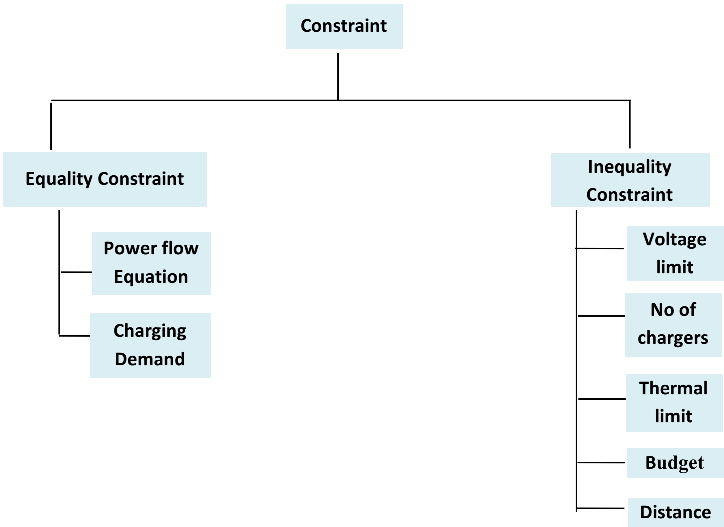


FIGURE 9| Different constraints of charging infrastructure planning problem

Table 5|Review of research works based on objective function

Author	Year	Modelling Approach	Type	Objective function

Author	Year	Modelling approach	Type	Objective function
Hong et al. [43]	2016	Considering only transportation network	Multi-objective	EV flow and classic FRLM objective
Wang et al. [95]	2010	Considering only transportation network	Multi-objective	Cost and EV flow
Gopalakrishnan et al. [35]	2016	Considering only transportation network	Single-objective	Cost
Baouche et al. [8]	2014	Considering only transportation network	Multi-objective	Cost and distance
Baouche et al. [9]	2014	Considering only transportation network	Multi-objective	Cost and distance
Wu et al. [101]	2016	Considering only transportation network	Single-objective	EV flow
Lin et al. [58]	2015	Considering only transportation network	Single-objective	EV flow
Kim et al. [54]	2012	Considering only transportation network	Single-objective	EV flow
Ahn et al. [3]	2015	Considering only transportation network	Single-objective	Cost
Zhao et al. [108]	2016	Considering only transportation network	Multi-objective	Cost ,Environmental factors, Technical factors (Power loss, Power quality, harmonics)
You et al. [107]	2014	Considering only transportation network	Single-objective	EV flow
Andrews et al. [4]	2013	Considering only transportation network	Single-objective	Distance
Ge et al. [29]	2011	Considering only transportation network	Single-objective	Cost
JIA et al. [51]	2012	Considering only transportation network	Single-objective	Cost
Wang et al. [96]	2013	Considering only transportation network	Single-objective	EV flow

Author	Year	Modelling approach	Type	Objective function
Gavranovic et al.[28]	2014	Considering only transportation network	Single-objective	Cost
Diego et al. [31]	2014	Considering only transportation network	Single-objective	Charging Coverage
Lu et al. [60]	2015	Considering only transportation network	Single-objective	EV flow
He et al. [40]	2015	Considering only transportation network	Single-objective	Tour time (travelling time and recharging time)
Chung et al. [19]	2014	Considering only transportation network	Single-objective	EV flow
Hosseini et al. [44]	2015	Considering only transportation network	Single-objective	Cost
Wang et al. [97]	2016	Considering only transportation network	Single-objective	Cost
Nahrstedt et al.[67]	2016	Considering only transportation network	Single-objective	EV flow
Zhu et al. [111]	2016	Considering only transportation network	Single-objective	Cost
Arslan et al. [5]	2016	Considering only transportation network	Single-objective	Distance
Asamer et al. [6]	2016	Considering only transportation network	Single-objective	Covered trip
He et al. [41]	2016	Considering only transportation network	Single-objective	EV flow
Davidov et al. [23]	2016	Considering only transportation network	Single-objective	Cost
Hu et al. [47]	2013	Considering only distribution network	Single-objective	Cost
Liu et al. [59]	2013	Considering only distribution network	Single-objective	Cost
Yan et al.[104]	2014	Considering only distribution network	Single-objective	Cost

Author	Year	Modelling approach	Type	Objective function
Zheng et al. [110]	2014	Considering only distribution network	Single-objective	Cost
Prasomthong et al. [75]	2014	Considering only distribution network	Single-objective	Net benefit
Mohsenzadeh et al. [63]	2015	Considering only distribution network	Single -objective	Cost
Khalkhali et al. [53]	2015	Considering only distribution network	Single -objective	Net Benefit
Mohsenzadeh et al. [64]	2015	Considering only distribution network	Single -objective	Cost
Pazouki et al. [72]	2015	Considering only distribution network	Single -objective	Cost
Pazouki et al. [73]	2015	Considering only distribution network	Single -objective	Cost
Marcelo et al. [61]	2015	Considering only distribution network	Multi-objective	Active and reactive power loss increase
Shojabaadi et al.[82]	2016	Considering only distribution network	Single -objective	Net benefit
Pan et al. [70]	2016	Considering only distribution network	Multi-objective	Cost and Power supply moment balance index
Pazouki et al. [71]	2013	Considering both transportation and distribution network	Single -objective	Cost
Wang et al. [98]	2013	Considering both transportation and distribution network	Multi-objective	EV flow , power loss and voltage deviation
Yao et al. [106]	2014	Considering both transportation and distribution network	Multi-objective	EV flow, power loss and cost
Islam et al. [50]	2015	Considering both transportation and distribution network	Multi-objective	Transportation Energy loss cost, Build up cost and Substation energy loss cost

Leeprechanon et al. [56]	2016	Considering both transportation and distribution network	Single - objective	Charging coverage
ZHANG et al. [109]	2016	Considering both transportation and distribution network	Single - objective	Cost
Xiang et al. [103]	2016	Considering both transportation and distribution network	Single - objective	Cost

Table 6|Mapping between objective function, decision variables, constraints, and different approaches of dealing with charging station placement problem

	Feature	Considering only transport network	Considering only distribution network	Superposition of both transport and distribution network
Objective function that can be modelled	Installation cost	✓	✓	✓
	Maintenance cost	✓	✓	✓
	Operating cost	✓	✓	✓
	Waiting time cost	✓		✓
	Power loss penalty		✓	✓
	Net benefit of V2G		✓	✓
	Reliability		✓	✓
	Voltage stability		✓	✓
	EV flow	✓		✓
	Distance	✓		✓
	Transformer loss of life		✓	✓
Decision Variable	Bus number of distribution network		✓	✓
	Node of road network	✓		✓
	Charging station density	✓		✓
	Number of chargers	✓	✓	✓
Constraints	Budget	✓	✓	✓
	Power flow		✓	✓
	Thermal limit		✓	✓
	Voltage limit		✓	✓
	Number of charging point	✓	✓	✓
	Charging demand	✓		✓

A mapping between different modelling approaches and objective function, constraints is presented in Table 6. From Table 6 the superiority of modelling approach considering superimposition of transport and distribution network is clearly established.

OPTIMIZATION ALGORITHMS

The objective function in case of optimal placement of charging station problem is multi-variable and complex. Researchers have utilized both classical and evolutionary optimization algorithms for the solution of this problem. A brief review of the optimization techniques utilized for the solution of optimal placement of charging station problem is presented in this section.

Classical Optimization Algorithm

The traditional or classical optimization methods inspired by the differential calculus can be utilized for obtaining the optimum value of continuous as well as differentiable function.[77] Integer programming, Linear programming, Primal-Dual Method, Game Theoretic Approach are some of the classical optimization techniques having application in evaluating the solution of the charging station placement problem. An integer programming is an optimization technique where all or some of the variables are restricted to be integers .[57] A mixed integer programming is an optimization technique where only some of the variables are restricted to be integers .[15] Linear integer programming is used for solution of the charging station placement problem in many literature. [8, 9, 22, 19, 97, 23, 100] Mixed integer linear programming is utilized for the solution of the charging station placement problem in a number of literature.[95, 107, 4, 34, 51, 44, 6]

Evolutionary Algorithm

Evolutionary algorithms are nature inspired algorithms based on the principle of "Survival of the fittest". [7] The central idea of most of the evolutionary algorithm is similar. It initiates the search with a randomly generated set of population. As the search progresses only the best candidates survive in the subsequent generations. Some of the advantages of these evolutionary algorithms are-

1. Computational and conceptual simplicity
2. Broad range of applications starting from simple problem to complicated engineering problems
3. Hybridization with classical algorithms
4. Faster convergence criterion

Because of all these aforementioned advantages, evolutionary algorithms have extensive application in the charging station placement problem. A brief review of the applications of the evolutionary algorithms in charging station placement problem is presented in Table 7. Table 8 represents a comparative analysis of different evolutionary algorithms in terms of computational burden, computational time, and convergence criteria.

Table 7|Evolutionary Algorithms applied to optimal placement of charging station problem

Evolutionary Algorithm	Origin	Reference number where the algorithm is applied
Genetic Algorithm [32, 24]	Natural process of evolution of new offspring from a set of randomly generated population by the process of selection, crossover and mutation	29, 40, 111, 90, 104, 63, 64, 72, 73,61, 82 83, 70, 71
Particle Swarm Optimization [52, 74]	Optimization algorithm inspired by the natural phenomenon of bird flocking	58, 75, 109
Differential Evolution [86]	Evolution of new offspring by adding weighted difference between population vector and target vector	53, 106
Firefly Algorithm [105]	Movement of firefly towards light	50
Ant Colony Optimization[25]	Trail laying and following behaviour of real ants	56

Table 8|General comparative analysis of different optimization algorithms applied to charging station placement problem

FUTURE DIRECTIONS OF RESEARCH

Optimization algorithm	Computational Complexity	Computational time	Convergence Criteria
Genetic Algorithm	Less than other evolutionary algorithms	More than other evolutionary algorithms	More than other evolutionary algorithms
Particle Swarm Optimization	More than GA	Less than GA	Premature Convergence (the algorithm ending up with local solution)
Differential Evolution	More than GA	Less than GA	Less than GA
Firefly Algorithm	Less than PSO	Less than PSO	Less than PSO
Ant Colony Optimization	Less than PSO	Uncertain	Uncertain

The field of research is comparatively new and still in its nascent stage. EVs are still diminishingly small, but growing minority of the World vehicle population. The future directions of research in this field are as follows-

1. Problem formulation of the optimal placement of charging infrastructure
2. Optimization technique applied to solve the optimal placement of charging infrastructure problem
3. Feasibility Analysis and location-based planning of the hybrid charging station supported by renewable energy resources

Problem formulation of optimal placement of charging infrastructure

The existing works in the paradigm of charging infrastructure planning clearly indicate the multifarious nature of the problem. The problem formulations of the existing works still have limitations. In most of the works, it is observed that the approach adopted to define objective function has many limitations and the objective function needs to be reformulated. The problem needs to be considered from a multi-objective approach with installation, operating, maintenance cost, power loss penalty cost, reliability indices, voltage stability indices, waiting time as the objective function. Another important factor to be addressed while defining the problem is that the maintenance cost. The maintenance cost is not constant and follows the well-known bath-tub curve (similar to a parabola).[39] Distribution system reliability indices like SAIFI, SAIDI, ASIDI cannot be neglected while defining the objective function .[14] Also, the voltage stability indices like L index, FVSI index must be taken into account while formulating the problem. [92, 66] Another observation noticed in all the literature is that the uncertainty in road traffic is neglected in most of the literature. The uncertainty in road traffic can be modelled by algorithms like the Bayesian algorithm.[48]

Optimization technique applied to solve optimal placement of charging infrastructure problem

It is seen that GA is applied by the majority of researchers for solving the charging station placement problem. The latest efficient evolutionary algorithms with better convergence criterion like Teaching Learning Based Optimization technique [78], Spider monkey optimization algorithm [11] can be explored for the solution of the placement problem. Hybrid optimization algorithms combining classical techniques with evolutionary algorithms can also be adopted for the solution of this complex and dynamic placement problem.

Feasibility Analysis and location -based planning of hybrid charging station supported by renewable energy resources

EVs are free from local exhaust emissions. However, the power required for charging the EVs produced using non-renewable sources is not emission free. The increasing number of EVs in the market is accompanied by escalated electricity demand to charge them. Consequently, there is necessity of increasing the peak power generation capacity. While moving in traffic and stopping to charge, EVs form spatial peaks varying in time. The grid may not be sufficient to meet the demand, particularly at the moment of a peak demand. Additionally, the peak power should not be satisfied using non-renewable sources of energy. Thus, to reduce CO_2 emissions and satisfy the increasing charging power demand renewable sources of energy must be utilized. In this context, the feasibility analysis of hybrid charging stations is a new promising area of research for the coming years.

Conclusions

The adoption of EVs has been still at an early stage. The charger locations have mostly been selected to serve demonstrations and early adopters. Extensive use of EVs will pose charging station location problem in a serious manner. The chargers need to serve EVs, enable smooth traffic, and maintain the stability of the power grid. Our review presented the recent trends in the paradigm of charging infrastructure planning. The global scenario of charging infrastructure planning is presented identifying the social, economic, and technological barriers hindering the development of charging infrastructure. It was observed that the charging infrastructure planning in different parts of the World is yet in developing stage. For the development of charging infrastructure collaboration between researchers, industrialists and government are required.

The main focus of the work was to present a comprehensive review of the recent trends in the charging infrastructure planning problem. The contributions of different researchers in the paradigm of the charging infrastructure planning reveal the multifarious nature of the problem formulation and optimization algorithms applied to solve the problem. The future direction of work possible in this area were identified and presented.

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