Chapter 2

Electric Vehicle Infrastructure

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Chapter 2

Electric Vehicle Infrastructure

Several Association of Southeast Asian Nations (ASEAN) countries have strategies for low-emissions mobility, with decreasing oil import dependency as a main objective. The strategies emphasise, amongst others, removing obstacles to the electrification of transport to promote market development of plug-in electric vehicles (PEV), especially cars, powered two-wheelers, and light-duty vehicles or vans.

Removing obstacles means that ASEAN countries must secure critical technological system requirements: road electric vehicle (EV) manufacturing and supporting or supplier industries, and the corresponding EV charging infrastructure.

Since January 2018, the ASEAN Free Trade Agreement has dropped import duties for vehicles originating in other ASEAN countries to 0%. Investment in the domestic EV manufacturing industry might benefit the countries if the final purchasing price of the vehicles can compete with those of imported vehicles.

Whilst EV manufacturing and its support industries might rely mostly on integration with global value chains, developing charging points needs significant domestic public and private investment. This chapter focuses on building the decision-making framework for charging infrastructure investment to encourage EV deployment.

We start with a brief introduction on the state of charging technology development, including the different charging technologies and modes, and the need for standardisation to ensure interoperability. We then discuss the costs of the different charging technologies, followed by a synthesis of the ‘chicken-and-egg’ relationship between charging infrastructure and the EV penetration rate. The most-used indicator is the number of PEVs per charging point. Some argue that developing more charging infrastructure will stimulate PEV penetration, but it is often the electric car manufacturers that encourage deploying the infrastructure (Li et al., 2016).

We then present a simple model called the public charging supply-cost model and implement the model as an exercise to calculate the number of chargers in the Lao PDR with some other related indicators that give a high-level indication of the impacts of these chargers rolling out such as the power load on the charger, comfort to users, and the needed installation costs.

We give illustrations of some more sophisticated models to optimally roll-out charging infrastructure that consider mobility or spatial and electricity aspects. We also present some strategies that have been done in the forerunning countries to facilitate charging infrastructure investments. At the end we also discuss the charging scheme strategy to ensure that electric vehicle charging activities would not have a harmful effect to the power load on the grid as well as to the emissions from power plants.

1. Introduction to Electric Vehicle Charging Infrastructure

Internal combustion engine (ICE) vehicle users benefit from refuelling station networks being located nearly everywhere. But PEV charging infrastructure is in its early development stage, especially in ASEAN countries.

In principle, a PEV can simply be plugged into a home wall-mounted box, which is the simplest EV service equipment, but home charging is not as simple as it seems, and the long charging time is its main inconvenience. Moreover, increasing grid pressure is a risk as home charging takes place mainly in the late afternoon after working hours, when household electricity demand is peaking. These are the main reasons for developing different types of chargers and installing them in public spaces such as parking lots, workplaces, petrol stations, and motorway rest areas.

1.1. Charger Types

Chargers on the market can, in principle, be divided into slow and fast. Slow chargers use an alternating current (AC) under 400 volts, whilst fast chargers use a direct current (DC) of 400 volts and above. Most charging stations are slow and more than 88% have 22 kilowatt (kW) power or lower. This category includes 2.3 kW household plugs that take about 9 hours to completely recharge a common PEV. Most PEVs can be home-charged via an AC outlet of 3.3–11 kW.

Slow chargers are level 1 (120 volts) and level 2 (200–240 volts) and suitable for short trips, whilst DC fast chargers, most often found in public locations such as motorway rest areas, are best for longer journeys (Hall and Lutsey, 2017). Both recharging times are significantly longer than ICE vehicle refuelling time.

Table 2.1 classifies chargers into four modes, each corresponding to a specific charging speed, required voltage, electric current, and level of communication between vehicle and power outlet.

Slow chargers are also often grouped into slow and semi-fast. It takes 6–8 hours to fully charge a pure battery electric vehicle (BEV) using slow chargers with a single-phase 3.3 kW of power and 120–240 volts. This practice corresponds to home charging using a shared circuit without any safety protocol.

Table 2.1: Different Modes of Plug-in Electric Vehicle Charging

Mode	Name	Power (kilowatt)	Current	Phase	Charging Time	Place	Voltage (volt)	Power Range (ampere)	Communication Level	Further Description
1	Slow	3.3	AC	Single	6–8 hours	Household, workplace wall box	120–240	Up to 16	NA	Shared circuit without safety protocols
2	Slow, semi-fast	7.4	AC	Single	3–4 hours	Household, workplace wall box and public charging poles	120–240	Over 16 and up to 32	Semi-active connection to vehicle to communicate for safety purpose	Shared or dedicated circuit with safety protocols, including grounding detection, overcurrent protection, temperature limits, and a pilot data line
3	Slow, semi-fast or fast	10	AC	Three	2–3 hours		240	Any	Active connection between charger and vehicle	Wired-in charging station on a dedicated circuit, mode-2 safety protocols, active communication line with the vehicle, i.e., smart charging suitability
		22	AC	Three	1–2 hours	Mostly public charging poles				
4	Fast	50	DC	–	20–30 minutes	Motorway service area or dedicated charging stations in urban areas (current standard)	400		Active connection between charger and vehicle	Mode-3 features with more advanced safety and communication protocols

Mode	Name	Power (kilowatt)	Current	Phase	Charging Time	Place	Voltage (volt)	Power Range (ampere)	Communication Level	Further Description
		120	DC		10 minutes	Motorway service area or dedicated charging stations in urban areas (future standard)				

AC = alternating current, DC = direct current, NA = not applicable.

Sources: E-Mobility NSR (2013), Hall and Lutsey (2017), Spöttle et al. (2018).

With slow to semi-fast chargers, charging time should be reduced from 4 hours to 1 hour. Facilities with power greater than 3.3 kW but less than 22 kW can be found in households, workplaces, and public spaces. Chargers with power lower than 22 kW allow a maximum speed up to 2 hours of charging and can be applied to shared or dedicated circuits with safety protocols. Facilities with power higher than 22 kW reduce charging time down to 1 hour. Semi-fast chargers are installed mostly in public charging facilities often equipped with an active communication line between the charging point and the vehicle.

Finally, the DC fast chargers allow BEVs to be fully charged in less than 111 hours. They are often installed in motorway service areas or in urban dedicated charging stations where long charging time is less tolerated.

The situation is, however, complicated. Compatibility between PEVs and charging point technology standards is an issue as there are at least five technology standards or connector types:

- Type-1 AC. Amongst the most popular PEV connectors in this category are some produced by the Japanese manufacturer Yazaki, following the North American SAE J1772 standard. They are mostly slow chargers and can be found in North America and Japan.
- Type-2 AC. Most are fabricated by the German company Mennekes, following the AC charging technology standard gaining market share in Europe and China. This type is compatible with most PEVs and AC chargers and can facilitate only single-phase and three-phase AC charging.
- Type-3 AC. Built by the PEV Plug Alliance, mostly in Italy and in France, and used only up to 2012, when the Type-2 AC became dominant in Europe.
- Type-4 DC. Also known as the Japanese standard, CHAdeMO. It was the first widespread technical standard for DC fast charging developed by a Japanese consortium. This type is found not only in Japan but also in European countries, mostly in France.
- CCS or combined charging system. The combined AC and DC fast-charging plugs are CCS Combo 1, preferred by United States (US) car manufacturers, and CCS Combo 2, preferred by German manufacturers.
- Tesla supercharger infrastructure. This DC fast charger is used mostly in North America.

1.2. Standardisation and Interoperability

Charging stations are considered interoperable if they can serve a large variety of PEV models and offer payment methods accessible to all PEV drivers (Spöttle et al., 2018). Standardisation guarantees interoperability, provides clarity to manufacturers, allows for economies of scale, and ensures compliance with safety standards. PEV charging interoperability means that PEV users can charge their cars at any charging point using their usual choice of authorisation and payment method.

Charging infrastructure – at least the physical equipment, payment systems, and charging protocol – must be standardised. In Europe, for example, Type-2 AC and Type-3 AC coexisted, as did CHAdeMO and CCS Combo 2. In 2014, European Commission Directive 2014/94/EU required that all providers of public chargers include a Type-2 AC connector where level-2 or fast AC charging is available, and a CCS connector where level-3 charging is provided. In Southeast Asia, the rolling out of charging infrastructure is still in its development phase, but some trends are visible: Type-2 connectors are available for AC charging, and CCS Combo connectors are also available for DC charging in Thailand, Malaysia, and Singapore. CHAdeMO is available in Thailand and Malaysia.

Many charging station network operators in the early years of PEV penetration developed their own payment systems. PEV users normally subscribe to a charging station operator and cannot always charge or pay at a station belonging to another operator. A simple solution is for the user to subscribe to more than one operator. A more sophisticated solution is to allow roaming between operators as mobile phone network operators have been doing for years.

Finally, charging activity needs protocols that standardise the communication interface between the car, the charging stations, and the system that oversees monitoring and managing of the charging station, including the roaming platforms. That system is usually referred to as the charge point operator or charging service operator. For example, Europe has the open clearing house protocol supported by national charging infrastructure providers in Belgium, Germany, the Netherlands, Luxembourg, Austria, Ireland, and Portugal; open charge point protocol, initiated by ElaadNL, which is also involved in open clearing house protocol; and open charge point interface, supported by European operators.

1.3. Cost of Charging Infrastructure

Simple home charging can compete with more efficient gasoline cars and is even significantly cheaper when a time-of-use (TOU) electricity tariff with lower prices in off-peak periods is in place. More powerful home charging is sensitive to capital cost but competitive with moderately efficient ICE vehicles and would be substantially cheaper under a TOU regime (Lee and Clark, 2018).

The issue, however, is how to develop non-home-based charging points or stations as home charging has limitations. Developing such stations needs significant investment, supporting regulations, an adequate business model, and, in many places, central government intervention or initiatives.

China's central government, for instance, has funded a programme in 88 pilot cities, led by Shanghai, Beijing, and Shenzhen, to provide one charging point for every eight PEVs. The charging points are grouped into stations, which must be no more than 1 kilometre from any point within the city centre (Hall and Lutsey, 2017).

The 13th Five-Year Plan (2016–2020) states that China shall build a nationwide charging-station network that will fulfil the power demand of 5 million EVs by 2020 (Xin, 2017). The

State Grid Corp of China, the state-owned electric utility monopoly, had built more than 40,000 charging stations by 2016 and was planning to build a network of 120,000 public-individual charging points for electric cars by 2020, throughout major regions in China (Chen et al., 2018). China's National Energy Administration says that the country had a total of 450,000 stationary charging points in 2017, including around 210,000 publicly accessible units (Ying and Xuan, 2018).

Another example, Singapore's Land Transport Authority announced in 2016 it would install 2,000 charging points, and in 2017 reached an agreement with a private company, BlueSG Pte Ltd., to launch a nationwide car-sharing programme with a fleet of 1,000 plug-in hybrid electric vehicles (PHEVs). The company planned to install and operate the charging points. Singapore Power Group, the state-owned electricity and gas distribution company, planned to roll-out 1,000 charging points by 2020, of which 250 would be 50 kW fast DC chargers able to fully charge a car in 30 minutes. Normal slow chargers cost around $3,700, whilst fast chargers cost $48,000. By September 2018, hybrid electric vehicles (HEVs) made up 4.3% of the total of around 615,000 registered vehicles, PHEVs 0.06%, and BEVs 0.08% (Tan, 2018). Many industrial players think the lack of charging facilities has been a main cause of slow PEV penetration.

In Japan, the government created the massive Next Generation Vehicle Charging Infrastructure Deployment Promotion Project to fund charging stations around cities and highway rest stations in 2013 and 2014 (CHAdeMO Association, 2016). The nationwide Nippon Charge Service, a joint project of the state-owned Development Bank of Japan with Nissan, Toyota, Honda, Mitsubishi, and Tokyo Electric Power Company, operates almost 7,500 stations.

In the US, by 2017, around 47,000 charging outlets had been built all over the country. The General Services Administration had installed EV charging stations for federal employees and other authorised users, and more than 10 states were offering rebates and tax credits to commercial customers and homeowners for installing charging stations (Lu, 2018).

In several PEV front-runner countries in Europe, the public sector and private investors financed early charging infrastructure when the use of chargers was not yet high enough to be profitable. Public subsidies will be phased out in 2020–2025. Technological acceptance and spread and economies of scale should stimulate similar developments in other European countries (Transport & Environment, 2018).

What follows is a summary of public charging facility costs in PEV front-runner countries. We focus on the top priority for ASEAN countries, which is to develop slow or semi-fast level-2 charging facilities, and on fast-charging infrastructure, installation of which will be much more limited, depending on mobility purposes and needs.

Slow to Semi-fast AC Charging Facility Costs

Table 2.2 shows that the hardware costs of slow to semi-fast charging facilities are comparable, even between the US and Europe and India.

Table 2.2: Examples of Slow and Semi-fast Charging Facility Purchase and Installation Costs

Countries (Currency)	Application	Costs	Included Items	Report
United States ($, 2017)	L2 – home	450–1,000 (50–100)	Charging station hardware (additional electrical material costs in parentheses)	Fitzgerald and Nelder (2017)
	L2 – parking garage	1,500–2,500 (210–510)		
	L2 – curb side	1,500–3,000 (150–300)		
France, Germany, Italy, Netherlands, Spain, UK (€ 2017)	3.7 kW new residential building	1,170	Materials (for installation, including cables); wall-box (hardware of charging station, excluding cables); and labour (around 20% of total costs)	CREARA Analysis (2017)
	3.7 kW operating residential building	1,280		
	7.4 kW new non-residential building	1,760		
	7.4 kW operating non-residential building	2,025		
Germany (€ 2017)	>3.7 kW – one charging point	1,200	Complete hardware, including communication and smart meter	NPE (2018)
	11 kW or 22 kW – two charging points	5,000		

Countries (Currency)	Application	Costs	Included Items	Report
India ($, 2019)	Bharat charger AC 001-1 point(s)-3 phase 415 volt-3 x 3.3 kW	980	Approximate cost, including goods and services tax at 18%	Pillai et al. (2018)
	Type-2 AC Charger-1 point(s)-7.2 kW	1,050		
	CCS-2-1 point(s)-3 phase 415 volt-25 kW	9,800		
European Union 28 average (€, 2018)	AC mode 2 – home (up to 11 kW)	<800	Purchase cost for a single charging point, not installation, grid connection, or operational costs	Spöttle et al. (2018)
	AC mode 2 – commercial (up to 19.4 kW)	<2,000		
	AC mode 3 – fast (22 kW of 43 kW)	1,000–4,000		

AC = alternating current, kW = kilowatt.
Source: Authors' compilation.

In the US, a simple home 3.7 kW charger costs only around $500, whilst a 7.2 kW charger that can fully charge a PEV in around 4 hours costs around $1,000 – almost the same as in Europe and India, which shows that local content of charger production in India is low. For chargers of 22 kW or more, costs in India are much higher than in the US or Europe, which means India still does not enjoy economies of scale for charging hardware production.

The charger's power, electric power phases, and number of charging points are amongst the factors that determine the cost of PEV charger hardware and materials.

Home installations are used less intensively and have lower safety requirements and are therefore less costly than public stations, which are more sophisticated and might include liquid-crystal display screens, advanced payment and data tracking communication, and dual-port power routing capabilities (Fitzgerald and Nelder, 2017).

Installation methods significantly affect total installation costs: installation from scratch is always cheaper than from partially make-ready facilities such as those that are pre-piped or pre-cabled. Several European governments stimulate development of partially make-ready charging facilities by the private sector, e.g., building or utility owners (CREARA Analysis, 2017).

Fast DC Charging Facility Costs

DC level-3 charging stations reduce charging time, but they cost significantly more than a level-2 charger because of two factors: expensive equipment and the frequent need to install a 480 V transformer. Fast-charger hardware is significantly more expensive than level 2, and in the US a transformer might cost another $10,000–$20,000 (Fishbone, Shahan, and Badik, 2017). Installing DC fast charging stations in the US typically costs as much as $50,000. Inclusion of project development, design, permits, and system upgrades can raise the total cost of DC fast charging deployment as high as $300,000 each (Fitzgerald and Nelder, 2018).

Table 2.3: Examples of Fast-Charging Facility Purchase and Installation Costs

<table>
<tr><th>Countries (Currency)</th><th>Application</th><th>Costs</th><th>Included items</th><th>Report</th></tr>
<tr><td>United States ($, 2017)</td><td>DC fast charging</td><td>12,000–35,000
(300–600)</td><td>Charge station hardware (plus extra electrical materials)</td><td>Fitzgerald and Nelder (2017)</td></tr>
<tr><td>Germany (€, 2017)</td><td>50 kW</td><td>25,000</td><td>Complete hardware, including communication and smart meter</td><td>NPE (2018)</td></tr>
<tr><td rowspan="2">European Union 28 average (€, 2018)</td><td>DC fast – standard (20 kW–50 kW)</td><td>20,000</td><td rowspan="2">Purchase cost for a single charging point, not installation, grid connection, or operational costs</td><td rowspan="2">Spöttle et al. (2018)</td></tr>
<tr><td>DC high power – fast
(100 kW–400 kW)</td><td>40,000–60,000</td></tr>
</table>

DC = direct current, kW = kilowatt.
Source: Authors' compilation.

2. Electric Vehicles and their Charging Infrastructure: A Chicken and-Egg Issue

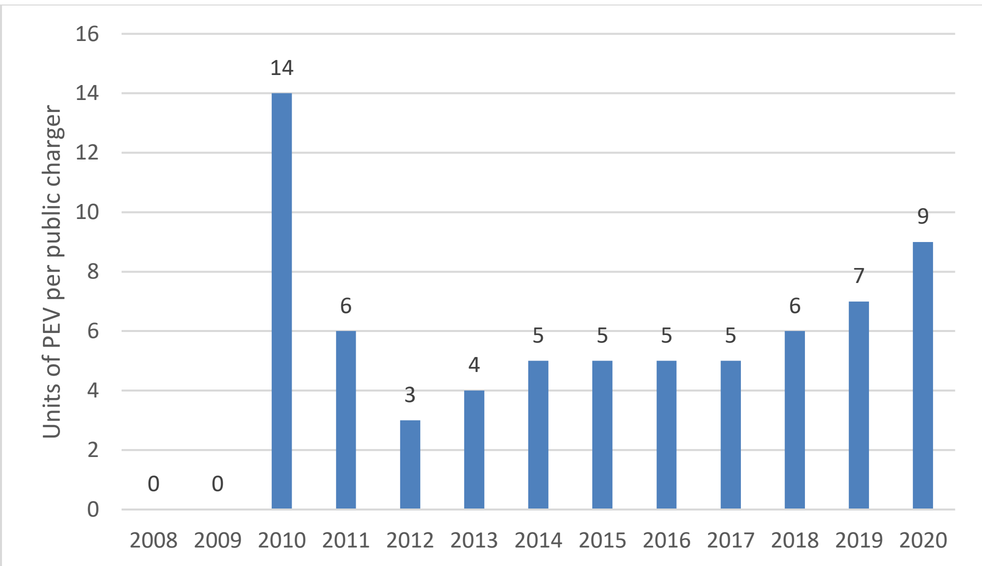
Fast-charging stations need to achieve a sufficiently high utilisation ratio to compensate for the high total cost of installation and operation where grid impact will be low. DC fast-charging hubs should serve high-usage fleets and ride-hailing vehicles, ideally along high-usage corridors and commuting routes around major cities, and rest areas for interurban trips on major highways (Lee and Clark, 2018).

Since 2011, we have witnessed the unprecedented growth of PEV sales and the number of charging infrastructure points in different parts of the world.

The European Alternative Fuels Observatory (EAFO, 2021) database shows that in the European Union (EU)-27 and in six non-EU countries (United Kingdom, Iceland, Norway, Switzerland, Turkey, and Lichtenstein), total road PEV sales have increased from only 1,792 units in 2010 to 1,117,546 units in 2020, i.e., more than 620-fold during the 10-year period. Around 93% of the total road PEV sales in 2020 consisted of passenger cars (M1 category). The EAFO database reveals that recharging infrastructure points in Europe have increased from 400 in 2010 to 224,237 in 2020 – more than 560-fold during the same period. In 2020, almost 89% of recharging points are normal chargers with power equal or less than 22 kW. The rest 11% are fast chargers with power higher than 22 kW.

The ratio of the number of PEV units per charger has fluctuated between 2008 and 2020 in the EAFO countries, i.e. EU-27 plus the United Kingdom, Iceland, Norway, Switzerland, Turkey, and Lichtenstein. As shown in Figure 2.1, there was practically no public charging in 2008 and 2009. In 2010 around 400 chargers were built and operated. A massive installation of chargers in those countries reduced the ratio from 14 in 2010 to 3 in 2012. The ratio went up again afterwards to reach around nine PEVs per public charger in 2020.

Figure 2.1: Units of PEV per Public Charger in EAFO Countries



EAFO = European Alternative Fuels Observatory, PEV = plug-in electric vehicle.
Source: EAFO (2021).

Public charging infrastructure is key to EV market growth. Rough apparent patterns are observed between EV uptake and charging infrastructure availability, with substantial variability across markets. The development of a robust charging infrastructure network is a key requirement for large-scale transition to electromobility, but there is no universal benchmark for the number of EVs per public charge point (Hall and Lutsey, 2017).

Table 2.4 shows that the average ratios of PEVs to charging station in EV front-runners vary greatly between or even within regions.

Table 2.4: Indicated Average Ratios of Electric Vehicles per Public Charge Point

Country/Region	Region	Electric Vehicle /Public Charge Point Ratio	Source
China	China average	8 (pilot cities) 15 (other cities)	NDRC (2015)*
World	Worldwide	8 (2015) 15 (2016)	IEA Electric Vehicle Initiative (2016, 2017)*
United States	United States average	7–14	Cooper and Schefter (2017)*; EPRI (2014)*
		24	Wood et al. (2017)*
	California	27	CEC and NREL (2017)*
European Union	European Union average	10	European Parliament (2014)*
	The Netherlands	3.6	Spöttle et al. (2018)
	Norway	15.2	
	Germany	6.7	
	The UK	9.7	
	France	7.6	

Note: * From Hall and Lutsey (2017).

EU data show that the PEV market share of new registrations rises as the vehicle to charging point ratio drops from 25 to 5. A low ratio would benefit PEV uptake but infrastructure coverage denser than 1 charging point per 10 PEVs would be inefficient: sales numbers become insensitive with a decreasing ratio. The high costs of additional charging infrastructure, therefore, do not justify high investments (Harrison and Thiel, 2017).

A study on the relationship between the number of PEVs and the publicly accessible charging points in Europe (EU 28 + Norway) demonstrates two interesting findings. First, with some variation in the countries' national context, the density of charging infrastructure generally correlates positively with PEV adoption. A range of other factors are proven or suspected to be correlated with PEV uptake, such as model availability, financial incentives, urban density, etc. Charging infrastructure is necessary but not enough for PEV adoption. Most front-runner countries have applied a demand-oriented approach to rolling out charging infrastructure. Second, the ideal ratio of PEVs per charging point will, in the long run, lies between 10 and 16 (Spöttle et al., 2018).

The roll-out of charging infrastructure may be oriented towards demand or coverage. The demand-oriented approach assumes that charging infrastructure should be constructed where existing and future demand can be determined and aims for optimal allocation and utilisation of all charging points and avoids redundancies. The coverage-oriented approach is premised on public infrastructure guaranteeing a minimum standard of service to the widest possible public by minimising the distance between the charging points. None of the front-runner countries take the coverage-oriented approach, except the US, with its designated alternative fuel corridors; China, which has required 88 pilot cities to install a charging network with charging points positioned no farther than 1 kilometre (km) from any point within the city centre; and Norway, where the government financed the deployment of at least two fast-charging stations every 50 km on all main roads by 2017 (Figenbaum, 2019).

A study for Thailand by Thananusak et al. (2020) proposed two types of policies to deal with the chicken-and-egg issue. The first type of policy, the 'demand pull' deals with boosting demand for electric vehicles. This type might consist of providing rebates and tax credits for consumers, increasing the demand for electric vehicles through government procurement activities, establishing regulations and standards that facilitate demand growth, and the building of consumer awareness. The second type of the policy, the 'technology pull' might consist of policies that aim at giving favourable loans with low interest rates for investors, providing public co-funding charging stations, setting up preferential electricity selling rates, providing financial support for chargers and equipment purchase, providing rebates, investment subsidies, tax incentives, tax holidays, and so on, and creating EV charging consortia to lay the foundation of interoperability.

3. Public Charging Supply-Cost Model

In this chapter we implemented a methodology of public charging supply-cost model to the Lao PDR. The method was developed by Transport & Environment (2020) and can be used to calculate the number of public electric vehicle chargers needed at an aggregated level as well as the costs needed to roll-out those chargers.

This implementation is nevertheless a mere exercise as it involved many assumptions that are made based on practices in other countries or literature. A more proper implementation of the method should include an in-depth series of consultation and survey with many stakeholders in the Lao PDR which is beyond the scope of this study.

Further lower-level results such as the spatial distribution of chargers can be determined using other methods whose illustrations are given in section 4.

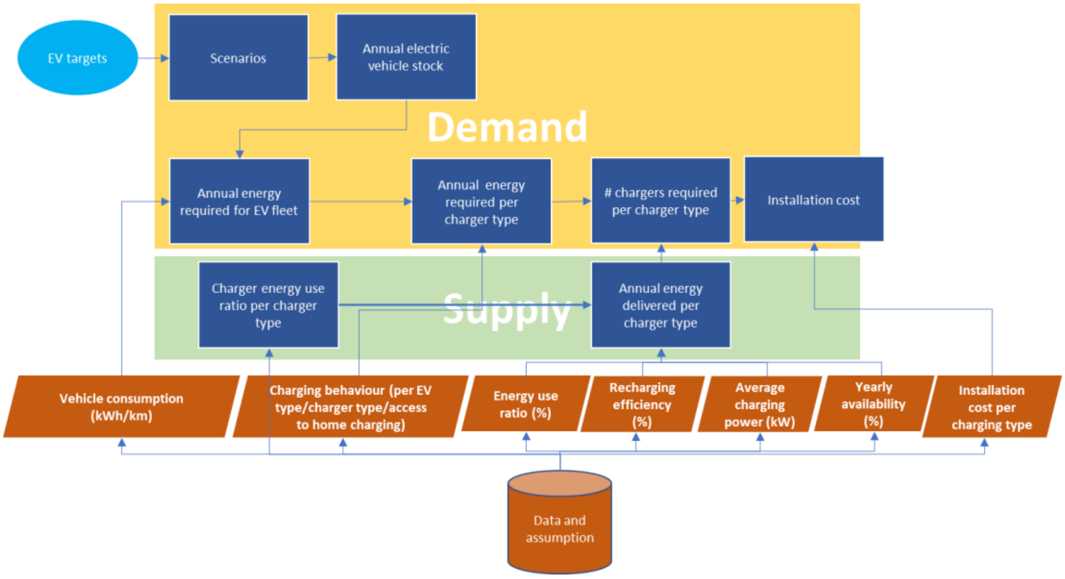
3.1. Methodology

The public charging supply-cost model considers the determination of the number of public charging from both demand and supply sides.

Basically, the number of electric vehicle chargers in the model is calculated by dividing the electric energy needed per charger type, which represents the demand side, by the electric energy to be delivered by each charger type, which represents the supply side. Therefore, from the demand side we need to have at least four main inputs, i.e., the energy required by the electric vehicle fleet, the number of electric vehicles, charging behaviour, and battery efficiencies of the electric vehicles. From the supply side, we need to have the following inputs at charger type level, i.e., charger energy use ratio, energy use ratio, recharging efficiency, charging power, and periodical charger availability.

Figure 2.2 shows the flowchart summarising the public charging supply-cost model. Paragraphs that follow explain the detailed calculations of the model. In line with chapter 1, the time scope of this exercise for the Lao PDR would be the period between 2018 and 2040 with calculation done on a yearly basis.

Figure 2.2: Flowchart of Public Charging Supply-Cost Model



EV = electric vehicle, km = kilometre, kW = kilowatt, kWh= kilowatt hour.
Source: Authors' adaptation of the model from Transport & Environment (2020).

Demand Side

Calculated at electric vehicle type level, as given in equation (1), the annual electricity required by the electric vehicle fleet is calculated by multiplying the number of electric vehicles, the average battery efficiency, and the average kilometres travelled of the corresponding year. The total electricity needed by all electric vehicle is simply the sum of electricity needed for all electric vehicle types (equation (2).

$$\boldsymbol{ENEREQEV_{ev\,type} = VEHTOT_{ev\,type}.\,BATTEFF_{ev\,type}.\,MILEAGE_{ev\,type}}$$

1 **(1)**

Where

$ENEREQEV_{ev\,type}$: annual energy required for each electric vehicle type (kWh)

$VEHTOT_{ev\,type}$: total stock of electric vehicle per electric vehicle type

$BATTEFF_{ev\,type}$: average battery efficiency for each electric vehicle type (kWh/km)

$MILEAGE_{ev\,type}$: average annual travelled kilometre for each electric vehicle type (km)

$$\boldsymbol{ENEREQTOT = \textstyle\sum_{evtype} ENEREQ_{evtype} \,.\, 10^{-6}}$$

2 **(2)**

Where

$ENEREQTOT$: annual total energy required for all electric vehicles (GWh)

The annual energy required for each charger type is calculated by multiplying the total electric energy required to feed electric vehicles by the usage percentage of each charger type and the access to chargers as given in equation (3).

The usage percentage of each charger type represents the charging behaviour, i.e., how power is distributed in the different charger types in a particular region and period. Since public chargers have been usually rolled out starting from the slow types, it is logic to assume high usage percentages of slow chargers at the beginning of the period. With time, semi-fast and fast chargers should be quantitatively more available and therefore the usage percentages should also be shifting gradually from the slow to semi-fast and fast charger types.

$$\boldsymbol{ENEREQCHAR_{charger\ type} = ENERQTOT.CHARBHV_{charger\ type}.CHARACC_{charger\ type}} \quad \mathbf{3} \qquad \mathbf{(3)}$$

where

$ENEREQCHAR_{charger\ type}$: annual energy required for each charger type (GWh)

$CHARBHV_{charger\ type}$: charging behaviour or usage percentage amongst the different charger types (%)

$CHARACC_{charger\ type}$: access to charger (home charger: 95%, the rest of chargers: 100%)

Supply Side

Annual electric energy delivered by each charger type is calculated using equation (4) as the result of multiplying recharging efficiency or losses from plug to battery, the availability of each charger during the day, the ratio of total electric energy delivered to the total maximum energy capacity (charger at maximum power of 24 hours in 7-day period), and the average power level than can be delivered by a charger in one hour.

$$\boldsymbol{ENERDLVCHAR_{charger\ type} = CHAREFF_{charger\ type}.AVAILYEAR_{charger\ type}.ENERATIO_{charger\ type}.CHARPWR_{charger\ type}.24.365} \quad \mathbf{4} \qquad \mathbf{(4)}$$

where

$ENERDLVCHAR_{charger\ type}$: annual electric power delivered by each type of charger (GWh)

$CHAREFF_{charger\ type}$: recharging efficiency or losses from plug to battery (%)

$AVAILYEAR_{charger\ type}$: availability or uptime during the day (%)

$ENERATIO_{charger\ type}$: energy use ratio (%) or the ratio of total energy delivered to the total max power capacity (charger at maximum power of 24 hours in 7-day period)

$CHARPWR_{charger\ type}$: average power level can be delivered by a charger in one hour (kW)

As shown in equation (5), the number of needed chargers is calculated by dividing the annual power required for each charger type, obtained by the equation (3), by the annual power delivered by each charger type obtained inequation (4). The number of public chargers is the sum of all chargers that belong to public charger categories as given in the equation (6).

$$\boldsymbol{NBCHAR_{charger\ type} = \frac{ENEREQCHAR_{charger\ type}}{ENERDLVCHAR_{charger\ type}}}\ldots \quad \textbf{(5)}$$

where

$NBCHAR_{charger\ type}$: number of chargers needed by charger type (GWh)

$ENEREQCHAR_{charger\ type}$: annual energy required for each charger type (GWh)

$ENERDLVCHAR_{charger\ type}$: annual energy delivered by each type of charger (GWh)

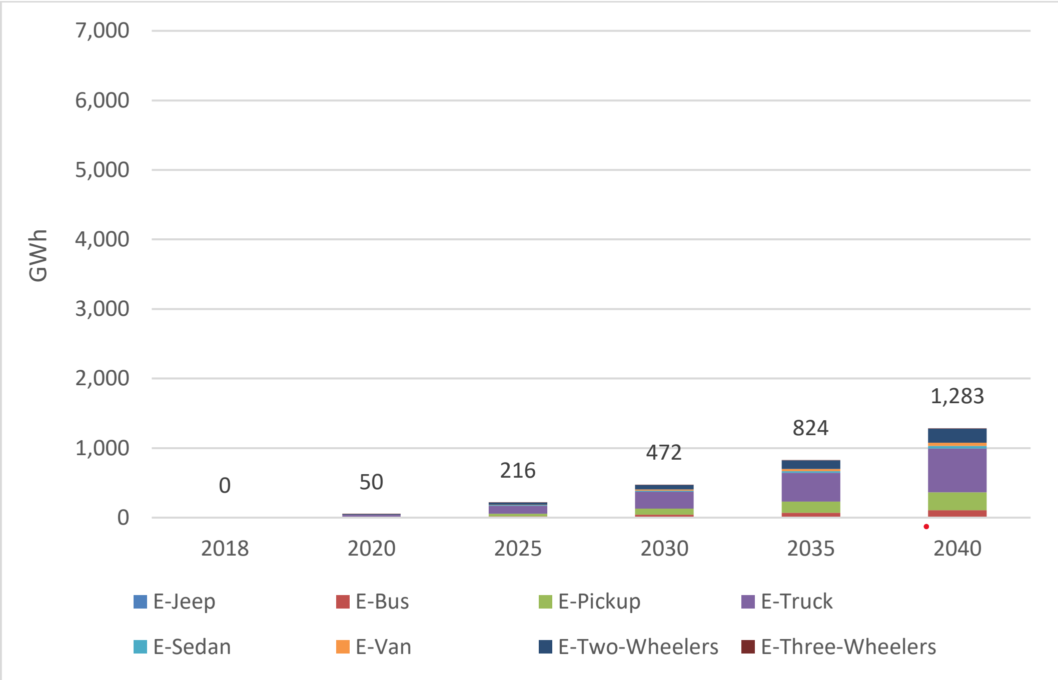
$$\boldsymbol{TOTNBCHAR = \sum\nolimits_{charger\ type \in public} NBCHAR_{charger\ type \in public}} \quad \textbf{(6)}$$

3.2. Results

Electricity Demand of Road Transport Vehicles

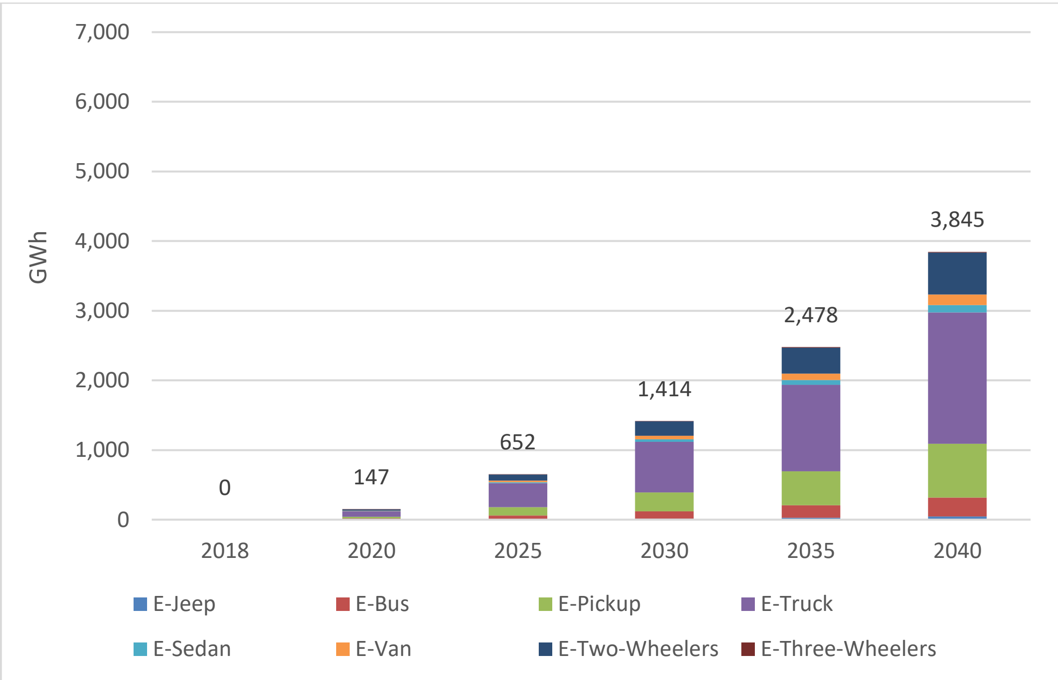
The demand for electric power to feed electric vehicles in three scenarios, i.e., EV10, EV30, and EV50 was calculated in the previous chapter in section 5. Figure 2.3 to Figure 2.5 show the electricity needed in the three scenarios differentiated by electric vehicle types, i.e., e-jeep, e-bus, e-pick up, e-sedan, e-truck, e-van, e-two-two-wheelers, and e-three-three-wheelers. In the three scenarios we can see that e-trucks would need almost 50% of the total electric power and therefore have the lion share of the electricity for the electric vehicles. With around 20%, e-pick ups' electricity demand share would be the second highest, whilst e-two wheelers' share would be the third highest (15%).

Figure 2.3: Electricity Demand of Road Transport Vehicles in EV10 Scenario



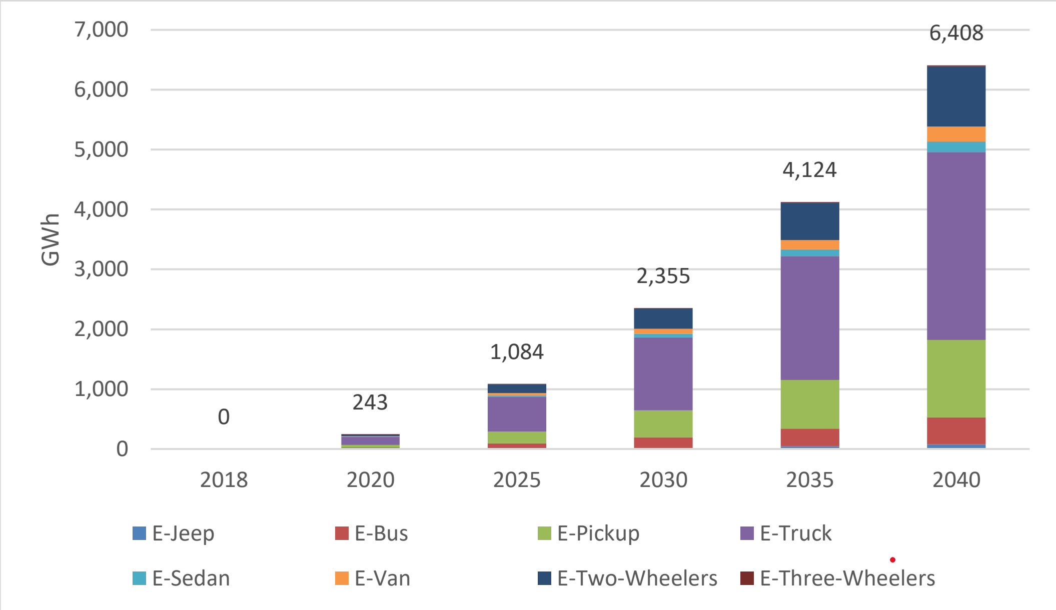
GWh = gigawatt hour.
Source: LEAP Model run (2021).

Figure 2.4: Electricity Demand of Road Transport Vehicles in EV30 Scenario



GWh = gigawatt hour.
Source: LEAP Model run (2021).

Figure 2.5: Electricity Demand of Road Transport Vehicles in EV50 Scenario



GWh = gigawatt hour.
Source: LEAP Model run (2021).

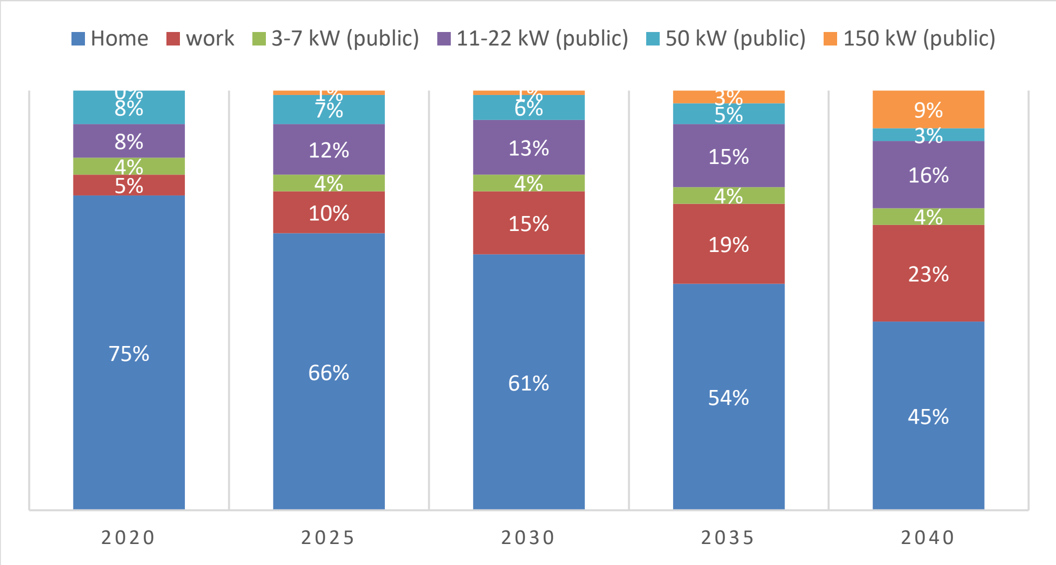
Electricity Demand by Charger Type

To calculate the electricity demand by charger type, as determined by equation (3) we need to have charging behaviour, i.e., the distribution of energy shares amongst the different charger types. As shown in Figure 2.6, we assume that home charging would constitute 75% of the electricity at the beginning of the electric vehicle penetration period and this share would decrease to reach only 45% of the share by 2040. By this time, the power share of faster charger types should grow, and we assume that by 2040, 23% of power would be obtained at work, 4% at 3–7 kW public chargers, 16% in 11–22 kW public chargers, 3% in 50 kW public chargers, and 9% in 150 kW public chargers. The total private (home and work) power share would decrease then from 80% in 2020 to 68% in 2040, whilst that of public charging would increase from 20% in 2020 to 32% in 2040.

For comparison, in 2020, the average charging behaviour in the EU countries as reported in Transport & Environment (2020) consisted of around 45% home charging, 15% charging at work, 10% 3–7 kW public chargers, almost 15% 11–12 kW public chargers, and around 1% 150 kW superfast chargers. By 2030, the estimated average charging behaviour in the EU countries as reported in the same study would consist of around 60% home charging, 30% charging at work, 10% 3–7 kW public chargers, almost 20% 11–12 kW public chargers, and around 3% 150 kW superfast chargers.

The average charging behaviour in the Lao PDR in 2040 was then assumed to be just slightly better than that of the EU countries in 2020 in term of share of private chargers (home and work) and the penetration of superfast 150 kW chargers. The assumption of strong use of 150 kW chargers was taken considering the high demand of electricity of heavy-duty electric vehicles especially e-trucks, penetration in the Lao PDR as shown in Figures 2.3, 2.4, and 2.5. E-trucks should be equipped with big batteries that would need to be charged rapidly using super-fast chargers.

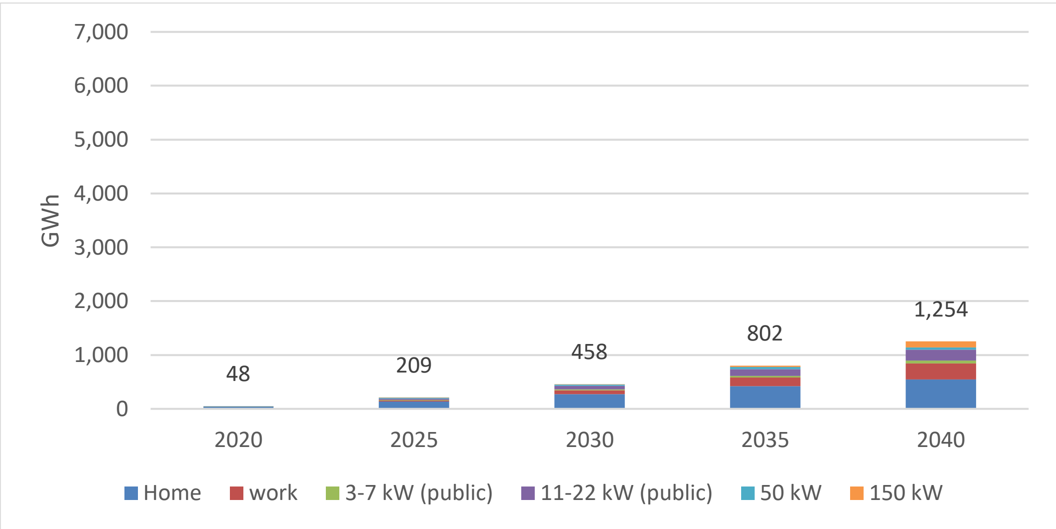
Figure 2.6 :Charging Behaviour Assumption



kW = kilowatt.
Source: Authors' elaboration.

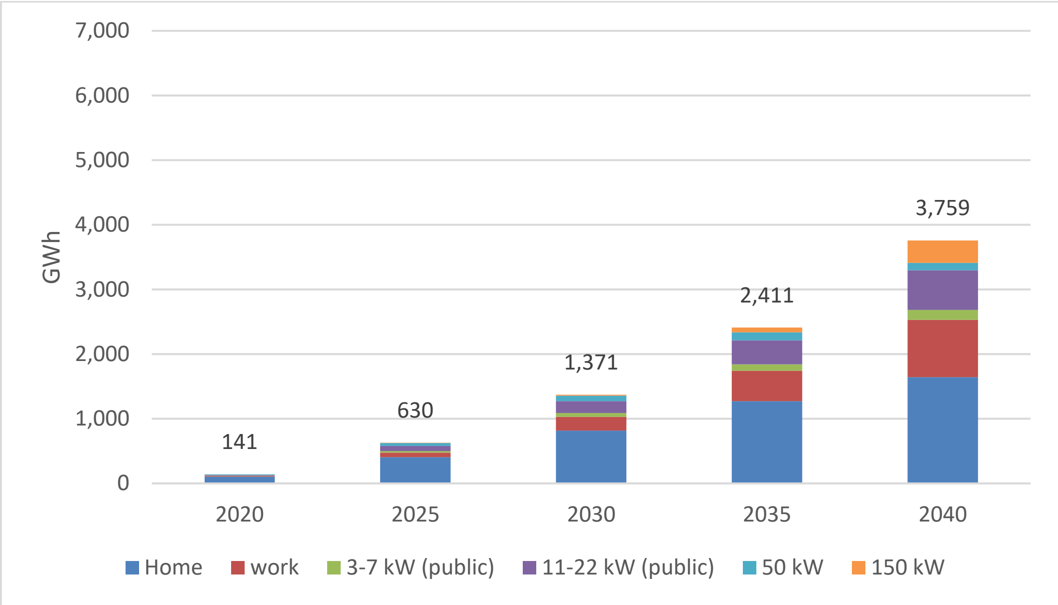
Assuming that public chargers would be 100% accessible and private chargers 95%, the electricity demand by charger types in the three scenarios are given in Figure 2.7, 2.8, and 2.9.

Figure 2.7: Electricity Demand by Charger Type in EV10 Scenario



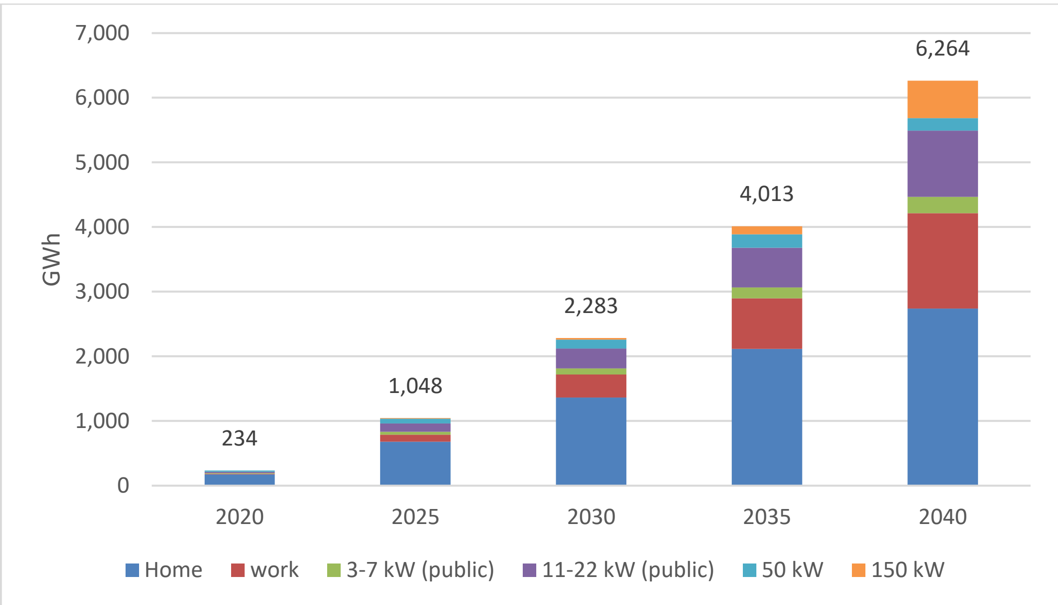
GWh = gigawatt hour, kW = kilowatt.
Authors' calculation.

Figure 2.8: Electricity Demand by Charger Type in EV30 Scenario



GWh = gigawatt hour, kW = kilowatt.
Source: Author's calculation.

Figure 2.9: Electricity Demand by Charger Type in EV50 Scenario



GWh = gigawatt hour, kW = kilowatt.
Source: Authors' calculation.

The 95% accessibility assumption for private home chargers means that not all users live in dwelling units with garages that are equipped with electric plugs that can be used to charge their electric vehicles. Users who do not have a garage or live in flats without individual indoor parking spaces are amongst the 5%. In consequence, the total electric power needed by the electric vehicle fleet given in Figures 2.3, 2.4, and 2.5 are then slightly higher than the total electricity needed by chargers.

Table 2.5 shows three other important assumptions from the supply side, i.e., the availability or uptime of chargers, recharge efficiency or losses from plug to battery, and the average charging power of each charger type.

Uptime of chargers is assumed to increase from 95% in 2020 to 99% in 2040, whilst recharge efficiency is assumed to be constant at 95% during the analysed period.

Table 2.5. Assumptions on Availability (AVAILYEAR), Efficiency (CHAREFF), and Charging Power (CHARPWR)

	2020	2025	2030	2035	2040
Availability (or uptime)	95%	96%	97%	98%	99%
Recharge efficiency (losses from plug to battery)	95%	95%	95%	95%	95%
Average charging power (kW)					
Home	5.0	5.0	5.0	5.0	5.0
work	5.0	5.0	5.0	5.0	5.0
3–7 kW (public)	5.0	5.0	5.0	5.0	5.0
11–2–22 kW (public)	15.0	15.0	15.0	15.0	15.0
50 kW (public)	50.0	50.0	50.0	50.0	50.0
150 kW (public)	150.0	150.0	150.0	150.0	150.0

kW = kilowatt.
Source: Authors' estimation based on Transport & Environment (2020).

Table 2.6 and Table 2.7 show two distinct assumptions of energy use ratio, which is the ratio of total energy delivered with the total maximum energy capacity, i.e., charger at the maximum power 24 hours x 7 days. Assumption 1 (Table 2.6) signifies that energy ratios of all public chargers would increase gradually from 2020 to 2040. Assumption 2 (Table 2.7) signifies that energy use ratios of public chargers will only increase between 2020 and 2025. From 2025 onwards the energy use ratios of public chargers stay constant.

Table 2.6: Assumption 1: Increasing Energy Use Ratio in Public Charging from 2020 to 2040

	2020	2025	2030	2035	2040
Home	12.0%	12.0%	12.0%	12.0%	12.0%
Work	12.0%	12.0%	12.0%	12.0%	12.0%
3–7 kW (public)	3.0%	5.0%	7.0%	10.0%	14.0%
11–22 kW (public)	1.0%	2.0%	3.0%	5.0%	8.0%
50 kW (public)	1.0%	2.0%	2.0%	4.0%	7.0%
150 kW (public)	0.0%	1.0%	1.0%	3.0%	5.0%

kW = kilowatt.
Source: Authors' assumptions.

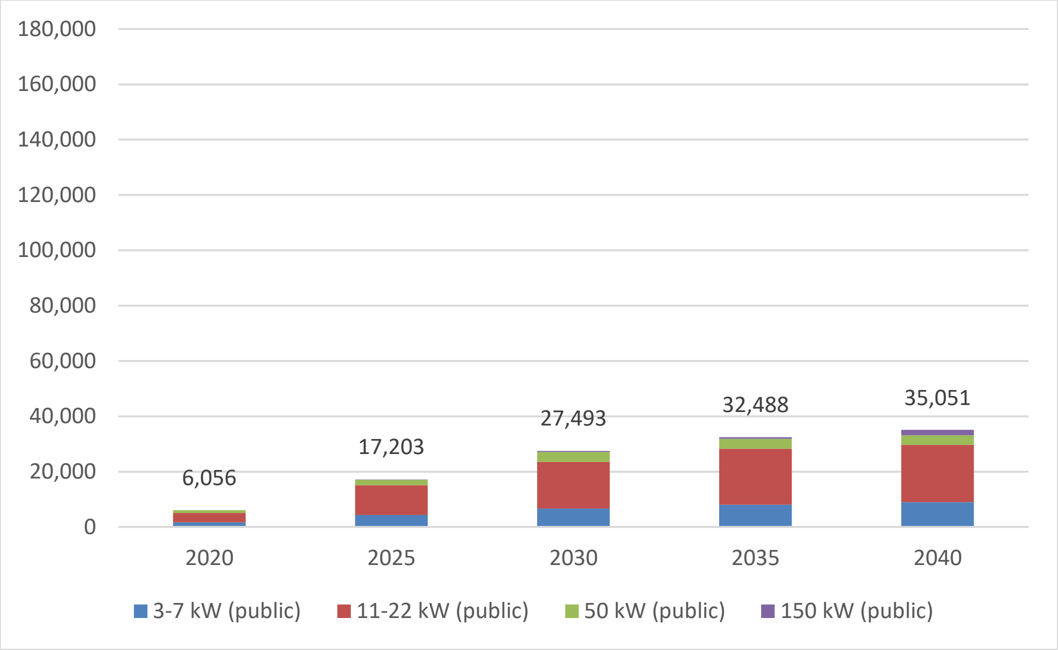
Table 2.7: Assumption 2: Constant Energy Use Ratio in Public Charging from 2020 to 2040

	2020	2025	2030	2035	2040
Home	12.0%	12.0%	12.0%	12.0%	12.0%
Work	12.0%	12.0%	12.0%	12.0%	12.0%
3–7 kW (public)	3.0%	5.0%	5.0%	5.0%	5.0%
11–22 kW (public)	1.0%	2.0%	2.0%	2.0%	2.0%
50 kW (public)	1.0%	2.0%	2.0%	2.0%	2.0%
150 kW (public)	0.0%	1.0%	1.0%	1.0%	1.0%

kW = kilowatt.
Source: Authors' assumptions.

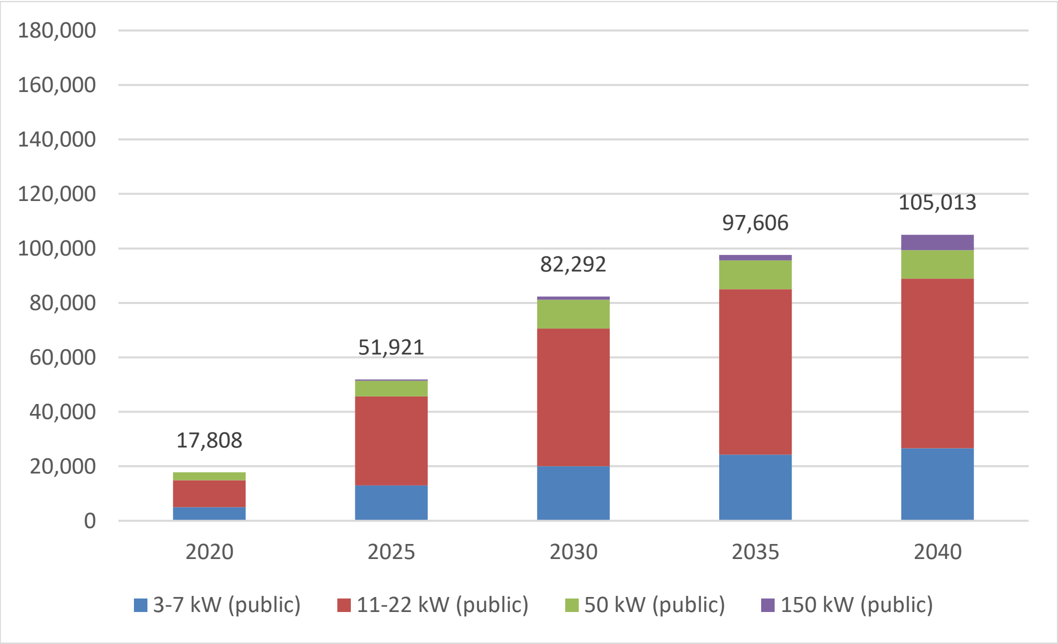
The effects of the two assumptions are seen in the calculated number of public chargers. As shown in Figure 2.10, 2.11, and 2.12, under Assumption 1 where the energy use ratios increase gradually from 2020 to 2040, the total number of public chargers would grow at an annual rate of around 9.3% in the three EV scenarios. By 2040, 11–22 kW chargers would comprise 59% of the total chargers, whilst 3–7 kW chargers would comprise around 25%, followed by 50 kW chargers (10%), and 150 kW chargers (5%).

Figure 2.10: Number of Public Chargers – EV10 Scenario – Energy Use Ratio Assumption 1



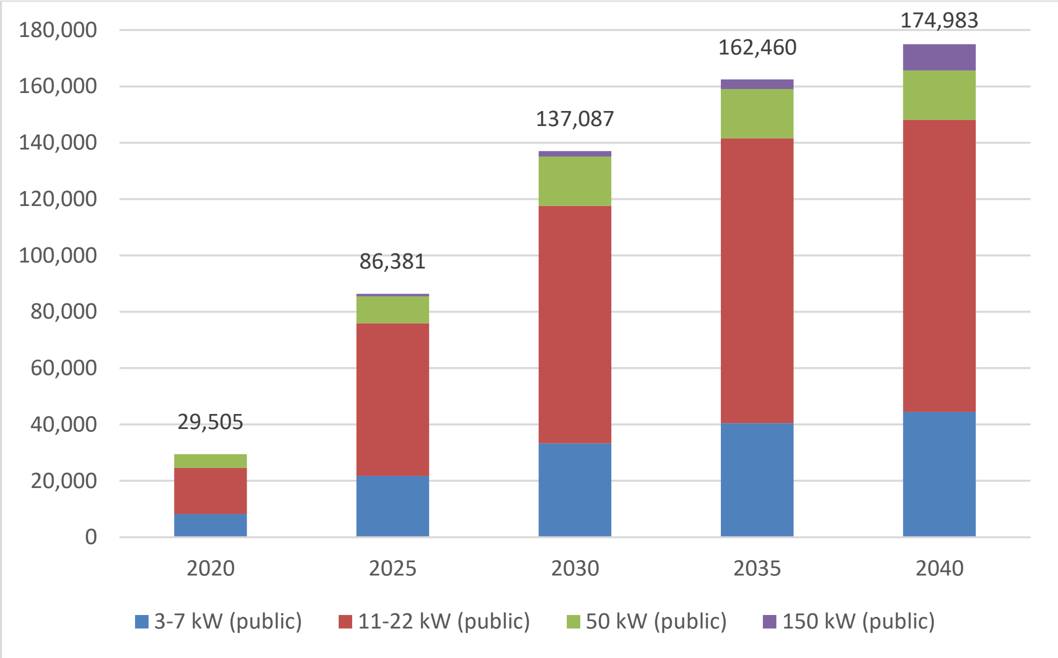
kW = kilowatt.
Source: Authors' calculation.

Figure 2.11: Number of Public Chargers – EV30 Scenario – Energy Use Ratio Assumption 1



kW = kilowatt.
Source: Authors' calculation.

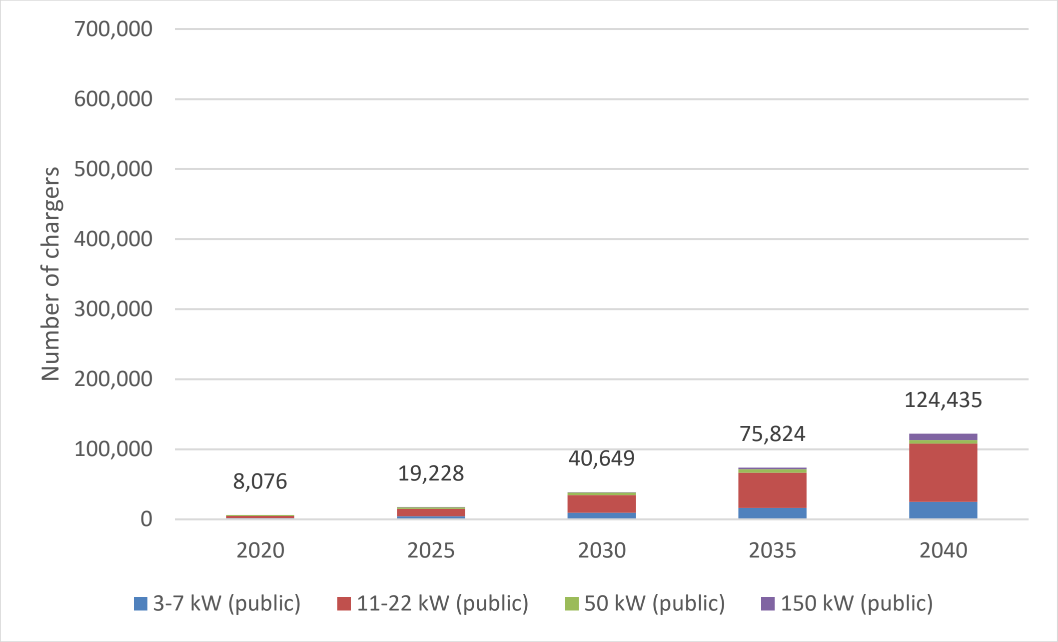
Figure 2.12: Number of Public Chargers – EV50 Scenario – Energy Use Ratio Assumption 1



kW = kilowatt.
Source: Authors' calculation.

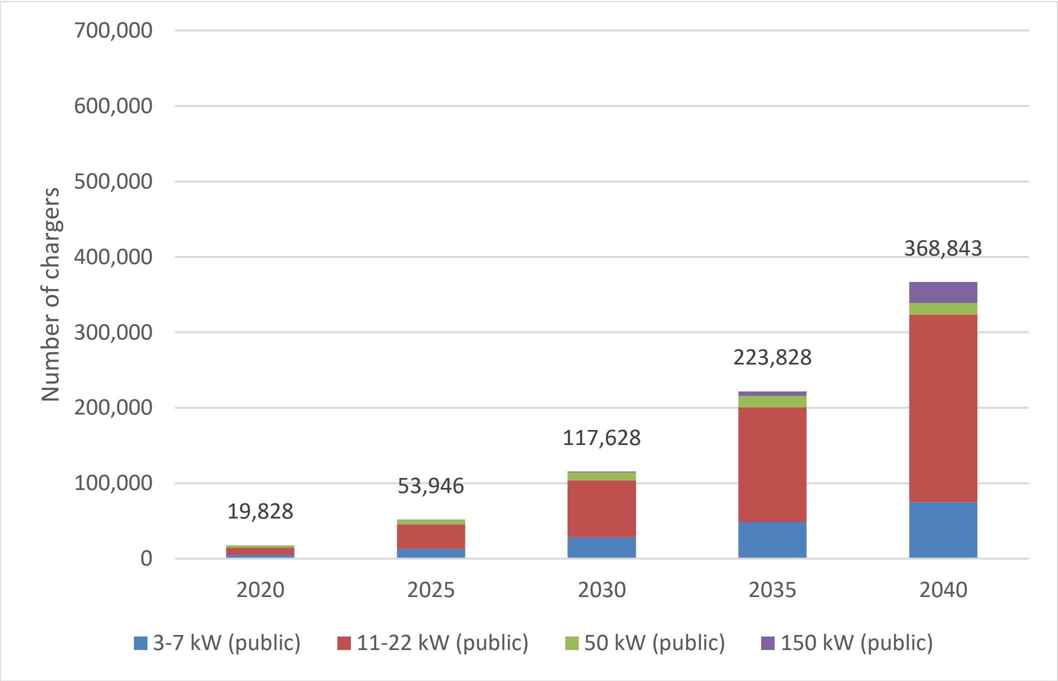
As shown in Figure 2.13, 2.14, and 2.15 , under Assumption 2 where the energy use ratios are assumed to remain the same between 2025 to 2040, the total number of public chargers would grow at an annual rate of around 16.3% in the three EV scenarios, which is faster than that of Assumption 1. By 2040, 11–22 kW chargers would comprise 68% of the total number of chargers, whilst 3–7 kW chargers would comprise around 20%, followed by 50 kW chargers (5%), and 150 kW chargers (8%).

Figure 2.13: Number of Public Chargers – EV10 Scenario – Energy Use Ratio Assumption 2



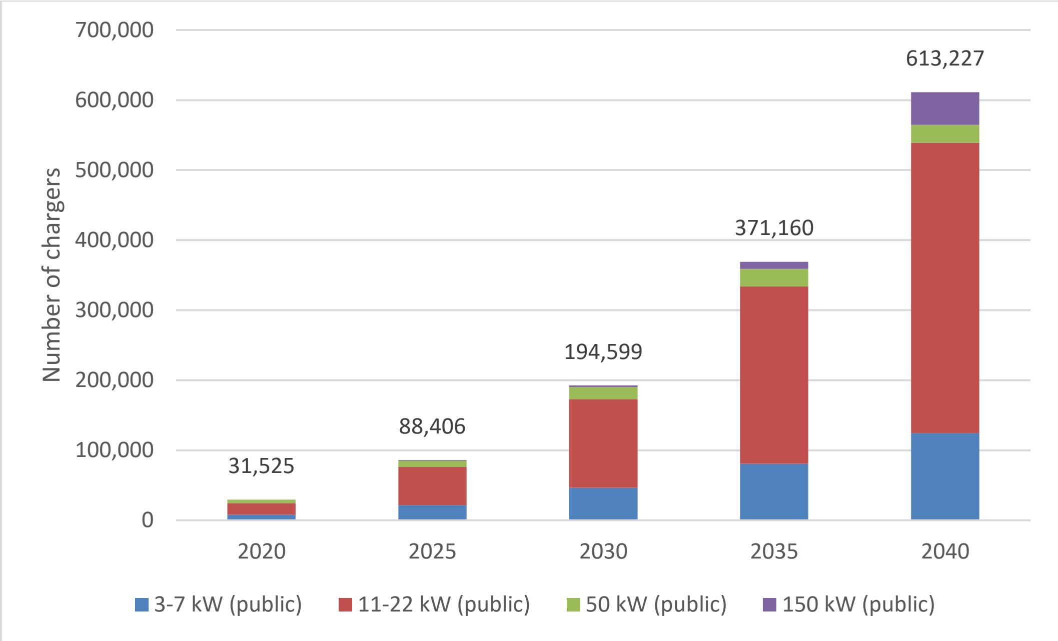
kW = kilowatt.
Source: Authors' calculation.

Figure 2.14: Number of Public Chargers – EV30 Scenario – Energy Use Ratio Assumption 2



kW = kilowatt.
Source: Authors' calculation.

Figure 2.15: Number of Public Chargers – EV50 Scenario – Energy Use Ratio Assumption 2

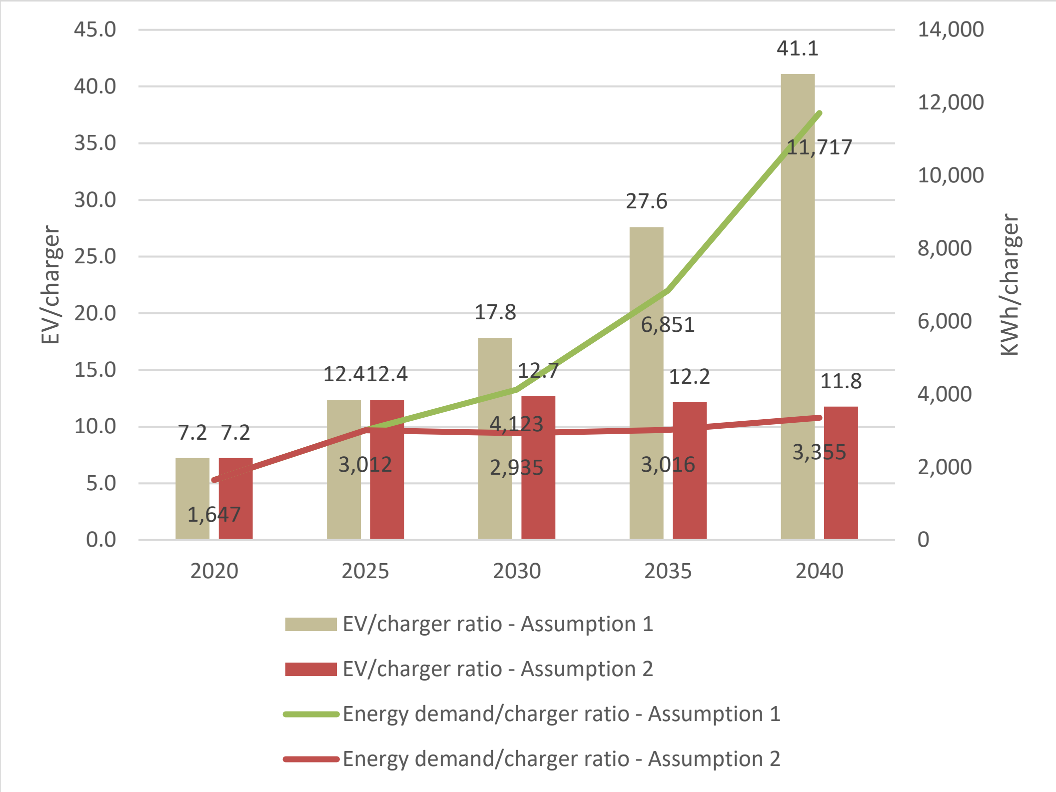


kW = kilowatt.
Source: Authors' calculation.

Figure 2.16 shows two additional indicators, i.e. the ratio of electric vehicles to chargers and the ratio of electric power consumption to charger. The increasing energy use ratios keep the number of chargers relatively low, therefore the ratio of electric vehicles to the number of chargers would increase from 7.2 units of electric vehicle per charger in 2020 to 41.1 units of electric vehicle per charger in 2040. In contrary, the stable energy use ratios between 2025 and 2040 in Assumption 2 means faster growth of the number of chargers and automatically the ratio of the number of electric vehicles to the number of charges remain relatively low, i.e., 12.4 in 2025 to 11.8 in 2040.

The ratio of electric power per charger would also increase in Assumption 1, from 1.647 GWh per charger in 2020 to 11.717 GWh per charger in 2040. In contrary under Assumption 2, the ratio of consumed power would remain relatively constant, i.e. 3.012 GWh per charger in 2025 to 3.355 GWh per charger in 2040.

Figure 2.16: Two Indicators of Charging Infrastructure



EV = electric vehicle, kWh = kilowatt hour.
Source: Authors' calculation.

Increasing energy use ratios would avoid the need for constructing more charging infrastructure. However, fewer chargers would also mean more power load on each charger, and this might also trigger less comfort for users such as longer waiting times or longer queues in charging stations or even longer travel distances and times to reach those stations.

In the other direction, building more chargers would avoid high power load on chargers and increase comfort for users. However, building more chargers means the need for more costly investment.

We took some installation costs per charger from various sources in Table 2.8 to calculate the total costs of installing chargers in the two assumptions for each of the three scenarios.

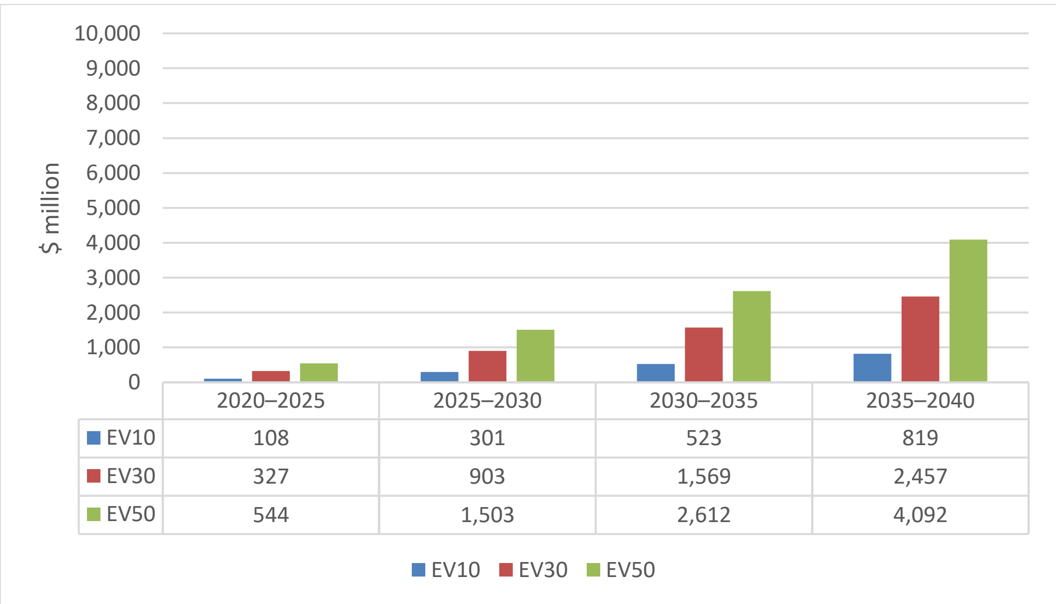
Table 2.8: Assumed Installation Costs

Power (kW)	Installation cost per charging point	Currency	Country	Sources	$	Kip (million)
7.2	69,000	฿	Thailand	https://www.futurecharge.co.th/	2,154	20
22	95,000	฿	Thailand	https://www.futurecharge.co.th/	2,966	28
50	25,000	€	Germany	NPE (2018)	29,769	282
150	50,000	€	European Union	Spöttle et al. (2018)	59,538	565

kW = kilowatt.
Source: Authors' compilation.

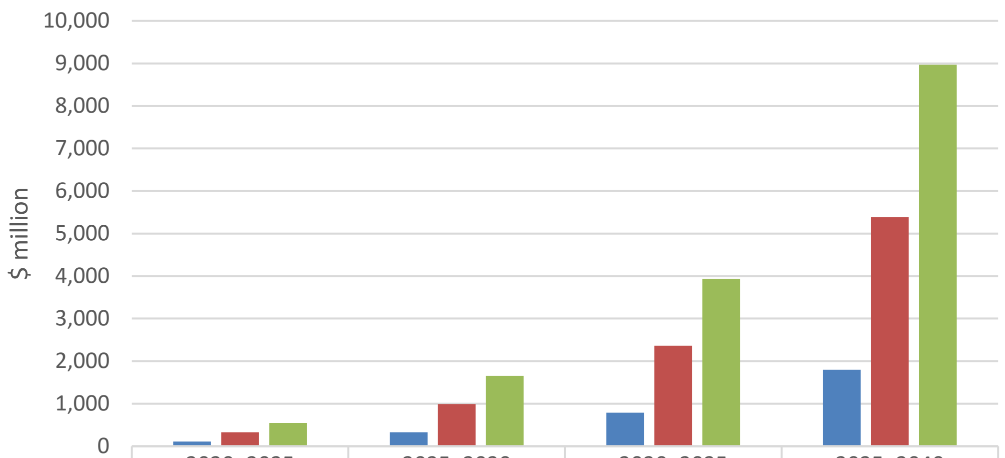
Under Assumption 1 where energy ratios are increased to keep the number of chargers relatively low, the accumulative costs might reach from around $819 million to $4,092 million by 2035–2040 (Figure 2.17). Under Assumption 2 as shown in Figure 2.18, where the number of chargers increases, total cumulative costs by 2035–2040 would reach between $1,794 million to $8,965 million. The accumulative costs of Assumption 2 are therefore more than double Assumption 1 in each scenario.

Figure 2.17: Accumulative Cost – Energy Ratio Assumption 1



Source: Author's calculation.

Figure 2.18: Accumulative Cost – Energy Ratio Assumption 2



	2020–2025	2025–2030	2030–2035	2035–2040
EV10	108	331	787	1,794
EV30	327	995	2,364	5,383
EV50	544	1,657	3,936	8,965

Source: Authors' calculation.

4. Optimal Deployment of Charging Infrastructure

The public charging supply-cost model as demonstrated in section 3 is a simple method to determine the number of chargers needed in a region at a highly aggregated spatial level such as country, the type of charger needed, and the impacts of the possible solutions to the demand side as indicated by the ratio of electric vehicles per charger, to the supply side as indicated by the electricity consumption per charger and to the cost of charger roll-out.

To deploy electric vehicle charging infrastructure at the lower spatial level such as cities or municipalities, we need to determine not only the number of chargers, their required type, but also the spatial distribution of those chargers in a determined period. The research questions are then how many chargers should be built, the required type, and where.

Many types of approach exist to locate and optimise EV charge point locations answering the above research questions. Most studies focus on demand modelled by demographic, traffic, or individual trip data. Two types of approach are usually combined to answer those questions. The first type is the transportation approach that focuses on the transportation perspective such as mobility flows, road network configuration, and travel demand. The second type is the electric approach that considers factors such as demand from electric vehicles, user behaviour patterns, electric grid infrastructure, aim to locate charging stations in power systems such that their capacity and security requirements are satisfied, and the investment costs needed to upgrade them are minimised The following paragraphs illustrate some recent research work that looks for deploying optimally electric vehicle charging infrastructure.

Wagner, Götzinger, and Neumman (2013) for example is based on a transportation approach. Using data from Amsterdam, amongst the cities in the world with the highest number of EV users, the research first investigated the influence of possible local trip destinations of EV owners on charging point usage. The trip destinations, so called 'points of interest' (POI), were grouped in 92 different categories, and proved that these POIs have significant influence on the actual charging behaviour of EV owners in Amsterdam. A ranking procedure to rate individual POIs based on the surrounding charge point usage behaviour was developed and the individual POI ranking contributed to the POI category ranks, which in turn was used to assess the 'charge point attractiveness' of selected urban areas.

A location model was finally built to provide city planners with the optimal locations for new charging point infrastructure not only based on POI locations but also, spatially, in demand coverage.

Tian et al. (2018) proposed an optimisation model of charging stations that was based on waiting time. The target of this optimisation model was to minimise the time cost to electric vehicle drivers. Even if their main objective is from the transportation perspective, i.e. reduction of driver's time cost, Tian et al. (2018) proved the necessity of EV driver behaviour prediction, i.e., the estimation whether drivers choose to charge EVs at a point in time. When the EV driver chooses to charge his vehicle, there are several optional charging stations in the range of the distance that the remaining power can support.

EV drivers might go to the nearest charging station, but they might need to wait to charge. The waiting time might be lower if they chose to go to the second nearest and the total time cost for charging would be less than that for the nearest station.

The total time cost without behaviour prediction of EV drivers is 27.28% more than the total time cost in driver behaviour prediction mode, and the average waiting time is 1.68 minutes more.

Tian et al. (2018) built a queuing model based on the number of drivers (vehicles) that are predicted to go to each station and the station capacity, based on which the waiting time is calculated. Finally, an optimisation model is built to determine the location of charging stations based on the minimised charging time cost.

The last example, i.e. Mourad and Hennebel (2020) developed a mathematical formulation aiming at maximising the covered recharging demand, whilst respecting investment budget limits and the available capacities provided by the electric grid. With the main objective at finding the optimal locations for deploying EV charging stations and finding the number of chargers that need to be installed at each charging station, they considered the different mobility flows and recharging demands as well as the constraints imposed by the available electric grid and the availability of alternative energy sources, i.e., photovoltaic.

Having the maximisation of the total covered charging demand based on the covered paths as the objective function, Mourad and Hennebel's mathematical model had several constraints:

- the sum of location costs and charger installation costs does not exceed total budget limit
- a minimum of the overall charging demand must be satisfied
- charging demands for vehicles and trucks at each path must be satisfied
- the number of fast chargers (for vehicles and trucks) to be installed must be within the specified limits at each charging location
- the electric power required to operate the installed chargers does not exceed the available electric capacity at the charging locations

Mourad and Hennebel (2020) started by defining a set of coupling nodes, a set of potential charging locations, and a set of mobility paths that represented electric vehicle flows and their recharging demands. Through a case study on the Paris Saclay area in the Île-de-France region in France, the research obtained the optimal locations for deploying EV charging stations as well as the number of chargers that need to be installed at each charging station.

5. Facilitating Charging Infrastructure Investment

Developing charging infrastructure needs significant investment. The public sector cannot bear the total burden and needs to attract private investors. The main challenge is convincing investors that the investment will be profitable as there are not yet enough EVs on the road.

Some EV front-runner country strategies for rolling-out charging facilities are summarised below.

5.1. China

The world leader in the number of EVs sold, China started in 2009 with the '10 cities, 10,000 vehicles' business model to promote EV development, but established targets only in June 2012: 500,000 vehicles by 2015 and 5 million by 2020.

The programme's first step was top-down selection of experimental sites where the central government could either test policy or try out innovative practices. The second step – evaluation and absorption – combined bottom-up and top-down approaches. Central government agents evaluated the performance of pilot projects, whilst local participants reported their progress to the central authorities, documenting the most advanced practices for wider diffusion. The third step – diffusion by the central government – popularised successful practices through the media and endorsement by leading politicians. The final step was the learning and feedback loop (Marquis, Zhang, and Zhou, 2013).

Five models were created in the pilot cities: state leadership in Beijing based on public sector support; platform-led business in Shanghai replicating international models; cooperative commercialisation in Shenzhen based on a leasing model through strategic partnership; flexible rental in Hangzhou; and fast-charging models in Chongqing, which is close to the Three Gorge Power Grid.

The city-based pilot programmes, however, focused on local goals and firms rather than a long-term national agenda. Competition for central government support eroded cities' willingness to cooperate with each other on setting national or international standards and goals; manufacturers or players were barred from entering other cities.

5.2. United States

EVs are becoming more popular in the US. California leads with 2% PEV share of total road vehicles, followed by Hawaii (1.2%), Colorado (0.56%), Texas (0.23%), and Ohio (0.15%). Measures in urban areas promoted PEV charging facilities include:

- development of make-ready locations by utilities that would support a variety of third-party charging stations (California, Colorado);
- implementation of TOU rates that encourage users to charge during off-peak periods (California, Ohio, Hawaii);
- provision of significant rebates of charging development for the private sector (Colorado, Texas); low-interest loans for businesses, non-profit organisations, public schools, and local governments for installing charging stations (Ohio); and grants to build stations (Texas);
- legal framework that favours private ownership of charging stations by allowing private companies to resell electricity supplied by a public utility to charge EVs (Colorado);
- partnership between public utilities and private companies in developing and operating charging stations (Texas); and
- explicit right to site charging on premise for multifamily dwellings and townhouses (Hawaii) (Fitzgerald and Nelder, 2017).

5.3. Europe

Measures taken by two PEV front-runner European countries – the Netherlands and Germany – are summarised below:

- **The Netherlands**. Between 2010 and 2014, seven grid operators (state owned and regional) invested in developing charging infrastructure (Living Lab Smart Charging, 2017), which was later included in the Green Deal Electric Driving Programme (2016–2020) backed by a consortium of central and regional governments, grid operators, the automotive sector, and universities. The programme provides funding for public charging poles equally from government, municipalities, and market players, and for installation of the Netherlands Knowledge Platform on Public Charging Infrastructure (Hamelink, 2016). The programme not only develops charging facilities but also the roaming system and implements international protocol standards.

- **Germany**. The country has several financial support programmes at different government levels. The Federal Ministry of Transport's programme for EV charging infrastructure and the regional model of electromobility finance and/or subsidising development of charging infrastructure that require local or private investment.

In other European countries – front-runners or followers – state-owned agencies, with or without big private partners such as grid operators, first financed or organised deployment of charging infrastructure. Agencies or consortia then offered financing programmes to the private sector or local government to develop charging infrastructure.

6. Charging Scheme Strategy

The expansion of PEVs and their demand for charging facilities have become increasingly important. The associated electricity demand will affect energy markets and the grid infrastructure. Studies on Portugal (Nunes, Farias, and Brito, 2015) and the European Union (Kasten et al., 2016) show the impact of EVs once they make up 5%–10% of total road vehicles.

The amount of electricity needed to meet additional demand and the greenhouse gas emissions produced to generate electric power are calculated based on the average of total power plant mix. PEVs' environmental performance would be better than conventional vehicles' performance if additional demand was met by a low-carbon intensive energy mix. Even if there were 300 million electric cars, if power generation was not decarbonised, CO_2 emissions would be insignificantly reduced by less than 1% (Sauer, 2019). Electric vehicles may reduce local pollution but not global emissions.

China, the EV front-runner in Asia, is struggling to curb the share of coal-fired-based electric energy from 75% to 50% and to increase that of renewable sources from 25% to 50% in 2030, bringing down power generation carbon intensity by one-third and ensuring that EVs will be less carbon intensive than they are now. China uses more electricity from coal-fired generating plants during fast charging peak demand periods and after working hours in the evening. Slow charging during off peak hours, when energy from renewables such as wind turbines is available, would reduce CO_2 emissions (Chen et al., 2018).

When and how PEVs are charged determine which generation plants satisfy additional electricity demand and have an impact on emissions. Depending on their total system and marginal costs, different types of power plants may increase production. Including this charging scheme in the analysis might change the calculation results.

Uncontrolled or user-driven charging occurs mostly after work in the evening, when electricity demand is already high, increasing system load and costs of utilities (Brandmayr et al., 2017).

User-driven charging would raise severe concerns about generation adequacy and may jeopardise the stability of the power system (Schill and Gerbaulet, 2015). Fast-charging stations use large amounts of power for short periods of time, meaning that expensive upgrades will be needed for a relatively low use rate (Hall and Lutsey, 2017). In the US, if EVs constitute 25% of all road vehicles, uncontrolled charging would increase electricity peak demand by 19%, but spreading charging over the evening hours would increase demand by only 6% (Fitzgerald and Nelder, 2017).

Reducing carbon emissions and the load on the local grid will be solved only by charging management schemes, some of which are described below.

- **Off-peak or network-oriented charging** includes policies and structures that encourage off-peak-period charging, including workplace or daytime charging and night-time home charging, to avoid network congestion and physical capacity constraints. This strategy should increase system stability and grid functioning but producing electricity during low-demand periods using conventional energy sources might have negative environmental effects.
- **Cost-oriented charging**. This strategy aims to reduce EV charging cost by shifting the charging time to periods of low energy prices. EV owners could benefit from low energy costs, and load patterns might be smoothed as the low charging cost period coincides often with low demand. Additional conventional production during low-cost periods could have negative environmental effects. Some findings are the following (Schill and Gerbaulet, 2015). First, cost-driven charging promotes renewable energy more than user-driven charging, but cost-driven charging might also increase the use of the emissions-intensive lignite power generation. Germany, for example, has the lowest marginal costs for thermal technology and uses more hard coal than user-driven strategies. Second, cost-driven charging reduces unused generated power more than uncontrolled charging. The opposite happens in countries with a high share of renewables, such as Denmark, which has a low share of emissions-intensive generators and a high share of wind power. Using a cost-driven charging system, Germany and the Association of Southeast Asian Nations (ASEAN) countries will reduce CO_2 emissions only if they build more renewable-energy generators. Cost-driven charging will work only if emissions externalities are correctly priced.
- **Smart charging** includes controlled charging and demand response. A simpler solution such as the use of in-vehicle timers to take advantage of TOU rates could help minimise stress on the electrical grid, whilst also saving money for consumers. Smart charging strategies are less practical for DC fast charging than for level-2 charging as drivers expect fast charging to be available on demand (Hall and Lutsey, 2017). As the fast-changing market continues to grow, fast chargers should be placed near adequate high-capacity electrical infrastructure.

- **Combined smart and cost-oriented charging.** Decreasing real time price increases renewable energy share, such as wind as it is available during that period. The variability of wind power drops as its share increases. In this situation, CO2 emissions could be higher than the average of the total power plant energy mix, if coal, for example, due to its low marginal costs, dominates the lower price part of the merit order (Dallinger, Wietschel, and Santini, 2012).
- **Renewable energy-oriented charging** or **low emissions-oriented charging** aims to increase environmental performance or avoid negative impact of greenhouse gases and air pollutant emissions. The measure shifts charging times to periods of high or surplus renewable energy generation, resulting in reduced additional production by conventional plants. However, conditions vary in different energy systems and this strategy requires sufficient renewable power generation to meet additional electricity demand.