C40 CITIES FINANCE FACILITY

ZERO-EMISSION BUS CHARGING SYSTEMS:

INSIGHTS FROM JAKARTA

Contents

About the C40 Cities Finance Facility:

The C40 Cities Finance Facility (CFF) is a collaboration of the C40 Cities Climate Leadership Group and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The CFF supports cities in developing and emerging economies to develop finance-ready projects to reduce emissions to limit global temperature rise to 1.5°C and strengthen resilience against the impacts of a warming climate. The CFF is funded by the German Federal Ministry for Economic Development and Cooperation (BMZ), the Children's Investment Fund Foundation (CIFF), the Government of the United Kingdom and the United States Agency for International Development (USAID).

KEY INSIGHTS

1. **Bus technologies and their requisite charging strategies need to be analysed as a system. It is not necessarily true that shorter routes require smaller batteries and longer routes require larger batteries.**
2. **A strategy that replaces 100% of buses on a designated route with zero-emission vehicles rather than split over multiple routes can make it easier for operators to evaluate deployment and ensure reliable, high-quality information for analysis and decision-making.**
3. **It is necessary to understand the relationship between operational requirements, such as air conditioning, loading and distance, and measured battery range to develop an optimal charging strategy.**
4. **The preferred charging schemes and infrastructure must be considered within the context of local grid capacity and the potential to upgrade capacity in the future.**

Objective of this report

The aim of this report is to provide city officials and practitioners with an understanding of the key elements and considerations involved in determining an appropriate and cost-effective charging system for the deployment of zero-emission buses, drawing on the CFF's experience of supporting Jakarta in planning for the city's first 100 zero-emission buses.

This report is a comprehensive update of an earlier version published in 2020.

Zero-emission bus systems

Deploying zero-emission buses (ZEBs) is not as simple as merely replacing an internal combustion engine (ICE) bus. It calls for a carefully balanced ecosystem of technologies interlinked with social, environmental, financial and operational considerations. Figure 1 illustrates this interlinked approach and highlights the areas covered in this report.

While ZEB technologies include the use of hydrogen and electric trolleybuses, these technologies are just emerging and are their deployment remains largely limited to cities with existing trolleybus infrastructure. Therefore, this report will focus on the core components of battery electric bus technologies (Figure 2). You can find further information on electric trolleybus technologies in Electrifying Bus Routes – Insights from Mexico City's Eje 8 Sur.

City officials will have to take on a range of practical questions, including which routes to electrify first, the size of battery pack needed, the charging speed necessary, the benefits that commuters and the general public can expect, and whether the electricity grid can accommodate the increase in power demand. Making the most informed decisions on these issues will be key to ensuring a successful transition to ZEBs. It is, therefore, important that city officials, decision-makers and operators are familiar with these topics.

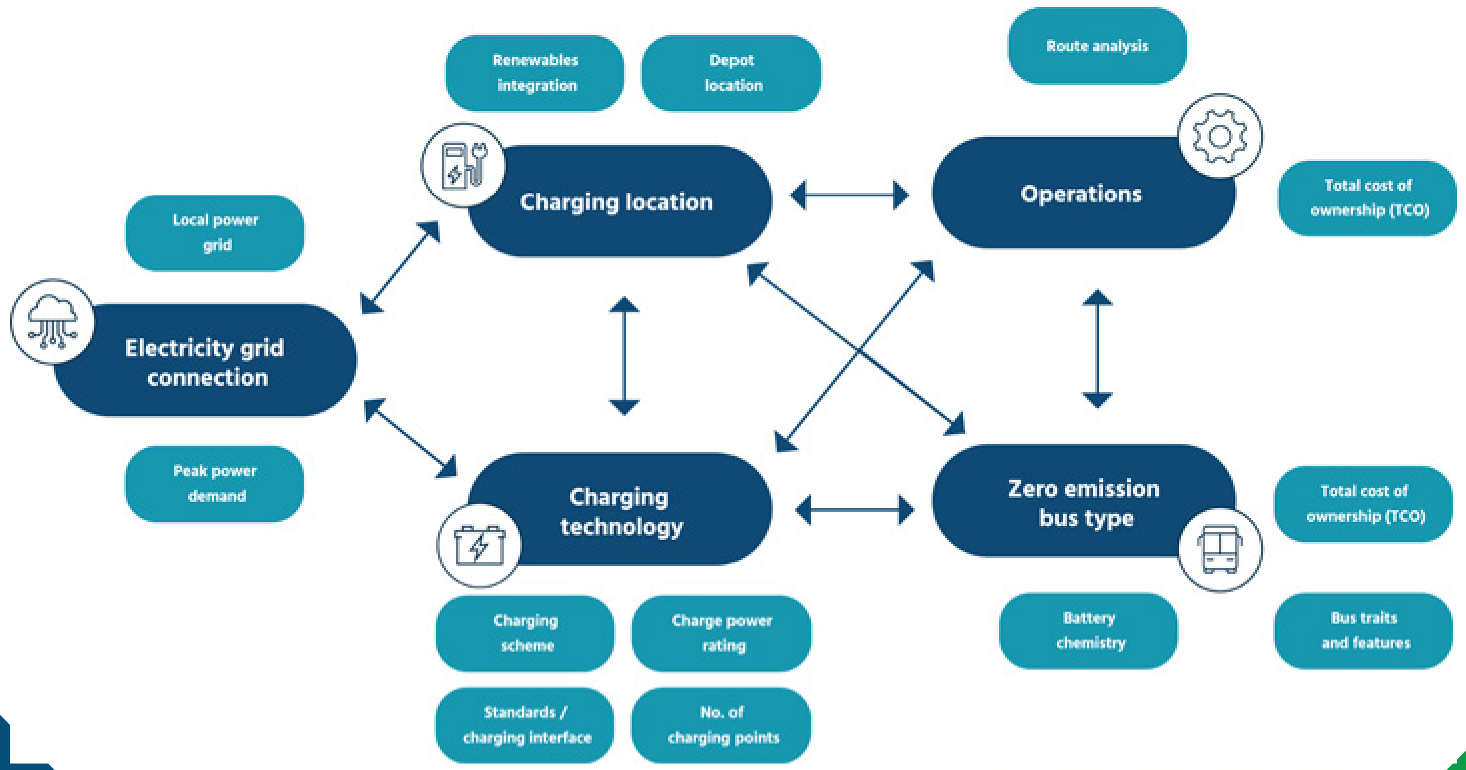

Figure 1. The interlinked considerations when deploying zero-emission buses.

Bus types

Municipal buses vary significantly when it coms to accessibility specifications (low- and high-entry floor, for example), bus height (single or double decker), user capacity, build quality and size – with vehicles ranging from seven-metre minibuses to 24-metre bi-articulated buses. While there are numerous zero-emission bus models available around the world for smaller 9–12-metre capacity buses (though options may be more limited in certain countries or regions), there are fewer options available for 18-metre or double decker buses because of their higher weight. Many ZEBs also have additional features to provide a better user experience, such as on-board charging points, wireless internet and live passenger information systems.

TransJakarta, a government-owned enterprise that manages the bus rapid transit (BRT) system in the Indonesian capital, has a diverse fleet of 3,700 buses from micro- to articulated buses (Figure 3). It operates a 244 kilometre (km) BRT network comprising 13 main corridors and 155 feeder services that make up hundreds of unique routes.

Gross cost contract

A **gross cost contracting scheme** is a contracting system whereby owners or operators of private bus fleets are paid for meeting specific service or performance milestones, such as number of buses provided, or kilometres serviced.

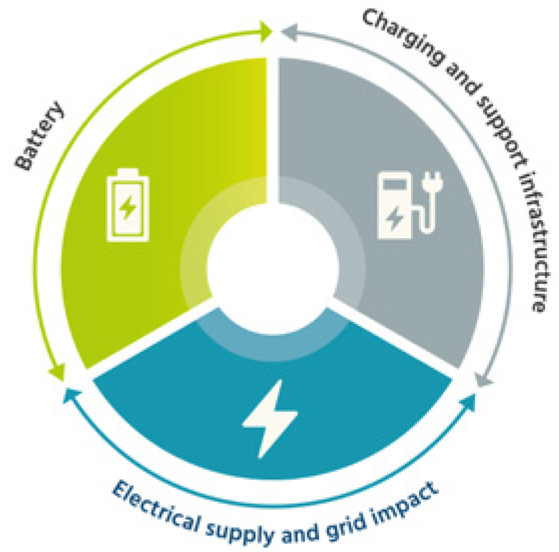

Figure 2. Core components of a zero-emission bus.

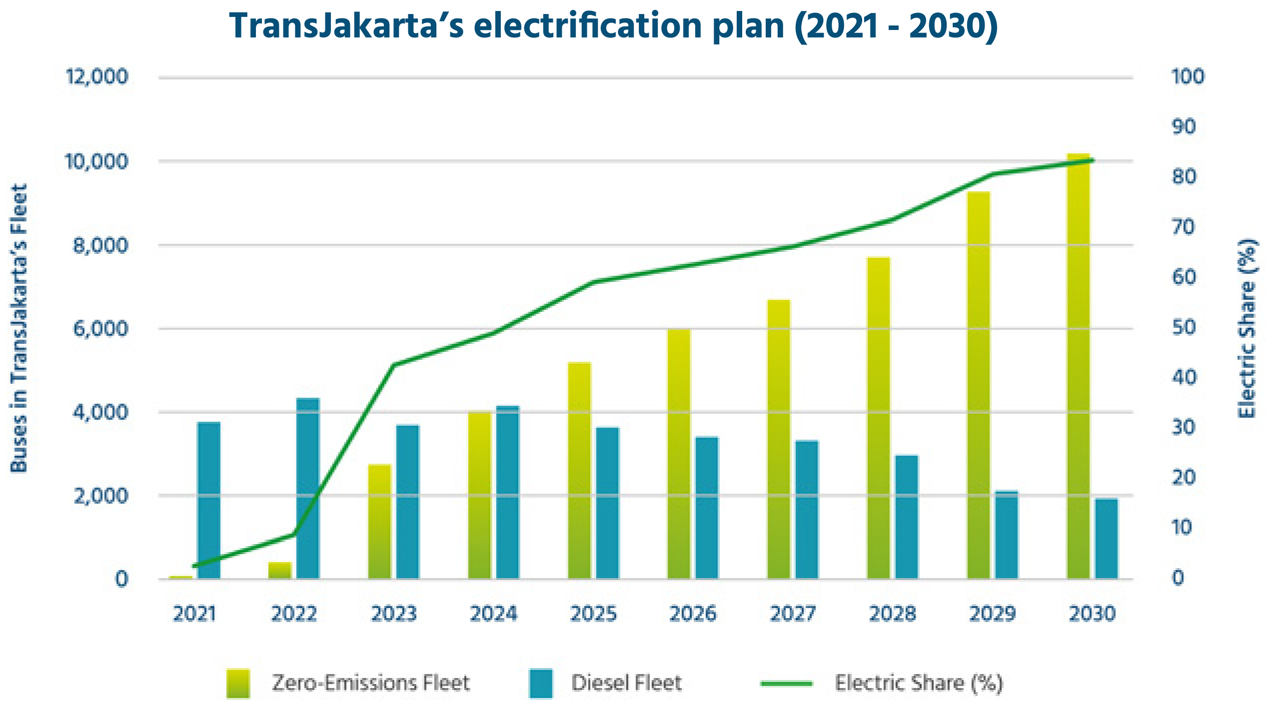

Figure 3. Composition of TransJakarta's bus fleet. Source TransJakarta

Selecting routes

There are many metrics that can help city officials to make an informed choice when selecting the first network bus routes on which to deploy ZEBs. These include passenger ridership, bus availability and daily utilisation, battery range, replacement ratio and total cost of ownership (TCO).

Passenger ridership – The number of people using a particular bus route per day. Routes with the highest ridership are excellent candidates for initial electrification, as they generate high earnings per kilometre, are high profile and can help build confidence among operators.

Bus fleet availability – The extent to which a percentage of the fleet is available for operation (in other words, the percentage of buses not currently being repaired). With effective inspection and maintenance protocols in place, ZEBs typically have significantly lower maintenance costs and better availability. Selecting routes with lower bus fleet availability can result in larger operational savings.

Bus utilisation – An indicator of the extent to which a bus is used on a given parameter. The most common parameters include the number of vehicles in operation as a percentage of total operational vehicles (that is, excluding those that are in for repair). Because of their higher capital expenditure (capex) costs and lower operating costs, select routes with high utilisation rates to reduce the TCO (described below).

Battery range – Batteries have limited ranges, which vary according to factors such as topography, use of air conditioning or heating, passenger loading and battery degradation over time. The ranges can either be estimated or informed by data from trial buses and used to identify routes within the battery range.

Replacement ratio – A ratio of bus utilisation to battery range. This indicates how many ZEBs are needed to replace the existing buses on a particular route. Current ZEB planning does not always result in a one-to-one replacement; this will depend on the route in question and its operational characteristics. Selecting routes with a similar total number of buses is generally the most cost-effective solution. By replacing all of the buses on each route, the collection and analysis of performance data will be better quality and more reliable for future decision-making.

Total cost of ownership (TCO) – The TCO is a metric that incorporates the capex and net present value of ongoing operating costs over the lifetime of a bus. The cost of the bus, the charging infrastructure and operating costs are the major components. TCO is a useful metric enabling comparisons between ZEBs (which have higher capex, but lower operating expenditure (opex) costs) and ICE buses (which have lower capex, but higher opex costs). As TCO is a crucial measure for bus operators, cities that provide subsidies based on kilometres travelled and route-level analyses can support the prioritisation of certain routes over others.

The experience of Jakarta

TransJakarta's preparation for ZEB deployment in Jakarta started with a broad analysis of current bus operations. Expert judgement was used to prioritise which routes to analyse, as it would be impractical to analyse hundreds of unique routes. As the entity chose to fully electrify rather than partially electrify routes, routes that ran along a single or minimum number of corridors were preferable. This resulted in 13 BRT routes and 37 non-BRT routes being studied.

Following the analysis, 6 BRT and 13 non-BRT routes were shortlisted as good candidates for ZEB deployment. Three routes were ultimately selected as having the most advantageous combination of passenger ridership, bus utilisation and fleet availability, replacement ratios and TCO. The selection also closely matched TransJakarta's target to initially deploy 100 ZEBs.

Batteries

Perhaps one of the most integral components of a ZEB is its battery pack. Many battery technologies have been developed, but the lithium-ion group is by far the most common in bus applications. The lithium-ion chemistry (see Figure 5) can influence a battery's performance characteristics. The most commonly used electrode chemistries include lithium iron phosphate (LFP), lithium titanium oxide and lithium nickel manganese cobalt oxide (NMC).

Two of the most important considerations when it comes to battery performance are energy density and power density. Energy density, or specific energy, is the capacity to store energy and is typically measured in watt hours per kilogramme (Wh/kg). In general, high specific energy will translate into a longer ZEB range. Lithium-ion battery packs typically have a range of 80-220 Wh/kg.

Power density, or specific power, is the amount of power a battery can output. In general, a higher specific power will enable better ZEB acceleration. Modern batteries already exceed the power density of internal combustion engines, so optimising a battery for greater specific energy is often more useful. The most common battery packs on the market for ZEBs are 180kWh and 324kWh packs, often referred to simply as 'medium' and 'large' batteries. It is important to note that a battery pack's lifespan is typically defined as when it has deteriorated to hold only 80% of its original capacity (though it can have static second-life applications well beyond this point).

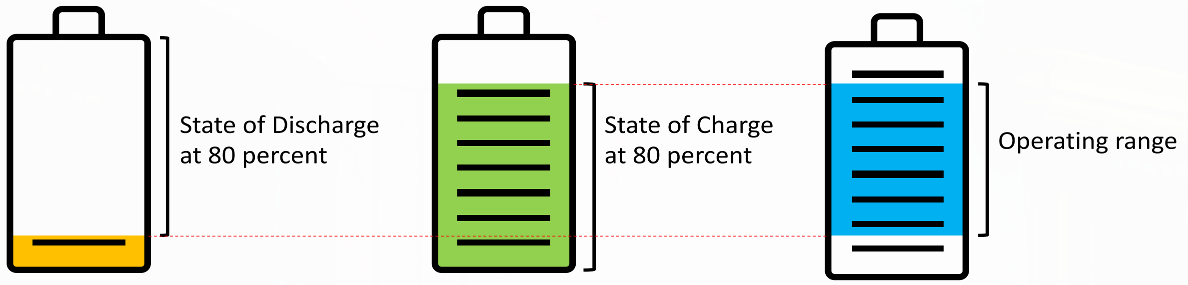

Figure 6. State of charge and discharge.

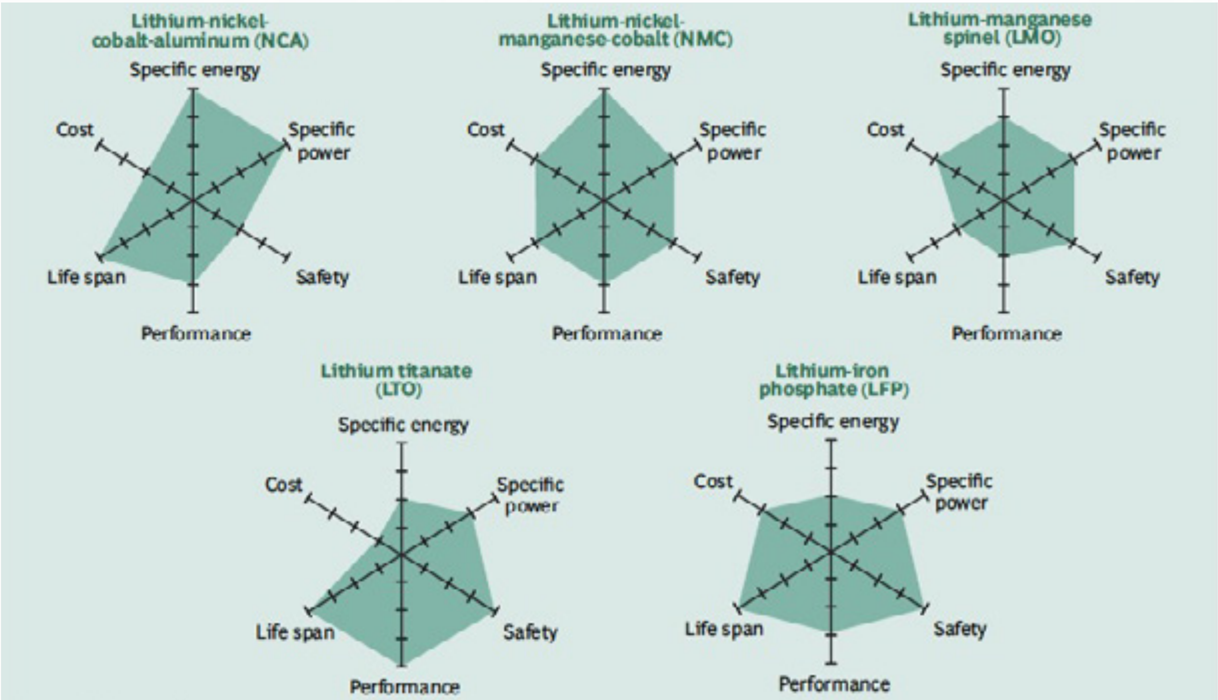

Figure 5: Lithium-ion Chemistries and their Performance Trade-offs.

Source: "Batteries for Electric Cars Challenges, Opportunities, and the Outlook to 2020", Boston Consulting Group

The estimated time for a battery to reach this state of deterioration is measured in cycles, or how many times the battery pack is charged and discharged. Consequently, battery management practices have been put in place to prolong the lifespan of battery packs, including recommended states of charge and discharge, which are often set at 80 percent to keep the battery pack operating at optimum levels (figure 6).

Additional considerations to bear in mind when deciding on battery chemistry include:

Safety – One of the most significant safety risks is 'thermal runaway', typically caused by overcharging, high discharge or short-circuit, to which some battery chemistries are more prone.

Operating temperature – Certain battery chemistries operate differently at various temperatures, so may be better suited to colder or hotter climates.

Cost - The cost of batteries can change considerably and are typically denoted per kilowatt hour (US$/kWh).

Jakarta's zero-emission bus pilot

TransJakarta managed to secure several ZEBs from manufacturers to conduct performance testing for climate and road conditions in Jakarta. Taking into account passenger loading, air conditioning and recommended state of discharge using 12-metre buses, the pilot scheme measured an energy efficiency of about 0.8-1.46 kWh/km.

These findings closely matched the battery performance observed in other tests that looked into factors affecting battery range. In theory, based on these figures, a 324 kWh 'large' battery pack has a theoretical maximum range of 382 km, though several operating factors reduce this significantly, as can be seen in table 2. Taking these operating factors into account results in an operating energy efficiency of around 1.36 kWh/km and a maximum range of 239 km.

Knowing the daily operating range per route including empty kilometres (the distance from the depot to the actual service route) and the battery's operating performance, TransJakarta determined that a 324 kWh battery pack with depot-only charging was the most appropriate option for non-BRT routes. On BRT route 6, in contrast, a 324 kWh 'large' battery pack would not be sufficient to meet the required range, so opportunity charging during the workday would be necessary. To minimise the upfront costs of opportunity charging, a smaller battery, such as a 180 kWh 'medium' battery pack, could be used.

TransJakarta also determined that LFP and NMC batteries were the most appropriate chemical compositions due to their fast-charging capabilities.

Factors which affect battery range	Multiplier	Range (Km)
Theoretical range	-	**382 Km**
Depth of discharge (80%)	x 0.80	305 Km
Air conditioning	x 0.92	281 Km
Passenger loading	x 0.85	239 Km
Operational range	-	**239 Km**

Table 2 – Factors that affect the battery range of a zero-emission bus. Source TransJakarta.

Charging

There are two key aspects that need to be considered:

1. **The charging strategy** - the manner in which and where the buses will be charged, for example, opportunity charging, depot-only or mixed schemes.

2. **Technology and standards** - charging speeds for buses, power ratings, specific connector or socket types based on national standards, and charging types, for example, plug-in or pantograph.

Depot charging involves buses being charged in depots when not in service, typically overnight. A typical ZEB, therefore, will need a sufficiently large battery pack to run continuously throughout the day. The system may require larger upfront costs, but will avoid the more costly infrastructure improvements of an opportunity charging system. However, depot charging may still require significant local grid upgrades to cope with the rise in localised electricity demand.

Opportunity charging involves the installation of charge points along or at the end of a service route. It may replace the need for overnight depot charging, but, in practice, often ends up as a complementary, mixed charging system. It typically employs fast charging (150kW and above) to avoid disrupting the bus timetable. In contrast to depot-only charging, opportunity charging allows smaller battery packs to be used and, potentially, energy demand to be distributed across multiple local grids and time.

Whether en-route or in-depot, the infrastructural installation requirements will depend on the chosen charging strategy. When planning charging infrastructure, it is important to bear in mind practical considerations, such as space requirements and layout, to minimise any potential loss of space due to the need for additional infrastructure, as well as safety concerns when working with electricity. For more information on the key considerations when electrifying a bus depot, including space, depot selection, grid connections, maintenance and safety, see Bus depot electrification – Insights from Mexico.

Plug-in charging systems consist of plugs and sockets or inlets, also referred to as 'gun charging'. They require manual connection and disconnection.

Automated charging systems, often in the form of pantographs, incorporate an articulated arm installed on the ZEB ('pantograph up') or the charge point ('pantograph down') that extends automatically to make contact without manual operation.

Induction charging systems are similar to wireless mobile phone charging technology. Induction coils embedded in the ground surface and underneath the ZEB pass alternating current through magnetic fields, which is then converted to direct current to charge the battery pack.

Figure 8. Different types of charging system

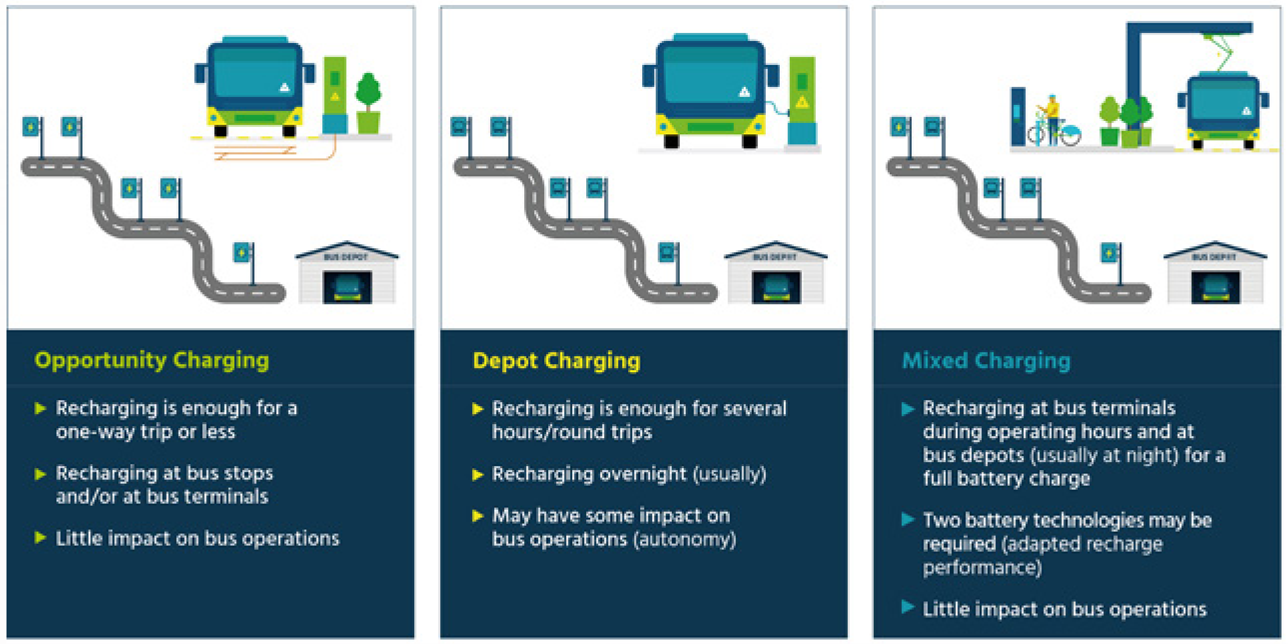

Figure 7. Zero emission bus charging strategies.

As in many other countries, Indonesia's National Standardization Institution (BSN) and Ministry of Energy and Mineral Resources have set various regulations and technical charging standards for electric vehicles (Figure 8). However, automated and induction systems have yet to be considered. The standardisation concerns three major aspects, (1) the physical design of the connecting components, (2) the charging method (slow or fast charging) and (3) the communication between the vehicle and the charging infrastructure. By meeting national standards, ZEBs will be able to use public charging facilities in case of emergency and the same will hold for private electric vehicles and ZEB charge points.

TransJakarta's Charging Plan

Following the decision on charging schemes, TransJakarta conducted a simulation to determine the necessary charging power rates.

The analysis demonstrated that for a 324 kWh battery pack with depot-only charging, an 80 kW-rated charger was optimal. However, the number of charging units deployed would depend on operating requirements. Further information regarding Jakarta's charging plan following their bus procurement.

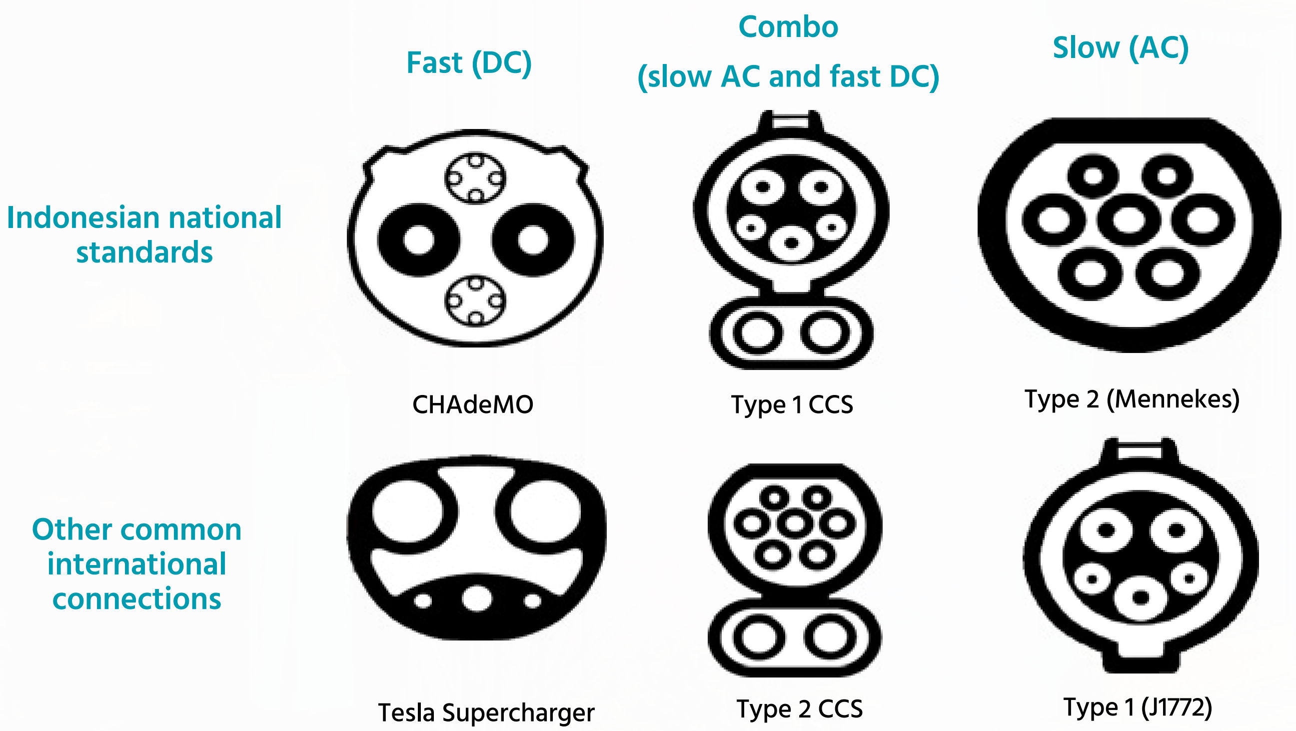

Figure 9. Indonesian national standards & other international standards for plug-in charging sockets.

The electric grid

The main source of electricity in the grid is traditional power plants, which produce very large quantities of energy at a small number of locations, so are centralised. Countries are increasingly committing to greater shares of renewable energy, however, such as solar and wind, which can be provided on a small-scale domestic basis (by solar photovoltaic (PV) cells on roofs, for instance) or large-scale commercial operations.

High-voltage transmission lines are used to transmit electricity over long distances, such as from power stations to smaller subsystems and further down to main substations where distribution utilities can further distribute to secondary substations.

In each step, electricity is generally stepped down to lower voltages until it reaches the end-user at the needed power rating. For ZEB depots, cables rated to at least 1.5 megavolt amperes (MVa) - the unit of apparent power in an electrical system - are typically needed.

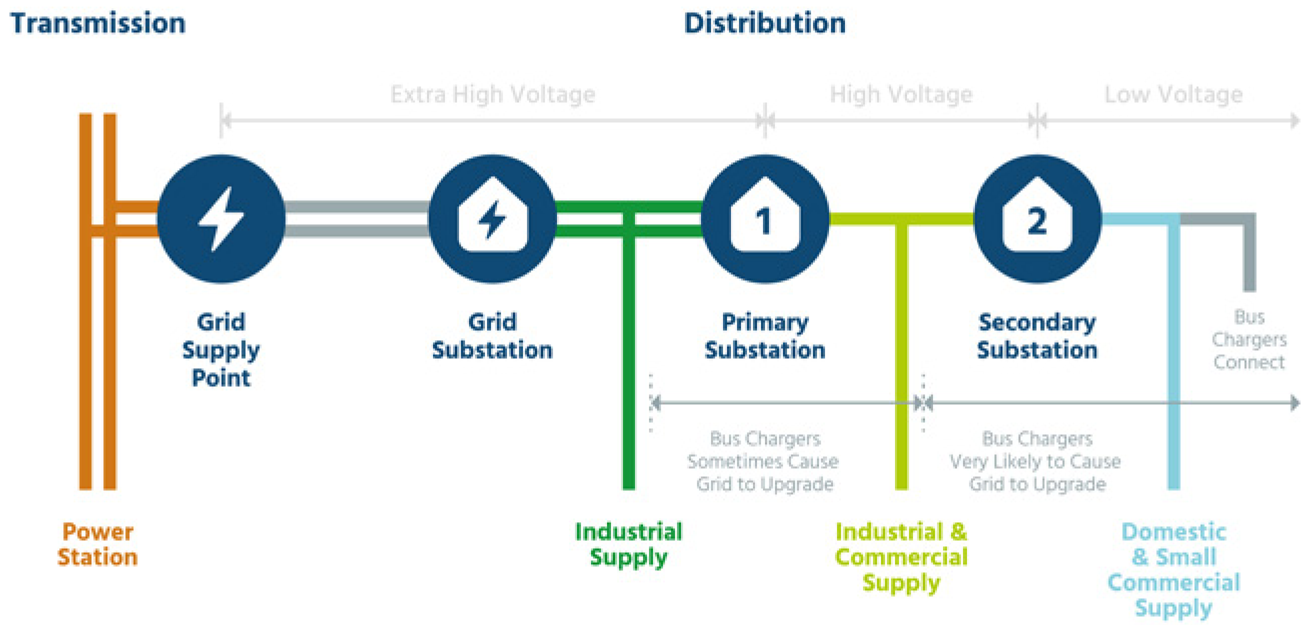

Figure 13. Transmitting power from grid to consumer via substations

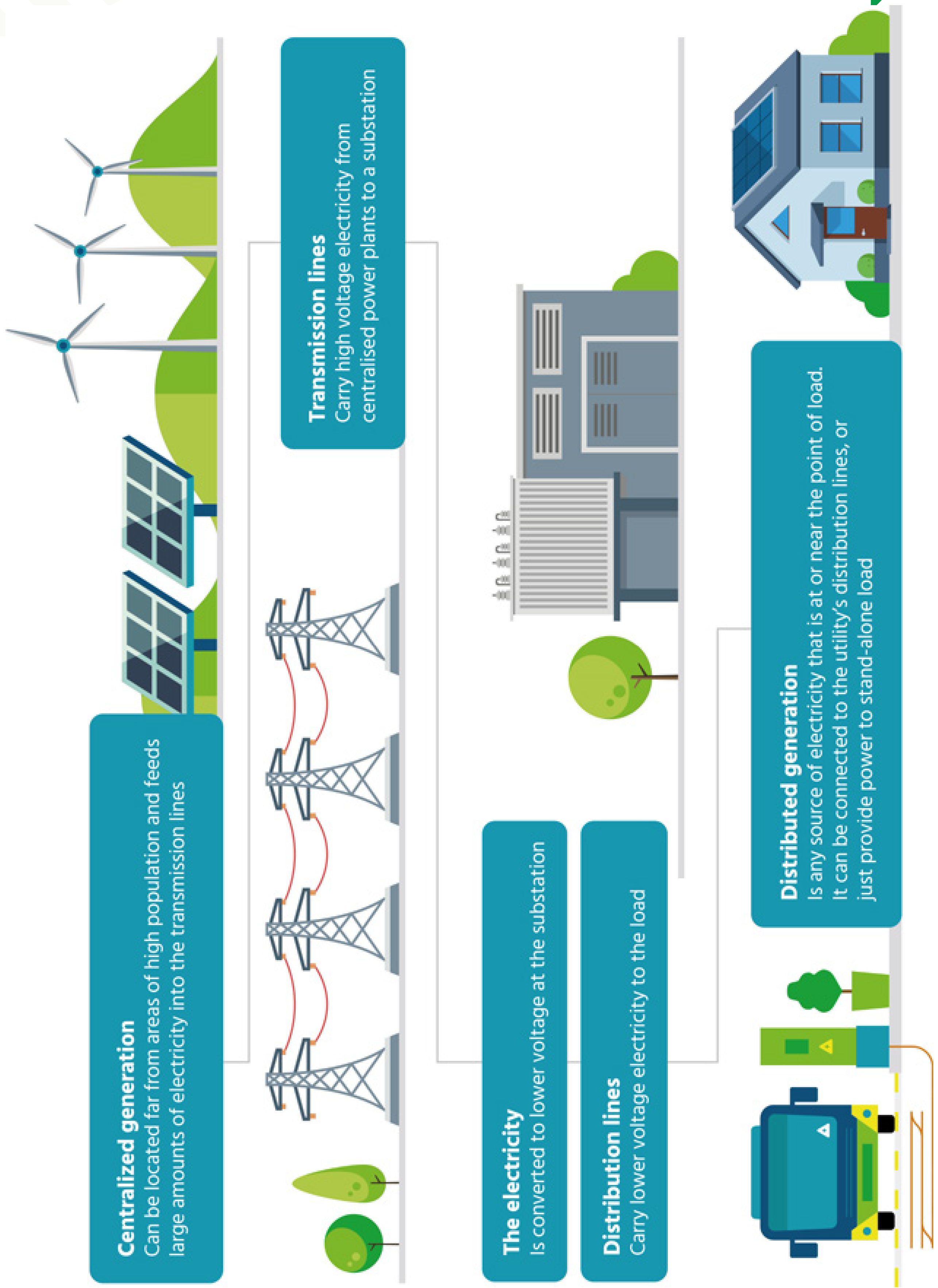

Figure 12. Typical components of an electric grid.

Power demand and peak load

Daily energy demand can be estimated using the total distance travelled per day (including dead kilometres) and the total number of buses in operation. In Jakarta, the energy requirement for the first 100 buses was estimated at 31-36MWh. Most of this energy would be needed for overnight depot charging and the remainder for end-of-route or en-route opportunity charging.

Looking at peak load on a per-depot basis, with the known power rating needs and number of charging units, it was determined that the theoretical maximum power demand, with 17 chargers at 80 kW utilisation, was 1.36 MW (80 kW x 17 = 1360 kW or 1.36 MW). However, this assumes that all charge points would be charging simultaneously at the maximum rating, which is unlikely, especially when using a smart charging system that intelligently controls the charging rate to reduce the peak load and thus minimise infrastructure upgrades (figure 14)

Understanding peak load is important, especially from the perspective of local grid capacity and understanding the size of transformer required on site. If the peak load needed to charge the e-buses exceeds the current capacity of the local grid, upgrades will be necessary. Depending on the policies and fees of the distribution utility, the upgrade costs may significantly influence the financial viability of the overall initiative. Thus, an appropriate charging strategy and infrastructure must be considered in the context of local grid capacity.

Great Jakarta Power Grid System

Jakarta's electricity is provided by the Greater Jakarta power-grid system, supplied through 7 subsystems and 55 main substations, with a total capacity of 12,090 MW at present and a total load of 9,140 MW. Thus, there is a significant margin of nearly 3,000 MW, or about 32 percent of total capacity, to accommodate additional load on the grid system.

The three depots, each with 1.36 MW of maximum peak load, only add 4 MW (1.36 MW x 3) of additional peak load. Given the margin of nearly 3,000 MW, the impact of deploying 100 ZEBs imposes a negligible burden on the grid (less than 1 percent).

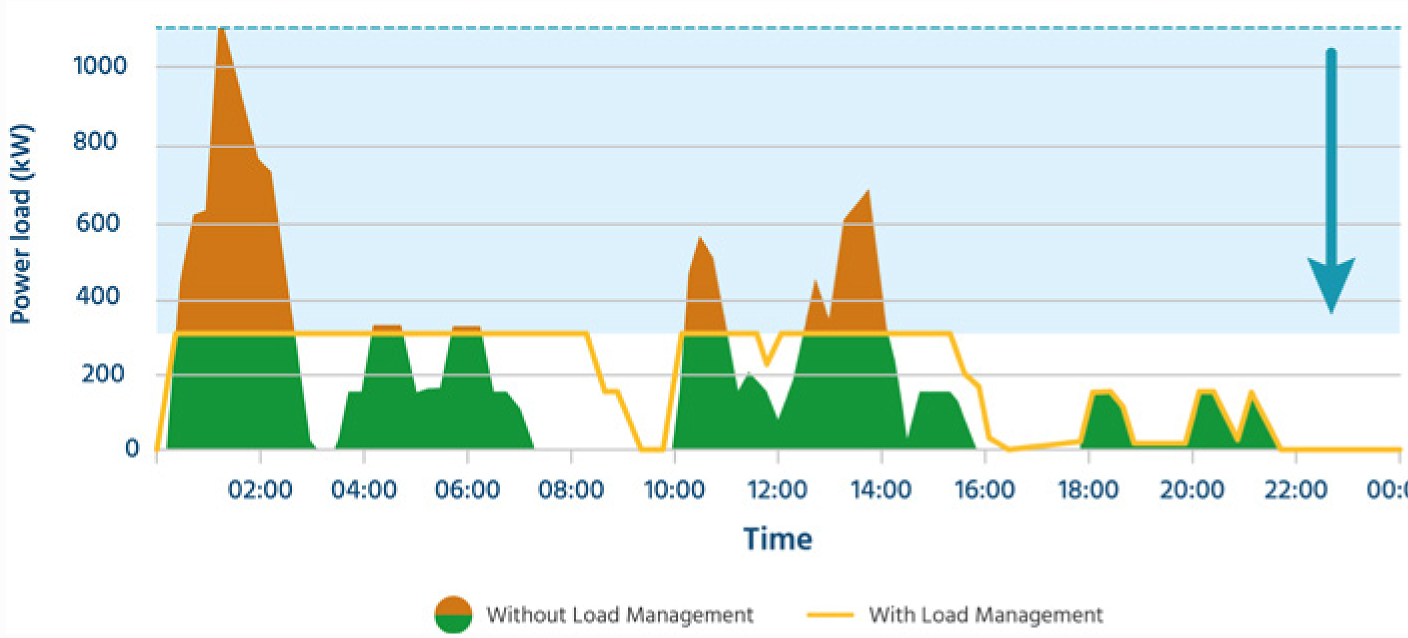

Figure 14 – Comparison of the grid load with and without load management. Source -

Further reading

1. **C40 (2020) How to shift your bus fleet to zero emission by procuring only electric buses.**
Last accessed 05/07/201. Available here.

2. **CFF (2021) Bus depot electrification – Insights from Mexico.** Available soon.

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Disclaimer: Due to the impending tender of Jakarta's first 100 zero-emission buses, specific details have intentionally been left out of the report. These will be reflected in the final version of the report, which will be published in late 2021.

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