C40 CITIES FINANCE FACILITY

# ZERO-EMISSION BUS SYSTEMS:

## Depot electrification for zero-emission bus systems.

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**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).




Frontpage photo credit - Terminal El Conquistador - Copec Voltex , Santiago de Chile.

## Objective of this report

This report, aimed at public transport authorities, private operators and practitioners, presents an overview of the key steps and considerations needed when designing or retrofitting a zero-emission bus depot as part of accelerating zero-emission bus deployment in urban areas. It draws on the experiences of C40 Cities Finance Facility (CFF) projects on depot electrification in Guadalajara and Monterrey (Mexico), as well as a literature review of other international experiences.

# Introduction

**Cities are increasingly looking for ways to deliver on their ambitions and strategies to improve air quality, reduce greenhouse gas emissions and create a better society for their residents.**

Deploying zero-emission buses is often given high priority because of the high-profile impact of zero-emission buses, because conventional internal combustion engine (ICE) vehicles produce a disproportionately high amount of pollutants and because it is possible to have a greater degree of control over a public bus fleet.

However, many of the cities and fleet operators that explore the possibility of transitioning to a zero-emission fleet soon realise that it is not possible to simply replace the buses: system-level transition is necessary. And a system-level approach needs the operator (in collaboration with relevant partners) to consider how the key components of the system – battery bus, charging infrastructure and electrical supply – can be deployed.

The interconnected nature of zero-emission bus systems (Figure 1) means that a lack of knowledge can become a key barrier to deployment.

Guidance on deploying zero-emission bus systems has been developed by a wide range of financial institutions, non-governmental organisations, municipal networks, partnerships and private actors, but there is a clear knowledge gap about a crucial aspect of these systems: electrifying bus depots.

This report, aimed at public transport authorities, private operators and practitioners, presents an overview of the key steps and considerations needed when designing or retrofitting a zero-emission bus depot as part of accelerating zero-emission bus deployment in urban areas. It draws on the experiences of C40 Cities Finance Facility (CFF) projects on depot electrification in Guadalajara and Monterrey (Mexico), as well as a literature review of other international experiences.

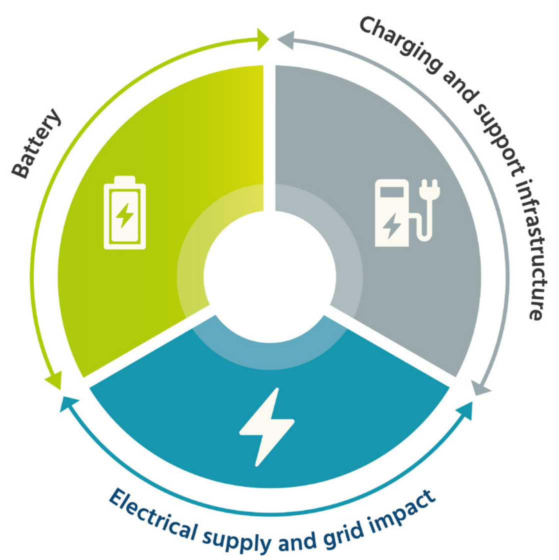



Figure 1. Core components of a zero-emission bus. Source CFF (2020a)

# Principles and approach

Introducing a zero-emission bus system to a city is a far greater challenge than simply replacing the buses themselves. The need for a robust charging mechanism and new approaches to route planning and vehicle maintenance require system-level thinking.

The large number of dependent variables and complexities involved mean that creating a "perfect" system is very challenging, and seemingly minor miscalculations could result in a system failing to deliver its objectives. Potential systemic failures range from buses that do not have sufficient battery capacity to complete their entire route, to bus routes where the headway[1] is below the required level because too few buses can operate.

Although it is clearly necessary to consider the financial viability of the operation, it is just as important to tailor the system to meet the unique demands of each city. This report therefore takes a conservative or risk averse approach to system development and errs on the side of caution, to help ensure that the system is able to operate effectively from the outset, even if this is a little more expensive than for large-scale system deployment.

Once an operator or public authority has gained experience of electrifying a depot and has gathered much clearer operational data, it is likely that the system can be optimised to give a much better balance in terms of financial performance (and technical performance), and lessons learned can feed in to further deployment of depots.

Some key examples of this conservative approach to depot electrification include:

- Having the potential to draw more power than initially planned for;
- Installing more charging infrastructure than technically necessary;
- Under-utilising depot space to begin with.

1. "Headway" here refers to the time or distance between vehicles in a transit system. The minimum headway may be either the headway that is contractually required by a public transport authority or from internal requirements to deliver a consistent service.

# Selecting a depot for electrification

Changing an entire municipal bus fleet to a zero-emission system will require electrification of every depot. Careful selection of the initial depots to be built or upgraded can make electrification easier because conversations about how to electrify other, more-challenging depots can continue.

There are a number of key considerations when choosing which depot(s) to upgrade. It is important that – at a minimum – all the factors listed below are assessed. But local factors should also be taken into account.

### Proximity to existing electrical infrastructure

Often the single most variable expense when retrofitting a depot is the cost of getting electricity from a local high-voltage access point to the "gate" of the depot. This will depend on local regulations, policies of electricity providers and distance from the access point.

Therefore it is essential to prioritise those depots that are physically close to existing high-voltage infrastructure that has the capacity to cater for the requirements of the depot for at least the short and medium term, to futureproof operations.

### Depot ownership

Installing new infrastructure at a depot can cause short-term issues to operations. This can be mitigated by installing infrastructure in a modular format, but that will almost certainly be far more expensive than electrifying the entire bus depot all at once. However, operational issues can be mitigated by having the existing fleet work out of other depots if the depots are publicly owned or if the private operator owns multiple depots. overcome these issues.

Such changes, even though temporary, may mean that agreements need to be made between the bus operators and the public transport authority on how to mitigate and overcome these issues.

### Space

The additional infrastructure requirements for an electric depot – including cabling, chargers and transformers – can reduce the amount of space available for typical bus depot operations. This can be largely mitigated by careful space planning and by choosing infrastructure that takes up minimal space. However, in very space constrained depots, the fleet size may need to be reduced.

### Topography

Topography affects zero-emission bus depots in two important ways:

• If the bus depot is located near a steep hill that is not on the bus route this can reduce the range of an electric bus – just on its journey to and from the route;

• If the chosen location of the depot is lower than the surrounding roads or land, it could be at risk of flooding. Flooding is a far greater concern for an electric bus depot because of (1) the electrical infrastructure; and (2) the ground will lose its capacity to absorb floodwater because of the increased groundwork for the depot.

Although unfavourable topography is not necessarily a reason for excluding a particular location or depot, it is important to commission or carry out a risk analysis and assessment of the probability of flooding under future climate change scenarios and ensure that any mitigation measures are put in place.

### Proximity to route

For ICE buses it is usual to have depots located near to the bus routes to minimise fuel use and the time that buses are on the road; but for a zero-emission bus with an electric powertrain[2] and longer charging times, minimising distance between the depot and the route is essential to ensure operation throughout the day.

### Easy access to roads

Zero-emission buses with larger batteries are typically heavier than their ICE counterparts and thus can have a greater impact on the roadways. Having access to well-paved roads at the depot's entranceways and exits is important to avoid long-term maintenance issues.


2. The powertrain configuration of a typical municipal electric bus includes an energy source (a battery), a single traction motor with controller and a final drive differential gearbox.

## Case Study: Auckland, New Zealand

**In 2018, with the support of C40's Financing Sustainable Cities Initiative (FSCI), Auckland undertook an analysis to understand the investment costs necessary to upgrade its electricity grid in order to fully electrify its municipal bus fleet, and to decide which depots should be prioritised.**

Figure 2 presents a breakdown of these costs per depot. Please note that the depot electrification costs in Auckland are relatively high because of the geology and dispersed electrical system and this example should be used to demonstrate the variability of upgrades and not the specific costs.

The study concluded that there is considerable variability of upgrade costs between the depots, with costs ranging from approx. USD 450,000 (650,000 New Zealand dollars (NZD)) to USD 3.1 million (NZD 4.4 million). These costs would be even higher if depot operators chose to upgrade the infrastructure in stages rather than a total conversion.

Those depots with higher upgrade costs should be left until later, because they could take advantage of ongoing electrical upgrades undertaken by the distribution network operators (also known as DNOs). To take full advantage of this, depot owners (supported by transport authorities) should have early conversations with distribution network operators to inform them of plans to electrify bus depots and influence their decisions of where to provide upgrades.

The single most influential factor on the cost of upgrading a depot is almost always the distance to the nearest primary substation (see Grid connections, below). This is reflected in Auckland, with the cheapest upgrade located just 0.1km away from the primary substation compared with 3.4km for the most expensive.

Further information and the full analysis can be found in C40 Cities (2018a).

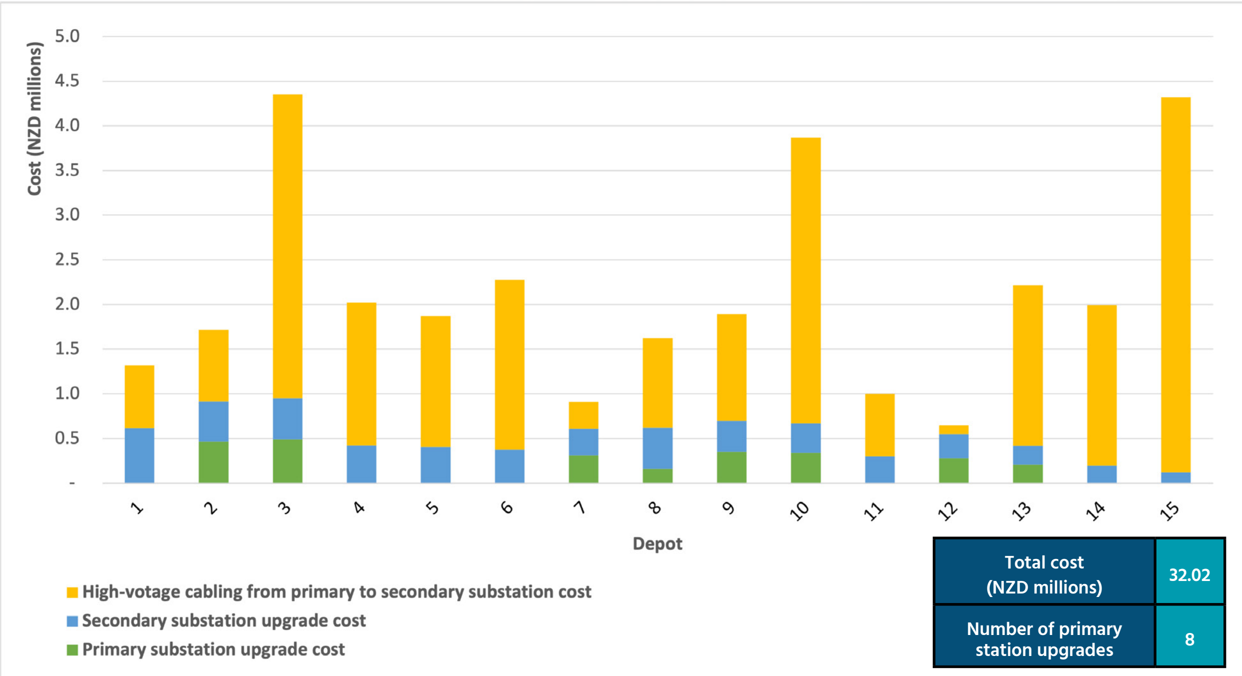



Figure 2. Costs of upgrading the grid connection to accommodate overnight depot charging. Source: C40 Cities (2018a)

# Grid connections

While energy sources, regulations and operations differ significantly from country to country, traditionally the core components and process of creating electricity and then distributing it to an end user across a grid are very similar, and basically comprises the following four stages (Figure 3):

1. A centralised electricity generation (power) station converts energy from a resource such as coal, natural gas, hydroelectric power or geothermal into electricity;

2. The electricity is transported at high voltage through transmission lines from the power station to primary substations and secondary substations that are closer to the end user;

3. Electricity substations convert the electricity from very high voltage to lower voltages;

4. Distribution lines transfer electricity from substations to local transformers and areas where electricity is consumed by the end user at a typical mains voltage of 100–240V.

However, with the growth of new small-scale distributed renewable technologies to tackle climate change, a further stage – supplementing the traditional linear movement of energy – should be added:

5. Distributed electricity generation stations convert energy from a renewable source (such as solar or wind) into electricity and that may be directly consumed by the user or fed into the grid to supply other users.

The costs involved with laying down thousands of kilometres of distribution lines is exceptionally large, so distribution network operators try to avoid creating a distribution system with significant additional capacity that is not planned to be used. This means that if a considerable load is to be added to the grid (e.g. to supply a zero-emission bus depot), infrastructure upgrades may be necessary (Figure 4).

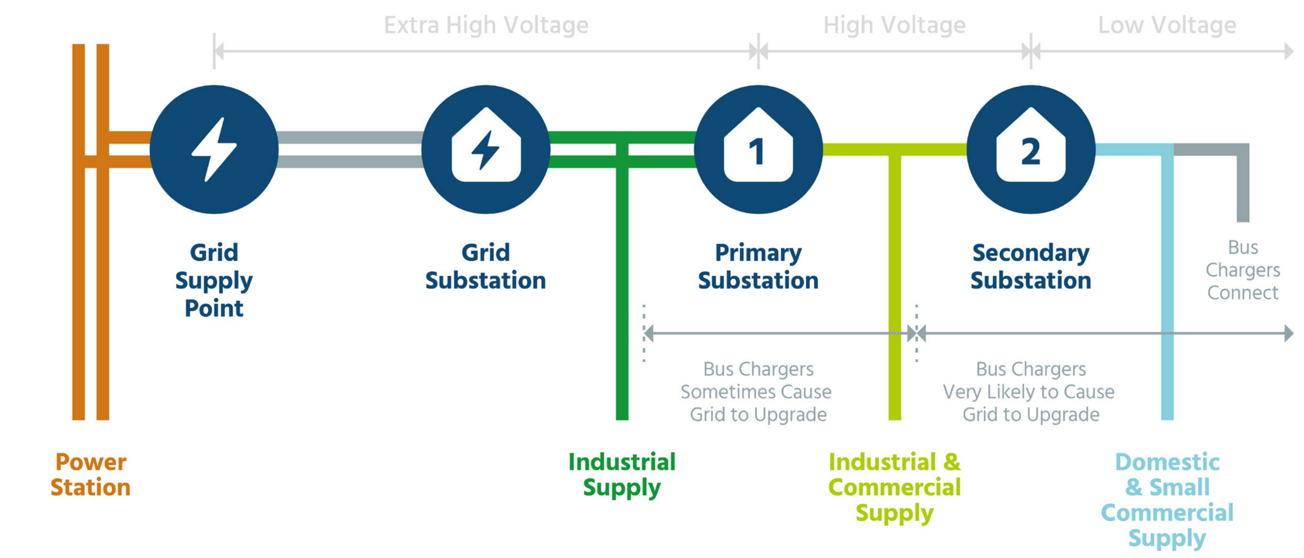



Figure 4. Distribution of electricity illustrating the need to upgrade grid infrastructure. Source: C40 Cities (2018a)

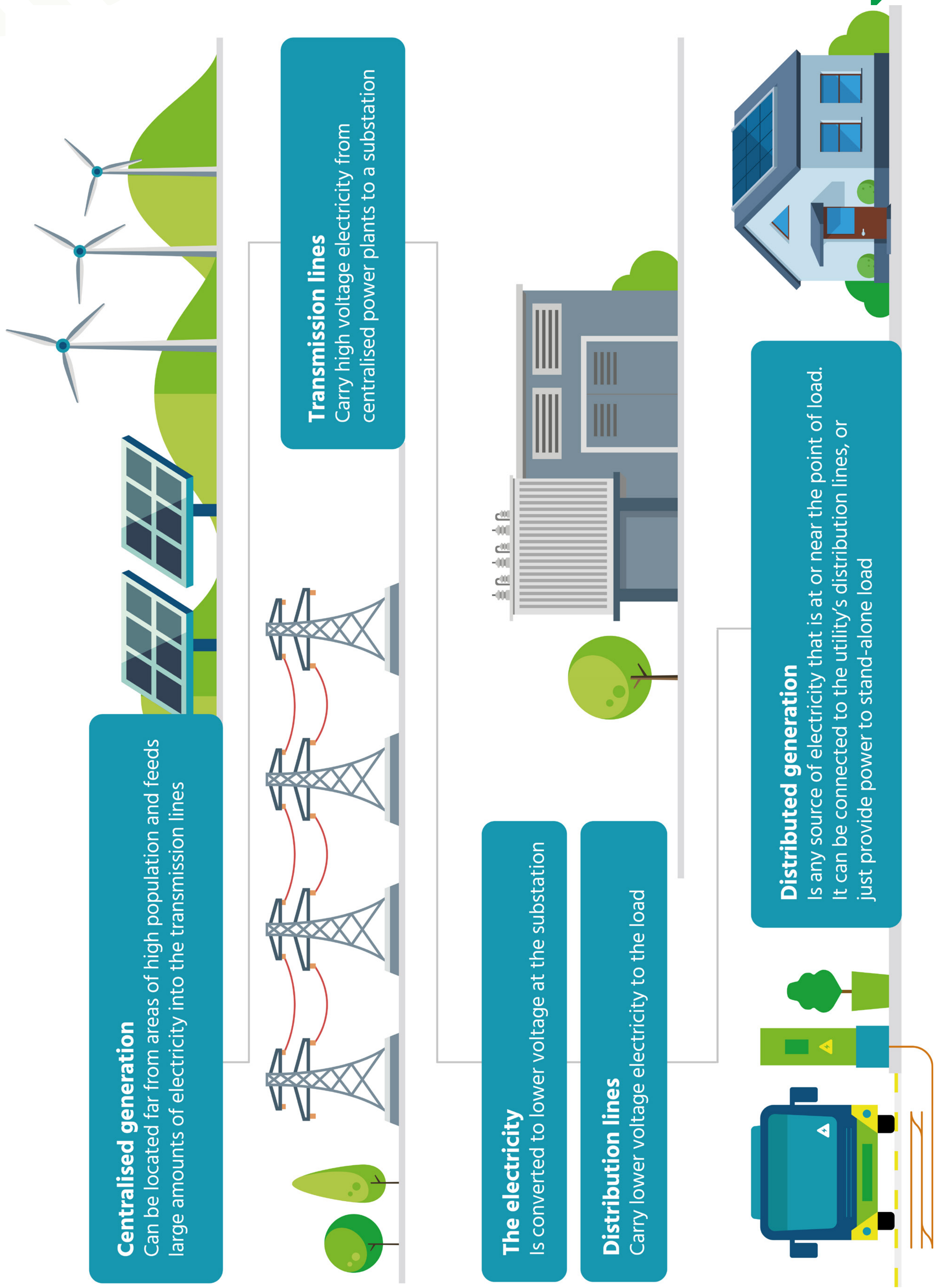



Figure 3. Typical electricity grid from generation to usage. Source CFF, (2020a).

The cost of installing new distribution lines from a primary high-voltage substation or access point to the "gate" of the depot can vary enormously from depot to depot. Depending on the local/national policies and regulations, distribution lines may have to be either overhead or buried, and either option will have a considerable impact on the cost and planning processes involved in installing the infrastructure.

It is possible to speed up deployment and achieve significant cost savings by prioritising – at the outset – those depots located physically close to existing high-voltage infrastructure that has the capacity to handle the requirements of the depot's operations. However, ongoing discussions will be necessary with electricity providers to allow for the electrification of other depots in the future.

Some distribution network operators companies may only be able to install the infrastructure at designated times and so having a clear indication of the upgrade timelines is essential, because it may be necessary to install a grid connection long before the rest of the depot is electrified in order to fit in with the supplier's timelines.

## Renewable integration

Integrating renewable energy into the operations of ICE buses provides little benefit to an operator because of the limited electricity demand of the depot and the larger capital expenditure costs. However, for zero-emission bus operators there are potentially significant gains to be made by integrating renewable energy – most commonly solar panels (photovoltaics (PV)) – into operations, because this will minimise greenhouse gas emissions, provide air quality benefits, and either provide a revenue source or reduce electricity costs.

In practice, with zero-emission buses using overnight slow-charging infrastructure there is a mismatch between when solar panels create electricity (during the day) and when electricity is used to charge electric buses overnight. This means that electricity generated by onsite renewables needs to be either stored in a battery or fed in to the electricity grid under some sort of commercial arrangement (either electricity is provided to the grid for free then receives a similar amount during the night, or electricity is purchased and sold at differential rates as determined by the utility and any applicable government subsidies).

Batteries have several advantages, such as providing resiliency to the depot to mitigate the impact of power outages; reducing the need for wider grid infrastructure improvements; and helping to even out power demand for the depot and the wider city (Viriciti, 2021). Some of these factors can also be significant advantages to the utility provider or/and distribution network operators; an argument which could be used to put more favourable financial terms in place.


Figure 5. The London Solar Opportunities Map. Source: Greater London Authority (2021)

There are several factors to consider when analysing the commercial potential for onsite, integrated solar PV:

• Typical commercial electricity rates, including any total capacity charges, administrative charges, energy rates (peak and off-peak). For example, Eskom applies service and administrative charges per day; network capacity charges per day based on the maximum voltage and transmission length; energy charges for peak and off-peak periods during low and high demand season; and ancillary charges;

• Estimated solar potential of buildings and open land, and thus the electricity that will be available for use. Some cities, such as London, have solar maps (Figure 5) available for residents and businesses to use to identify the potential of installing solar PV panels (Greater London Authority, 2021);

• Incentives or favourable tariff rates from utility companies, subnational or national governments to subsidise and promote solar PV deployment. For example, some state electricity regulatory commissions in India have set up preferential tariffs for solar power per kWh produced.

Commercial rates and incentives are public knowledge, but early conversations with utility providers and distribution network operators are necessary to inform them of plans to upgrade and to understand the arrangements that could be put in place which provide benefits to the grid and thus receive benefits in return. An analysis is necessary to understand how profitable this would be, considering seasonal variations, the total area of solar PV and the quantity of electricity that could be produced.

Eskom is the state-owned electricity utility in South Africa. Current tariffs are shown at https://www.eskom.co.za/CustomerCare/TariffsAndCharges/Pages/Tariffs_And_Charges.aspx.

# Electricity demand

Understanding the operational requirements for electricity at the depot is essential in order to identify the electrical infrastructure upgrades necessary, the size/number of transformers required, whether it is economically feasible to integrate renewable energy, and so on. Estimates do not replace the real-world values provided by a pilot or small-scale operation, but data from other cities can provide relatively accurate estimates (with a suitable buffer) to plan operations.

It can be challenging to balance (1) minimising the installed power; (2) the additional cost of the infrastructure; and (3) the ability to charge buses during the cheapest periods. There is no one-size-fits-all solution: the appropriate balance depends on what the operator chooses to prioritise, while still meeting the operational requirements of the depot.

For example, as shown in Table 1, charging buses in the off-peak period will have significant cost/kWh savings compared with charging buses throughout the day: to be able to charge all buses within the desired period.

There are several calculations that are needed when planning a depot and its additional requirements:

- Daily operational electricity requirements;
- Average power demand;
- Peak power demand.

The calculations for reach are throughout this section, each accompanied by a worked example based on a case study from Guadalajara, Mexico.

| Cost category | Cost sub-category | Units | Cost (Mexican pesos - MXN) |
|---|---|---|---|
| Account cost | – | MXN/month | 518.46 |
| Distribution | – | MXN/kW | 156.80 |
| Capacity | – | MXN/kW | 317.52 |
| Energy | Peak | MXN/kWh | 0.8456 |
| Energy | Intermediate | MXN/kWh | 1.4904 |
| Energy | Off-peak | MXN/kWh | 1.6740 |

Table 1: Electricity tariffs in Guadalajara on 01 September 2020. Source: Adapted from CFF (2021d).

## Daily operational electricity requirements

The formula below can be used to calculate the electricity required by a depot.

$$E_{req} = \frac{(E_{route} + E_{battery} + E_{HVAC})}{F_{drive}}$$

Where:

$E_{req}$ – the electricity requirements for the depot under a conservative scenario;

$E_{route}$ – the electricity requirements for the route (typically calculated as kilowatt-hours per kilometre, kWh/km);

$E_{battery}$ – energy remaining in the battery at the end of the operational period (typically, around 20%);

$E_{HVAC}$ – energy consumed by non-critical components of the bus such as heating, ventilation and air conditioning (HVAC) through the operational period;

$F_{drive}$ – a contingency factor for driver efficiency for drivers inexperienced with regenerative breaking (typically, this should improve over time).

### Case Study – Guadalajara (daily operational requirements)

In order to meet the route requirements, 20 buses must make a minimum of 4 trips per day, with the route being a total of 72km long (288km in total). Based on previous bus operations, an energy efficiency of 1.2 kWh can be used, and a 10% battery reserve is suitable to meet operational requirements. A driver contingency factor of 90% has been used as a conservative estimate. The HVAC system from previous experience uses on average 3.0kWh over the 10 hour operational period.

$$E_{req} = (E_{route} + E_{battery} + E_{HVAC}) / F_{drive}$$

$$E_{req} = ((1.2 \times 288) + (1.2 \times 288 \times 0.1) + (3 \times 10)) / 0.9$$

$$E_{req} = (345.6 + 34.56 + 30) / 0.9$$

$$E_{req} = 455.73 \text{ kWh per bus}$$

$$E_{req} = 9.11 \text{ MWh per depot}$$

Therefore, to meet the daily operational needs of the route, each bus requires approximately 456 kWh of electricity, while the depot requires 9.11 MWh.

## Average power demand

The average power demand for the given charging window (i.e. time when charging takes place) can be calculated using the electricity requirement (Ereq) value calculated above. The charging window can be chosen on the basis of the charging strategy, the applicable electricity costs and operational requirements.

$$P_{demand} = \frac{E_{req}}{C_{window}}$$

Where:

$C_{window}$ = the average charging window (in hours);

$P_{demand}$ = the average power demand over the given charging window.

**Case Study – Guadalajara (average power demand)**

In Guadalajara, a slow overnight charging strategy is being considered, with the charging window between the hours of 00.00 and 06.00 (i.e. 6 hours), taking advantage of the lowest cost of electricity.

$$P_{demand} = E_{req} / C_{window}$$

$$P_{demand} = 455.73 / 6$$

$$P_{demand} = 76.0\text{kWh}$$

While other factors may be considered, such as choosing faster chargers for more conservatism, or whether ultra-fast chargers should be installed throughout the city to mitigate the need for grid upgrades. A calculation of the average charger size needed is helpful to understand the scale of infrastructure that is needed. The calculation above demonstrates that under the scenario where there is 1 bus to 1 charger, a charger will need to be rated to at least 76kW. However, in reality, to accommodate for late returns to a bus depot, faults with chargers or to be able to "pre-condition" (warm or cool) the bus to a specific temperature without using its battery capacity before starting the day, a higher value than 76kW would be recommended in this example.

## Peak power demand

The peak power demand is an important because it has implications for the size of transformer required; electricity infrastructure needed; and the total capacity of electricity to be purchased from the utility provider, which can be charged at a premium.

$$P_{peak} = (P_{demand} \times N_{buses}) + P_{cont}$$

Where:

$P_{peak}$ = the peak power demand of the depot given in kW or megawatts (MW);

$P_{demand}$ = the average power demand over the given charging window;

$P_{cont}$ = the contingency power demand;

$N_{buses}$ = the number of buses.

**Case Study – Guadalajara (peak power demand)**

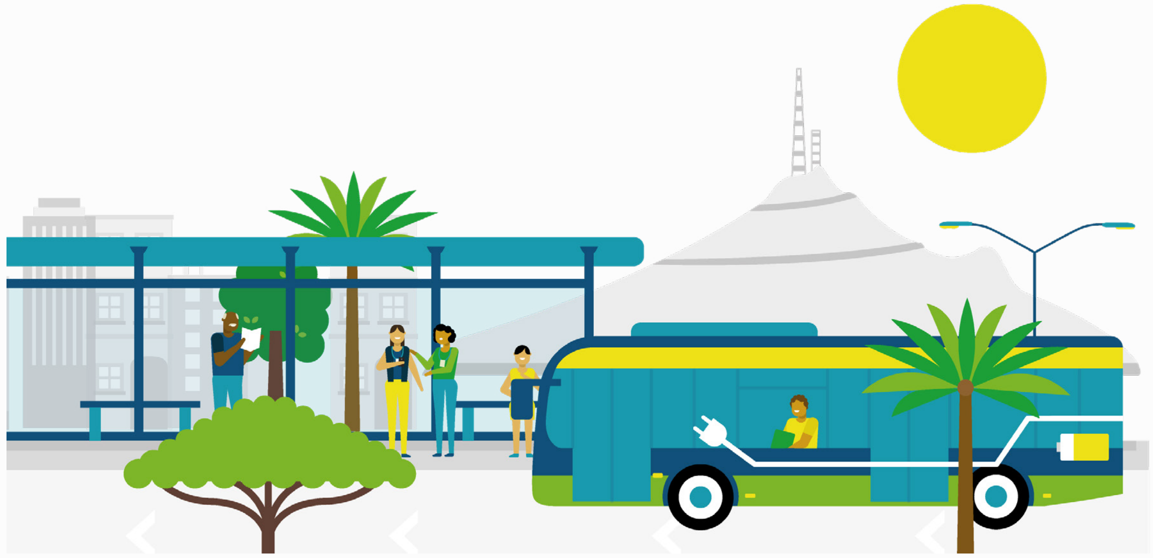
For Guadalajara, using the figures above and a contingency demand of 25%, the peak power demand can be estimated as:

$$P_{peak} = (P_{demand} \times N_{buses}) + P_{cont}$$

$$P_{peak} = (76 \times 20) + 0.25\,(76 \times 20)$$

$$P_{peak} = 1520 + 380$$

$$P_{peak} = 1{,}900\text{kW (1.9MW)}$$



# Depot space

Space can be a key challenge when converting a bus depot to accommodate zero-emission buses. The additional space required for transformers and charging points will leave less space for buses. If space is already limited within a depot the operator may have to reduce the number of buses operating or move a small part of the fleet elsewhere, either of which could be a significant operational hurdle. Similarly, the space requirements are likely to be considerably larger if both electric and ICE buses are operating out of the same depot because of the need for two separate fuelling/charging infrastructure systems.

This section explains how to plan a depot by calculating the space requirements for electric buses and their floor-mounted, slow-charge charging units (currently the most common location for charging units). It also discusses ways to reduce space requirements by incorporating other charging placement options.

It is generally recommended to avoid having buses parked in a manner where buses cannot move until another vehicle has been moved to minimise operational challenges:

- A parking space at a 45-degree angle with a 10m turning space should allow for relative ease of parking and turning for medium-sized buses.

Using this information it is possible to calculate the minimum area needed for a given number of buses. The following worked example uses a 12m bus. As can be seen in Figure 6, buses parked at a 45-degree angle will have a 12m length plus 2m for the charging infrastructure resulting in a total "length" of 14m. Two buses using a single charging unit (the most common charging set-up) will also have a "width" of 23.5m, with each additional bus space having a width of 11.2m.

The following formula can be used to calculate the area needed:

$$\textbf{Area} = \textbf{(Length + Turning space)} \times \mathbf{(W_2 + W_a\ (no.\ buses - 1))}$$

Where:

**Area =** minimum space needed for parking, charging infrastructure and the turning circle;

**$W_2$ =** width of two buses;

**$W_a$ =** width of each additional buses.

As other factors such as maintenance zones, spaces for staff, inspection areas and cleaning areas are not expected to have any size variations compared with those for ICE buses, so these have been excluded. However, when calculating the total area needed for an entirely zero-emission bus depot, they should be integrated.

The one additional factor that needs to be included for an electric bus depot (but is not included in the formula above) is the space required for transformers – approximately the size of one additional bus.

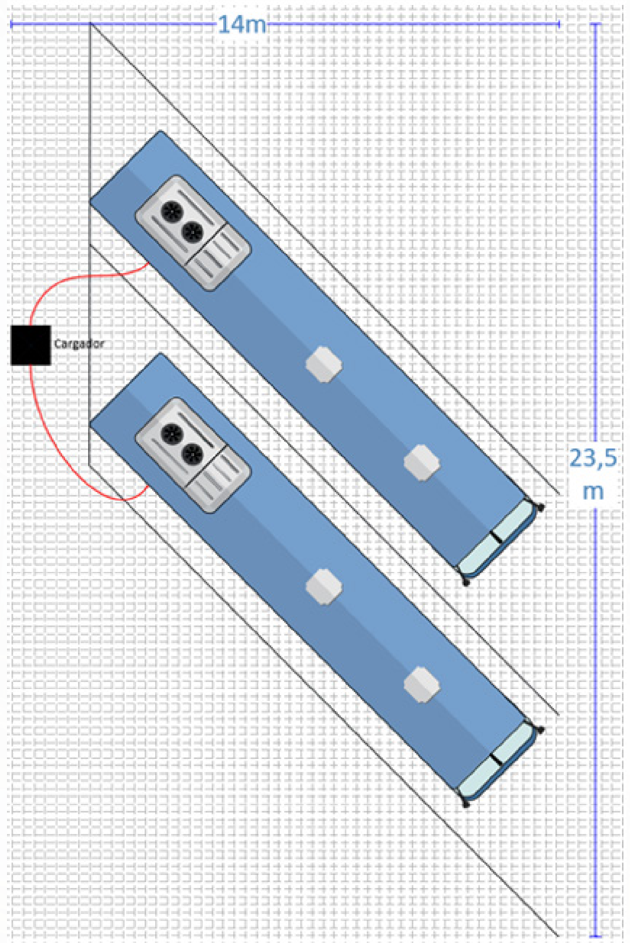
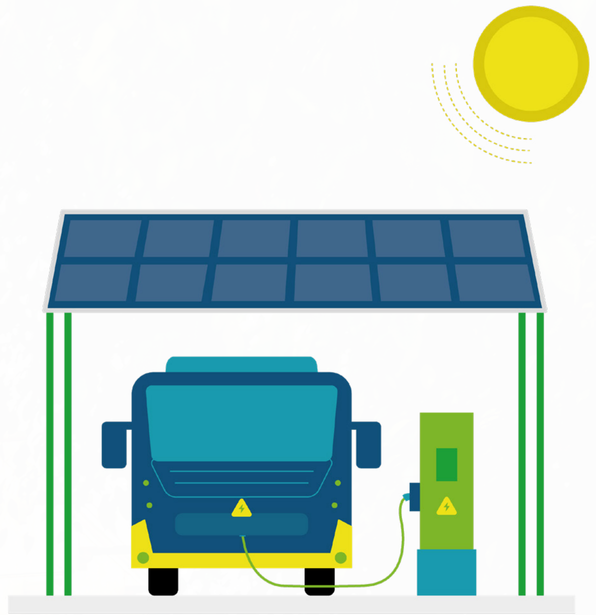


Figure 6. Space requirements for a 12m bus parking space.



**Case Study – Monterrey**

Using the example of Monterrey, one depot will include 31 buses.

$$\textbf{Area} = \textbf{(Length + Turning space)} \times \mathbf{(W_2 + W_a\ (no.\ buses - 1))}$$

$$\text{Area} = (14 + 10) \times (23.5 + 11.2 \times (31 - 1))$$

Minimum area = **8,628m$_2$**

However, the length of land for the depot is a maximum 180m in length, so it was recommended that charging be split into 3 rows. Redoing the calculation to take this into account gives:

Row 1 area (for 11 buses) = (14 + 10) x (23.5 + 11.2 (11 – 1))

Row 2 area (for 11 buses) = (14 + 10) x (23.5 + 11.2 (11 – 1))

Row 3 area (for 9 buses) = (14 + 10) x (23.5 + 11.2 (9 – 1))

Minimum area = 3,252 + 3,252 + 2,714.4 = **9,218.4m$_2$**

There are several ways to reduce the amount of space needed for charging infrastructure, for example:

• Installing charging infrastructure around the perimeter of the depot. This will typically be space that is used less frequently; it can also be cheaper and easier to install equipment there;

• Using charging 'islands' where buses are lined up perpendicular to the charger, which minimises 'dead' space. However, when buses leave the depot, they would have to exit in order (Figure 7);

• Installing a "canopy charging" system, where charging equipment is built into a roof over the top of the buses so that either plug-in or pantograph charging units plug into the bus. This is one of the most space- and cost-efficient methods because it minimises civil works for distribution cables. The upcoming La Elipa bus depot in Madrid uses this concept (Figure 8)[4].

Figure 8. Example of how charging infrastructure can be built into the roof to lessen space requirements.

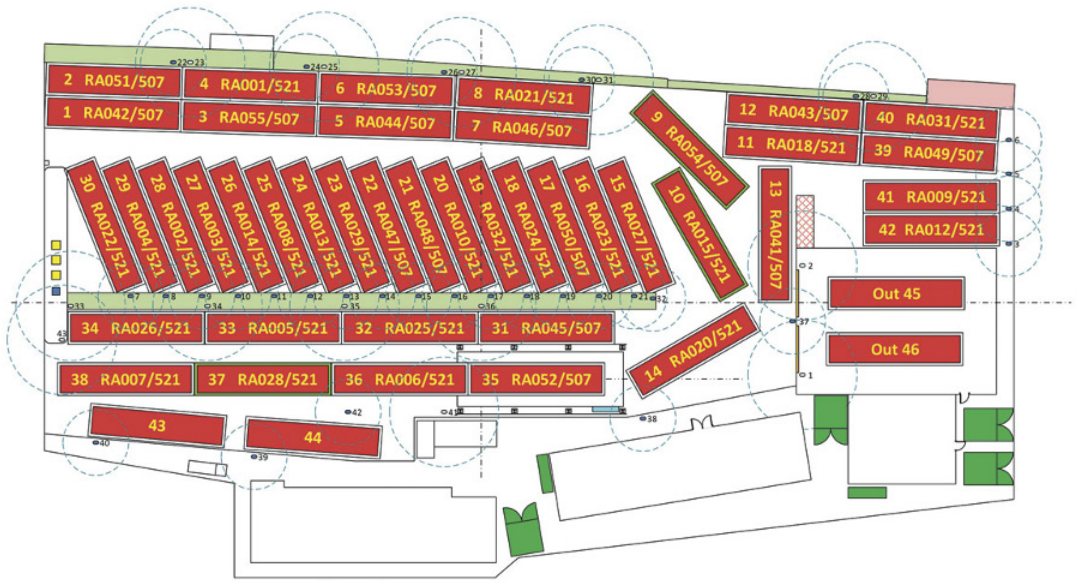



Figure 7: Depot schematic and run-out schedule of GoAhead's Waterloo electric bus depot, London, UK. Source: Go Ahead (2019).

4. See https://www.youtube.com/watch?v=X3w4ldtoHF0



# Electrical infrastructure

**This section describes some of the key electrical infrastructure and components that are required, which includes:**

- Local electrical transformer (typically on site);
- Switchboard;
- Medium/low-voltage cabling to charging points;
- Chargers;
- Connections;
- Backup/reserve systems;
- High-voltage cabling to local substation (see Grid connection, above).

## Electrical transformers

All but the smallest bus depots would need to have a transformer located on or very close to the site. To minimise energy losses through cables, the transformer should be located as close as possible to the point of use. The transformer "steps down" the electricity from a high voltage to a medium or low voltage so that it can be used by the bus chargers, which are floor mounted depending on their size and mass. Local legislation or policies from the distribution network operators providers will state how these should be managed, how frequently they will be tested and whether 24-hour access will be required by distribution network operators companies.

Although it could be more expensive, if a depot requires a transformer of more than 1MW, operators should consider whether to purchase multiple transformers of up to 2MW, because doing so can provide greater reliability and reassurance in the case of the failure of one of the units. For example, in Guadalajara, the depots were planned to require 2.4MW of power and so use two 1.2MW transformers.

## Switchboard

The switchboard receives power from the transformers (and a backup power source if applicable) and delivers it to the necessary charging components. The design and selection of switchboards needs to be carefully considered, because a failure in the switchboard will have an impact on all of the chargers it manages – which could be some or all of the charging stations.

## Cabling

Electricity is distributed to each charger via traditional cables or conductor bars. Both distribution methods need to be accessible and regularly inspected and maintained, regardless of whether they are buried under the ground or are part of a canopy charging system (i.e. cables in the roof). Therefore, if cables or conductor bars are buried into the ground regular inspection points should be planned and constructed at the outset to facilitate this and minimise costs.

- Traditional cable distribution – Cables (Figure 9) are very flexible and can be used in numerous circumstances. There are many different types, standards and qualities on the market. Cables should be in conduits to provide protection from physical damage and environmental conditions. They can be installed and maintained by a qualified tradesperson (no specialist knowledge required);
- Conductor bar distribution – The conductor bars (Figure 10) are much more (up to 98%) energy efficient. Because of their modular design, they are safer and quicker to install and repair.

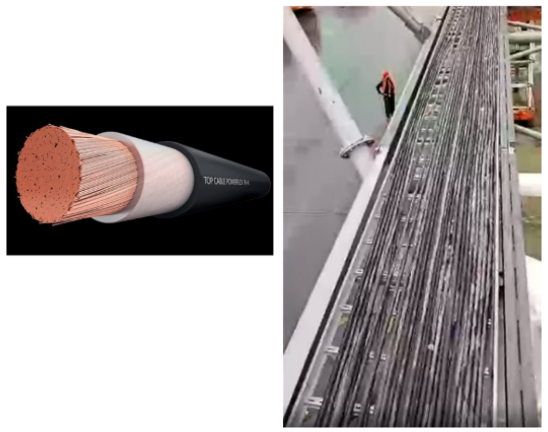


Figure 9. Cable distribution does not need specialist knowledge to install or repair.

Figure 10. Conductor bar distribution.

## Backup power supplies

Some depots choose to have backup systems to ensure that even if there are regional or local power outages, or there are failures in some of the equipment, the depot is still able to deliver a service. The decision whether or not to proceed with a backup system, and if so how big it should be, should be taken after evaluating the reliability and service provision of the network of the local electricity terminal. If reliability is very high and there are only very infrequent short outages, then it may be feasible to not have a backup; whereas for a system with more frequent outages it may be preferable to have a backup of over 50% or the minimum power needed to charge all buses.

There are two main options for a backup or reserve system:

• Energy storage – typically through large static batteries;

• Instant energy generation – typically through a diesel or natural gas generator.

Energy storage through batteries can be an expensive option for an energy reserve because of the high capital expenditure costs of purchasing large batteries. However, there is the potential to couple batteries with slower forms of energy generation such as solar PV, which can also provide a long-term revenue source or reduce energy dependency on the grid. Further, some utility companies may provide favourable rates or provide incentives to companies using battery storage if they can provide grid balancing functions (i.e. feeding in to help match demand to supply). Further information can be found in the section on Renewable energy integration.

The vast majority of depots currently choose overnight slow-charging chargers; however, some are opting for fast plug-in chargers or fast pantograph chargers (Figure 11). Extensive construction work is needed when installing the latter to ensure there is a solid and reliable concrete base on which the charger can be built. If charging units over 150kW are needed, it is also necessary to consider cooling, to ensure a smooth operation and to avoid damage to chargers. To ensure longevity, chargers will also need shielding to limit exposure to the sun and rain, which can cause degradation. Further information on charger selection, charging strategies, charging connections and the insights from Jakarta's (Indonesia) transition plan can be found in Zero-Emission Bus Charging Systems: Insights from Jakarta (CFF, 2020a).

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 11. Different charging technologies for zero-emission buses. Source CFF, (2020a).

## Interoperability

When considering physical charging connections, software protocols or charging speeds, interoperability provides the most flexible way for cities and operators to manage a zero-emission bus fleet, interoperability can be essential to overcome challenges that may arise with emerging technologies. In addition, having a city-wide standard can allow buses to be charged in other depots if necessary or on common "opportunity charging" infrastructure throughout the city.

As part of their electromobility policies, some cities and countries (e.g. Indonesia) have developed physical connection standards to help remove operational barriers (see Figure 12). Similarly, software protocols such as the Open Charge Point Protocol (OCPP) enable electrical vehicle charging systems and central management systems from different suppliers to communicate with each other[5].

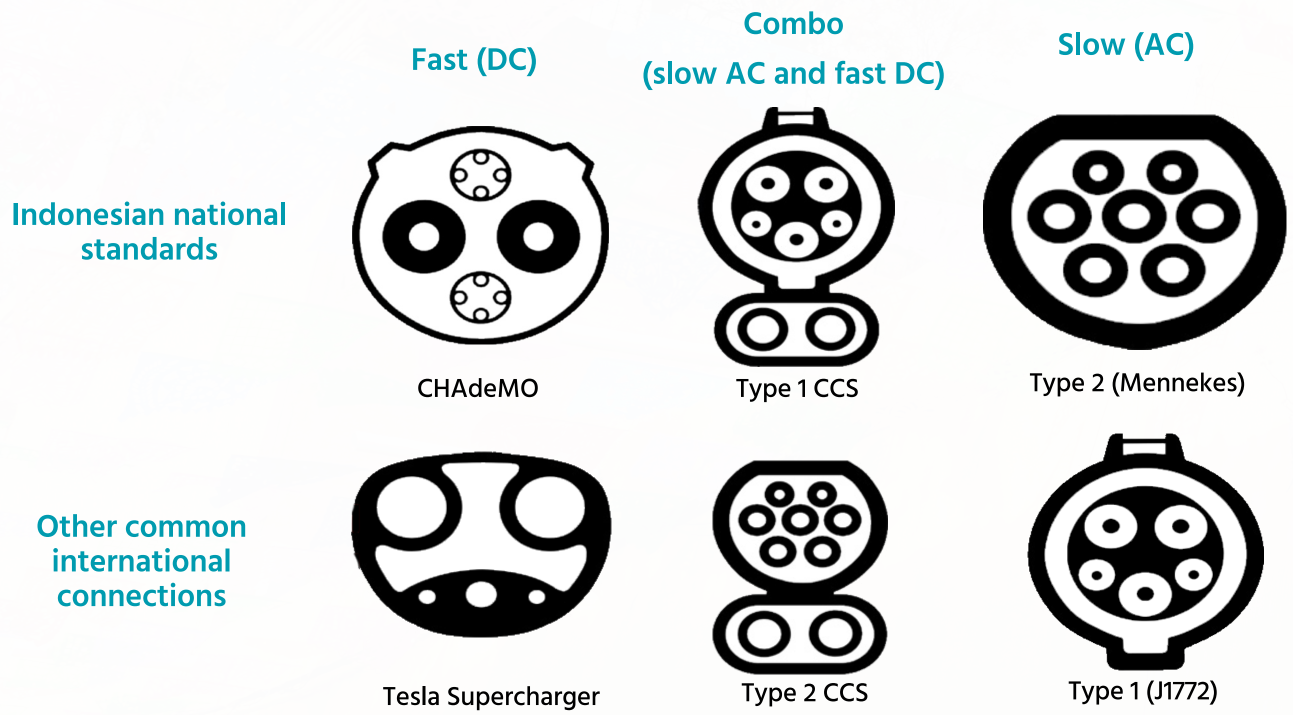



Figure 12. Common charging connections and standards in Indonesia. Source CFF, (2020a).

5. OCPP (currently edition 2.0.1), is an open application protocol created by the Open Charge Alliance – a coalition of OEMs, software providers, research organisations and charging network operators. See https://www.openchargealliance.org/protocols/ocpp-201/.

Photo credit: Terminal El Conquistador - Copec Voltex , Santiago de Chile.

# Maintenance

Maintenance is one area where electric buses have a significant advantage over traditional ICE buses. Zero-emission buses have no moving engine parts so their maintenance requirements are considerably less than those of a bus with a combustion engine. This is one of the main reasons why zero-emission buses have lower operating costs. Figure 13 illustrates the maintenance costs in detail of different bus technologies in Seattle, while in Medellín, operational and maintenance costs of electric buses were respectively 25% and 50% lower than the compressed natural gas (CNG) buses in operation (C40 and ICCT, 2021). Experience gained by the bus operators in Santiago de Chile found that, when well maintained, failures in zero-emission buses are no more frequent than those experienced by ICE buses, with failures more frequently associated with traditional auxiliary components such as doors, HVAC systems or lighting (ZEBRA, 2020).

Maintenance needs for electric buses differ significantly from ICE buses, requiring different practices, training and processes to ensure that the vehicles are always available for operation (Figure 14).

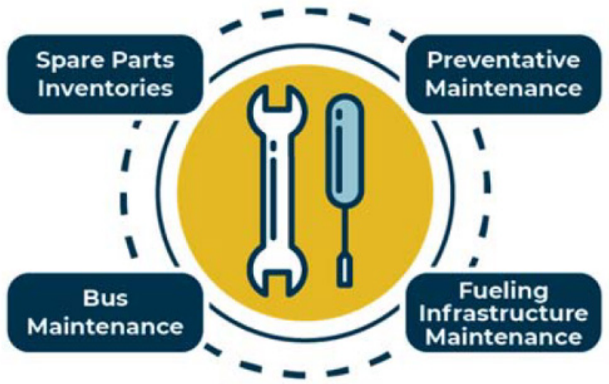



Figure 14. Key maintenance components for a zero-emission bus. Source: CFF (2021c)

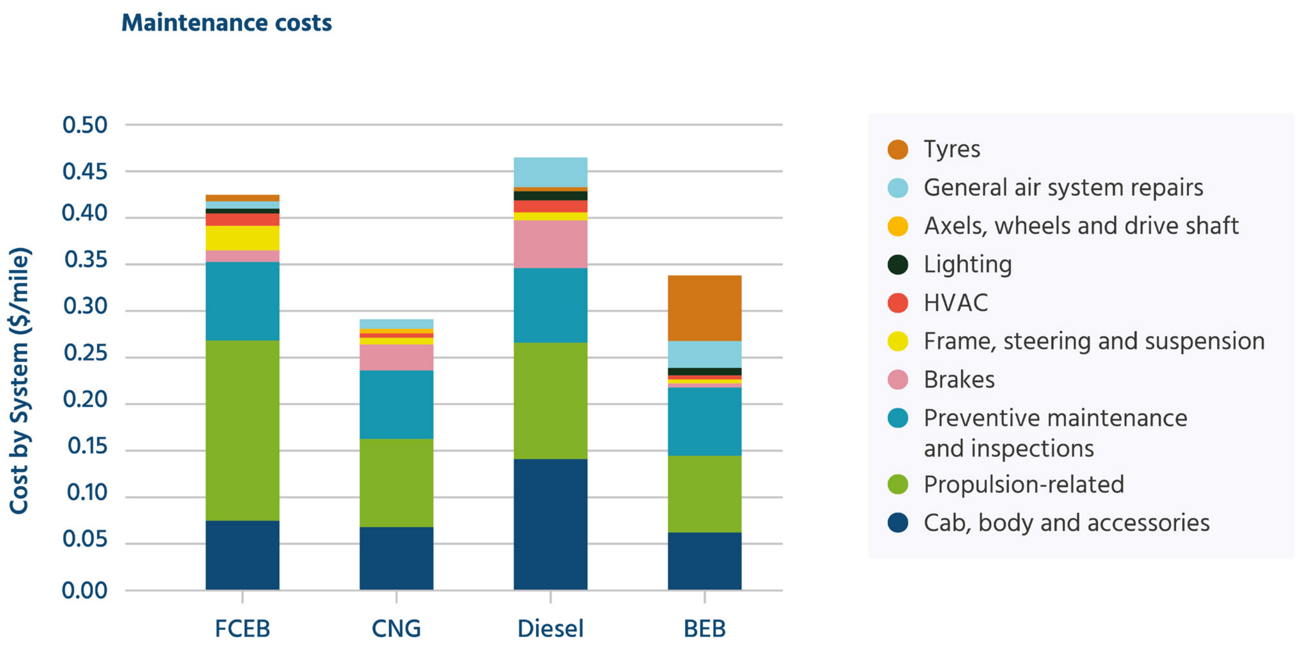



Figure 13. Examples of maintenance costs for a fuel cell electric bus (FCEB), a compressed natural gas (CNG) bus, a diesel bus and a battery electric bus (BEB). Source: CFF (2021c)

One of the most significant differences is the greater focus on visual inspections and checks for preventative maintenance compared with the typical replacement of parts and fluids.

The schedule of frequent visual inspections and checks need not (and should not) be developed from scratch. Instead, bus and infrastructure manufacturers and suppliers should provide a list of maintenance activities which will outline the preventative maintenance activities necessary and describe the time and expertise required to complete them and to diagnose the identify problems.

Regular inspection routines for each bus, the charging infrastructure and the wider depot should include:

- Monitoring the batteries' "state of health" (SOH);
- Checking for dirt, dust or moisture;
- Checking connection points for signs of abrasion or wear;
- Tightening and retorquing connectors;
- Running diagnostic tests using monitoring and charging software;
- Cleaning and/or replacing filters;
- Replacing cords and connectors;
- Checking and recording current and voltage levels;
- Inspecting for loose connection points on battery terminals.

Bus maintenance practices should be consistent across a fleet (for each specific model of bus), but maintenance routines for battery charging will need to be adapted to suit fast and slow charging units. Slow charging stations are typically modular in design: thus they require limited maintenance and it is relatively easy to replace components. There is also the advantage that they are located within the depot. Fast charging stations often require more intensive maintenance because they have cooling systems and filters to cope with the higher voltage and dust, and are often located outside of the depot (on or at the end of a route), which may be more challenging to access.

Driver training/re-training is important because an efficient driving style and use of regenerative braking can maximise battery range, as well as minimise wear and tear to key components, prevent failures and prolong the lifespan of a bus by up to 10% (ZEBRA, 2020).

At the time of writing, it can take longer than usual to obtain replacement parts and electrical maintenance equipment because of a surge in demand for zero-emission buses and the limited number of original equipment manufacturers (OEMs) and third-party suppliers. This will change as OEMs transition to providing only zero-emission options in the future, but in the interim operators need to ensure that they contact parts suppliers early and have a comprehensive inventory of spare parts to minimise operational issues.

### Four steps to a well-maintained zero-emission bus fleet

1. **Monitor** – the heath of batteries and core components regularly;
2. **Prepare** – for repairs by having a sufficient inventory of key spare parts;
3. **Develop** – training and inspection plans for staff;
4. **Optimise** – driver behaviour to maximise lifetimes of components.

# Safety

As with ICE bus depots, an electric bus depot is a relatively safe place to work, but safety must be considered at all stages of planning, constructing and operating a depot to minimise the risks to staff and limit damage to expensive equipment. This section discusses the various aspects of safety that must be considered, but further detail on safety considerations relating to operations and staff training is available on the CFF website.

The specific risks and hazards relating to electric buses are considerably different to those that occur in an ICE bus depot. By far the most significant risks are related to working with electricity, such as "arc flash" (see Box on 'Arc flash'), which underlines the clear need to design-out some risks and create standard operating procedures (SOPs). Other hazards worth noting include working with very quiet buses or working at height (if using roof mounted batteries).

### Arc flash

An "arc flash" is a significant burst of light and heat caused by a high-voltage electrical discharge travelling through the air between two conductors[6]. The burst of light and heat can cause fires and injuries such as burns and shrapnel wounds. Without personal protective equipment (PPE) and proper procedures in place arc flash can result in serious injury or death. Arc flash can be caused by:

- Airborne dust;
- Particulate matter;
- Corrosion;
- Faulty installation.

In the case of zero-emission buses, an arc flash is most likely to happen between the battery and any conductive tools or equipment.

| Ratio of workplace safety incidents to fatalities | |
|---|---|
| Mechanical incidents | Electrical incidents |
| 300:1 | 10:1 |

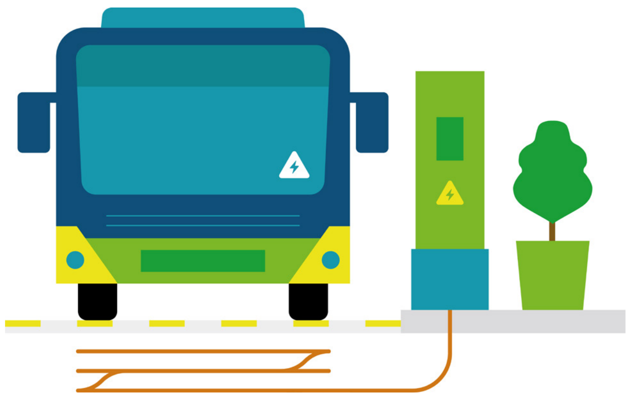
Bus depot operators will be fully aware of any national, state or municipal regulations that must be complied with for ICE vehicles. However, there will be additional compliance requirements for zero-emission bus depots. Would-be zero-emission bus operators should review and understand all relevant national, state or municipal policies, laws and emergency services regulations related to working with electricity and electric vehicles. Further, it is recommended that operators start speaking to other applicable agencies such as utility providers or/and distribution network operator (including informing them of long-term strategies) or emergency services who may already have policies or recommendations in place which should be used. Speaking to these groups early on and understanding roles and responsibilities of different parties with respect to safety inside and outside the depot can avoid significant delays to depot refurbishment and operation.

Measures to minimise, mitigate and manage hazards and risks associated with zero-emission bus depots can be placed into three categories (DGUV, 2012):

1. Technological/design – Measures that will design-out hazards, minimise exposure or, in the case of an incident, stop the hazard (e.g. emergency shutdown buttons in accessible locations, or parking aids);

2. Organisational/process improvements – The development and observance of protocols and processes (e.g. waiting times to allow for the dissipation of voltage or training for maintenance staff);

3. Personal – Members of staff take responsibility for safety measures (e.g. use of PPE).



Technological and/or design measures are a key part of the infrastructure changes needed to electrify a depot, so the rest of this section focuses on the safety aspects of those measures. For more extensive information on the electric hazards caused by working on electromobility, training recommendations and standards for staff working with/around electric vehicles and PPE usage see Further reading.


Photo credit: Terminal El Conquistador - Copec Voltex , Santiago de Chile.

6. Government agencies responsible for workplace health and safety provide guidance on arc flash. See, for example, https://www.osha.gov/sites/default/files/2018-12/fy07_sh-16615-07_arc_flash_handout.pdf.

## Technological and design measures

Electric buses produce significant less noise than their ICE counterparts, so the dangers associated with vehicle–human collisions are significantly higher. To mitigate this, pedestrian areas must be well marked and highly visible and should ideally be separate from driving areas. This also applies to areas where there are dangerous components such as transformers, maintenance areas, areas with high-voltage electricity or any location where PPE is needed.

Charging infrastructure and electric buses are costly to purchase and to replace core components. In addition, collisions between buses and charging infrastructure can be dangerous because of the risk of exposing electricity infrastructure, creating short circuits or thermal runaway (Figure 15) and fires in batteries, leading to possible injuries or even death, as well as other significant operational issues.

Technological and/or design measures are a key part of the infrastructure changes needed to electrify a depot, so the rest of this section focuses on the safety aspects of those measures. For more extensive information on the electric hazards caused by working on electromobility, training recommendations and standards for staff working with/around electric vehicles and PPE usage see Further reading.

Common risks and solutions:

• Collisions between buses and charging infrastructure: simple solutions include having stopping points on the floor of parking spaces to inform drivers when they have reached the desired location, as shown in Figure 16;

• In the case of electricity harming a person, or is no longer under control, the correct response is to immediately isolate and turn off the electricity source to eliminate the problem. Emergency shutdown mechanisms should be placed throughout a depot, at key locations where risk is greatest (e.g. next to transformers or in inspection/repair stations);

• Dust: treatments can be applied to floors or other surfaces. These can improve the lifespan of chargers and vehicles and also prevent dust causing arc flash.

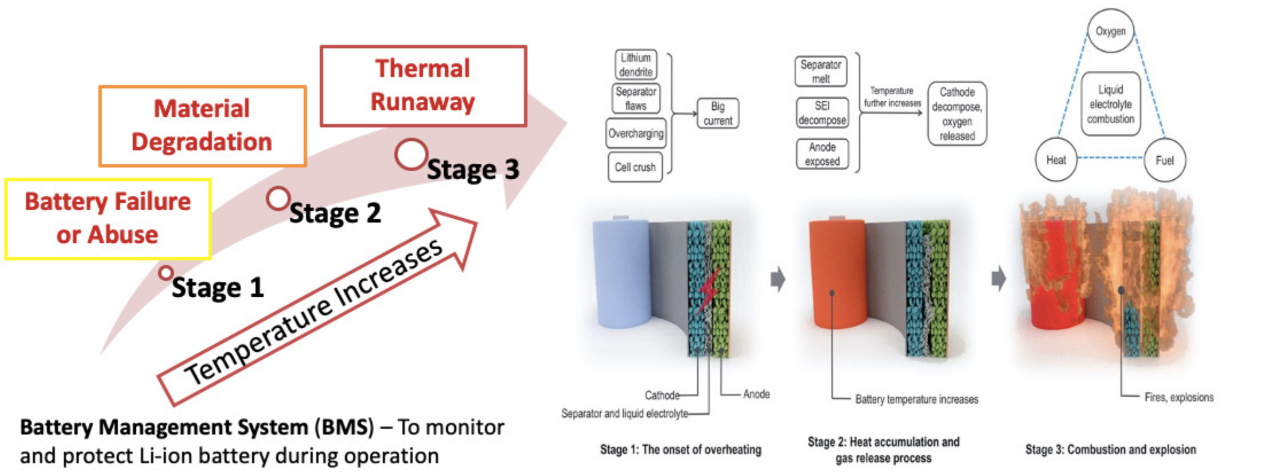



Figure 15. The stages and dangers of thermal runaway in a battery. Source: adapted from figure 1 of Liu et al (2018).

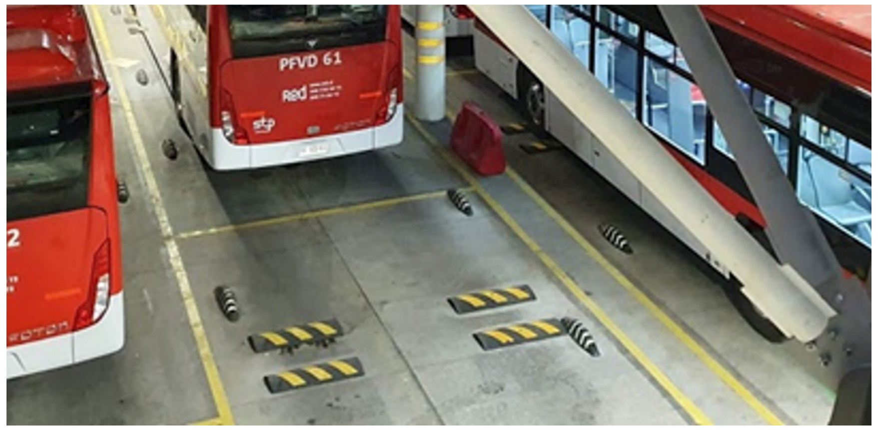


Figure 16. Stopping points on the floor of a bus depot inform the driver they have reached the desired stopping location.

## Standard operating procedures

Careful design and use of technological solutions on their own can mitigate a significant amount of day-to-day risk but are no replacement for implementing comprehensive procedures and ensuring that everyone is trained. SOPs are essential for anyone working around or at risk of exposure to high-voltage electricity. Successful strategies include the following:

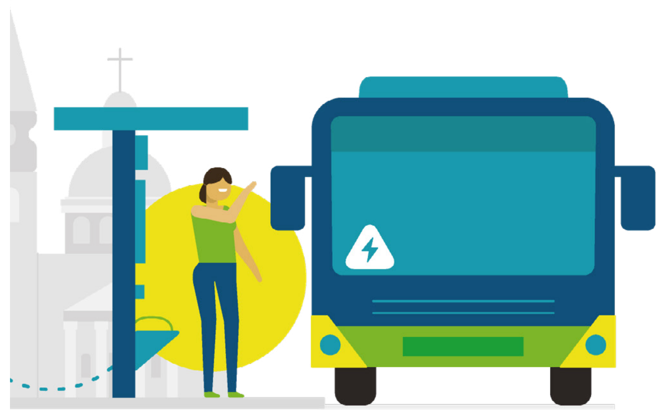
• Increase the frequency of monitoring and inspecting vehicles and charging equipment for faults or defects, compared with SOPs for ICE vehicles;

• Always disconnect electrical circuits when working on a vehicle;

• Restrict access to certain areas so that only staff who have training on working close to high-voltage components can enter;

• Alert all staff to the national or local regulations governing when PPE must be worn if they are working with or near to electricity (minimum voltage is typically based on national regulations, e.g. 30V in Canada or 50V in the USA).

Emergency services and first responders have highlighted the emergent risks around electric vehicles which, unlike ICE vehicles, currently lack standardised safety design protocols (e.g. during a fire) and thus pose additional risks to emergency responders and passengers (NTSB, 2020). Engaging with the local emergency services and training depot-based staff and drivers on how to respond to the specific electric bus model/brand for these unlikely incidents can help mitigate these risks[7].



7. A comprehensive list of emergency response guides from more than 35 manufacturers of alternative fuel vehicles is on the US National Fire Protection Association website at https://www.nfpa.org/Training-and-Events/By-topic/Alternative-Fuel-Vehicle-Safety-Training/Emergency-Response-Guides.

# Telematics and fleet management software

Over recent decades many bus operators have begun to integrate fleet management software into their operations to optimise planning and scheduling of their fleet, to track real-time locations and improve reliability and performance. Using electric vehicles has made this almost essential. Commercially available integrated telematics and fleet monitoring software can prolong the lifetime of buses, minimise failure rates and detect faults at an early stage, significantly reducing operational costs and minimising the need for on-route support, which can improve service and thus satisfaction.

Key to the success of electrification of a depot is being able to access up-to-date data for understanding and managing the charging profile of the fleet and the necessary charging upgrades.

For example, if an overnight charging strategy is to be used, buses will typically be plugged in to the charging infrastructure as soon as they are returned to the depot. If this happens without using charging management software (as shown in Figure 17), there is significant power load fluctuation throughout the night because many buses are all charging at the same time, resulting in significant peaks and troughs.

Charging management software can significantly even out the load profile throughout the night. The benefits of providing an even load profile are as follows:

- Significant reduction of the cost of charging infrastructure, because the cabling required can have lower power ratings, much smaller transformers can be used and fewer charging stations may be needed (although the latter can have operational challenges);
- Significant reduction of electricity costs from utility providers by timing the charging to use cheaper off-peak tariffs (subject to local legislation) and minimising peak power needs, which can attract significant surcharges.

**Case Study**

A study of a bus depot in Germany of 74 electric buses found that charging management to prioritise charging in periods of lowest cost reduced the peak load by **56.6%**. (Lauth et al, 2019).

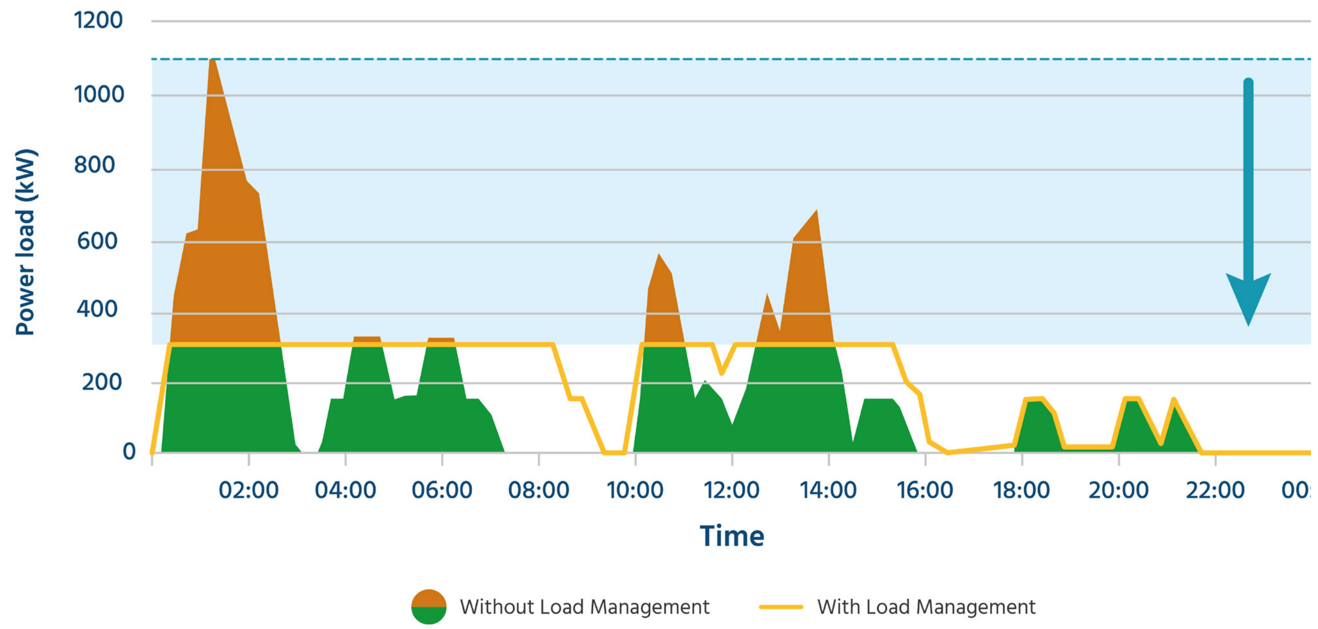



Figure 17. Benefits of charging management. Source: CFF (2020a)



# Adaptation and resilience

The impacts of global climate change are ever more apparent. Cities around the world are reporting warmer temperatures and greater extremes of weather, with increases in occurrence and magnitude of heatwaves, flooding and storms. Adapting to this new reality is essential to ensure that transport infrastructure is as resilient as possible, given the new reality of current and growing dangers caused by climate change.

Many countries and cities are mapping the risks relating to climate change and the hazards for society. For example, local temperatures are expected to increase on average by 1.5–5 degrees Celsius between now and 2050, while the likelihood of extreme precipitation events (defined as a "once in 50 years" event) is expected to be four times higher in some regions than it was in 1950–1981 (McKinsey, 2020) and 66% of the world's population are expected to be living in water-stressed conditions by 2025 (C40, 2018b).

To ensure longevity and promote resilience any new infrastructure projects must consider the impacts of climate change, including extreme heat, inland flooding, coastal and storm surges, drought and wildfires, and identify steps to mitigate and accommodate these risks. Some cities and nations have already considered risks and have Metropolitan Disaster Risk Reduction Management Plans in place, have signed up to initiatives like the Sendai Framework for Disaster Risk Reduction or have regulations in place to ensure environmental and social management policies and plans are implemented.

Within these city- or region-wide plans and policies, specific measures can be developed for zero-emissions bus depots (compared with ICE bus depots), such as measuring the greenhouse gas reductions and air quality improvements associated with electrifying the

depot. This information can also be important to develop the political case for greater electrification in the city, demonstrating commitment to mitigating emissions and building public support.

**Case Study**

In Quito, Ecuador, an assessment was undertaken of the impact of the climate change on two of the city's main bus lines – Ecovia and Trolebús – which the city plans to electrify. The assessment details the risks and identifies any potential mitigation measures (CFF, 2020b).

Precipitation rates in the city are expected to increase by 13.4–16.4% between 2016 and 2040, and by 21.8–31.3% between 2041 and 2070. Similarly, days of extreme rainfall per year are expected to increase from 28 to 31 days per year between 2016 and 2040 and up to 42 days per year by 2070.

The assessment also found that the bus terminals were among the most at-risk infrastructure along the routes (Figure 18), but that road infrastructure and electrical signage were also at risk. There was also likely to be a significant increase in demand for air conditioning, which would put further stress on electricity demand.

Operators should plan for these periods of extreme weather and the potential interruption of service delivery, which are likely to cause knock-on effects such as economic losses.

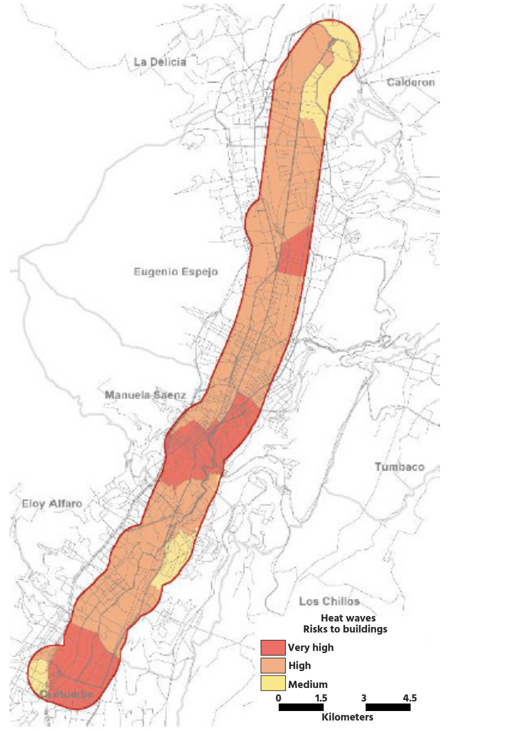



Figure 18. Risks to building infrastructure on the Trolebús corridor. Source: CFF (2020b)

| Common risks and mitigation measures for electric bus systems | | |
|---|---|---|
| **Type** | **Risks** | **Mitigation measures** |
| Heat Stress | Heat stress to electricity infrastructure outside the depot and affecting transmission into the depot | Greater shading using trees or structures |
| | Heat stress to electricity infrastructure inside the depot affecting charging rates | Cool surface treatments to reflect sunlight |
| | Heat stroke to employees working outside in the heat or in poorly ventilated indoor areas | Upgrading existing buildings to improve ventilation |
| | Lack of shading/cooling at bus stops leading to fewer users who choose alternative modes of travel | Plan for higher electricity use in the future |
| | Heat stress to roads | |
| | Increased electricity consumption through greater use of air conditioning | |
| Inland Flooding | Flooding of local electricity infrastructure | Install better drainage systems |
| | Flooding of in-depot electricity infrastructure | Landscape along flooding corridors |
| | Flooding on roads causing delays to service and affecting battery reserves | Construct micro-detention reservoirs |
| | | Use permeable materials for road and other surfaces (be wary around electrical infrastructure) |
| | | Avoid selecting depots in flood zones |
| | | Use waterproof membranes, sealants or shields |
| | | Provide emergency measures such as sandbags |
| | | Elevate charging infrastructure |
| | | Duplicate electricity cables or separate so at least half the fleet works |

Figure 19. Common risks and mitigation measures for electric bus systems. Source: CFF (2020b)

# Conclusions

As has been described throughout the guide, electrifying a bus depot – whether converting from diesel or from natural gas – is an involved process. Extensive planning and modifications are required to ensure that the depot is able to be resilient and operate effectively. However, if planned and implemented well, zero-emission bus systems will bring substantial benefits, such as a better user experience, reduced local and city-wide air pollution, lower greenhouse gas emissions and long-term financial savings. As with planning and deploying the rest of the zero-emission bus system, a key aspect of depot planning is identifying and talking to the new range of actors who will be involved, such as utility companies, distribution network operators, emergency services and electrical OEMs.

Although this guide provides advice on the specific aspects that should be considered when planning a depot, there remain some questions that operators need to consider during all stages, which will be specific to their own depots:

- How do each of the key areas of the depot (e.g. administrative, operations, parts storage bus storage and maintenance) need to change? Will their interactions with one another change?
- What is the current sequence of events in the facility? How will this need to change? How do operators interact with the facility?
- How does a vehicle typically flow through the facility? How does a bus get stored, fuelled, services, and made ready for service?

# Key references

The basis for significant parts of this report were based off four reports that the CFF commissioned as part of its technical assistance programme to support Monterrey and Guadalajara (Mexico) to plan the transition of their diesel bus depots to electric, as part of a wider package of assistance to aid the cities to transition from to a zero-emission bus fleet. Because of this, the reports have not been referenced throughout the report and are instead noted here.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2. Diseño funcional y operacional de los elementos fundamentales de los corredores. Available here.
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# Further reading


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