ELECTRIFICATION OF SINGAPORE HARBOUR CRAFT
– Shore and Vessel Power System Considerations

Maritime Energy and Sustainable Development (MESD) Centre of Excellence
Electrification of Singapore Harbour Craft
– Shore and Vessel Power System Considerations

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With inputs from Maritime and Port Authority of Singapore

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**Alternative Fuels for International Shipping**
*Published in April 2020*

**A Study on the Future Energy Options of Singapore Harbour Craft**
*Published in November 2020*
Executive Summary

Electrification of harbour craft considers the use of electrons stored in an onboard energy storage system for electric propulsion and hotel loads. In a prior study by Maritime Energy and Sustainable Development (MESD) Centre of Excellence, “A Study on the Future Energy Options of Singapore Harbour Craft”, electricity is recognised as one of the top energy options for the harbour craft industry. Therefore, this report deep dives into considerations for shore and vessel power systems of Singapore harbour craft to encourage efforts to meet Greenhouse Gas emissions reduction targets set by Singapore’s enhanced Nationally Determined Contributions and Long-Term Low-Emissions Development Strategy.

The study considered the different power configurations for electrified marine vessels in general; diesel-electric, parallel hybrid, plug-in hybrid and full-electric. The emissions baseline is established using the average thermal efficiencies of the harbour craft’s operations in diesel-mechanical power systems. The emissions reduction potentials are estimated to be between 13% and 48% across the different power configurations.

A review of four existing types of charging infrastructure showed that the most common type of charging infrastructure at the berth might not meet the operation profiles of Singapore harbour craft. Off-grid charging infrastructure, of either land-based or sea-based, would offer better opportunities for harbour craft to recharge during their idle duration.

Four local harbour craft were surveyed by MESD to understand the current sea and refuel operations. The harbour craft were selected from these categories: passenger ≤12 pax, passenger > 12 pax, lighter and tug boat. The survey results enabled the evaluation of electrification options for these harbour craft when switching to electric propulsion and onboard energy storage systems. Electricity was either drawn from the main grid or generated with an onboard diesel generator. Either one of the two power configurations (plug-in hybrid or full-electric) were considered for the surveyed harbour craft. The selection was based on their energy demands and available space for energy storage. As a result, the plug-in hybrid configuration was applied to the fast launch and lighter, and the full-electric configuration was used for the passenger ferry and tugboat. The results from these case studies highlighted the number of recharges required during the daily operations of each harbour craft.

A cost model, with key cost parameters, based on the concept of Total Cost of Ownership for the electrification of harbour craft, has been elaborated for an electric harbour craft and charging infrastructure. The cost model could estimate the total cost of owning and operating the assets, taking into account possible future costs and the time value of money. The payback period could also be estimated from dividing the incremental investments and expenses by the annual cost savings. The fuel and periodic maintenance costs are the two key cost parameters that determine the annual cost savings, as a result of a switch from the conventional diesel-powered harbour craft to an electric harbour craft.
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<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ABS</td>
<td>American Bureau of Shipping</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>BMS</td>
<td>Battery Management System</td>
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<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
</tr>
<tr>
<td>CO₂-eq</td>
<td>Carbon dioxide-equivalent</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EF</td>
<td>Emission Factor</td>
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<tr>
<td>EMA</td>
<td>Energy Market Authority</td>
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<tr>
<td>ESS</td>
<td>Energy Storage System</td>
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<tr>
<td>EV</td>
<td>Electric Vehicles</td>
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<tr>
<td>GEF</td>
<td>Grid Emission Factor</td>
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<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>GJ</td>
<td>Gigajoules</td>
</tr>
<tr>
<td>GT</td>
<td>Gross Tonnage</td>
</tr>
<tr>
<td>HC</td>
<td>Harbour Craft</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEE</td>
<td>Institution of Electrical Engineers</td>
</tr>
<tr>
<td>kg</td>
<td>kilogram</td>
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<tr>
<td>kW</td>
<td>kilowatt</td>
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<tr>
<td>kWh</td>
<td>kilowatt-hour</td>
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<tr>
<td>LFP</td>
<td>Lithium Iron Phosphate</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>LTO</td>
<td>Lithium Titanate</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>MESD</td>
<td>Maritime Energy and Sustainable Development Centre of Excellence</td>
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<tr>
<td>MGO</td>
<td>Marine Gas Oil</td>
</tr>
<tr>
<td>MJ</td>
<td>Megajoules</td>
</tr>
<tr>
<td>MPA</td>
<td>Maritime and Port Authority of Singapore</td>
</tr>
<tr>
<td>MtCO₂e</td>
<td>Metric tonne of Carbon Dioxide Equivalent</td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>N₂O</td>
<td>Nitrous oxide</td>
</tr>
<tr>
<td>NCCS</td>
<td>National Climate Change Secretariat</td>
</tr>
<tr>
<td>NCV</td>
<td>Net Calorific Value</td>
</tr>
<tr>
<td>NEA</td>
<td>National Environmental Agency</td>
</tr>
<tr>
<td>NMC</td>
<td>Nickel Manganese Cobalt</td>
</tr>
<tr>
<td>PF</td>
<td>Power Factor</td>
</tr>
<tr>
<td>PMS</td>
<td>Power Management System</td>
</tr>
<tr>
<td>SFOC</td>
<td>Specific Fuel Oil Consumption</td>
</tr>
<tr>
<td>TCO</td>
<td>Total Cost of Ownership</td>
</tr>
<tr>
<td>WTT</td>
<td>Well to Tank</td>
</tr>
</tbody>
</table>
Electrification of Singapore harbour craft (HC) signifies a change from the well-established Internal Combustion Engines (ICE) and low-cost Marine Gas Oil (MGO) as their main energy converters and fuels, respectively. Since electrical systems are discernibly part of most harbour craft, the key industry consideration is the cost-benefit associated with the extent of electrification. This report aims to assist stakeholders in the harbour craft industry when evaluating the efforts to electrify, improve energy efficiency and reduce carbon emissions of their vessels.

A background about Singapore’s harbour craft is found in the main report of “A Study on the Future Energy Options of Singapore Harbour Craft”. The same classification of harbour craft is used in both reports and follows MPA’s guidelines. Harbour craft have been assigned different prefixes to divide them into five types, namely, SP for passengers, SC (carries both cargo and passengers), ST for tugboats, SB for bunker tankers and SR for all others. The SP type is further divided into two types based on size: SP ≤ 12 pax and SP > 12 pax. There are around 2,300 harbour craft that operate within Singapore’s port limits.

The key findings from the main report are relevant to this topic of electrification. The study profiled the harbour craft’s population by their age, gross tonnage, engine power and engine maker. It ranked twelve alternative fuels and power options, and the full-electric option merged as one of the top three energy options for SP ≤ 12 pax, SP > 12 pax and SC harbour craft in the long term. Electrification of vessels has been considered in the main report under the power options of either hybrid, full-electric or fuel cell. Some of the harbour craft have favourable profiles to consider alternative energy options in the short term, either as new-built or retrofitted vessels. The recommendations were based on their age, engine size, gross tonnage and operation routes. For example, a large proportion of passenger craft (both ≤ 12 pax or > 12 pax) was found to be more than 20 years old, and several had fixed operation routes. Small engine sizes, coupled with sizeable gross tonnage and fixed operation routes, were preferred profiles when it came to using future energy options, due to the lower energy density of these energy options.

Recharging marine vessels with clean, renewable electricity reduce carbon emissions more than fossil-based electricity. However, carbon emissions reduction is not the only value proposition of electrification. There are other beneficial outcomes from the electrification of marine vessels[1-3], for example:

- a. Higher efficiency of the electric drivetrain and lower energy consumption during low-load operations.
- b. High torque at low-speed engine mode.
- c. Battery enhances optimal efficiency of the internal combustion engine in battery hybrid.
- d. Reduce maintenance costs due to fewer maintenance checks and moving components.
- e. Zero shipboard emissions for full-electric in protected environment.
- f. Low noise and vibration levels for ferries and fishing vessels.

However, the costs of electrification are high. In the case study reported by e-ferry Ellen, the costs of a full-electric ferry are reported to be significantly higher (up to 40% in CAPEX for a new passenger ferry) [4]. The profiling of Singapore’s harbour craft in the main report has reported a wide range of speed requirements, size and operations. Thus, the incremental costs to adopt electrification may

1 CAPEX: Capital Expenditure
easily exceed existing case studies. For many local harbour craft owners competing at low-profit margins, the economic costs alone can be a strong deterrent. Table 1.1 provides a summary of the other considerations by shipowners and authorities in the electrification of harbour craft.

<table>
<thead>
<tr>
<th>Harbour Craft Owners</th>
<th>Authorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Higher capital investment of electrified power systems in comparison to internal combustion engines</td>
<td>• Carbon emissions reduction to meet Singapore’s enhanced Nationally Determined Contributions</td>
</tr>
<tr>
<td>• Availability and convenience of charging points</td>
<td>• Uncertainty on standards for fast-charging infrastructure for harbour craft</td>
</tr>
<tr>
<td>• Change to the vessels’ operation profiles and refuelling frequency</td>
<td>• R&amp;D for electrification to be a competitive alternative fuel or power option</td>
</tr>
<tr>
<td>• Re-training for the crew on operating shipboard systems, recharging and maintenance</td>
<td>• High infrastructural costs to develop a charging network</td>
</tr>
<tr>
<td>• Actual fuel savings during operation and incentives to use electricity</td>
<td>• Impact to the power quality if significant power is drawn simultaneously</td>
</tr>
<tr>
<td></td>
<td>• A lack of access to the main grid for smaller islands and the anchorage areas</td>
</tr>
</tbody>
</table>

Table 1.1 Considerations by harbour craft owners and authorities on the electrification of harbour craft

The economic and environmental benefits of electrification are highly dependent on the harbour craft’s power configuration and operations profiles [2]. The benefits must be quantified carefully against the environmental and economic costs of electrification. In consideration of the wide range of size and operations across the types of harbour craft, projected cost-benefits analysis and optimisation of the power configuration will vary.

1.1 Different Power Configurations of Harbour Craft

Figure 1.1 illustrates the different types of propulsion and power configurations commonly found in ships. In practice, the design of the power system is based on the ships’ operation profile and the power requirements of the vessel and are usually customised.

The majority of Singapore harbour craft operates with the diesel-mechanical propulsion, which consists of an internal combustion engine that converts MGO into mechanical energy to propel the vessel. A gearbox ensures power transmission to the propeller and to reduce power to achieve more torque and less speed during starting and acceleration. An independent diesel-generator (also known as auxiliary engine) or an alternator attached to the main engine generates electricity for the harbour craft’s service loads.

In diesel-electric propulsion, several diesel generators are connected to a common main electrical bus, and the propulsion is driven by an efficient electric motor. The advantage is that the propulsion can be decoupled from the engine’s speed and better load sharing among the generators can be achieved. An electric motor already has full torque available during start-up, and therefore the gearbox is optional in the configuration (i.e. direct drive). With a gearbox, the motor is designed to be smaller and lighter. Ships inclined towards diesel-electric propulsion are cruise ships, icebreakers, ferries, shuttle tankers, chemical carriers and research vessels [5].

Hybrid propulsion has two types of propulsion, where a diesel-mechanical configuration provides high-efficiency during cruising, and an electric motor is coupled to the same shaft through a gearbox to provide propulsion for low-speeds. This motor may function as a generator for electrical loads and recharging batteries. Typical applications of this configuration are naval frigates and destroyers, towing vessels and offshore vessels [6].
Hybrid vessels have dual energy sources, and the common configuration includes batteries sized to assist the main engine in achieving optimal fuel consumption. In some vessels, the batteries are sufficiently sized to allow the vessel to sail short distances on all-electric mode. The main ship types are car or passenger ferries, offshore vessels, Ro-Ro cargo, tug boat, fishing vessels and other activities.

In a scenario where a larger battery capacity can be placed in the vessel, it is faster to recharge with electricity produced from an external power supply. This plug-in hybrid configuration will have an onboard charger to convert the electricity from AC\(^2\) to DC\(^3\). A longer all-electric mode is feasible with larger storage capacities. The main ship types are car or passenger ferries, fishing vessels, cruise ships and offshore vessels [7].

A full-electric vessel depends entirely on external electricity supply for its propulsion and service loads, although it may have a diesel generator as emergency backup power. The main ship type is car or passenger ferries, followed by fishing and other activities. Recent full-electric pilot projects include tug boat (Port of Auckland), container ship (Yara), offshore supply (Shenzhen Maritime Bureau), bulk carrier (Guangzhou Development Rui Hua) and bunker tanker (Asahi Tanker) [8-11].

Electrification of harbour craft is trending globally, with a significant number of projects found in countries that are obligated to meet their carbon emissions reduction targets by 2050. DNV GL Alternative Fuel Insights platform, as of July 2020, has registered 448 marine battery projects with the majority in Europe [12]. It is not a coincidence that these are the same countries, whose energy mix are significantly dominated by renewable energy. In comparison, Singapore relies mainly on fossil-fuelled power plants, where natural gas currently meets

\(^{2}\) Alternating current
\(^{3}\) Direct current
95% of its electricity production [13]. This section aims to estimate the Greenhouse Gas (GHG) emissions reduction potentials based on the calculation of GHG carbon dioxide-equivalent emissions per unit of energy consumption (g CO₂-eq/kWh) under different power configurations. The fuels which are used for the calculation are MGO (power generation for diesel-electric, hybrid and plug-in hybrid) and liquefied natural gas (LNG) for Singapore’s power plants (grid electricity generation for plug-in hybrids and full-electric).

In the short-term scenario, the first fleet of harbour craft is likely to be of diesel-electric, hybrid or plug-in hybrid power configurations. Full-electric harbour craft is included as an option for short routes and limited vessel operations. The diesel-mechanical power configuration (with MGO as fuel) is the baseline, with which the GHG emissions reduction potentials are determined.

The calculations focus on the energy output (shaft output) in kWh for harbour craft propulsion power. For most harbour craft, the service loads are a small proportion of the overall propulsion power demands. The main greenhouse gases, carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), which are produced during the upstream and downstream activities of a harbour craft’s power generation are estimated from published sources. Table 1.2 lists the upstream and downstream activities, which generates direct and indirect emissions during various stages of energy use. Similar studies would consider the upstream activities as “Well-to-Tank” and downstream activities as “Tank-to-Wake”. The summation of the GHG emissions from both upstream and downstream activities would be the total GHG CO₂-equivalent emissions produced under different power configurations (kg CO₂-eq/kWh).

Table 1.3 provides a comparison of the Net Calorific Value (NCV) and Emission Factors (EFs) for MGO and natural gas (NG). From the perspective of emissions generated during energy conversion, NG has a clear advantage over diesel on these main GHG gases, CO₂, CH₄ and N₂O over diesel oil, due to a higher NCV and lower EFs during combustion. The Global Warming Potentials (100-year) are 1, 28 and 265 for CO₂, CH₄ and N₂O, respectively [14].

The results from the calculations are shown in Figures 1.2 and 1.3. The baseline reflects a range of diesel engines with thermal efficiencies of around 32% to 36.5%, which is reasonable for the existing fleet of harbour craft. Diesel-electric and hybrids provide emissions reduction by means of enabling the diesel engines to operate at their optimal SFOC. Plug-in hybrids promote further reduction due to the lower emissions from the grid and lower transmission losses of the electrical systems. The wide range of reduction potentials suggests that optimisation may be carried out for each power configuration. If the plug-in hybrid is to demonstrate a significant reduction potential (> 31%) over a parallel hybrid harbour craft, the battery ought to be sufficiently sized to allow the vessel to draw at least 50% of its power demand from the grid.

Due to class regulations, the battery capacity required for full-electric is about twice the capacity of an equivalent hybrid harbour craft (see Section 3.1.4 ii on class regulations relevant to lithium-ion (Li-ion) batteries). From a life-cycle perspective, the larger energy storage reserve required in a full-electric harbour craft increases the emissions from battery production, when compared to a hybrid equivalent. The contribution of battery production emissions to overall emissions reduction from the use of grid electricity is further explored in later case studies (Refer to Section 3.3).
Marine Gas Oil Electricity (Main Grid)

<table>
<thead>
<tr>
<th>Upstream Activities</th>
<th>Production and transportation of marine gas oil⁴</th>
<th>Production and transportation of Liquefied Natural Gas⁷ (LNG is set to account for half of natural gas supply by 2025)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Combustion⁸ (Grid Emission Factor of Singapore’s power plants used to determine CO₂ and fugitive methane gases from EMA, N₂O estimated from a study on Singapore’s combined cycle plant⁹)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transmission (loss in the grid 2%)⁸</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Downstream Activities</th>
<th>Combustion⁵ (Average SFOC of a range of high-speed and medium-speed of marine diesel engines⁶)</th>
<th>Energy storage¹⁰ (Charging loss 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Generation of electricity by diesel genset (95% efficiency)</td>
<td>Transmission losses in the drivetrain¹⁰ (Discharging loss 5%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Applicable Types of Power Configuration</th>
<th>Diesel-mechanical (Baseline)</th>
<th>Diesel-electric</th>
<th>Hybrid</th>
<th>Plug-in hybrid</th>
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</table>

Table 1.2 Key sources of emissions during various stages of energy use

<table>
<thead>
<tr>
<th>Emission Stream Type</th>
<th>NCV GJ/tonne</th>
<th>CO₂ EF kg CO₂/GJ</th>
<th>CH₄ EF kg CH₄/GJ</th>
<th>N₂O EF kg N₂O/GJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Factor</td>
<td>Uncertainty</td>
<td>Factor</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>Gas/Diesel Oil</td>
<td>43.0</td>
<td>2.0%</td>
<td>74.1</td>
<td>2.0%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>48.0</td>
<td>4.0%</td>
<td>56.1</td>
<td>4.0%</td>
</tr>
</tbody>
</table>

Table 1.3 Default fuel combustion conversion factor and uncertainty values


⁴ WTT (MGO): 14 gCO₂/MJ [15]
⁵ Assumptions for average SFOC for various power configuration: 0-10% * SFOC⁷ for hybrid; 5-15% * SFOC⁶ for diesel-electric; 15-25% *
⁶ SFOC for diesel-mechanical [2]; SFOC of marine diesel engines: High-speed engines from 195-225 g/kWh, medium-speed engines from 175-200 g/kWh [16]
⁷ WTT (LNG): 110 gCO₂/kWh; the shorter transport distances from the source to Singapore is considered [17]
⁸ Carbon emissions (2018): 0.4188kg CO₂/kWh [13]
⁹ Fugitive methane: 0.00213 kg CH₄/kWh
¹⁰ Nitrous oxide: 0.00002 kg N₂O/kWh [18]
¹¹ [19]
**Figure 1.2 GHG emissions reduction potentials for different power configurations with a high-speed diesel-mechanical configuration as the baseline**

**Figure 1.3 GHG emissions reduction potentials for different power configurations with a medium-speed diesel-mechanical configuration as the baseline**
A charging infrastructure facilitates the recharging of harbour craft’s batteries from an external source. The infrastructure includes a connection to a reliable and low-carbon emissions energy source, the transmission and distribution network, energy converters, charging stations with plug and cable connections to the harbour craft, metering for public chargers and berth facilities for ships to moor securely while recharging.

2.1 Types of Existing Charging Infrastructure

The charging infrastructure can be differentiated by the source of electrons, location of infrastructure and power rating. Different power ratings are configured based on the required charging time and capacities of the onboard energy storage, and concurrently, these requirements will affect the designed voltage and current as well as the decisive use of automation to assist in the coupling of the vessel to the charging umbilical. Notably, safety consideration during operation increases with the use of medium-voltage (MV) when compared to low-voltage (LV). IEE defines AC LV as 690V and below, and MV from above 690 V to 6.6 kV.

The first charging stations used by the maritime industry were adopted from low-voltage electric vehicles (EVs) charging stations with powers starting from 22 kW for small and inland marine vessels [20, 21]. As the battery capacities of seagoing vessels are considerably larger than EVs, early commercial providers, for example, Cavotec, Stemmann-Technik, ABB (robotic plug system), Cavotec-Wartsila and EST-Floattech (inductive charging) have piloted marine chargers up to 8 MW [7, 22-25]. These have redefined the characteristics of marine charging infrastructure. In order to provide high power rating at a feasible size, the charging stations either supply medium AC voltages, or low to medium DC voltages, or use an automated cabling system to manage high-ampere cables [22]. The earliest charging infrastructure dedicated for marine vessels was piloted in 2015, and, notably, some of these early designs did not take off after their pilot trials due to high costs or technical issues. Some of the charging projects are detailed in Appendix I. Future development is to be expected in this area.

Table 2.1 describes and highlights some considerations for different types of charging infrastructure. There are four distinct charging locations, and they are (i) existing berth space, (ii) HC anchorage areas, (iii) purpose-built floating platform and (iv) floating power barge within port limits. Examples of existing berths may include landing steps and small floating platforms found in existing piers, jetty or waterfront space. HC anchorage areas are located in sheltered waters (near breakwaters), where idle harbour craft are moored to a floating buoy. A purpose-built floating platform can be extended from a suitable shore location that will serve to overcome limited space or limited infrastructure at the shore. The floating power barge can be considered when there is a lack of access to existing piers, and low-carbon or biofuels can be used as alternative fuels to generate electricity.
Charging Locations Considerations

I. Berth  
*existing pier structure*  
• Often designed with medium or high-power rating to reduce recharging time  
• Easiest to implement among the four types due to land-based infrastructure and use of existing berths and main grid  
• Harbour craft require to remain at berth during recharging  
• Use of medium-voltage equipment requires more safety regulations

II. HC Anchorage  
*anchorage areas for HCs, include breakwater areas*  
• Low to medium power charging improves battery life cycles  
• Low-power stations have lower electrical and electronic components costs  
• Allow charging to coincide with idle or rest durations  
• Electrical connection from anchorage to shore power is dependent on actual distances

III. Floating Platform  
*a purpose-built platform extended from the existing pier*  
• Often designed with medium or high-power rating to reduce recharging time  
• Flexible platform may include other functions, such as terminal batteries, the supply of fresh water, etc. and towed to different locations, and for use in areas with no berth and mooring infrastructure  
• Require design and building of a purpose-built platform

IV. Floating Power Barge  
*powered with alternative fuels*  
• Not dependent on grid supply and able to be implemented in areas with no power plant  
• Require design and building of purpose-built platform with its genset and/or ESS system  
• Require the supply chain for alternative fuels to be supplied to the power barge

| Table 2.1 Description of different types of charging infrastructure |

2.2 Electricity Generation in Singapore and Southern Islands

Singapore’s power grid is one of the most reliable in the world, based on an average electricity interruption time of less than one minute per customer per year (Source: ema.gov.sg). The gross efficiencies of the combined power plants have risen from 39% (2001) to 46.88% (2018). About 95% of Singapore’s electricity is generated using natural gas. The transmission loss of electricity is about 2%. Singapore’s Grid Emission Factor (GEF) is 0.4188 kg CO₂/kWh [13], and this factor has been reducing due to the more efficient Combined Cycle Gas Turbines (CCGTs) in new power plants. Majority of the gas power stations is located in the western part of Singapore. The power is then transmitted via high-tension cables to minimise energy losses, and then the voltage is stepped down through substations to reach consumers at 220V, 50 Hz. The connection from the distribution or consumer substation to consumer switchroom is managed through Singapore PowerGrid.

Singapore’s registered electricity generation capacity is 13,667 MW (last updated in 2019), while its monthly peak demand averaged at 7,215 MW for the first six months of 2019 and at 7,102 MW for the same period of 2020. Singapore has announced its plan to manage its emission peak at 65 MtCO₂e by around 2030. Data of Singapore’s emissions profile in 2017 from National Climate Change Secretariat (NCCS) shows that power generation accounted for about 40% of primary emissions. Thus, Singapore’s power generation sector has considered interventions, such as energy-efficient measures and CO₂ capture technologies. Therefore, this will benefit the maritime sector, when tapping on the electricity grid, to lower its carbon footprint.
A review of the electricity generation on some of the offshore islands (along the harbour craft’s routes in the case studies), was conducted to determine the feasibility of recharging at each stop. The survey showed that there were only a small number of offshore islands that drew power from the main grid. For example, underwater utility lines connect to the Southern Islands, such as Pulau Seringat, Lazarus Island and St. John’s Island. Most of the offshore islands rely on diesel generators and solar panels to meet relatively low electricity demand. Therefore, an upgrade of the power infrastructure will improve the reliability and power generation capability for high-powered charging stations.

### 2.3 Key Functions of a Maritime Charging Station

The charging station fulfils some or all of these roles: power conversion from AC to DC power (DC charging station), power supply equipment, control schemes and communication. Charging stations, which are in operation, are mostly supplying AC power. The supplied AC power is converted to DC power for charging the battery by an onboard charger. An onboard charger is mounted on the ship and designed to operate only on the vessel. In DC charging stations, the AC power is first converted to DC power on the shore (an offboard charger) and then supplied as DC power to the ship. As the power conversion is not limited to the size of the onboard power converter, thus DC charging stations are designed to supply higher power. Another added advantage for ships is that, when the power converter is located at the DC charging station, this reduces the onboard equipment and space is freed to house other equipment or a larger battery pack.

This review covers a list of functions that a high-power AC or DC charging station should provide:

- **a.** The charger’s power rating should be at least 350 kW, considering the typical onboard battery capacity of small harbour craft is around 100 kW to 300 kW.
- **b.** Control pilot functions provide a means to ensure safety and data exchange for different operation modes in a charging station, for example, these may include automatic checks for a proper connection, circuit insulation, short-circuit and fault detection.
- **c.** Specific test requirements of charging station such as electrical compliance, environment tests (for outdoor use), permissible surface temperature, electromagnetic compatibility and ease of servicing should be considered.
- **d.** Robustly constructed enclosure for the charging station to meet outdoor and marine equipment requirements, i.e. IP46 protection works satisfactorily in ambient air temperature up to 45 °C.
- **e.** Preferably a set of dedicated supply equipment, cable management and storage is required to be permanently connected to the charging station.
- **f.** The coupler shall have a safety function that automatically disconnects when the vessel’s mooring system is no longer secured (in the event of strong waves and bad weather).
- **g.** Provision of cables with exceptional flexibility and high tensile strength. The use of cables for the harsh marine environment also requires the cables to be sheathed with special sheathing compound that provides high moisture, chemical and weather resistance.
- **h.** Customised length of the charging cable connection, taking into account the preferred mooring methods and the size of harbour craft. For example, a regular berth or a buoy may be used.
- **i.** The horizontal and vertical reach of the cable connection must consider the tidal changes, length, height of harbour craft that are expected to berth at the charging infrastructure. If the manual or semi-automatic connection is suggested, the thicknesses of cables and a safe procedure should be manageable by a single crew.
j. The power factor (PF) should be designed as high as possible (> 0.8) to reduce power losses.

k. At each stage of AC to DC conversion, overcurrent, overvoltage, residual current and ground-fault protection devices as required at the maximum power rating should be included in the right locations. For example, in high-power systems, high-speed fuses are typically located both on the AC line and in series with each semiconductor device on each arm of the rectifier circuit. Other examples are voltage transient suppressor and ground-fault relays.

l. **Additional functions of DC charging stations:** A DC charging station requires the AC power (from the main grid) to be converted to DC power before supplying power to the ship. Thus, this step will require additional equipment, such as, an isolation transformer that separates the AC power and the DC output and an AC-to-DC rectification. Higher currents, typically a feature of DC charging station, will require excellent cooling management to prevent overheating. Digital communication systems (reference IEC 61851-24 digital communication for electric vehicle charging) may be recommended in DC charging station, which enables the vessel to control the charging protocols fully. Due to these additional functions and the tendency of higher power supplied by DC charging stations, they tend to have an increased footprint, and the feasibility of a DC charging station should be assessed at the site.

Currently, maritime charging stations are mostly built for a small number of electric vessels along fixed routes. Future development of the marine charging network should leverage the developments achieved by the electric vehicle charging network, for example:

a. Coordinated charging (encourage charging when demand is low).

b. Mitigating of grid issues when a large number of high-power chargers are used simultaneously. The mitigation may be achieved by deploying charging strategies using smart-grid technologies coupled with energy storage systems.

c. Energy storage system (ESS) can also enable increased peak load capacity and renewable integration or serve as backup power source backup when the main grid is interrupted.

d. An AC or DC bus distribution to enable energy sharing between chargers.

### 2.4 Criteria for Charging Infrastructure

i. **Meeting the charging schedule of harbour craft**

There are myriad charging schedules of plug-in hybrid and full-electric harbour craft. Most plug-in hybrid vessels may recharge briefly during loading and unloading operation for scheduled routes. These vessels may choose to perform slow-charge overnight to minimise daytime schedule disruptions. Whilst for full-electric vessels, the batteries may have to be recharged, depending on their state-of-charge, at each stop or after a round-trip.

ii. **Conveniently located charging stations**

The charging stations should conveniently be located at the identified piers, anchorage or bunkering locations. The number of charging points and recharge duration of the harbour craft must be considered when locating the charging infrastructure. For example, berth type chargers may be the high-power charger that allows quick recharging within the loading or unloading period, while recharging at anchorage is more amenable to the low-power charger that allows slower recharging.
iii. Reliable and low-carbon emission energy source

The reliability of the electricity generation is essential for a full-electric harbour craft, because of their high recharging frequency. If the energy source is from the main grid, the sufficiency of load capacity at the switchroom or sub-station must be guaranteed to prevent potential issues such as voltage instability, voltage sag, overloading of transformers and power quality degradation. The anticipated peak loads and peak currents drawn from the installed power system must be determined and communicated to the grid operator.

The charging infrastructure may be coupled to a low-carbon fuel genset in off-grid areas or to hybrid energy storage and renewable energy system. The off-grid electricity generation should ideally use low-carbon fuels, with a minimal carbon footprint to maximise the decarbonisation benefits. An environmental impact assessment should also be conducted when siting the charging infrastructure.

iv. Safety and operations

Fire-fighting equipment and storage areas should be provided if there is no nearby facility. Land-based fire and electrical codes should be adhered to, and approvals are sought from relevant authorities, should the charging station be located on land.

2.5 Planning for Charging Infrastructure

The key steps in the planning of charging infrastructure siting are illustrated in Figure 2.1. The steps begin with the understanding of the operation profiles and power requirements of the harbour craft. Optimisation of the battery system to meet power demand is important, as considerations for larger sizing of battery systems where extended operations are envisaged. The power rating and type of charging station are selected to meet the charging times and locations required by the operation profiles. The final step involves ensuring the power demand of the harbour craft is adequately matched by the supply of the electricity.

**STEPS**

1. Understand operations and power requirements of vessels
   - Power requirements and load factors during different operation modes and wave conditions
   - Average and maximum distances per trip

2. Sizing the storage capacity of ship batteries
   - Sizing of batteries to meet operations + spare capacity
   - Select type of batteries to optimise power and energy
   - Decide plug-in hybrid or full-electric

3. Selecting power rating and AC/DC type for charging station
   - Charging time determines the rated power, current rating and voltages
   - Voltage/Current determines feasibility and safety of connections

4. Planning the power load (kVA) required during peak loads
   - Peak loads determine the switchroom’s designed load
   - Sufficiency of grid supply determines the need to build terminal batteries

*Figure 2.1 Illustration of the steps to size a berth type charging infrastructure*
Electric Harbour Craft

Electric ships are not new, with the first documented electric boat with zinc batteries started in 1830. However, in the 1920s, efficient internal combustion engines became popular and disrupted the utilisation of electric ships. Full-electric small boats, however, continue to operate in environmentally sensitive areas in rivers and lakes. It was until 1985 that solar-powered ships popularise electric ships. In the past five years, due to the falling prices of batteries, bigger battery capacities sufficient for electric propulsion becomes economically feasible for full-electric ships. The biggest marine battery (awarded as of March 2019) is for the Norwegian coastal hybrid passenger ferries, with each vessel expected to house a 6.1 MWh battery. Notably, full-electric ships tend to operate at moderate speeds and for regular routes that allow frequent recharge. The majority of these vessels are still hybrid ships (53%), followed by an almost equal number of plug-in hybrid (22%) and full-electric (18%) (Source: DNV GL Alternative Fuels Insights). Some high-profile electrification trials are detailed in Appendix II.

3.1 Electrical Systems and Key Components

This brief review of electrical systems on harbour craft focuses on electric propulsion systems for medium-power vessels and the key components on plug-in hybrid or full-electric harbour craft. The energy efficiency characteristics of electrical systems and components are critical in the electrification of harbour craft because the fuel savings and lower maintenance costs are the financial incentives for ship operators.

The shipboard power system design generally requires the following tasks:

a. Selecting the optimum power system configuration and voltage level best suited for the ship’s operation profile.

b. Load analysis to size the electrical generator kW and kVA ratings and the prime mover’s horsepower rating.

c. Power distribution routes for propulsion and service loads.

d. Sizing the feeder cables and for limiting voltage drops.

e. Fault current analysis and protection device rating at key locations.

f. Sensor types and locations to monitor system health.

3.1.1 Electric Propulsion

The electric propulsion of ships requires electric motors to drive the propellers. The fuel comes from either a diesel generator or energy storage systems. The complexity of electrical grid systems increases typically with the required propulsion power. Ship service loads are often designed to be of fixed voltages and frequencies, which may differ from the requirements for propulsion. Figure 3.1 illustrates an example of separate distribution buses to provide for propulsion and auxiliary power distribution on a full-electric harbour craft.

The key components of electric propulsion drives are:

a. **Electrical Converter**: Electrical converters are required in electronic circuits to convert AC to DC and vice versa. An AC-DC converter is required when charging the batteries from its AC supply source. A DC-AC converter is commonly found when the distribution
bus is a DC grid since most ships still use AC motors. A DC-DC converter is required to convert a source of DC from one voltage level to another.

b. **Transformer**: A transformer performs the role of either stepping up or stepping down of voltages. Ships with huge electrical loads may have generators operating at high voltages (HV) of 3.3 kV, 6.6 kV or even 11 kV, and high voltages make the high-power system more economically necessary to reduce the size of current, conductors and equipment. However, lightning and low power supplies usually operate at 220VAC, and even 110 VAC and thus step-down transformers are used to lower or increase the voltage when necessary.

c. **Variable frequency drive**: AC motor speed control is achieved by power electronics converter that converts fixed-frequency, fixed voltage into a variable frequency, variable voltage power source.

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**Figure 3.1 Simplified line diagram of electrical power distribution on a full-electric harbour craft**

There are a number of electric propulsion configurations, depending on the power demand. For low or medium-power demands, electrical power may be delivered by AC induction motors with variable frequency converters or by DC motors with variable voltage converters [26]. The propeller drive is often directly driven from the electric motor from inside the ship, while some external drives are being fitted outside of the ships’ hull, e.g. azimuth thrusters found in Norled’s MF Ampere full-electric battery ferry [27].

Electric propulsion can be optimised for increased energy and space efficiencies, for example:

a. Providing the flexibility of layout as diesel engines can be located in the best location and remote from the propeller shaft. Cable run is a very versatile transmission medium and allows optimisation of the layout even at different decks.

b. Meeting load diversity between ship service load and propulsion. Passenger craft may have substantial electrical loads, whereas tankers and cargo ships tend to require high-power for ship services when the demands of the propulsion system are low.

c. Economical part-load running.
3.1.2 Shipboard Electrical Distribution

Currently, electrical power is often generated at 400/415/230 VAC, 50 Hz for service loads. Harbour craft, which require high propulsion power, will have a high voltage bus and transformers to step up accordingly. The electrical distribution bus can be AC (de facto option for mid-sized marine vessel) or DC. AC distribution is currently the de facto design in most harbour craft, as AC standard circuit breakers and cables are easily available, and power losses in AC system are generally lower as inverters create more losses than switches. However, there is a trend towards DC distribution, especially on full-electric ships, because of ease of integration with DC energy sources and better fuel efficiency, depending on ship types and operating profiles.

The DC-grid system can operate with variable frequencies and no reactive power losses; thus, it has been reported that it could reduce fuel consumption and emissions by up to around 20%, depending on ship type. The limitation for DC systems is that it is not able to meet higher power requirements of large ships. In general, power systems and required converters and breakers above 400 kW are mainly AC type.

3.1.3 Electrical Energy Storage Systems

The current energy density of rechargeable batteries is often cited as the limiting factor for business-as-usual profiles of current harbour craft running with the diesel-mechanical drivetrain. Based on high-speed and medium-speed diesel engines with a range of SFOC of between 195 g/kWh and 225 g/kWh, the equivalent volumetric energy density of MGO is around 3,800 Wh/L to 4,400 Wh/L. The energy density of MGO is about 40 times higher than a pack-level Li-ion marine battery’s energy density of 83 Wh/L to 100 Wh/L [28]. Thus, hybrids are expected to remain essential in short term to medium term. High energy density fuels are still preferred, and the use of alternative sustainable fuels on a hybrid may be encouraged as an economically viable option to reduce emissions. Full-electric harbour craft are likely limited to scheduled short routes when presented with an opportunity for frequent charging.

Due to the environmental concerns over the use of current fossil fuels, battery capacities being installed in electric vessels, have been increasing steadily. Figure 3.2 illustrates the scale of marine battery capacities when compared with battery capacities of other applications. The power rating of a charger is dependent on the storage capacity of the battery and the desired charge rate. In general, high-powered chargers are being developed specifically for the maritime industry to shorten the charging times.

The dominant battery type for electric propulsion is Li-ion batteries, which exhibit favourable characteristics such as high energy density, lightweight, fast charging, low self-discharging rate, and low memory effect. There are several chemistries for Li-ion, with different benefits, being offered by maritime battery manufacturers. However, from a survey of various sources from the maritime and transportation industries, there are three main Li-ion chemistries that have stood out for these industries [28-33]. They are labelled according to their cathode or anode types; Nickel Manganese Cobalt (NMC) as the cathode, Lithium Iron Phosphate (LFP) as cathode and Lithium Titanate (LTO) as the anode. Their performance attributes are summarised in Figure 3.3. The key attributes required for the transportation industries are the cost, safety, power or energy density. Over the decades, a number of maritime battery manufacturers have released a number of Li-ion products specifically for the marine industries and to name a few key players; they are Corvus, Akasol AG, EST-Floattech, Siemens, Rolls-
Royce, Saft, Samsung, Spear Power Systems and Forsee Power. Local technology player Durapower has also begun its foray into the maritime sector. Li-ion marine batteries have constantly been improving in both their mass and volumetric energy densities; a reflection of their demand in a growing market.

A number of technical and environmental considerations on the energy storage for electrification are summarised here.

a. A higher charge or discharge current is often required for high-power requirements, but the life cycle of the batteries is sacrificed. The manufacturers highly recommend that the right type of battery is selected based on the energy and power requirements of the vessel’s operation.

b. An optimisation of the configuration, power requirements and storage capacity is recommended. As maritime batteries are more complex due to safety measures, size of auxiliary systems and cost per energy storage ($/kWh), a well-designed and optimised system is essential [28].

c. Recent measures for second-life use (i.e. in off-grid hybrid renewable systems) of batteries and disposal management of batteries are important steps that should be established as marine batteries are predicted to retain about 80% battery capacity during their replacement.

d. Economical and energy-efficient Li-ion battery recycling methods and recycling regulations will address the future management of increased e-waste.
In the short term, the maritime battery manufacturers are likely to continue to use mature storage technologies, and the Li-ion cells will not be replaced by emerging storage technologies of higher density. Instead, manufacturers will focus on reducing the size of auxiliary systems (e.g. liquid cooling system) and improvements made in Li-ion batteries. Significant improvements to energy density are only expected in the medium term (beyond 2030) when the industry is ready to adopt solid-state or hybrid battery technologies.

### 3.1.4 Safety Management with Electrical Systems

#### i. Ground switching when charging from shore

For a plug-in hybrid, a vessel may have multiple energy sources, i.e. it may receive onshore power (electricity is supplied to run auxiliary loads while at berth), recharge its batteries with grid electricity or using the onboard generator. Multiple energy sources increase the complexity of the electrical wiring and safety risks. Thus, a vessel must ensure a few key points:

- Only one source is allowed to power loads at any one time (interlocking).
- Energy sources must be completely isolated from one another.

Ground switching is required when the vessel is connected to onshore power supply. The neutral-to-ground connection is provided through the cable connection to the charging station, and the neutral-to-ground connection on board must be disconnected. However, when the vessel uses its onboard generator or inverter power, the generator will “switch on” its neutral-to-ground connection.

#### ii. Use of lithium batteries and battery management system

Due to the high energy density and technology maturity required for the marine vessels, a Li-ion battery is currently the choice for most large ESS on ships. As a result, the safe use and charging of lithium batteries are important and reflected in several recent guidelines by classification societies. General requirements for using lithium batteries on board may refer to DNV GL’s “Considerations for ESS fire safety” [34], DNV GL’s “Li-ion batteries” [35] and ABS’s “Guide for the use of lithium battery in the marine and offshore industries” (ABS, 2020) [36]. Inevitably, the vessel must have a battery management system (BMS) to monitor the status and raise the alarm in the event of faults. Fixed fire extinguishing system in the gas-tight battery compartment is recommended in addition to portable fire extinguishers. Most vessels have at least two separate battery compartments that are subjected to the structural fire protection requirements. The vessel’s power management system (PMS) needs to be monitored at the navigation bridge for the batteries’ state-of-charge, power and remaining range or time for a planned voyage.

#### iii. Emergency power supply

An emergency electrical power service is normally provided on board in the event of a main power failure. Regulations require that the emergency power source can be a generator, or batteries, or both. The emergency power source must be self-contained and independent. For example, a fully-charged battery, or an internal combustion engine with its fuel supply tank, starting equipment and switchboard. The emergency power source will come into action automatically following a main supply power failure. The type of emergency power supply varies depending on the size and main operations of the vessel.
iv. Maintenance

Electric motors and ESS systems generally require less maintenance when compared to diesel engine and fuel tanks. Li-ion batteries have class-approved guidelines and follow test requirements listed by various classes [35, 36]. Batteries do degrade gradually, and from pilot studies, it is reported that they are to be replaced after 5 to 10 years, where a projection of degradation indicates that they have reached about 80% of the original capacity. A new-built vessel is expected to have about 3 to 4 battery changes in its lifetime. Thus, it is also recommended that the ESS components can be easily replaced or upgraded, and the BMS should be updated as recommended.

3.2 Electrical Consumption of Harbour Craft in the Case Studies

MESD conducted interviews with harbour craft owners and a survey of four existing local harbour craft to understand their current operation modes and energy demand. The harbour craft are from the following categories, (i) a fast launch (SP ≤ 12 pax), (ii) a passenger ferry (SP > 12 pax), (iii) a lighter (SC) and (iv) a tugboat (ST). The objective is to estimate the electricity consumption of these types of harbour craft in a scenario where recharging from an external source is applicable.

Table 3.1 summaries the general characteristics of the four harbour craft from the case studies. In the absence of space optimisation and to retain net tonnage, the available battery space on board a harbour craft is assumed to occupy part or all of the space taken by fuel tanks. Based on the volumetric density of Li-ion marine battery of about 66 Wh/L (system level) [28] and the fuel tanks’ volume, installed battery capacities for the fast launch and lighter are around 75 kWh. 25% of the volume is reserved for fuel tanks required in hybrids. In both hybrid and full-electric configurations, the available battery capacities are further reduced by 20% and 55% of installed capacities, respectively, to mitigate ageing and meet class regulations for power reserve. The power ratings of chargers are assumed to be 4000 kW for the tugboat and 350 kW for the other types of harbour craft. The efficiency, including charging and discharging losses, of the electric drivetrain is taken as 86%.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Fast Launch SP (≤12 pax)</th>
<th>Passenger Ferry SP (&gt;12 pax)</th>
<th>Lighter Four-stroke, high-speed diesel</th>
<th>Tugboat Four-stroke, high-speed diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Main Engine</td>
<td>Four-stroke, high-speed diesel</td>
<td>Four-stroke, high-speed diesel</td>
<td>Four-stroke, high-speed diesel</td>
<td>Four-stroke, high-speed diesel</td>
</tr>
<tr>
<td>Main Engine (kW) x No</td>
<td>331 x 2</td>
<td>320 x 2</td>
<td>167 x 2</td>
<td>1,864 x 2</td>
</tr>
<tr>
<td>SFOC g/kWh</td>
<td>215</td>
<td>215</td>
<td>220</td>
<td>209</td>
</tr>
<tr>
<td>GT</td>
<td>30.5</td>
<td>59</td>
<td>30</td>
<td>473</td>
</tr>
<tr>
<td>Cruise Speed (knots)</td>
<td>20-23</td>
<td>10-11</td>
<td>11-14</td>
<td>9-10</td>
</tr>
<tr>
<td>Installed ESS (kWh)</td>
<td>75</td>
<td>270</td>
<td>75</td>
<td>5,000</td>
</tr>
<tr>
<td>Available ESS (kWh)</td>
<td>60</td>
<td>120</td>
<td>60</td>
<td>2,250</td>
</tr>
<tr>
<td>Charger Power (kW)</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>4,000</td>
</tr>
<tr>
<td>Recharging Time (min)</td>
<td>17</td>
<td>34</td>
<td>17</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 3.1 Case studies on the electrification of four local harbour craft
Figure 3.4 shows the assumed profiles of the available battery capacities, grid electricity consumption and the number of recharges per day of these harbour craft from the case studies. The recharge frequency (No. of recharges per day) considers the number of round trips and idle times (operation profiles) of the harbour craft. At this frequency, electricity will meet about 18% to 22% of the daily energy demand for the fast launch and lighter, and 100% of the daily energy demand for the full-electric passenger ferry and tugboat.

Some concerns have been observed during the survey, which could be addressed in future studies and trials of harbour craft.

a. Space constraint on board smaller vessels require reconfiguration to optimise and increase the battery capacity if energy storage is to meet a higher percentage of their energy demand.

b. Design of electrified harbour craft, including its hull form, weight and energy management, is not well-purposed for electrical power systems and may have to be re-designed.

c. The mass of the ESS has not been used to size the storage capacity in these case studies. However, it is worth noting that the mass of the ESS may have an impact on the designed maximum speed of the harbour craft.

b. Charging stations will have to be placed at strategic locations along the route of a passenger ferry for a full-electric configuration.

c. A high-power charging station will be required for the tug boat, and this will incur high-cost and additional safety requirement for a medium voltage charging station.

d. For all vessels, it is clear that the ship operations will have to manage the schedule around frequent recharging (7 to 19 times daily). In comparison, small harbour craft based on MGO refuels twice a day during the peak schedule. Frequent recharging reduces the operational readiness of harbour craft. The costs incurred are not only the higher CAPEX of electric propulsion and batteries but also opportunity costs.

e. Mitigating solutions will have to be considered; planning for more high-powered charging stations near to operations for opportunistic recharging, or increase the number of vessels (rotating shifts) during high seasonal demand.

Figure 3.4 Available battery capacities, grid electricity consumption and number of recharging per day applicable to the operation profiles of four harbour craft
3.3 Potential Emissions Savings from the Case Studies

The annual emissions savings with the use of grid electricity are obtained by determining the differences in emissions from the use of electrified harbour craft (vessel profiles in Section 3.2) and its diesel-mechanical equivalent, which uses MGO as a fuel. The results are illustrated in Figure 3.5. The passenger ferry has the least emissions savings after a year of operation, because of its fewer number of trips.

One of the concerns about electrification is that the production of batteries would have incurred significant upstream emissions. Therefore, the upstream emissions have been calculated based on the installed battery capacities in the harbour craft using an emission factor of a system-level marine battery (around 370 kg/kWh) [18].

The plug-in hybrids (fast launch and lighter) could expect emission payback within months because of their smaller batteries. The ferry has a longer payback period (about one year) due to its low fuel consumption. Considering that batteries are designed to last for 5 to 10 years of operation, these results show that the emissions savings from the use of grid electricity may be achieved within a year of operation.

Several ways may be encouraged to reduce emissions from battery production. For example:

a. The schedule of the harbour craft allows for frequent recharge.

b. Batteries are produced with low-emission energy source.

c. Second-life use of batteries is encouraged.
In general, the harbour craft owners are sensitive to the operating costs due to low-profit margins in this industry. This section elaborates the concept of Total Cost of Ownership (TCO) and lists the cost parameters for a new-build or retrofit harbour craft. The cost model can be used to estimate the total cost of owning and operating the electric harbour craft and charging infrastructure. TCO consists of costs incurred throughout the life cycle of an asset, including acquisition deployment, operation, support, and disposal. TCO broadens the baseline understanding of spending and identifies sourcing opportunities beyond the purchase price. It can assist business owners in looking beyond short-term savings and determining the long-term benefits that will reduce overall costs for acquiring a product with a long lifetime. However, the complexity of the TCO model lies in the estimation of unknown costs.

The payback period is another key indicator in the electrification of harbour craft. Cost savings from fuel and maintenance help to offset the higher CAPEX costs, that are typically associated with the electrical propulsion and energy storage systems. On a positive note, some electrification pilots have reported a payback period within 4 to 10 years [37].

### 4.1 General Cost Model for the Total Cost of Ownership

TCO refers to all the costs incurred in owning and operating an asset\(^{11}\). A TCO cost model can compute 1) the costs of purchasing or retrofitting an electric harbour craft and its lifetime operation and maintenance costs; 2) the costs of investing in a charging infrastructure and its lifetime operation and maintenance costs. This model has been adapted from the cost model for electric vehicles [38].

Figure 4.1 illustrates the approach in finding the total cost of ownership, which comprises the capital cost (buying/retrofitting an electric harbour craft; investing in charging infrastructure) and ownership cost that includes operating cost and periodic maintenance cost. The total cost of ownership is calculated by discounting all future costs to present value, following the equation:

\[
TCO = CC_0 + \frac{CC_n}{(1 + r)^n} + \sum_{n=1}^{N} \left[ OC \frac{1}{(1 + r)^n} + \sum_{m=k}^{N} PMC \frac{1}{(1 + r)^m} \right]
\]

where \(CC\) represents Capital Cost (\(CC_0\) represents the costs incurred at year 0, \(CC_n\) represents the costs incurred at the end of lifetime), \(OC\) represents Operating Cost (assumed to occur at year-end for calculation purpose), \(PMC\) represents Periodic Maintenance Cost (assumed to occur at year-end and \(k\)-year intervals), and \(r\) represents the rate of return for discounting purpose.

\(^{11}\) In this report, the costs of assets are assumed borne by a single entity, comprised of all the stakeholders. In the case where the assets are owned by multiple entities or provided by the government, the cost parameters may be separately analysed for individual entity.
The cost model could estimate the total cost of owning and operating the electric harbour craft and charging infrastructure, taking into account possible future costs and the time value of money. In addition, the Payback Period (in years) can be estimated by dividing the incremental investments and costs over the annual cost savings. The fuel and periodic maintenance costs are the two key cost parameters that determine the annual cost savings, as a result of a switch from the conventional diesel harbour craft to an electric harbour craft.

### 4.2 Cost Parameters for Electric Harbour Craft

Following the TCO approach, as illustrated in Figure 4.1, Capital Cost, Operating Cost and Periodic Maintenance Cost are summarised in Table 4.1. The list of costs was modified for the case of an electric harbour craft [39]. It is worthy to note that other costs may differ from a conventional harbour craft. For instance, residual/disposal value may be substantially different as proper disposal would be required if there are battery systems on the vessels. Routine and periodic maintenance requirements may also be different for electric harbour craft as compared to conventional ones.

<table>
<thead>
<tr>
<th>Category</th>
<th>No.</th>
<th>Cost Parameters</th>
<th>Details</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>1</td>
<td>Pre-acquisition cost</td>
<td>Costs incurred in the search and sourcing of suitable ships.</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Initial price of the ship</td>
<td>It depends on whether the vessel is a new-built or retrofitted one.</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Battery management system and battery packs (during retrofit)</td>
<td>E.g. Procure or lease battery packs.</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Charging equipment cost and installation cost (if retrofit)</td>
<td>E.g. Cables required to connect to the local electricity grid, data gateway, transformer unit, onboard charger.</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Residual value</td>
<td>Resale value or scrap value of the ship.</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Disposal cost</td>
<td>Costs incurred to dispose of the ship/battery.</td>
<td>One-time</td>
</tr>
</tbody>
</table>

*Table 4.1 Cost parameters for electric harbour craft*
<table>
<thead>
<tr>
<th>Category</th>
<th>No.</th>
<th>Cost Parameters</th>
<th>Details</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Cost</td>
<td>7</td>
<td>Financing cost</td>
<td>Interest on the loan to purchase the ship</td>
<td>Monthly</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Harbour Craft licence and dues</td>
<td>E.g. HC licence fee, port dues, miscellaneous fees, etc.</td>
<td>Annually</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Manpower cost</td>
<td>E.g. Wages for captain, crew, engineers, travel fee, insurance, manning licence, etc.</td>
<td>Monthly</td>
</tr>
</tbody>
</table>
|                                | 10  | Consumables                            | 1) Deck consumables: e.g. charts, mooring rope, navigation lights, wires, etc.  
2) Engine consumables: e.g. grease and lubricants, tools, electrical spares, instrument spares, etc.  
3) Stores and provisions: e.g. cleaning products, personal protection devices, fire extinguishers, etc. | Monthly       |
|                                | 11  | Repairs and maintenance                | E.g. Routine maintenance, breakdowns.                                                                                                                                                                | Yearly        |
|                                | 12  | Downtime costs                         | Missed revenue due to ship breakdown time.                                                                                                                                                             | Yearly        |
|                                | 13  | Insurance                              | E.g. Hull and machinery insurance, P&I, etc.                                                                                                                                                           | Yearly        |
|                                | 14  | Handling cost                          | E.g. Cargo handling (loading, discharging, allowance of claims), berthing fee, mooring fee, etc.                                                                                                       | Monthly       |
|                                | 15  | Fuel/electricity cost                  | It depends on the operation profile, energy consumption and the price of electricity.                                                                                                                 | Daily use     |
|                                | 16  | Other general costs                    | To include all additional miscellaneous items.                                                                                                                                                        | Monthly       |
| Periodic Maintenance Cost      | 17  | Battery replacement cost               | E.g. Battery replacement and installation, battery disposal, etc.                                                                                                                                   | Every five years |
|                                | 18  | Other periodic maintenance costs       | E.g. Dry docking, special surveys for certification, compulsory annual inspection, etc. (Dry docking requirements differ for Class-approved vs. non Class-approved) | Depends       |

*Table 4.1 Cost parameters for electric harbour craft (Cont’d)*
4.3 Cost Parameters for Charging Infrastructure

The costs of charging infrastructure are grouped into the categories of Capital Cost, Operating Cost and Periodic Maintenance Cost, as presented in Table 4.2. Capital Cost consists of three major cost components, for power supply infrastructure, communication and metering, and charging station. Operating cost mainly refers to the regular safety checks for integrity assurance. There is also periodic maintenance cost for regular system maintenance and components replacement.

<table>
<thead>
<tr>
<th>Category</th>
<th>No.</th>
<th>Cost Parameters</th>
<th>Details</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>1</td>
<td>Pre-acquisition cost</td>
<td>Costs incurred in the search and sourcing</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Power supply infrastructure</td>
<td>E.g. Direct utility, land and building, substations, laying of power transmission cables, etc.</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Communication and metering</td>
<td>E.g. Information and Communication Technology (ICT) in Smart Grid Environment</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Charging station</td>
<td>E.g. Terminal battery or floating platform, solar panels, etc.</td>
<td>One-time</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Disposal cost</td>
<td>Costs incurred to dispose of the charging infrastructure</td>
<td>One-time</td>
</tr>
<tr>
<td>Operating Cost</td>
<td>6</td>
<td>Checks for safety integrity</td>
<td>E.g. Manpower, Repairs, Insurance, Other general costs, etc.</td>
<td>Weekly</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Downtime costs</td>
<td>Missed revenue due to breakdown</td>
<td>Yearly</td>
</tr>
<tr>
<td>Periodic Maintenance Cost</td>
<td>8</td>
<td>Replacement of worn or damaged components such as plug, socket, cables</td>
<td>E.g. System maintenance, etc.</td>
<td>Monthly</td>
</tr>
</tbody>
</table>

*Table 4.2 Cost parameters for charging infrastructure*
Conclusions

In this study, a review of the charging infrastructure for electric harbour craft reveals that pilot trials on charging an electric harbour craft with the main grid are promising as there is increasing global adoption of electrification for marine vessels. Technology enablers of electrification are constantly being adapted from other industries or being developed explicitly for marine vessels. The higher investment cost of an electric vessel has been reported to be justified with significant fuel savings, in a reasonable payback period of four to ten years for ferries. The payback period is highly dependent on the design and power requirements of the harbour craft and the grid’s electricity price.

Despite the positive signs, this study has observed challenges in the electrification of Singapore harbour craft. Firstly, the electrification of harbour craft is a significant step because the bulk of the fleet relies on high energy density MGO and low-cost diesel engines. Most commercial activities revolve around fast turn-around times, and a high ratio of harbour craft to berths means short durations are spent at the berth. These are not favourable economic and operating profiles for wide-scale acceptance of electrification for harbour craft owners. Thus, economic policies and measures are also needed to encourage and incentivise a sustainable adoption of electrification.

Secondly, Singapore has a reliable power generation, transmission and distribution network on the main island and has seen encouraging trends to further reduce the carbon emissions of the power plants. However, most off-grid areas do not have excess power generation and high electricity demand. Thus, electricity generation infrastructure in off-grid areas needs to be developed.

Thirdly, there are existing technology gaps and a lack of standardisation in electric ships and charging infrastructure. In one example, the low energy density of batteries results in the need to recharge frequently. The maritime industry tends to favour mature and reliable energy storage technologies. Therefore, it is unlikely to consider newer battery technologies in the short term—instead, technology development favour towards more compact cooling technologies and reduction of system-level size and weight.

A holistic approach may include forming a framework to rope in relevant stakeholders to discuss the challenges and gaps in electrification. It is important to encourage green technology innovation and adoption and promote standardisation of electric vessels and charging infrastructure. Pilot trials will assist harbour craft owners to better understand electric propulsion and advanced power management systems.

If installation space is not limited at the shoreside, a DC charging station can be considered. Otherwise, an AC charger will be required on board. The power rating of the charging station is selected based on the required turn-around time and battery capacity. A shoreside battery can be considered to manage peak loads or integration of renewables.

Innovative charging infrastructures developed specifically for charging harbour craft in sheltered port waters or near harbour craft’s anchorage areas are worth exploring to improve the scalability and flexibility of charging a vessel.
### Appendix I Summary of existing charging infrastructure developed recently for the maritime industry

<table>
<thead>
<tr>
<th>Description and Example</th>
<th>Company, Country</th>
<th>Power Rating</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contactless inductive power transfer</td>
<td>Wartsila Norway</td>
<td>Up to 2.5 MW for single system High frequency 2-8 kHz 690VAC/1,000VDC</td>
<td>• No mechanical wear and reduce exposure to environmental factors (snow, fouling, corrosion); • Easily disconnect when ships need to leave the dock urgently; • High-cost as components are rated 3x the nominal current at the rated voltage to compensate for changing airgap distances.</td>
</tr>
<tr>
<td>Pilot demo in 2017-2018 on MS Folgefonn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic cable connection plug-in system</td>
<td>Stemmann-Technik under Wabtec, Germany</td>
<td>Low voltage (AC/DC) up to 690 VAC, 200 kW – 4MW, Medium voltage (AC) up to 8 MW</td>
<td>• A tower is built to manage differences in tidal difference up to 8m tested; • Automated connection of charger to ferry in less than a minute.</td>
</tr>
<tr>
<td>&quot;pantograph&quot; FerryCHARGER On Fjord1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floating platform houses a battery and cable charging station</td>
<td>Not reported</td>
<td>No information</td>
<td>• Piloted at a place that lacks good access to electricity the platform houses a battery to allows slow recharging; • The platform is able to house other services required by the ferry.</td>
</tr>
<tr>
<td>Future of the Fjords project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic Plug-in System Trondelag 2019</td>
<td>Cavotec [22]</td>
<td>Up to 1,000VAC, 3,000A Up to 1,000VDC, 4,400A About 4 to 5 MW</td>
<td>• A gravity-based plug and self-retracting cable hangs vertically down towards the receiver side on the ship; • Has limited compensation for the movements of the ship; • Offers both manual and automatic mooring systems; • Cost is estimated at $50 million on the land side when combined with automated mooring.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-automatic charging station AMPDispenser</td>
<td>Cavotec, Switzerland [22]</td>
<td>Up to 1,000 VAC Offers up to 3 cables at 1,050A About 1 MW</td>
<td>• Lower cost than fully automated systems; • Cable management system helps handles heavy cables; • Plug-in is manual and one crew on board to manage.</td>
</tr>
<tr>
<td>Robotic charging arm Helsingborg-Helsingor route between Sweden and Denmark, 2017</td>
<td>ABB Marine</td>
<td>7.2 MW Up to 10kV AC, 400A Also offer 120 kWh</td>
<td>• Greater flexibility as avoid the use of heavy, inflexible cables; • Able to handle high voltage with automation; • Connection time 10 minutes.</td>
</tr>
<tr>
<td>Replaceable batteries Idea by a consortium in a feasibility study for Trondheim high-speed catamaran [40]</td>
<td>Consortium led by Transportutvikling, Norway</td>
<td>No information</td>
<td>• Batteries can be recharged on land slowly, better lifespan; • No charging time required at berth so vessels can move off quickly; • Automatic cranes and charging systems yet to be developed; • Development idea proposed in 2017.</td>
</tr>
</tbody>
</table>
## Appendix II Examples of electric ships

<table>
<thead>
<tr>
<th>Vessel Name and Launch Year</th>
<th>Vessel Type</th>
<th>Country</th>
<th>Charging Method and Power</th>
<th>Battery Capacity</th>
<th>Operations and Speed</th>
</tr>
</thead>
</table>
| MF Ampere 2015              | Car Ferry, new built | Norway | Cavotec plug + ST.Panograf 1.2 MW | 1,040 kWh | • 5.7 km, 20 min crossing at 10 kn  
• Charges at each port from high-capacity batteries |
| MS Folgefonn [7] 2015       | Plug-in hybrid Ro-Ro, retrofitted | Norway | Inductive (1 MW) + NG3 plug | 1,000 kWh | • Stord, Tynes and Huglo  
• Autonomous docking, wireless charging |
| MF Future of the Fjords [25] 2018 | Passenger ferry | Norway | Cavotec plug (2.1 MW) | 1,800 kWh | • Flam and Gudvangen, 16 kn  
• Charges from the grid on one port, and from a floating battery platform at the other end  
• Charges in 20 min with 800 kWh |
| Color Hybrid 2019           | Plug-in hybrid, Cruiseferry | Norway | NG3 (7 MW) | 5,000 kWh | • Sandefjord to Strömstad, 17 kn  
• Less than an hour to charge fully |
| Yara Birkeland (Skredderberget, 2018; Riviera, 2019) | 120 TEU Open hatch, autonomous container feeder | Norway | Not determined yet as of 2 May 2019. | 7 MWh | • Eco-speed 6-7 kn with max speed 13 kn  
• Herøya – Brevik (approx. 7 nm)  
• Herøya – Larvik (approx. 30 nm) |
| Elektra 2017                | Full-electric car ferry with diesel as backup | Finland | Cavotec’s APS 900 V, 68 A | 1 MWh | • Crossings between Nauvo and Paraaiinen, 1.6 km in 15 minutes, up to 11 kn, charges for 5.5 minutes at both ports (top-up charge) |
| Eidsfjord and Gloppefjord 2019 | Full-electric Ro-Ro ferries | Norway | NA | 1.04 MWh | • Nordfjord’s Anda-Lote crossing, 9 minutes recharging in ports with vacuum docking |
| Ellen 2019                  | Full-electric ferry | Denmark | Mobimar’s charging arm and onshore station at 4 MW | 4.3 MWh | • Travels 38 km for 13-15 kn  
• Charges only at the home harbour, partially charges after every round trip, no emergency generator |
| Astrid Helene 2018 [41]     | Full-electric fish farming boat | Grovfjord, Norway | Plug to grid overnight | 440 kWh | • Able to last for a workday with 45% reserve left, slow speed at 6-7 knots. Houses 32t crane and electric winch hauling nets |
| MF Tycho Brahe 2017         | Car and passenger ferry retrofitted full-electric propulsion | Denmark/Sweden | 11 MW, the robotic arm (IRB 600) installed by ABB | 4.16 MWh | • HH ferry route, 4-5km between Helsingor and Helsingborg. Crossing takes 20 min and departs every 15 min, up to 14 kn |
| Happiness 2017              | Retrofit Passenger eferry | Kaoshiung, Taiwan | Dockside 380V | 100 kWh, Li-Ion | • Uses DC hybrid-electric microgrid  
• Travel 650m at 5 km between Gushan Ferry Pier and Cijin Island |
| Hetunhao 2019               | Cargo Ship | China | NA | NA | • 2.5 h to charge fully and 80km distance |
| Junlvhao 2019               | Passenger Ferry | China | NA | NA | • 10 kn (max), 7 kn and endurance is 8 hours |
References


