Department of Mechanical and Aerospace Engineering

The case for a bicycle-friendly linear electric ferry service on the River Clyde as a local emissions free congestion reduction measure

Author: Dominic McMahon

Supervisor: Dr Daniel Costola

A thesis submitted in partial fulfilment for the requirement of the degree
Master of Science
Sustainable Engineering: Renewable Energy Systems and the Environment
2019

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Dominic McMahon Date: 23/08/2019

Abstract

With time running out to avert the worst impacts of climate change, this paper addresses sustainable transport by assessing an electrified linear ferry service which would also lessen congestion issues and improve air quality in urban areas.

Based on a case study of the River Clyde in Glasgow, a vessel route and associated travel demands around each of the stops was determined. After a particular electric ferry was chosen, scheduling was completed to serve the demand and discover how many vessels would be required. The energy requirements, emissions and cost were all assessed. This was compared to two other scenarios: Business as Usual and Diesel Ferries.

Accounting for the carbon intensity of the UK grid, Electric Ferries are found to produce the lowest carbon dioxide emissions of the three scenarios and cause no localised air pollution. On a per passenger-kilometre basis, Electric Ferries have a third of the energy requirements of Diesel Ferries, a similar value to electric cars and more than three times that of buses and trains from Business as Usual. Electric Ferries were found to be profitable and, despite a high capital cost, return on investment was expected within 14 and 23 years for the two modelled demand modal shifts.

The study demonstrates that a well-used linear electric ferry service, while not being a more energy-efficient method of passenger transportation than land-based public transport modes, would still be preferable to single car use. As well as reducing city congestion and improving air quality, allowing bicycles onboard will promote active travel. These three factors all contribute to the health and wellbeing of the local population.

Acknowledgements

I would firstly like to extend huge thanks to my supervisor Dr Daniel Costola whose calming guidance throughout the project has been invaluable. His words of "perfect is the enemy of good" will stick with me on my career journey as I look to shake off perfectionism in favour of productivity.

Further thanks are reserved for course co-ordinator Dr Paul Tuohy who planted the electric ferry seed in my mind back in the group projects phase of the course, even if spelling his surname correctly has proved a challenge all year. Seriously though, the course is very well run and the site visits in March provided great insight into different local renewable energy projects.

I also thank Fredrik Thornell of Green City Ferries who provided me with information on the company's vessels that was otherwise unavailable through online research.

On the financial side, I am very appreciative of the scholarship grant that I received from the Scottish Funding Council which enabled me to undertake this postgraduate course.

From the course, I would like to thank all of my lecturers. I have been equipped with strong knowledge and habits from your teachings. Also, thanks to my peers who have made it an enjoyable year.

Lastly, I would like to thank my friends and family who have put up with all the boat chat as well as supporting me through the periods of angst associated with such an intense individual project. Although I don't often say it, I do appreciate you all immensely.

"There is another alphabet
Whispering from every leaf,
Singing from every river,
Shimmering from every sky."
Dejan Stojanovic, Forgotten Home.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Problem Definition

With the onset of climate chaos, many strategies are pursued to curb fossil fuel consumption. Transport accounts for 33% of UK carbon dioxide (CO_2) emissions. (Dept for Business, Energy and Industrial Strategy, 2019) One such method is to encourage public transport use by producing high quality services. Another is to eliminate the requirement for fossil fuels in the transport sector by producing electric vehicles (EVs) powered by the charging of a battery system. This being greener than internal combustion engine (ICE) vehicles is dependent on the generation methods of the electricity source. It can be connected to the local electricity grid which must decarbonise by improving the national renewable electricity supply, or alternatively, by powering charge points (CPs) via on-site renewables. By electrifying high quality public transport services, these two methods can be combined.

Another fundamental issue within city centres throughout the world is road traffic congestion. As well as increasing transit times for commuters, cars crawling along in queues reduces local air quality in regions where the majority of people live and work. Meanwhile, in many of these cities urban waterways which often served historical purposes are underused. This open channel could be utilised with high speed passenger ferries to offer current car commuters a faster and less stressful transport experience.

Worldwide, urban councils are looking at ways to integrate active travel into commuting routes. This includes providing bike parking at train stations to solve the “first mile” problem and bike share schemes in city centres to combat the “last mile” problem. At peak times on trains, there is minimal space for cyclists to take their bike on board. By creating an urban ferry with bike parking onboard, both the first and last mile problems could be solved. Furthermore, cyclists would be less hesitant to use their expensive or treasured bike for commuting if it is not being left at a train station all day. It enables cyclists to use their own bike for the full journey as some may be resistant to depend on bike share schemes due to uncertainties around availability, docking, quality or payment methods.

1.2. Aim/Motivation

To conduct a feasibility study into the energy requirements of delivering an electric ferry service serving a linear route on the River Clyde in Glasgow.

1.3. Objectives/Scope

- Select a suitable ferry route on the River Clyde and develop a demand estimation based on current transport trends around proposed terminals.
- Select an electric vessel to fulfil the route and determine its energy requirements.
- Compare to a similar-sized diesel vessel and a business as usual case in terms of emissions generated from use, energy requirements and travel time by mode.
- Conduct an economic analysis of the service and compare with the diesel ferry scenario.
- Determine the impact of rooftop solar panels on energy requirements.

1.4. Methodology

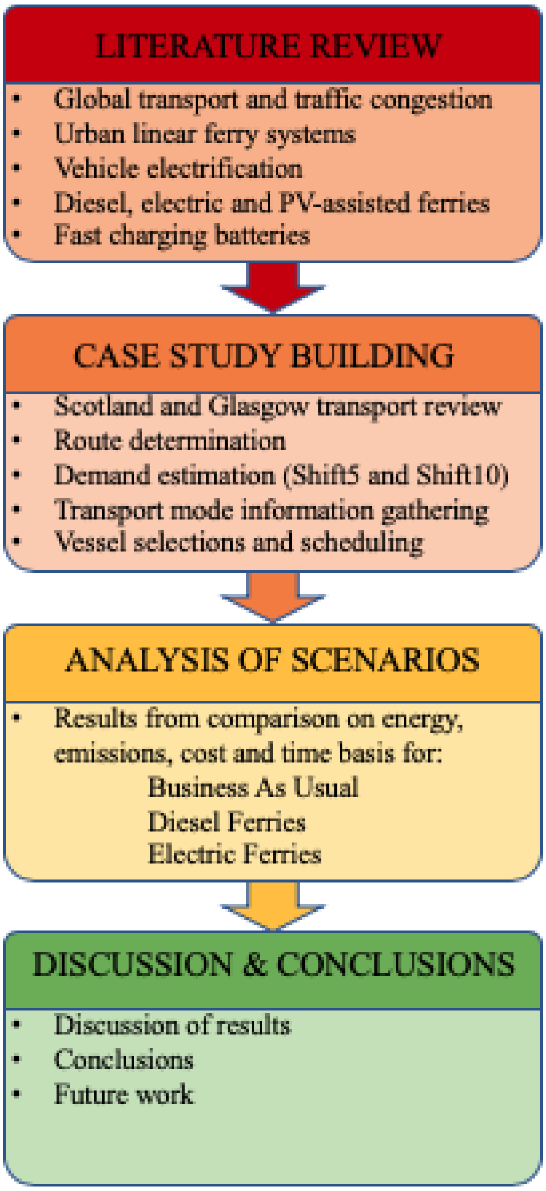


Figure 1: Methodology Diagram (Own Design)

1.5. Structure of Thesis

Chapter 2 tackles the literature review for the work. This includes the current problems related to congestion and transition towards decarbonising transport around the world. It then looks at how active travel, urban waterways and electrification of transport can ease these problems. Focus then moves to ferries: hull forms, diesel and electric propulsion and use of solar power. Finally, there is a brief overview of battery systems used for electrifying transport.

Chapter 3 moves on to the case study, building a picture of transport policy and modes in Scotland and Glasgow, including historical and existing ferry services.

Chapter 4 describes the methods conducted to fulfil the outputs intended from the objectives.

Firstly, the route selection is conducted, with information gathered about the existing transport system and potential catchment zones for each chosen terminal point.

Next, a demand estimation for travelling to Glasgow is determined for each of the towns within the catchment zones to develop overall profiles for weekday peak time, weekday off-peak and weekend demands by rail, bus and car use. The concept of "modal shift" is introduced here, with Shift5 representing 5% of the overall demand from towns with terminals changing from their current, or business as usual (BAU), mode to using the ferry and Shift10 representing a 10% shift.

Then for the BAU scenario, by analysing the demands by mode and town, the collective energy and emissions data are determined for Shift5 and Shift10.

For the Diesel Ferries scenario, a vessel is selected and a schedule is determined to meet the demands for Shift5 and Shift10. From this, energy, emissions and cost are found.

For the Electric Ferries scenario, a vessel is selected and analysis of the battery system is conducted. A schedule is determined to meet Shift5 and Shift10 and energy, emissions from the grid and cost are found. There is a brief analysis on the potential power output from rooftop solar PV panels.

Chapter 5 contains the results obtained from following the methods stages.

Chapter 6 is the discussion section, focusing on the interpretation of the results, limitations of the study and recommendations.

Chapter 7 contains the conclusions and scope for future work.

2. Literature Review

2.1. Worldwide Congestion and Transport Decarbonisation Necessity

Since the industrial revolution, there has been a mass migration of populations from rural areas, where agriculture was the main means of providing for a family, towards urban areas, where the accumulation of industrial wealth could be spread to workers traditionally in the manufacturing of goods from the Earth’s raw materials and more recently in the developed world in the provision of services.

This has led to a large concentration of inhabitants working in dense cities, which prove to be the monetary centres upon which national economies are built. Affordability of private vehicle ownership enabled workers to make residence in outer-city areas, where land ownership was more affordable, air quality was better and safer neighbourhoods for raising families became available. An unfortunate consequence of this trend has been road congestion at peak times throughout the day, with many citizens needing to enter and exit the city at the same times.

This results in significant time loss and an often stressful experience for drivers, which can bleed into the workplace to impact productivity. (Novaco & Gonzalez, 2009) This non-working time could be better served spending time with family or pursuing hobbies which are both known to have a positive impact on wellbeing. Furthermore, stop-start and slow driving have a detrimental impact on fuel efficiency and so this leads to a wasting of fuel. As well as hitting the driver in the pocket, this also raises environmental concerns since more fossil fuels are required than would be for a smooth and consistent driving experience. Moreover, if vehicles are slowed down in the same areas each day, then tailpipe emissions will drastically reduce the air quality of the local vicinity. This is likely to discourage those inclined to active travel modes such as walking and cycling.

According to the 2018 INRIX traffic ranking (Reed & Kidd, 2019) comprising 220 cities, the top ten worst cities for congestion by time lost to traffic per capita are Moscow, Istanbul, Bogota, Mexico City, Sao Paulo, London, Rio de Janeiro, Boston, Saint Petersburg and Rome. The 2018 TomTom Traffic Index (TomTom, 2019) of 404 cities ranking by percentage extra journey time compared to uncongested conditions has a wider coverage and includes Mumbai, Lima, New Delhi, Jakarta and Bangkok among its top ten. This spread of cities shows the extent to which this is a global issue. Studies by the World Health Organisation show that ambient air pollution caused 4.2 million premature deaths in 2016. (WHO, 2018) PM2.5 (particulate matter of less than 2.5 microns) is commonly used as a measure of air quality since its particle size is small enough that it can enter the respiratory system to cause human health problems. The targeted safe level of PM2.5 of 10micrograms/m^3 was met by just 27.3% of monitored European cities and a mere 1.2% in South Asia. (IQAir AirVisual, 2019) The source of such particles can be natural, e.g. from dust storms, but mainly in population centres it comes from combustion of fuels in vehicle engines, industry and power plants. Just as the burning of coal in power plants and for industry is seen as the dirtiest fuel in terms of particulate matter, in vehicles, diesel creates fumes more harmful to human health than petrol. Although fuel efficiency is often better in diesel vehicles and so, on average 24% less CO_2 is released from their tailpipes, petrol cars have been found to release 86-96% less Nitrogen Oxide and Dioxide (NO_x) gases. (O'Driscoll, et al., 2018) NO_x gases have detrimental impacts on air quality and public health and contribute towards eutrophication of water sources. (Jonson, et al., 2017)

In the battle to avert damaging and irreversible climate change, a significant decarbonisation of our energy requirements is a necessity. Globally, in 2008, transportation of people and goods contributed 23% of carbon dioxide emissions, with 72% of these coming from road transport.

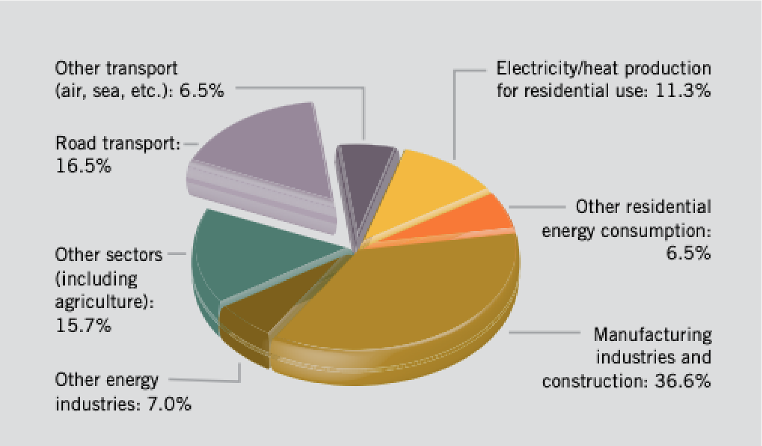


Figure 2: CO_2 emissions by sector in 2008 (WHO, 2011)

A similar trend was found in 2016 for the EU-28, with 27% of all greenhouse gas emissions coming from transport and 74% of these coming from road transport. (European Environment Agency, 2018) This has been a 26% increase on 1990 reference levels, where the goal is to drop the 1990 level two-thirds by 2050 as established in the 2011 Transport White Paper.

Global aviation and freight shipping are challenging to decarbonise due to their immense energy requirements. However, for land-based vehicles, the technology is already developed, which is reflected in the increasing presence of electric cars on the road. This growth is likely to significantly reduce demand for petrol and diesel in the coming years. Although it is worth noting that electrification of transport must come in line with an increased renewable fraction of the national grid, otherwise fossil fuel dependence is merely shifted from the transport sector to electricity generation.

Many strategies have been pursued to combat these issues such as congestion charges, trialling of free public transport and the building of further roads. (Börjesson, 2015) However, the strategies that will be considered in this thesis are promotion of active travel, greater exploitation of waterways and electrification of transport.

2.2. Promotion of Active Travel

Governments around the world are acutely aware of the emission and congestion issues surrounding vehicles in urban areas and one of the main strategies to combat this has been to promote active travel. This can be defined as making journeys by physically active means, most commonly by walking or cycling. There are various reasons that make this focus a logical move.

First of all, since the majority of car commutes are completed solo, in terms of space occupancy bicycles are much less land intense both when in motion and when parked. With an increase in bicycle commuters, road congestion is reduced directly by vehicle-bike substitution and indirectly since cars which enter the city require less time to find a parking space.

Second, both walking and cycling are emissions-free activities. This is favourable for the local environment.

Third, they provide a means for reaching public transport connections. A study conducted on Amsterdam’s bike-train system (Williams & Te Brommelstroet, 2017) found that cycling can open up a much wider catchment area for stations, which results in increased public transport network efficiency, and the normalisation of cycling as part of daily journeys, which is crucial for a societal shift. Public transport journeys can be split into three sections: access (or first mile), which describes the journey from home to the transport stop; transit, which covers the longest distance at the fastest speed; and egress (or last mile), from exiting the transport mode to the workplace. Trains have limited space for bicycle storage so it is most often the case that bikes can only cover either the first or last mile of the journey. Solving the First Mile/ Last Mile (FMLM) problem is a challenge for many urban centres.

Fourth, they reduce sedentary time, keeping muscles in good condition, improving physical fitness and in the long term, reducing strain on health services. Regular exercise has been hailed as a “wonder-drug” with physical health benefits felt among a wide range of areas including cardiovascular, metabolic and musculo-skeletal health as well as a reduction in cancer rates and in the probability of falls in geriatrics. (Public Health England, 2016)

Fifth, keeping active has positive impacts on mental wellbeing. In an American survey of transport modes bicyclists have been found to be the happiest travellers (Morris & Guerra, 2015). Moreover, a study on the three largest Swedish urban districts highlights the considerable effect of mundane daily activities such as commuting on overall happiness finding that commuters are most satisfied when walking or biking. (Olsson, 2013)

Achieving these aims requires clever urban planning to ensure safe and enjoyable navigable routes with adequate end-point bike parking facilities to provide a meaningful alternative to car travel.

2.3. Exploitation of Urban Waterways

Historically, cities were often constructed around the banks of rivers for reasons of water supply and to provide channels through which communities could be connected. Rivers have been described as “the first highways, moving belts of water” and played an important role in trade dealings for burgeoning empires. (Mumford, 1961) With increased commercialisation of these waterways, boat technology evolved from man-powered canoes to steamboats to large diesel-powered ships of today. (Kondolf & Pinto, 2017)

However, in modern times the major urban transportation channels have shifted from the water to the land and while road congestion proves to be a distinct urban challenge, relatively few cities are turning back to their waterways as a commuter transport solution.

Urban ferries can be broadly classified into two realms: crossing ferries or linear ferries. Despite the decline of river-dependent industry, crossing ferries, i.e. bank-to-bank, remained popular in many cities for many years but save for a few exceptions, these have been largely replaced by the construction of bridges and tunnels. (Cudahy, 1990) Linear ferries, i.e. running parallel to the banks, have started to appear mainly over the last 25 years in a select few cities due to a desire to latch onto ex-industrial waterfront areas for modern development and to ease road congestion. This was enabled by advances in marine technology which has delivered vessels with high speeds and capacities but low wash and noise levels. (San Francisco Bay Area Water Transit Authority, 2003)

Examples of cities with linear ferry systems include Brisbane, London, New York, Bangkok, Gothenburg, Hamburg and Copenhagen, each with at least one linear route comprising five or more stops. (Tanko & Burke, 2017) Each city has its own unique stamp on its approach to providing a linear ferry service, with regards to number of vessels, vessel size, speed, facilities, route length, terminals, running hours and frequencies. As a trend, the older and often lower speed systems tend to use monohull ferries, with the more modern ones requiring high speed employing catamarans. It should be noted that only Gothenburg and Copenhagen have significant on-board bike parking facilities with more than a quarter bike spaces per passenger. This is perhaps owing to the success in the promotion of active travel in Scandinavia. Limited space is available in London, between 4-14 spaces, and similar in Brisbane.

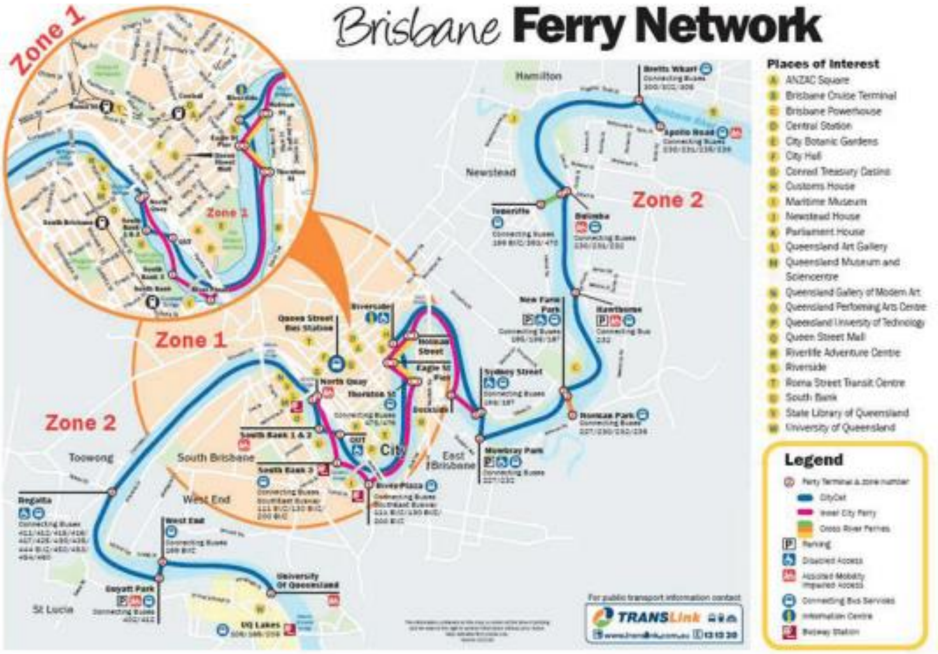


Figure 3: Brisbane's Urban Ferry Network (Tsai, 2015)

The benefits of such a linear ferry service include the utilisation of existing vacant space. This ample space provides the possibility to have a variety of vessel sizes and to serve a number of different routes. Unlike major transport infrastructure projects on land, building ferry terminals causes minimal disruption. There is also research to suggest that building a ferry system can have a positive impact on the economic development of the areas which it serves, with private developers partially or fully funding the construction of new ferry terminals in Brisbane. (Sipe & Burke, 2011) Proximity to ferry terminals can also have the effect of land value uplift, with increases of 4% per kilometre of distance. (Tsai, 2015) It can also help to connect transit deserts: areas currently underserved by public transport options. Furthermore, it can be used to stimulate tourism by centring the service as part of the wider city branding strategy.

A 6-month study (November-April) into smart card transactions on Brisbane's river ferry network (Soltani, 2015) provided some interesting insights into passenger behaviour. As expected, midweek peak times were between 7am-9am and 5pm-7pm which indicated that the vessels are used primarily for commuting. On weekends, the overall patronage is reduced considerably and a more consistent spread of passengers throughout the day was observed. 84.2% of all trips were linear which supports the idea that cross-ferries are less of a necessity, 14.2% of journeys were combined with a secondary public transport mode, which strengthens the case for inter-modal connectivity and average travel time and distance were 16 minutes and 7.4km respectively. The monthly usage was found to be pretty consistent, save for a slight drop in December and January, likely owing to these being times of summer holidays for universities and workplaces alike. Due to the months studied, the effect of the colder winter season in the Southern Hemisphere has not been analysed. However, on New York's East River Ferry it has been found that ridership is only adversely affected by cold weather in the case of leisure passengers, with the biggest difference being spotted on the weekend. (New York City Economic Development Corporation, 2015)

It is not a be-all-and-end-all panacea solution to solving transportation issues since there are a number of caveats that detract from its viability in many cases. First of all, there is a limited catchment area since there must be a suitable demand from residential areas close enough to the riverbank. Second, it may have to compete with other existing public transport modes, such as bus, train or metro lines. Time savings compared to other modes may be insignificant and the frequency of service may be less. Third, it may not be applicable for all cities, particularly those with narrow river channels where high-speed vessels would be unsuitable or impossible with current laws as is the case in Paris. (Bignon & Pojani, 2018) Lastly, vessels are expensive compared to other public transport vehicles and the fuelling requirements for traversing water are significant so it is unlikely to prove profitable on fare prices alone and will need Government subsidy.

2.4. Electric Vehicles

Governments around the globe are looking to increase electric mobility as part of their strategies to curb fossil fuel consumption from the transport sector. EVs effectively replace the powering mechanism of an internal combustion engine with a battery system.

The market for electric vehicles is experiencing a period of significant growth. Bloomberg report global sales for 2018 at over 2 million, up from a few thousand in 2010 when they first entered the market. It is anticipated that annual sales will rise to 10 million by 2025 and 28 million by 2030 with declining battery costs leading to price parity with ICE vehicles in the mid-2020s. Although they currently account for just 0.5% of the global fleet, they are expected to eclipse annual sales of ICEs by 2038, reaching 29% global fleet share by 2040. (Bloomberg NEF, 2019)

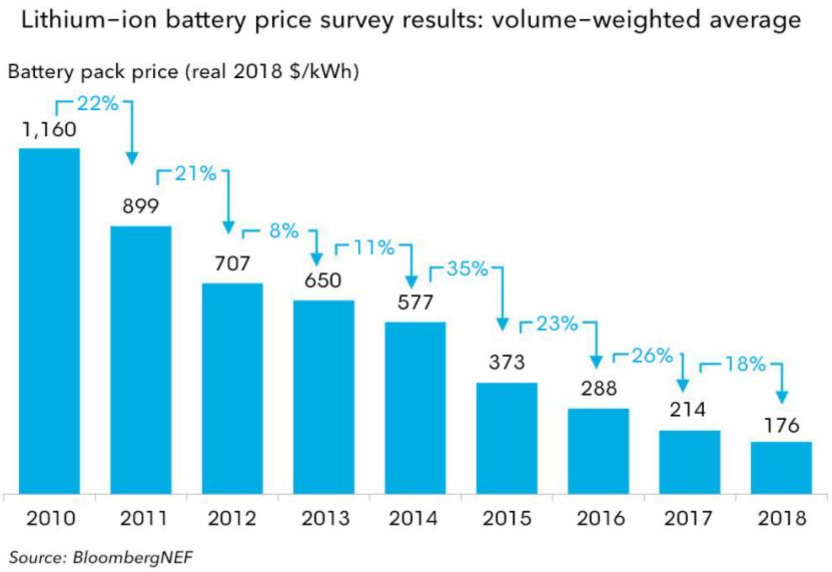


Figure 4: Average Lithium-Ion Price Decreasing by Year (Bloomberg NEF, 2019)

Despite offering no direct subsidy to vehicle purchase, Norway has proven itself to be the leading nation in promoting EV uptake, with the EV market share for 2017 of 40% dwarfing the rate of other nations. For comparison, the UK was 2% and Brazil, perhaps with the influence of bioethanol lobbying groups sold just 66 EVs, less than 0.00004% of the market share. (Rietmann & Lieven, 2019) A wide variety of policy measures have driven Norway’s success, many of which were introduced in the 1990s and 2000s as experimental EVs took hold but the rewards were not reaped until the industrialisation and commercial potential of Lithium-Ion batteries were realised from 2010 onwards. These measures have included indirect monetary incentives such as tax benefits; traffic incentives such as free municipal parking and use of toll roads, discounted car ferry use and ability to enter bus lanes; as well as recent developments in providing suitable infrastructure with 14.5 charging stations per highway kilometre. (Figenbaum, 2017)

One of the major barriers to widespread adoption of EVs is the idea of "range anxiety", i.e. fear caused by the distance restrictions imposed by the EV battery. However, after a year-long study into driving behaviour of 484 ICEVs in the US, it was discovered that without charging throughout the day, an EV with 150 mile range will meet the average driver's needs in all but 9 days per year. (Pearrea, et al., 2011) For context, the UK's top selling pure EV is the Nissan Leaf, with the basic model having a range of 168 miles. (Nissan, 2019) With sufficient supply of public charging infrastructure, EVs begin to look like a viable substitute for the vast majority of current ICEV trips. For some consumers, however, there is a reactionary rhetoric to range anxiety around what society feels that a car should be with regards to freedom of travel and no technical range improvements can solve this until the range matches what can be achieved on a tank of fuel. (Noela, et al., 2019)

Beyond private vehicles, it is becoming more commonplace to find the electrification of larger vehicles suitable for public transport applications. Electric powered trams, trains and trolleybuses with overhead lines are not a new development. However, the adoption of large battery storage systems is beginning to encourage the creep of cableless electric solutions into the market. Since these have a fixed route and operate to a schedule, sizing of the battery system for a specified range should in theory be a more straightforward process than for private vehicles. Choosing suitable public transport routes to electrify could also consider the local environmental impact assessment, in order to prioritise the improvement of air quality in the worst-affected regions. (May, 2018)

2.5. Ferries

"Water is 784 times denser than air and takes a lot more energy than rolling a car along a flat road."

Konrad Bergstrom, CEO of X Shore (Motor Boat & Yachting, 2019)

Vessel Design

The two key parameters that determine the power requirements for a boat are vessel design and weight. Vessel design is crucial to minimise energy lost to wave formation and the weight of the boat determines how much water is displaced. (Pollefliet, 2018) The designs considered in this work will be Monohull, Catamaran and Air Supported Vessel (ASV).

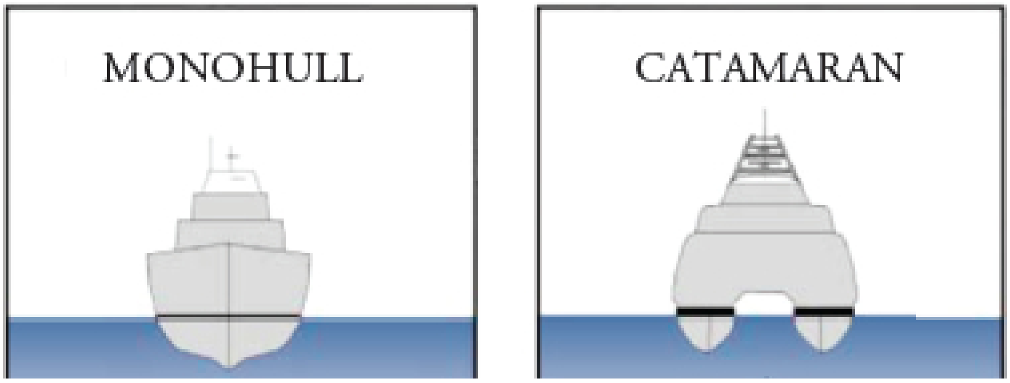


Figure 5: Monohull and Catamaran Vessel Designs (Picard, 2017)

Monohulls, as the name suggests, have a single hull and is the most conventional ship design. The name catamaran is derived from 1670s Tamil "kattu-maram" meaning logs tied together. (Online Etymology Dictionary, 2019) In modern parlance, this represents a boat with two hulls connected in the centre. This gives the vessel greater stability and reduces the immersion depth in the water since the weight and hence water displacement is spread evenly across the two hulls. Air Supported Vessels combine the idea of hovercrafts, which ride on an air cushion contained within a flexible skirt to vastly reduce surface friction, with more conventional, rigid hull forms. Fan action is used to raise the hull from the water, reducing water displacement and hull resistance. (Maritime Journal, 2015)

Diesel Ferries

Current linear ferry services are powered by twin diesel engines. For example the 2nd and 3rd generation of CityCat vessels in Brisbane built by Norman R. Wright and Sons use two 302kW (at 2100rpm) Cummins QSM 11 diesel engines. The Thames Clippers in London, built by Incat Tasmania, employ two 625kW (at 2300rpm) Scania DI-12

072M diesel engines with either propeller or waterjet propulsion. (Thames Clippers, 2015)

Diesel-electric marine propulsion works by burning fuel in the engines and using generators to convert this mechanical energy into electric energy. This is fed to a power management system, which in turn feeds electric motors to provide kinetic energy to the propulsion in the water. The power management system is in place to ensure equal thrust to each propeller and to control the supply of electric power to the hotel load. It works by the use of clutch gearbox systems to control the rotational speed of the engine and hence its power output.

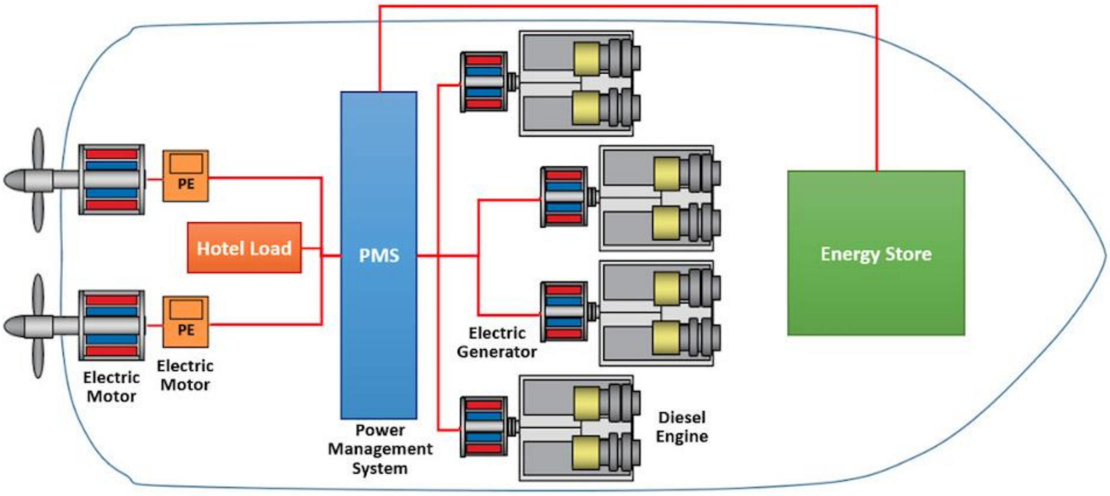


Figure 6: Diesel Electric Marine Propulsion System Schematic (MFame, 2016)

Electric Ferries

With battery development improving the range of EVs, now could be the time to implement a fossil-fuel free solution. Electrification of marine propulsion works by employing a battery system, which can be charged by plugging in to an offshore grid connection. This can be done quickly by use of a high-power supercharger or slowly using a lower power connection. The energy stored in the batteries is sent to the power management system (PMS) and then used to power the electrical loads of the vessel, chiefly its propulsion system via electric motors and any hotel loads.

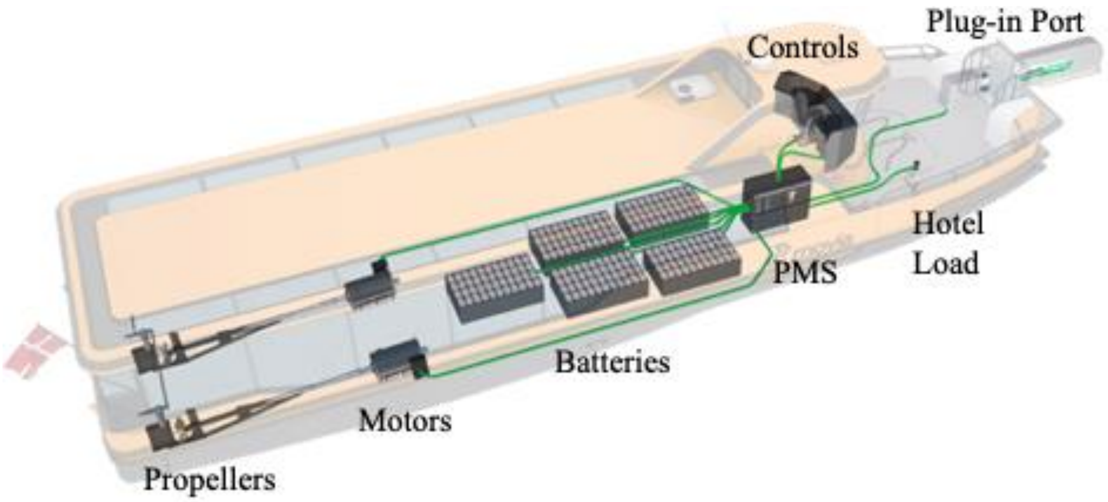


Figure 7: Electric Marine Propulsion Systems Schematic with own annotations (Damen, 2019)

Norway has led the way in providing electric-powered boats, owning 40% of all worldwide vessels in late 2018 including the world's first all-electric vessel, the MS Ampere, delivered in 2014. (Mjos, 2018) The MS Ampere, operated by Norled, is an aluminium catamaran capable of carrying 120 cars and 360 passengers on a 20 minute crossing 34 times per day. Its 1MWh Lithium-polymer battery pack receives a 10-minute recharge at each port, with grid-charged battery buffers required since its power requirement would otherwise swamp the local village grid. For propulsion, this powers the 2x450kW Azimuth thrusters and 2x450kW motors. (Spath, 2015)

Figure 8: MS Ampere, world's first all-electric ship (NCE Maritime CleanTech, 2015)

In other worldwide developments, China delivered the first ever all-electric cargo ship, ironically being used to transport 2000 tonnes of coal per trip. (Press Trust of India, 2017) In Sweden, Green City Ferries retrofitted Stockholm's Movitz boat from a 335hp diesel engine to twin 125kW electric motors and 180kWh Ni-MH batteries which can be charged in 10 minutes. It serves a 10km route and can travel for an hour per charge with an average speed of 9knots. (Barry, 2014) These batteries have since been upgraded with Toshiba Lithium Titanium Oxide (LTO) ones. (Vattenfall, 2019) Canal boats are being retrofitted with Lithium-Iron-Phosphate (LFP) batteries in Amsterdam, with conversion cost per vessel in the region of £200,000 and payback expected within 12 years. (Wall, 2018) In Bangkok, Thailand, one 40-passenger ship serving a 5km route on the Chao Phraya River has been retrofitted to replace its 205hp diesel engine with twin 10kW electric outboards and Lithium-ion storage. (Smallridge, 2018) Further to this, there are plans in the offing for 54 new-electric vessels to enter the transport equation by February 2020, with one 20km route expected to take 40 minutes using a 200-passenger vessel with an 800kWh battery pack. (Rungfapaisarn, 2019)
A 20knot, 135 passenger, all-electric commuter ferry in Wellington, New Zealand anticipated by late 2019. (East by West, 2018) This is further complemented by the first two fully-electric, zero emission ferries to be built in the US titled Maid of the Mist which will serve tourist trips to the Niagara Falls from September this year. (Mogg, 2019) The power system is to be delivered by ABB, with the catamaran vessels having twin battery capacity of 316kWh able to deliver up to 400kW propulsion power to the motor, with shoreside charging taking just 7 minutes. (ABB, 2019)

With the assistance of €3.2M EU funding awarded in 2012, by 2016 Green City Ferries had developed an Air-Supported Vessel (ASV) known as AiriEl or BB Green 20. (BB Green, 2016) The ASV technology reduces friction by blowing 15m3/s of air into the cavity to reduce wet surface by 80%, which reduces energy consumption by 40% compared to catamaran. It also has a small wake size, producing waves of just 16cm and carries 80 passengers at a speed of 28 knots. Its 426 kWh LTO batteries are capable of charging at a 4 coulombs rate from 70% depth of discharge (300kWh) in 12 minutes using a 1500kW supercharger. (Thornell, 2018) This vessel has been further refined to offer the larger BB Green 24, capable of travelling at 30 knots, with full battery power supporting a distance of 15 nautical miles (approximately 28km). (Green City Ferries, 2019) It also offers cycle storage space for 30 bikes alongside its 150 passenger seats.

(Green City Ferries, 2019) An alternative hybrid version is available, featuring two 440kWh diesel engines and a 70kWh LTO battery. (BB Green, 2018)

In January 2018, as part of the EU's Horizons 2020 research programme, €11.7M was awarded to the TrAM (Transport: Advanced and Modular) Project proposed by NCE Maritime CleanTech and Rogaland County Municipality in Norway to develop a modular design, high-speed, all-electric passenger ferry. (European Commission, 2018) This is intended for a route between Stavanger and Hommersak but with a view to acting as a Thames Clipper vessel in London and as a starting point for a barge design for the Zenne Canal system in Belgium. The vessel is intended to travel at 23/25 knots, carry 150 passengers and 20 bikes and is to be constructed by the Fjellstrand shipyard, who previously delivered the aforementioned MS Ampere. (Launes, 2018) The focus is on using equipment that is lighter, more compact and efficient since weight is a crucial factor in a high-speed vessel. (Moore, 2019) The modular and replicable natures of design are expected to reduce production costs by 20% and engineering costs by 75%. (TrAM, 2018)

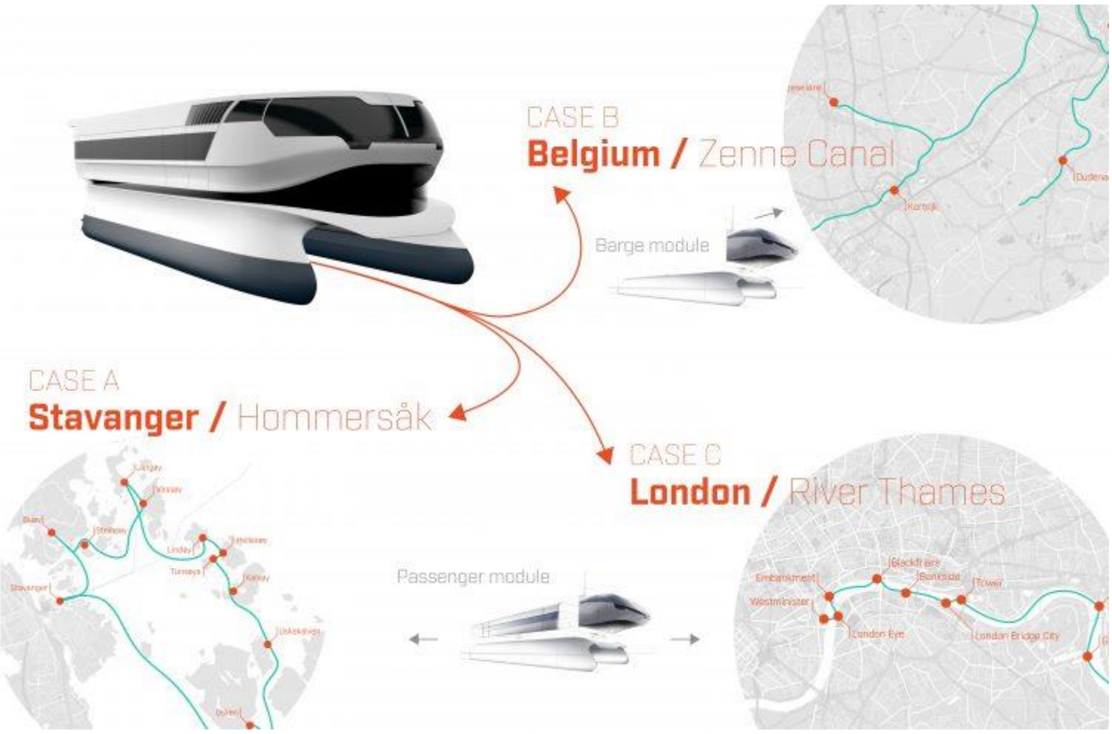


Figure 9: TrAM Project Concept Vessel and Proposed Routes (Maritime Clean Tech, 2018)

A “willingness to pay” study into boating tourism on Italian lakes found that users would be willing to pay 15.68-18.51% more on ticket prices if there was introduction of electric boats. (Bigerna, et al., 2019)

Solar PV Ferries

With the introduction of battery systems into marine propulsion, this also gives the potential to incorporate renewable generation methods to provide energy for storage. Photovoltaic (PV) powered boats have been developed for research and commercial purposes. In Thailand, a research boat was developed to be tested for sustainable tourism purposes. The 7.5m vessel has six 300W solar panels and at a normal cruise power of 2,000W, it travels at a speed of 7.77 km/h. (Panprayun & Pitaksintorn, 2018) A 54-feet catamaran developed by Solarwave is on the market that is claimed to be able to cruise at 5 knots with unlimited range. Its powertrain consists of twin 60kW motors, 80 kWh batteries and 15 kW of PV panels. (Lambert, 2016) In Cantabria, Spain, the ECOCAT 120-passenger ferry travels six 13km trips per day and when fully-charged can run for 8 hours with no sunshine at its normal cruising speed of 7 knots. It is powered by twin 50kW motors and has total battery capacity of 244kWh. (Smallridge, 2018)

2.6. Fast Charging Battery Technology

The following equations govern the rate at which a battery can be charged or discharged.

$$Charge\ Rate\ (C) = \frac{Power\ Supplied\ (kW)}{Energy\ Capacity\ (kWh)}$$

$$Discharge\ Rate\ (C) = \frac{Power\ Consumed\ (kW)}{Energy\ Capacity\ (kWh)}$$

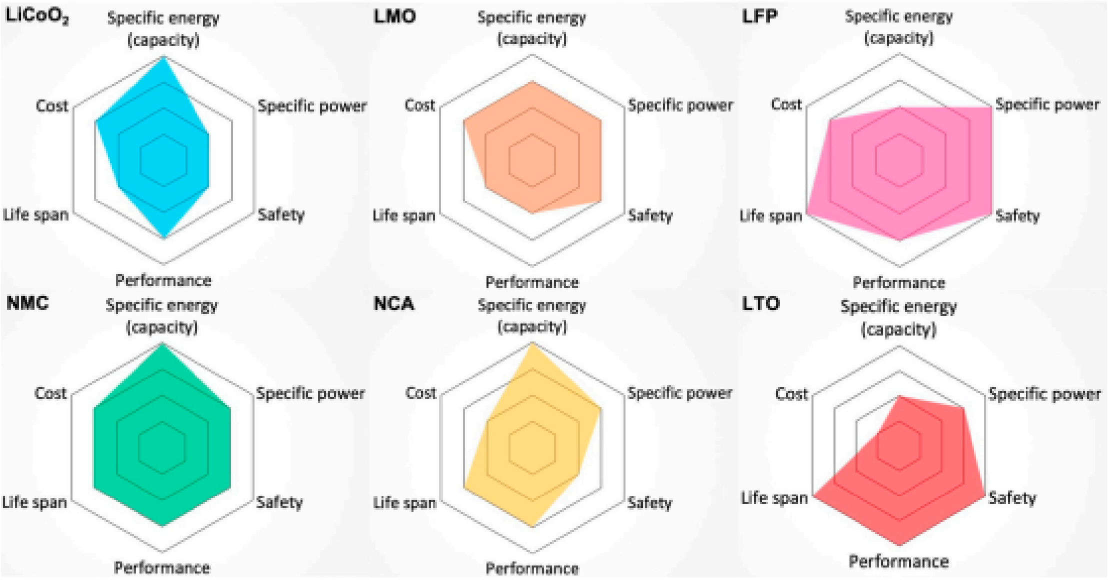


Figure 10: Lithium Ion Battery Comparison by Characteristic Schematic (Miao, et al., 2019)

Table 1: Lithium Ion Battery Comparison by Characteristic (Battery University, 2019)

Battery Type/ Characteristics	LCO	LMO	LFP	NMC	NCA	LTO
Specific Energy (Wh/kg)	150-200	100-150	90-120	150-220	200-260	50-80
Lifespan (cycles)	500-1000	300	2000	1000-2000	500	20000
Charge Rate (C)	0.7-1	0.7-3	1	0.7-1	0.7	1-5
Discharge Rate (C)	1	1-10	1	1-2	1	0.2-5
Cost ($/kWh)	-	-	580	-	350	1005

Despite being expensive and of low energy density, Lithium Titanium Oxide (LTO) batteries are seen as the most suitable option for high speed and high frequency electric ferry applications. This is because of their ability to withstand high charge and discharge rates, their ability to undergo 100% depth of discharge without compromising cycle life and their high safety and low temperature performances. (Han, et al., 2019)

3. Case Study: River Clyde

3.1. Transport in Scotland

Transport Scotland's stated approach is that:

"The strategies we put in place to make sure that we are always looking to the future, keeping Scotland moving, active and green."

Scotland aims to have the best air quality in Europe and phase out the sale of new petrol and diesel cars by 2032. This is reflected in the £20.6M funding handed out to local councils to support private ownership of EVs to improve infrastructure and deliver 800 new charge points via the Switched on Towns and Cities Challenge Fund and the Local Authority Installation Programme. (Transport Scotland, 2019)

Further, Transport Scotland supports the promotion of active travel, i.e. walking and cycling, with the intention to secure 10% of all trips to be taken by bicycle by 2020. This would have benefits in terms of pollution levels, congestion, encouraging green space use and have a positive impact on wellbeing. This is particularly striking since 34% of all car journeys within Scotland are less than 2 miles. (Transport Scotland, 2019) Investment in active travel more than doubled from £39.2M to £80M from 2017-2018 to 2018-2019, with a further £80M allocated for the current year. (Transport Scotland, 2019)

Throughout Scotland, 62.3% of people drive a car as their main mode of travel to work, with 9.8% by bus, 5.1% by rail and only 3% cycling. (Transport Scotland, 2018) While this is a crude Scotland-wide trend including rural areas, it is fairly stark how low the patronage of public transport options in comparison to the convenience of a private vehicle. I believe that the bike-boat combination could convert some of these drivers as well as public transport users due to a more comfortable public travel experience among the pleasant surroundings of the waterway.

Bus use was at 388 million journeys in 2017/18 but has decreased 8% over the past 5 years. Only 37% of users in 2017 were travelling by bus for commuting or education purposes and those over 60, with free bus use, accounted for 32% of trips. Just 61%

feel that bus tickets offer good value and only 62% see buses as environmentally friendly. Bus revenue is heavily subsidised with 44% of £684M total revenue in 2017/18 supplied by Government support.

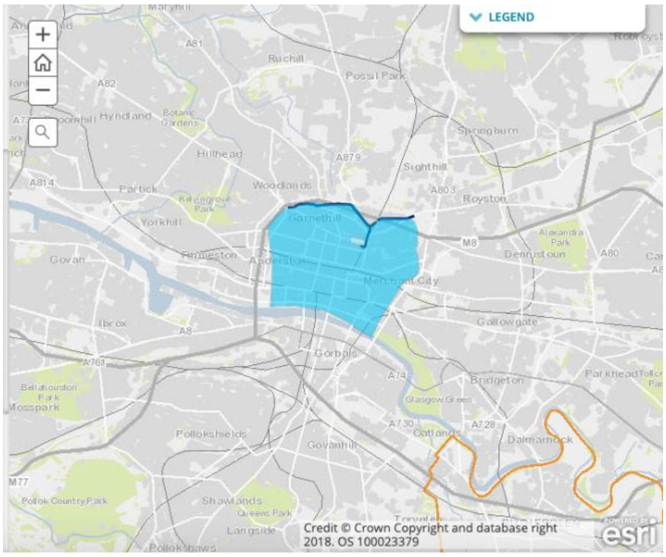
As bus use decreases, rail use is on the rise with the 97.8 million passenger journeys in 2017/18 increasing 31% on a decade earlier. Passenger surveys indicate that this may be down to 91% being satisfied with journey times, 83% happy with both punctuality and frequency despite only 60% believing the service offers value for money and just 52% satisfied with management of delays. Rail services in 2016 generated £519M in revenue, 56% (£293M) (Bell, 2017) of which came from Government support.

The Scottish Government also subsidises a wide ferry network, required to serve the many islands and archipelagos on its western and northern coastlines. Those 36 vessels on the West coast and firth of Clyde are run by Caledonian Maritime Assets Ltd (CMAL), 31 of which are leased to CalMac Ltd. The majority are of large monohull, roll-on roll-off style, designed to carry vehicles as well as passengers. These ferries are serving local and tourist access functions to rural and island areas. However they also have two passenger-only ferries, MV Ali Cat and MV Argyll Flyer which operate the Gourock-Dunoon service on the Firth of Clyde. The majority of Scottish ferries are predominantly run on diesel fuel, however more recent vessels manufactured by Ferguson Marine Engineering Ltd, such as MV Hallaig, have been fitted with diesel-electric hybrid propulsion systems.

3.2. Transport in Glasgow

Glasgow is a city of great environmental ambition. This year at the All-Energy Exhibition and Conference I witnessed in person First Minister Nicola Sturgeon, backed by Scottish Power, announce that Glasgow intends to become the UK's first "net zero city". This is reflected in recent policy measures such as the creation of Scotland's first Low Emission Zone (LEZ) within the city centre which states that light duty petrol and diesel vehicles must conform to Euro 4 and Euro 6 standards respectively and heavy duty vehicles must conform to Euro VI. (Glasgow City Council, 2018) Also, there has been a removal of free all-day street car parking on Sundays.

(BBC, 2019) There is a clear intent to not only reduce the number of vehicles in the city centre, but also to ensure that those which do so have lesser impacts on local air pollution.



Credit © Crown Copyright and database right 2018. OS 100023379

Figure 11: Glasgow's Low Emission Zone in Blue (Glasgow GIS, 2018)

Table 2: Glasgow LEZ Emission standards, enforced for local buses from 31 December 2018 and all other vehicles from 31 December 2022

Vehicle Type	Light Duty Petrol (RAC, 2018)	Light Duty Diesel (RAC, 2018)	Heavy Duty Diesel (ICCT, 2016)
Emission Standard	Euro 4	Euro 6	Euro VI
Permitted emissions (g/km)			
Carbon Monoxide (CO)	0.5	0.5	4.0
Methane (CH4)	-	-	0.5
Total Hydrocarbons (THC)	0.1	-	0.16
Nitrous Oxides (NO_x)	0.08	0.08	0.46
HC + NO_x	-	0.17	-
Particulate Matter (PM)	-	0.005	0.01
PM No. (/km)	-	6x10^11	6x10^11

According to the INRIX city rankings, Glasgow has the 3rd worst congestion time per capita in the UK (Reed & Kidd, 2019) and TomTom data states that during peak hours 15-16min is added to every 30 min trip, i.e. an extra 50%. (TomTom, 2019)

Glasgow is looking to address these issues with the introduction of Ultra Low Emission Vehicle (ULEV) buses and modern, low-energy electric trains on selected lines. (Hitachi, 2018)

The River Clyde in Glasgow has a long association with boats, harking back to its ship building past when it was known as the second city of the British Empire. As international trade swelled, engineers developed solutions to deepen the river to accommodate larger ships. (Clyde Waterfront, 2014) The John Brown Shipyard in Clydebank provided colossal cruise liner ships such as the Queen Mary and Queen Elizabeth 2. This provided a sense of great pride in the local community, where emotional and joyous days were experienced on the day the ships were launched after months of toil.

Figure 12: Queen Elizabeth 2 Vessel on launch day in Clydebank (Cruise Critic, 2007)

In the past, several ferry services operated on the Clyde, categorised into Cross Ferries which performed river crossings and Cluthas which travelled up and down the length of the river. The Cluthas were introduced in 1884, reaching a peak of 12 steam-powered vessels. These served a 3-mile route from Victoria Bridge to Whiteinch Ferry, taking in 11 stops either side of the river and lasting 45 minutes. In the year from July 1896, they carried approximately 2.8M passengers. However by 1903 they were withdrawn and replaced by electric tram lines on either side of the river. (Blaikie, 2019)

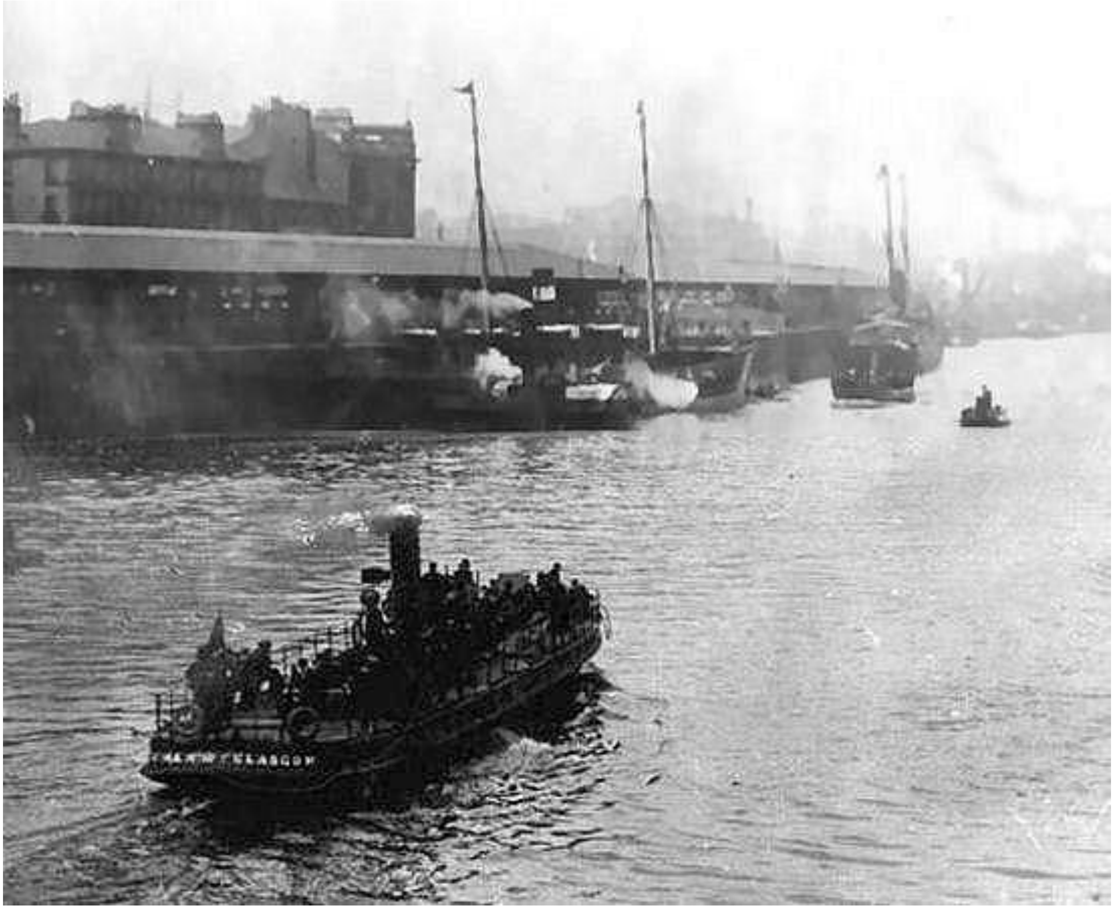


Figure 13: Clutha no.10 on the Clyde (Blaikie, 2019)

Nowadays, the Clyde has very little traffic with the exception of two short crossings covered by very small passenger ferries: the year-round private-run Renfrew ferry from Yoker to Renfrew (Clyde Waterfront, 2014) and the fare-free summer season on-demand Govan ferry from the Riverside Museum to Govan funded by local groups. (Get in to Govan, 2019) This paucity of river traffic provides a wide-open space when the roads are congested, existing as an underutilised transportation channel.

Drawing inspiration from the Brisbane CityCat and London Thames Clipper services, I feel that there is potential for Scotland to expand its fleet to urban areas, providing passenger and bicycle only catamaran-style vessels to provide a commuter service along the River Clyde in Glasgow.

Such an idea has been floated in the past. Indeed, 10 years ago, local transport provider SPT invested £100k into a joint project between Glasgow City Council and Argyle and Bute Council to explore its feasibility. The report was released in January 2009. The objectives were to assess demand and decide on suitable service routes. Positive conclusions taken were that the service could aid urban regeneration, integration would be achievable with other transport methods, there would be enough potential demand and that vessels could be stored overnight at Bowling harbour. However, it was also felt that the routes were well enough served already by bus and rail and that it would be expensive to start-up in terms of capital costs since they recommended 13 vessels across 4 service routes and would require significant subsidy to make it commercially viable. One such route was labelled the Inner Area Express and had stops in Bowling, Erskine, Clydebank, Braehead and Central Glasgow. (MacLennon, 2009)

However, I feel that with recent policy developments, enough time has elapsed to re-assess this idea using electric-powered vessels rather than those using diesel fuel in internal combustion engines.

4. Modelling Methods

4.1. Route Selection

Selecting an appropriate route for an electric ferry is bounded by a few factors. First, the total length of route must be suitable for the range of the battery system unless pierside chargers are to be installed at each terminal. Second, terminal location optimisation is important to reduce the number of stops to achieve competitive travel times with road and rail transport while securing a reasonable catchment area for commuters.

The River Clyde map can be seen below.

Figure 14: River Clyde Map (Google Maps, 2019)

The river is widest where it reaches the Firth of Clyde, to the west of Bowling. The width is very consistent due to the engineering works in the past and as it reaches in the city centre, it has a width of approximately 100m as can be seen below.

Figure 15: River Clyde Width in City Centre (Google Maps, 2019)

The River Clyde narrows and begins to meander more in the Eastern direction from the city centre. This will increase journey times and make it less suitable for a high-speed ferry service that will attract users of other modes of transport. This is reflected in the screenshot of Cambuslang below where the with is less than 40m.

Figure 16: River Clyde Width in Cambuslang, East of Glasgow (Google Maps, 2019)

For this reason, it was decided to route the vessel from towns west of the city centre. The Glasgow city council area runs west until the town of Yoker north of the river. Further west of this, covering Clydebank, Bowling and Dumbarton is the council of West Dunbartonshire.

On the south of the river, GCC runs West until Govan and from there Braehead, Renfrew and Erskine belong to the Renfrewshire council area. The table indicates the population of each council area and the figure maps the area of West Dunbartonshire in pink and Renfrewshire in green.

Table 3: Council Area Populations (National Records of Scotland, 2011)

Council Area	Population
West Dunbartonshire	90720
Renfrewshire	174908
Glasgow	590507

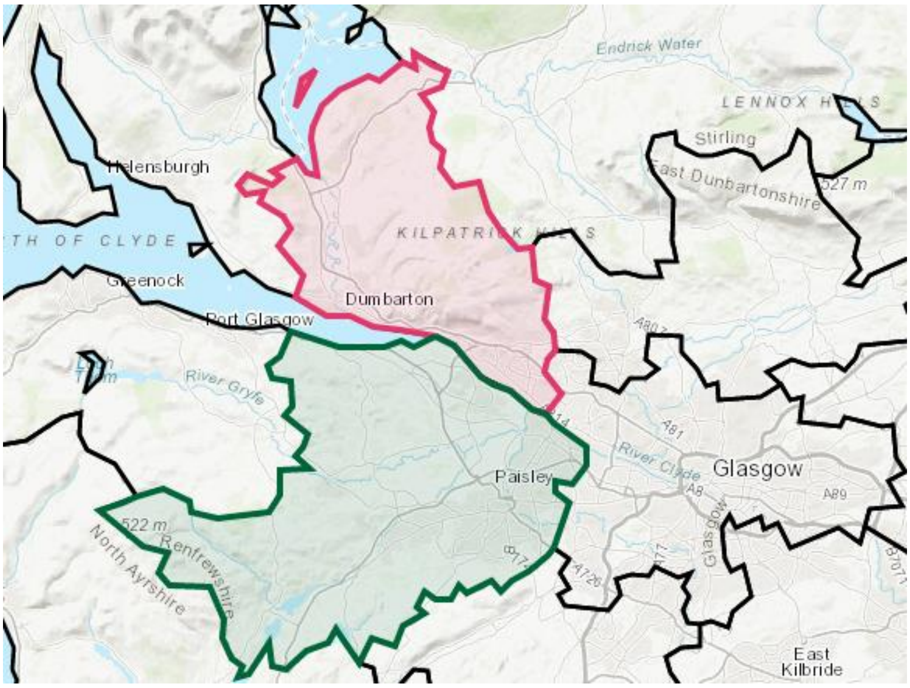


Figure 17: Council Areas by Map Area with West Dunbartonshire in pink and Renfrewshire in green (National Records of Scotland, 2011)

Route Map

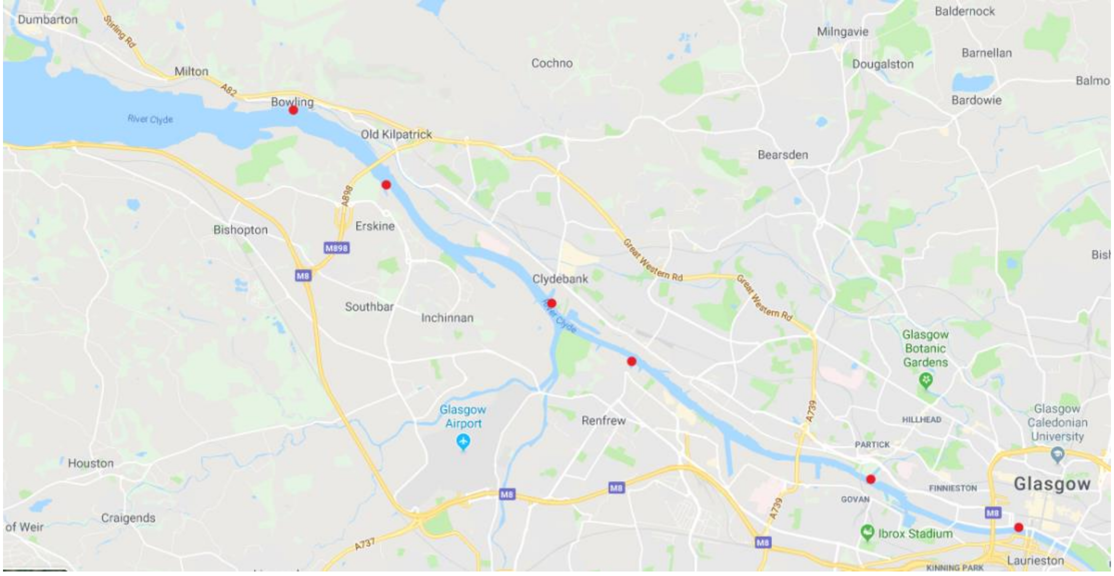


Figure 18: Selected Vessel Route Map with Annotated Stops in Red (Google Maps, 2019)

The selected stops are Bowling, Erskine, Clydebank, Renfrew, Partick, Glasgow City Centre.

Inspiration was taken from the Inner City Express Service earmarked by the SPT study to select a 17km route from Bowling to the city centre. (MacLennon, 2009) However, the Braehead stop is substituted for Renfrew since it is less of a commercial area and more residential and so is deemed to collect more commuters. Further, a stop has been added in Partick because there would otherwise have been an 8km stretch of journey with no stops. It also opens up the service to commuters who may work in the west end of the city and provides an inter-modal connection with the subway network.

Terminal Locations

Bowling

Distance from Glasgow is safely within the means of electric fast ferries on the market (15 nautical miles or 27.8km) and the existing harbour could act as an overnight storage location for vessels. Although Bowling has a small population, it is well-connected by bike paths to adjacent towns of Dumbarton and Old Kilpatrick.

Table 4: Bowling Terminal Area Information

Council Area	West Dunbartonshire
Population	959 (Bowling & Milton)
Distance to Glasgow by boat	17km
Distance and journey time by bike	18km (58min)
Distance and journey time by car	M8, 32.3km (peak: 30-50min, normal: 26-35min) or A82, 22.5km (peak: 30-65min, normal 26-45min)
Public transport	Train. Model: EMU 318/320. Bowling. Time: 31min; Frequency: 30min; Price: Peak £6.90 return, Off-Peak £4.50 return (Trainline, 2019)
Potential catchment areas	Milton (2km), Dumbarton (6km, population 19,912), Old Kilpatrick (2km, population 3,199)
Station bike parking	Bowling (10, uncovered); Kilpatrick (10, uncovered); Dumbarton Central (10, covered), Dumbarton East (6, covered) (Scotrail, 2019)
Recent development	Littlemill Court (71 flats) (Clyde Waterfront, 2017)

Erskine

Erskine is justified by its large population and lack of nearby train station, meaning that most commuters are affected by traffic congestion.

Table 5: Erskine Terminal Area Information

Council Area	Renfrewshire
Population	15,537
Distance to Glasgow by boat	14km
Distance and journey time by bike	20.8km (68min)
Distance and journey time by car	M8, 26.2km (peak: 24-40min, normal: 20-28min)
Public transport	Bus. Model: Enviro200. XP23. Bridgewater – Hope St. Time: 32-52min; frequency: 10 min. X23. Time: 51 min; frequency: 30 min 23. Time: 69 min; frequency: 30 min Price: £5.50 return. (McGill's Buses, 2019)
Potential catchment areas	Inchinnan (3.5km, population 1,797), Bishopton (4km, population 4,708)
Station bike parking	Bishopton (10, covered); (Scotrail, 2019)
Recent development	Riverside (246 properties) (BBC, 2019)

Clydebank

Clydebank is justified by having the largest population of all western towns on the Clyde and also the current development of Queen’s Quay which will bring 1200 new waterfront residences to the town. This may also lead to housing developers paying for the ferry terminal to attract buyers. (Tsai, 2015)

Table 6: Clydebank Terminal Area Information

Council Area	West Dunbartonshire
Population	28,799
Distance to Glasgow by boat	10km
Distance and journey time by bike	12km (41min)
Distance and journey time by car	A814, 15.2km (peak: 22-50min, normal: 20-40min)
Public transport	Train. Model: EMU 318/320. Clydebank. Time: 21min; freq: 30min. Singer. Time: 23min; freq: 15min Dalmuir. Time: 25min; freq: 10min Price: Peak: £5.60 return, off-peak: £3.70 return (Trainline, 2019)
Potential catchment areas	Duntocher and Hardgate (3.2km, population 7156), Faifley (4.5km, population 5088)
Station bike parking	Clydebank (10, uncovered); Singer (10, uncovered); Dalmuir (20, covered) (Scotrail, 2019)
Recent development	Queen’s Quay (1200 residences) (Clyde Waterfront, 2018)

Renfrew

Renfrew is justified by its swelled population due to the Ferry Village development over the last decade. The lack of train service in the town also makes commuters susceptible to traffic congestion.

Table 7: Renfrew Terminal Area Information

Council Area	Renfrewshire
Population	21,854
Distance to Glasgow by boat	8km
Distance and journey time by bike	12.1km (41min)
Distance and journey time by car	M8, 14.7km (peak: 18-30min, normal: 16-24min)
Public transport	Bus: Model: Enviro200. XP23 Renfrew Cross – Hope St. Time: 28-31min; frequency: 10 min. X23. Time: 28min; frequency: 30 min. 23: Time: 47min; frequency: 10 min. Price: £5.50 return (McGill's Buses, 2019)
Potential catchment areas	Yoker and Scotstoun (11,960) – relies on use of existing crossing ferry or building of future bridge expected in 2022 (Paisley, 2019)
Recent development	Ferry Village (2000 properties) 2007-2013 (Clyde Waterfront, 2013)

Partick

Provides a stop for commuters who work in the west end of the city, a connection to the subway service and has an existing ferry terminal used for the Govan crossing service.

Table 8: Partick Terminal Area Information

Council Area	Glasgow
Population	8,884
Distance to Glasgow by boat	3km
Distance and journey time by bike	4km (16min)
Distance and journey time by car	M8, 6.6km (peak 13-24min, normal 13-24min) A814 and M8, 9.2km (peak 13-22min, normal 13-18min)
Public transport	Train: Partick – Glasgow Queen Street. Time: 6min. Freq: 7min. Price: £2.90 return (Trainline, 2019) Subway: Partick - Buchanan Street. Time: 10min. Freq: 4 min. Price: £3.30 return (SPT, 2019)
Potential catchment areas	Govan (population 5,860) – relies on use of existing crossing ferry
Station bike parking	Partick (22, covered) (Scotrail, 2019)
Recent development	CGAP Housing Projects, 2009-12 (500 homes); Govan Water Row, 200 homes (Clyde Waterfront, 2013)

The assumption is made that existing crossing ferries for Yoker-Renfrew and Govan-Partick can be utilised to increase catchment for Renfrew and Partick stops respectively.

Glasgow City Centre

Council: Glasgow City Council

High density of workplaces which people who live in towns on the Clyde commute to and there is already an existing quay at Broomielaw pontoon.

The table below provides further justification for the vessel routing since Dumbarton Road, which travels from Dumbarton to Glasgow north of the river is above the targeted pollution level for NO_2 and close to the limit for PM_{10}. Broomielaw, where the vessel is intended to complete its route also exceeds the targeted NO_2 limit.

Table 9: Annual Mean Concentration of Pollutants at Broomielaw and A814 (Reid, 2018)

			Annual Mean Concentration of Pollutant ($\mu g/m^3$)				
Location	Pollutant	Target Limit ($\mu g/m^3$)	2013	2014	2015	2016	2017
Broomielaw	NO_2	40	47	41	41	37	44
Dumbarton Rd (A814)	NO_2	40	-	38	41	45	43
Dumbarton Rd (A814)	PM_{10}	18	19	17	17	15	15

4.2. Demand Estimation

Demand estimation entails analysis of the transport trends for towns surrounding the terminal locations selected in the route selection. The stops selected can be split into three council areas: West Dunbartonshire, Renfrewshire and Glasgow. To determine the demand for passengers travelling from the terminal locations to Glasgow, data is initially gathered on the fraction of trips from each council area travelling to Glasgow.

Table 10: Rail passengers from council areas to Glasgow. Adapted from (Transport Scotland, 2018)

Council Area	Annual Rail Journeys to and from Area	Annual Rail Journeys to and from Glasgow from Area	Fraction of Rail Journeys to and from Glasgow from Area
West Dunbartonshire	2560000	1614000	0.630
Renfrewshire	3663000	2358000	0.643
Glasgow	35972000	14482000	0.403

Using the following assumptions, hourly rail demand for each council area travelling to Glasgow can be determined for weekday peak times; weekday off-peak times and the weekend.

Assumptions:

- 55% of all rail journeys are commutes (Department for Transport, 2018)
- Commuting only occurs at peak time, 7-9am and 5-7pm from Monday to Friday
- Peak demand is spread evenly across the 2-hour windows in the morning and evening
- 45%, i.e. all other trips, are spread evenly Monday to Sunday and split equally among the off-peak hours of each day
- Off-peak hours are 9am-5pm and 7-10pm Monday to Friday
- Weekend off-peak hours are 7am-10pm
- All passengers make return journeys

Table 11: Determination of Daily Passengers to Glasgow by Council Area

Council	Return Journeys to Glasgow	Daily Returns to Glasgow	Daily Commutes (Mon-Sun spread)	Daily Commutes (Mon-Fri spread)	Daily Off-Peak (Mon-Sun spread)
West Dunbartonshire	807000	2211	1216	1702	995
Renfrewshire	1179000	3230	1777	2487	1454
Glasgow	7241000	19838	10911	15276	8927

From this, a picture can be built up of rail travellers in each council area. However, to generate the demand profile, we must also consider those who travel by car and by bus. The following table displays the transport mode share fractions for commuters to Glasgow. Using the rail calculations as a basis, the number of bus and car users per hour can be determined by scaling up by modal share fraction.

Table 12: Glasgow Commuters Transport Mode Share. Adapted from (Understanding Glasgow, 2011), data originally from 2011 Census

Main Commute Mode to Glasgow	Modal Share Fraction
Car (driver)	0.326
Car (passenger)	0.083
Bus	0.203
Train	0.077
Walk	0.251
Cycle	0.016
Underground	0.026
Other	0.018

Assumptions:

- From the table above, there are 2.64 times as many bus passengers, 4.23 times as many car drivers and 5.31 times as many car drivers and car passengers as rail passengers. Average occupancy of a car is 1.255 people.
- Subway trips can be included in rail journeys since both modes are electrified in Glasgow

Table 13: Daily Commuters by Rail, Bus and Car by Council Area

Council	Daily Rail Commuters	Daily Bus Commuters	Daily Car Commuters
West Dunbartonshire	1702	3206	6459
Renfrewshire	2487	4684	9437
Glasgow	15276	28766	57956

The table above shows the number of daily passengers at peak times. However, the same process is followed to determine the daily off-peak passengers for weekdays and for the weekend.

Now, to determine the demand from each town by rail, bus and car, the travel trends for the trips from council areas into Glasgow can be scaled down by population to towns within the council area. For the following tables, green rows represent towns with terminals and blue rows represent towns in the wider catchment area.

Table 14: Council area population fractions for towns

Populations taken from (National Records of Scotland, 2011)

Town	Council Area	Town Population	Council Area Population	Council Fraction
Bowling/Milton	West Dunbartonshire	959	90720	0.011
Erskine	Renfrewshire	15537	174908	0.089
Clydebank	West Dunbartonshire	28799	90720	0.317
Renfrew	Renfrewshire	21854	174908	0.125
Partick	Glasgow	8884	590507	0.015
Dumbarton	West Dunbartonshire	19969	90720	0.220
Old Kilpatrick	West Dunbartonshire	2970	90720	0.033
Inchinnan	Renfrewshire	1797	174908	0.010
Bishopton	Renfrewshire	4708	174908	0.027
Duntocher/Hardgate /Faifley	West Dunbartonshire	12244	90720	0.135
Yoker/Scotstoun	Glasgow	11960	590507	0.020
Govan	Glasgow	5860	590507	0.010

The table below shows the total number of daily commuters from each town. The hourly number is half of the total since it is assumed all commuters travel in the two hour period between 7-9am. The same process is followed to determine off-peak passengers, except the daily total will be divided by a larger number of hours, 11 for weekday and 15 for weekend.

Table 15: Number of commuters at peak times for all towns

Town	Rail	Bus	Car	Total	Hourly
Bowling/Milton	18	47	96	161	81
Erskine	221	582	1174	1977	988
Clydebank	540	1425	2871	4836	2418
Renfrew	311	819	1651	2781	1390
Partick	230	606	1221	2056	1028
Dumbarton	375	988	1990	3353	5906
Old Kilpatrick	56	147	296	499	1677
Inchinnan	26	67	136	229	249
Bishopton	67	176	356	599	114
Duntocher/Hardgate/Faifley	230	606	1220	2056	300
Yoker/Scotstoun	309	816	1643	2768	1028
Govan	152	400	805	1356	1384

Sample calculations for the demand estimation for the town of Erskine for peak weekday, off-peak and weekend can be found in Appendix A.

Shift Definitions

The shifts represent a fraction of commuters who would change their current mode of transport for travel into Glasgow from their current, be it car, bus or rail to using a ferry on the River Clyde.

Table 16: Commuter Mode of Transport and Modal Share Across Scotland (Transport Scotland, 2018)

Commuter Main Mode of Transport Across Scotland	Modal Share Fraction
Car (driver)	0.623
Car (passenger)	0.054
Bus	0.098
Train	0.051
Walk	0.12
Cycle	0.03
Other	0.024

Based on the representation of commuting trips across Scotland in the table above, a ratio of walkers to cyclists of 4:1 is assumed. This is applied to denote the ratio of modal shift shares for towns, with the assumption that those who live in the towns with terminals (green) can walk and those in towns further out (blue) will cycle.

Shift5 represents A 5% modal shift for trips to Glasgow in towns with theoretical ferry terminals and a 1.25% shift for other towns within 6km.

Shift10 represents A 10% modal shift for Glasgow commuters in towns with theoretical ferry terminals and a 2.5% shift for other towns within 6km.

4.3. Business as Usual

To determine the business as usual case, the total annual passengers by each mode that could undergo a modal shift are determined for both Shift5 and Shift10.

To determine emissions and energy results, analysis of the trains, buses and cars likely to be used for the business as usual journeys must be undertaken.

Rail

The train calculations were based upon the EMU 318/320 trains built in 1985-1986/ 1990 which currently serve the North of Clyde Line, including stations in Partick, Clydebank and Bowling. Average electricity usage for Scotrail EMUs in 2018 was 1.9kWh per km. (Scotrail, 2018)However, electricity use for 318 and 320 class trains is 8kWh/km. (SYSTRA, 2015)

These have 3 carriages and 232 seats (scaled from 4-carriage EMU321 (UK Transport, 2017)), and based on an average Scotrail occupancy of 30% (ORR, 2012), there are 70 passengers on an average trip. They are electrified and rely on the grid for energy supply.

Table 17: Energy Use and CO_2 Emissions from EMU318/320 Train

Train	Unit Energy Use (kWh/km)	Passenger Energy Use (kWh/pass.km)	Grid CO_2 Emissions (g CO_2/kWh)
EMU 318/320	8	0.115	180

Unit Energy Use from (SYSTRA, 2015) and Grid CO_2 Emissions from (Dept for Business, Energy and Industrial Strategy, 2019)

Emissions of nitrogen oxides and particulate matter are considered as zero since their emission data for grid electricity is unobtainable and this is justified because their impact on air quality is not felt in the vicinity of the vehicle and local area.

Passenger energy use was determined using the following equation.

$$Passenger\ Energy\ Use\ = \frac{Unit\ Energy\ Use}{Number\ of\ Passengers}$$

Distances of train line from stations to Glasgow were measured by map.

For each town, the following are determined:

$$\begin{aligned} &Weekly\ rail\ passengers \\ &\qquad = 5(daily\ peak\ passengers + daily\ offpeak\ passengers) \\ &\qquad + 2(daily\ weekend\ day\ passengers) \end{aligned}$$

$$Annual\ rail\ passengers = 52 \times Weekly\ rail\ passengers$$

$$Annual\ passenger\ travel\ distance = Annual\ rail\ passengers \times Trip\ distance$$

$$\begin{aligned} &Annual\ Rail\ CO2\ Emissions \\ &\qquad = Annual\ Passenger\ Travel\ Distance \\ &\qquad \times Annual\ Passenger\ Energy\ Use \times Grid\ CO2\ Emissions \end{aligned}$$

Then for total, i.e. all towns:

$$Total\ Annual\ Rail\ CO2 = \sum Annual\ Rail\ CO2\ (towns)$$

Bus

The bus calculations were based upon the diesel-fuelled single-decker Alexander Dennis Enviro200 buses which are being employed by McGill's bus services south of the river, including the X23 serving Erskine and Renfrew. These meet Euro VI emissions standards for heavy duty diesel vehicles. (Alexander Dennis, 2018)

These have 93 seats (Alexander Dennis, 2019) and based on an occupancy of 70% (Scot Gov, 2004), there are 65 passengers on an average trip.

Table 18: Emissions from Enviro200 Bus

Bus	Engine Efficiency (mpg or L/km))	CO_2 Emissions (g CO_2/pass.km)	NO_x Emissions (g NO_x /pass.km)	PM Emissions (gPM/pass.km)
Enviro200	13.5 or 0.209	12.2	0.0071	0.0002

Efficiency from (FACTS, 2014) CO_2 from (LowCVP, 2017), NO_x and PM from Euro VI standard (ICCT, 2016)

Table 19: Diesel Energy Content (Engineering Toolbox, 2008)

Energy Content of Diesel (MJ/L)	Energy Content of Diesel (kWh/L)
38.243	10.623

$$Unit\ Energy\ Use\ (kWh) = Engine\ Efficiency(\frac{L}{km}) \times Fuel\ Density(\frac{kWh}{L})$$

$$Passenger\ Energy\ Use\ (\frac{kWh}{pass.km})\ =\ \frac{Unit\ Energy\ Use\ (kWh/km)}{Number\ of\ Passengers}$$

The assumption is made that the distance travelled by bus is the same as would be travelled by car since they both occupy roads.

$$\begin{aligned} Weekly\ bus\ passengers &= 5(daily\ peak\ passengers + daily\ offpeak\ passengers) \\ &+ 2(daily\ weekend\ day\ passengers) \end{aligned}$$

$$Annual\ bus\ passengers = 52 \times Weekly\ bus\ passengers$$

$$Annual\ passenger\ travel\ distance = Annual\ bus\ passengers \times Trip\ distance$$

$$\begin{aligned} Annual\ Bus\ CO2\ Emissions &= Annual\ Passenger\ Travel\ Distance \\ &\times CO2\ Emissions\ per\ Passenger\ per\ Kilometre \end{aligned}$$

$$\begin{aligned} Annual\ Bus\ NOx\ Emissions &= Annual\ Passenger\ Travel\ Distance \\ &\times NOx\ Emissions\ per\ Passenger\ per\ Kilometre \end{aligned}$$

$$\begin{aligned} Annual\ Bus\ PM\ Emissions &= Annual\ Passenger\ Travel\ Distance \\ &\times PM\ Emissions\ per\ Passenger\ per\ Kilometre \end{aligned}$$

Then for total, i.e. all towns:

$$Total\ Annual\ Bus\ CO2 = \sum Annual\ Bus\ CO2\ (towns)$$

$$Total\ Annual\ Bus\ NOx = \sum Annual\ Bus\ NOx\ (towns)$$

$$Total\ Annual\ Bus\ PM = \sum Annual\ Bus\ PM\ (towns)$$

Car

The average age of a car in Scotland is 6.6 years and the share of light-good vehicles is 51% petrol, 48% diesel and 1% electric.

Since the average age is 6.6 years, the assumption is made that 50% of these vehicles will be of Euro 5 emissions standard (enforced for all new registrations January 2011) and 50% as Euro 6 emissions standard (enforced for all new registrations September 2015). (RAC, 2018)

Table 20: Real Data Average CO_2 and NO_x Emissions for Cars by Engine Type and Road Type (O'Driscoll, et al., 2018)

Engine Type	Urban CO_2 Emissions (g/km)	Motorway CO_2 Emissions (g/km)	Urban NO_x Emissions (g/km)	Motorway NO_x Emissions (g/km)
Petrol (Euro 5)	210	160.2	0.09	0.03
Petrol (Euro 6)	210	160.2	0.04	0.04
Diesel (Euro 5)	170.2	152.3	0.72	0.74
Diesel (Euro 6)	170.2	152.3	0.44	0.33

The assumption is also made that trips will be 50% urban and 50% motorway.

Table 21: Real Data Average PM Emissions for Petrol and Diesel Cars with Euro 5 Engines (Helmers, et al., 2019)

Engine Type	PM Emissions (g/km)
Petrol (Euro 5)	0.0030
Diesel (Euro 5)	0.0051

This is assumed to be equally applicable for Euro 6 engines since the emissions standard for particulate matter of 0.005g/km remained constant from the Euro 5 to the Euro 6 law.

The electric vehicles will be based on the top-selling full-electric car in the UK, which is the Nissan Leaf. Carbon dioxide emissions will be taken as those of grid electricity.

Table 22: Scottish Fleet Share Fraction and Averaged Emissions by Car Type

Car Type	Fraction of Scotland's Cars	CO_2 Emissions (g/km)	NO_x Emissions (g/km)	PM Emissions (g/km)
Petrol	0.51	185.100	0.050	0.003
Diesel	0.48	161.250	0.558	0.005
Electric	0.01	30.205	0	0

Table 23: Energy Content (Engineering Toolbox, 2008) and Engine Efficiency (RAC Foundation, 2018) for Petrol and Diesel

Engine Type	Fuel Energy Content (MJ/L)	Fuel Energy Content (kWh/L)	Engine Fuel Efficiency (mpg)	Engine Fuel Efficiency (L/km)
Petrol	34.613	9.615	51.7	0.055
Diesel	38.243	10.623	61.2	0.046

Table 24: Energy Efficiency of Electric Car (Nissan, 2019)

Car Type	Energy Efficiency (Wh/mile)	Energy Efficiency (kWh/km)
Electric	0.27	0.168

Average passenger occupancy for cars commuting to Glasgow is found from the following equation:

$$Car\ Occupancy\ or\ Number\ of\ Passengers$$
$$= \frac{Modal\ Share\ of\ Car\ Drivers + Modal\ Share\ of\ Car\ Passengers}{Modal\ Share\ of\ Car\ Drivers}$$
$$= \frac{0.326 + 0.083}{0.326} = 1.255$$

$$Unit\ Energy\ Use\ (kWh) = Engine\ Efficiency(\frac{L}{km}) \times Fuel\ Density(\frac{kWh}{L})$$

$$Passenger\ Energy\ Use\ (\frac{kWh}{pass.km})\ = \frac{Unit\ Energy\ Use\ (kWh/km)}{Number\ of\ Passengers}$$

$$\begin{aligned} Weekly\ car\ drivers &= 5(daily\ peak\ drivers + daily\ offpeak\ drivers) \\ &+ 2(daily\ weekend\ day\ drivers) \end{aligned}$$

$$Annual\ car\ drivers = 52 \times Weekly\ car\ drivers$$

$$Annual\ passenger\ travel\ distance = Annual\ car\ drivers \times Trip\ distance$$

$$\begin{aligned} Annual\ Car\ CO2\ Emissions &= Annual\ Passenger\ Travel\ Distance \times (Petrol\ Fraction \\ &\times Petrol\ Car\ CO2\ Emissions\ per\ Passenger\ per\ Kilometre \\ &+ Diesel\ Fraction \\ &\times Diesel\ Car\ CO2\ Emissions\ per\ Passenger\ per\ Kilometre \\ &+ Electric\ Fraction \\ &\times Electic\ Car\ CO2\ Emissions\ per\ Passenger\ per\ Kilometre) \end{aligned}$$

$$\begin{aligned} Annual\ Car\ NOx\ Emissions &= Annual\ Passenger\ Travel\ Distance \times (Petrol\ Fraction \\ &\times Petrol\ Car\ NOx\ Emissions\ per\ Passenger\ per\ Kilometre \\ &+ Diesel\ Fraction \\ &\times Diesel\ Car\ NOx\ Emissions\ per\ Passenger\ per\ Kilometre \\ &+ Electric\ Fraction \\ &\times Electic\ Car\ NOx\ Emissions\ per\ Passenger\ per\ Kilometre) \end{aligned}$$

$$\begin{aligned} Annual\ Car\ PM\ Emissions &= Annual\ Passenger\ Travel\ Distance \times (Petrol\ Fraction \\ &\times Petrol\ Car\ PM\ Emissions\ per\ Passenger\ per\ Kilometre \\ &+ Diesel\ Fraction \\ &\times Diesel\ Car\ PM\ Emissions\ per\ Passenger\ per\ Kilometre \\ &+ Electric\ Fraction \\ &\times Electic\ Car\ PM\ Emissions\ per\ Passenger\ per\ Kilometre) \end{aligned}$$

Then for total, i.e. all towns:

$$Total\ Annual\ Car\ CO2 = \sum Annual\ Car\ CO2\ (towns)$$

$$Total\ Annual\ Car\ NOx = \sum Annual\ Car\ NOx\ (towns)$$

$$Total\ Annual\ Car\ PM = \sum Annual\ Car\ PM\ (towns)$$

Finally, the total annual emissions from all modes from business as usual is determined:

$$\begin{aligned} &Total\ Annual\ BAU\ CO2\ Emissions \\ &\qquad = Total\ Annual\ Rail\ CO2 + Total\ Annual\ Bus\ CO2 \\ &\qquad + Total\ Annual\ Car\ CO2 \end{aligned}$$

$$\begin{aligned} &Total\ Annual\ BAU\ NOx\ Emissions \\ &\qquad = Total\ Annual\ Rail\ NOx + Total\ Annual\ Bus\ NOx \\ &\qquad + Total\ Annual\ Car\ NOx \end{aligned}$$

$$\begin{aligned} &Total\ Annual\ BAU\ PM\ Emissions \\ &\qquad = Total\ Annual\ Rail\ PM + Total\ Annual\ Bus\ PM \\ &\qquad + Total\ Annual\ Car\ PM \end{aligned}$$

These calculations are undertaken for both Shift5 and Shift10.

4.4. Diesel Ferries

Vessel Selection

To choose a suitable vessel, research was undertaken into existing linear ferry systems, with particular focus on Brisbane and London. This was because the vessels in these cities are capable of high-speed operation of 25-30knots (approximately 46-56km/h). (Tanko & Burke, 2017) This level of speed would be required to be time-competitive with existing modes of transport.

The vessel chosen was the 2015 built Neptune Clipper vessel in London. This was selected because it was a fairly recent design and it was possible to obtain a vessel specification sheet. (incat, 2015)

Figure 19: Neptune Clipper Vessel (Thames Clippers, 2015)

Table 25: Neptune Clipper Vessel Information (incat, 2015)

Name	Neptune Clipper
Type	Catamaran
Length	35m
Passengers	150
Bike spaces	10
Top speed (no passengers)	30knots
Top speed (with passengers)	25knots
Hull Material	Marine Grade Aluminium
Diesel fuel tank capacity	3000L
Twin engines	625kW (total 1250kW) Scania DI-16 072M
Gearboxes (x2)	ZF2000
Waterjets (x2)	Rolls Royce Kuwara 40A3
Generators (x2)	Kohler 33EFOZDJ

Vessel Routing

The first task is to review the chosen route map and find the distances between stops.

Table 26: Distance between stops matrix (Own design)

Distance (km)	Bowling	Erskine	Clydeb’k	Renfrew	Partick	Glasgow
Bowling	0	3	7	9	14	17
Erskine	3	0	4	6	11	14
Clydeb’k	7	4	0	2	7	10
Renfrew	9	6	2	0	5	8
Partick	14	11	7	5	0	3
Glasgow	17	14	10	8	3	0

The time to travel between stops is then evaluated using a range of vessel speeds from 25-30knots.

Then to determine the time spent at each stop, analysis is carried out of the route which the vessel serves on the Thames Clipper service in London, which is the purple line.

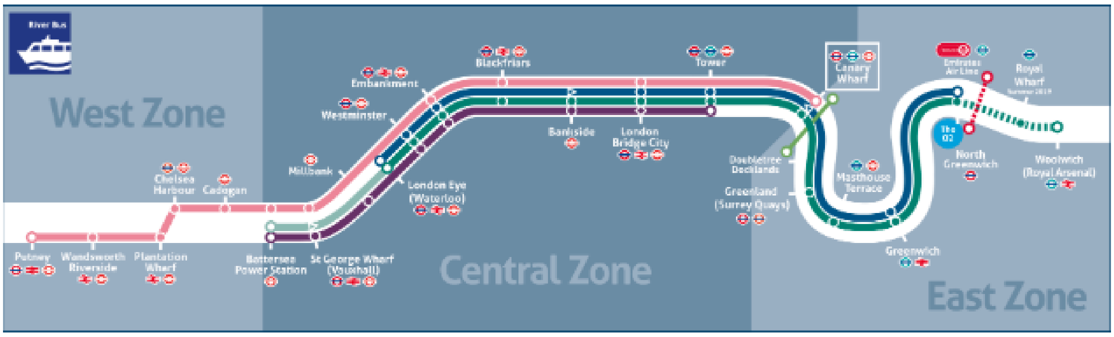
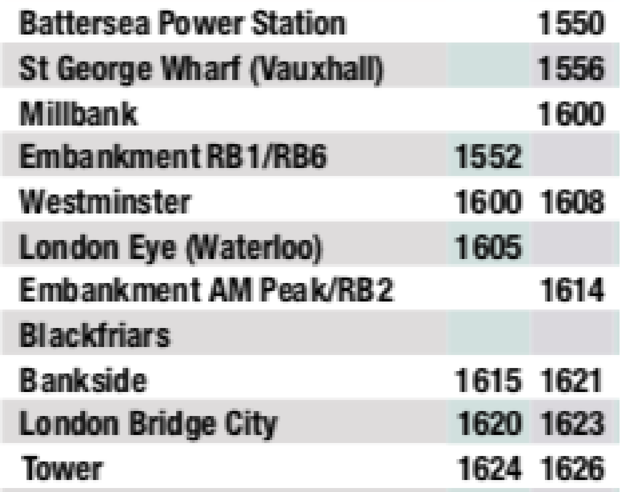


Figure 20: Thames Clipper Route Map (Thames Clippers, 2019)



Battersea Power Station		1550
St George Wharf (Vauxhall)		1556
Millbank		1600
Embankment RB1/RB6	1552	
Westminster	1600	1608
London Eye (Waterloo)	1605	
Embankment AM Peak/RB2		1614
Blackfriars		
Bankside	1615	1621
London Bridge City	1620	1623
Tower	1624	1626

Figure 21: Thames Clipper Purple Line Scheduling (Thames Clippers, 2019)

Figure 22: Purple Line Route Distance (Free Map Tools, 2019)

From the schedule, it can be seen that the full line takes 36 minutes. From the map drawing, it can be seen that the route distance is 6.71km. There are 8 stops in total but only 6 intermediate stops that impact the journey time

For a vessel travelling at speed 25 knots (46.3km/h) with no stops, time taken to complete route:

$$Route\ Time\ (no\ stops) = \frac{Route\ Distance}{Vessel\ Speed} = \frac{6.71km}{46.3km/h} = 0.145h = 8.7min$$

$$Scheduled\ Route\ Time = 36\ min$$

$$Time\ at\ Stops = Scheduled\ Route\ Time - Route\ Time(no\ stops) = 36 - 8.7$$
$$= 27.3min$$

$$Time\ per\ Stop = \frac{Time\ at\ Stops}{No.Stops} = \frac{27.3min}{6\ stops} = 4.55min$$

Therefore, the assumption is made that for the vessel on the River Clyde, each stop will be 5 minutes. Included in this stop time will be the time for decelerating, mooring, boarding and setting off again. This accounts for 20 min of each route, 5 min at each of the 4 intermediate stops.

Now, it is possible to find the time to complete the route for the range of vessel speeds 25-30knots.

Table 27: Time to Complete Route with and without stops for various vessel speeds

Vessel Speed (knots)	Time to Complete Route Without Stops (min)	Time to Complete Route With Stops (min)
25	22	42
26	21.2	41.2
27	20.4	40.4
28	19.7	39.7
29	19	39
30	18.4	38.4

The final step of the vessel routing is the scheduling of ferries. This is, in effect, creating a timetable. It enables the number of trips per day to be evaluated but also the number of vessels required in the fleet to serve the route. The demand estimation stage determines how many ferry sailings are required per hour at peak and off-peak times.

The number of ferries required is dependent on the ferry turnaround. This will depend on the occupancy and hence the speed but for a given speed will be:

$$\begin{aligned}&\mathit{Ferry\ turnaround\ (diesel)} = \mathit{Time\ to\ complete\ route} + \\ &\mathit{Mooring\ Time\ at\ Glasgow\ stop} + \mathit{Time\ to\ complete\ route} + \\ &\mathit{Mooring\ Time\ at\ Bowling\ stop}\end{aligned}$$

During peak hours, it has been decided that the ferry will only operate a stopping service in one direction. This will be in the Bowling to Glasgow direction in the morning and in the Glasgow to Bowling direction in the evening. This is because there is anticipated to be very little demand in the opposite direction at peak times and this will reduce the ferry turnaround. This has the effect of returning the vessel sooner and hence fewer vessels are required in the fleet.

$$\begin{aligned} &Peak\ Ferry\ turnaround\ (diesel) \\ &\qquad = Time\ to\ complete\ route\ with\ stops \\ &\qquad + Mooring\ Time\ at\ Glasgow\ stop \\ &\qquad + Time\ to\ complete\ route\ without\ stops \\ &\qquad + Mooring\ Time\ at\ Bowling\ stop \end{aligned}$$

The vessel schedules for weekdays can be found in the results and for weekends in Appendix B.

Energy and Emissions

Table 28: Real emission data based on a similar engine, Scania DI-16 43M (Pecorari, et al., 2013)

Vessel	CO_2 Emissions (g CO_2/kWh)	NO_x Emissions (g NO_x /kWh)	PM Emissions (gPM/kWh)
Neptune Clipper	616.14	1.38	0.11

Table 29: Diesel Fuel Density (ExxonMobil, 2019), and engine efficiency (Scania Marine Engines, 2018)

Fuel Density (g/L)	890
Engine Efficiency @2300rpm (g/kWh)	219

To determine effective energy use of a vessel, the power and efficiency of the engines and size of fuel tank must be considered.

$$Mass\ of\ fuel = Volume\ of\ fuel \times Density\ of\ fuel$$

$$Effective\ Energy\ of\ fuel\ per\ tank = \frac{Mass\ of\ fuel\ per\ tank}{Engine\ Efficiency}$$

$$Engine\ run\ time\ per\ tank = \frac{Engine\ power}{Effective\ Energy\ of\ fuel\ per\ tank}$$

$$Effective\ Energy\ consumed\ (single\ trip) = \frac{Trip\ time}{Engine\ run\ time\ per\ tank} \times Effective\ Energy\ of\ fuel\ per\ tank$$

From vessel routing, the number of trips required were determined and hence total time of engine running per year can be determined.

For energy calculations, the assumption is made that the engine is only on for 20 minutes per trip, i.e. when the vessel is in motion. 20 minutes is chosen as an approximate average trip moving time between vessel speeds of 25-30knots.

The following calculations account for the annual requirements for the whole fleet to serve the vessel routing.

$$Total\ vessel\ capital\ cost = No.vessels\ required \times Vessel\ cost$$

$$No.fuel\ tanks\ per\ year = \frac{No.trips\ per\ year \times Trip\ time}{Engine\ run\ time\ per\ tank}$$

$$Annual\ fuel\ consumption = No.fuel\ tanks\ per\ year \times Volume\ of\ fuel\ per\ tank$$

$$Annual\ effective\ energy\ use = No.fuel\ tanks\ per\ year \times Energy\ of\ fuel\ per\ tank$$

$$Annual\ CO2\ emissions = Annual\ effective\ energy\ use \times CO2\ emissions\ per\ kWh$$

$$Annual\ NOx\ emissions = Annual\ effective\ energy\ use \times NOx\ emissions\ per\ kWh$$

$$Annual\ PM\ emissions = Annual\ effective\ energy\ use \times PM\ emissions\ per\ kWh$$

To determine energy use per passenger, alongside the effective energy provided to the engine, we must also consider the energy lost in the ICE. We must consider the fuel energy density and engine efficiency.

As in the BAU section, energy density of diesel is 10.623kWh/L.

$$Energy\ Density\ by\ Mass\ (kWh/g) = \frac{Energy\ Density\ by\ Volume\ (\frac{kWh}{L})}{Fuel\ Density\ (\frac{g}{L})}$$

$$= \frac{10.623}{890} = 0.01194\ kWh/g$$

$$Engine\ Efficiency = 219g/kWh$$

By inversion, this is equivalent to:

$$Engine\ Efficiency = 0.00457kWh/g$$

So engine efficiency as a fraction of energy density of the fuel:

$$Engine\ Efficiency = \frac{Engine\ Efficiency(kWh/g)}{Energy\ Density\ by\ Mass\ (kWh/g)} = \frac{0.00457}{0.01194} = 0.3826$$

So the engine efficiency is 38.26% and actual energy consumed by the engine is given by:

$$Annual\ Total\ Energy\ Consumed = \frac{Annual\ Effective\ Energy\ Use}{Engine\ Efficiency}$$

$$Unit\ Energy\ Use\ (kWh/km) = \frac{Annual\ Total\ Energy\ Consumed}{Number\ of\ trips\ per\ year \times Trip\ Distance}$$

$$Passenger\ Energy\ Use\ (\frac{kWh}{pass.km})\ = \frac{Unit\ Energy\ Use\ (kWh/km)}{Number\ of\ Passengers}$$

Cost

Table 30: Vessel cost (Thames Clippers, 2015) and fuel cost (AA, 2019) of diesel ferry

Vessel Cost (£)	3,250,000
Fuel Cost (£/L)	1.311

$$Total\ capital\ cost = No.vessels\ required \times Vessel\ cost$$

$$Total\ Operating\ Costs = Annual\ fuel\ cost + Annual\ maintenance\ cost$$

$$Annual\ fuel\ cost = Annual\ fuel\ consumption \times Fuel\ cost\ per\ litre$$

Annual maintenance cost is assumed to be 5% of fuel cost. (SPAR Associates, Inc., 2012)

$$Annual\ maintenance\ cost = 0.05 \times Annual\ fuel\ cost$$

To conduct an economic analysis of the diesel ferry system, a ticket price must be set to discover the annual revenue of the scheme.

This is assumed to be the same price as the existing peak time public transport modes in the towns planned to have terminals, with the nearby towns assumed to have the same price.

Table 31: Return ticket prices for the diesel ferry

Town	Return Ticket Price (£)
Milton/Bowling/Dumbarton/Old Kilpatrick	6.90
Erskine/Inchinnan/Bishopton	5.50
Clydebank/Duntocher/Hardgate/Faifley	5.60
Renfrew/Yoker/Scotstoun	5.50
Partick/Govan	2.90

The total annual passengers can be determined from the demand estimation section.

$$\begin{aligned} Weekly\ passengers(town) &= 5(daily\ peak\ passengers + daily\ offpeak\ passengers) \\ &+ 2(daily\ weekend\ day\ passengers) \end{aligned}$$

$$Annual\ passengers(town) = 52 \times Weekly\ passengers\ (town)$$

$$Annual\ Revenue(town) = Ticket\ price(town) \times Annual\ passengers(town)$$

$$Total\ Annual\ Revenue = \sum Annual\ Revenue\ (town)$$

The initial capital costs, annual operating cost and annual revenue can be calculated over a 25-year basis to determine the payback time for the investment.

4.5. Electric Ferries

Vessel Selection

The selected vessel was the BB Green 24. This was the only electric passenger vessel on the market capable of competing with the speeds of the high-speed diesel catamarans in London and Brisbane's urban linear ferry systems. It can host 150 passengers and 30 bikes. (Green City Ferries, 2019)

Figure 23: BB Green 24 Vessel (Green City Ferries, 2019)

Through correspondence with the Sales and Projects Manager of Green City Ferries, a company business case presentation was obtained and it was discovered that the standard battery size is 500kWh and the power requirements are 800kW (+ fan use) for a full ferry to travel at 25knots or for an empty ferry to travel at 30 knots. Alternatively 1100kW power, or an extra 300kW, would enable the full ferry to travel at 30 knots. The ship weight is 31 tonnes without passengers, including the 6-tonne battery pack. (Green City Ferries, 2019)

Table 32: BB Green 24 Vessel Info (Green City Ferries, 2019)

Name	BB Green 24
Type	Air Supported Vessel
Length	24m
Passengers	150
Bike spaces	30
Top speed (no passengers)	30knots
Top speed (with passengers)	25knots
Hull material	Carbon Fibre Composite
Battery size	500kWh

Some calculations were required to verify that the battery size was suitable.

The energy use of 800kW is assumed to be propulsion and hotel load. Air lift fan power can be 20% of effective propulsive power (Fang & Duan, 2014), which if an assumed propeller/waterjet efficiency of 60% at 25knots (Barczak, 2019) is taken would be 432kW, giving 86kW for the air lift fan. The hotel load is typically 10% of the propulsion and fan power, giving 80kW. (De Breuker, et al., 2009)

If the battery system is sized for the maximum weight, i.e. full passenger occupancy, at 25 knots, the energy requirements of the trip is found by:

$$Energy\ required = Moving\ time(propulsion\ power + fan\ power + hotel\ load) + Stationary\ time(hotel\ load) = 22min \times \frac{1h}{60min}(720kW + 86kW + 80kW) + 20min \times \frac{1h}{60min}(80kW) = 352kWh$$

For a 500kWh battery, depth of discharge:

$$DOD = \frac{Energy\ Use}{Battery\ Capacity} = \frac{352kWh}{500kWh} = 70\%$$

This depth of discharge is within the capabilities of an LTO battery and leaves spare buffer energy to account for external factors that could impact energy consumption such as high winds.

Table 33: Electric Vessel Power and Energy Requirements Summary

2x Propulsion Motors	720kW total
Hotel load	80kW
Air lift fan	86kW
Trip energy use	352kWh
Depth of discharge	70%

The BB Green 24 vessel is intended to be charged by a dockside 1500kW fast-charging station. (Green City Ferries, 2019) Using this, the charge rate is determined.

$$Charge\ Rate\ (C) = \frac{Power\ Supplied\ (kW)}{Energy\ Capacity\ (kWh)} = \frac{1500kW}{500kWh} = 3C\ or\ 3h^{-1}$$

This is equivalent to a 20 minute charge time.

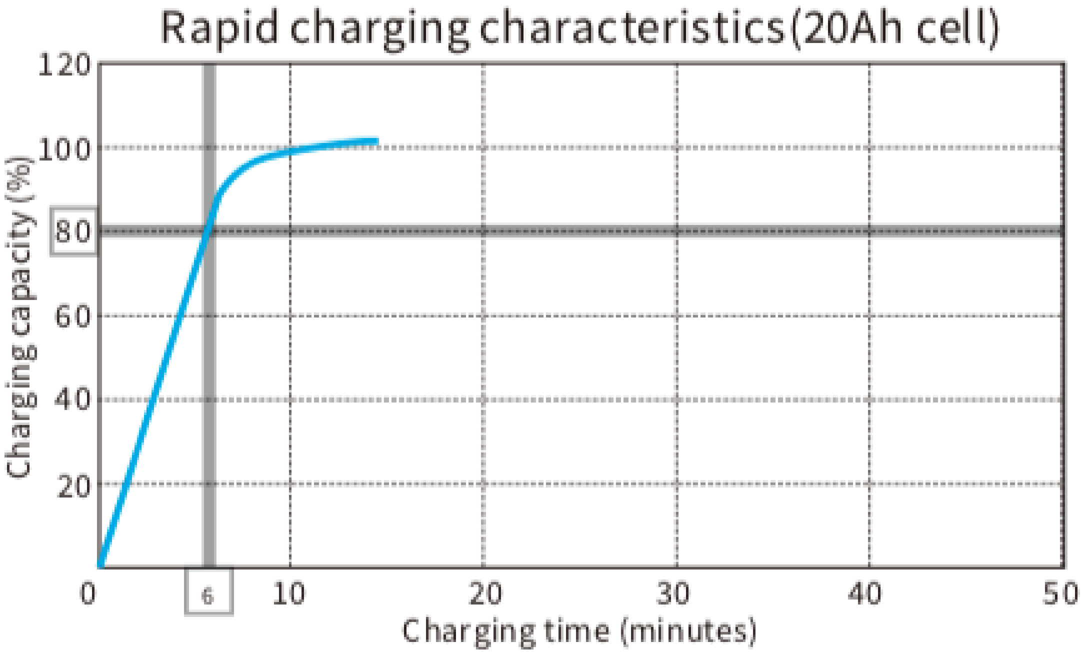


Figure 24: Rapid Charge Profile of Toshiba LTO Battery (Toshiba, 2019)

Based on the rapid charging profile above of a Toshiba LTO battery, with a charge time from 0-100% of 12 minutes, the first 80% of charging occurs in 6 minutes, which is half of the total charge time and the final 20% occurs in the last 6 minutes.

Using this ratio, this is scaled for a battery-charger system with a 20 minute charge time to give 10 minutes of charge for the first 80% and 10 minutes for the final 20%.
If the battery starts from 30% level of charge as is the case in the BB Green 24 application with DOD of 70%, then assuming this stage of charging is linear as above, then charging from 30 to 80% will take:

$$Charge\ time\ from\ 30\ to\ 80\% = \frac{50}{80} \times 10min = 6min$$

And given that

$$Charge\ time\ from\ 80\ to\ 100\% = 10min$$

Then

$$\begin{aligned} &Charge\ time\ from\ 30\ to\ 100\% \\ &\qquad = Charge\ time\ from\ 30\ to\ 80\% \\ &\qquad + Charge\ time\ from\ 80\ to\ 100\% = 6min + 10min = 16min \end{aligned}$$

So, after each trip 16 minutes is required to recharge the vessel to 100%.

The discharge rate can be broken into two phases of operation, when the vessel is in motion between stops and when it is stationary at the intermediate stops.

$$Discharge\ Rate\ (C) = \frac{Power\ Consumed\ (kW)}{Energy\ Capacity\ (kWh)}$$

$$Moving\ Discharge\ Rate\ (C) = \frac{886kW}{500kWh} = 1.8C$$

$$Stationary\ Discharge\ Rate\ (C) = \frac{80kW}{500kWh} = 0.2C$$

These are within the tested discharge rate range by the manufacturer of 0.2 to 5C. (Toshiba, 2019)

Vessel Routing

The vessel scheduling is similar to the process for the diesel ferries. Since the electric ferries can operate at the same speeds, they will follow the same schedule. However, the critical difference is that more ferries will be required because after each trip, the vessel will have to recharge, increasing the ferry turnaround.

This recharge will take 16 minutes for each trip. The assumption is made that the recharge can take place as soon as the ferry docks in the 5 minute mooring time and hence relative to the diesel ferry, the electric ferry turnaround will be an extra 11 minutes at the two end terminals, 22 minutes extra in total.

$$\begin{aligned} &\mathit{Ferry\ turnaround}\ (\mathit{electric}) \\ &\qquad = \mathit{Time\ to\ complete\ route} + \mathit{Charge\ Time\ at\ Glasgow\ stop} \\ &\qquad + \mathit{Time\ to\ complete\ route} + \mathit{Charge\ Time\ at\ Bowling\ stop} \end{aligned}$$

$$\begin{aligned} &\mathit{Peak\ Ferry\ turnaround}\ (\mathit{electric}) \\ &\qquad = \mathit{Time\ to\ complete\ route\ with\ stops} \\ &\qquad + \mathit{Charge\ Time\ at\ Glasgow\ stop} \\ &\qquad + \mathit{Time\ to\ complete\ route\ without\ stops} \\ &\qquad + \mathit{Charge\ \ Time\ at\ Bowling\ stop} \end{aligned}$$

Energy and Emissions

For the electric ferries, the annual energy requirements are dependent on the energy requirement per trip and the number of trips and hence charges per year. The number of trips per year is determined for Shift5 and Shift10 in the vessel routing section.

$$\mathit{Trips\ per\ week} = 5 \times \mathit{Trips\ per\ weekday} + 2 \times \mathit{Trips\ per\ weekend}$$

$$\mathit{Annual\ trips} = 52 \times \mathit{Trips\ per\ week}$$

$$\mathit{Annual\ energy\ use} = \mathit{Trip\ energy\ use} \times \mathit{Annual\ trips}$$

Annual carbon dioxide emissions are based on the electricity provided by the grid:

$$\mathit{Annual\ CO2\ emissions} = \mathit{Annual\ energy\ use} \times \mathit{Grid\ CO2\ emissions\ per\ kWh}$$

To determine energy use per passenger,

$$\mathit{Unit\ Energy\ Use}\ (kWh/km) = \frac{\mathit{Annual\ Energy\ Use}}{\mathit{Number\ of\ trips\ per\ year} \times \mathit{Trip\ Distance}}$$

$$\mathit{Passenger\ Energy\ Use}\ (\frac{kWh}{pass.km}) = \frac{\mathit{Unit\ Energy\ Use}\ (kWh/km)}{\mathit{Number\ of\ Passengers}}$$

Cost

Table 34: Costs for electric ferries

Vessel Cost (€/£)	4,200,000/3,822,000
Charging Station Cost (€/£)	800,000/728,000
UK Electricity Cost (£/kWh)	0.1437

Vessel and charging station costs (Green City Ferries, 2019) had to be converted from euros to pounds. This was done using the exchange rate at time of calculation, which was 0.91£/€. (XE, 2019) The number of vessels and charging stations required is governed by the vessel routing section for Shift5 and Shift10.

$$\begin{aligned} &Total\ Capital\ Cost \\ &\quad = Total\ vessel\ capital\ cost \\ &\quad + Total\ charging\ station\ capital\ cost \end{aligned}$$

$$Total\ vessel\ capital\ cost = No.\ vessels\ required \times Vessel\ cost$$

$$\begin{aligned} &Total\ charging\ station\ capital\ cost \\ &\quad = No.\ charging\ stations\ required \times charging\ station\ cost \end{aligned}$$

$$\begin{aligned} &Total\ Operating\ Costs \\ &\quad = Annual\ electricity\ cost \\ &\quad + Annualised\ battery\ replacement\ cost \end{aligned}$$

Annual electricity cost is based on the average UK unit cost of 14.37p/kWh. (Eco Experts, 2019)

$$Annual\ electricity\ cost = Annual\ energy\ use \times Grid\ electricity\ cost$$

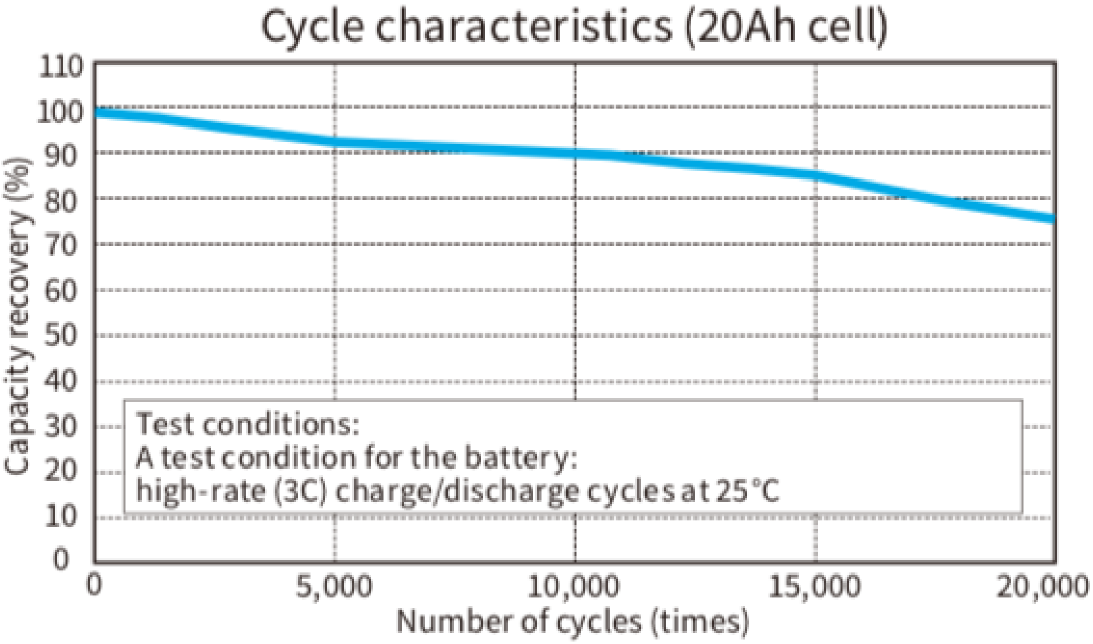


Figure 25: Cycle Lifetime of Toshiba LTO Battery with 100% DOD (Toshiba, 2019)

To determine the 500kWh battery replacement cost, the exchange rate of 0.82 £/$ was used. (XE, 2019)

Table 35: LTO Battery Cost (Battery University, 2019) and Cycle Life (Toshiba, 2019)

Cost ($/kWh)	Cost per Battery ($)	Cost per Battery (£)	Lifetime Cycles
1005	502,500	412,050	20,000

$$Annual\ Charges\ per\ Vessel = \frac{Total\ Annual\ Trips\ per\ year}{Number\ of\ Vessels}$$

$$Battery\ Lifetime = \frac{Lifetime\ Cycles\ of\ LTO}{Annual\ Charges\ per\ Vessel}$$

$$Annualised\ battery\ replacement\ cost$$
$$= Number\ of\ vessels \times \frac{Cost\ per\ Battery}{Battery\ Lifetime}$$

To conduct an economic analysis of the electric ferry system, a ticket price must be set to discover the annual revenue of the scheme. This is set at 18% higher than the ticket price for diesel ferries following on from the “willingness to pay” study. (Bigerna, et al., 2019)

Table 36: Return Ticket Prices for Electric Ferry

Town	Return Ticket Price (£)
Milton/Bowling/Dumbarton/Old Kilpatrick	8.14
Erskine/Inchinnan/Bishopton	6.49
Clydebank/Duntocher/Hardgate/Faifley	6.61
Renfrew/Yoker/Scotstoun	6.49
Partick/Govan	3.42

The total annual passengers can be determined from the demand estimation section.

$$
\begin{aligned}
&Weekly\ passengers(town)\\
&\qquad = 5(daily\ peak\ passengers + daily\ offpeak\ passengers)\\
&\qquad + 2(daily\ weekend\ day\ passengers)
\end{aligned}
$$

$$Annual\ passengers(town) = 52 \times Weekly\ passengers\ (town)$$

$$Annual\ Revenue(town) = Ticket\ price(town) \times Annual\ passengers(town)$$

$$Total\ Annual\ Revenue = \sum Annual\ Revenue\ (town)$$

The initial capital costs, annual operating cost and annual revenue can be calculated over a 25-year basis to determine the payback time for the investment. The year by year analysis can be found in Appendix C.

Rooftop PV

An investigation is carried out to see whether it would be worthwhile from an energy perspective to install solar panels on the roof of the electric vessel.

The first step was to find the approximate available roof space of the vessel for panels.

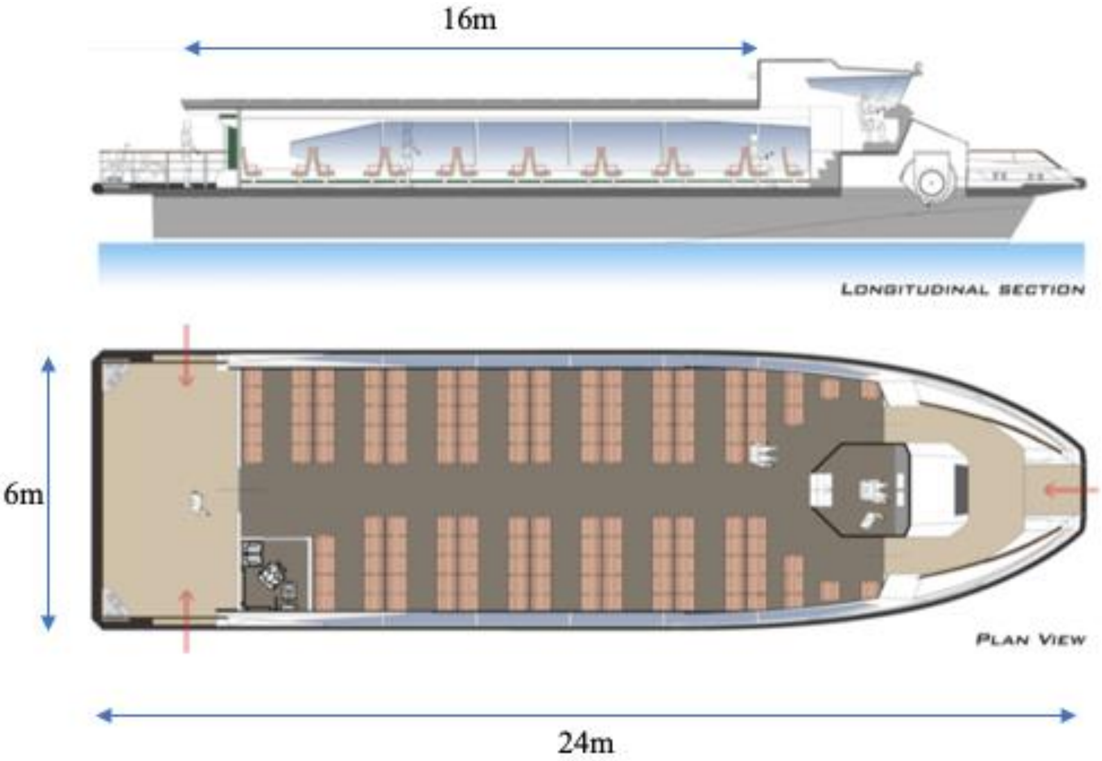


Figure 26: Plan View of BB Green 24 Vessel with own annotations (Green City Ferries, 2019)

Table 37: Available Roof Space Specifications

Available Roof Space Length (m)	16
Roof Space Width (m)	6
Available Roof Space Area (m2)	96

The solar panel selected for investigation was the Siemens 110W module (SM110). (Siemens, 2000) The tilt is set to 0 degrees since the boat will travel in different directions and so having no tilt is favourable for output.

Table 38: Individual SM110 Panel Specifications

Panel Length (m)	1
Width (m)	0.66
Area (m2)	0.66
Weight (kg)	11.5

$$Number\ of\ SM110\ that\ will\ fit\ length\ wise = \frac{Available\ Roof\ Space\ Length}{Panel\ Length}$$

$$= 16$$

$$Number\ of\ SM110\ that\ will\ fit\ width\ wise = \frac{Available\ Roof\ Space\ Width}{Panel\ Width}$$

$$= 9$$

$$Number\ of\ panels\ on\ roof$$
$$= Number\ of\ SM110\ that\ will\ fit\ length\ wise$$
$$\times Number\ of\ SM110\ that\ will\ fit\ width\ wise = 16 \times 9 = 144$$

Table 39: Solar Panel Array Specifications

Panel Array Length (m)	16
Panel Array Width (m)	5.94
Area (m2)	95
Weight (kg)	1656

Using MERIT software developed by the Energy Systems Research Unit (ESRU) at the University of Strathclyde, climate data for a location can be matched with renewable generation to discover the power, or indeed energy output likely to be generated by a renewable energy system. (ESRU, 2019)

The number of SM110 PV panels on the roof at 0 degree tilt was set against the Glasgow climate file to discover the power output throughout the year.

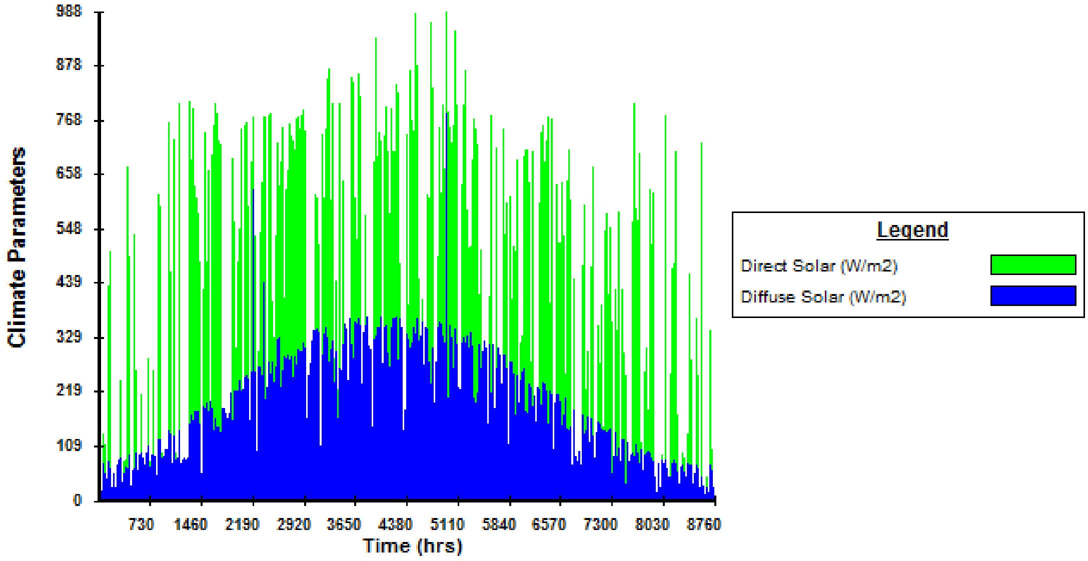


Figure 27: Annual direct and diffuse solar radiation data for Glasgow climate from Merit software

As mentioned previously, from correspondence with Green City Ferries, it was discovered that 300kW extra power output is required for to maintain the same speed of 30 knots for a full ferry. If the weight of a passenger is assumed to be 80kg, then the weight of 150 passengers is 12tonnes. So it is assumed that for 12 tonnes of added weight, power requirements increase by 300kW to maintain speed.

So the extra power required for the weight of the solar panels would be:

$$Extra\ power\ required\ for\ solar\ array = \frac{300kW}{12tonnes} \times total\ weight\ of\ solar\ panels$$

5. Results

5.1. Route Selection

As referred to in the methods section, the selected stops are Bowling, Erskine, Clydebank, Renfrew, Partick, Glasgow City Centre.

5.2. Demand Estimation

The following demand estimations were determined for Shift5 and Shift10, based on the total daily demand travelling to Glasgow from each town being divided to an hourly basis relative to the operating hours per day of peak, off-peak and weekends.

Table 40: Hourly Peak Demand to Glasgow from Each Town with Shift5 and Shift10

Town	Hourly Peak Demand	Shift5: 5/1.25% Modal Shift	Shift10: 10/2.5% Modal Shift
Bowling/Milton	81	4	8
Erskine	988	49	99
Clydebank	2418	121	242
Renfrew	1390	70	139
Partick	1028	51	103
Dumbarton	1677	21	42
Old Kilpatrick	249	3	6
Inchinnan	114	1	3
Bishopton	300	4	7
Duntocher/Hardgate/Faifly	1028	13	26
Yoker/Scotstoun	1384	17	35
Govan	678	8	17
TOTAL	**11336**	**363**	**726**
Sailings per hour		**2.42 (3)**	**4.84 (5)**

From this estimation, it was determined that for Shift5, 3 sailings per hour, i.e. at a frequency of 20 minutes, was required for ferry scheduling to meet the peak-time demand.

For Shift10, 5 sailings per hour were required, i.e. at a frequency of 12 minutes.

Table 41: Hourly Off-Peak Demand to Glasgow from Each Town with Shift5 and Shift10

Town	Hourly Off-Peak Demand	Shift5: 5/1.25% Modal Shift	Shift10: 10/2.5% Modal Shift
Bowling/Milton	9	0	1
Erskine	105	5	11
Clydebank	257	13	26
Renfrew	148	7	15
Partick	109	5	11
Dumbarton	178	2	4
Old Kilpatrick	39	0	1
Inchinnan	12	0	0
Bishopton	32	0	1
Duntocher/Hardgate/Faifly	109	1	3
Yoker/Scotstoun	147	2	4
Govan	72	1	2
TOTAL	**1217**	**39**	**77**
Sailings per hour		**0.26 (1)**	**0.52 (1)**

From this estimation, it was determined that at off-peak times on weekdays, only one sailing is required per hour, i.e. frequency of service is 1 hour.

Table 42: Hourly Weekend Demand to Glasgow from Each Town with Shift5 and Shift10

Town	Hourly Weekend Demand	Shift5: 5/1.25% Modal Shift	Shift10: 10/2.5% Modal Shift
Bowling/Milton	6	0	1
Erskine	77	4	8
Clydebank	188	9	19
Renfrew	108	5	11
Partick	80	4	8
Dumbarton	131	2	3
Old Kilpatrick	19	0	0
Inchinnan	9	0	0
Bishopton	23	0	1
Duntocher/Hardgate/Faifly	80	1	2
Yoker/Scotstoun	108	1	3
Govan	53	1	1
TOTAL	**883**	**28**	**57**
Sailings per hour		**0.19 (1)**	**0.38 (1)**

As in the case for off-peak weekdays, it was determined that on weekend, only one sailing is required per hour, i.e. frequency of service is 1 hour.

5.3. Business as Usual

The following table shows the annual emissions data by car, bus and train users for the BAU scenario with Shift5.

Table 43: Shift5 BAU Annual Emissions Data by Mode and Total

Shift5	Car Users	Bus Users	Train Users	Total
Annual CO_2 Emissions (kg/year)	944,805	41,705	18,166	1,004,676
Annual NO_x Emissions (kg/year)	1,609	24	0	1,633
Annual PM Emissions (g/year)	21,838	525	0	22,363

The table below represents the same but for Shift10.

Table 44: Shift10 BAU Annual Emissions Data by Mode and Total

Shift10	Car Users	Bus Users	Train Users	Total
Annual CO_2 Emissions (kg/year)	1,889,609	83,411	36,332	2,009,352
Annual NO_x Emissions (kg/year)	3,218	48	0	3,266
Annual PM Emissions (g/year)	43,677	1,050	0	44,727

It can be observed that for both modal shift levels, the emissions from car users vastly outweigh those of bus and train users. Nitrogen oxides and particulate matter for bus users is however, of a smaller relative significance than carbon dioxide emissions compared to the car users.

5.4. Diesel Ferries

The following table represents the vessel scheduling for a weekday for diesel ferries in Shift5 where a 20 min frequency service is required at peak time. The first departure represents the vessel leaving the first stop, Bowling with arrival being the time it reaches the final stop, Glasgow. The next departure and return represent the time it takes to complete the return journey from Glasgow to Bowling. Ready for departure represents the time that the vessel will be ready to complete the original Bowling-Glasgow trip again.

Orange represents the vessels operating the non-stop return service at peak time in the Bowling-Glasgow direction. Yellow represents the vessels operating the non-stop return service at peak time in the Glasgow-Bowling direction. Green represents off-peak travel in the Bowling-Glasgow direction with stopping service in both directions.

Table 45: Weekday Vessel Scheduling for Diesel Ferry Shift5

Departure	Arrival	Departure	Return	Ready for Departure	Vessel No.
06:40	07:22	07:27	07:45	07:50	1
07:00	07:42	07:47	08:05	08:10	2
07:20	08:02	08:07	08:25	08:30	3
07:40	08:22	08:27	08:45	08:50	4
08:00	08:42	08:47	09:05	09:10	1
08:20	09:02	09:07	09:25	09:30	2
08:40	09:22	09:27	09:45	09:50	3
09:00	09:39	09:44	10:23	10:28	4
10:00	10:39	10:44	11:23	11:28	1
11:00	11:39	11:44	12:23	12:28	2
12:00	12:39	12:44	13:23	13:28	3
13:00	13:39	13:44	14:23	14:28	4
14:00	14:39	14:44	15:23	15:28	1
15:00	15:39	15:44	16:23	16:28	2
16:00	16:39	16:44	17:23	17:28	3
16:40	17:22	17:27	17:45	17:50	4
17:00	17:42	17:47	18:05	18:10	1
17:20	18:02	18:07	18:25	18:30	2
17:40	18:22	18:27	18:45	18:50	3
18:00	18:42	18:47	19:05	19:10	4
18:20	19:02	19:07	19:25	19:30	1
18:40	19:22	19:27	19:45	19:50	2
19:00	19:39	19:44	19:23	19:28	3
20:00	20:39	20:44	20:23	20:38	4
21:00	21:39	21:44	21:23	21:48	1
22:00	22:39	22:44	22:23	22:58	2

The table below represents the same as above but for Shift10 with frequency of service being 12 minutes.

Table 46: Weekday Vessel Scheduling for Diesel Ferry Shift10

Departure	Arrival	Departure	Return	Ready for Departure	Vessel No.
06:24	07:06	07:11	07:29	07:34	1
06:36	07:18	07:23	07:41	07:46	2
06:48	07:30	07:35	07:53	07:58	3
07:00	07:42	07:47	08:05	08:10	4
07:12	07:54	07:59	08:17	08:22	5
07:24	08:06	08:11	08:29	08:34	6
07:36	08:18	08:23	08:41	08:46	1
07:48	08:30	08:35	08:53	08:58	2
08:00	08:42	08:47	09:05	09:10	3
08:12	08:54	08:59	09:17	09:22	4
08:24	09:06	09:11	09:29	09:34	5
08:36	09:18	09:23	09:41	09:46	6
08:48	09:30	09:35	09:53	09:58	1
09:00	09:40	09:45	10:25	10:30	2
10:00	10:40	10:45	11:25	11:30	3
11:00	11:40	11:45	12:25	12:30	4
12:00	12:40	12:45	13:25	13:30	5
13:00	13:40	13:45	14:25	14:30	6
14:00	14:40	14:45	15:25	15:30	1
15:00	15:40	15:45	16:25	16:30	2
16:00	16:40	16:45	17:25	17:30	3
16:24	17:06	17:11	17:29	17:34	4
16:36	17:18	17:23	17:41	17:46	5
16:48	17:30	17:35	17:53	17:58	6
17:00	17:42	17:47	18:05	18:10	1
17:12	17:54	17:59	18:17	18:22	2
17:24	18:06	18:11	18:29	18:34	3
17:36	18:18	18:23	18:41	18:46	4
17:48	18:30	18:35	18:53	18:58	5
18:00	18:42	18:47	19:05	19:10	6
18:12	18:54	18:59	19:17	19:22	1
18:24	19:06	19:11	19:29	19:34	2
18:36	19:18	19:23	19:41	19:46	3
18:48	19:30	19:35	19:53	19:58	4
19:00	19:40	19:45	19:25	19:30	5
20:00	20:40	20:45	20:25	20:40	6
21:00	21:40	21:45	21:25	21:50	1
22:00	22:40	22:45	22:25	23:00	2

The weekend schedules can be found in Appendix B.

The vessel scheduling was required to determine the number of vessels required to run the service which can be found below.

Table 47: No. Diesel Vessels Required for Shift5 and Shift10

	Shift5	Shift10
Vessels required	4	6

The energy and emissions data for diesel ferries with Shift5 and Shift10 are found below.

Table 48: Annual Energy and Emissions from Diesel Ferries for Shift5 and Shift10

	Shift 5	Shift 10
Annual Total Energy Use (kWh)	18,350,195	25,146,563
Annual Effective Energy Use (kWh)	7,020,000	9,620,000
Annual CO_2 Emissions (kg/year)	4,325,303	5,927,267
Annual NO_x Emissions (kg/year)	9,688	13,276
Annual PM Emissions (g/year)	772,200	1,058,200

Despite ridership doubling from Shift5 to Shift10, energy use and hence emissions only increase 37%. This is a quirk of the scheduling, which enables a higher occupancy per vessel trip.

Table 49: Cost Results for Diesel Ferries for Shift5 and Shift10

	Shift 5	Shift 10
Capital Cost (£)	**13,000,000**	**19,500,000**
Annual Fuel Cost (£/year)	2,264,613	3,103,358
Annual Maintenance Cost (£/year)	113,231	155,168
Annual Operating Cost (£/year)	2,377,843	3,258,526
Annual Revenue (£/year)	1,739,971	3,479,943
Annual Revenue - Operating Costs (£/year)	**-637,872**	**221,417**
Payback Time (years)	**-**	**89**

For Shift5, the diesel ferry service operates at a loss every year and so payback of the capital costs will never be achieved. For Shift10, a small profit is made every year but 89 years is required for pay-off, way beyond what can realistically be expected for the lifetime of the vessels.

5.5. Electric Ferries

The following table represents the vessel scheduling for a weekday for electric ferries in Shift5 where a 20 min frequency service is required at peak time. The colours represent the same as for the diesel ferry scheduling, with the key difference being the length of time between arrival and departure increasing to 16 minutes for charging.

Table 50: Weekday Vessel Scheduling for Electric Ferry Shift5

Departure	Arrival	Departure	Return	Ready for Departure	Vessel No.
06:40	07:22	07:38	07:56	08:12	1
07:00	07:42	07:58	08:16	08:32	2
07:20	08:02	08:18	08:36	08:52	3
07:40	08:22	08:38	08:56	09:12	4
08:00	08:42	08:58	09:16	09:32	5
08:20	09:02	09:18	09:36	09:52	1
08:40	09:22	09:38	09:56	10:12	2
09:00	09:39	09:55	10:34	10:50	3
10:00	10:39	10:55	11:34	11:50	4
11:00	11:39	11:55	12:34	12:50	5
12:00	12:39	12:55	13:34	13:50	1
13:00	13:39	13:55	14:34	14:50	2
14:00	14:39	14:55	15:34	15:50	3
15:00	15:39	15:55	16:34	16:50	4
16:00	16:39	16:55	17:34	17:50	5
16:40	17:22	17:38	17:56	18:12	1
17:00	17:42	17:58	18:16	18:32	2
17:20	18:02	18:18	18:36	18:52	3
17:40	18:22	18:38	18:56	19:12	4
18:00	18:42	18:58	19:16	19:32	5
18:20	19:02	19:18	19:36	19:52	1
18:40	19:22	19:38	19:56	20:12	2
19:00	19:39	19:55	20:34	20:50	3
20:00	20:39	20:55	21:34	21:50	4
21:00	21:39	21:55	22:34	22:50	5
22:00	22:39	22:55	23:34	23:50	1

The table below represents the same as above but for Shift10 with frequency of service being 12 minutes.

Table 51: Weekday Vessel Scheduling for Electric Ferry Shift10

Departure	Arrival	Departure	Return	Ready for Departure	Vessel No.
06:24	07:06	07:22	07:40	07:56	1
06:36	07:18	07:34	07:52	08:08	2
06:48	07:30	07:46	08:04	08:20	3
07:00	07:42	07:58	08:16	08:32	4
07:12	07:54	08:10	08:28	08:44	5
07:24	08:06	08:22	08:40	08:56	6
07:36	08:18	08:34	08:52	09:08	7
07:48	08:30	08:46	09:04	09:20	8
08:00	08:42	08:58	09:16	09:32	1
08:12	08:54	09:10	09:28	09:44	2
08:24	09:06	09:22	09:40	09:56	3
08:36	09:18	09:34	09:52	10:08	4
08:48	09:30	09:46	10:04	10:20	5
09:00	09:40	09:56	10:36	10:52	6
10:00	10:40	10:56	11:36	11:52	7
11:00	11:40	11:56	12:36	12:52	8
12:00	12:40	12:56	13:36	13:52	1
13:00	13:40	13:56	14:36	14:52	2
14:00	14:40	14:56	15:36	15:52	3
15:00	15:40	15:56	16:36	16:52	4
16:00	16:40	16:56	17:36	17:52	5
16:24	17:06	17:22	17:40	17:56	6
16:36	17:18	17:34	17:52	18:08	7
16:48	17:30	17:46	18:04	18:20	8
17:00	17:42	17:58	18:16	18:32	1
17:12	17:54	18:10	18:28	18:44	2
17:24	18:06	18:22	18:40	18:56	3
17:36	18:18	18:34	18:52	19:08	4
17:48	18:30	18:46	19:04	19:20	5
18:00	18:42	18:58	19:16	19:32	6
18:12	18:54	19:10	19:28	19:44	7
18:24	19:06	19:22	19:40	19:56	8
18:36	19:18	19:34	19:52	20:08	1
18:48	19:30	19:46	20:04	20:20	2
19:00	19:40	19:56	20:36	20:52	3
20:00	20:40	20:56	21:36	21:52	4
21:00	21:40	21:56	22:36	22:52	5
22:00	22:40	22:56	23:36	23:52	6

The weekend schedules can be found in Appendix B.

The vessel scheduling was required to determine the number of vessels and charging stations required to run the service which can be found below.

Table 52: No. Electric Vessels and Charging Stations Required for Shift5 and Shift10

	Shift5	Shift10
Vessels required	5	8
Charging stations required	2	4

The number of charging stations is increased to 4, with 2 at each end terminal since the service frequency at peak times is less than the charging time.

The energy and grid emissions data for electric ferries with Shift5 and Shift10 are found below.

Table 53: Annual Energy Use and Grid CO2 Emissions for Electric Ferries for Shift5 and Shift10

	Shift5	Shift10
Annual Energy Use (kWh/year)	5,932,653	8,129,931
Grid CO_2 Emissions (kg/year)	1,067,877	1,463,388

Much like in the diesel ferries scenario, the energy use and associated emissions for the electric vessels do not double in line with patronage due to vessels becoming more full, particularly at off-peak and weekend hours where the vessel frequency remains constant.

Table 54: Cost Results for Electric Ferries for Shift5 and Shift10

	Shift5	Shift10
Vessel Costs (£)	19,110,000	30,576,000
Charger Costs (£)	1,456,000	2,912,000
Capital Cost (£)	**20,566,000**	**33,488,000**
Annual Electricity Cost (£/year)	771,245	1,056,891
Annualised Battery Replacement Cost (£/year)	347,111	475,671
Annual Operating Cost (£/year)	1,118,356	1,532,562
Annual Revenue (£/year)	2,053,166	4,106,333
Annual Revenue – Operating Cost (£/year)	**934,811**	**2,573,771**
Payback Time (years)	**23**	**14**

From the economic analysis, for Shift5, the electric ferry service makes a profit of almost £1M/year and capital costs are paid off in 23 years. For Shift10, a profit of £2.5M/year is made and pays off capital costs in 14 years.

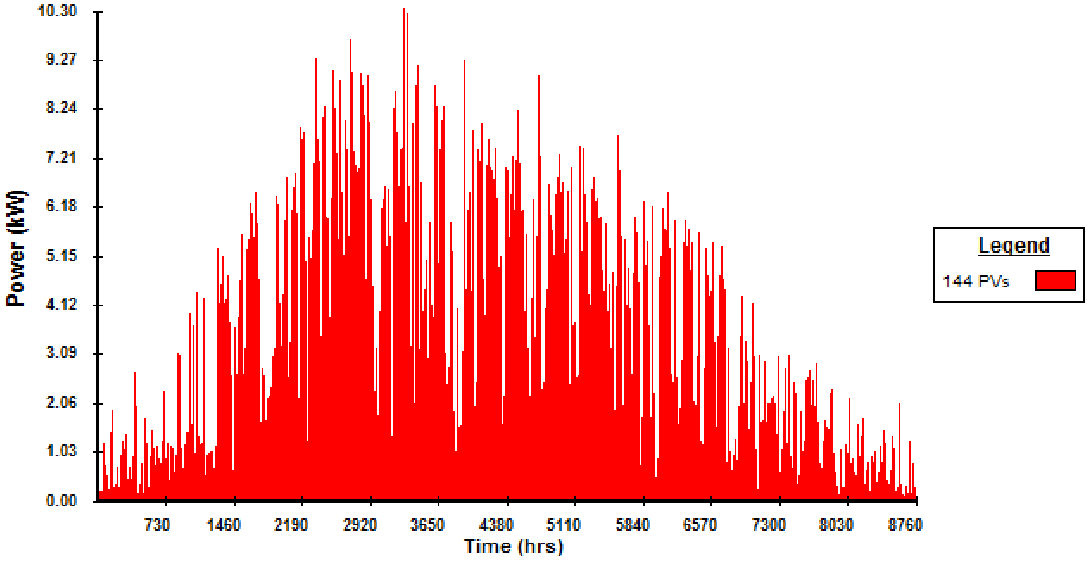


Figure 28: Hourly power output across a year for 144x SM110 PV panels in Glasgow from Merit software

Table 55: Power requirements to carry and power output from rooftop PV on Electric Ferry Vessel

Power required to move extra weight of solar panels (kW)	41.4
Maximum power output for Glasgow climate (kW)	10.3

The power from the propulsion system required to move the extra weight of the solar panels is greater than the maximum power output at any time throughout the year in the Glasgow climate. For this reason, it is deemed an unsuitable addition for a vessel that intends to minimise weight by using lightweight vessel materials in favour of high speed.

5.6. Results Comparison by Scenarios

Time

Table 56: Time comparison by ferry, car and public transport for towns with terminals

Town	Journey Time to Glasgow by Ferry at 25 knots (min)	Journey time to Glasgow by Car at Peak Time (min)	Journey Time to Glasgow by Public Transport at Peak Time (min)
Bowling	42	30-50	31
Erskine	33	24-40	32-52
Clydebank	23	22-52	21-25
Renfrew	15	18-30	28-31
Partick	4	13-24	6

At peak times, ferry systems are seen to be competitive with car and public transport journeys.

Energy

Assuming full occupancy of ferries, trains and buses, and that the average car occupancy was determined as 1.255 people.

Table 57: Energy Use per passenger kilometre for transport modes

Mode	Energy Use (kWh/pass.km)
Electric Ferry	0.138
Diesel Ferry	0.427
Train	0.034
Bus	0.024
Electric Car	0.134
Petrol Car	0.418
Diesel Car	0.389

Ferry use is seen to be significantly higher than other public transport modes of bus and train. The diesel ferry with its ICE is just 32% as efficient as the electric ferry and similar ratios are observed for electric and ICE powered cars.

Emissions

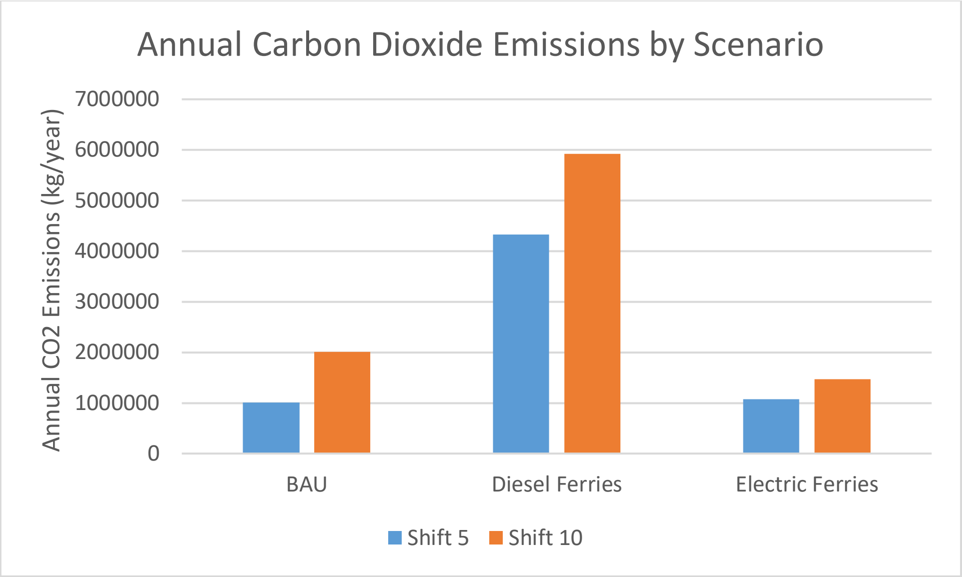


Figure 29: Annual Carbon Dioxide Emissions for the 3 Scenarios: BAU, Diesel Ferries and Electric Ferries

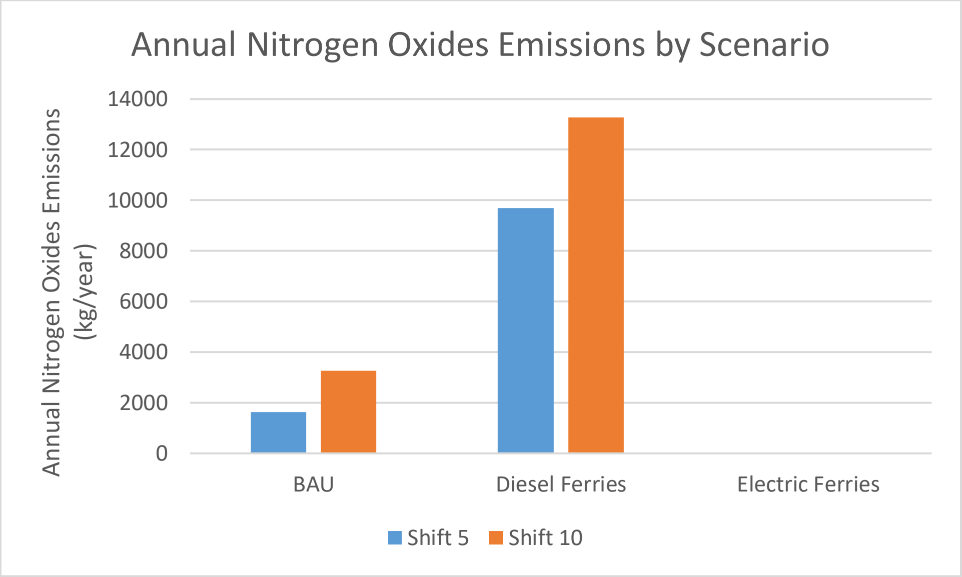


Figure 30: Annual Nitrogen Oxides Emissions for the 3 Scenarios: BAU, Diesel Ferries and Electric Ferries

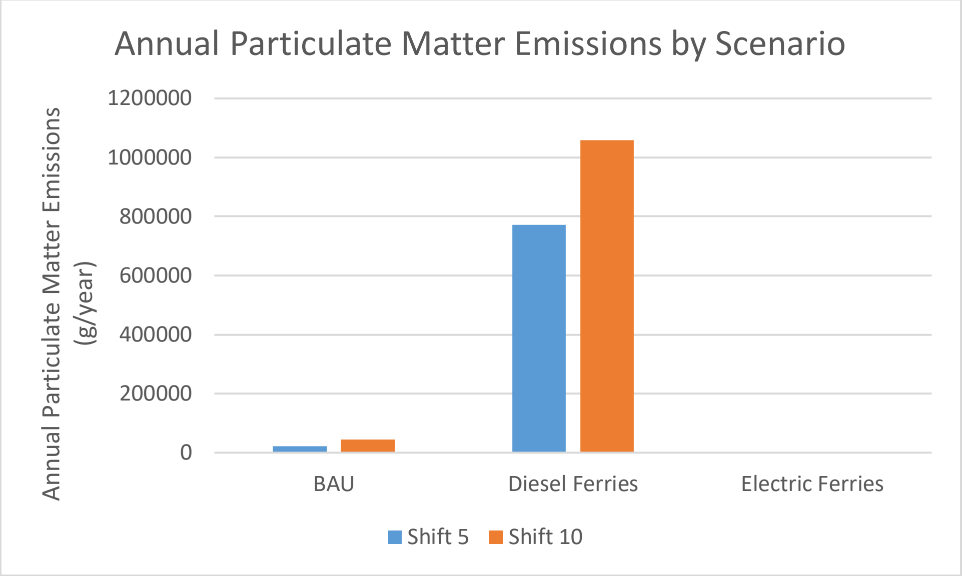


Figure 31: Annual Particulate Matter Emissions for the 3 Scenarios: BAU, Diesel Ferries and Electric Ferries

The diesel ferries scenario is found to be the highest emitter of CO_2, NO_x and PM. The electric ferries scenario is comparable to BAU for CO_2 emissions for Shift5 but becomes less emitting at Shift10. For the electric ferries scenario, NO_x and PM are assumed as zero for since it relies on grid electricity and these pollutants would not affect local air quality.

Cost

Table 58: Cost comparison for Diesel and Electric Ferries

	Diesel Ferries (Shift5)	Diesel Ferries (Shift10)	Electric Ferries (Shift5)	Electric Ferries (Shift10)
Capital Cost (£)	13,000,000	19,500,000	20,566,000	33,488,000
Annual Revenue Minus Operating Cost (£/year)	-637,872	221,417	934,811	2,573,771
Payback time (years)	-	89	23	14

The capital costs are greater for electric ferry services compared to diesel but they prove to be more profitable.

6. Discussion

6.1. General Results Discussion

The main limitation of the demand estimation is the assumption that there is equal demand spread throughout the operating hours of off-peak times and weekends. This means, for example, that on a Sunday there are as many people travelling from Bowling to Glasgow at 7am as there are at 12pm. This is unlikely to be the case and so sometimes one vessel per hour may well meet the demand and others it may not. Running a one vessel per hour frequency could also dissuade potential users of the service since if the vessel was fully occupied, they would have to wait an hour for the next one. It is much less convenient when compared to the higher frequency of other public transport modes and indeed, the freedom of car users. This was considered a justifiable result because the aim of the project was to address the congestion challenge and so most emphasis should be placed on peak-time travel.

The demand estimation for car users for the Partick portion of the route is likely to have been overestimated because it is only 3km in distance. This makes it walkable, cyclable and there are fast non-congested existing modes of transport in the form of rail and subway. Further, general mode shift percentages are likely overestimated because there will be a high relative distance to travel north and south to and from the river compared to the west-to-east direction which makes it a less logical choice than other land-based modes.

The higher emissions for car users relative to bus and train for the BAU case can be attributed to there being a higher portion of travellers using this mode compared to public transport as well as the higher energy use per passenger kilometre. The smaller relative emissions for PM and NO_x compared to CO_2 for bus use relative to car use can be attributed to the assumption that all buses have engines which meet the Euro IV heavy duty standard for these pollutants, whereas the cars are a 50-50 split of Euro 5 and Euro 6 standards for light goods vehicles.

6.2. Time

A ferry service travelling between 25-30knots was found to be time competitive with other modes of transport to Glasgow, particularly at peak times. This is expected to provide a greater incentive to the towns considered south of the river which do not have train services passing through since travelling by boat may be their only option for avoiding congestion at peak times. However, this time only considers travel from their local terminal to the Glasgow terminal and so the true commute time will depend on the mode taken to travel the distances to the river bank from both home and work.

Limitations of the travel time determination is that acceleration and deceleration rates of the vessel were not considered. It is assumed to travel at constant speed. It is expected that the electric ferry will have faster acceleration than the diesel ferry since this is the case with electric and ICE cars due to the ability of electric motors to develop instant torque. (Barnard, 2015) The assumption that the vessel stops for 5 minutes was based on a crude analysis of a London Clipper timetable route. This is unlikely to be too similar to the Glasgow experience because the distance between stops is shorter in London and so the vessel will spend much of its travel time below top speed.

6.3. Energy

The energy requirements for the ferry per passenger kilometre are considerably higher than other public transport modes when assuming full occupancy. This is expected since the ferry travels on water and not purely through air and uses a propeller in liquid for propulsion rather than wheels on a solid surface. The energy requirement for diesel ferries of 0.427kWh/passenger.km is approximately one quarter for diesel ferries as has been found in Queensland Australia, which is 5.89MJ/passenger.km (CTEE, 2015) or 1.636kWh/passenger.km. This may be because full ridership of 150 passengers is assumed for the Glasgow calculation and perhaps the Queensland figure is based on average occupancy. The ferry energy figures could be doubled at peak time to account for the no stopping service return route so in reality, each passenger is contributing to two vessel trips.

Even at full occupancy, the ferry energy requirements per passenger kilometre for diesel and electric propulsion are very similar to those for fossil fuelled and electric cars respectively which carry just 1.255 people on average. This creates debate over whether it is worthwhile as a public transport mode if it is not saving energy. However, it still has validity due to its congestion saving ability.

The effect of bike users and hence extra weight of bikes is not considered in energy consumption calculations, but the maximum weight would likely be 8kg (FireX, 2018) multiplied by 30 bikes, giving 240kg, equivalent to the weight of just 3 people. This is likely to be quite insignificant.

The effect of drawing large power from the local grid to fast charge the electric ferries has not been investigated but it is anticipated that in a built-up urban environment, the power draws are already quite significant so it would not be beyond what the grid can handle. Furthermore, since there are a fair number of vessels each with its own energy storage, there is potential for the batteries to discharge at night to act as a vehicle-to-grid (V2G) balancing mechanism for the likely increase in overnight home charging that will be brought about by increased EV uptake.

6.4. Emissions

The CO_2 emissions from the electric ferries scenario for Shift5 is similar to what is produced in the BAU scenario however since this is dependent on the grid emissions, they are not localised. Further, with the commissioning of large-scale renewable projects such as off-shore wind, the grid will become less dependent on fossil fuels for electricity production and hence the equivalent CO_2 emissions from any grid-dependent vehicle will decrease.

The diesel ferries emissions seem astronomical in comparison to the other scenarios. These were based on real-life emissions from a similar model of engine to the one found on the Neptune Clipper but of a smaller size. Although the results were from 2013, its NO_x emissions of 1.38g/kWh comply with the Tier III regulations introduced for newly built ships in 2016 of 2g/kWh for engines operating at speeds of greater than 2000rpm. (IMO, 2016)

6.5. Cost

It is perhaps unsurprising to see that the diesel ferries either operate at a loss or make a very small profit for the two shifts. It is common for public transport services, particularly ferry systems to operate at a loss. (Odeck & Bråthen, 2009) This is likely owed to the high fuelling costs from purchasing diesel. The electric ferries had higher capital costs since more vessels were required to meet peak demand, higher vessel purchase cost and the need for charging stations. However, the combination of the assumption that 18% higher ticket prices can be charged and cheaper fuelling requirements proved telling as they returned payback within 23 and 14 years for Shift5 and Shift10 respectively. This is a fairly long period of time to wait for a return on investment but the expected lifetime of a boat is generally between 20-30 years (Dinu & Ilie, 2015) and relative to the diesel alternative, it looks favourable. To determine the revenue, a daily ticket price was taken. This is deemed quite reasonable for off-peak travellers but in reality, it is likely that commuters would get some discount on monthly or annual passes and this would reduce profitability.

One notable limitation of the costing analysis was that the battery cost per kWh capacity was assumed constant and this is likely to decrease over time in line with other Lithium-ion battery types. (Bloomberg NEF, 2019) The assumption that the batteries can undergo 20,000 cycles is based on the manufacturer's internal testing at 25°C and charge/discharge rates of 3C and intended operation is within this range. (Toshiba, 2019) However, studies on LTOs at higher charge/discharge rates have shown that the cell can heat to 34°C and although this is a fairly low temperature for battery applications, the time taken to return to normal operating temperature can be up to 2h. (Hrzina, 2018) This could have implications for the intended fairly short times between charges and this would require further investigation for its effect on cycle life.

Diesel fuel and electrical costs are also assumed constant. Fossil fuels are dictated by market conditions but it is likely to increase with greater scarcity and electricity costs may change depending on the actions of energy suppliers. Further, staffing costs for crew members of the vessels were not considered. This may have slightly increased the payback periods but not to a significant degree as it is likely much less than major operating costs such as fuelling.

6.6. Recommendations

I feel that a linear electric ferry service could be a viable option for the River Clyde. Based on the cost analysis undertaken in this study, the financial case is reasonable and if the EU project on modularity of ship design (TrAM, 2018) is successful then the capital costs per vessel can be reduced further to be more cost competitive with ICE vessels. Further to this, the infrastructure costs are fairly low since there are no tracks or roads to build or maintain and there is minimal disruption to other activities in constructing terminals since it is so close to the waterside. The energy requirements are hefty but it contributes to no local pollution and with a decarbonising grid the equivalent emissions are likely to reduce in future. Furthermore, its higher energy use may be an acceptable trade-off given that it has the ability to divert traffic from the roads and its batteries could be used as a grid-balancing mechanism. Beyond the energy, environmental and engineering considerations, it provides a method of promoting active travel by catering for bike users and encouraging users to walk to the river. This could result in benefits to health and wellbeing, with positive knock-on effects on workplace productivity.

7. Conclusions

A linear ferry route was determined, beginning in Bowling, stopping at Erskine, Clydebank, Renfrew and Partick before ending in Glasgow city centre. Two demand profiles were developed based broadly on a 5% shift (Shift5) and 10% shift (Shift10) for current trips to Glasgow by car, bus and rail being converted to ferry.

The BB Green 24 electric vessel was chosen and scheduling required 5 and 8 vessels for Shift5 and Shift10 respectively. Annual energy requirements were approximately 5.9GWh and 8.1GWh per year, which was about a third of the requirements for diesel ferries. Full vessel occupancy gave a passenger energy use of 0.138kWh/pass.km. This was more than three times the energy required for buses and trains and was comparable to an electric car.

The electric ferries have significantly lower carbon dioxide emissions than diesel ferries. They are comparable to BAU for Shift5 but save approximately 25% for Shift10. They also have no localised emissions of nitrogen oxides or particulate matter.

Ferry travel times were found to be mostly comparable to BAU modes, but sometimes better.

As regards economic matters, the electric ferries, despite having a high capital cost, do give a return on investment within 23 and 14 years for Shift5 and Shift10 respectively. Diesel ferries, on the other hand, do not prove profitable due to high fuel costs.

Rooftop solar panels were investigated and it was decided that they were not a worthwhile investment for a high-speed vessel applications.

Despite the simplicity of some of the assumptions made during the study, I feel that it has been demonstrated that a linear electric ferry system could be a viable option for Glasgow’s River Clyde.

7.1. Future Work

Beyond what has been covered in this study, there are a number of related areas to a linear electric ferry system that may be worth further exploration.

Firstly, the effect of drawing large power from the local grid could be explored. Secondly, the suitability of the battery system for use as a grid balancing mechanism in vehicle to grid for overnight EV charging could be investigated.

Thirdly, environmental impacts could be explored, such as the effect of high-speed vessels on aquatic wildlife, assessment of the likelihood and implications of flooding on the system or the impacts of waterflow or adverse weather conditions on the energy requirements.

Lastly, the ideas from this study could be superimposed onto other cities with underutilised water channels and congestion issues, such as Cairo.

8. References

AA, 2019. *Fuel price report (July 2019).* [Online]
Available at: https://www.theaa.com/driving-advice/driving-costs/fuel-prices
[Accessed 3 August 2019].

ABB, 2019. *ABB powers tourists to the Niagara Falls with first US built all-electric vessels.* [Online]
Available at: https://new.abb.com/news/detail/23054/abb-powers-tourists-to-the-niagara-falls-with-first-us-built-all-electric-vessels
[Accessed 20 July 2019].

Alexander Dennis, 2018. *Enviro 2000 Specifications*. [Online]
Available at: https://www.alexander-dennis.com/media/83813/enviro200-spec.pdf
[Accessed 12 July 2019].

Alexander Dennis, 2019. *Enviro200.* [Online]
Available at: https://www.alexander-dennis.com/products/single-deck/enviro200/
[Accessed 1 August 2019].

Börjesson, M. e. a., 2015. Factors driving public support for road congestion reduction policies: Congestion charging, free public transport and more roads in Stockholm, Helsinki and Lyon. *Transportation Research Part A: Policy and Practice,* 88(8), pp. 452-462.

Barczak, N., 2019. *Waterjets: When to Use, Pros and Cons: Efficiency.* [Online]
Available at: https://dmsonline.us/waterjets-when-to-use-pros-and-cons/
[Accessed 6 August 2019].

Barnard, M., 2015. *Why Are Teslas Quicker Than Gas Cars?*. [Online]
Available at: https://cleantechnica.com/2015/12/19/teslas-quicker-gas-cars/
[Accessed 2019 August 19].
Barry, K., 2014. *Stockholm's New Electric Ferry Takes Just 10 Minutes to Charge.* [Online]

Available at: https://www.wired.com/2014/04/stockholm-electric-ferry/
[Accessed 21 July 2019].

Battery University, 2019. *BU-205: Types of Lithium-ion.* [Online]
Available at: https://batteryuniversity.com/learn/article/types_of_lithium_ion
[Accessed 8 August 2019].

BB Green, 2016. *This is BB Green.* [Online]
Available at: http://bbgreen.eu/
[Accessed 21 July 2019].

BB Green, 2018. *Three faces of Green.* [Online]
Available at: http://bbgreen.eu/index.php/this-is-bb-green/bb-green-2/
[Accessed 21 July 2019].

BBC, 2019. *Glasgow city centre's free Sunday parking comes to an end.* [Online]
Available at: https://www.bbc.co.uk/news/uk-scotland-glasgow-west-48811319
[Accessed 5 July 2019].

BBC, 2019. *Persimmon unveils £60m Erskine development plans.* [Online]
Available at: https://www.bbc.co.uk/news/uk-scotland-scotland-business-47707122
[Accessed 26 July 2019].

Bell, S., 2017. *Give Scotrail back to the public: Cross-party support emerges for railway reform after major report.* [Online]
Available at: https://www.commonspace.scot/articles/12069/give-scotrail-back-public-cross-party-support-emerges-railway-reform-after-major
[Accessed 26 July 2019].

Bigerna, S., Micheli, S. & Polinori, P., 2019. Willingness to pay for electric boats in a protected area in Italy: A sustainable tourism perspective. *Journal of Cleaner Production,* 224(19), pp. 603-613.
Bignon, E. & Pojani, D., 2018. River-based public transport: Why won’t Paris jump on board?. *Case Studies on Transport Policy,* 6(2), pp. 200-205.

Blaikie, G., 2019. *Clyde Ferries and Docks.* [Online]
Available at: http://www.scotcities.com/railways/ferries.htm
[Accessed 4 July 2019].

Bloomberg NEF, 2019. *Bloomberg NEF - Electric Vehicle Outlook 2019.* [Online]
Available at: https://about.bnef.com/electric-vehicle-outlook/#toc-viewreport
[Accessed 10 July 2019].

Clyde Waterfront, 2013. *Central Govan action plan.* [Online]
Available at: http://www.clydewaterfront.com/projects/greater-govan--glasgow-harbour/public-amenity/central_govan_action_plan
[Accessed 6 July 2019].

Clyde Waterfront, 2013. *Ferry Village - Best Developments.* [Online]
Available at: http://www.clydewaterfront.com/projects/renfrew-riverside--scotstoun/housing/ferry_village_best
[Accessed 26 July 2019].

Clyde Waterfront, 2014. *History of the River Clyde.* [Online]
Available at: http://www.clydewaterfront.com/clyde-heritage/river-clyde/history-of-the-river-clyde
[Accessed 4 July 2019].

Clyde Waterfront, 2014. *Renfrew Yoker Ferry.* [Online]
Available at: http://www.clydewaterfront.com/projects/clyde-wide/c13---renfrew-yoker-ferry
[Accessed 6 July 2019].

Clyde Waterfront, 2017. *Little Mill.* [Online]
Available at: http://www.clydewaterfront.com/projects/old-kilpatrick-to-dumbarton/housing/littlemill
[Accessed 26 July 2019].

Clyde Waterfront, 2018. *Queens Quay residential.* [Online]
Available at: http://www.clydewaterfront.com/projects/clydebank--erskine/housing/queens_quay_residential_phase_1
[Accessed 26 July 2019].

Cruise Critic, 2007. *QE2 Launch.* [Online]
Available at: https://boards.cruisecritic.com/topic/535403-qe2-launch/
[Accessed 6 July 2019].

CTEE, 2015. *Queensland Transport Facts 2015,* Spring Hill: The Centre for Transport, Energy and Environment and Pekol Traffic and Transport.

Cudahy, B. J., 1990. *Over and Back: The History of Ferryboats in NY Harbor.* 1st Edition ed. New York: Fordham Press.

Damen, 2019. *Damen and Arriva Extend Ferry Service fom Copenhagen City Centre to Port Area with Two Additional Damen Ferries 2306E3.* [Online]
Available at:
https://www.damen.com/en/news/2019/04/damen_and_arriva_extend_ferry_service_from_copenhagen_city_centre_to_port_area
[Accessed 16 July 2019].

De Breuker, S., Peeters, E. & Driesen, J., 2009. *Possible applications of Plug-in Hybrid Electric Ships.* [Online]
Available at: https://www.researchgate.net/figure/Standard-load-profile-of-workboats-ferries-governmental-vessels-tugs-barges-large_fig4_251885224
[Accessed 2019 August 10].

Department for Transport, 2018. *Rail Factsheet.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761352/rail-factsheet-2018.pdf
[Accessed 28 July 2019].

Dept for Business, Energy and Industrial Strategy, 2019. *2018 UK GREENHOUSE GAS EMISSIONS, PROVISIONAL FIGURES*, London: Crown.

Dinu, O. & Ilie, A., 2015. *Maritime vessel obsolescence, life cycle cost and design service life.* Mamaia, IOP.

East by West, 2018. *New electric ferry for Wellington.* [Online]
Available at: http://www.eastbywest.co.nz/new-electric-ferry-wellington
[Accessed 21 July 2019].

Eco Experts, 2019. *Electricity Prices per kWh.* [Online]
Available at: https://www.theecoexperts.co.uk/kwh-electricity-prices
[Accessed 9 August 2019].

Engineering Toolbox, 2008. *Fossil and Alternative Fuels - Energy Content.* [Online]
Available at: https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html
[Accessed 6 August 2019].

ESRU, 2019. *MERIT: Dynamic demand/supply matching-design tool for renewable energy systems.* [Online]
Available at: http://www.esru.strath.ac.uk/Programs/Merit/Merit_overview.pdf
[Accessed 13 August 2019].

European Commission, 2018. *TrAM Transport: Advanced and Modular.* [Online]
Available at: https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/waterborne/tram
[Accessed 20 July 2019].

European Environment Agency, 2018. *Greenhouse gas emissions from transport.* [Online]
Available at: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11

ExxonMobil, 2019. *ExxonMobil Marine Distillate Fuel.* [Online]
Available at: https://www.exxonmobil.com/english-GQ/Commercial-Fuel/pds/GLXXExxonMobil-Marine-Distillate-Fuel
[Accessed 9 August 2019].

FACTS, 2014. *ADL Enviro 200 trio for Coach Services Ltd.* [Online]
Available at: https://www.factsmagazine.co.uk/news/adl-enviro-200-trio-coach-services-ltd/
[Accessed 4 August 2019].

Fang, H. & Duan, M., 2014. Chapter 5 - Special Problems in Sea Petroleum Engineering for Beaches and Shallow Sea Areas. In: H. Fang, ed. *Offshore Operation Facilities Equipment and Procedures.* Beijing: Offshore Oil/Gas Research Center, China University of Petroleum, pp. 687-780.

Figenbaum, E., 2017. Perspectives on Norway's supercharged electric vehicle policy. *Environmental Innovation and Societal Transitions,* 25(4), pp. 14-34.
FireX, 2018. *How Much Do Bikes Weigh? The Importance of Bicycle Weight.* [Online]
Available at: https://thexfire.com/bike-weighs
[Accessed 19 August 2019].

Free Map Tools, 2019. *Measure Distance Map.* [Online]
Available at: https://www.freemaptools.com/measure-distance.htm
[Accessed 2 August 2019].

Get in to Govan, 2019. *Free Govan Summer Ferry 2019.* [Online]
Available at: http://www.getintogovan.com/free-govan-summer-ferry-2019/?fbclid=IwAR2HLcKCrhEVGII20zoyeHvT12N5oVijH17ig6wo9ndQeePMtXLYhYUHYJ0
[Accessed 4 July 2019].
Glasgow City Council, 2018. *Low Emission Zone (LEZ).* [Online]
Available at: https://www.glasgow.gov.uk/LEZ
[Accessed 5 July 2019].

Glasgow GIS, 2018. *Glasgow's Low Emission Zone.* [Online]
Available at:
https://glasgowgis.maps.arcgis.com/apps/MapSeries/index.html?appid=a1cca42f50834e9ab30bec4769af1a09
[Accessed 6 July 2019].

Google Maps, 2019. *Google Maps - Glasgow.* [Online]
Available at: https://www.google.com/maps
[Accessed 18 July 2019].

Green City Ferries, 2019. *Our Ferries.* [Online]
Available at: http://www.greencityferries.com/page1.html#header9-s
[Accessed 28 July 2019].

Green City Ferries, 2019. *Presentation - The future is waterborne: With emission free high-speed ferries and supercharging,* Stockholm: Green City Ferries.

Han, X. et al., 2019. A review on the key issues of the lithium ion battery degradation among the whole life cycle. *eTransportation,* 1(1), pp. 32-43.

Helmers, E., Leitao, J., Tietge, U. & Butler, T., 2019. CO2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: Assessing the climate benefit of the European "diesel boom". *Atmospheric Environment,* 198(1), pp. 122-132.

Hitachi, 2018. *Class 385 for Scotland.* [Online]
Available at: http://www.hitachirail-eu.com/index.php/products/projects/class-385-scotland
[Accessed 18 July 2019].

Hrzina, P., 2018. Optimal discharging conditions for battery storage systems. *Journal of Energy Storage,* 20(6), pp. 473-477.

ICCT, 2016. *A technical summary of Euro 6/VI vehicle emission standards.* [Online]
Available at: https://theicct.org/sites/default/files/publications/ICCT_Euro6-

VI_briefing_jun2016.pdf
[Accessed 7 July 2019].

IMO, 2016. *Nitrogen Oxides (NOx) – Regulation 13.* [Online]
Available at:
http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx
[Accessed 19 August 2019].

incat, 2015. *Hull 076 - 35m Passenger Ferry.* [Online]
Available at: https://www.incat.com.au/wp-content/uploads/2018/02/hull-076-35m-mini-spec.pdf
[Accessed 23 July 2019].

IQAir AirVisual, 2019. *2018 World Air Quality Report Region & City PM2.5 Ranking,* Goldach, Switzerland: IQ Air Group.

Jonson, J. et al., 2017. Impact of excess NOx emissions from diesel cars on air quality, public health and eutrophication in Europe. *Environmental Research Letters,* 12(9), pp. 1-11.

Kondolf, G. M. & Pinto, P. J., 2017. The Social Connectivity of Urban Rivers. *Geomorphology,* 277(2), pp. 182-196.

Lambert, F., 2016. *A new solar and battery-powered catamaran with a virtually unlimited range: Solarwave.* [Online]
Available at: https://electrek.co/2016/11/02/solar-battery-powered-catamaran-virtually-unlimited-range-solarwave/
[Accessed 28 July 2019].
Launes, M., 2018. *Awarded 11.7 Million Euros to develop all-electric high-speed passenger vessel.* [Online]
Available at: https://maritimecleantech.no/2018/01/29/awarded-nok-110-million-develop-fully-electric-high-speed-passenger-vessel/
[Accessed 21 July 2019].

LowCVP, 2017. *LEB Certificates.* [Online]
Available at: https://www.lowcvp.org.uk/Hubs/leb/LEBCertificates.htm
[Accessed 2 August 2019].

MacLennon, G., 2009. *River Clyde Waterbus/Ferry Study.* [Online]
Available at: http://www.spt.co.uk/documents/rtp130209_agenda9.pdf
[Accessed 25 June 2019].

Maritime Clean Tech, 2018. *Transport: Advanced and Modular.* [Online]
Available at: https://maritimecleantech.no/project/the-tram-project/
[Accessed 21 July 2019].

Maritime Journal, 2015. *Air Supported Vessels.* [Online]
Available at: https://www.maritimejournal.com/news101/comment-and-analysis/air-supported-vessels
[Accessed 8 July 2019].

May, N., 2018. Local environmental impact assessment as decision support for the introduction of electromobility in urban public transport systems. *Transportation Research Part D: Transport and Environment*, 64(7), pp. 192-203.

McGill's Buses, 2019. *Check your new ClydeFlyer timetable.* [Online]
Available at: http://www.mcgillsbuses.co.uk/news/check-your-new-clydeflyer-timetable.aspx
[Accessed 26 July 2019].

McGill's Buses, 2019. *X23 - Erskine to Glasgow city centre.* [Online]
Available at: http://www.mcgillsbuses.co.uk/mcgills-bus-timetables/x23-erskine-to-glasgow.aspx
[Accessed 26 July 2019].

McGill's Buses, 2019. *X7 - Kilmacolm to Glasgow -Temp TT from 5/8/19-15/8/19.* [Online]

Available at: http://www.mcgillsbuses.co.uk/mcgills-bus-timetables/x7-greenock-to-glasgow.aspx
[Accessed 26 July 2019].

MFame, 2016. *Improving Engine Robustness for Diesel Electric Vessels.* [Online]
Available at: http://mfame.guru/improving-engine-robustness-diesel-electric-vessels/
[Accessed 5 August 2019].

Miao, Y., Hynan, P., von Jouanne, A. & Yokochi, A., 2019. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. *Energies,* 12(6), p. 1074.

Mjos, N., 2018. *Leading the charge.* [Online]
Available at: https://www.dnvgl.com/expert-story/maritime-impact/leading-the-charge.html
[Accessed 20 July 2019].

Mogg, T., 2019. *Niagara Falls' iconic Maid of the Mist tourist boats to go electric.* [Online]
Available at: https://www.digitaltrends.com/cool-tech/niagara-falls-iconic-maid-of-the-mist-boats-to-go-electric/
[Accessed 20 July 2019].

Moore, R., 2019. *Norwegian shipyard to build zero-emissions fast ferry.* [Online]
Available at: https://www.rivieramm.com/news-content-hub/news-content-hub/norwegian-shipyard-to-build-zero-emissions-fast-ferry-55587
[Accessed 21 July 2019].

Morris, E. & Guerra, E., 2015. Mood and mode: does how we travel affect how we feel?. *Transportation,* 42(1), pp. 24-43.

Motor Boat & Yachting, 2019. *X Shore Eelex 800: Could this electric boat become the Tesla of the seas?.* [Online]
Available at: https://www.mby.com/reviews/rib-and-sportsboats/x-shore-eelex-800-

electric-boat-tesla-inspired?lazyload=0&utm_campaign=flipboard_rss_feed&utm_content=mby&utm_medium=app&utm_source=flipboard
[Accessed 25 July 2019].

Mumford, L., 1961. *The city in history: Its origins, its transformations, and its prospects.* 1st Edition ed. New York: Houghton Mifflin Harcourt.

National Records of Scotland, 2011. *Scotland's Census.* [Online]
Available at: https://www.scotlandscensus.gov.uk/ods-web/area.html
[Accessed 24 July 2019].

NCE Maritime CleanTech, 2015. *MS Ampere.* [Online]
Available at: https://maritimecleantech.no/project/ms-ampere/
[Accessed 10 July 2019].

New York City Economic Development Corporation, 2015. *Citywide Ferry Study 2013.* [Online]
Available at:
https://www.nycedc.com/sites/default/files/filemanager/Resources/Studies/2013_Citywide_Ferry_Study/Citywide_Ferry_Study_-_Final_Report.pdf
[Accessed 5 July 2019].

Nissan, 2019. *Nissan Leaf - Range & Charging.* [Online]
Available at: https://www.nissan.co.uk/vehicles/new-vehicles/leaf/range-charging.html
[Accessed 14 July 2019].
Noela, L., Zarazua de Rubensa, G., Sovacool, B. K. & Kester, J., 2019. Fear and loathing of electric vehicles: The reactionary rhetoric of range anxiety. *Energy Research & Social Science,* 48(2), pp. 96-107.

Novaco, R. & Gonzalez, O., 2009. Commuting and Well-Being. In: Y. Amichai-Hamburger, ed. *Technology and Psychological Well-Being.* Cambridge: Cambridge University Press, pp. 174-205.

Odeck, J. & Bråthen, S., 2009. The Efficiency of Norwegian Ferries in Providing Public Transport Services. *International Journal of Transport Economics,* 36(1), pp. 121-139.

O'Driscoll, R. et al., 2018. Real world CO2and NOx emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars. *Science of the Total Environment,* 621(1), pp. 282-290.

Olsson, L. e. a., 2013. Happiness and Satisfaction with Work Commute. *Social Indicators Research,* 111(1), pp. 255-263.

Online Etymology Dictionary, 2019. *catamaran (n.).* [Online]
Available at: https://www.etymonline.com/word/catamaran
[Accessed 12 July 2019].

ORR, 2012. *Costs and Revenues of Franchised Passenger Train Operators in the UK.* [Online]
Available at: https://orr.gov.uk/__data/assets/pdf_file/0019/4933/toc-benchmarking-report-2012.pdf
[Accessed 1 August 2019].

Paisley, 2019. *Clyde Waterfront and Renfrew Riverside.* [Online]
Available at: https://paisley.is/invest/clyde-waterfront-and-renfrew-riverside/
[Accessed 6 July 2019].
Panprayun, G. & Pitaksintorn, S., 2018. Development and Evaluation of Solar Powered Catamaran for Sustainable Tourism in Southeast of the Gulf of Thailand. *International Journal of Renewable Energy Research,* 8(2), pp. 1124-1129.

Pearrea, N. P., Kempton, W., Guensler, R. L. & Elangob, V. V., 2011. Electric vehicles: How much range is required for a day's driving?. *Transportation Research Part C: Emerging Technologies,* 19(6), pp. 1171-1184.

Pecorari, E. et al., 2013. WATERBUS: A model to estimate boats' emissions in "water cities". *Transportation Research Part D: Transport and Environment,* 23(6), pp. 73-80.

Picard, 2017. *Unconventional fast ships.* [Online]
Available at: https://defenseissues.net/2017/05/16/unconventional-fast-ships/
[Accessed 10 July 2019].

Pollefliet, J., 2018. e-Mobility. In: L. Reading, ed. *Power Electronics: Drive Technology and Motion Control.* London: Academic Press, pp. 1-19.
Press Trust of India, 2017. *China launches world's first fully electric cargo ship.* [Online]
Available at: https://www.hindustantimes.com/world-news/china-launches-world-s-first-fully-electric-cargo-ship/story-ceg5ZbMb67yOLpYFZNdg4I.html
[Accessed 20 July 2019].

Public Health England, 2016. *Working Together to Promote Active Travel: A briefing for local authorities,* London: Crown.

RAC Foundation, 2018. *Environment.* [Online]
Available at: https://www.racfoundation.org/motoring-faqs/environment
[Accessed 8 August 2019].

RAC, 2018. *Euro 1 to Euro 6 video guide – find out your vehicle's emissions standard.* [Online]
Available at: https://www.rac.co.uk/drive/advice/emissions/euro-emissions-standards/
[Accessed 8 July 2019].

Reed, T. & Kidd, J., 2019. *INRIX.* [Online]
Available at: http://inrix.com/scorecard/
[Accessed 24 June 2019].

Reid, K., 2018. *2018 Air Quality Annual Progress Report (APR) for Glasgow City Council.* [Online]

Available at: https://www.glasgow.gov.uk/CHttpHandler.ashx?id=42974&p=0
[Accessed 28 July 2019].

Rietmann, N. & Lieven, T., 2019. How policy measures succeeded to promote electric mobility – Worldwide review and outlook. *Journal of Cleaner Production,* 206(1), pp. 66-75.

Rungfapaisarn, K., 2019. *New electric ferries to ply the 'Venice of the East' in Bangkok.* [Online]
Available at: https://thethaiger.com/hot-news/air-pollution/new-electric-ferries-to-ply-the-venice-of-the-east-in-bangkok
[Accessed 21 July 2019].

San Francisco Bay Area Water Transit Authority, 2003. *A Strategy to Improve Public Transit with an Environmentally Friendly Ferry System,* San Francisco: San Francisco Bay Area Water Transit Authority.

Scania Marine Engines, 2018. *DI16 072M. 625 kW (850 hp).* [Online]
Available at: https://www.scania.com/content/dam/scanianoe/market/master/products-and-services/engines/pdf/specs/marine/DI16072M_625kW.pdf
[Accessed 5 August 2019].

Scot Gov, 2004. *Bus Occupancy Surveys,* Glasgow: Scottish Government.

Scotrail, 2018. *Scotland's Railway: The ScotRail Alliance 2018.* [Online]
Available at:
https://www.scotrail.co.uk/sites/default/files/assets/download_ct/scotrail_sustainability_2018_single_page_web_0.pdf
[Accessed 12 July 2019].

Scotrail, 2019. *Scotrail Stations and Facilities: Interchange.* [Online]
Available at: https://www.scotrail.co.uk/plan-your-journey/stations-and-facilities/
[Accessed 28 July 2019].

Siemens, 2000. *Solar module SM110/SM100.* [Online]
Available at: https://www.rvtechlibrary.com/electrical/SM110_SolarSpecs.pdf
[Accessed 12 August 2019].

Sipe, N. & Burke, M. I., 2011. Can River Ferries Deliver Smart Growth? Experience of CityCats in Brisbane, Australia. *Transportation Research Record: Journal of the Transportation Research Board,* 2217(1), pp. 79-86.

Smallridge, T., 2018. *Thailand's first all-electric passenger ferry is powered by Torqeedo.* [Online]
Available at: https://www.torqeedo.com/en/news-and-press/blog/blog-2018-11-28.html
[Accessed 21 July 2019].

Smallridge, T., 2018. *Torqeedo powers Spain's first solar-electric passenger ferry.* [Online]
Available at: https://www.torqeedo.com/en/news-and-press/blog/blog-2018-6-26.html
[Accessed 28 July 2019].

Soltani, A. e. a., 2015. Travel Patterns of Urban Linear Ferry Passengers: Analysis of Smart Card Fare Data for Brisbane, Queensland, Australia. *Transportation Research Record: Journal of the Transportation Research Board,* 2535(1), pp. 79-87.

SPAR Associates, Inc., 2012. *Estimating Commercial Ship Life Cycle Cost & Required Freight Rate (3-Port Model).* [Online]
Available at: http://www.sparusa.com/Presentations/Presentation-Commercial%20Ship%20Life%20Cycle%20&%20Required%20Freight%20Rate%20(RFR)%20Cost%20Model.pdf
[Accessed 5 August 2019].

Spath, N., 2015. *Seatrade Award for DNV GL classed Ampere, world's first fully electric vessel.* [Online]
Available at: https://www.dnvgl.com/news/seatrade-award-for-dnv-gl-classed-

ampere-world-s-first-fully-electric-vessel--24038
[Accessed 20 July 2019].

SPT, 2019. *Subway: Tickets.* [Online]
Available at: http://www.spt.co.uk/subway/tickets/
[Accessed 6 July 2019].

SYSTRA, 2015. *Larkhall – Milngavie Railway Project Evaluation Study Final Report.* [Online]
Available at: https://www.transport.gov.scot/media/32433/j372238.pdf
[Accessed 8 July 2019].

Tanko, M. & Burke, M., 2017. Transport innovations and their effect on cities: The emergence of urban linear ferries worldwide. *Transportation Research Procedia,* 25(6), pp. 3957-3970.

Thames Clippers, 2015. *Galaxy Clipper and Neptune Clipper to join the fleet.* [Online]
Available at: https://www.thamesclippers.com/news/detail/galaxy-clipper-and-neptune-clipper-to-join-the-fleet
[Accessed 2 August 2019].

Thames Clippers, 2019. *Route Timetable.* [Online]
Available at: https://www.thamesclippers.com/route-time-table/book-now
[Accessed 2 August 2019].

Thornell, H., 2018. *Green Fast Ferries: Report on demonstration activities.* [Online]
Available at:
https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bed3de55&appId=PPGMS
[Accessed 2019 July 21].

TomTom, 2019. *TomTom.* [Online]
Available at: https://www.tomtom.com/en_gb/traffic-index/ranking/
[Accessed 24 June 2019].

Toshiba, 2019. *Industrial Lithium-ion Battery SCiB SIP series.* [Online]
Available at: https://www.scib.jp/en/download/Toshiba_SCiB_SIP_en.pdf
[Accessed 8 August 2019].

Toshiba, 2019. *Toshiba Rechargeable Battery SCiB.* [Online]
Available at: https://www.scib.jp/en/download/ToshibaRechargeableBattery-en.pdf
[Accessed 8 August 2019].

Trainline, 2019. *Trainline.* [Online]
Available at: https://www.thetrainline.com/
[Accessed 26 July 2019].

TrAM, 2018. *Shipbuilding: Rewriting the Book.* [Online]
Available at: https://tramproject.eu/2019/03/20/shipbuilding-rewriting-the-book/
[Accessed 21 July 2019].

Transport Scotland, 2018. *Scottish Transport Statistics No 37 2018 Edition*, Edinburgh: National Statistics.

Transport Scotland, 2019. *About walking and cycling policy.* [Online]
Available at: https://www.transport.gov.scot/active-travel/about-walking-and-cycling-policy/#42959
[Accessed 6 July 2019].

Transport Scotland, 2019. *Active Travel Budget Allocation 2018 - 19.* [Online]
Available at: https://www.transport.gov.scot/media/43939/active-travel-budget-allocation-2018-2019.pdf
[Accessed 6 July 2019].

Transport Scotland, 2019. *Over £20 million to support electric vehicles across Scotland.* [Online]
Available at: https://www.transport.gov.scot/news/over-20-million-to-support-electric-vehicles-across-scotland/
[Accessed 6 July 2019].

Tsai, C.-H. e. a., 2015. Exploring property value effects of ferry terminals: Evidence from Brisbane, Australia. *Journal of Transport and Land Use,* 10(1), pp. 119-137.
UK Transport, 2017. *British Rail Class 321.* [Online]
Available at: https://uktransport.fandom.com/wiki/British_Rail_Class_321
[Accessed 1 August 2019].

Understanding Glasgow, 2011. *Glasgow Trends.* [Online]
Available at:
https://www.understandingglasgow.com/indicators/transport/travel_to_work/trends/glasgow_trends
[Accessed 28 July 2019].

Vattenfall, 2019. *Vattenfall and Echandia Marine cooperate on electric ferry with superfast charging.* [Online]
Available at: https://group.vattenfall.com/press-and-media/news--press-releases/pressreleases/2019/vattenfall-and-echandia-marine-cooperate-on-electric-ferry-with-superfast-charging
[Accessed 21 July 2019].
Wall, M., 2018. *How Amsterdam's canal boats are going electric - at a cost.* [Online]
Available at: https://www.bbc.co.uk/news/business-45783085
[Accessed 20 July 2019].

WHO, 2011. *Health in the Green Economy: Health co-benefits of climate change mitigation – Transport sector* , Geneva: World Health Organisation.

WHO, 2018. *9 out of 10 people worldwide breathe polluted air, but more countries are taking action.* [Online]

Available at: https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action

Williams, T. & Te Brommelstroet, M., 2017. *Combining the Power of Bicycle Use and Public Transport: Implementing the Bike-Train System in the New Zealand Context.* Hamilton, Jacobs, pp. 1-9.

XE, 2019. *XE Currency Converter.* [Online]
Available at:
https://www.xe.com/currencyconverter/convert/?Amount=1&From=EUR&To=GBP
[Accessed 15 August 2019].

XE, 2019. *XE Currency Converter: 1 USD to GBP.* [Online]
Available at:
https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=GBP
[Accessed 19 August 2019].

Appendices

Appendix A – Sample calculation for demand estimation

For town of Erskine. Same method repeated for all towns.

Peak

Peak hours: Mon-Fri: 7am-9am and 5pm-7pm (4 hours total but 2 hours in each direction due to nature of commuting)

Renfrewshire council area:

$$Return\ Rail\ Journeys\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{Fraction\ of\ journeys\ to\ Glasgow \times Total\ annual\ journeys}{No.\ days\ in\ a\ year \times return\ journey\ factor}$$

$$= \frac{0.644 \times 3663000}{365 \times 2} = 3230$$

$$Rail\ Commuters\ R'shire\ to\ Glasgow\ per\ day$$

$$= Commute\ Fraction$$

$$\times Return\ Rail\ Journeys\ R'shire\ to\ Glasgow\ per\ day$$

$$\times 5\ day\ conversion\ fraction = 0.55 \times 3230 \times \frac{7}{5} = 2487$$

$$Bus\ Commuters\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{Mode\ share\ bus}{Mode\ share\ train}$$

$$\times Rail\ Commuters\ R'shire\ to\ Glasgow\ per\ day = \frac{0.203}{0.077} \times 1777$$

$$= 6557$$

$$Car\ Commuters\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{Mode\ share\ car\ (dr) + Mode\ share\ car\ (pass)}{Mode\ share\ train}$$

$$\times Rail\ Commuters\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{0.326 + 0.083}{0.077} \times 2487 = 13211$$

Erskine:

$$Rail\ commuters = \frac{Population\ Erskine}{Population\ Renfrewshire} \times Rail\ Commuters\ R'shire\ to\ Glasgow\ per\ day = \frac{15537}{174908} \times 2487 = 221$$

$$Bus\ commuters = \frac{Population\ Erskine}{Population\ Renfrewshire} \times Bus\ Commuters\ R'shire\ to\ Glasgow\ per\ day = \frac{15537}{174908} \times 6557 = 582$$

$$Car\ commuters = \frac{Population\ Erskine}{Population\ Renfrewshire} \times Car\ Commuters\ R'shire\ to\ Glasgow\ per\ day = \frac{15537}{174908} \times 13211 = 1147$$

$$Total\ peak\ demand = Rail\ commuters + Bus\ commuters + Car\ commuters = 221 + 582 + 1147 = 1977$$

$$Hourly\ peak\ demand = \frac{Total\ peak\ demand}{No.peak\ hours} = \frac{1977}{2} = 988$$

$$Ferry\ demand\ for\ 5\%\ modal\ shift = 0.05 \times Hourly\ peak\ demand = 0.05 \times 988 = 49$$

<u>Off-peak</u>

Off-peak hours - Mon-Fri: 9am-5pm and 7pm-10pm (11 hours)

Renfrewshire council area:

$$Off - Peak\ Rail\ Travellers\ R'shire\ to\ Glasgow\ per\ day = (Non\ commute\ Fraction) \times Return\ Rail\ Journeys\ R'shire\ to\ Glasgow\ per\ day = 0.45 \times 3230 = 1453$$

$$Off - peak\ Bus\ Travellers\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{Mode\ share\ bus}{Mode\ share\ train} \times Off$$

$$- Peak\ Rail\ Travellers\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{0.203}{0.077} \times 1453 = 3831$$

$$Off - peak\ Car\ Travellers\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{Mode\ share\ car(dr) + Mode\ share\ car(pass)}{Mode\ share\ train} \times Off$$

$$- Peak\ Rail\ Travellers\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{0.326 + 0.083}{0.077} \times 1453 = 7718$$

Erskine:

$$Off - peak\ rail\ travellers\ per\ day$$

$$= \frac{Population\ Erskine}{Population\ Renfrewshire} \times Off$$

$$- Peak\ Rail\ Travellers\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{15537}{174908} \times 1453 = 129$$

$$Off - peak\ bus\ travellers\ per\ day$$

$$= \frac{Population\ Erskine}{Population\ Renfrewshire} \times Off$$

$$- Peak\ Bus\ Travellers\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{15537}{174908} \times 3831 = 340$$

$$Off - peak\ car\ travellers\ per\ day$$

$$= \frac{Population\ Erskine}{Population\ Renfrewshire} \times Off$$

$$- peak\ Car\ Travellers\ R'shire\ to\ Glasgow\ per\ day$$

$$= \frac{15537}{174908} \times 1453 = 686$$

$$Total\ off - peak\ demand$$

$$= Off - peak\ rail\ travellers\ per\ day + Off$$

$$- peak\ bus\ travellers\ per\ day + Off$$

$$- peak\ car\ travellers\ per\ day = 129 + 340 + 686 = 1155$$

$$Hourly\ off - peak\ demand = \frac{Total\ off - peak\ demand}{No. off - peak\ hours} = \frac{1155}{11} = 105$$

$$Ferry\ demand\ for\ 5\%\ modal\ shift = 0.05 \times Hourly\ off-peak\ demand$$

$$= 0.05 \times 105 = 5$$

Weekend

Operating hours: 7am – 10pm (13 hours)

$$Hourly\ weekend\ demand = \frac{Total\ weekend\ demand}{No.weekend\ operating\ hours} = \frac{1155}{15} = 77$$

$$Ferry\ demand\ for\ 5\%\ modal\ shift = 0.05 \times Hourly\ weekend\ demand$$

$$= 0.05 \times 77 = 4$$

Appendix B – Weekend Vessel Routing

Table 59: Weekend Day Vessel Scheduling for Diesel Ferry Shift5

Departure	Arrival	Departure	Return	Ready for departure	Vessel No.
07:00	07:39	07:44	08:23	08:28	1
08:00	08:39	08:44	09:23	09:28	2
09:00	09:39	09:44	10:23	10:28	3
10:00	10:39	10:44	11:23	11:28	4
11:00	11:39	11:44	12:23	12:28	1
12:00	12:39	12:44	13:23	13:28	2
13:00	13:39	13:44	14:23	14:28	3
14:00	14:39	14:44	15:23	15:28	4
15:00	15:39	15:44	16:23	16:28	1
16:00	16:39	16:44	17:23	17:28	2
17:00	17:39	17:44	18:23	18:28	3
18:00	18:39	18:44	19:23	19:28	4
19:00	19:39	19:44	20:23	20:28	1
20:00	20:39	20:44	21:23	21:28	2
21:00	21:39	21:44	22:23	22:28	3
22:00	22:39	22:44	23:23	23:28	4

Table 60: Weekend Day Vessel Scheduling for Diesel Ferry Shift10

Departure	Arrival	Departure	Return	Ready for Departure	Vessel No.
07:00	07:39	07:44	08:23	08:28	1
08:00	08:39	08:44	09:23	09:28	2
09:00	09:39	09:44	10:23	10:28	3
10:00	10:39	10:44	11:23	11:28	4
11:00	11:39	11:44	12:23	12:28	5
12:00	12:39	12:44	13:23	13:28	6
13:00	13:39	13:44	14:23	14:28	1
14:00	14:39	14:44	15:23	15:28	2
15:00	15:39	15:44	16:23	16:28	3
16:00	16:39	16:44	17:23	17:28	4
17:00	17:39	17:44	18:23	18:28	5
18:00	18:39	18:44	19:23	19:28	6
19:00	19:39	19:44	20:23	20:28	1
20:00	20:39	20:44	21:23	21:28	2
21:00	21:39	21:44	22:23	22:28	3
22:00	22:39	22:44	23:23	23:28	4

Table 61: Weekend Day Vessel Scheduling for Electric Ferry Shift5

Departure	Arrival	Departure	Return	Ready for Departure	Vessel No.
07:00	07:39	07:55	07:34	07:50	1
08:00	08:39	08:55	08:34	08:50	2
09:00	09:39	09:55	09:34	09:50	3
10:00	10:39	10:55	10:34	10:50	4
11:00	11:39	11:55	11:34	11:50	5
12:00	12:39	12:55	12:34	12:50	1
13:00	13:39	13:55	13:34	13:50	2
14:00	14:39	14:55	14:34	14:50	3
15:00	15:39	15:55	15:34	15:50	4
16:00	16:39	16:55	16:34	16:50	5
17:00	17:39	17:55	17:34	17:50	1
18:00	18:39	18:55	18:34	18:50	2
19:00	19:39	19:55	19:34	19:50	3
20:00	20:39	20:55	20:34	20:50	4
21:00	21:39	21:55	21:34	21:50	5
22:00	22:39	22:55	22:34	22:50	1

Table 62: Weekend Day Vessel Scheduling for Electric Ferry Shift10

Departure	Arrival	Departure	Return	Ready for Departure	Vessel No.
07:00	07:39	07:55	08:34	08:50	1
08:00	08:39	08:55	09:34	09:50	2
09:00	09:39	09:55	10:34	10:50	3
10:00	10:39	10:55	11:34	11:50	4
11:00	11:39	11:55	12:34	12:50	5
12:00	12:39	12:55	13:34	13:50	6
13:00	13:39	13:55	14:34	14:50	7
14:00	14:39	14:55	15:34	15:50	8
15:00	15:39	15:55	16:34	16:50	1
16:00	16:39	16:55	17:34	17:50	2
17:00	17:39	17:55	18:34	18:50	3
18:00	18:39	18:55	19:34	19:50	4
19:00	19:39	19:55	20:34	20:50	5
20:00	20:39	20:55	21:34	21:50	6
21:00	21:39	21:55	22:34	22:50	7
22:00	22:39	22:55	23:34	23:50	8

Appendix C – Economic Analysis of Electric Ferry

Table 63: Economic Analysis Electric Ferry Shift5

Year	Costs (£)	Revenue (£)	Balance (£)
year 0	-20,566,000	0	-20,566,000
year 1	-1,118,356	2,053,166	-19,631,189
year 2	-1,118,356	2,053,166	-18,696,379
year 3	-1,118,356	2,053,166	-17,761,568
year 4	-1,118,356	2,053,166	-16,826,758
year 5	-1,118,356	2,053,166	-15,891,947
year 6	-1,118,356	2,053,166	-14,957,137
year 7	-1,118,356	2,053,166	-14,022,326
year 8	-1,118,356	2,053,166	-13,087,515
year 9	-1,118,356	2,053,166	-12,152,705
year 10	-1,118,356	2,053,166	-11,217,894
year 11	-1,118,356	2,053,166	-10,283,084
year 12	-1,118,356	2,053,166	-9,348,273
year 13	-1,118,356	2,053,166	-8,413,463
year 14	-1,118,356	2,053,166	-7,478,652
year 15	-1,118,356	2,053,166	-6,543,842
year 16	-1,118,356	2,053,166	-5,609,031
year 17	-1,118,356	2,053,166	-4,674,220
year 18	-1,118,356	2,053,166	-3,739,410
year 19	-1,118,356	2,053,166	-2,804,599
year 20	-1,118,356	2,053,166	-1,869,789
year 21	-1,118,356	2,053,166	-934,978
year 22	-1,118,356	2,053,166	-168
year 23	-1,118,356	2,053,166	934,643
year 24	-1,118,356	2,053,166	1,869,454
year 25	-1,118,356	2,053,166	2,804,264

Table 64: Economic Analysis Electric Ferry Shift10

Year	Costs (£)	Revenue (£)	Balance (£)
year 0	-33,488,000	0	-33,488,000
year 1	-1,532,562	4,106,333	-30,914,229
year 2	-1,532,562	4,106,333	-28,340,458
year 3	-1,532,562	4,106,333	-25,766,687
year 4	-1,532,562	4,106,333	-23,192,916
year 5	-1,532,562	4,106,333	-20,619,145
year 6	-1,532,562	4,106,333	-18,045,374
year 7	-1,532,562	4,106,333	-15,471,603
year 8	-1,532,562	4,106,333	-12,897,832
year 9	-1,532,562	4,106,333	-10,324,061
year 10	-1,532,562	4,106,333	-7,750,290
year 11	-1,532,562	4,106,333	-5,176,518
year 12	-1,532,562	4,106,333	-2,602,747
year 13	-1,532,562	4,106,333	-28,976
year 14	-1,532,562	4,106,333	2,544,795
year 15	-1,532,562	4,106,333	5,118,566
year 16	-1,532,562	4,106,333	7,692,337
year 17	-1,532,562	4,106,333	10,266,108
year 18	-1,532,562	4,106,333	12,839,879
year 19	-1,532,562	4,106,333	15,413,650
year 20	-1,532,562	4,106,333	17,987,421
year 21	-1,532,562	4,106,333	20,561,192
year 22	-1,532,562	4,106,333	23,134,963
year 23	-1,532,562	4,106,333	25,708,734
year 24	-1,532,562	4,106,333	28,282,505
year 25	-1,532,562	4,106,333	30,856,276