SPRING 2022

ENERGY DIVERSITY IN THE TIDAL THAMES

MAPPING FUTURE OPTIONS FOR ALTERNATIVE FUELS ON THE THAMES

Contents

1. Executive Summary

Building on work by the PLA on air quality and decarbonisation, in 2021, Royal HaskoningDHV and the consultancy UMAS worked to develop a model of the future fuels and geographic spread of demand and supply on the river ,which provides the first planning tool for all Thames stakeholders.

There are a number of areas showing potential for both supply and distribution of alternative fuels in the future. The technology opportunities for all fleets on the river is still limited in the near and short term, but the longer-term solutions are seeing significant investment both locally and globally to increase certainty of future requirements in the Thames estuary.

There are still regulatory constraints and effects outside of the control of the PLA and Port stakeholders; however there are also solutions coming to light that may help the PLA with constrained areas in the future. The study also clearly identifies there will be an opportunity for investment and business development for infrastructure owners adjacent to, on and in the Tidal Thames.

2. Introduction

2. 1 .Context

In 2019 the PLA undertook a technology review that produced a potential roadmap for a range of inland operations in the Tidal Thames. This only focused on the potential of technology to meet the demand assuming no operational changes, and only briefly considered how quickly infrastructure could respond. The work did not take into account restrictions on carriage and bunkering, nor the production of the fuel locally.

What was clear from this work was that appropriate infrastructure was essential in facilitating any technology shift. Therefore in 2021 the PLA commissioned Royal HaskoningDHV to carry out analysis on the basis of previous work, national and international regulatory changes and decarbonisation forecasting, to consider what the estuary and its asset owners might be able to plan and respond to in order to decarbonise shipping with the Thames and Port of London.

This public report has been compiled by the PLA to help operators (both vessel and terminals), investors and regulators benefit from the analysis.

2.2. Policy and regulations

With the adoption of the initial International Maritime Organisation (IMO)'s Greenhouse Gas strategy in 2018, an ultimate goal of 50% reduction in total GHG emissions from international shipping by 2050 compared to a 2008 baseline has been set, and an 85% reduction in CO_2 emissions per ship, given expectations of a growth in demand and therefore the size of the fleet. This target is in parallel with an ambition for a reduction in the carbon intensity of transport by at least 40% by 2030 and 70% by 2050, as well as ambitions to peak GHG emissions from shipping as soon as possible and to pursue achieving a pathway of CO_2 reduction for international shipping consistent with the Paris Agreement temperature goals.

The Energy Efficiency Design Index (EEDI) first entered into force for shipping in 2013, prior to the adoption of the IMO's Initial GHG Reduction Strategy in 2018, dictating energy efficiency requirements of most new ships. It has set a CO_2 reduction level of 20%, with a further 30-50% reduction by 2022 or 2025 dependent on ship type. The IMO Energy Efficiency Existing Ship Index (EEXI) and an operational Carbon Intensity Indicator regulation (CII) comes into force in 2023, which both set new efficiency standards for existing ships. EEXI on the technical/design efficiency, and CII on the operational efficiency as evaluated using reports to IMO of each ship's actual fuel consumption used, and the distance it has travelled).

Annex VI of The International Convention for the Prevention of Pollution from Ships

(MARPOL) (Prevention of Air Pollution from Ships) limits the main air pollutants contained in ships' exhaust gas, including sulphur oxides (SO$_X$) and nitrous oxides (NO$_X$), and prohibits deliberate emissions of ozone depleting substances. The Port of London is in the North Sea Sulphur Emission Control Area and the sulphur limit for fuel is 0.1%. The North and Baltic seas are also Emission Control Areas (ECA) for nitrogen oxides: from 2021, new build vessels must install new 'Tier III' standard engines, with lower emissions limits for nitrogen oxides, and operate within the Tier III limit whenever they are in ECA. In May 2021, the UK Government published the draft Merchant Shipping (Prevention of Air Pollution from Ships) (Amendment) Regulations 2021 to implement these requirements into national legislation. Whilst the UK is no longer a member of the EU, international shipping that operates both within the EU and the Port of London will need to adapt to meet any incoming European requirements, and it is possible that the UK may ultimately follow the EU's lead with respect to decarbonisation of maritime transport. Within the European Green Deal, proposals have been made to reduce the EU's net emissions (including all other measured sources) by at least 55% by 2030 and end maritime fossil-fuel subsidies. The EU Fit for 55 package sets out proposals to achieve these goals by strengthening existing legislation and presenting new initiatives across a range of policy areas and economic sectors including climate, energy and fuels, transport, buildings and land use.

Under the Climate Change Act 2008 (2050 Target Amendment), the UK has set a goal of Net Zero greenhouse gas emissions by 2050, compared to 1990 levels. Under the Sixth Carbon Budget, an emissions reduction of 78% by 2035 for the whole of the UK has been set, with both domestic and the UK's share of international shipping now being included within carbon budgets for the first time.

The Government Vision for the maritime sector, Maritime 2050, includes a desire for the UK to lead the way on clean maritime growth, with a need for a transition to zero-emission shipping and continued multi-billion-pound investment into maritime infrastructure. The Clean Maritime Plan aims for zero-emission capable commercial vessels to be in operation by 2025, with all new vessels to be designed with zero-emission propulsion. By 2035, the Plan aims for clean maritime clusters to be in place while having low/zero emission bunkering options available across the UK and also being a world leader in the zero-emissions maritime sector.

The goals of both the 25 Year Environment Plan and Marine Policy Statement are similar: to achieve good environmental status in seas whilst allowing marine industries to thrive, with marine businesses acting in a way to respect environmental limits and being rewarded in the marketplace for doing so.

In July 2021, the UK Government launched the Transport Decarbonisation Plan, which sets out the government's commitments and actions to decarbonise the entire UK transport system. It establishes specific targets for the maritime industry (subject to public consultation during 2021-22) including a 'Course to Zero' to accelerate decarbonisation and achieve Net Zero by no later than 2050 and earlier if possible including phasing out the sale of new, non-zero emission domestic vessels.

Within the tidal river Thames, the PLA itself and the Greater London Authority (GLA) are the two key policymakers for GHG emissions. Through the Zero Carbon London Plan (2018), the GLA has set a goal of London becoming a Net Zero carbon city by 2050. Since their publication, the Mayor has brought forward London's Net Zero target to 2030. While vessels on the Thames are not included with this, it is assumed that vessels will need to adhere to these limits, though offsetting remains an option to achieve this. The introduction of minimum emissions standards for river and maritime vessels on the Thames has been proposed in the London Environment Strategy alongside the increased utilisation of the Thames for transportation of municipal waste. Furthermore, the Mayor of London has lobbied the government to introduce a new regulator or Clean Air Act to greater reduce the emissions from vessels on London's waterways.

Principle 8 of the Transport for London Passenger Pier Strategy is to ensure environmentally sustainable Thames's piers which generate their own energy and facilitate low-emission vessels. Principle 8.2 proposes that the GLA and PLA investigate the use of shore-side power on piers to support the uptake of hybrid or zero-emission vessels.

Through its Air Quality Strategy, the PLA has set an overarching target of reductions in CO_2, with the 2051 target of Net Zero across its fleet, and a 60% and 95% reduction in CO_2 emissions for shipping and inland vessels respectively in the tidal Thames. This is to occur in parallel with the objectives of the PLA Thames Vision. The PLA has since committed to the reduce its own emission to Net Zero by 2040 or before, ahead of that stated in the current strategy

2.3. Approach

Royal HaskoningDHV was appointed, together with UMAS, to complete a study to investigate the potential energy provision options and associated infrastructure requirements needed to decarbonise the PLA's operations by 2040, and the Port of London (from Teddington to the North Sea) by 2050.

This work looks at the river as a whole, with the potential for infrastructure to supply both inland vessels, domestic and international shipping alike, increasing investment return, but also with a significant shift from current operations which is reliant on bunker barges with the relevant compliant fuels supplied to vessels in different locations.

The overarching objectives were:

- To investigate the energy provision solutions to meet the potential energy demand for decarbonising the PLA's fleet by 2040 and the vessels using the River Thames by 2050.
- To identify optimal areas for the provision of infrastructure for the proposed energy solutions.
- To help form the basis of the infrastructure development plan for the tidal Thames indicating the type, locations, and timeframe for provision of infrastructure.
- To help the PLA to make an informed decision on its investment in technologies and fuel types for decarbonising the PLA's fleet and feed into the overall renewable energy strategy.
- To support operators and technology providers in their decision making in relation to low/zero emission technologies.

3. Methodology

3.1. Establishing the existing status

Desk-based research was undertaken to establish the existing circumstances on the Thames, with respect to the vessel fleet currently operational and their existing energy demand patterns. A diverse range of vessel types are active on the Thames however the operational patterns can be largely grouped into two main categories:

- Intra-port i.e., those for which all operational activities are contained within the Port of London limits (defined as the 'Inland Fleet' for the purposes of this study)
- Inter-port i.e., those for which operational activities pass in and out of the Port of London, whether moving between different port locations in the UK or overseas, or between offshore aggregate extraction sites (defined as the 'International Fleet' for the purposes of this study)

These operational differences, together with the relative influence of different aspects of the legislation and policy framework on the inland and international fleet strengthens the logic of dividing the fleet in this way.

It is noted that as an inland waterway, the Thames is subject to the EU Fuel Quality Directive 2009/30/EC which obligates the use of low sulphur fuel oil (10 ppm). The majority of inland vessels operating in the PLA jurisdiction therefore burn either LSFO (0.5%), ULSFO (0.1%) or, more recently, biofuel in the form of Hydrotreated vegetable oil. Given the small difference between the carbon emissions factor associated with HFO and LSFO however it was considered reasonable to estimate fuel consumption in this manner for this study.

International vessels are also obligated to burn lower sulphur fuel oil following the recent implementation of IMO 2020 regulations reduced the limit for Sulphur in fuel oil used on ships from 3.5% to 0.50%. There is also a requirement for vessels entering the Emission Control Areas (Baltic Sea, North Sea, North America, and the United States Caribbean Sea) that fuel oil with a maximum of 0.1% Sulphur (Ultra low) or Gas Oil be used.

3.2. Energy provision & solutions

The Study considers the energy provision options (technological and alternative fuel based) likely to be available on a commercially viable basis across the next 30 years and identifies those best suited to meet the needs of the inland and international fleets in a safe and regulated manner.

In addition to the identification of best suited energy solutions, the Study considered the potential locations for supporting infrastructure along the tidal Thames to identify optimal positioning that addresses the diversity of demand whilst utilising minimal operational land or water space in a safe manner. Needing to account for the varied constraints experienced throughout the available space on the Thames such as historical and environmental constraints, in addition to existing energy infrastructure, and with minimal disruption to shipping routes and other users.

3.3. Vessels in the Port of London

In the Clean Maritime Plan and the UK Sixth Carbon Budget the maritime sector is divided into domestic and international shipping, whereby domestic ships are those which have come from a UK port and are making a call at a different UK port; international shipping meanwhile is defined as ships calling at the UK port which have come from or are going to an international destination. For waterborne freight in the UK, the definition is slightly different splitting domestic traffic into Coastwise (between ports in the UK, including the Isle of Man and Channel Islands) and One-port (which captures vessels moving in and out of a single port location, such as offshore support vessels or aggregate dredgers).

For the purpose of this Study, the Inland Fleet is closely aligned with the defined 'domestic' fleet, however it is important to clarify that it is more specifically those vessels which may have the entirety of their movements within the Port of London as well as those which have their home berths in the Port of London yet may regularly carry out operations that takes them to other UK ports (e.g., Medway ports) and nearby EU ports (such as Antwerp). It does not however include aggregate dredgers which are covered by international regulations and as such are captured for the purposes of this Study in the International fleet.

It should be noted that non-merchant vessels and fishing vessels are not considered within this Study (as defined in the international categories in the Emissions Inventory e.g., naval, yacht, fishing vessel) and neither are private/recreational vessels.

3.3.1. Inland vessel numbers and fuel consumption

This data was then further sorted according to vessel categories (as defined in the 2016 Emissions Roadmap and analysed to separate out unique vessel movements from any movements of the same vessel between different berths. From this, estimated numbers of vessels in each inland category utilising the Thames in 2016 could be extracted and considered alongside the detailed operator fleet breakdown provided by the PLA. In order to identify the potential for changes in the fleet distribution, a desk-based review of the inland operators active on the Thames (and their respective fleets) was undertaken. Having established the number of vessels in each category within the inland fleet, current demand was estimated using the fuel consumption figures calculated for the archetypal vessels defined in the 2016 Emissions Roadmap.

Due to issues linked to commercial sensitivity it was not possible to secure specific data on annual bunkering demand and volume of different fuel types supplied on the Thames. Instead, building on the work completed to inform the Emissions Roadmap, the current energy demand and associated supply chain was inferred from a combination of publicly available information about the different bunker providers (including their existing

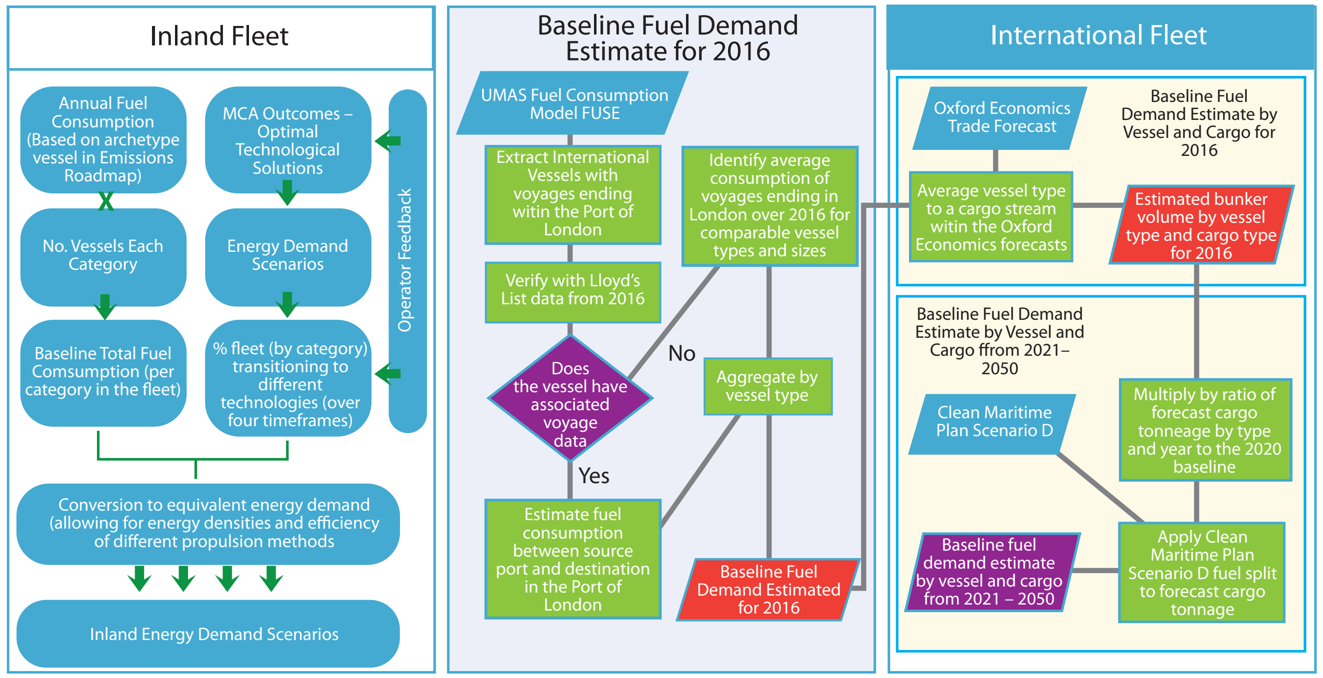

Figure 1 Process charts for demand calculations

barges and the fuels they supply) and the current infrastructure used for petroleum products and gas storage. In addition, frequency and location of bunkering activity was explored through interpretation of automatic identification system (AIS) data from a representative year (2016) with assumptions confirmed through consultation with stakeholders within the PLA and wider Thames community. In addition, a review of the inland fleet and publicly available information available on current fuel types utilised by different operators provided an additional quality assurance element to the current demand calculations.

3.3.2. INTERNATIONAL VESSEL NUMBERS AND FUEL CONSUMPTIONS

For the purposes of this Study, AIS data from 2016 was also analysed to identify international vessels with a voyage ending or beginning within the Port of London. This data was then verified according to a list of vessels observed within the Port of London during 2016 by Lloyd's List. Around 50% of the vessels included within the Lloyd's List data had associated voyage data. This is the same data set used in the Emission Inventory for the Port of London in 2016. For the vessels with voyage data, the total estimated fuel consumption of each vessel between the international source port and the Port of London destination port was calculated using UMAS' proprietary global AIS fuel consumption estimation model, FUSE. The Fuel Use Statistics and Emissions (FUSE) database draws on a time history of a ship's activity through AIS in combination with engineering and statistical models developed and validated against a series of ship owner reports to the IMO.

For the remaining vessels without voyage data that clearly ended within the PLA jurisdiction, the average fuel consumption figures of voyages that end in London over 2016 for the corresponding vessel types and sizes of those with observed voyage data into London were used as proxies. In this way, all vessels that are known through Lloyd's List to have visited the PLA jurisdiction are accounted for in this estimate.

The estimated fuel consumption was then aggregated by vessel type, to provide baseline fuel demand estimates for 2016. Each vessel type was then assigned a cargo type to map to the taxonomy used in the Oxford Economics trade forecasts prepared for the PLA in relation to the Thames Vision 2050. This generated an estimated bunkering load by vessel and cargo type for 2016. The fuel mix used to inform the current demand levels was based on the international fuel distribution for scenario D calculated in the 2019 Department for Transport Clean Maritime Plan and included a mixture of liquified natural gas (LNG), Low sulphur fuel oil (LSFO) and marine diesel oil (MDO).

3.4. SPATIAL DISTRIBUTION OF SOLUTIONS & DEMAND

The detail of these operational patterns was an important element of establishing the baseline for this Study and in particular to understand any 'hot spots' of activity and therefore operational synergies (or potential conflicts) that may be relevant for future energy supply patterns. The movement of the vessels and the key infrastructure used by different vessel types was analysed using a number of key data sources provided by the PLA and available publicly.

Understanding the relative intensity of 'home berth occupation' as well as regular 'calling points' of different operators was important when considering the potential for different supply models as they may be relevant for various technological solutions. The central reaches around Westminster Bridge to Charing Cross Railbridge, to Waterloo Bridge and London Bridge to Tower Bridge for example are known to experience vessel traffic levels near/at capacity with some congestion developing during peak periods. A capacity study completed in 2016 considered the existing distribution of risk across central London reaches identifying hot spots adjacent to Tower Pier and HMS Belfast, Westminster/London Eye, Bankside Pier and Coin Street Moorings.

A Geographical Information System (GIS) model of the tidal Thames has been developed as part of this Study to facilitate the identification of potential locations for infrastructure to support the energy demand scenarios identified. Data was collated from the PLA and supplemented with information compiled from a range of publicly available data sources relating to:

- The existing infrastructure on or adjacent to the Thames.
- Planned infrastructure on or adjacent to the Thames.
- Existing site and land use data.
- Geospatial constraint data linked to operational constraints such as navigational limitations.
- Geospatial constraint data linked to ecological and non-ecological constraints.

All broadscale data utilised to in the spatial constraints analysis were drawn from reputable open-source data layers including for example, the Ordnance Survey, National Grid etc. More localised data was drawn from relevant local authority web portals (i.e., to map future development areas and allocated land) and operator websites (i.e., to understand expansion plans).

The following scenarios have been explored through the site selection process:

- For the PLA's fleet, two potential long term end points were considered, based on a high proportion of the fleet transitioning to one of two long term energy options (with the potential to meet the long-term targets for decarbonisation). Within this, transitional options are explored within the context of the four PLA sites.
- For the inland vessels three potential energy transition end points were considered, based on a high proportion of the inland fleet transitioning to one of the three long term energy options (with the potential to meet the long-term targets for decarbonisation). As for the PLA fleet, transitional options are explored along with smaller scale supply options linked to energy demand by reach (where relevant).
- For the international vessels an upper bound approach was adopted, taking the maximum long term potential demand for the international fleet.

For each of these scenarios a set of basic functional requirements was prepared using the annual demand quantities estimated, linked to 'whole river', 'whole fleet' and, where appropriate, 'reach specific' demand.

The 'functional requirements' for infrastructure vary based on a number of key factors, including:

- The supply chain/distribution model;
- Whether the energy carrier is imported or generated locally; and
- Whether the energy carrier is a fuel or battery (electricity) based.
- Whether the infrastructure is designed to support a large quantity of energy carrier/fuel.
- Whether the infrastructure is intended to be a permanent/long term asset or temporary/moveable option.

The preferred features of the sites were prepared based on the following aspects:

- Size: Is the footprint of the site sufficient to support the likely scale of infrastructure needed to store or generate the alternative fuel and ancillary infrastructure like site access?
- Vessel access: Is the channel depth and berth pocket sufficient (or can it be made so) to enable the vessel types typically used to import the alternative fuel / anticipated vessels to be used for import of the alternative fuel?
- Existing features: Does the site have some existing infrastructure that could help to reduce the capital expenditure and/or the complexity of planning associated with the alternative fuel/energy source?
- Geographic: Is the location of the site within a reasonable travel distance of the end consumers of the alternative fuel/ energy source?

The following key constraints were integrated as 'negative drivers' of the spatial analysis:

- Designations: Protected areas of the river or land adjacent to the river with ecological/non-ecological designations such as world heritage sites.
- Surrounding land use/infrastructure: Proximity to locations that are likely to be incompatible due to the hazards associated with certain alternative fuels. For example, highly flammable or toxic fuel types will not be compatible with areas with high densities of people such as residential areas/areas used for commercial purposes (e.g., office), or critical transport infrastructure (e.g., rail).
- Operational constraints: Any designated exclusion zones, or areas of the river considered navigational pinch points.

For the purposes of the site selection process, some 'hard constraints' were defined, these are outlined in Table1. These are the land and marine areas that were considered to be 'red flags' at present, for infrastructure development and are applicable for both the inland and international fleet.

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Table 1 Hard Constraints defined for site selection

Designations	Operational constraints
Ancient woodland	Land adjacent to tunnel prohibited anchoring areas
Natura 2000 (RAMSAR, SAC, SPA)	Exclusion zones defined by the PLA's by-laws, wreck obstruction points and zones
Coastal saltmarsh	The Thames Estuary 2100 potential barrier locations
Coastal vegetated shingle	Dumped munitions
Reedbeds	
Saline lagoons	
Other nature reserves	
Scheduled monuments	
World heritage sites	

3.5. OPTIMAL SOLUTION SELECTION

Given the myriad factors influencing the suitability of different energy carriers for different vessel categories active on the Thames, a multi-criteria analysis (MCA) approach was taken to the assessment of the various options. This methodology is in line with the guidance presented in PIANC WG185: Ports on greenfield sites, guidelines for site selection and master planning. It is important to note that whilst this PIANC guidance document refers to greenfield sites, it is not the intention or recommendation of this Study that infrastructure be built on greenfield sites; rather It is the approach to using an MCA in site selection and master planning contained within this guidance. which represents industry best practice, that has been utilised to inform this Study.

This approach was applied to identify optimal solutions taking into account a wide range of drivers including safety and operational considerations, environmental and social implications, commercial aspects, and technical feasibility. Importantly, this approach gave appropriate weighting to the relative opportunity presented by each technological solution to achieve decarbonisation within the necessary timescales. The optimal technological solutions must meet the operational needs of the inland and international fleet.

The next stage was to consider the future energy demand and understand the spatial and infrastructure implications of servicing that demand i.e., supplying the required amounts of different fuel types in the optimal locations. This site selection process explored a number of different scenarios to reflect the outputs from the multi-criteria analysis.

The initial criteria for technology solutions were defined based on two main aspects:

1. The likely maturity of the alternative fuel and the technologies associated with the fuel or energy carrier (e.g., production, storage, bunkering and propulsion technologies). This criterion necessarily reflects both availability at a commercial scale and the existence of pilot projects that are underway, helping to demonstrate the viability of the technology for different vessel categories.
2. The ability of the alternative to meet the known policy targets and regulatory requirements within the timeframe in question, drawing on the outcomes of policy review.

Initially appraising the list of available fuels and technologies, then specifically considering their use in the Thames environment, the port constraints and urban areas (Table 2).

Several factors were taken into consideration when choosing the most effective refined evaluation criteria, drawing on industry best practice:

- Completeness: have all important objectives and sub-criteria been included and is there agreement on what is most important?
- Effective: is there enough information available to score the sub-criteria, and do the sub-criteria discriminate between the options?
- The options be assigned on one sub-criteria without knowing the scores for other sub-criteria?
- Double counting: can sub criteria be combined to minimize the effects of double counting?
- Size: are there enough sub-criteria to form an effective and critical evaluation but with no more sub-criteria than necessary?

It is important to note that the MCA is focussed on assessing the technological solutions (i.e., the fuel/energy carrier) through the lens of the whole Thames community (e.g., the operational vessels, the people living and working on and around the river).

As per the PIANC WG 185 framework, a comparative evaluation of relative criteria importance was undertaken by comparing each criterion against every other within the objective group to arrive at weightings. This is referred to as a 'pairwise comparison'. The pairwise weighting system works by stating that one criterion is more important than another on a defined scale and producing corresponding counts against each criterion

3.6. Demand Scenarios used

Due to the differing timelines and targets relevant for decarbonisation and emission reduction, the criteria was based on four defined time horizons for Inland vessels;

- Near term: 2021-2025
- Short term: 2026-2030
- Medium term: 2031-2040
- Long term: 2041-2050.

3.7 Uncertainties, assumptions and limitations

Data used by Royal HaskoningDHV and UMAS provided by the PLA, as well as information secured through Lloyds Register, AIS systems and public sources. During the course of the Study, additional information has become available (either from the perspective of policy or pilot project engagement from operators) reflecting the rapid pace of change in this field at the time of writing. It is possible that some of these details are absent from this report because of the timing of the analysis work and the need to complete investigations within the confines of the Study programme.

Table 2 Multi Criteria chosen for analysis

Objective	Criteria
Environment & Social	Reduction in GHG emissions (tank to wake)
Environment & Social	Reduction in other air pollutants (NO_x/SO_x/PM etc)
Environment & Social	Level of potential harm to the environment and human health if spilled/ leaked (e.g., toxicity/ methane slip etc)
Environment & Social	Spatial extent of infrastructure required (to reflect scarcity of land on Thames and opportunity cost of the land use)
Commercial	Estimated cost of energy/fuel relative to current business as usual fuels (e.g. MGO)
Commercial	Scale of investment needed for storage and bunkering infrastructure/ assets
Commercial	Scale of investment needed in the vessels
Commercial	Opportunity to create a biproduct with additional income benefits or local circular economy opportunities
Commercial	Likelihood of external funding availability based on investment landscape (both positive and negative movements)
Technical	Likelihood of reliable feedstock for Thames's region
Technical	Maturity of regulations/ guidelines for fuel use/ power source
Technical	Requirement for ancillary infrastructure upgrades to support the alternative (e.g., grid capacity)
Technical	Potential to integrate with the existing fleet
Safety & Operations	Level of risk associated with the use, carriage and storage of the alternative linked to flammability/ volatility and compatibility with other products being handled adjacent to the river.
Safety & Operations	Spill hazards and scale of potential impact on operations during or post incident
Safety & Operations	Compatibility of the alternative fuel with vessel's geometry, weight requirements and operational profile (range, frequency of stops)
Safety & Operations	Level of complexity for operational transition

The PLA's reports on passenger pier use, capacity study, technology road map, Emission Inventory, Thames Vision, and Trade Forecast were also utilised. The PLA also conducted a survey of operators which was anonymised and shared with the Study. However, many requests were not returned so limiting the use of this source. The confidential nature of activity, i.e. bunkering provision, limited some certainty in the model.

The approach used for international vessels is based on vessel arrivals rather than unique vessels visiting over the course of the year. This is considered to be a reasonable basis for the international fleet as this is more representative of levels of activity and therefore a useful proxy for bunkering opportunity (and thus potential demand) within the Port of London.

The Oxford Economics forecasts are unconstrained forecasts which assume that the supporting infrastructure either has capacity to handle the predicted growth, and the different cargos to be handled or that it will develop at a pace necessary to support additional cargo handling, including any increases in vessel size and draught. Specific data on existing berth cargo utilisation at the main international terminals on the Thames was not available to inform this energy demand study however industry knowledge indicates that some capacity is likely to exist both in terms of berth availability and vessel capacity although this is known to be limited.

In order to explore the relative potential of the different modular options, a review of the available data linked to grid infrastructure also informed this part of the site selection process. Limited publicly available data was available related to the grid infrastructure.

It is important to note that information about the age of the existing fleets was not available to inform this Study and it was not therefore possible to take the timing of fleet replacement into account in the scenarios.

4. Current energy supply and demand

Supply

There are a total of sixteen existing terminals along the Thames banks that are licenced and able to store large volumes of chemicals or fuels with the potential to cause serious harm to people and/or the environment designated under Control Of Major Accidents Hazards (COMAH) Regulations. Some of those already provide marine fuel to the bunker vessels.

Bunkering of international vessel categories is expected to be primarily executed by means of a mobile bunker barge, with bunkering taking place as the vessel is berthed at its destination terminal. Current demand for bunker fuel from the international fleet is quite low in the Thames and largely influenced by macroeconomic factors beyond the control of the PLA and other operators on the river.

There is a geographic demand difference as a result of the bunker service, type of vessel and the demand (Table 3).

Table 3 Geographical spread of vessels

Type	Location of operation on the river.
Inland vessels	
Tug/Supply	Tugs operate across the stretch of the Thames; ● Ship towage tugs operate as far west as Tower Bridge. ● Freight tugs operate from a number of wharves across the river.
Work boat	Both across the Thames and further outside of the PLA's jurisdiction
Service Vessel	Construction and maintenance operations utilising these vessels occur all throughout the river, and beyond.
Harbour Vessel	Harbour vessels operate in three separate areas: ● upper from Teddington to Putney; ● middle from Putney to Barking; and ● lower from Dagenham downriver.
Emergency vessels	Not restricted to a particular stretch of the Thames
Crossing Ferry (Ro-Ro)	Woolwich Reach
Crossing Ferry Passenger	Crossing routes on the Thames are Gravesend-Tilbury and Canary Wharf- Rotherhithe.
Charter vessel	Berths and operations span further West than Teddington, to further East than Gravesend
Small Charter vessel	Operate across the Thames, with their operational range extending outside of the PLA's jurisdiction.
Tourist Vessel	Central London, with the furthest berths called at being Westminster to Greenwich. Some vessels traverse to Hampton Court Downriver as Southend Pier, travelling to Queenborough
High Speed Passenger	Currently operations span from Putney to Woolwich (Royal Arsenal).
Rib	PLA operates a single rib and as such is operates from Gravesend to Teddington. Other operators are based from Westminster to focus on tourists in Central London
Shipping	
Passenger Cruise	Tilbury, Greenwich Ship Tier, George's Stairs, Tower Bridge Upper, West India Docks and the Royal Docks.
Bulk Carrier	Thames Refinery being the most upstream berth accessible by these vessels prior to the Thames Barrier
Containership	Below the Dartford Crossing, so regularly dock at either the Tilbury or London Gateway terminals
Dredgers	Victoria Deep Water Terminal is the further upstream international dredgers operate.
Chemical/LNG/LPG Tanker	Stolthaven Dagenham and Calor Gas terminals, with smaller vessels appearing to transit across the Thames Barrier.
Oil Tankers	With the furthest destination upstream of Stolthaven terminal, Dagenham, many terminals up to Stolthaven are serviced by these vessels

4.1. Demand

Inland

The fleets often use the same floating bunker services provided to the domestic and international shipping. In some sites where the operating company owns a home berth, pier of jetty, within the infrastructure there is fuel stored for interim bunkering to the operational vessels.

Although the majority of inland vessels continue to be fuelled by traditional low sulphur marine diesel, a number of operators are already adopting lower emission fuel options with the uptake of biofuels (including HVO and gas-to-liquid (GTL)) a particular growth area in recent years. Onshore electric charging (also referred to as 'shore power' or 'cold ironing') is also increasing on the river.

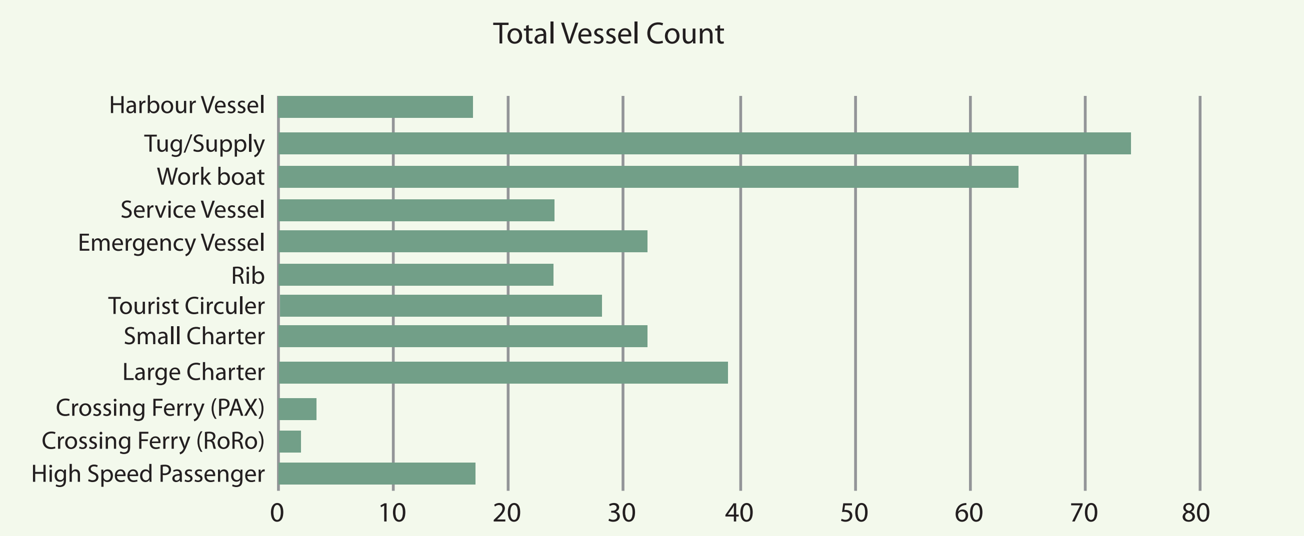

Figure 2 Total count of inland vessels

4.2. International and Domestic shipping

The 'size' of the international fleet active within the Thames fluctuates over the course of any given year, influenced by macroeconomic factors and drivers of the international shipping and logistics markets linked to different commodities, so the baseline year can only be considered as an indicative year.

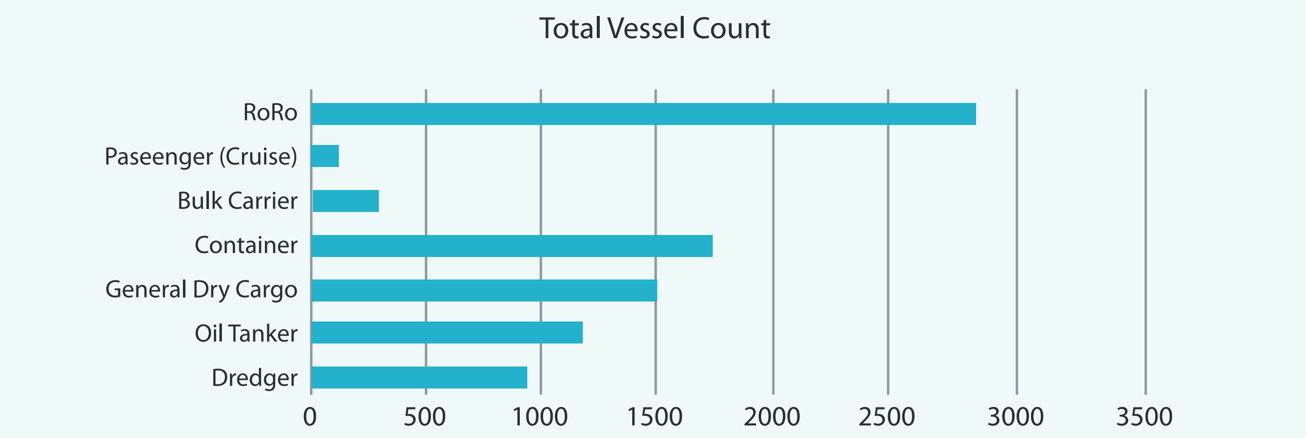

Figure 3 Total count of International vessels

5. Technological Fuel solutions

The current fuels used throughout the Thames are all derived from fossil products and while they provide complete compatibility with the current Thames fleet, their continued use is incompatible with the aim of Net Zero carbon emissions by 2050.

A wide range of potential alternative energy carriers are currently being considered by the maritime sector as options to enable decarbonisation of inland and international shipping;

- **Biofuels** are produced from biomass and produce lower carbon emissions from Well-to-Wake than conventional fuels. Depending on the feedstocks and production chain, biofuels can effectively be carbon neutral due to carbon sequestered by the biomass used to produce the fuel. Due to their similar chemical characteristics to conventional fuels, these can often be used as "drop-ins", with no or minimal changes required to a vessel to accommodate this fuel type. Much of the existing bunkering infrastructure on the Thames could be transitioned to biofuels with relatively minimal changes. The compatibility of drop-in biofuels with international vessels appears high with several successful trials already conducted although there are concerns about availability of biofuels for maritime given competition from other sectors, specifically aviation.
- **Diesel-electric hybrid** vessels still run on fossil-fuels but can either utilise electric motors for peak-shaving of operations or utilise a plug-in hybrid model where vessels are charged at shore to later use the stored energy during voyages. These typically offer 15% fuel/carbon savings compared to conventional fossil fuels and powertrains. There a number of different types of hybrid vessels operating on the river. For retrofits however, to enable the installation of a hybrid/battery energy system, the volume of either fuel stored, or

cargo carried would likely need to be partially sacrificed.

- **LPG (Liquid Petroleum Gas)** is made from a mixture of hydrocarbon gases, often propane and butane, and is widely used in domestic and industrial uses globally. Due to this widespread handling, LPG already has several recognised regulations and guidance documents, facilitating its safety in use as a maritime fuel. When combusted, LPG has much lower air pollutant emissions than conventional fuels (97% less SO_X and 90% less PM), and slightly lowered carbon emissions, though the level of total carbon emissions is dependent on the production pathway. One of the largest constraints is its volumetric density, requiring a larger volume to store the same amount of energy as conventional fuels, reducing cargo/passenger capacity on vessels.
- **LNG (Liquid Natural Gas)** is made from natural gas, primarily methane with a smaller concentration of ethane. With its industrial and residential use globally, several key regulations and standards are in place for its safe transport, with LNG covered by the IMO IGF code. Similar to LPG, LNG has multiple generation pathways, though LNG generally offers lower air and carbon emissions than LPG (up to 100% less SO_X and 90% less NO_X and PM emissions than conventional fuel). LNG bunkering is currently offered at 96 ports globally, including at the Isle of Grain Terminal in the River Medway.
- **Hydrogen (H_2)** when utilised as a fuel can be either stored as a compressed gas (GH), or cryogenic liquid (LH) and offers comparatively high gravimetric energy density, though with higher operational costs. Hydrogen can be either produced from natural gas or ammonia in a reformer (fossil/grey), from residual biomass in an anaerobic digester and reformer (bio), or in an electrolyser powered by low-carbon electricity to split water into oxygen and hydrogen (green). While several standards are available on hydrogen generally, there are currently no regulatory clarity on its use as a marine fuel. Evidence suggests that hydrogen Internal Combustion Engines (ICEs) are only operational at demonstration level with a maximum output of 1-2MW. As a fuel hydrogen can be used in both ICE and fuel cells, with fuel cells offering higher powertrain efficiency and no GHG or air pollutants, while ICEs require a pilot fuel such as diesel. Hydrogen generation and storage requires investments in infrastructure to manage boil-off gas or pressure, however, the conversion of storage infrastructure to store hydrogen from LPG is relatively straightforward.
- **Ammonia (NH_3)** is currently widely traded globally due to its use in the fertiliser industry, it has high potential for use as a marine fuel, but challenges arise from its safe usage. With this high current trade, much infrastructure to accommodate ammonia is already present in the UK and EU, with ammonia terminals already in operation in the UK. Several ammonia-powered international vessels are in development, though no inland vessels are currently being progressed. As for hydrogen, ammonia is able to be used in either an ICE or fuel cell, however nitrogen oxides are produced when burnt in an ICE, requiring selective catalytic reduction to eliminate NO_X emissions. It is generally stored semi-refrigerated or under pressure, and is highly corrosive to certain materials, with storage vessels requiring protection against this. While more toxic than hydrogen, ammonia offers benefits in its comparatively higher energy density and cheaper storage options. Current IGC code permits the transport of ammonia, however international regulations currently prohibit its use as a marine fuel, with significant uptake of the fuel not expected until 2030.

- **Methanol** offers an alternative zero/low carbon option, that is generally safe when used a marine fuel. It is currently widely transported globally and benefits from widespread familiarity as a bulk product, though is toxic to humans. While methanol use as a marine fuel is currently limited, the IMO has recently published interim guidelines on the use of methanol as a marine fuel. With several generation pathways, the level of carbon emissions can vary widely depending on its source. While methanol has been suggested for use in inland vessels, current examples are limited to the "Methatug" at the Port of Antwerp. Methanol benefits from many ports globally having current methanol storage facilities, while current conventional fuel storage facilities would only require minor changes to enable methanol storage. ICE retrofit options are available by modifying the fuel injection system but due to a lower volumetric density, methanol would require approximately 2.3x more space to house the same amount of energy as conventional fuels.
- **Battery-electric** vessels utilise on-board battery storage to power a motor that then controls the propeller and are charged at berth normally through a direct cable connection. These systems enable zero tailpipe and noise emissions, and if combined with a renewable energy source, can be a zero-carbon form of transport. Many fully electric inland and international vessels are in operation or development, with inland battery electric vessels in operation since 2014. However, batteries suffer from greatly reduced

energy densities, producing issues for retrofitting due to requirements for much increased volume and weight to store the same amount of energy. Current battery-electric ships ranges limited to approximately 95km and therefore battery-electric suits inland vessels more than international vessels. To supply sufficient electricity to vessels at berth, spare capacity in local grids is often needed, with local renewable generation possible to offset a proportion of the total energy demand.

Many of the 'new' fuels being considered for marine use have been commonplace in industry for many years. Hydrogen, Methanol and Ammonia for example have been produced stored and transported in various forms for some time. As a result, we can look to sectors such as petrochemical and fertiliser production can be used as exemplars for guidance on appropriate regulation, guidance and best practice. Similarly, much of the supporting engineering services around clean fuel systems and installations can be informed from experience in industry in its broader sense. As a result, all major engineering institutes (e.g., IMechE, IGEM, IEEE) are developing guidance and standards in this topic area. The Maritime & Coastguard Agency (MCA) have yet to publish marine guidance notes covering these topics (although they are currently consulting on a draft guidance note covering nuclear powered ships).

Where standards do not yet exist for maritime use a suitable proxy has been identified; for example in relation to hydrogen bunkering the requirements for LNG bunkering have been considered an acceptable proxy and the recommendations set out by the Society for Gas as a Marine Fuel (SGMF) Working Group 2 have been used to inform safety constraints. For smaller volumes of hydrogen storage, guidelines that exist for hydrogen refuelling stations for the land transport sector are utilised, with consideration also given to LNG refuelling as appropriate.

Table 4 Technological solutions temporal availability and suitability

	Near Term (2021-2025)		Short Term (2026-2030)		Medium Term (2031-2040)		Long Term (2041-2050)	
Technological Solution	**Inland**	**International**	**Inland**	**International**	**Inland**	**International**	**Inland**	**International**
Heavy fuel oil/ marine gas oil/ marine diesel oil	*Included to provide a business-as-usual benchmark against which to assess alternative options. As a solution it does not meet any of the Gate 1 criteria linked to emission reduction targets.*							
Diesel - electric hybrid	Y	Y						
LPG (Fossil)	Y	Y						
LPG (Bio)	Y	Y	Y	Y	Y	Y		
LNG		Y						
LNG (Bio)				Y		Y		
LNG (E)				Y		Y		
Biofuels (HVO/FAME/HTL/ Pyrolysis fuel oils etc	Y	Y	Y	Y	Y	Y		
Ammonia (Fossil/Blue)		Y						
Ammonia (Bio)								
Ammonia (Green)				Y		Y	Y	Y
Hydrogen (Grey/Blue)		Y						
Hydrogen (Green)	Y	Y	Y	Y	Y	Y	Y	Y
Hydrogen (Bio)								
Methanol (Fossil)		Y						
Methanol (Blue)								
Methanol (Bio)	Y		Y	Y	Y	Y	Y	Y
Methanol (E)	Y		Y	Y	Y	Y	Y	Y
Battery-Electric	Y		Y		Y		Y	

6. REGULATORY AND SAFETY CONSTRAINTS

Thames Specific Regulatory Review by Arcsilea for the PLA.

Most of regulations set by the Port of London Authority relevant to future fuels, deal mainly with operational matters – navigational issues, restrictions on the river, reporting requirements, oil spills. In examining these regulations, it is likely that changes need to be made in some parts as follows:

- Reportable incidents relevant to alternative fuels,
- Definition of bunkering for reporting,
- Listed propulsion fuels within the port limits,
- Pilot Requirements for vessels carrying fuels as cargos,
- Navigational simulation Requirements, and
- Training requirements

The issue of exemptions or exceptions or special permission has been investigated. Generally, exemptions to the Byelaws may not be granted, however exemptions to the Directions, Thames Freight Standard and Codes of Practice may be allowed subject to an application. For navigational issues, passage planning and a navigational risk assessment needs to be submitted however the exact requirements are on a case by case basis.

For alternative fuels, batteries and wind propulsion, a clear regulatory framework that takes into account new safety requirements, providing an overview of the new risks and possible mitigating actions, is missing to facilitate certainty of port regulation. In the event that bunkering and storage of alternative fuels is implemented on the Thames, guidance on safety distances would be required.

While these aspects are being considered by the PLA and discussed with regulators the PLA has issued a Statement regarding the existing approach. https://www.pla.co.uk/Environment/Statement-Working-toward-bringing-new-alternative-fuels-onto-the-river

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7. FUTURE ENERGY SUPPLY AND DEMAND

Bunkering activities within the Thames are understood to take place by means of (a combination of) the following modes:

- By mobile bunker barge,
- By static bunker barge (permanently moored),
- By road tanker (lorry),
- By flexible hose, connecting to terminal pipelines.

For the inland vessel categories, bunkering takes place wholly within the PLA's jurisdiction albeit in various locations depending on demand patterns. Bunkering is prohibited within certain areas of the river such as the exclusion zones present along the river.

The majority of the bunker barges operating on the Thames provide traditional Low Sulphur Gas Oil (LSGO) or Ultra Low Sulphur Gas Oil (ULSGO) however HVO and GTL fuel are also available. GTL is a diesel alternative that is made from natural gas (as opposed to crude oil) and can lower local emissions.

7.1. INLAND

The Study's analysis resulted in the same technology types as the Emissions Roadmap, being most appropriate with the inland fleet and largely aligned with the previous work, but one additional fuel, methanol, has been added to the present work as an emerging option for inland craft.

7.1.1. INLAND NEAR TERM

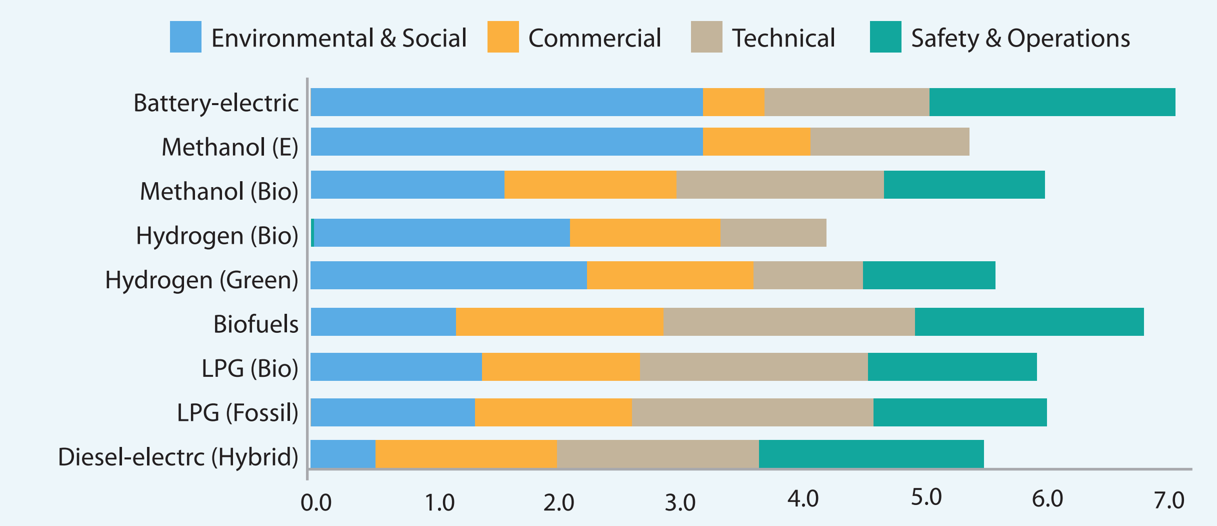


Figure 4 Inland available technology Near Term

In the Near Term therefore, energy demand scenarios should provide for broadscale adoption of biofuels with some pilot battery-electric adoption, and diesel-electric hybrid. There is potential also for pilot projects linked to hydrogen/methanol, however these are anticipated to be linked to specific funding opportunities and pick up on operator feedback indicating interest from some in these alternatives in the near to short term.

7.1.2. Inland Short Term

In the short term, biofuels and battery-electric continue to score strongly for the inland fleet with a slight increase in the scores linked to hydrogen. Methanol also scores reasonably well although there is limited change from the near-term score due to the relative maturity of the regulatory landscape around its use as a marine fuel (in comparison to hydrogen).

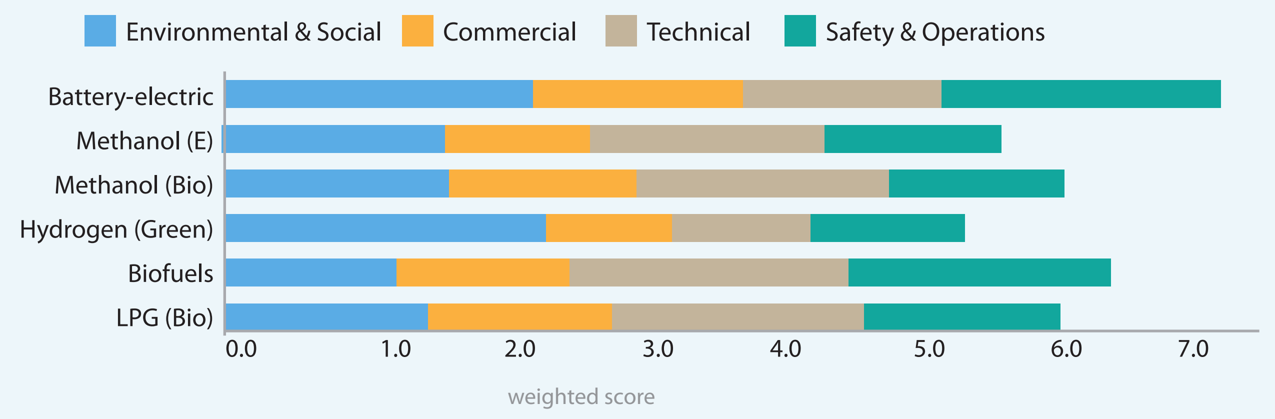


Figure 5 Inland available technology Short Term

7.1.3. Inland Medium Term

In the medium term, there is a more pronounced shift for zero emission fuels/energy carriers, for example hydrogen, reflecting the increasing pressure on achievement of decarbonisation targets and associated unfavourable landscape (commercially) for carbon-based solutions.

The policy trajectory suggests that securing new build vessels powered by fossil fuels is likely to be very challenging beyond 2030 (potentially impossible) and therefore demand for fossil fuels will instead be limited to supporting the remaining lifetime of existing assets in a reducing way. Furthermore, as supporting infrastructure is established more broadly in the UK to provide a supply chain/feedstock for alternative fuels.

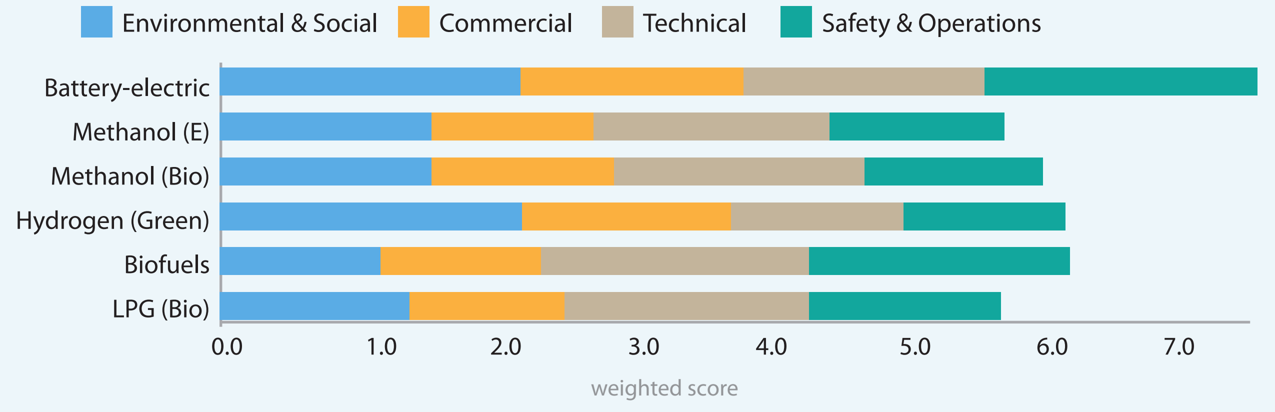


Figure 6 Inland available technology Medium Term

7.1.4. Inland Long Term

In the long term, demand for fossil based and transitional fuels falls away with zero emission technologies taking over. Although the MCA attributes very low scores to any fuels that are not zero emission in this decade, taking on board operator feedback and giving consideration to the Emissions Roadmap, it is recognised that there may likely still be some small demand for low emission fuel options, such as biofuels, but these will be in diminishing volumes as existing vessels come to the end of life and/or are replaced by newer vessels which are Net Zero enabled.

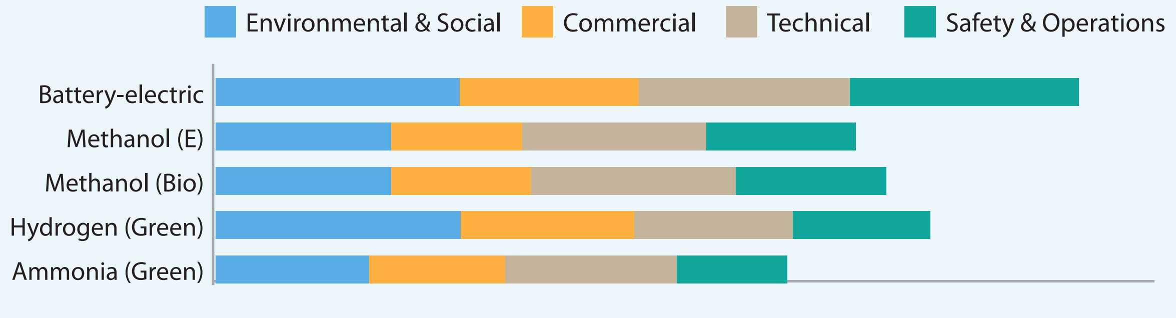


Figure 7 Inland available technology Long Term

7.2. Shipping

The trajectory for the international fleet is different to the inland fleet, reflecting the different challenges that ocean going ships face in terms of distance between port calls and therefore the larger volumes of fuel required to facilitate those journeys.

Electrification for example is anticipated to have a limited number of niche applications for international vessels, primarily as the size (and weight) of batteries versus power output are likely to be a challenge for some time. The requirement from international shipping to depend on fuels with high energy densities (and therefore possible to be carried without taking too much space or adding too much weight) is likely to restrict the uptake of battery-electric for this part of the fleet. Research carried out by UMAS indicates that significant breakthroughs in battery capacity and cost by 2050 would be required to out-compete liquid fuels in those larger ships and longer journeys that make up the majority of UK emissions.

LNG has a transitional role for international shipping however the challenges of securing finance for carbon-based fuels beyond 2025 is anticipated to shift focus onto more rapid uptake of ammonia or hydrogen. Many shipping lines, including those visiting the Thames have announced, or are, adopting LNG in the immediate future. As shipping lines would need to make significant investments to retrofit existing ships/order new vessels, and in light of the fact that LNG is not a fuel which offers zero emissions benefits, there is potential that the uptake of this option will be limited.

Biofuels feature in the energy mix for international shipping, particularly in the earlier time horizons, reflecting its current availability and the technical feasibility of their use as 'drop in' fuels. As time passes however competition from other users (i.e., aviation) and challenges with securing ethically robust feedstocks present barriers to uptake sustaining demand into medium time horizons.

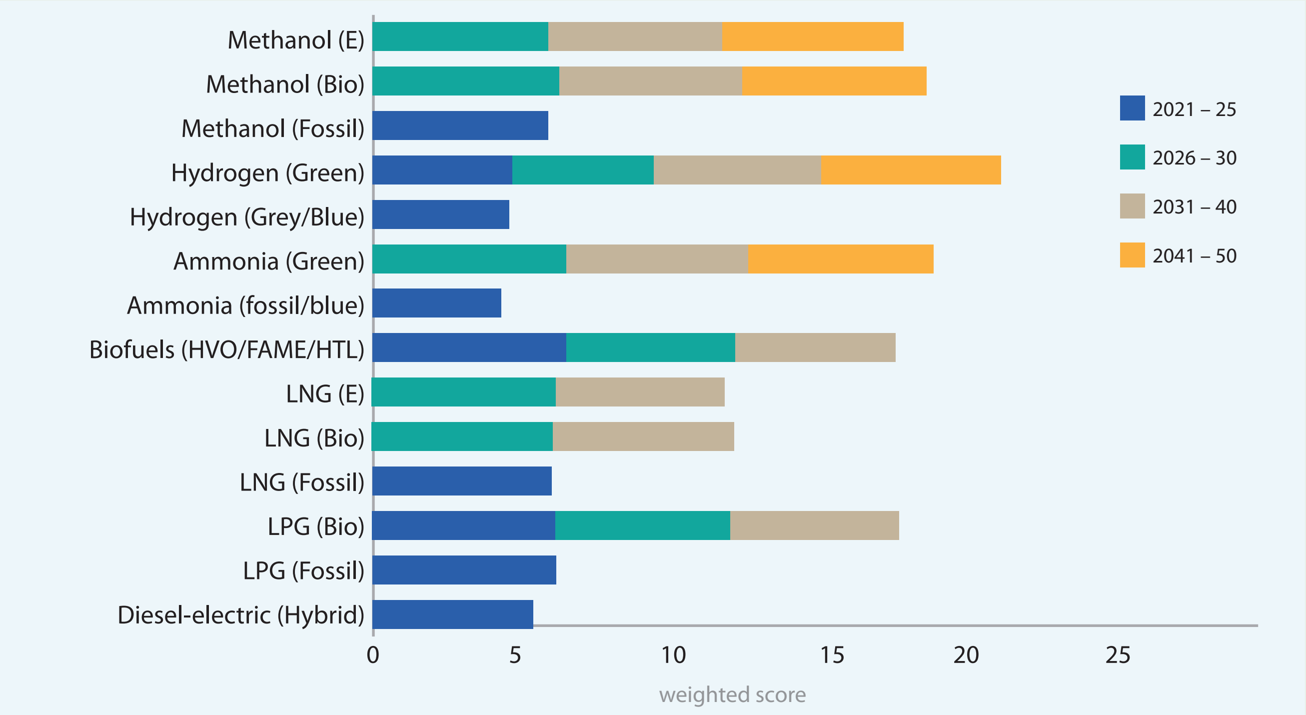


Figure 8 International available technology over all time horizons

Despite the low safety scores linked to health and safety risks associated with handling ammonia as a fuel, it scores well from a technical and commercial perspective for the international fleet due to the potential to retrofit ship engines at relatively low cost, the higher energy density of ammonia compared to hydrogen (and therefore a much lower commercial penalty due to smaller fuel tanks onboard taking up less space), and the lower cost of ammonia production compared to methanol by the medium time horizon.

More importantly, hydrogen looks set to be more expensive than ammonia for some time to come and as infrastructure decisions need to be made in the next 10 years or so (in order to enable a zero emissions outcome by 2050) the higher confidence levels in commercial scalability of ammonia as a marine fuel is anticipated to drive a dominance of this energy carrier over hydrogen.

This outcome is in line with the scenarios used to underpin the Clean Maritime Plan in the UK and picks up on the changing trajectory of regulation for shipping in Europe as well as the shifting picture of shipping finance.

8. Demand

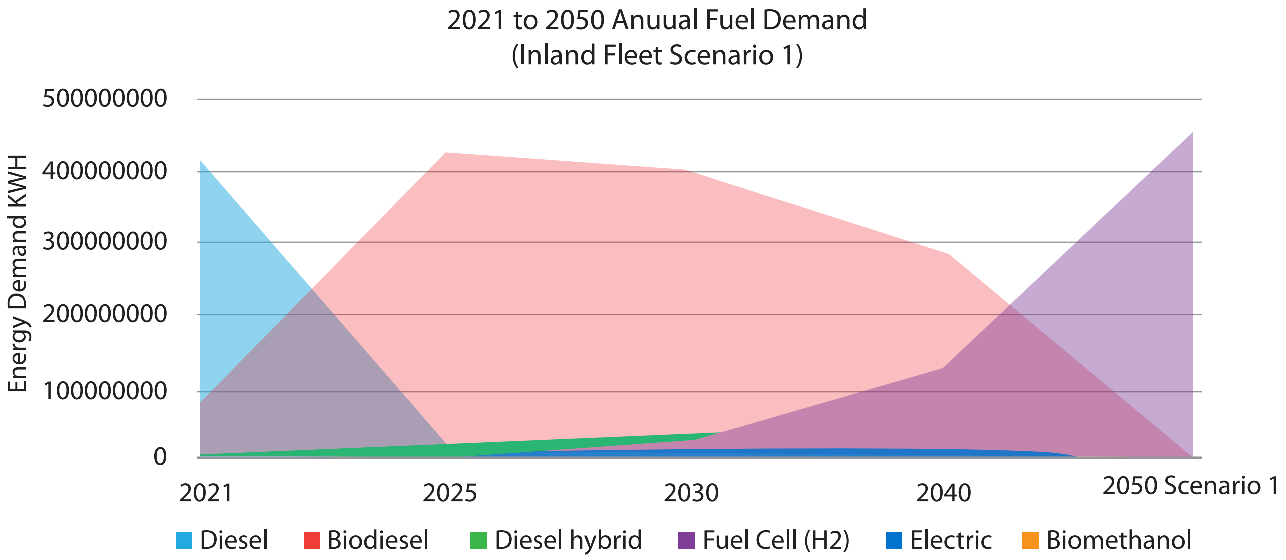
8.1. Inland Scenarios

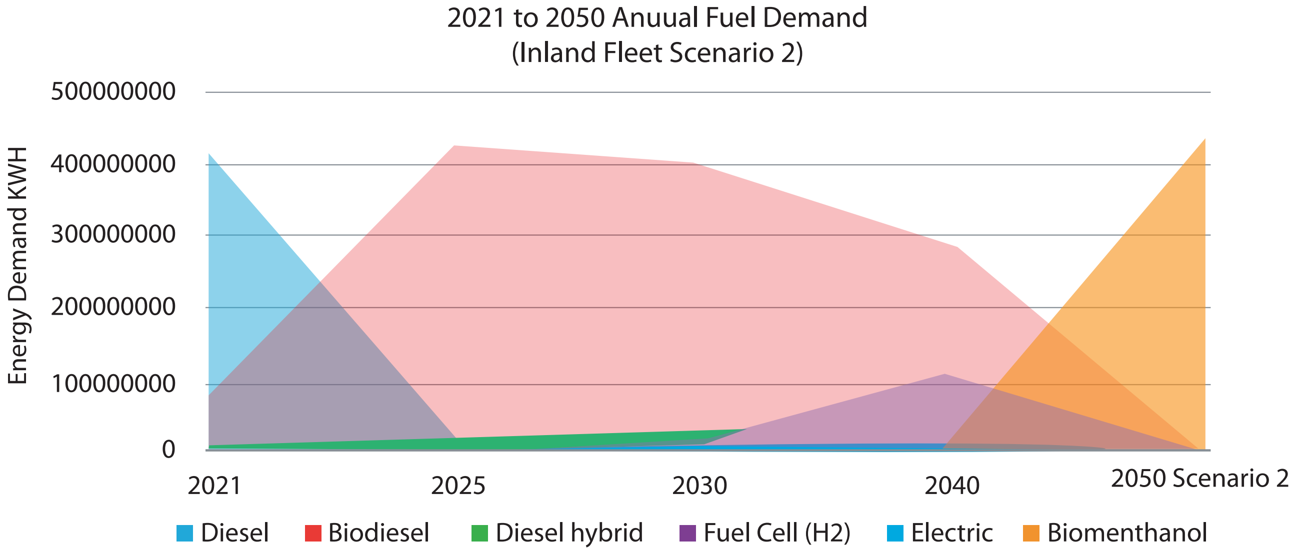
The technology transition scenarios for the inland fleet, based on outcomes of the multi-criteria analysis were defined. These scenarios are linked to the 'whole energy demand' requirements of the inland fleet (in order to understand the maximum demand potential that may need to be met);

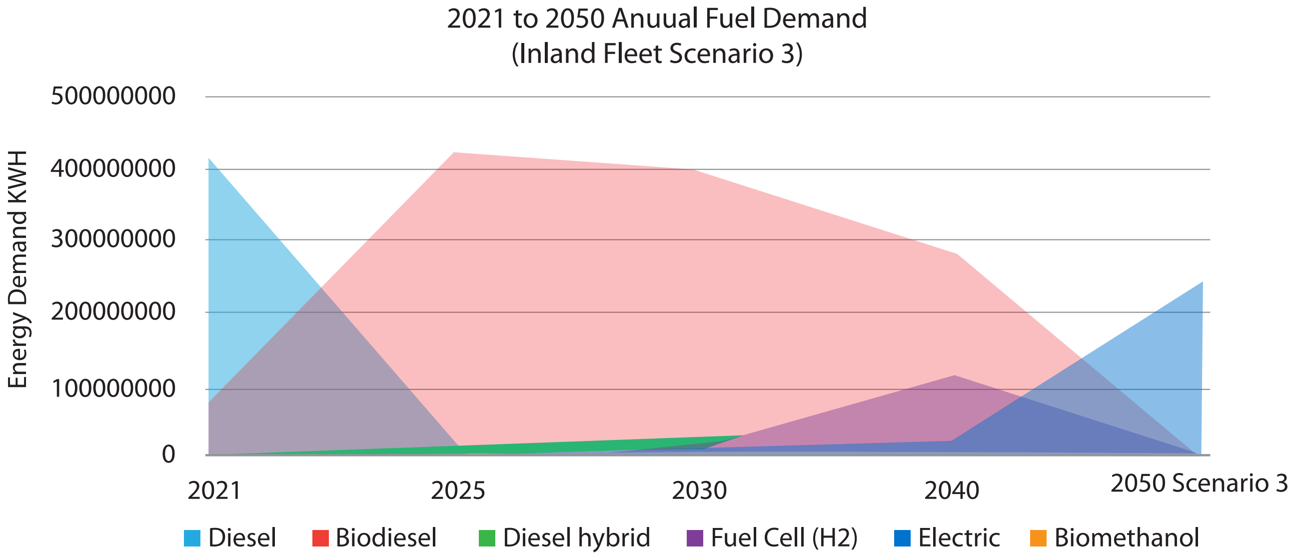
- Scenario 1 – Full inland fleet transitions to Hydrogen fuel cell
- Scenario 2 – Full inland fleet transitions to biomethanol
- Scenario 3 – Full inland fleet transitions to battery-electric
- Scenario 4a – Passenger vessels & ribs transition to battery-electric (inland fleet), all other vessels transition to hydrogen fuel cell (hub model, imported)
- Scenario 4b – Passenger vessels & ribs transition to battery-electric (inland fleet), all other vessels transition to hydrogen fuel cell (hub model, generated locally)
- Scenario 5a – Part of the inland fleet transitions to battery-electric, part to biomethanol, hub model, imported
- Scenario 5b – Part of the inland fleet transitions to battery-electric, part to biomethanol, hub model, generated locally.
- Scenario 6 – Shore power hotel load demand (for whole fleet, information only)
  Scenario 7a & b – Transition of the PLA fleet to hydrogen fuel cell or battery-electric
- Scenario 8a & b – International potential demand scenarios, explored for spatial requirement information primarily

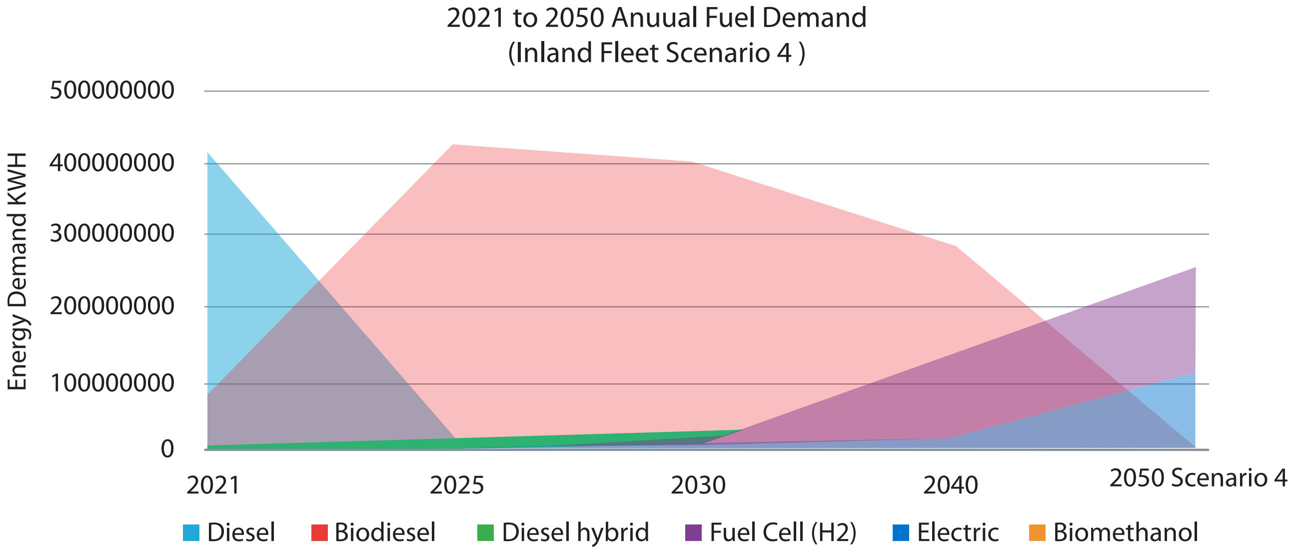
In each scenario for inland fleets, the demand was linked to the fleet size of each vessel category taking account of operator feedback (and their known plans for fleet expansion/reduction) and policy implications (Figure 9).

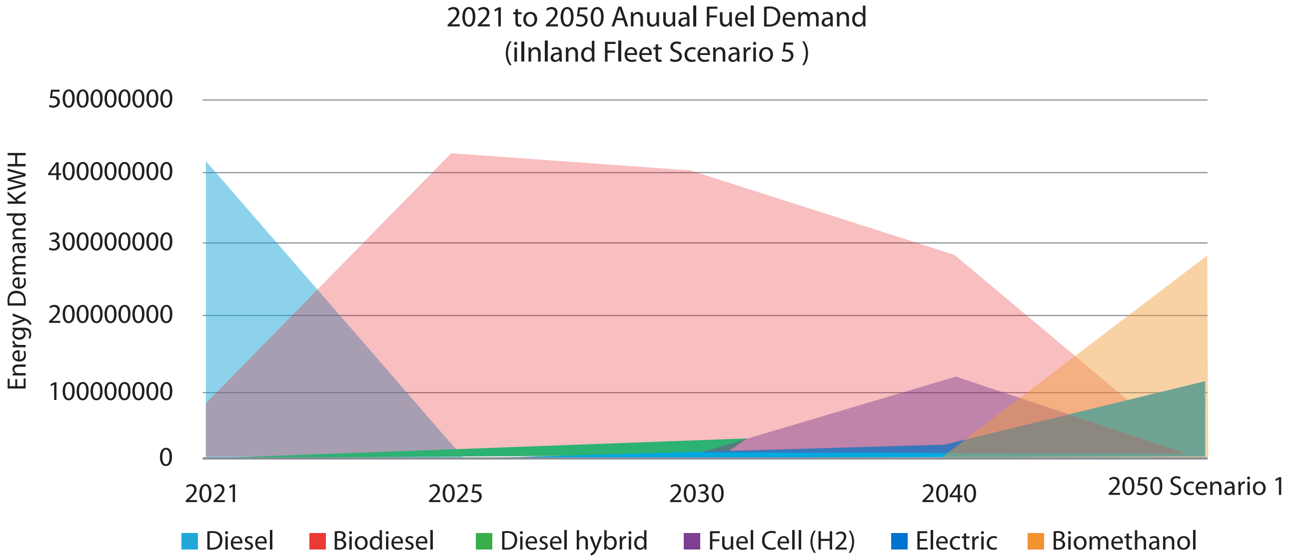
Figure 9: In each scenario for inland fleets, the demand was linked to the fleet size of each vessel category taking account of operator feedback (and their known plans for fleet expansion/reduction) and policy implications











8.1.1. Spatial distribution

The outcome of the site selection process has identified a number of areas of opportunity for hosting energy infrastructure at both the strategic scale (i.e., whole river, with potential to service the inland and elements of the international fleet) as well as options for addressing smaller scale demand 'by reach' for the inland and PLA fleet.

From calculating the energy demand by reach it is clear that areas of highest demand (perhaps not unsurprisingly) align with those where the highest number of operators have their home berths i.e., Kings Reach and Gravesend Reach (Figure 10). It is important to note however that it is not only a feature of the number of vessels active in these reaches, but also the types of vessels. Kings Reach, hosts the majority of the tourist and charter vessels which also have high energy demands because of the nature of their operations. Similarly, but for different reasons, the level of energy demand at Gravesend Reach is high because of the proportion of tugs based in this area.

Over time, as the energy mix changes, there are likely to be fluctuations in the level of demand (primarily as a function of the different energy densities of different energy carriers and therefore the amounts required to power the fleet); however, the reaches with the highest energy demand, it is predicted to remain broadly similar. The top 5 areas identified were Gravesend Reach, Kings Reach, Medway (outside of PLA area), Bugbys Reach and Woolwich Reach.

Another important factor when considering the energy demand for the inland fleet is the influence of vessels operating on the Thames with home berth locations outside of the PLA jurisdiction. Demand arising from these vessels is therefore 'mobile' and could be captured within any of the main reaches. In order to give due consideration to this, particularly when considering the potential for energy infrastructure locations, total energy demand was attributed to different reaches on the basis of known, regular operational areas.

For operators with bases outside the PLA jurisdiction known to be active in any location between Battersea and Sea Reach, the total energy demand associated with their fleet was split evenly across the 17 reaches. A similar approach was taken to 'spread' energy demand from operators based wholly within the Thames, where this activity could be linked to regular patterns.

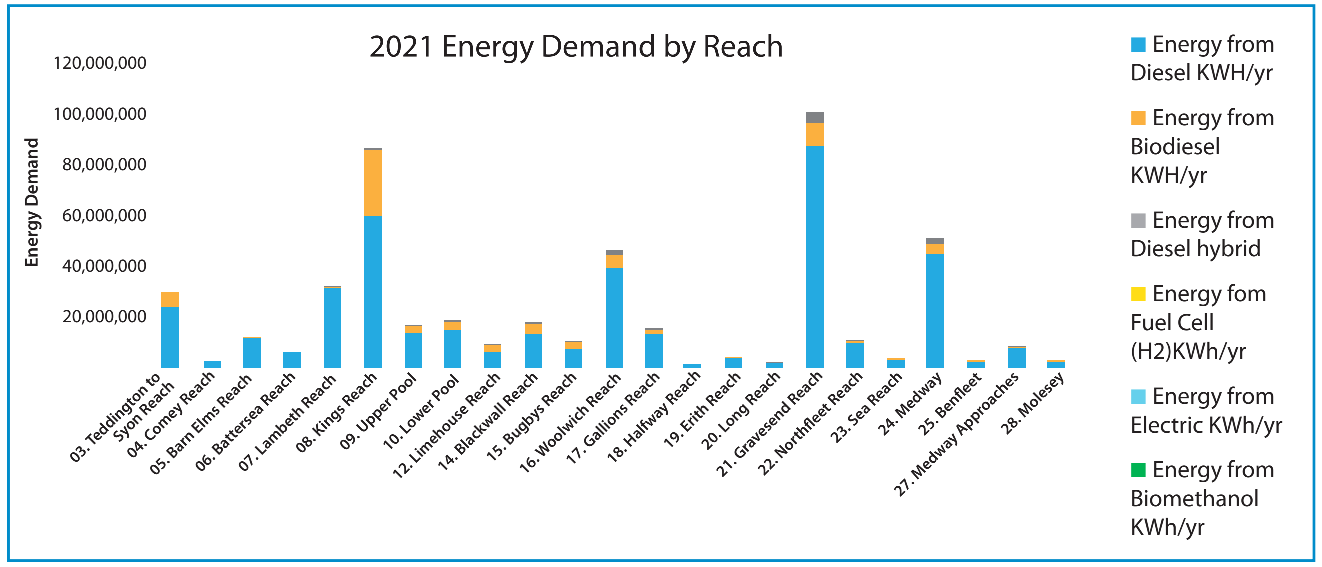


Figure 10: Current Energy by reach taking account of operational activity, including operators with bases outside of the PLA jurisdiction

8.1.2. Inland Shorepower

Shore power solutions rely on a number of key factors linked to vessel characteristics and their behaviour in port including:

- The berths that the vessels call at (home berths and berths called at)
- The duration of vessel calls
- The estimated power consumption levels for the different vessel types
- The voltage and frequency requirements associated with the specifications of different vessels

Mapping the distribution of this energy demand according to their home berth locations enabled the exploration of infrastructure requirements needed to support uptake of on shore power, particularly when considered alongside those demand scenarios that indicate adoption of battery-electric and hybrid technologies to achieve decarbonisation. It is suggested that specific requirements and hotelling calculations are picked up in a Case Study.

8.2. Shipping scenario

Due to commercial sensitivity surrounding the current volume of fuels sold by bunker providers on the Thames, no data outlining the current bunker volumes sold to the international fleet on the Thames was available to form the basis for this Study. In the absence of this baseline data, an alternative approach has been developed to estimate an upper bound for the future potential annual international bunkering demand to 2050 from commercial vessels.

It is recognised that information for potential expansion plans is commercially sensitive and therefore additional capacity/changes may be planned for the Thames that could influence the approach to estimating fuel demand. Future reviews of the demand estimations should be informed by this information as it becomes available.

Within the Clean Maritime Plan Scenario D, two sub scenarios were developed, one for international ships and one for domestic ships. For the Clean Maritime Plan, international shipping was defined as those ships that spend less than half of their total annual voyage time within a single country. This distinction typically captures the majority of medium to large commercial cargo-carrying vessels.

To account for the fact that the 2016 Port of London fleet fuel mix is varies from the UK-wide 2016 fuel mix used as the baseline year in the 2019 Clean Maritime Plan modelling, the Clean Maritime Plan Scenario D fuel mix was indexed to the 2016 Port of London fuel mix. From here, the forecast fuel mix of the PLA fleet was modified by the proportional change in each fuel from the Clean Maritime Plan model outputs. A caveat to this approach is that as the estimates move further into the future, the fuel mix of the PLA fleet has been assumed to move closer to the estimated UK-wide fuel mix.

The transitioning energy mix to 2050 was implemented by scaling the 2020 fuel consumption distribution by the international fuel mix for scenario D calculated in the 2019 DfT Clean Maritime Plan, using economic scenario results generated by UMAS. Scenario D was chosen because it was created with policies such as the EEDI and an escalating maritime carbon tax that guide the global maritime fleet to decarbonisation by 2050, relying heavily on ammonia as an alternative fuel past 2030. This scenario also aligns with the Thames 2050 target of decarbonisation and that of UK Government by 2050.

The sub scenario for the international fleet was applied to large vessels that have a clear commercial cargo-carrying functionality, including bulk carriers, unitized container ships, and crude/chemical tankers. This scenario was also applied to cruise ships. The sub scenario for the domestic fleet was applied to vessels that are known to operate within a single port, for example dredging fleet.

It is not likely that every vessel that berths in the Port of London replenishes exactly the fuel consumed on its inbound voyage. This is a generalisation based on the bunker capacities of many ship types and the potential endurance/range this implies relative to voyage lengths. It is certainly applicable to large ocean-going container ships and can also be a valid generalisation for smaller coastal vessels including Ro-Ros, except where they have been designed bespoke for a specific route and bunkering strategy. For this reason, the forecast fuel demand figures represent an upper bound on the possible bunkering demand each year.

9. Site locations

A variety of constraints are present for potential developments on the Thames, from residential developments and historical, to environmental and navigational. These constraints range in form from legally protected designated sites with heavy restrictions on nearby development, to sensitive receptors needing consideration, and those constraints specifically affecting development on the Thames.

While development within London is often costly due to high land prices, development on the Thames tends to present additional challenges. With historically high land prices for London, in addition to the competition between commercial port activity and highly profitable riverside residential development, the acquisition of shoreside land on the Thames can be prohibitively expensive. Certain sensitive receptors such as residential properties, hospitals or schools may render sites incompatible with certain alternative fuels due to the high level of risk associated with them. While safety and risk still need to be considered, land typically used for port activity such as safeguarded wharves may provide more suitable locations due to their protection from non-port related development, and fewer competing interests as a result.

The Thames itself provides a large area of rare intertidal habitat, resulting in many environmental constraints present across the Thames. Varying levels of legislative protection are offered to these sites, from those with the highest level of protection, Natura 2000 sites (RAMSARs, SPAs, SACs), to lesser protected site such as Local Nature Reserves. The consideration of proximity, and resultant potential impacts arising from development, ranging from noise, light, air, etc, is important due to the potential for the degradation of these sites. Historical constraints such as Listed Buildings or World Heritage sites can similarly be affected by developments, potentially altering the character of the sites/building requiring similar consideration. Sites of the highest importance require a high level of scrutiny be applied to any potential development that could impact on the quality of the site, with detailed impact assessments often needed to assess the significance of impacts.

Constraints such as overhead lines or maritime wrecks need to be accounted for to enable assessments of risk for each proposed site. Conversely, the provision of infrastructure may act as key constraints, with access to the national gas network or national grid acting as key constraints for technologies such as LNG or battery-electric respectively. In addition to the constraints described above, there are also navigational aspects relevant for operations that may take place on the river which must also be taken into consideration.

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10. Infrastructure potential

10.1. Large scale production and supply

To assess – at very high level – initial possible separation distances related to safety requirements associated with the scenarios involving (highly) flammable, explosive and/or toxic fuel types like hydrogen and ammonia, four safety zone layers were considered within the GIS model:

- Safety zone 1 – 250m from existing marine infrastructure (from connection point between loading arm and vessel). Opportunity areas were identified in locations where this marine safety exclusion zone did not encroach on either the authorised shipping channel or on industrial/ commercial adjacent areas).
- Safety zone 2a – 250m from areas from locations defined as commercial within ordnance survey data. This was to estimate the lower bound of the risk distance contour (see below for clarification)
- Safety zone 2b – 1500m from areas defined as residential areas within ordnance survey data. This was to estimate the lower bound of the effect distance contour (see below for clarification)
- Safety zone 3 – 750m from areas defined as residential areas within ordnance survey data. This zone was introduced in addition to 2b in order to expand the number of potential sites identified through the initial spatial constraints analysis (see below for clarification)

It is important to highlight that using safety zones 2a and 2b yielded very few options (i.e., only those sites which are already utilised as facilities for storing/processing petroleum products/COMAH sites) and therefore an additional safety zone was introduced (3) to explore the potential for additional sites.

The safety zones included in the spatial analysis take account of two specific safety elements, drawing on a probabilistic (or risk based) approach to determining safety zones in line with the ISO 20519 *Specification for bunkering gas fuelled ships*. The size of the safety zone therefore seeks to take account of both risk distance and effect distance which are defined as follows:

The risk distance is the distance at which the so-called individual risk 10-6 per year contour is located. The individual risk is defined as the probability of a fatal injury per year of a hypothetical individual who is continuously present at a particular distance from the hazardous substance. Within 10-6 per year contour the probability of getting killed due to an accident are at least one death once per one million years.

The effect distance gives an impression of the distance at which deadly casualties may occur, in some references the 1% lethality effect distance is given. For this distance the probability of a fatal injury of a hypothetical individual present at a particular distance from the hazardous incident is 1%.

Using the zones identified above, strengthened with expert judgement, an assessment of the residual pockets of land was undertaken to identify potential opportunity areas. A long list of sites was identified (Table 5). The functional requirements for each scenario and the 'soft constraint' data described in further detail was subsequently used to assess the advantages/ disadvantages of each opportunity area.

Whilst in the longer term it is anticipated that those locations currently used as hubs for petroleum products will transition to alternative fuels of the future and therefore offer optimal future hub sites, other areas of opportunity have also been identified which may currently be used for other operations and/or allocated for other future activities. These are intended to provide a basis for further consideration.

Large Scale Opportunity areas	Scenario Suitability
Canvey Island	1a & 1b H2 hub 2a Biomethanol hub (import) 3b Battery-electric hub 4a & 4b Ammonia hub
Tilbury	1a & 1b H2 hub 2a Biomethanol hub (import) 3b Battery-electric hub 4a & 4b Ammonia hub
Thurrock	1a H2 hub (import) 2a Biomethanol hub (import) 3b Battery-electric hub 4a Ammonia hub (import)
Dartford	1a & 1b H2 hub 2b Biomethanol hub (generate) 3b Battery-electric hub 4b Ammonia hub (generate)
Rainham & Purfleet	1a & 1b H2 hub 3b Battery-electric hub 4b Ammonia hub (generate)
Belvedere	1a & 1b H2 hub 2b Biomethanol hub (generate) 3b Battery-electric hub 4b Ammonia hub (generate)
Dagenham	2b Biomethanol hub (generate) 3b Battery-electric hub
Beckton	2b Biomethanol hub (generate) 3b Battery-electric hub

Table 5 Regions of infrastructure opportunity

10.2.2. Hub sites

10.2.1. Shorepower and Battery Electric

To assess – at very high level – initial possible separation distances related to safety requirements associated with the scenarios involving the flammable substances associated with containerised batteries, a similar approach to the approach used for the liquid fuel hub scenarios was adopted. The safety zone, however, was reduced to 50m from the areas identified as 'built up' within the ordnance survey data.

Other key requirements for battery hub storage relate to a power supply to charge the batteries and operate cooling technologies to prevent overheating. Ideally this power will be supplied from a renewable source and therefore proximity to renewable energy infrastructure (or space for implementation) is advantageous. In the longer term however as the grid converts to 100% renewable energy supply proximity to a grid connection with this guarantee will be an alternative approach. Existing power infrastructure information is therefore important as it provides a useful indication of feasibility of utilising different sites to host a battery storage hub.

Using the safety zone identified above, tempered with expert judgement an assessment of the residual pockets of land was undertaken to identify potential opportunity areas for this scenario. A long list of sites was identified (Table 5), using the functional requirements for this scenario and the 'soft constraint' data to assess the advantages/disadvantages of each opportunity area.

Currently there is not sufficient grid capacity along the Thames to support extensive increases in demand from the maritime fleet. This is not, however, anticipated to be a long-term barrier. The 2021 UK Transport Decarbonisation Plan takes the position that grid infrastructure will be upgraded to enable the deployment of widespread electrification of transport (including some maritime demand) and does not identify grid capacity as a specific barrier to progress.

Based on operator feedback (and the current refuelling patterns on the Thames), it would be preferable for the vessels to be able to take advantage of a slow, long charge overnight (whilst not in active operation) at the home berth and be then able to 'top-up' charge at several points during the working day.

Technology is being developed to enable 'fast charging' of electric vessels, particularly for ferry crossing routes (where vessels are going back and forth between two points at a consistent speed). On Lake Ontario in Canada for example, fast charging technology is being installed for two fully electric car and passenger ferries that are already in operation. The selected systems will be connected into the harbour grid and should be able to fully recharge in 10 minutes at each port on the route and has been designed to charge each vessel up to 7,850 times annually, equating to more than 78,500 charge cycles over the solution's estimated 10-year life expectancy.

Due to the tidal nature of the Thames, many of the passenger vessel piers/calling points are set some way out in the river and this is also an important consideration in relation to delivering electricity to vessels. Charging infrastructure, particularly for rapid charging, can be large and heavy, limiting the feasibility of deployment on floating structures or stand alone systems without substantial strengthening.

A number of charging/docking stations could be established to facilitate smaller scale deployment, with batteries being swapped on-and-off inland vessels in a suitable location, although standard guidelines for safety exclusion zones/operational limitations around land-based docking stations are yet to be developed. Delivery of the battery packs from the hub locations to the docking stations(Table 6) in the first instance could be achieved by road, although the PLA will focus on waterbourne carriage.

Alternatively, it is theoretically possible that a barge carrying multiple battery packs could deliver the batteries to a location closer to the demand hotspots identified for the inland reaches, although this has yet to be trialled.

Regulations and guidance around the deployment of battery 'ship to ship' transfer for the purposes of 'refuelling' are yet to be developed, however it is anticipated that as more swappable battery solutions are developed for inland waterways greater certainty will be achieved in the short-medium term. In the absence of specific exclusion requirements and clear guidance, it is suggested that this aspect of the site selection be approached as part of the case study phase, from the perspective of 'maximum available operational space' in certain locations.

In order to facilitate uptake of battery-electric technology, and promote the use of shore power, all operational bases (home berths) have been reviewed for their opportunities and challenges with respect to hosting modular shore power and swappable battery solutions. More information is provided on these options below. In addition, alongside the review of existing wharves/berthing infrastructure for smaller scale hydrogen storage, the potential for other locations to support electric charging infrastructure has also been reviewed at a high level.

	Grid Connected	Fuel Cell Supported	Battery
Description	Various solutions are available on the market designed to be modular and portable, allowing for ease of scaling up (and down) depending on demand. With all necessary components contained within standard shipping container (20ft or 40ft high cube), many of these units still require a grid connection although technology is available that allows for microgeneration of the power within the modular unit.	Hydrogen fuel cells can be used to supply power to Onshore Power Supplies where they may be unable to connect to the grid.	Technology is also being developed to facilitate swappable battery packs that can be charged on land and replaced into vessels as required.
Examples	Wartsila for example produce a modular shore power unit designed to fit within a standard 40ft high cube container which can deliver up to 7.2 MVA transferable power at 6600V/60Hz and 45ºC; the system can be integrated with a step-down transformer where necessary to service low voltage applications. Smaller 20ft container units can also be produced.	The Port of Los Angeles recently used hydrogen fuel cells to allow ships at berth to run lighting, heating, and other onboard systems. Similarly, in Honolulu Harbour a containerised 100kW hydrogen fuel cell has been successfully used to replace a diesel generator and power up to 10 refrigerated containers. Specific options are also available to purchase 'off the shelf' such as eCap Marine's H2PowerPac. .	Currently being trialled on the Rhine, according to the Netherlands based company, an inland vessel can travel some 50 to 100 km on two charged ZES-Packs – depending, among other factors, on the currents and the vessel's size and draught. The lithium battery technology is contained within a standard 20ft container, insulated to reduce fire risk and additional safety systems to mitigate issues connected with heat. Each ZES pack is guaranteed to last for 10 years, after which the capacity of the batteries is reduced by about 20%.

Table 6 Modular Shorepower types considered

10.2.2. LIQUID FUEL BUNKERING

The current regulations around road transport hydrogen refuelling stations (HRS) are based on the Dangerous Substances and Explosive Atmosphere Regulations which are administered by the UK HSE and stipulate clear requirements for hazard areas linked to relevant British Standards (for pipework etc in explosive atmospheres, BS EN 60079). The majority of HRS store volumes of less than 2 tonnes and on this basis, the following designated minimum safe distances are as follows:

- For H2 dispensers the distance to an occupied building, public footpath, roadway or potential ignition source shall be 3m
- Separation distance for H2 storage and compression equipment from dispensing and other fuel storage shall be 8m
- Separation distance from H2 storage and compression equipment to a footpath/public right of way shall be 5m
- Separation distance to a legacy canopy (i.e., a canopy not specifically designed for the presence of H2) from H2 storage and compression equipment shall be 5m
- For HRS receiving deliveries of gaseous H2 (tube trailers or cylinders) offloading cannot be undertaken if offloading is underway of a petroleum fuel unless separation distance is at least 25m and there is a clear line of sight between the two vehicles.

Additional rules apply if the H2 is being

stored/dispensed in proximity to other fuel types (i.e., petroleum, diesel) because of the additive explosion risks etc, however these are specifically linked to the characteristics of the other fuels, volumes stored and potential for overlapping dispensing activities etc.

Modular options exist for storage of smaller quantities of hydrogen, either in containerised tanks (equivalent in size to 20ft shipping container) or in cylinders of pressurised hydrogen. These options could offer transitional Thames solutions that could support the adoption of hydrogen fuel cell technology, or diesel/hydrogen hybrid solutions, requiring limited storage space, supporting ancillary infrastructure and considerably lower capital investment than permanent assets (which would also likely attract more onerous consenting requirements).

Multiple potential sites were identified through this approach, including some which align with the areas of highest energy demand (Table 7). However, some of these are considered to be constrained for operational reasons because of the number of vessels operating in particular reaches already during busy periods. Given the current lack of clarity around carriage of hydrogen as a cargo within the inland Thames, locations with good road access were ranked higher than those with limited/poor quality road access. It is recognised that in time additional clarity will be available to allow carriage of hydrogen on the inland Thames and this may affect the outcomes of this site selection process to date.

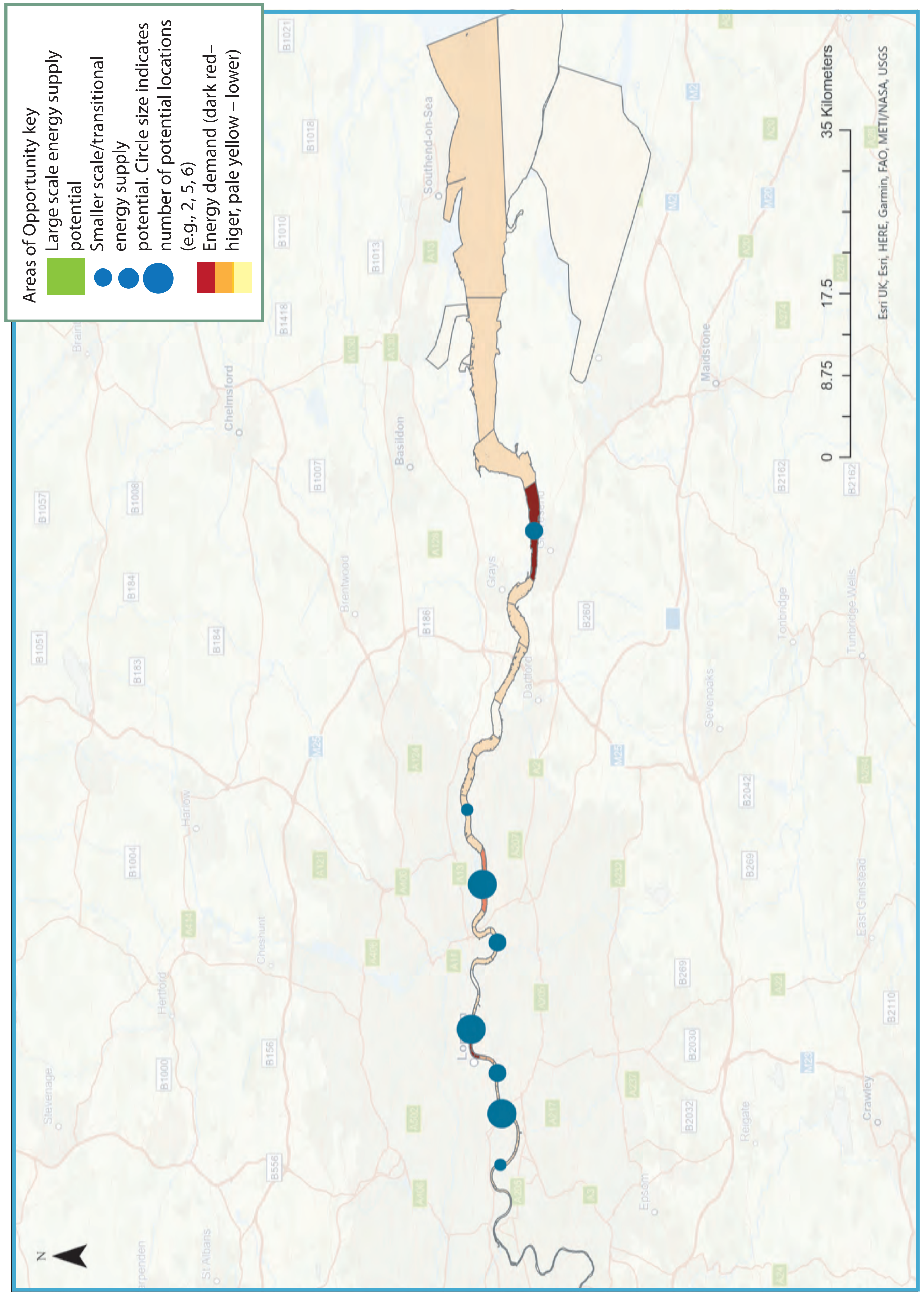
Thames Reach	Demand (H/M/L)
Teddington	Low
Corney Reach	Low (with potential to supply adjacent reaches)
Barn Elms Reach	Medium
Wandsworth Reach	Low/Med
Battersea Reach	Low/Med
Chelsea Reach	Medium (with potential to supply adjacent reaches)
Nine Elms Reach	Medium (potential to supply adjacent reaches)
Lambeth Reach	Medium
Lambeth Reach	Potentially suitable for floating storage
Kings Reach	High – multiple end users, some sites more constrained
Upper Pool	Medium (potential to supply adjacent reaches, floating storage)
Limehouse Reach	Low
Limehouse Reach	Medium
Greenwich Reach	Medium
Blackwall Reach	Low (potential to supply adjacent reaches)
Bugby's Reach	Low/Medium
Woolwich Reach	Medium/High
Gallions Reach	Low/Medium (potential to supply Woolwich Reach demand)
Barking Reach	Low (potential to supply busier adjacent reaches)
Halfway Reach	Low
Erith Reach	Low
Long Reach	Low
Northfleet Hope	High - Multiple end users
Gravesend Reach	High – Multiple end users
Lower Hope Reach	High
Sea Reach	Low

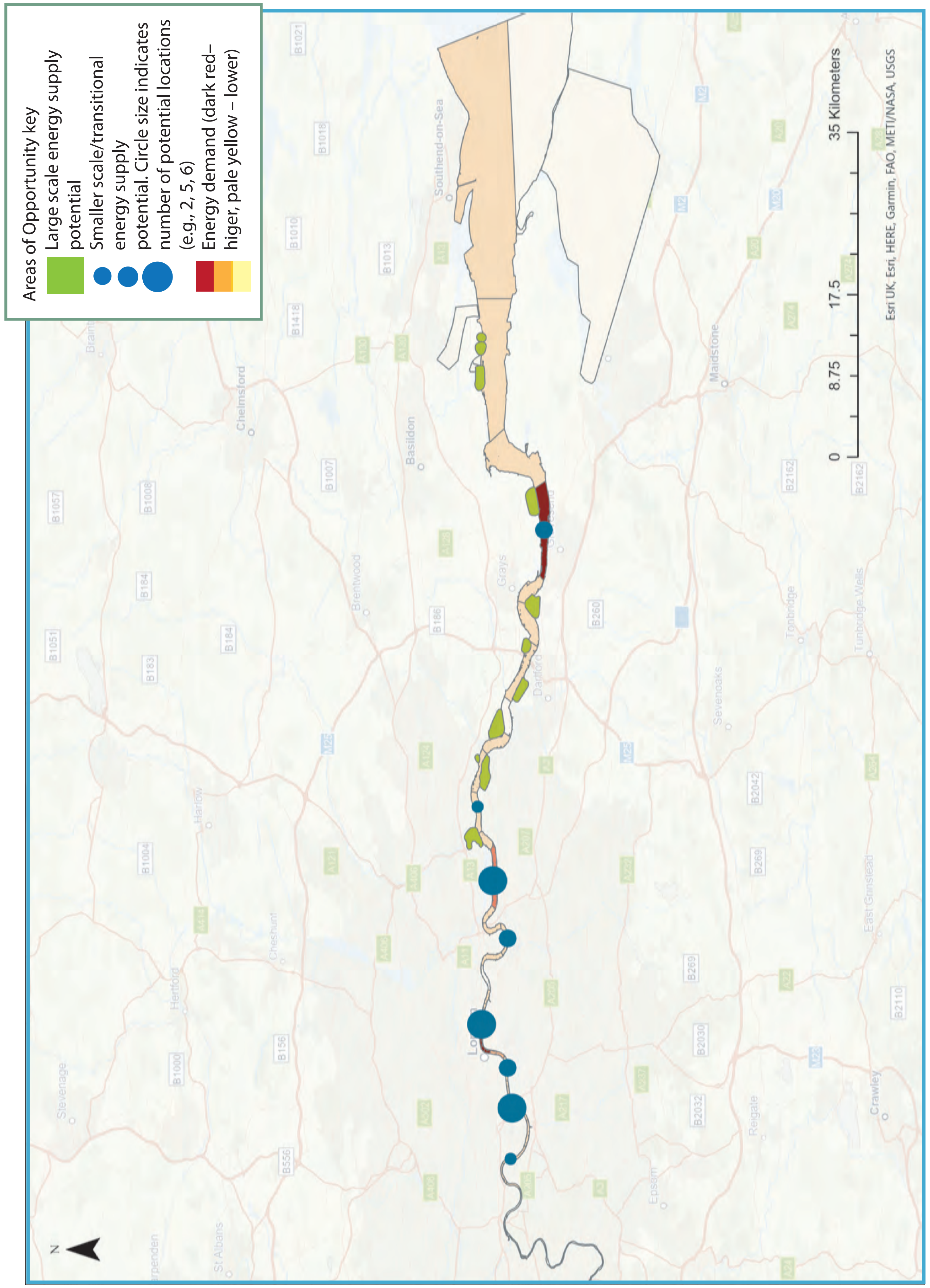
Table 7 Reaches with potential sites for H_2 provision

10.3. Spatial demand and Supply mapping

All operator home berths have been reviewed for the potential for accommodating modular shore power and/or battery-electric infrastructure. Multiple potential sites were identified through this approach, including some which align with the areas of highest energy demand. In recognition of the transitional nature of these solutions, the outcomes of the site selection process were ranked according to the 'current feasibility' of different home berth locations both from the perspective of shore power infrastructure with direct grid connections as well as microgeneration and modular battery options. Additional existing wharf/jetty infrastructure was also reviewed for their potential to 'host' energy infrastructure of this nature, highlighting where demand overlapped with berthing infrastructure even if not currently utilised as home berth facilities. This was particularly relevant for busier reaches (such as Kings and Lambeth) and sites adjacent to them which offer potential to service demand from a less congested location.

With an overlay of the potential wider fuel supply there are clear areas of focus for the river, where demand remains high during transition with the same top five reaches. The adjacent sites with demand will benefit from work and investment in supply in the hotspots (Figure 11).





11. Conclusion

This Study covers both the international and the inland fleet and, as such, a strategic approach to potential solutions has formed an important part of the work. In other words, for each potential technological solution, as well as the suitability of the technology for each vessel category (and the associated operational profile) on an individual basis, consideration has also been given to the potential for synergistic benefits across the Thames as a whole. For example, biomethanol offers potential zero carbon fuel opportunities for both international and inland vessels and does not carry the same health and safety risks as hydrogen; furthermore, a potential feedstock in the form of energy from waste may well soon be available on the Thames. Similarly, hydrogen fuel cell technology is increasingly highlighted as a potential solution for both inland and international vessels, albeit at different scales and in different forms; the UK Hydrogen Strategy also highlights the importance of hydrogen in decarbonising the wider mobility sectors in the country paving the way for consistent supply and demand beyond maritime that may make this a more strategically attractive option in some cases than, for example, battery-electric.

The pace of change in the field of energy transition for maritime vessels is a recognized challenge with any study such as the Emissions Roadmap and, indeed, this Energy Diversity Study. Some of the technological solutions considered in this Study did not feature in the Emissions Roadmap primarily due to this. The Emissions Roadmap did not, for example, consider biomethanol as an option for the fleet, although in recent months an increasing number of pilot projects have been deployed trialling this alternative fuel on a wider scale.

The outcomes of the multi-criteria analysis completed as part of this Study and the wider research carried out to underpin it largely concur with the outcomes of the Emissions Roadmap work for the inland and PLA fleet. As described above, the potential for biomethanol as a fuel being added into the picture is the only significant change. For the international fleet, the outcomes indicate that whilst hybrid technology and battery solutions may have a role in some elements of the fleet, the energy density volume advantages of alternative energy carriers such as hydrogen and ammonia result in these options becoming more dominant over time. The role of LNG in the transition, particularly with the growing trend for dual fuel ships (i.e., ammonia enabled) is recognised, though anticipated to decline beyond 2025.

Long-term scenarios have been explored for both the international and inland fleet, considering locations for 'energy hub' infrastructure that appear feasible within the highly constrained tidal Thames. It is anticipated that with technology development and a clearer regulatory framework, a bunker distribution model will ultimately be achieved for alternative energy carriers in the long term. The transitional phases require a different approach retaining flexibility and limiting capital investment to enable pilot projects to progress and inform wider understanding of the feasibility of different solutions. This section of the report provides a discussion on the key conclusions and challenges identified through the course of the Study as well as making recommendations for next steps.

11.1. Inland Vessels Demand

The scale of inland vessel operators provides a 'captive market' on the Thames which means that the uptake of alternative fuels or energy sources by operators is directly influenced by a combination of policy measures, identifying opportunities to create synergies between operators and by safeguarding sites to support the transition to alternative fuels. For these vessels, the PLA has the opportunity to work with operators to facilitate a transition pathway (or a number of pathways) which provides a balanced outcome for different stakeholder groups as well as working within

Thames specific spatial and operational constraints. The multi-criteria analysis considered the influence of policy measures on various technological solutions (along with other drivers) and identified a number of potential options that could support decarbonisation of the inland fleet within the relevant time period to 2050. This process was also informed by operator feedback where available (i.e., where stakeholders indicated that they are currently planning for a particular technological solution for their fleet), to ensure a comprehensive approach to the potential demand scenarios and subsequent site selection process. At the moment, there remains too much uncertainty to identify a single clear future energy solution that can be recommended for adoption by the entirety of the inland fleet. Instead, the outcomes of this Study indicate that the long-term energy demand for the inland fleet is likely to be focussed around the use of hydrogen (fuel cell), biomethanol or battery-electric power.

The exact transition path is anticipated to be steered by national and local policy which at the time of writing is weighted in favour of hydrogen and battery-electric. In addition, given the concentration of freight and transportation in and around the tidal Thames (and therefore other users of decarbonised energy solutions), it is likely that efficiencies of scale linked to shared energy demand could also represent a core driver for accelerating commercial scalability of one solution over another. For biomethanol specifically, the availability of an appropriate feedstock is an important pre-requisite despite the clear advantages in terms of the lower risks associated with handling the fuel and the relative simplicity of converting the existing fleet to adopt it, as well as the advanced levels of regulation and guidance available for its use in the maritime sector. In the absence of a strong source of supply close to the Thames coupled with a wider demand from other sectors it is less likely to progress ahead of hydrogen or battery-electric.

During the transition period, biofuels are likely to continue to play a significant role in the decarbonisation of the inland fleet, including the PLA fleet as they seek to reduce their emissions by 50% by 2025 (in comparison to 2014 levels). Operator preference for biofuel use appears to be growing, reflecting the minimal transition investment required to switch vessels over from more traditional LSFO products and the growing availability of biofuel options on the river. In addition, battery-electric looks likely to become more widely adopted because of the emission reduction advantages it offers and its synergy with a growth in shore power implementation (which is anticipated to become more widespread, particularly in light of recent policy announcements indicating potential for regulation in this arena)

11.2. Inland Supply Infrastructure

All of the large-scale areas of opportunity, are further east than Woolwich which is less than ideal for those inland vessels whose principal operating area is west of this point. In the absence of a bunker barge arrangement, travelling such distances to refuel is unlikely to be practical for many inland operators – both from the perspective of time (particularly when factoring in tides) and cost. Modular options (e.g., containerised/cylinders) exist which offer alternative solutions for inland locations, many of which can be easily scaled over time – or indeed replaced, if more traditional bunkering technology (i.e., that allows ship-to-ship bunkering similar to the supply chain model currently used for diesel) is developed for alternative fuel. These options could offer transitional solutions that could support the adoption of hydrogen fuel cell technology, or diesel/hydrogen hybrid solutions, requiring limited storage space, supporting ancillary infrastructure and considerably lower capital investment than permanent assets (which would also likely attract more onerous consenting requirements). Small scale options are also available for pressurised hydrogen which can be stored in container sized units.

The potential for floating storage/refuelling infrastructure represents a positive future option (due to availability of in-river moorings within the same area as demand) however proximity to the authorised channel may present limitations in some locations. Taking account of safe distances between operations and the authorised channel (e.g. 15m from the berthing face required for new piers, 20m from a berthed tanker etc) a number of mooring areas have been identified as offering potential which may be operationally preferable to some landside options (though would require more detailed exploration of the safety exclusion zones). Indeed, from a storage capacity perspective the in-river moorings provide an important option for the Thames (assuming the regulatory aspects of such options can be resolved).

Comparing the inland demand profile with the potential energy storage capacity (i.e. potential to accommodate supply) locations indicates a positive correlation at a high level. Nine sites have been identified as having 'greatest potential' in light of their lesser constrained position (from the perspective of both operational complexity and physical constraints). Another 20 or so sites are also identified as offering medium/high potential to accommodate energy supply infrastructure. This indicates a significant opportunity for operators on the Thames to investigate new revenue potential arising from accommodating energy infrastructure.

The distribution of these areas of opportunities is not evenly spread over the length of the Thames. For example, in some reaches, several options have been identified as offering similar levels of potential and it is unlikely that all of these would be required to service predicted demand. There are opportunities with potential to service demand from adjacent reaches which may be particularly relevant for very busy areas of the river (e.g. Kings/Lambeth reaches and Woolwich reach) but also for stretches of the river where demand may be lower but spread across a wider area (e.g. Syon to Chiswick reaches). Importantly, the areas of opportunity align positively with key 'operational sections' of the river and navigational landmarks. For example, a site in Corney Reach could service demand from the upper reaches whilst sites in Wandsworth Reach could supply demand in and around Battersea Bridge; sites have also been identified either side of the busy Central London reaches in Nine Elms Reach and Limehouse Reach.

More detailed review of these locations would be necessary to identify the most appropriate specific technology to be deployed as well as the exact scale of demand that could be met within the available footprint however this list could provide a guide to focus next steps in assessing feasibility of delivery.

Shore power requires charging points to be provided at geographically dispersed points that are used by vessel types with similar charging requirements (e.g., power and frequency) for a sufficient period of time (plugging in and charging both take up valuable operational time). Deploying the supply infrastructure to support shore power in this way is recognised as being a sub-optimal long-term solution, particularly as progress continues on securing a 100% renewable national grid and investment from the UK government improves capacity available to enable widespread electrification of various transport sectors.

As a transitional option however whilst barriers remain in terms of distances from existing grid infrastructure /unique locations i.e., on pontoons/piers for the infrastructure itself 'remote' shore power solutions through microgeneration offer value for the Thames fleet.

11.3. Bunkering Alternative Fuels

Despite the alternative options investigated as part of this Study it is clear that all come with disadvantages in comparison to the current floating bunker supply chain model. As ship-to-ship bunkering is the dominant bunker mode for conventional bunkering of inland vessels on the Thames and because of its time efficiency, this would be the preferred bunker mode from the perspective on inland ship operators. The main advantages of a pontoon/floating storage tank are that it does not occupy quay space and that in case of varying water levels, the height difference between vessel and pontoon is always limited. Furthermore, a floating facility is less exposed to flooding and possible resulting damage.

As an intermediate solution, the storage tanks could be placed on land while hydrogen is delivered to the vessels from a pontoon. However, if a pontoon is used for delivery of the fuel to the ships, attention needs to be paid to the movement of the pontoon so that equipment is not damaged, and sufficient space is required on the landside for tank storage. Some cross over may also be achievable with the international fleet. Small scale hydrogen through the deployment of, for example cylinders, may also offer a cost-effective pilot approach, particularly if combined with other propulsion technology e.g., diesel, battery-electric, fuel cell etc.

Given the large fuel tank capacities of international vessels, operators are able to choose from a wider range of international bunkering ports taking advantage of lower prices driven by economies of scale etc. The Thames' proximity to these alternatives means that it is reasonable to assume that these factors will continue to be relevant into the future and that demand from the international fleet will be relatively small in comparison to demand from the inland fleet.

The nature of the alternative fuels and technological solutions adopted by the international fleet in the future is similarly likely to be driven by macro factors rather than the influence of local or national policy applicable for the Thames. Based on the information reviewed to inform this Study the future energy solution for the international fleet is anticipated to be ammonia, with the transition period likely to involve a wider mix of fuels including LNG and potentially LPG. Research is ongoing with respect to commercial deployment of hydrogen to service the international fleet however it is worth noting that gaseous hydrogen is unlikely to offer a large-scale solution because of the achievable speed of bunkering. A recent study completed by DNVGL quoted speeds of 60g/s and noted that problems arise at higher speeds with rapid excessive heating of the storage system by adiabatic compression. For liquid hydrogen however higher bunkering speeds are achievable and thus is a more realistic option for larger ocean-going vessels. There are however larger safety distances required for storing liquid hydrogen creating further challenge with respect to inland locations for bunkering (given limitations on available space). The higher costs associated with this energy carrier and the relatively underdeveloped supply chain in comparison to ammonia are among the main reasons why NH3 is considered to be the frontrunner at the time of writing.

Although bunker demand is currently low, the approach taken to estimate the potential upper bound of international demand in this Study indicates the opportunity that could be available to the PLA (and operators on the Thames) if advanced investment/development linked to generation/storage of (for example green H2 or NH3) happens to establish London as a refuelling hub.

Future of the river and fuel

This Study is part of a programme of works by stakeholders and the PLA to understand the future of alternative fuels in the Thames for decarbonisation and trade. The results will be used by the Maritime Hydrogen Highway Programme, led by the PLA with industry experts, academics and regulators looking at the safe and economic transfer of hydrogen in a maritime setting.

There are two case studies also produced for the PLA as a result of the model, which have been produced separately. This method of site appraisal is available to any party interested in a particular site's potential for investment. The case study is confidential to the client and Royal HaskoningDHV but the results must feed into the model. Separate documentation is available to explain the process. All enquiries are through the PLA at environment@pla.co.uk.

There are still uncertainties about which scenarios the Port of London will see, however by collaborating with the model the river users will be able to increase certainty and maximise investment, working from a stronger baseline.

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