Accelerating Investment for Decarbonising UK Freight Transport

Findings from DUKFT project

Decarbonising
UK Freight Transport

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Decarbonising UK Freight Transport Network is one of the five Decarbonising Transport Networks programme funded by the Engineering and Physical Sciences Research Council (EPSRC), part of the UK Research and Innovation (UKRI). The Network consists of eleven universities and thirty industry partners, that prioritises rigorous and co-created research (academia and industry) to unleash significant investment into the freight sector's decarbonisation and guide enabling policy.

For more information and latest news visit: www.decarbonisingfreight.co.uk

Decarbonising UK Freight Transport is part of the Decarbonising Transport Networks+ programme. This programme is funded by the Engineering and Physical Sciences Research Council (EPSRC), which is part of UK Research and Innovation (UKRI).

Decarbonising UK Freight Transport is hosted by University College London. We are partnered with a further ten universities where our academic and research staff are based.

Executive summary

The decarbonisation of UK freight transport represents both opportunity and risk to UK stakeholders. Shipping, road freight, air freight and rail transport make up approximately 7% of UK's CO_2 emissions. The report will focus on shipping and road freight (particularly HGV's) which have some of the largest shares of UK freight activity and GHG emissions.

Operating over three years, the UKRI funded 'Decarbonising UK Freight Transport' (DUKFT) project has undertaken a series of research projects and stakeholder discussions on how to accelerate investment that can enable UK freight decarbonisation whilst managing risk and maximising opportunity. Three inter-related key findings from the projects are (for more detail see section 'How – can investment be accelerated'):

- UK freight decarbonisation pathways can be most efficiently informed by a whole freight system, whole UK analysis capability. This needs to couple detail on both infrastructure[1] and vehicle/vessel fleets with operational and technology specifics, resolved at granular space and time detail. Agent Based Modelling was evidenced to provide a viable and valuable platform for this objective.
- Co-creation processes are key for future research on UK freight decarbonisation, not only to maximise the relevance and quality of research, but also for the co-benefits of creating and enabling shared visions within stakeholder communities, framing of the challenge ahead and helping to enable a dialogue between industry and government stakeholders.
- Ports are key nodes in the UK freight sector's decarbonisation. They are both interfaces between the modes (road, rail and shipping), but also represent locations where infrastructure and decarbonisation solution synergies are most likely exploited. They are also likely to be hubs for wider offtake of electrification and RFNBO, for example for decarbonising collocated industry. Port's role in the UK's transition needs to be considered broadly to help reframe them as centres for green opportunity.

Why is investment needed?

Freight transport modes have common challenges to decarbonise. They can all further reduce GHG emissions through further efficiency improvements. However, efficiency improvements cannot create the scale and speed of GHG reduction to enable a proportionate response to UK Climate Change Act (2008) objectives. Road freight transport and shipping will rapidly need to transition away from reliance on fossil fuels to new energy commodities and energy supply chains. Sustainable biofuels that could be dropped-in and used with existing fleet and infrastructure, may be used in the sector but are not considered scalable and able to achieve the decarbonisation objectives. Furthermore, drop-in biofuels may increase reliance on carbon fuels and delay transition to net zero. The road freight and shipping sectors both require significant fleet and infrastructure investment.

Evidence compiled through DUKFT indicates the pathways for these modes as follows:

- Maritime freight – predominantly substitution to RFNBOs, but also electrification (in ports, when at berth, and battery electrification for shorter voyages), and wherever possible direct use of wind propulsion.
- Road freight – predominantly electrification, which could be through battery vehicles, road electrification (e.g. through catenaries and catenary enabled HGVs), or hybrid solutions which combine these two technologies. RFNBOs may have a limited role to play in the UK for a subset of routes that cannot make an investment case for electrification infrastructure and are a significantly lower efficiency use of renewable electricity.
- Rail freight - Despite an increasing proportion of the UK rail network being electrified, rail freight still travels predominantly on diesel trains. The transition pathway is similar to road freight, and therefore requires investments in electrification, and isolated use of RFNBO if/where electrification cannot be enabled.

1 e.g. charging, production and supply of Renewable Fuels of Non-Biological Origin (RFNBO) i.e. green hydrogen derived fuels, such as methanol and ammonia, as well as logistics infrastructure such as ports and distribution centres.

What is the gap between investment deployed and what is needed in these pathways?

At the conclusion of the DUKFT project in 2022, there remains a large gap between the investment deployed to decarbonise UK freight, and what is needed for these sectors to reach zero emissions. Public spending aligned with deep decarbonisation of UK freight has been minimal (e.g. a total of £40m in 2021-22), and by association so has private sector investment. This is of significant concern given the longevity of asset lives (fleet and infrastructure), and the timescales that are needed for renewal. Whilst road freight fleet may be able to be replaced through technologies applied to new vehicles alone, for maritime freight, the existing fleet is likely to need either early replacement or retrofit to RFNBO compatibility (which DUKFT found evidence could be achieved).

The report finds that the majority of investment needed to enable decarbonisation of maritime freight is on land, and in the energy supply chain rather than on the vessels. This includes port electrification investment – particularly connections to grid and provision of electricity at berth for cold ironing, as well as investment in the production of RFNBO. Hydrogen investment activity is starting, driven by UK wider hydrogen strategy, and could count towards maritime and road freight decarbonisation investment. But there are limited examples of RFNBO production investment specifically for supply to freight transport. RFNBO production investment could be co-located in or near the port (such as H2H Humber, aiming to develop a 600MW hydrogen production facility), in which case there can be synergy with electrification investment. It could also be located elsewhere in UK with other industry off-takers, or for export overseas. Uncertainty on the relative role and value of UK produced or overseas produced hydrogen may be affecting investment confidence, however this should be countered by recent strengthening of the UK's hydrogen strategy to production of 10GW of low carbon hydrogen by 2030.

For HGV and road freight electrification, there is only activity towards pilot and trials. The nature and extent of investment that will be needed on land or on vehicles will significantly depend on whether the dominant solution is electrified – via Electric Road Systems (ERS) and/or battery electrification of vehicles – or hydrogen-based solutions. An electrification pathway is gaining more traction due to expected costs involved, but the solution for charging road vehicles, and whether this needs to be bespoke for freight vehicles or can be integrated with charging of other vehicles, will also influence the decision-making and investment needs. The urgency of decarbonisation and uncertainty of timelines for delivering energy and transport infrastructure on which freight decarbonisation is dependent implies that there is little time for real-world demonstration projects. This highlights the importance of the role of modelling and simulation, for complementing and minimising

How can investment be accelerated?

DUKFT combined a series of studies commissioned over the three-year period and stakeholder events to help identify actions that could address the evidenced and urgent need for accelerated investment. There were three overarching findings, which resulted in associated recommendations for future research:

1 The need for a whole system, whole UK approach to identify technology pathways

DUKFT found that there was broad understanding in the stakeholder community of the technologies that will be needed to decarbonise freight. Although not widely deployed in the freight sector as yet, components required for deep decarbonisation e.g. batteries, electrolysers, motors, fuel cells and low emission combustion machinery solutions were broadly understood and recognised. Whilst further research into the components could be appreciated (e.g. for performance optimisation and cost reduction), this was not holding back the ability to identify a clear technology pathway for investment. Instead, DUKFT found that clarifying the technology pathway for UK freight is critically dependent on integrating understanding of vehicle and infrastructure technology options, with a detailed representation of UK logistics. The parameters for logistics of cost, time and reliability need to be brought together in the review of any solution.

To date, most efforts to understand technology pathways have focused on techno-economic approaches, that focus only on cost and efficiency. One of the DUKFT studies evidenced how the state of the art could be extended through development of a pilot multimodal agent-based freight system model. Although only at pilot scale, this modelling showed the viability and value of bringing together the specifics of infrastructure constraints alongside vehicle technology options, within a model that could consider both space and time dimensions at the scale of individual journeys.

Furthermore, the modelling showed the value when different freight modes are represented within a single model, for understanding the synergies between modes' decarbonisation solution (for example the potential for leveraging shared infrastructure investment associated with electrification). Multi-modal modelling showed that it is necessary to consider freight modes as a whole system; failure to do so runs the risk of unexpected consequences. The pilot nature of the study meant a broader geographical perspective than a subset of UK freight was not considered, but the pilot showed how larger geographical scales, including those that recognise that maritime and road freight systems have both national and international connections, could help further identify synergies beyond those that take just a technology perspective.

Recommendation: **There remains a clear need for identifying and articulating the least-cost technology pathways for UK freight decarbonisation. Mature existing modelling techniques are limited in providing further clarification and this sector would significantly benefit from modelling capability that can integrate operations and technology, space and time characterisation of multi-modal fleet and infrastructure at fine granular scales.**

2 The importance of co-creation in freight research

Both stakeholder events, and several of the studies, revealed the fragmented nature of the freight stakeholder space and the challenge ahead for creating a shared vision on how to decarbonise these sectors. Signals had been received by industry stakeholders that major change was expected, including from key strategies such as Transport Decarbonisation Plan, Clean Maritime Plan, however the specifics of policies that will incentivise change are not clear.

In early consultation and studies, DUKFT found little evidence that business-to-business engagements are incentivising freight decarbonisation investment at the speed needed, and clear evidence that stakeholders are waiting on regulation to create certainty for investment to be deployed.

It was a key finding that when effort was invested to bring stakeholders from different parts of freight value chains together (industry, academia, NGO and government stakeholders), there was good potential to identify a shared vision and co-create ideas for both public and private actions aligned with unlocking investment in decarbonisation. DUKFT primarily had the resources to explore co-creation regionally, which showed that even within the UK, freight decarbonisation can require place-based specialisation.

Recommendation: **Research funding should deploy a sustained multidisciplinary research effort alongside stakeholder community engagement and ensure a broad spectrum of the freight sector's value chain in co-creating solutions. This can unlock multiple benefits:**

- **Academia, acting as an evidence-led information broker can help articulate the scale of investment and change needed, and enable a constructive discussion between industry and government about how decarbonisation can most efficiently be incentivised. Assembling a common view of the challenge ahead and building trust is a key first step.**
- **Enabling a shared vision, underpinned by discussions of specific technology pathways, and potential barriers to solutions, can start to align mindsets and strategies, smoothing the path for regulation and commercial action.**
- **Social science researchers working closely with stakeholders across policy and commercial roles have a key role to play in testing the results from engineering and techno-economic analysis and quantitative modelling, and identifying gaps between theory and solutions that might have more practical benefits**

3 Ports as decarbonisation hubs

DUKFT studies found UK ports can combine multiple roles including being energy consumers, energy suppliers (including to freight vehicles calling to them), and also act as energy nexuses e.g. for interconnecting energy networks, creating charging opportunities and for throughput of offshore or imported liquid energy commodities. This contrasted with views in the stakeholder community that were often focused on narrower nearer term issues such as cold ironing, constraints on accessing grid electricity supply and maximising port throughput.

In particular, ports were identified as having a key role in the development of new energy supply chains associated with RFNBOs. The opportunity could vary depending on the specifics of the port, some may be used as major import terminals for RFNBO produced offshore or overseas. Some may need significant RFNBO storage infrastructure in order to meet the demands of shipping (e.g. bunkering). Others may be suited to local production of blue hydrogen, taking advantage of their proximity to gas and CCS infrastructure or local production of green hydrogen interconnected to large offshore wind generation. The existing collocation of ports with UK heavy industry, and increasingly distribution logistics infrastructure, mean that there are even wider opportunities than looking at their synergies with freight decarbonisation alone.

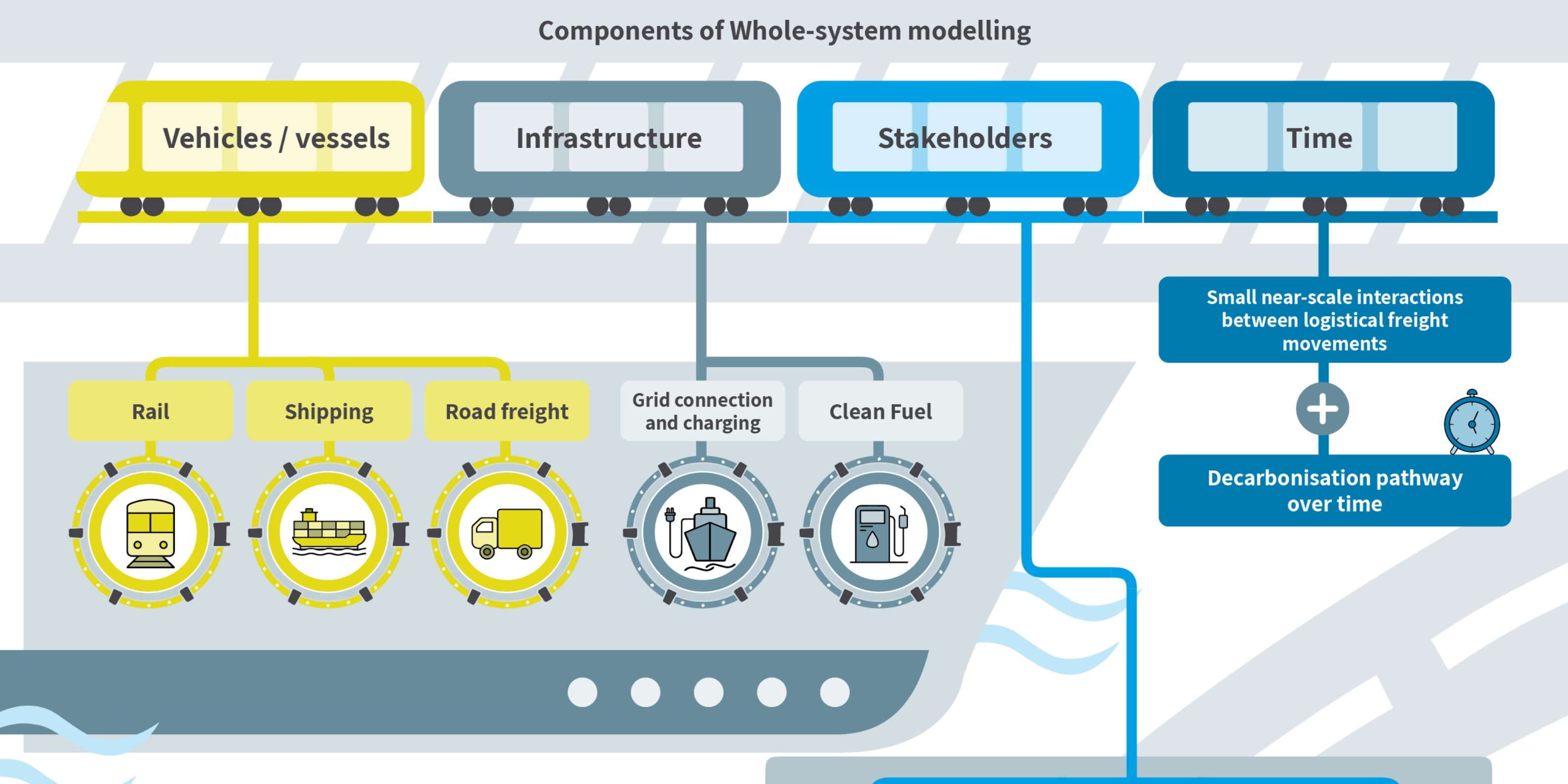
Recommendation: Further research should continue to explore how ports' opportunities in the transition can be characterised and assessed. This can not only help with the identification of synergies that occur across electrification and hydrogen investment related to the decarbonisation of the port and the UK freight modes connected to it, but also help identify their potential roles in wider UK transition, electrification and use of hydrogen. This should be part of ensuring balance of freight decarbonisation to consider infrastructure investments equally and alongside technology and investment at the vehicle/vessel level.

How to accelerate investment for UK freight transport decarbonisation

Decarbonising UK freight transport in-line with 1.5 degree goals is feasible, but requires acceleration of investment into its solutions. Academic research has a key role to play – our findings of three key topics are:

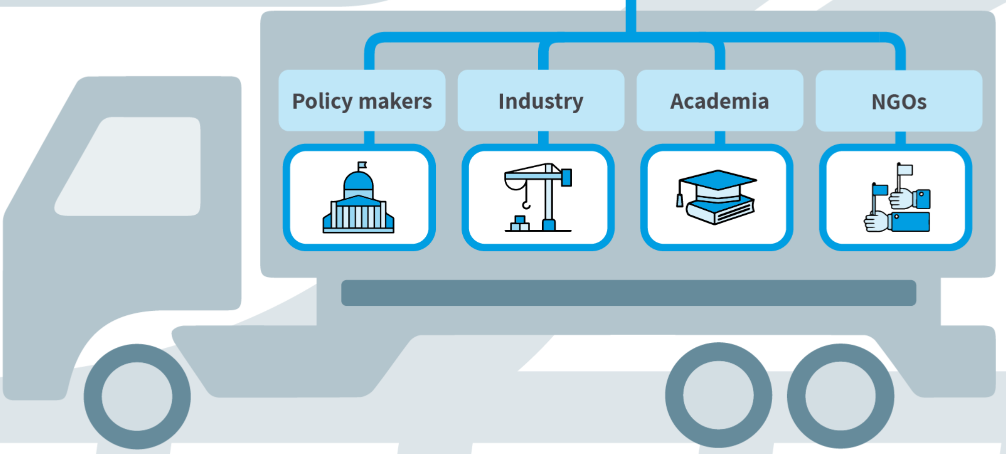
1 The need for a whole system, whole UK approach to identify technology pathways

Clarifying the technology pathway for UK freight decarbonisation is critically dependent on integrating understanding of vehicle and infrastructure technology options, with a detailed representation of UK logistics. DUKFT Whole-system modelling simulates the interaction of the following agents:



2 The importance of co-creation in freight research

Evidence showed that bringing stakeholders from different parts of freight value chains together to identify a shared vision and co-create ideas for both public and private actions aligned with unlocking investment in decarbonisation.



How to accelerate investment for UK freight transport decarbonisation

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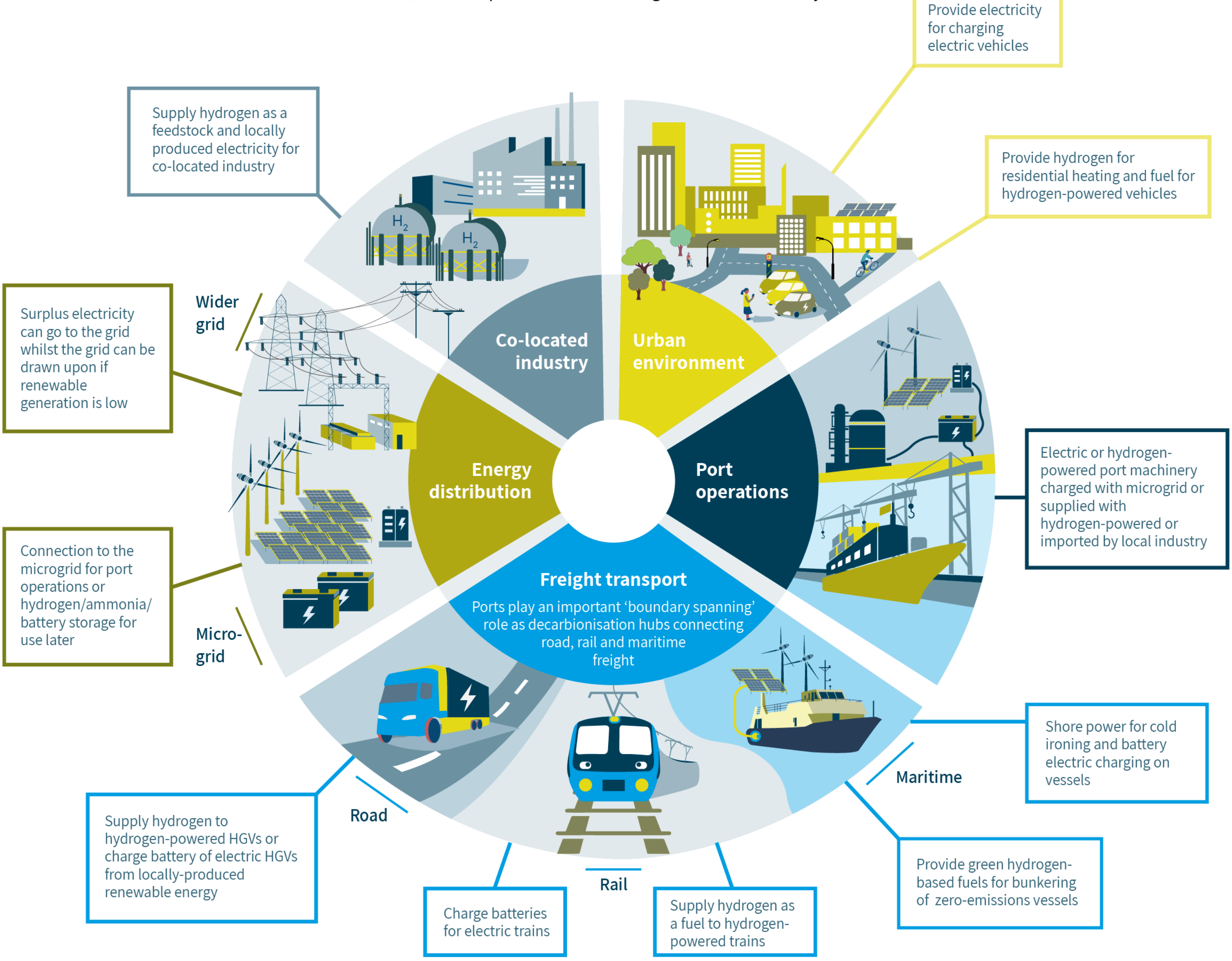
3 Ports as decarbonisation hubs

Ports are locations where infrastructure and decarbonisation solutions synergies can be exploited for UK freight and wider industries. They are also likely to be hubs for wider offtake of electrification and the development of hydrogen and hydrogen derivatives, for example for decarbonising co-located industry.*



*Synergies between domestic freight decarbonisation and internationalpolicies are not being addressed

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1 Introduction

The decarbonisation of UK freight transport represents both opportunity and risk to UK and UK stakeholders. Shipping, road freight, air freight and rail transport make up approximately 7% of UK's CO_2 emissions. Shipping and road freight (particularly HGV's) have some of the largest shares of UK freight activity, and GHG emissions and are the focus of this report. Progress towards decarbonisation of transport has been criticised by the Committee on Climate Change. More recently, these freight modes have received attention in the Transport Decarbonisation Plan, and some initial public spending focused on identifying their technology pathways has been launched.

Both of maritime and road freight modes interface at ports, and the DUKFT project intentionally combines analysis of the modes with analysis of the role of ports in decarbonisation – both the decarbonisation of the port and that of its interfacing transport modes.

The report starts with a consideration of the current state of the art evidence of the decarbonisation of maritime (Section 2) and road freight (Section 3): the technology pathways for these sectors, the scale and current level of investment. The report leverages findings from DUKFT on stakeholder perspectives on investment (Section 4). Finally, decarbonisation of road and maritime freight is considered through the lens of the port (Section 5). Conclusions and recommendations are presented (Section 6). The DUKFT project is now concluding and will follow this report with a final report, including summaries of all activities and commissioned underpinning research.

2 Maritime freight decarbonisation

The maritime industry has been regarded as relative to the energy sector, a 'hard-to-abate' sector, owing to the longevity of asset lives (fleet and infrastructure) and timescales that are needed for renewal. Together, with the uncertainty of the fuel/machinery pathway that most efficiently reaches zero emissions, and subsequent potential for a technology lock-in, ship owners and operators are reluctant of making an impulsive decision and choosing an unfit fuel to cover the transition. However, without rapid action to reduce emissions this decade, the shipping sector will continue to lag behind wider efforts to decarbonise, and this will result in a more costly and disruptive transition. Hence, the UK Government has recently explicitly included UK's international shipping in their sixth carbon budget; as a result, it shares the goal of reaching net zero emissions by 2050 with action commencing in 2023 (Climate Change Committee, 2020).

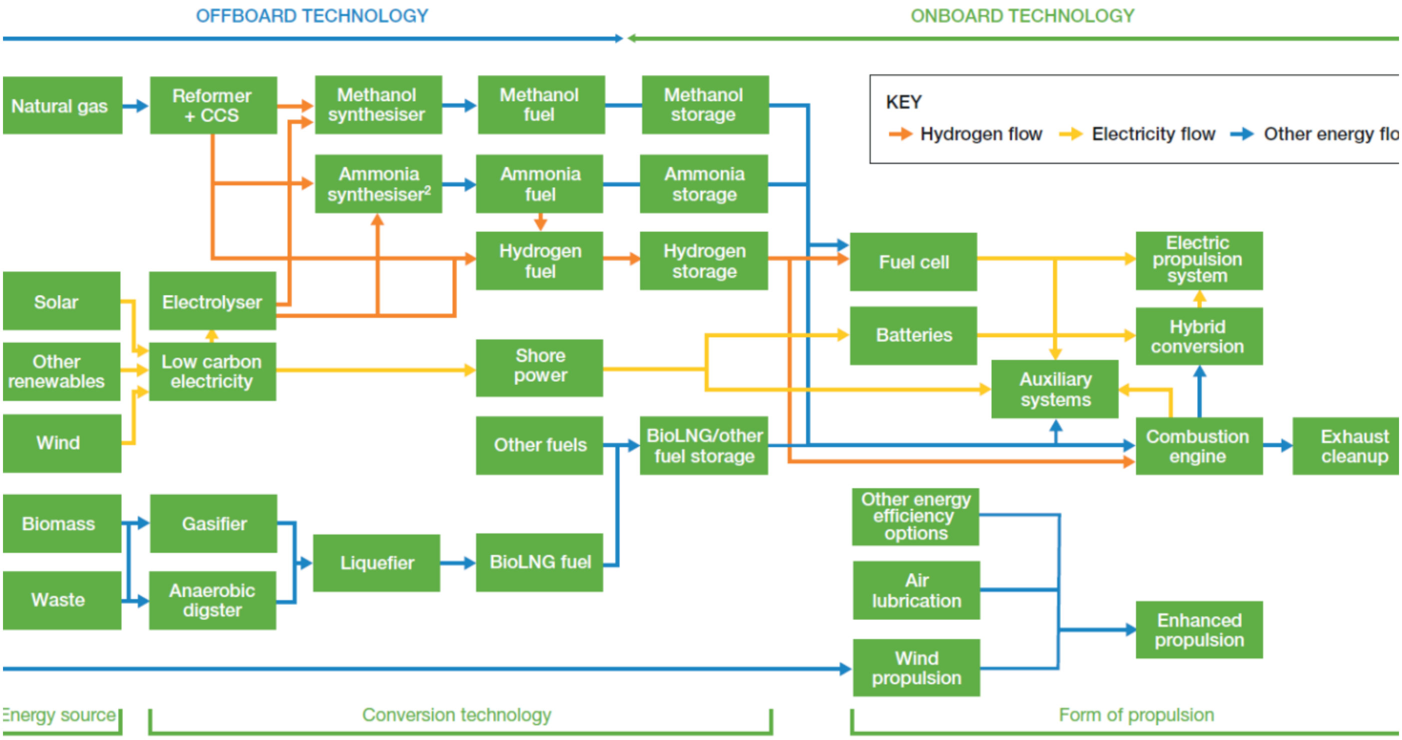
A maritime transitional strategy combined with a whole freight system approach is necessary for the UK to achieve zero emissions. This requires coupling the needs of the whole freight system by advancing infrastructure e.g. charging and RFNBO production and supply, as well as coordinating transition with that of logistics infrastructure such as ports and distribution centres.

2.1 Technology Pathway

There are ways of reducing emissions from the shipping industry now: energy-efficiency technologies and operational measures such as wind-assisted technologies, route optimisation, hull design modifications or machinery to harness waste power improve the overall efficiency of the ship and reduce fuel consumption by up to 30-50% (IMO 2017; IMO 2021b). Whist efficiency measures reduce emissions in the short term and are a step in the right direction, they cannot create the scale and speed of GHG reduction to enable a proportionate response to UK Climate Change Act (2008) objectives.

Several alternative fuels and their corresponding technologies are proposed to enable decarbonisation in the maritime sector (see figure 1 for proposed fuels and technologies available for maritime decarbonisation). LNG and biofuels are currently commercially available; however, their scalability and overall emission reduction potential do not offer a clear pathway to full decarbonisation (Smith, T et al., 2021; Englert, D et al., 2021). RFNBO (green hydrogen and green hydrogen-derived fuels such as methanol and ammonia) are currently being scaled. Evidence suggests that RFNBO (ICS, 2021; Taylor, J et al., 2022), but also electrification (in ports, when at berth, and battery electrification for shorter voyages), and wherever possible direct use of wind will be key fuels and technologies in the maritime freight transition. (ICS, 2021; Taylor, J et al., 2022). The focus now points towards the significant investment required for land and port infrastructure and developing onboard technology that can store and utilise these alternative fuels.

Figure 1 – Technologies and fuels pathways to zero-emission shipping (Department for Transport 2019)



The existing fleet is likely to need either early replacement or retrofit to RFNBO compatibility. Although there is uncertainty on a dominant fuel, the relative ease of converting/retrofitting an engine to operate on another fuel means the risk is significantly reduced when investing in dual-fuel engines (Hansen, S, T. MAN Energy Solutions, 2022). As such, retrofitting will likely become a major driver of the transition: Findings from a recent report suggest the number of ships retrofitted to operate on RFNBO may be roughly equal to the number of newbuild RFNBO ships (Smith, T et al., 2021).

2.2 Transition Pathway

The current GHG strategy, developed in 2018 by the International Maritime Organisation (IMO), is not sufficient and does not align with the 2015 Paris Agreement (Smith, T et al., 2021). The IMO is set to revise this target in 2023 (International Maritime Organisation, 2021) with the UK and other member states including the US leading global efforts to secure greater ambition (Department for Transport, 2021a). Awaiting international binding regulations, however, is not an effective strategy. Findings from a recent report highlight that important early-stage action from past transitions originates from 'smaller actors/geographical groupings' before a larger regulatory body sets rigidity to the regime (Smith, T et al., 2021).

The UK, seen to have set the most ambitious target yet must act as an early mover in the transition. The imminent revision of the Clean Maritime Plan, incorporating a plot of an ambitious 'Course to Zero' with indicative targets (Department for Transport, 2021a), will set precedent for the global shipping sector and a clear pathway to achieve domestic targets by 2050. It is suggested that by 2030 5% of the global shipping fuels must be made up by RFNBO (Osterkamp, P et al., 2021), and action taken by the UK can make a material contribution towards that objective.

Public sector backing and private sector investment will play a major role in facilitating the development of green fuel corridors and supply chains this decade, coupled with the rapid growth of renewable energy expansion. The joining of 22 different countries in the Clydebank Declaration – a mission to create green shipping corridors (Department for Transport, 2021d) and Government led Clean Maritime Demonstration competition, pledging to fund 55 projects demonstrating shipping decarbonisation projects (Department for Transport, 2021a) showcases the crucial role collaboration of the private sector and public backing in scaling green fuels this decade. From this, the emergence of 'first-mover' routes will showcase and reduce the cost of RFNBO and technologies through economies of scale, and generate the demand further afield, setting a clear trajectory across the sector.

Throughout the transition, emerging forces from multiple external facets – including first movers and green initiatives – will apply pressure on the regulators to act and change the regime. This will most likely come in the form of economic instruments such as a predefined price for the amount of CO_2e emissions produced i.e., carbon tax, or an Emissions Trading System (also known as cap-and-trade) allowing auctioning or distribution of allowances which can be sold to other entities exceeding baseline levels (Baresic, D et al., 2022). Alternatively, performance, technology, or emissions targets such as the IMO's Energy Efficiency Design Index (EEDI) to ensure cleaner technology is being utilised onboard ships.

The regulator's role will be crucial in defining a 'level playing field' and enabling price competitiveness with conventional shipping (Osterkamp, P et al., 2021). This will allow the transition to unfold beyond a tipping point and aid the rapid adoption of RFNBO.

2.3 Scale of investment required

2.3.1 Liquid fuels pathway

The scale of cumulative investment needed between 2030 and 2050 to achieve full decarbonisation of maritime freight globally by 2050 would require USD 1.9 trillion dollars (based on green ammonia being the primary zero-carbon fuel adopted by the shipping industry)[2]. Maritime decarbonisation is inherently a global endeavour. Nations cannot easily take measures to reduce their own domestic and international shipping emissions. The success of the sectors' transition to zero emissions rests upon the coherent and coordinated roll-out of zero carbon vessels and related infrastructure. But if the global costs to decarbonise the industry were split up among maritime nations, in the UK, costs for zero-carbon vessel and shore-side infrastructure are estimated at £75 billion (Marine Capital, UMAS & Lloyd's Register, 2022).

In terms of the global fleet the largest share of investments are needed in the land-based infrastructure and production facilities for zero carbon fuels, which make up around 90% of the total. This includes investments in the production of zero carbon fuels, and the land-based storage and bunkering infrastructure needed for their supply. Only around 10% of the investments needed are related to the ships themselves, which include the machinery and onboard storage required for a ship to run on low carbon fuels in newbuilds and, in some cases, for retrofits (LR & UMAS, 2020). However, domestically the share of costs will differ due to the much greater demand for battery electrified systems onboard vessels for short-sea shipping rather than zero-carbon fuels which will be the solution for non-domestic voyages.

On the land-based production of liquid fuels, most of the cost of production, around 80%, stems from the cost of converting the primary energy to electricity i.e., the cost of renewable electricity generated from renewable sources such as wind and solar (LR & UMAS, 2019). The projected upstream and midstream costs (including storage costs) for UK shipping by 2050 will be approximately £8.2 billion – based on the total demand for hydrogen of 85 TWh[3] (Department for Business, Energy & Industrial Strategy 2021).

As a result, from a total cost of ownership (TCO) perspective[4] the fuel-related voyage costs represent a significant share of the TCO. For example, a panamax ship (80,000 DWT) running on green ammonia with an internal combustion engine, the voyage costs represent around 85% of the TCO, followed by 10% capex investment in the engine conversion and storage costs and 5% revenue loss from extra storage of the fuel (LR & UMAS, 2020). Although this specific type of ship does not offer a quintessential representation of the domestic freight maritime sector, such TCO findings were found to be indicative of the differentials in coastal ships running on green ammonia (UMAS, Forthcoming).

In conclusion, in a liquid fuel pathway, the land side infrastructure for producing and supplying new fuels will be a critical component of maritime freight transition. The cost of producing and supplying, where majority of investment is needed, will in turn drive the cost of fuel and therefore OPEX at the ship level. Green ammonia and hydrogen are expected to be three to five times the cost of conventional shipping fuel (Lloyd's Register & UMAS 2020). This difference will be higher in the short term before reductions and price competitiveness are achieved through economies of scale and necessary renewable energy expansion.

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2 Under different assumptions, hydrogen, synthetic methanol, or other fuels may displace ammonia's projected dominance, but the magnitude of investments needed will not significantly change for these other fuels.

3 Predictions based on a S-curve demand uptake of RFNBO making up 5% of shipping fuels by 2030, 40% by 2040 and 100% by 2050. Levelized electricity costs cover all relevant costs including pre-development, capital, operating, and financing costs (i.e., life-cycle costs) of renewable energy, hydrogen storage and distribution costs

4 storage system + impact on revenue due to the space requirements of the fuel storage system.

2.3.2 Electrification pathway

Electrification is expected to be a significant enabler of domestic shipping's transition to zero emissions. The pathway is often already cost-competitive, relative to liquid fuels, for small-sized ships and those performing relatively shorter journeys e.g., small to medium-sized passenger and car ferries, small cargo vessels (mainly drybulk and container) performing short-sea voyages, offshore and service vessels. This pathway also allows for greater use of grid electricity to replace the reliance of ships on their auxiliary power systems while the ship is moored in port, referred to as cold ironing or shore power. In addition, some port machinery and equipment (such as forklifts or mobile cranes) currently using liquid fuels, will need to be electrified (UMAS & Frontier Economics, 2019).

Under a scenario of ambitious decarbonisation, electricity demand for full electric ships (battery propulsion) is estimated to far outstrip shore power demand by almost 7:1, and the total UK port electricity demand is estimated to rise to more than 4 Terawatt-hours (TWh) by around 2050. Most of the power demand arises from a significant share of full electric ships, which account 75% of the total power demand by 2050 (UMAS & Frontier Economics, 2019). Assuming that the large majority of internationally trading vessels will not run on solely batteries, around 75% of the demand will arise from domestic shipping operations. The remaining share will be demand for cold ironing from international and domestic shipping and port operations.

The total demand equates to ~3% of the currently installed renewable electricity supply (Department for Business, Energy & Industrial Strategy, 2022a). In terms of capacity, the extra demand could easily be met by scaling up renewable energy capacity by 2050, costing approximately £140 million, based on an S curve adoption rate equivalent to that of zero emission fuel (Osterkamp, P., Smith, T., Søgaard, K 2021) with levelized costs of renewable electricity (Smith et al. 2022).

Although upstream costs are considered relatively inexpensive and could be easily overcome, in any electrification scenario the bulk of capital required to enable cold ironing/shore power arises from port and energy infrastructure including interconnection of the port to the grid. Limited literature exists on the capital investments on-land, and further, a call for evidence from the UK government implies the specific costs at UK ports are highly uncertain (Department for Transport, 2022d). In response to the call for evidence, the industry point toward a 12-part policy plan to steer the widespread adoption of shore power at UK ports following new research from Hong Kong-based Fung Research (UK Chamber of Shipping, 2022).

Available evidence does suggest the costs are highly variable and dependent on several factors related to either grid-to-port, in-port and port-to-ship factors (Bullock. S, 2020) including current grid capability, frequency of grid and proximity to high voltage networks etc. Recent international installations can give an indication of the scale of investment required including the Port of Hamburg, where a 33.5MW capacity project cost €76 million and 12.8MW capacity project at Kiel cost €15 million (British Ports Association, 2020).

Concerning onboard capital investments, a newbuild ship will incur negligible costs to include shore power capability (British Ports Association, 2020). Although for retrofits, which are expected to be a major driver in the transition, costs can be highly variable – up to £1 million for large complex projects although much lower for average vessels (British Ports Association, 2020). Battery electric ship build costs are highly influenced by the cost and capacity of batteries installed. And these should further reduce over time: currently, prices for lithium-ion batteries are approximately $230/kWh, but cost projections expect a reduction to half the costs by the early 2030s and further reductions to ~$70/kWh by 2050 (Mauler, L et al., 2021).

2.4 Current state of investment

To date, there has been limited investment accelerating a decarbonisation pathway for maritime freight and a large gap remains between the level of investment required for freight decarbonisation in the UK and what has been deployed. Public spending aligned with deep decarbonisation of UK freight has been minimal (e.g. a total of £40m in 2021-22, and by association, low public spending there has also been limited private investment). Despite this, the private sector has been responsible for a relatively larger share of investment compared to the public spending in all major geographies including the UK. As such, pilot projects are mostly funded privately and some through public-private funding from the EU and further afield. Although the transitional pathway is becoming clearer for maritime freight, investors are reluctant to make decisions. This mainly stems from regulatory uncertainty and inadequate stringency of measures of long-term decarbonisation policy, both at national and international level.

2.4.1 Liquid pathway

In view of the newly revised target by the UK Government to double the low-carbon hydrogen output to 10GW by 2030 (Department for Business, Energy and Industrial Strategy, 2022b), support for hydrogen is highlighted in the number of maritime hydrogen projects in the Clean Maritime Demonstration Competition.

Launched in March 2021, the UK Governments Clean Maritime Demonstration Competition is funding 55 projects, totalling £33.5 million, and a large portion of these are showcasing hydrogen or zero carbon fuels (Department for Transport & Innovate UK, 2021). Yet, much in the same manner as bringing shore power to ports, there is uncertainty on fuels and bunkering availability. Because of this, a plethora of activity has emerged to establish green shipping corridors among busy shipping routes; notably at COP26, where the Clydebank Declaration was initiated involving 22 countries. Led by the UK government, the group seeks to develop six green corridors by the middle of the decade aiming to help collaboration, develop regulation and ensure action is taken on pledges. The prospective bunkering locations of UK-international corridors can support the uptake and clustering of zero emission fuels in domestic shipping.

Notable planned projects and pilot studies that could well be part of future green shipping corridors and clustering have taken a multi-disciplinary approach. This reduces the risk of stranded assets for the maritime industry whilst providing a holistic solution that can be mutually beneficial for multiple applications. For example, an agreement to develop a renewable energy hub at Port Shoreham in West Sussex promises to accommodate the future of the maritime decarbonisation demand by supplying renewable electricity and green hydrogen, firstly to heavy goods vehicles and port vehicles, following on to deliver green ammonia and hydrogen and renewable electricity to coastal marine electricity (Shoreham Port, 2021). Similarly, as part of a wide ambition to achieve a net zero industrial cluster in the area, H2H Humber (led by Equinor) aims to develop a 600-megawatt (MW) hydrogen plant and 300MW ammonia plant. Equinor are already trialling hydrogen-fuelled projects and supply vessels in Norway as part of its green shipping programme, and with their large fleet that operate in the area, part of the scope is to offer refuelling capabilities at the Port of Hull (Equinor, n.d.).

Regarding the transitional investment onboard ships, activity from large players such as Maersk and major cargo owners involved in the coZEV initiative (Cargo Owners for Zero Emission Vessels), suggests a progressive movement with lateral consensus across the industry to act quickly. There has been a flurry of orders for methanol ships from Maersk and CMA GGM for example, cleaner alternative fuels (hydrogen and ammonia), are currently being trialled among a host of pilot studies, while leading engine manufacturers are developing ammonia engines with commercial readiness as early as 2024. Analysis by (GMF, 2022) shows an increasing focus on hydrogen-based fuels over the last few years.

2.4.2 Electrification pathway

In a country where the electricity costs are relatively high, there is little incentive for private investment in the electrification of ports without the backing of a wider policy framework (e.g. mandate) or public funding. This barrier has subsequently caused a chicken and egg situation. Ship and port owners have not received clarifications on whether there will be public investment to act as support for shore power infrastructure, and hence there has been general inactivity. UK ports have fallen short in developing the shore power connection. A recent report found that the US, Canada, Norway and Sweden have more than double the UK’s shore power facilities (Prevljak 2022).

To date, there have been minimal investments in cold ironing in ports and onboard ships. Port investment surpassed over £1 billion in 2021; however, there were no significant investments in shore power. Yet a few pilot projects – mostly privately funded or public-private funded by the EU – have surfaced over recent years. Regarding shoreside investments, two ports in the UK have planned to, or have developed, grid-to-ship capability. Southampton Port has commissioned two shore power terminals as part of a £9 million project to enable cruise ships to operate with zero emissions whilst at port (Brooke-Jones 2022). Similarly, in the Orkney Isles, cold ironing has been installed on a ferry terminal, supplied with locally produced green electricity to power the ship whilst at the port – a first of its kind in the UK when it was launched in 2019 (British Ports Association 2020).

A similar account has transpired over recent years onboard ships: sporadic investment involving small-scale pilot projects showcasing the technologies. Notable examples include the Victoria of Wight ferry, sailing to and from the Isle of Wight and the mainland, propelled by a hybrid electric powertrain, and three hybrid ferries in Scotland, serving the Clyde and Hebrides network.

A review of electrification projects and investment across the UK suggests a focus on delivering hybrid powertrains; this is before a widespread charging infrastructure can facilitate the uptake of fully battery electric ships (Department for Transport & Innovate UK, 2021). Much like the automotive's sector advancements in hybrid technology, the hybrid solution offers a near-term solution to a long-term problem, but it may be years before fully battery electric solutions are commonplace. The energy density as a function of weight offers a small zero emission voyage range and the 'UK shore power is far behind' – recently echoed by the CEO of the UK Chamber of Shipping, suggesting as much as 20 years behind where it needs to be (Tresedor 2022).

A supposed lack of demand or drive for ships converting to battery electric has caused a degree of uncertainty for port authorities; but likewise, the inefficient investment from port causes insecurity for proposers of electrified solutions and heightens the chance of stranded assets. Since the launch of the Clean Maritime Competition and UK SHORE funding, the UK has started to try and address this, albeit with limited funds. Grants have been provided for trial projects and feasibility studies in various areas in the UK including the South Coast, Northern Ireland, The Broads and The Thames (Department for Transport & Innovate UK, 2021).

3 Road freight decarbonisation

3.1 Technology Pathway

Decarbonising road freight in the UK is a major requirement in reaching 2050 government climate goals. 16% of domestic transport GHG emissions are produced from freight carrying Heavy Good Vehicles (HGVs) (Department for Transport, 2021) and it is suggested emissions could increase by 45% under a business-as-usual scenario using the same technologies as today (Climate Change Committee, 2019). Therefore, finding a zero-emission solution is crucial for enabling heavy-duty vehicles to transition from fossil fuels.

The CCC reiterate the importance of trialling zero emission HGVs with associated infrastructure within the UK (CCC 2019) to embark on a pathway to determine the optimum solution(s). However, the urgency of decarbonisation and uncertainty of timelines for delivering energy and transport infrastructure on which freight decarbonisation is dependent implies that there is diminishing time available for real-world demonstration projects.

Headway can be made to reduce emissions in the near term, independent of any future measure. Data tools and models can be employed, with collaboration between businesses and fleet providers to improve the effectiveness and efficiency of supply chains (Department for Transport, 2021a). The DfT estimates that 28% of HGV travel in the UK involves empty vehicles (Department for Transport, 2022b). It is estimated that improvements in logistics in the supply chain could reduce GHG emissions by 11% (Climate Change Committee, 2020), also indirectly helping the current challenges of driver shortages through operational efficiencies. With conventional energy measures such as heat recovery and hybridisation enabling GHG savings of up to 21% (Climate Change Committee, 2020), significant savings can be made in the short term.

While efficiency measures are important, radical changes are required to operate road freight with zero carbon emissions, however there is uncertainty surrounding the technology and trajectory of the industry (Department for Transport, 2021). Electrification is gaining the most attention in the industry and is regarded as the most effective way to decarbonise road freight, including for motorways and A-roads (Ainalis, D. T et al 2020). This could be through battery vehicles, road electrification (e.g. through catenaries and catenary enabled HGVs) (Ainalis, D. T et al 2020)), or hybrid solutions which combine these two technologies. Liquid fuels, such as hydrogen, may be more suitable to move freight independently, outside of the range of electric road systems but they are expected to play a limited role in the UK (Ainalis, D. T et al 2020). The alternative to electrification is for potential modifications of existing engines, novel dual fuel engines and fuel cells enabling HGVs to run on the zero-carbon fuel. However, extensive infrastructure changes and major increases in the production of green hydrogen are required to achieve significant emissions reductions (Searle, C et al 2022; Raeesi, R et al 2022). Demand among multiple sectors could unfold synergetic and rapid growth of hydrogen, reduce the price of the fuel and associated technologies and bring large-scale infrastructure change across the UK's road network, however this would remain a less efficient use of renewable electricity and therefore likely a more expensive solution than the direct electrification (battery or electric road) option.

It is possible that a combination of technologies will form a wider solution and therefore it is essential that there is continued evaluation of the parameters that constitute the most appropriate solution for a national transition.

3.2 Transition Pathway

The transition of road freight is currently seeing modest shifts to new technologies, compared to personal and small commercial vehicles. But this next decade is expected to see imminent trialling followed by rapid investment in zero-emission technology and infrastructure (Department for Transport, 2021a). The UK government has recently announced proposals for banning the sales of conventional HGVs at two different dates: In 2035, for the sale of HGVs under 26 tonnes where solutions are starting to enter the market; and in 2040, for the sale of HGVs over 26 tonnes, where transitioning is more difficult (Department of Transport, 2021b).

Measures could also be coupled with a general encouragement to transfer more freight to rail and inland waterways (Climate Change Committee, 2020b). Though for much of the sector, shifting modes from road to rail is more challenging. Due to the limited connectivity of rail compared to road in the UK, research has shown that journeys would still require the use of HGVs and could be just as long. It is expected that there will not be a significant shift within in-land freight movements unless organisations make significant changes to relocate logistical hubs. Until rail freight reaches the level of electrification that we are seeing within passenger rail, there may be limited benefits to shifting freight movement from road to rail.

Despite this, the UK government have pledged that all rail (passenger and freight) will be net zero by 2040 (Department for Transport, 2021a) and have announced £20 million to support the modal shift of freight transportation, highlighting that freight by rail is 76% more environmentally friendly compared to road (Climate Change Committee, 2020b). The UK's leading grocery retailer, Tesco, has also committed to removing HGVs off the road, specifically reducing 72,000 HGV journeys by investing £5 million in their rail network – a pledge that will attribute to Tesco's net zero target by 2035 (Department for Transport, 2021a).

Private sector intervention is crucial in achieving the targets proposed by the UK Government, but the DUKFT found little evidence that business-to-business engagements are incentivising freight decarbonisation investment at the speed needed, and clear evidence that stakeholders are waiting on regulation to create certainty for investment to be deployed. As the freight sector is so diverse, incorporating 205,000 enterprises from small to medium sized enterprises (SMEs) to multi-national logistic providers (Department for Transport 2022c), engagement with local councils and the government are instrumental to identify a shared vision and co-create ideas for both public and private actions aligned with unlocking investment in decarbonisation.

3.3 Scale of investment required

3.3.1 Electric pathway

Whether an electric pathway comprises of an Electric Road System, battery electric vehicles or a combination of both, the scale of investment is driven by the infrastructural cost. Earlier work suggests an Electric Road System (ERS) is the cheapest and quickest way to achieve zero emissions for road freight (Ainalis, D. T et al 2020). Specifically, the overhead catenary system which has been gaining traction as the leading electro-road system. Trials have already taken place in Germany and Sweden and together, with feasibility studies in the UK, they provide a good indication of the costs of installing the technology across motorways and main roads in the UK. The total cost of covering 65% of UK road freight movements is estimated at £19.3 billion (Ainalis, D. T et al 2020).

Capital expenditure in-vehicle is relative to the size of the battery required. In a modest ERS pathway, a vehicle can suffice with 100 kwh battery storage (approximately the size of an electric car battery) with other additional equipment for electric road compatibility. This equates to premium of 15% over traditional diesel HGV (Ainalis, D. T et al 2020). However, it should be noted that vehicles are not constrained to specific journeys with fleets prioritising vehicle flexibility and there would an operational cost to increasing vehicle specificity that these calculations do not consider.

Another electrification pathway is one in which battery electric HGVs are the main form of freight transportation without an ERS. This option is now gaining more traction: with battery technology developing rapidly, manufacturers are now producing HGVs with ranges of 300-600 miles, removing the need for an ERS and its associated infrastructure. However, the battery size in-vehicle and charging infrastructure required would be significantly increased compared to an ERS. Despite this, overall capital expenditure is only ~2% greater than a combined ERS and BEV pathway (Hill, N et al 2019); although more of this cost will be attributed in-vehicle due to the larger battery packs (300-600kwh) (Cebon, D 2020) The trade-off between vehicle cost and flexible operations has not been fully explored but is becoming increasingly important as the sector starts to consider the implications of large scale BEV operations.

In the electrification of road freight, energy must be supplied by renewable electricity to ensure overall emissions are reduced, and thus, significant energy demands will be placed on the UK electricity grid, requiring an expansion of renewable electricity production. Using the energy demand from HGVs from 2019 (72TWh/yr), the estimated upstream costs by 2050 for expanding renewable electricity generation (DfT & UMAS 2022) are approximately £2.3 billion[5].

The investment required for electricity production is approximately a third of the cost of a hydrogen pathway. This is because connection directly to the grid in an electrified system mitigates the need of a medium to store the electrical energy, for which in a liquid fuel pathway is a case of a highly energy-intensive electrolysis process and then the reverse within a fuel cell. With both electrical transmission losses and battery efficiency losses, electrification offers superior overall efficiency and thus reduces the total cost from an end-to-end perspective.

3.3.2 Hydrogen fuel pathway

Although not expected to be the least cost solution for road freight, it is worth understanding the scale of investment that would be needed in a liquid fuel pathway. Hydrogen is the primary liquid fuel candidate being considered for use in Heavy Goods Vehicles (HGV). For hydrogen use in HGVs to become widespread there must be extensive infrastructure change across the UK roads, including nationwide refuelling stations, mid-stream transportation networks (through pipelines or by road via liquid fuelled stations) and upstream production capacity expansion (via electrolyser and renewable energy). In any case of fuelling transformation, the infrastructure required is the largest barrier and represents the majority of the costs to implement.

Pipelines are expected to be introduced for distribution of hydrogen to large refuelling stations where it is economical viable. For smaller hydrogen refuelling stations, tube trailers are more cost-effective (Searle, C et al 2022). But to reduce the costs of distribution of hydrogen, co-locating production sites and hydrogen refuelling stations could eliminate all but a small number of associated transportation emissions. Installation of 5000 stations (vs 8,000 existing diesel/petrol fuel stations) would suffice the widespread adoption (Energy Transitions Commission 2020). A single refuelling station is predicted around $2-3 million, therefore, the cost of a hydrogen network for HGVs would roughly require $10-15 billion investment (Energy Transitions Commission 2020). Although the network would be less extensive than an equivalent hydrogen car network (Energy Transitions Commission 2020), the deployment of refuelling stations would need to be standardised across UK roads to allow nationwide operators security in their technology. Further, the technological pathway of the UK's neighbours in the EU must also be considered, continuity is paramount to ensure a smooth transition and continuation of current trade routes.

The costs in-vehicle to operate with hydrogen fuel cells are fundamentally dependent on the price of hydrogen, and thus, on the price of renewable electricity if green hydrogen is used. Using cheaper blue hydrogen, the fuel cost still represents upwards of 60% of the total cost of operation (Energy Transitions Commission 2018). The Centre for Sustainable Road Freight (CSRF) conducted a study which found that hydrogen fuel cells will not be price competitive to diesel over the course of its operation in the UK. However, the Energy Transitions Commission found that the total cost of operation (TCO) of FCEVs using green hydrogen could be price competitive to diesel/petrol ICEs by 2030 with an annual TCO of $64,000 compared to a diesel ICEs TCO of $65,000 (Energy Transitions Commission 2020). This is assuming green hydrogen is below $15 cents/kWh, which the IEA expects to be achievable in many geographies (IEA 2019). The differing findings are subject to the variation of projected electricity costs used in calculations. This stresses the impact that electricity pricing has on the technological outcome.

3.4 Current state of investment

Before fleet owners invest in alternative technologies, assurance of return on investment is necessary. Physical trials are therefore important in establishing solution(s) that adhere to the operators and activities so that the industry can ensure reliable operation. Following a host of feasibility studies, the UK Government have announced £200 million to initiate the world's largest set of road trials of electric and hydrogen fuel cell technologies (Department for Transport 2022). This follows a £20 million fund from Innovate UK granted to small trials in 2021, delivering six successful feasibility studies. A parallel consultation phase submitted to the industry (vehicle manufacturers, companies with large fleet, supply chain companies, etc), highlighted the importance of a widespread system in providing commercial viability of zero-emission HGVs (Department for Transport 2022e).

5 Based on the energy demand of an ERS and BEV freight system over an transitionary time period

The demonstration projects will be rolled out over the coming years as part of a 3-year programme, in line with advice from the CCC. The trials will inform decisions on the transition pathway to zero emission for the sector, particularly the infrastructure necessary. However, these real-world trials are overshadowed by the urgency of decarbonisation and uncertainty of timelines for delivering energy and transport infrastructure on which freight decarbonisation is dependent on. This highlights the importance of the role of modelling and simulation, for complementing and minimising more costly and time-consuming trials/pilots. The current shortcomings in national scale modelling and analysis means a pathway is likely to still be unclear until the mid-2020s, and until then, private investment will likely remain minimal.

3.4.1 Hydrogen fuel pathway

As part of the £20 million Innovate fund, a host of feasibility studies were performed on hydrogen solutions, both infrastructure and in-vehicle. This consisted of an extensive set of proposal demonstrations representative of a hydrogen road freight system, from designing an ultrasonic hydrogen refuelling metering system to a full-scale on-road trial refuelling infrastructure and vehicle trials in the Midlands and Scotland (Department for Transport 2022).

A notable project that will be receiving funding as part of the £200 million demonstration funding boost programme was a hydrogen fuel cell design study, which will go on to trial hydrogen fuel cell trucks and new refuelling infrastructure in Scotland. A similar study will develop HGVs in the Midlands, encompassing all infrastructure required with refuelling stations, a delivery system and a trial lease system for truck operators. Moreover, in the East of England, the Aggregated Hydrogen Freight Consortium (AHFC) is a vehicle-operator led project assessing the nationwide rollout of hydrogen trucks in the next 5 years with a 2-month demonstration from OEMs providing trucks and hydrogen suppliers providing refuelling stations.

3.4.2 Electric pathway

The demonstration programme will also fund electric road trials establishing infrastructure and in-vehicle technologies and trials. As part of the £20 million funding, feasibility studies were performed to explore the effectiveness of Electric Road Systems and various other studies including the design of an efficient refrigeration unit and Advanced Driver Assistance System (ADAS) to control the vehicle more efficiently. But most notably, £10 million was provided to Leyland Trucks who deployed 20 DAF battery electric HGVs and the required end-to-end solutions including charging infrastructure for the use of the public sector such as the NHS.

The demonstration has spurred investment from Amazon, purchasing 5 DAF electric trucks to replace diesel HGVs and covering over 100,000 annual road miles with charging supplied by their new 360kW chargers. Amazon’s role will play a role in decarbonising road freight and is an important step to their 2040 goal; however, investments as such will likely be limited to large fleet owners who can afford to implement their own high-speed charging infrastructure at sites. This highlights the importance of a common transitional pathway and corresponding policy levers to initiate private spending, with public-backed funding, to enable participation also by smaller players in the industry. Given the breadth and diversity of the industry, demonstration trials are crucial in creating clarity in the technological pathway and inaugurating a managed and predictable transition. As part of the demonstration fund, an Electric Road Catenary System on a 20km stretch of the M180 in the East of England is proposed.

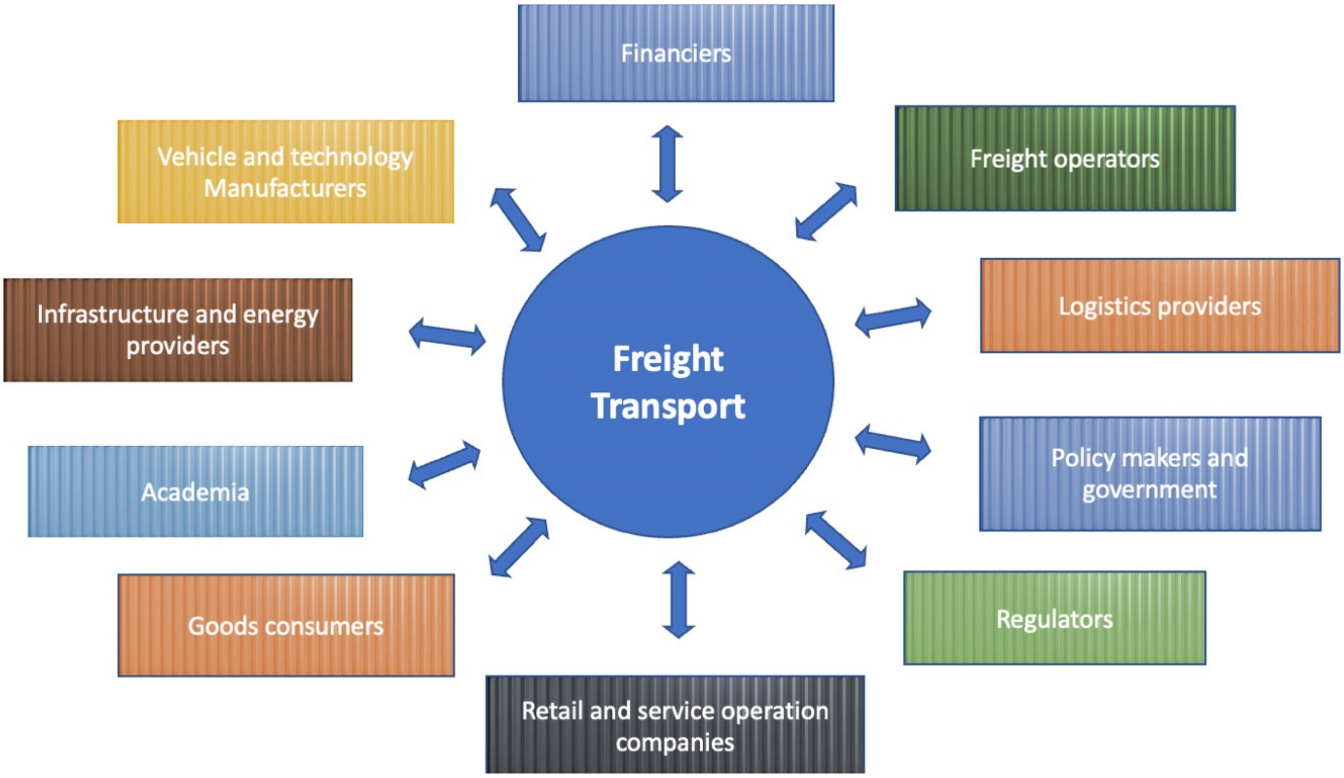
Further to demonstration trials, the UK Government will continue to provide plug-in and charging point grants for electric vehicles. Having already provided £582 million for all vehicle grants to date, the plug-in grant provides 20% of the purchase price of a HGV up to £25,000, whilst the EV charger point grant provides up to 75% towards the cost of installing a charging point.

4 Stakeholder composition, positions and barriers

Understanding the positions of freight stakeholders and the barriers to decarbonisation they face is crucial in defining a route forward and inspiring engagement from all facets of the industry. As the previous section highlights, minimal decarbonisation-aligned action and investment are happening on the ground and delving into the decision-making process of various actors in the freight sector will help understand the barriers, and thus enable solutions, investment and the accelerated uptake of cleaner fuels.

The UK government is making some headway in incentivising technological decision making, by focusing on key technologies for the road and maritime freight for further investigation, for example in the CMDC and road freight equivalent. However, evidence from consultations suggests the industry/private sector is struggling to act with a clear sense of direction. The Clean Maritime Plan provides some clarity on transition pathway for maritime and recent interventions of phasing out of diesel HGVs have enabled more freight investors to begin to assess climate risk and stranded asset risk exposure. Findings from the DUKFT studies show that the economic/business case is the top priority and until new technologies are incentivised to the level where they are very clearly economically viable, the business case for investing in more costly fuel switching will not occur (DUKFT 2021).

Figure 2 – Various stakeholders within freight transport



However, a number of the studies funded by DUKFT, and workshops held with the industry (including many of the stakeholder categories in Figure 2 from the public and private sector) suggested that that the government and international policymaking organisations are falling behind industry ambition (DUKFT 2021). Stakeholders expressed the need for an ambitious transitional strategy and corresponding policy, subsidies and incentives to give certainty to investors and accelerate decarbonisation (DUKFT 2021). This was evident in outreach to UK freight stakeholders where one study highlighted the importance of ensuring whole-life costs were price competitive with fossil fuels to justify investments from the asset owners and investors.

The experience on the project suggests that an ambitious, concrete, overarching and long-term policy framework is critical to providing clarity and levels of certainty for the robust business cases which can accelerate investment in freight decarbonisation. It is vital to create synergies within stakeholder communities to ensure policy design and implementation are done with the involvement of the right stakeholders at the right stage. One study finds that co-creation processes are key for such policies and transition roadmaps for UK freight decarbonisation, not only to maximise the relevance and quality of research but also for the co-benefits of creating and enabling shared visions within stakeholder communities, framing of the challenge ahead and helping to enable a dialogue between industry and government stakeholders.

Stakeholders, in general, are taking the wait-and-see approach with economic and strategic uncertainty driving this decision (DUKFT 2020). With increasing public awareness and availability of public data, consumers and other stakeholders such as financiers and cargo owners could drive the momentum toward green investment further down the value chain However, this will not be sufficient to drive the necessary investment for a systemic change – government engagement is necessary with stakeholders from the entire supply chain to create effective and enforceable policy (DUKFT 2020).

4.1 The role of early mover action in the emergence phase of the transition

Both shipping and road freight need deployment of new technologies and infrastructure that is likely to follow a classical transition pathway. The initial phase of transition will require early adopters in each of these modes, who are willing to be at the vanguard of technology and help to de-risk the solutions and make way for the mass market transition.

Operators' ambitions to be at the vanguard, for example because they see market advantage of being a pioneer, can enable them to capitalise on incentives intrinsic of an early adopter (DUKFT 2020). This can help to kick start the diffusion of zero/low carbon technology and fuels. Internationally, the maritime freight sector is starting to take steps to early adoption: Privately coordinated finance communities such as the Poseidon Principles are beginning to integrate the use of climate considerations and alignment in ship financing/lending decisions; Cargo Owners Zero Emission Vehicles (coZEV), a cargo owner-led network with members in EU and US is mobilising commitments from the customers of shipping to create demand for zero emission maritime freight services. They are also utilising the power of demand aggregation to purchase zero-emissions maritime freight as early as mid-2020. These initiatives have not yet seen significant impact on domestic-scale freight transport systems.

DUKFT found fewer examples of road freight early adopters. This was perhaps due to a lack of an overall sense of direction as well as a lack of infrastructure/refuelling solutions that means fleet owners are at risk of choosing a technology that will not be widespread and unusable until infrastructure is developed, consequently creating a greater risk of stranded assets (DUKFT 2020). The high degree of fragmentation within the road freight sector causes the sector to work in silos and inhibits holistic thinking. Unlike the maritime freight sector, this means government guidance is generally required for progression and this in itself can further inhibit early movers taking steps under their own initiative (DUKFT 2020). Financiers were another group found to be lacking clear examples of early adoption, with very few using climate alignment tools to assess their portfolios; many are just starting the process of understanding the alignment of their portfolios and merely taking on high-level guidance (DUKFT 2020).

5 The role of ports in freight decarbonisation

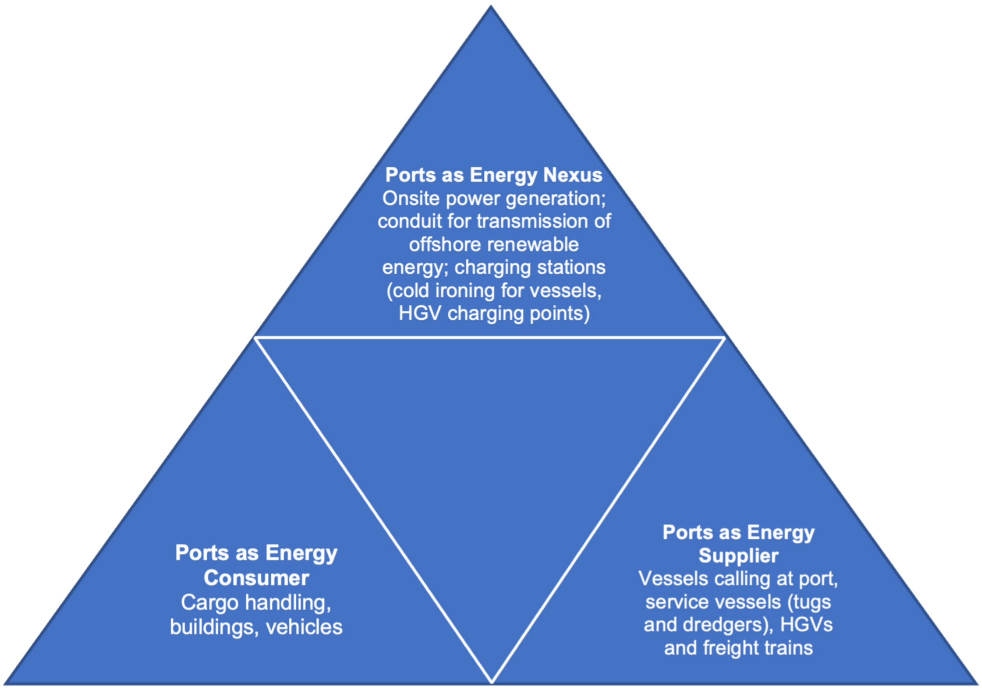
UK ports are vital to the UK economy as around 95% of British imports and exports (by volume) are transported into/ via UK ports (Frontier Economics & UMAS 2019). Ports are natural cross-modal points for sector coupling and energy system integration; they host many industry sectors, not just energy-related (generation, grids, offshore wind) but also transport, tourism and manufacturing industries and therefore can play a pivotal role in the UK's decarbonisation challenge.

Aiming to identify the transitions required for decarbonisation in and around UK ports, this section focuses on how UK ports can contribute to the decarbonisation of UK freight movements and how the transitional pathway to achieving this can be accelerated. A particular focus is on how ports can act as energy hubs for different modes of transport.

5.1 The current energy mix at UK ports

Ports are a complex system of industrial and commercial activities, engaging in generation, distribution and usage of energy; thus, they occupy multiple roles in the context of energy – energy consumers, energy suppliers and energy nexuses (see Figure 3).

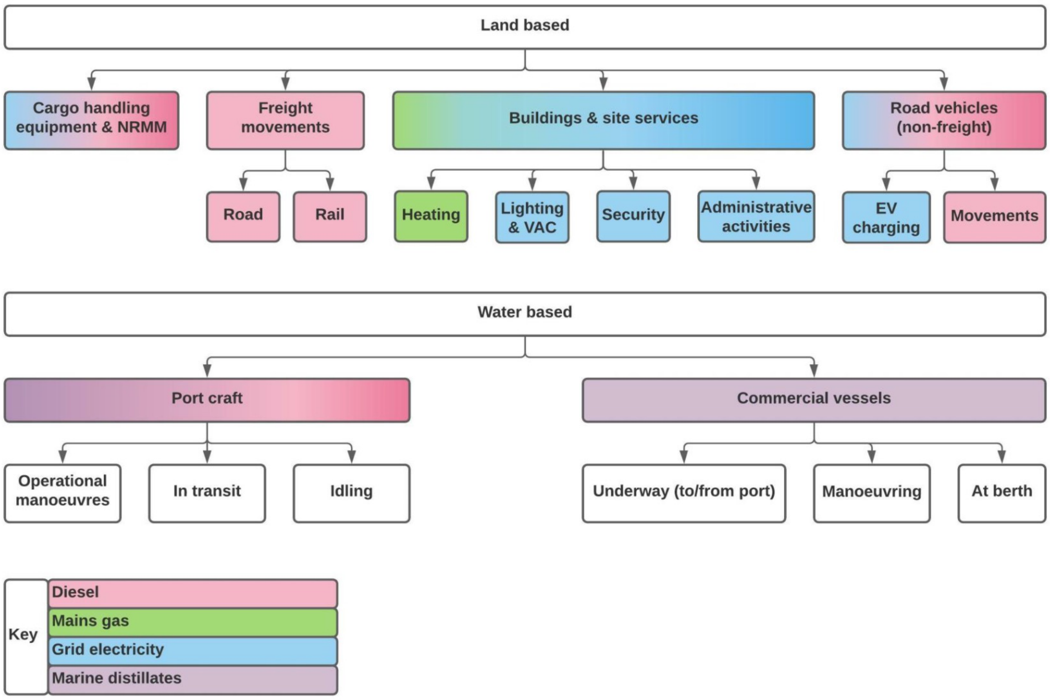
Figure 3 – Ports and energy roles



Multiple energy vectors exist at ports. Currently their roles are addressed mostly with fossil fuels including conventional bunker fuels i.e., Heavy Fuel Oil and marine distillates (Marine Diesel Oil etc), grid electricity for surrounding ancillaries, and natural gas for conventional heating. The energy types and their users for a typical intermediate-sized UK port are shown in Figure 4 below. Specific ports house or enable the transmission of other energy vectors: examples include LNG as a niche shipping fuel or for energy supply, ammonia as a fertiliser, and methanol for the chemical industry.

Due to the high energy demand – both from current fossil fuels and upcoming demand for cleaner fuels for a range of end uses – transitioning of ports could be particularly challenging. However, with a strategic and systemic approach across the UK, ports can be a major driver in facilitating the transition to RFNBOs and the electrification of transport.

Figure 4 – Energy types and users for a typical intermediate-sized UK ports (Bowkett, A 2021)



5.2 Some scenarios for UK ports' path to decarbonisation

Ports provide a variety of avenues for decarbonisation, from decarbonisation of the ports themselves, of the vessels that use them, of the heavy trucks and trains that transport goods to and from the ports, and of the surrounding industrial sites. Ports are often co-location sites for chemical industries and electricity plants as these profit from easy access to bulk transportation and from the advantages of an industrial-type site (e.g. suitable environmental regulations). Port sites, therefore, present a significant decarbonisation potential more generally.

The future technology developments for zero emission shipping, explored in Figure 1, and the level of demand for low carbon propulsion technology or fuel options are currently uncertain, but it is likely the maritime sector will employ various energy vectors e.g., ammonia, methanol and electricity (via batteries). This poses a challenge to UK ports as they have to decide in which energy infrastructures to invest, as well as whether to produce locally, source domestically or import; some hypothetical scenarios are posited in the following sections.

5.2.1 Production of green hydrogen/ammonia in UK ports

Hydrogen is already extensively used within industrial activities in refineries, steel making and the chemical industry – all characterised as hard-to-abate sectors. The presence of these energy-intensive industries in the vicinity of the ports could warrant a large demand of low carbon fuels, particularly in view of the government's Industrial decarbonisation strategy. Specifically, the Tees Valley and Durham which is a highly localised chemical industrial area and home to the second largest port in the UK (Bryson, J. R., Clark, J., & Mulhall, R. 2013). This exemplifies much of the North East of the UK: large industrial manufacturing areas with large exporting ports. Such areas will form a large portion of the 20WTh of expected low carbon fuel demand by 2030 (HM Government 2021).

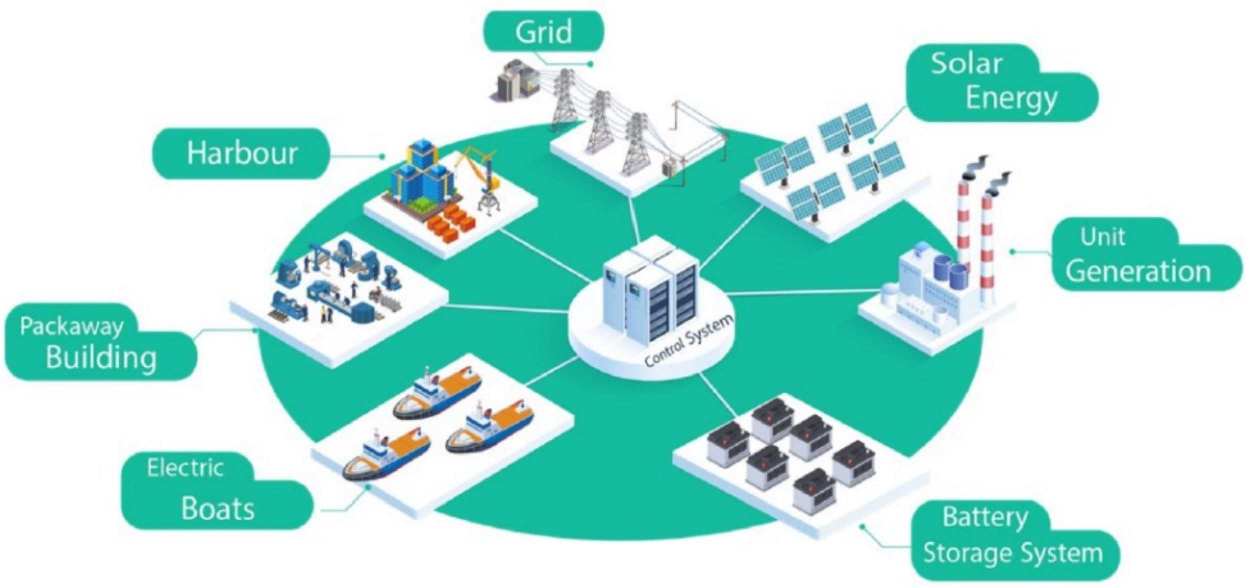
The North East of the UK and other areas in the UK are home to ports that have good access to local industries and a good transportation network can be ideal places to locate production facilities for hydrogen and ammonia. With a higher energy density than hydrogen, ammonia has the potential to become a carbon-free energy carrier, and therefore technically feasible for deep sea voyages. Ammonia is already gaining attraction on major trade routes:

The Castor Initiative [6] is working to develop a green corridor using two VLCCs (Very Large Crude Carrier) bunkering ammonia, thus, guaranteeing access to bunkered ammonia (Atchinson 2022). Moreover, the 'green corridor' concept has seen interest from significant players and could see ammonia being planned on major routes. It is worth stating that infrastructure for storage and distribution of ammonia already exists globally from the well-established distribution of ammonia fertiliser; thus, the expansion of existing networks and safety standards and regulations can be adopted for ship bunkering.

Some ports are natural hubs for connecting offshore energy to ports. For example, the industrial heartland of the Humber area has plans to capitalise on the closely located East Coast Cluster to produce zero carbon hydrogen on-site for multiple sectors, making it the world's first net-zero industrial area by 2040. Likewise, in the maritime industry there is growing interest to build infrastructure for the production of green ammonia and hydrogen in existing ports near offshore wind farms. Electricity produced by offshore wind turbines can be connected via undersea cables to onshore electrolysers, or alternatively, some are considering electrolysers that are on site on offshore wind turbines which can be transported via pipeline or ship. The latter option will only happen in niche instances, for example for refuelling small fishing fleets far away from ports or harbours.

A smart microgrid (see Figure 5) may be established in the port with a combination of two or more intermittent onshore and offshore renewable energy sources (solar, wind, wave or tidal) to provide a virtually continuous supply and thereby improve the cost-effectiveness of the whole process. A digital intelligence platform may be established to connect assets across the port and gather near real time operational information using smart metering for large but highly variable electrical uses. With real time measurement data, a demand-management system may enable supplying electricity by managing the local/regional grid and the largest local loads in the port as a function of variable supply. As such, these hubs could act as energy reservoirs for the surrounding areas by connecting to the national grid.

Figure 5 – Smart grid model for port authorities (Alzahrani, A et al., 2021)



Industrial areas near ports could potentially benefit from excess renewable wind power. If there is sufficient shipping and industrial fuel demand to warrant the initial investment of on-site hydrogen production infrastructure, during times of excess offshore renewable energy [7], hydrogen could be produced on-site to act as an energy store or fuel local industry or shipping. This instance would only be the case if the size of the connection from the offshore wind farm to the grid is not large enough – i,e, cannot contain voltage from the wind farm and would otherwise have to switch off wind turbines, or no additional load balancing is required on the grid.

6 A multinational coalition committed to zero carbon shipping includes MISC, LR, SHI, engine manufacturer MAN Energy Solutions (MAN), the Maritime and Port Authority of Singapore (MPA), Norwegian fertilizer company Yara International and Jurong Port (JP)

7 Currently this is infrequent but with the share of renewable energy increasing, times of excess renewable energy will become more frequent

Shoreham Port, on the South Coast of England, will showcase how locally produced green ammonia and hydrogen can act as an energy hub for surrounding area. An increase in capacity of on-site solar and onshore wind turbines will be combined with the parallel scaling of electrolysers to 20MW (Argus 2021). The expansion will enable Shoreham Port to become a key energy reservoir for the area and act as 'catalyst for the decarbonisation of transport across the region' (Argus 2021).

5.2.2 Importing green hydrogen/ammonia to UK ports

Transitioning UK shipping to operate on cleaner alternative fuels will require major conversion of ports and supply chains. With such large demands of hydrogen and ammonia expected for the maritime sector, demand may outstrip the supply of homegrown electro fuels. Alternatively, it may be economically beneficial to import cheaper green hydrogen and ammonia from areas that produce the fuel from cheaper renewable energy. Based on projected costs in 2035, there could be large cost savings of importing green hydrogen produced in areas of cheaper and more abundant renewable energy (e.g. the Middle East) compared to home-grown hydrogen (Jackson, C et al 2019). Importation of hydrogen from such geographies may be crucial for the UK industrial sector to achieve targets of developing at least one net zero industrial cluster by 2040 (HM Government 2021).

In certain scenarios, it will be more cost-effective to import green hydrogen in the form of ammonia and crack it into its constituents (hydrogen and nitrogen) in the UK than it will to produce green hydrogen in the UK. As an energy-carrier, ammonia with its established production, transportation, storage infrastructure could play a crucial role in enabling the use of hydrogen to decarbonise the UK energy system. Networks must be expanded with the employment of ammonia handling know-how from the fertiliser industry, along with the building of large ammonia carriers to transport the fuel at the quantities expected.

5.2.3 Strengthening the electricity grid for UK ports

Connectivity of ports to the national grid is crucial in enabling ports to become decarbonisation hubs for maritime and the surrounding areas/industries. Strengthening these connections not only will provide electrified solutions to a range of transport modes and port operations, but also will provide ports with better connectivity to localised offshore wind farms. Greater amounts of renewable energy can then be injected into the national grid, subsequently creating a more resilient electricity grid.

Grid connection also brings the benefit of enabling cold ironing in ports. This allows a reduction in local air pollution, noise and carbon emissions; however, it requires extensive infrastructural change at ports to provide electricity to the vessels. Shore power/cold ironing for ships is not the only process that demands electricity at ports; demand also comes from other entities such electrified freight handling equipment and service vessels, port buildings and storage facilities (especially cold storage) and other future electrified vehicles.

There is an urgent need to decarbonise and eliminate unhealthy criteria pollutants, such as NOx and PM, from heavy-duty road transport in and around ports. As large logistics hubs, it is likely that ports will have a significant requirement to offer charging to electric trucks. This requires major investments for a grid reinforcement in the port as well as sufficient space within the port for charging stations or alternatively enough charging stations outside the port if HGVs cannot stay in the port for an extended period. Please refer to the sections 2.3.2 and 2.4.2 for a greater study of cost implications and state of development within the UK.

5.2.4 Wider literature on port's future research challenges

A comprehensive review of research projects relevant to the decarbonisation of ports was carried out by Alzahrani et al 2021. As well as the high energy power consumption of power systems in ports, it was found that the lack of professional management of resources at ports was one of the main factors that contributed directly or indirectly to the level of GHG emissions. The findings demonstrate that the key factors contributing to decarbonising ports are applying renewable energy resources, cost optimisation, deploying intelligent technologies, and establishing rules and regulations to be implemented for greening ports (Alzahrani et al 2021).

Based on the comprehensive review and comparison of the available scientific literature, the following areas for future research gaps are suggested by Sifakis and Tsoutsos (Sifakis, N & Tsoutsos, T 2021):

- More research is needed regarding the less mature smart techniques and technologies
- There is a need to widen the range of studies regarding both the regionality and the size of the ports.
- More studies are needed concerning the cooperation between port-related parties.
- The available research work has to be implemented, up taken, and tested into actual port conditions, evaluating the measures' actual applicability. This accords with the view put forward by (Bjerkan and Seter 2019) who suggest that the existing literature gives an insufficient foundation for decision making in ports with the main reason being that few papers are based on empirical findings.

As nodes in global supply chains, UK ports generate environmental impacts through their various functions linked to cargo handling, connectivity to maritime and land transport networks, industrial and semi-industrial activities, logistics and distribution activities, and energy production and distribution. In this review, most feasible scenarios for UK ports' pathways to decarbonisation were reviewed and possible combinations between main energy production/ transmission and port end-uses are discussed. In summary grid connections need to be strengthened for direct electrification in the small and intermediate sized UK ports, while in addition there is a need for significant investment for green hydrogen/ammonia bunkering facilities in large UK ports. Researchers need to pay special attention to the smart port approach which can impact the overall ecosystem of the port by continuously harvesting information on port activities using the digital platform and making decisions using artificial intelligence and big data technologies.

Finally, a number of other topics, while they do not feature prominently in the literature, nonetheless may need to be considered:

- The future skills requirements of ports operatives
- Some ports are involved in wider transport and distribution of fossil and biofuels. What challenges and opportunities arise when there is a shift instead to shipping for example hydrogen and ammonia?
- Discussion of decarbonisation of maritime tends to focus on shipping and ports, with road and rail regarded as separate and distinct modes. However, developments at the landside-port interface too need to be better integrated e.g. rail and canal connections, electric trucking, inland and dry ports.
- Aspects of some global shipping networks owe their structure (nodes, hubs, links) to legacy issues e.g., the dominant tradewinds, location of bunkering facilities, origin of energy products, energy density of energy vectors (for example, coal ships needed more closely spaced bunkering ports than oil fuelled ships), etc. Therefore, future shipping networks could reorientate around provision/location of new energy vectors e.g., if for example the Middle East became a centre of cheap ammonia availability then we could envisage this location becoming an important hub for shipping given the expected 'pull' of cheap bunkers.
- And finally, the issue of climate precarity: how exposed is the existing network of ports to adverse weather such as flooding, high winds, etc. This has important implications for where the new, large-scale capital investment in port energy infrastructure should be located.

6 Concluding remarks and the synergies of freight decarbonisation

The preceding sections 2 to 5 explore the specifics of decarbonisation of road freight, maritime freight and ports, including the actor/stakeholder networks within which that decarbonisation will have to take place.

Combining these analyses, it can be observed that all end-uses may be supplied with the electricity from either grid or onsite generation based on local renewables or imported hydrogen/ammonia. Therefore, an electricity infrastructure seems a no-regret option as electricity is a common denominator in decarbonising the freight system. A summary of how the different energy vectors are applied to different freight transport applications is provided in Table 1.

Table 1 – Different combinations between energy production/transmission and end-uses in ports

End-uses	**Energy production/transmission**			
	Grid electricity	**Local generation of renewable electricity**	**Local generation of hydrogen/ammonia**	**Imported hydrogen/ ammonia**
Cold ironing	Power vessel's auxiliary systems during berthing	Direct connection to microgrid or connected to energy stores for later use	Electricity stored as chemical energy (hydrogen/ammonia) for periods when microgrid requires extra load	Electricity stored as chemical energy (hydrogen /ammonia) for periods when microgrid requires extra load
Port machinery	Electric port machinery connected to mains or use charged battery	Direct connection to microgrid or connected to energy stores for later use	Hydrogen as a fuel to run hydrogen powered port machinery	Hydrogen as a fuel to run hydrogen powered port machinery
Small vessels	Charge onboard battery for electric vessels	Charge onboard battery for small electric vessels	Supply hydrogen/ ammonia as fuels to the engines in small vessels	Supply hydrogen/ ammonia as fuels to the engines in small vessels
Bunkering	Charge onboard battery for small vessels	Charge onboard battery for small full electric vessels	Bunker deep-sea vessels with ammonia for intercontinental shipping	Bunker deep-sea vessels with ammonia for intercontinental shipping
Road freight vehicles	Charge battery for electric freight vehicles	Charge battery for electric freight vehicles	Supply hydrogen as a fuel to hydrogen powered road freight vehicles	Supply hydrogen as a fuel to hydrogen powered road freight vehicles
Rail head	Charge battery for electric trains	Charge battery for electric trains	Supply hydrogen as a fuel to hydrogen powered trains	Supply hydrogen as a fuel to hydrogen powered trains
Logistics facilities	Supply electricity to lights, heating and vehicles	Supply electricity to lights, heating and vehicles	Supply hydrogen as a fuel to hydrogen powered vehicles and provide heat energy	Supply hydrogen as a fuel to hydrogen powered vehicles and provide heat energy
Co-located industry	Supply heat energy using electricity	Supply heat energy using electricity	Use hydrogen to provide feedstock for co-located industry	Hydrogen may be used as feedstock for co-located industry
Urban environment (heat and passenger vehicles)	Provide heat and charge battery for electric passenger vehicles	Provide heat and charge battery for electric passenger vehicles using electricity	Decarbonise residential heating with hydrogen and supply hydrogen as a fuel to hydrogen passenger vehicles	Decarbonise residential heating with hydrogen and supply hydrogen as a fuel to hydrogen passenger vehicles

Across the areas studied, the transitions are still in the emergence phase. The scale of the challenge and its potential costs have been estimated, but the spend to date towards the multi-billion levels of investment needed has been minimal. This is true both for public and private sector investment.

Part of the explanation for the slow progress is that there remains some lack of clarity of the exact role that will be played by electrification and liquid fuels, and therefore the specifications needed both for national scale infrastructure and vehicles. However, there is also a lack of budget available for public sector spending, and few specifics of the policy that might incentivise a transition for these sectors. Many stakeholders pointed to the lack of policy specifics or public spending as reasons not to advance beyond incumbent technology and operations.

However, it is also clear that there are many overlaps between these different sectors, and a strong need for an integrated vehicle/vessel and infrastructure approach – including integration with the wider UK domestic energy transition. The fundamental shift in energy supply chains that is required, regardless of exact proportions of UK road and maritime vehicles/vessels that electrify or move to a new liquid/gaseous fuel, means that significant bespoke energy infrastructure will be needed.

In the worst-case scenario, investment decisions could be made incrementally, adding capacity for one application at a time (e.g. electrification investments for ships for cold ironing, battery electric ships, road freight, port electrification all taken in isolation). This would be both disruptive, expensive and inefficient. A preferable scenario is that the end point of a zero-emission freight transport system is the starting point for investment strategy, and a progressively decarbonising managed-risk investment runway is identified.

This latter scenario requires a level of national coordination, data transparency and collaboration that the UK freight system does not currently have, but which the DUKFT project provides some suggestions as to how to enable. Specifically:

- A key role for national-scale modelling of the freight system that can act as a repository for trials data and increasingly refine the fidelity.
- A co-creation approach bringing the communities of stakeholders together to both input to and learn from the development of detail of UK freight decarbonisation.
- A major role for ports as decarbonisation hubs, enabling opportunities both for freight transport decarbonisation (of all modes), as well as local energy entrepreneurship.

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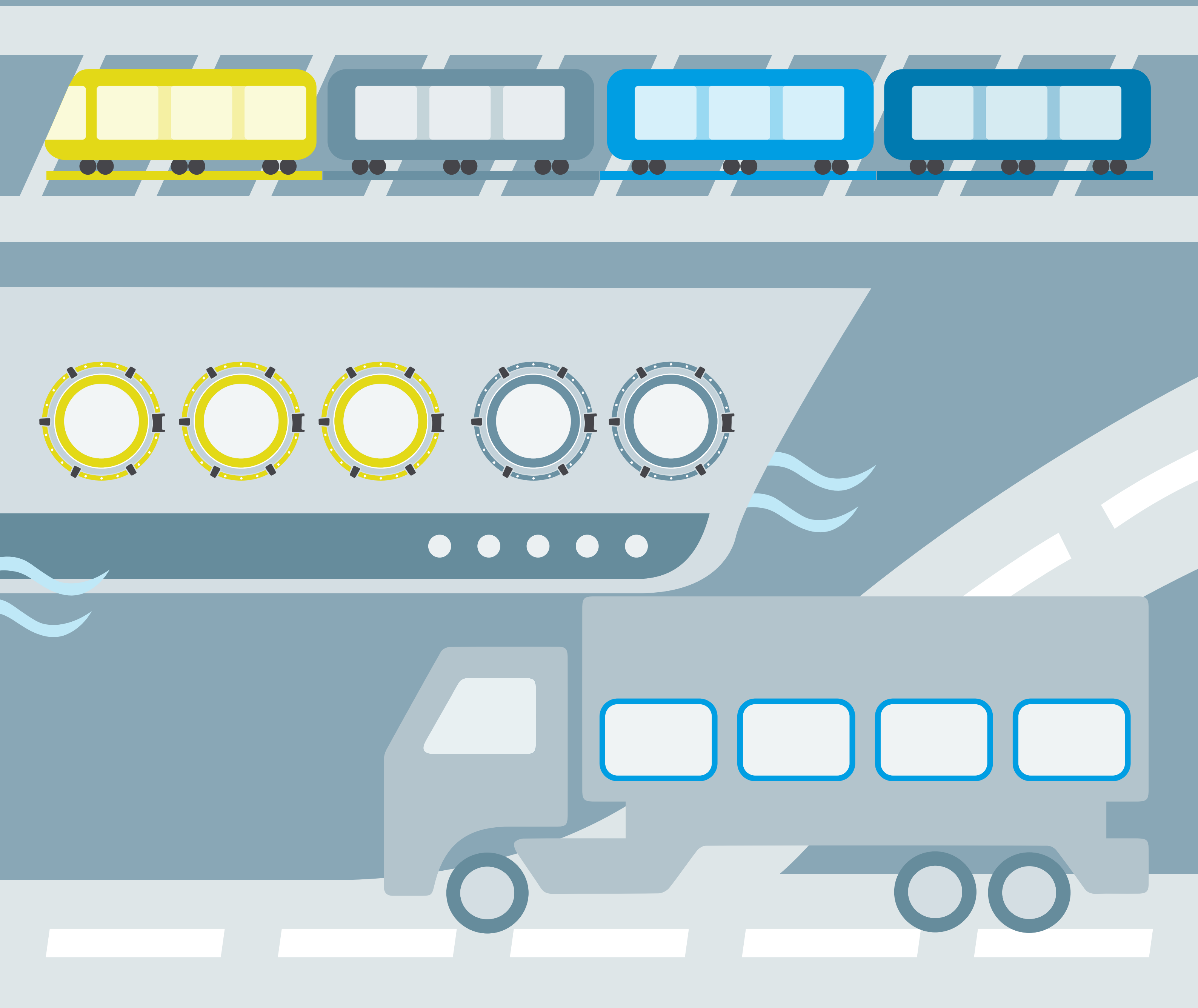

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