

Aberdeen Hydrogen Supply Hub Business Case

Final report

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Aberdeen is one of Europe's pioneering hydrogen cities and the Council is seeking to build on the successes already achieved

Aberdeen Hydrogen Hub – local context

- Aberdeen has established itself as a centre of excellence for HFC technologies, with a range of technology demonstration and other initiatives implemented in recent years, largely informed by the *Aberdeen City Region Hydrogen Strategy and Action Plan (2015 – 2025)*.
- Highlights in terms of deployment activities include:
 - Deployment of Europe's largest fleet of FC buses* and refuelling infrastructure that has been operating with extremely high availability levels since 2015.
 - Introduction of fleets of light duty fuel cell vehicles into the Councils' fleet and a car sharing club.
 - Trials of hydrogen-fuelled municipal vehicles (refuse trucks, road sweepers).
 - Commissioning of a MW-scale stationary fuel cell at TECA.
- Aberdeen has become one of Europe's pioneering hydrogen cities largely through the work of the Council and considerable public sector investment to overcome the challenges of high equipment prices due to technology immaturity and a lack of economies of scale.
- The existing means of hydrogen production in the city lead to relatively high cost fuel for transport applications (partly since opportunities to secure low cost energy supplies for hydrogen production have not yet been realised). While this is manageable for small-scale trials, high hydrogen prices are a significant barrier to more widespread uptake.
- With ACC's order for 15 new fuel cell buses in 2019, and plans to order up to 10 more buses in the near term, there is a need for new low cost, low carbon hydrogen supplies for Aberdeen.



A FC bus at the Kittybrewster HRS



The ACHES (Aberdeen City Hydrogen Energy Storage) HRS



*Energy centre at The Event Complex
Aberdeen (TECA)*

* The fleet of 10 Van Hool buses remains Europe's largest in operation (now joint with London) as of autumn 2019. However, larger fleets are planned in other cities (e.g. Cologne).

Aberdeen City Council is seeking to help establish a sustainable renewable hydrogen supply hub in the city

Aberdeen Hydrogen Hub study – objectives

- The hydrogen sector has now matured to the point where the cost of hydrogen production and distribution equipment has fallen sufficiently such that **plausible business models for the deployment of hydrogen as a fuel are emerging**. Several manufacturers are also beginning **series production of fuel cell vehicles** (especially cars and buses), which are leading to vehicle price reductions. In this context business models for the commercial deployment of hydrogen technology are beginning to emerge in certain markets.
- Hydrogen is a good fit for Aberdeen partly due to the local expertise in the oil and gas sector. Developing a local hydrogen economy will create a range of **opportunities in the supply chain** that local businesses are well placed to exploit.
- Building on the various existing projects that have made the city a leader in HFC technologies, Aberdeen City Council wishes to encourage **private sector stakeholders to work in partnership with the Council** to develop a thriving and economically sustainable hydrogen Hub in the city.
- The key requirement of the Hub is to **make hydrogen available at a price which makes further deployment of hydrogen vehicles (and other non-transport related demands) economically viable**, leading to new economic opportunities in Aberdeen and the surrounding areas.
- This will require the stimulation of **enough demand to ensure sufficient economies of scale** in the production and distribution of hydrogen that its cost can become affordable. It will also require new business models that link hydrogen production to low cost forms of green energy.
- Element Energy was commissioned to assess and develop the business case for a renewable hydrogen hub (supply system) that is **sustainable from an economic as well as an environmental perspective**.
- A key aim of the study was to develop a **real case and action plan** so that a delivery phase can begin from late 2019, thus unlocking further opportunities in Aberdeen.

This report is one of several outputs from the study – a standalone Executive Summary has also been provided

Study outputs – overview

- This document is the main report from the study and summarises the work undertaken between August and November 2019. The structure is as follows:
 - **Assessment of hydrogen demand** – we start with an assessment of the potential scale of demands for hydrogen as a fuel in Aberdeen and the surrounding region. Understanding the likely demands (scale, timing, etc.) is a key first step in developing and assessing Hub options.
 - **Hydrogen supply options** – gives an overview of the alternative supply options considered and rationale for selection of the preferred approach.
 - **Infrastructure deployment and siting** – summary of the key findings from work to identify potential sites for the Hub.
 - **Business case assessment** – results of techno-economic analysis for several scenarios and articulation of the business case for a new Hub.
 - **Funding, financing, and investment requirements** – funding requirements, potential options for financing the Hub, and stated preferences of potential suppliers and investors.
 - **Environmental and economic impacts** – results of assessment of the wider benefits of delivering the Hub, which inform the case for further public sector investment.
 - **Medium-term vision for hydrogen in north-east Scotland** – sets out a vision for hydrogen in the region to 2030 and key development milestones.
- Appendices include:
 - **Action Plan** – contains a set of recommendations for near-term actions for ACC to take to implement the Hub and help stimulate additional hydrogen demands.
 - **Strategy for existing assets** – recommended approach for existing hydrogen production and refuelling infrastructure owned by ACC.
 - **Assumptions and summary of stakeholder engagement** – contains detailed assumptions underpinning the analysis and a record of the stakeholder consultation undertaken as part of this project.

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Securing demand is essential to deploying hydrogen at scale, as illustrated by several global applications showing early signs of commercial success

Company(s)	Country	Supply chain aspects addressed	Summary
	France	Distribution & applications (taxis)	Taxi service operating 100 taxis in Paris, France, but with expansion plans to 600. Coupled FCEV-HRS deployment.
	Switzerland	H2 supply chain & vehicle licencing	A collaborative approach to create Swiss demand for hydrogen using >1,000 FC truck customers, driven by expensive taxes on diesel trucks.
	USA	Private consumer distribution	Leverages an App and customer-friendly HRS to simplify hydrogen refuelling with the aim of accelerating FCEV uptake among tech-savvy Californians.
	France	Public-private partnerships	Comprehensive strategy to supply zero-emission hydrogen over a large geographic area. Significant public and private sector backing.
	Canada	Private consumer distribution	Joint venture between HTEC and 7-Eleven, which will leverage 7-Eleven's existing gas station network for public refuelling starting in BC.
	Europe (three countries initially, including the UK)	Bus fleet operation	A collective 600 FC bus deployment plan enabling parties to benefit from lower cost buses. Economies of scale also achieved for fuel by clustering demand at large 100+ bus production and distribution sites.

The business case for the Hydrogen Hub focuses on demand from transport applications, but there is significant potential for heat & industrial applications

The Hydrogen Hub focuses on applications which can be implemented in the near term

- The table below shows the high-level potential and key barriers for transport, heating and industrial applications.
- It is uncertain whether heat & industrial markets will have been developed sufficiently in the timescale of the Hub, and therefore demand from these applications has not been explicitly included in the scenarios for the business case assessment.

Applications	Potential scale of benefits	Key barriers to adoption in 2020–2030	Indicative value for hydrogen
Transport	Transport accounts for 25% of UK greenhouse gas emissions; hydrogen could be applied alongside battery electric technologies to completely decarbonise this sector.	Already in use in many segments in the UK (buses, cars, vans, RCVs) and Europe (HGVs, trains, boats). <i>Lack of refuelling infrastructure is one of the main barriers to further uptake – one that the Hub aims to address.</i>	Up to £8/kg (depending on the application)
Domestic & commercial heating	Hydrogen could replace natural gas in many of these applications, which together account for around one third of UK greenhouse gas emissions. Applications include: district heating, hydrogen boilers, combustion for furnaces & other industrial heating systems. Hydrogen could be blended into the gas grid or ultimately replace natural gas in many areas of the grid.	Time is needed for demonstration projects to mature, and for regulatory changes relating to certifications and safety to be implemented.	Likely to be £2.50/kg or less (based on the current price of natural gas)
Industrial applications		Current costs of low carbon hydrogen production are too high for this market to develop without specific policy mechanisms.	

The demand for hydrogen in 2020–2030 will inform the requirements for the Hub; several scenarios have been developed to reflect uncertainty of demand

Overview of demand scenarios

Scenario	Summary	Key transport segments	Level of demand in 2030
1. Sector failure	25 buses operated until 2023; unsuccessful trial and no new demand	Buses	Demand drops to zero (in 2024)
2. No growth	25 buses only; no new demand	Buses	0.4 tonnes hydrogen/day
3. Demand growth	Gradual transition of public sector fleets & local freight to hydrogen	Buses, cars (e.g. taxis), council RCVs, HGVs	3.5 tonnes hydrogen/day
4. Demand growth + trains and marine	As above + 10 trains in 2025 + 8 boats by 2028	Buses, cars, council RCVs, HGVs, trains, boats	8.5 tonnes hydrogen/day

- The “Demand Growth” scenario forms the basis for the business case assessment, but it is possible that demand could follow any of the other scenarios. The approach and assumptions behind the demand growth scenario (including justification for the end uses included) are explored in the rest of the slides in this section.

The inclusion of various transport applications in the scenarios over time is largely based on the level of commercial readiness of hydrogen in different end uses

Commercial readiness factors to take into account

- Current availability of hydrogen vehicles or suitable conversion technologies
- Evidence of local appetite for adoption
- Vehicle cost premium (i.e. level of funding/subsidy needed to make vehicles available at an attractive price)
- Fuel cost premium (i.e. level of funding/subsidy needed to allow incumbent fuel cost)

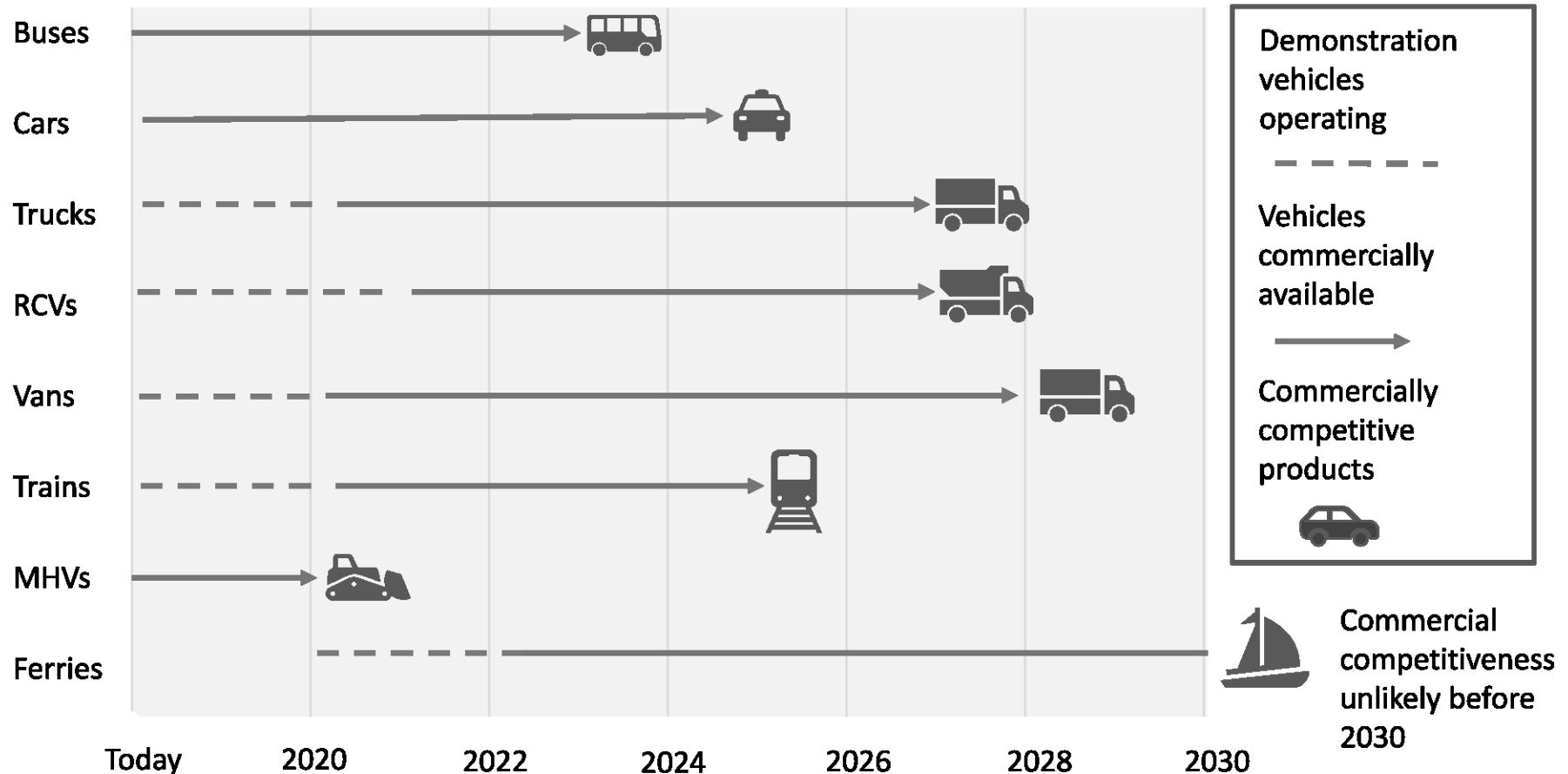
Potential adoption by 2030 is informed by the relative commercial readiness of different demand sectors

- The table below provides an indication of the relative levels of commercial readiness for different vehicle types according to the factors set out above. **A summary of availability and fuel cost factors is provided in pages 11–15 of this document, and further supporting data is shown in Appendix 4 (Market readiness).**

Vehicle type	Availability	Local appetite	Vehicle cost	Fuel cost	Relative readiness
Fuel cell bus					
Fuel cell car					
Dual fuel RCV/HGV					
Fuel cell RCV/HGV					
Fuel cell van					
Fuel cell train					
Dual fuel boat					

Commercial readiness level →	Highest				Lowest
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Multiple hydrogen transport modes could be commercially competitive by 2030, but adoption in the early 2020s is most likely for cars and buses
















Note: Commercially competitive products refers to hydrogen transport modes which are competitive with other forms of low/zero emission transport. They may still have a small total cost of ownership premium compared to conventional drive trains.

The next few pages provide more detail of the timelines for availability of different hydrogen vehicles and expected milestones for commercialisation.

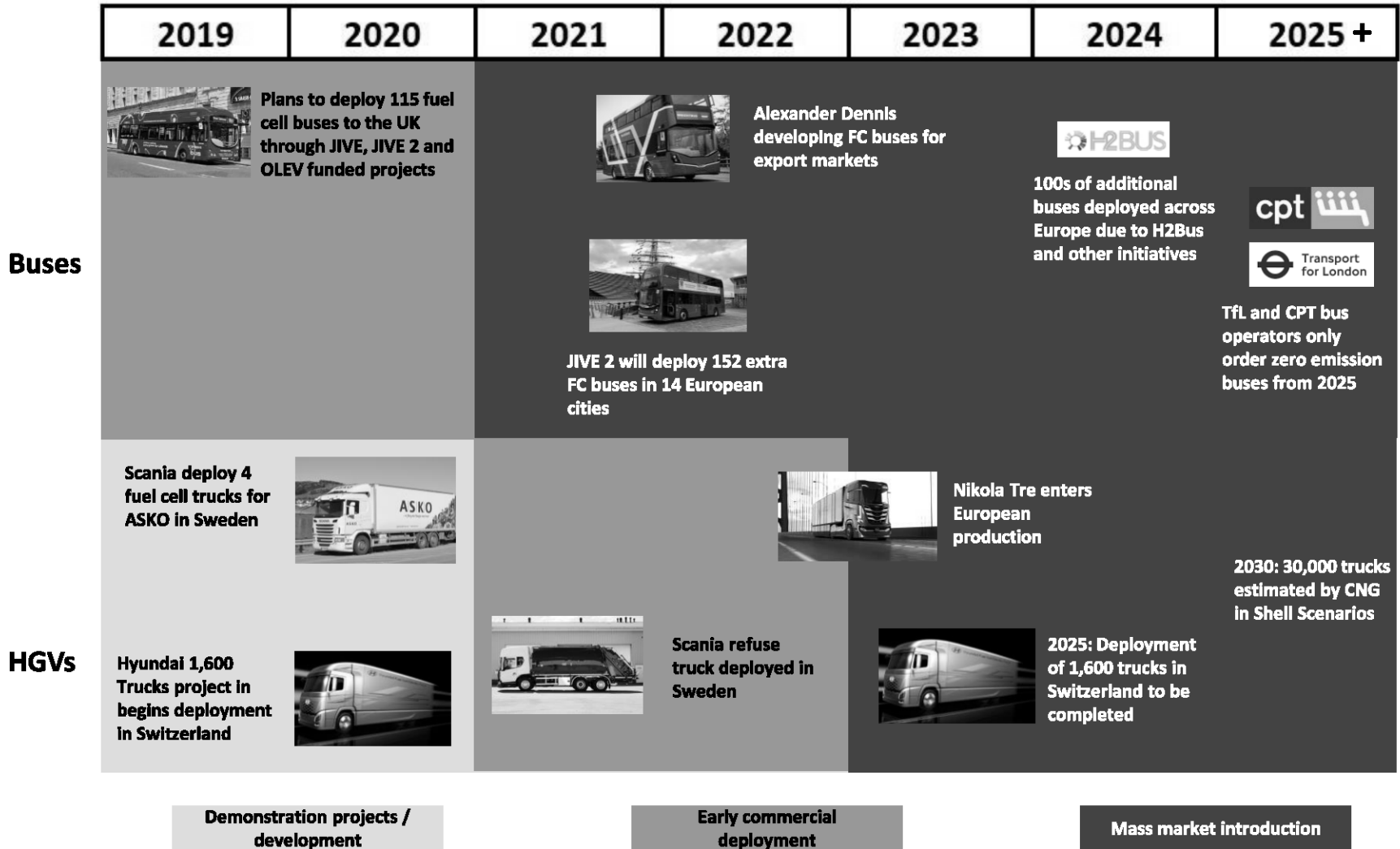
Hydrogen cars could start to be introduced to mass markets in the early 2020s, with vans to follow a couple of years later

Timeline of availability and key national and international milestones for hydrogen cars and vans

	2019	2020	2021	2022	2023	2024	2025 +
Cars	 <p>Deployment begins for 1st gen Toyota Mirai and Hyundai ix35</p>		 <p>2nd gen Toyota Mirai begins production of ~30,000 FCEVs per year worldwide</p>				<p>2025: Planned deployment of 3rd generation mass production Mirai</p>  <p>2025: UK H₂ Mobility target 6,000 FCEVs</p>  <p>Hydrogen Europe aim for 5 million FCEVs across Europe by 2030</p>
	 <p>Hyundai Nexo starts European deployment</p>		    <p>A range of other cars are being deployed worldwide, likely to come to the UK with the right support regime. Audi, BMW, Honda Daimler, PSA and many Chinese brands all have hydrogen plans in the early 2020s</p>				
Vans	 <p>100s Symbio/Renault Kangoos operating across Europe in 2019</p>		<p>Numerous Chinese initiatives to develop FC vans (e.g. SAIC), likely available in Europe in early 2020s</p>				
	 <p>Renault MASTER ZE Hydrogen available from 2020</p>		<p>787 Symbio/Renault Kangoos planned for EU deployment</p> 	<p>StreetScooter to produce over 400 Work L vans for DHL and Innogy in Germany</p> 			
	Demonstration projects / development		Early commercial deployment		Mass market introduction		

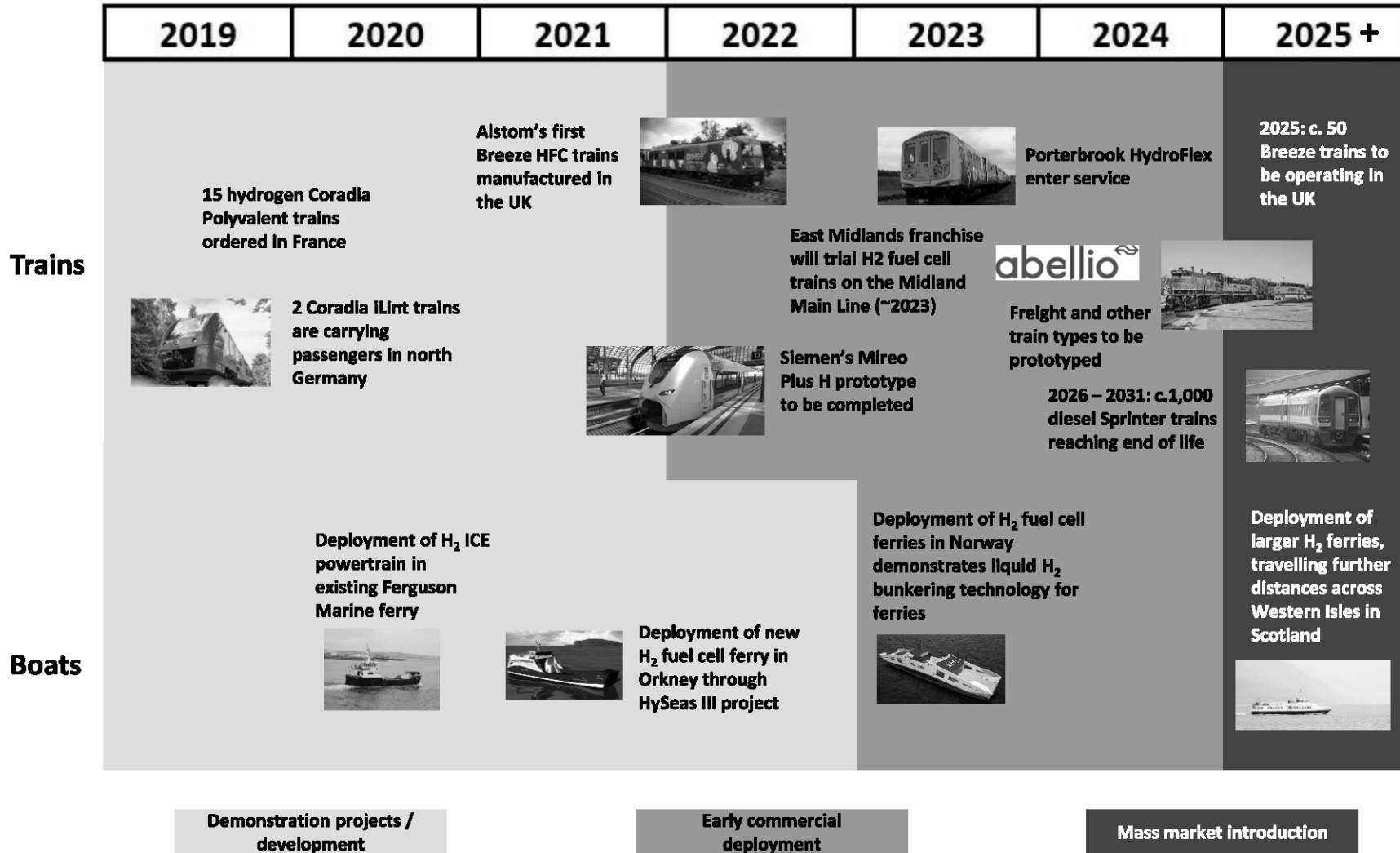
Hundreds of FC buses could be deployed in the UK in the early 2020s, while it is likely that hydrogen HGVs will still be at the trial stage

Timeline of availability and key national and international milestones for hydrogen buses and HGVs



Demonstration of hydrogen trains and boats in the UK could be envisaged in the early 2020s

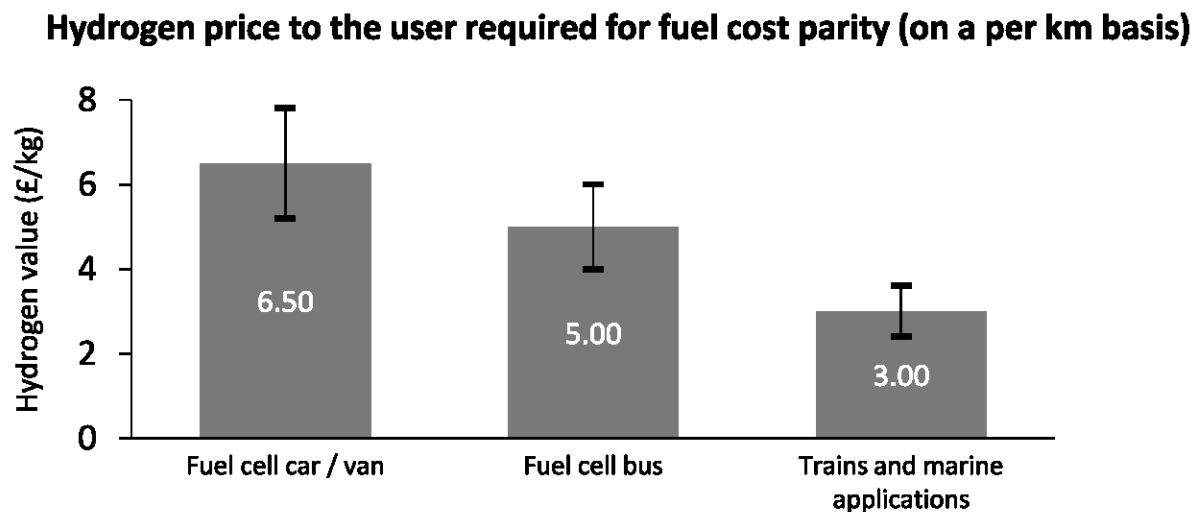
Timeline of availability and key national and international milestones for hydrogen trains and boats



Hydrogen revenues per kg from trains and marine applications could be lower than for cars, vans and buses, which would make these markets less attractive

The hydrogen price required for “fuel cost parity” can vary between applications

- To achieve fuel cost parity with diesel or petrol vehicles, hydrogen must be sold at a price that is equivalent to the fossil fuel price on a per km basis. What the end user pays for fossil fuel depends on the application; for some transport modes (e.g. trains and marine applications) fuel duty is not applicable (red diesel). This makes the “fuel cost parity” revenues, that the hydrogen supplier could expect to receive per kg of hydrogen sold, significantly lower than those where duty is paid on the incumbent fuel (this assumes that no fuel duty is paid on hydrogen).
- Hydrogen fuel subsidies could be set for different applications to reflect these differences OR users could be asked to adapt their business cases to fundamentally higher hydrogen prices.



The demand growth scenario for the business case assessment is based on a selection of key potential sources of H₂ demand within Aberdeen

The key sources of demand which have the highest market and technology readiness, combined with a significant level of potential demand, are listed below. These are incorporated into the “demand growth” scenario, which forms the basis for the Hub business case.

Scope of “demand growth” scenario

- **Buses**
 - **Cars: company cars & taxis**
 - **Vans: fleet users**
 - **RCVs / HGVs with local operations**
 - Municipal fleet
 - Port & offshore supply chain
- Can be realised with ‘local’ refuelling stations only
- Significantly higher numbers of fuel cell buses and cars are expected compared to RCVs and HGVs, due to the higher readiness of the car and bus markets, with multiple manufacturers and hundreds of cars and buses deployed across Europe to date.
 - **Uptake assumptions for the demand growth scenario are shown in p17–19, including the conditions required for this level of demand to be achieved.** Actions required to unlock this demand are set out in the Action Plan (Appendix 1).

Wider sources of potential demand

- HGVs with national operations
- Private cars and vans
- Trains
- Coaches (inter-city)
- Marine applications + FC port re-charging
- Materials handling vehicles
- Gas grid injection
- Multi-storey car parks and charging
- Local industry utilising hydrogen
- Stationary fuel cells for CHP
- These sources of demand depend upon multiple uncertain steps to be realised, or are expected to be low demand in the near-term, and so are not included in the following uptake projections. Notes on these potential demands are included in Appendix 4 (Market readiness).

Uptake assumptions: Cars and vans

Scottish Government target: No new petrol/diesel public sector LCVs after 2025

- Vehicles are split between company and private owned vehicle for the following reasons:
 - Differing fuel demands depending on vehicle type and usage.
 - Different uptake potential: commercial fleets can operate using a single HRS (in some cases), while private vehicles are more reliant on wider refuelling station availability.
- Assumptions are based on the Hydrogen Europe roadmap (2018): 4% private and 8% of commercial car and LCVs sales captured in 2030.

Vehicle	Ownership	No. of vehicles	Annual sales
Cars	Taxi + PHV	1,142	86
	Company	4,400	332
	Private	89,700	6,765
Vans	Company	4,275	322
	Private	4,725	356

Total fleet data for Aberdeen. For data sources see appendix.

Vehicle	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Company cars + vans and taxis/PHV	14 in operation	Assume capture on average 2% of sales in 2021 (15 vehicles per year) and rising to 5% in 2025 (37 vehicles per year) and 8% in 2030 (400 vehicles per year).									
Private cars + vans	No significant uptake assumed until 2025, when wider refuelling infrastructure is in place.					1% of vehicle sales in 2025, rising to 4% in 2030, giving a fleet of c.1,070 vehicles by 2030. <i>NB - not included in "demand growth" scenario</i>					
Conditions	Availability of hydrogen at a cost comparable to diesel vehicles.					Wider availability of HRS. Wider range of non-FC vehicles available					

Uptake assumptions: Buses

Low carbon buses are incentivised by the Scottish BSOG low emission vehicle payments²

- Bus operators are unlikely to buy more FC buses until JIVE vehicles have been run with high availability levels for 18–24 months.
- This implies a hiatus in growth in demand from buses until at least 2022/23. Steady uptake of FC buses beyond this date is assumed.
- Coaches are dependent upon refuelling availability across multiple cities – meaningful deployment unlikely before the mid to late 2020s.

Location	Vehicle	No. of vehicles	Annual sales
Aberdeen	Bus	187	12–16
	Coach	33	2–3
Cities within 100 miles	Bus	283	19–24
	Coach	50	2–4

Total fleet data for Aberdeen. For data sources see appendix.

Vehicle	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Buses - Aberdeen	25 buses in JIVE deployment			Assume steady uptake of FC buses following successful JIVE trial: 15 new FC buses per year to 2030, giving total fleet of 145 by 2030.							
Buses within 100 miles of Aberdeen ¹	No buses until successful JIVE demonstration			30 buses trial		Assume linear increase in hydrogen bus’s share of buses that are replaced annually from 20% in 2023 (6 buses/year) to 40% in 2030 (12 buses/yr)					
Conditions	<ul style="list-style-type: none">Sufficient hydrogen available at diesel parity			<ul style="list-style-type: none">High reliability demonstrated by JIVE buses.Further cost reductions for FC buses (capex and opex)Policies and actions to encourage modal shift towards buses							

¹ Of Aberdeen: Inverness, Dundee and Perth & Kinross

²More information [here](#)

Uptake assumptions: HGVs & RCVs

Scottish Government target: No new diesel/petrol public sector HGVs after 2030

We consider HGVs in two categories to account for differing fuel usages and refuelling infrastructure requirements:

- **Local (depot-based) HGVs/RCVs** – based on the stakeholder consultation, there appears to be appetite to trial hydrogen-fuelled vehicles in Aberdeen. This depends on appropriate vehicles becoming available.
- **Long distance HGVs** – trial or roll-out of these types of vehicles will require a national network of suitable HRS.

Vehicle	Owner	No. of vehicles	Annual sales
Local HGV	Public	96	10-20
	Private ¹	220	16–31

Total fleet data for Aberdeen. For data sources see appendix.

Given the uncertainties relating to the rate of potential uptake of hydrogen-fuelled HGVs for long distance operations, the demand projections here focus on the “local” fleets. These are further split into Council-owned vehicles (e.g. refuse collection vehicles) and private sector fleets.

Vehicle	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Local fleets (private)	0	3 vehicle initial trial		Steady uptake of 5 vehicles per year (NB Colin Lawson Transport expressed interest in FC HGVs, has a fleet of 70 vehicles and buys 5 – 10 new trucks per year).							
Local fleets (Public)	2	5 vehicle initial trial		Steady uptake of 3 vehicles per year until 2030							
Conditions		Support to reduce cost premium to diesel		<ul style="list-style-type: none"> • Availability of suitable FC vehicle models • Demonstration of adequate level of technology performance (vehicles and infrastructure) • Acceptable total cost of ownership relative to diesel HGVs 							

The level of hydrogen demand per vehicle informs the impact of each segment on the demand scenarios to 2030

Hydrogen demand per vehicle

- In developing scenarios for the potential short-term demand, combining the **potential demand per vehicle** with the estimated number of vehicles in Aberdeen by 2030¹ provides an indication of the **relative scale of demand from different segments**.
- The table below presents illustrative daily hydrogen demand figures on this basis. Note that in practice, daily mileages and fuel consumption within these segments will vary depending on the specific application.
- **This level of demand is relatively conservative and is intended to form the basis for an investible level of infrastructure; more ambitious uptake could be achieved provided that decisive steps are taken to address the remaining barriers (e.g. see Action Plan).**

Vehicle type	Daily mileage	Hydrogen consumption	Demand per vehicle	Vehicles in Aberdeen in 2030 ¹	Potential demand in 2030 (highest – lowest)
Fuel cell bus	200 km/day	8 kg/100km	16 kg/day	100	1,600 kg/day
Fuel cell car	50 km/day	1 kg/100km	0.5 kg/day	800	400 kg/day
Dual fuel RCV/HGV	100 km/day	8 kg/100km	8 kg/day	30	240 kg/day
Fuel cell RCV/HGV	100 km/day	8 kg/100km	8 kg/day	30	240 kg/day
Fuel cell van	100 km/day	1 kg/100km	1 kg/day	100	100 kg/day
Fuel cell train	500 km/day	70kg/100km	350 kg/day	(10)	(3,500 kg/day)
Dual fuel boat			200 kg/day	(10)	(2,000 kg/day)

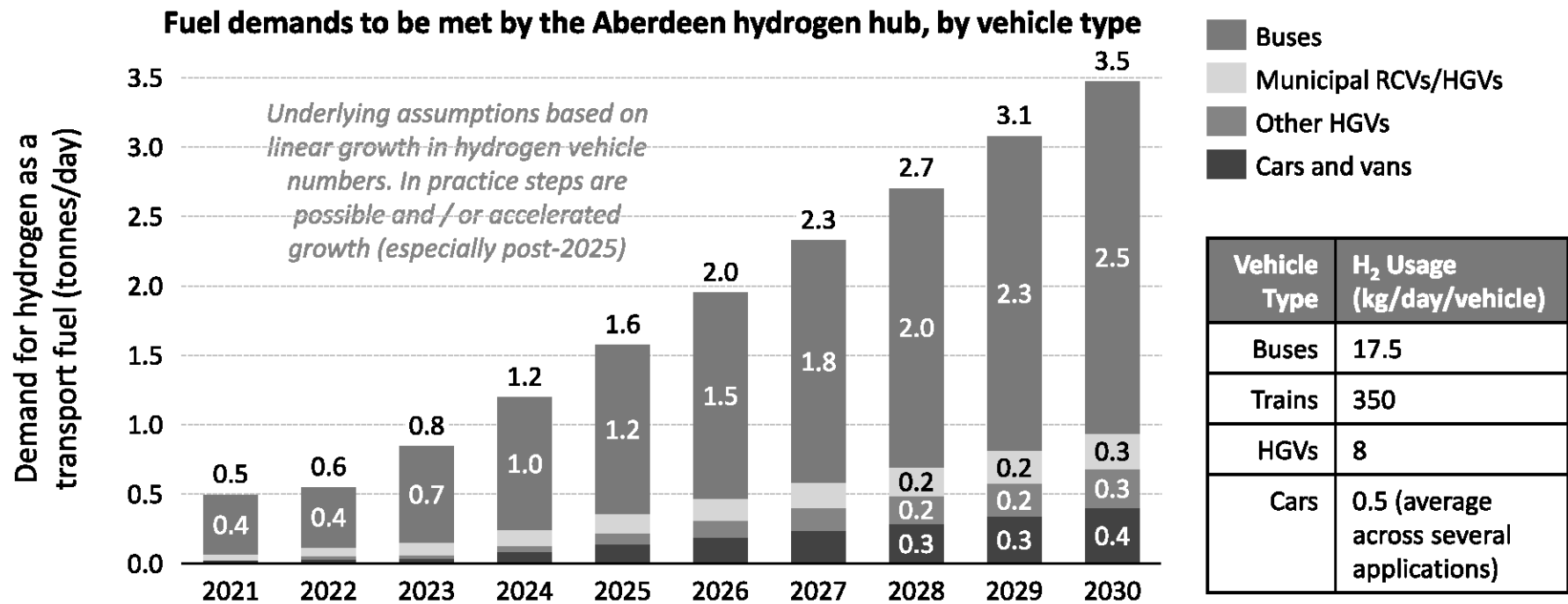
- **Buses are central to the demand scenarios**, as they could generate a significant level of demand, and have the highest level of overall “readiness”.
- **Trains & marine applications** could also generate a high level of demand, but due to the higher degree of uncertainty around initial deployment timings, they are **excluded from the main “demand growth” scenario** and treated as an upside sensitivity.

1 - The basis for these numbers is set out in the following slides and in the appendix.

Demand growth scenario: expansion of the FC bus fleet alongside growth in demand from cars and HGVs could require over 3 tonnes per day in Aberdeen

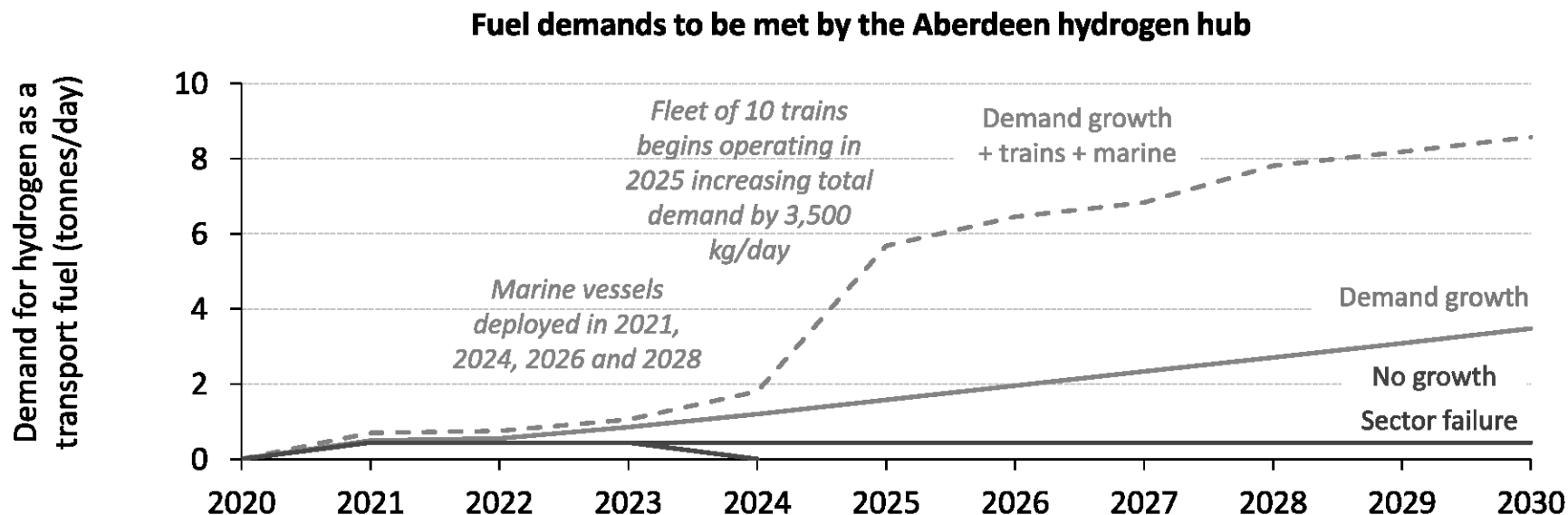
Hydrogen demand scenario: Demand growth

- The chart below shows the projected demand from the fleet of hydrogen-fuelled vehicles served by the hub, including **145 buses, 800 cars and c.70 HGVs by 2030**
- Demand is dominated by buses due to their high demand and anticipated high uptake. This means that strong signals of demand certainty from buses will be essential to ensuring investment based on demand growth in the Hub.
- This does not include additional demand from the wider region.



Other scenarios for future demand give an indication of the high uncertainty after 2022; growth from 2025 could be even more rapid than shown here

Hydrogen demand scenarios: Comparison across scenarios



- The focus for the business case analysis is the demand growth scenario.
 - **Note that this is a cautious approach and does not account for the potential further expansion of the sector (e.g. including much more uptake of hydrogen HGVs, cars, and heating applications) following the success of the initial phase of the hydrogen hub**
- Due to the uncertainty relating to the rate of deployment of hydrogen-fuelled trains / boats (which is compounded by the low cost of incumbent fuels for these applications, and the cost-gap that would need to be addressed for hydrogen as a fuel), these applications are not included in the business case analysis.
- There is also a risk that there is no growth in demand (e.g. if no additional buses are adopted after the JIVE buses), or in an extreme case complete failure of the sector.

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Three main local hydrogen supply routes are available for Aberdeen in the near term

The following hydrogen supply pathways could be realised within 1–2 years:

Production route	Distribution options	Interest from supply stakeholders	Conditions
1. Natural gas (or biogas) reformation plant near point of demand	<ul style="list-style-type: none">• Vehicles refuel at production site, or:• Hydrogen is delivered to multiple points of demand	<ul style="list-style-type: none">• None in the consultations• HyGear	<ul style="list-style-type: none">• n/a
2. Grid-connected electrolysis co-located with main point of demand	Production is at/close to the bus depot, and: <ul style="list-style-type: none">• Other vehicles also refuel at the site, or:• Hydrogen is delivered to additional points of demand	<ul style="list-style-type: none">• ITM Power• BOC• Vital Energi / Storengy• Hydrogenics	<ul style="list-style-type: none">• Low cost electricity supply
3. Centralised electrolysis co-located with renewable electricity (private wire)	<ul style="list-style-type: none">• Vehicles refuel at production site, and/or:• Hydrogen is delivered to multiple points of demand	<ul style="list-style-type: none">• Ryse / Vattenfall• Scottish Power Renewables• ITM Power / Orsted• Vital Energi / Storengy• BOC	<ul style="list-style-type: none">• Take-or-pay supply agreement or guaranteed demand

Further production routes are considered on the next page.

Future demand for hydrogen for heat could unlock further opportunities for the long-term supply of low-cost hydrogen in Aberdeen

Other hydrogen supply opportunities could become available beyond 2025:

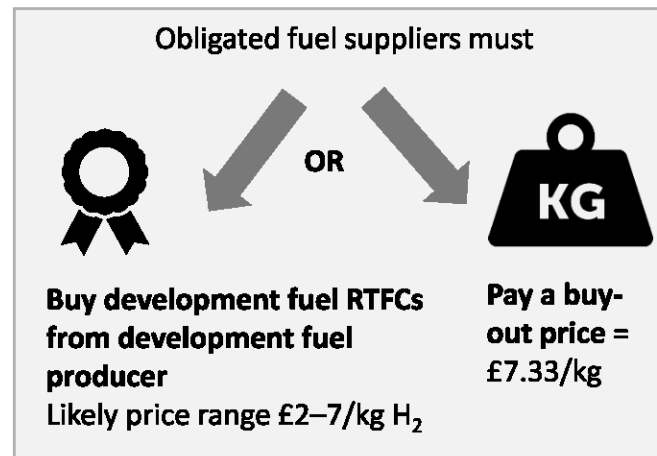
Production route	Distribution options	Interest from supply stakeholders	Conditions
4. Natural gas reformation + Carbon Capture and Storage in St Fergus; <u>dedicated hydrogen pipeline to Aberdeen</u>	<ul style="list-style-type: none">Hydrogen is delivered to multiple points of demand via pipeline (+ further tube trailer distribution)	<ul style="list-style-type: none">Project Acorn (Pale Blue Dot, SGN)	<ul style="list-style-type: none">BEIS Hydrogen Supply Competition fundingPipeline from St Fergus for supply of hydrogen in the gas network (20% blend then 100%)
5. Offshore hydrogen production from floating turbines	<ul style="list-style-type: none">Distribution by pipeline or road e.g. from the Harbour depending on demand	<ul style="list-style-type: none">Dolphyn project (ERM)	<ul style="list-style-type: none">BEIS Hydrogen Supply Competition funding

- Both of the production routes above could present a significant opportunity to supply low-cost, low-carbon hydrogen for transport applications in the late 2020s-early 2030s (as well as enabling the decarbonisation of heat). Initial hydrogen price estimates for the Dolphyn project are below £5/kg, and could be lower for Project Acorn.
- This could create a competitive risk for the nearer term supply routes. However, this risk could potentially be mitigated by explicitly **integrating a planned large scale supply of low carbon, low cost hydrogen as an option (after 2025) in the business model** for the Aberdeen Hydrogen Hub.

Renewable hydrogen production routes may be able to attract a £2–7/kg subsidy via the Renewable Transport Fuels Obligation (RTFO)

The RTFO now includes renewable hydrogen as a development fuel

- **Renewable hydrogen was introduced as a “development fuel” into the RTFO in 2018.**
- Classification as a development fuel means it **receives double certificates** to incentivise its production.
- There is a very ambitious sub-target for development fuels, creating a **market for hydrogen which current outstrips hydrogen demand from transport:**
 - Up to 14.4kt in 2020, which would require approx. 100,000 hydrogen cars if all of the target is met by hydrogen
 - Up to 230kt in 2030 (approx. 1.5 million cars) – although by then the competition with other development fuels makes the revenue from RTFCs more uncertain



The types of renewable hydrogen production which can benefit from RTFCs are described in guidance produced by DfT annually. The production methods which are currently able to benefit are:

- **Gas based hydrogen production**, where the methane comes from either biological waste (receives double RTFCs) or other biological origin (receives single RTFCs). **Biogas credits can also be used to convert any gas into “green gas”**, which is valuable provided the cost of the RTFC exceeds that of the green gas certificates. However, DfT signalled that the use of certificates for green hydrogen production is likely to be prevented from 2021.
- Hydrogen production by **electrolysis is only eligible if the electrolyser is only connected to a renewable generator**, and is designed so the majority of the energy uses flows direct from the wind turbine, or is eligible if the electrolyser is located in an area of **“grid constraint”**. In the current guidelines, the renewable generator must also be “additional”, which means the developer must demonstrate that the electrolyser is linked to a new renewable deployment.

Based on an assessment of the possible near-term supply routes, the centralised renewable electrolysis option is the preferred production route

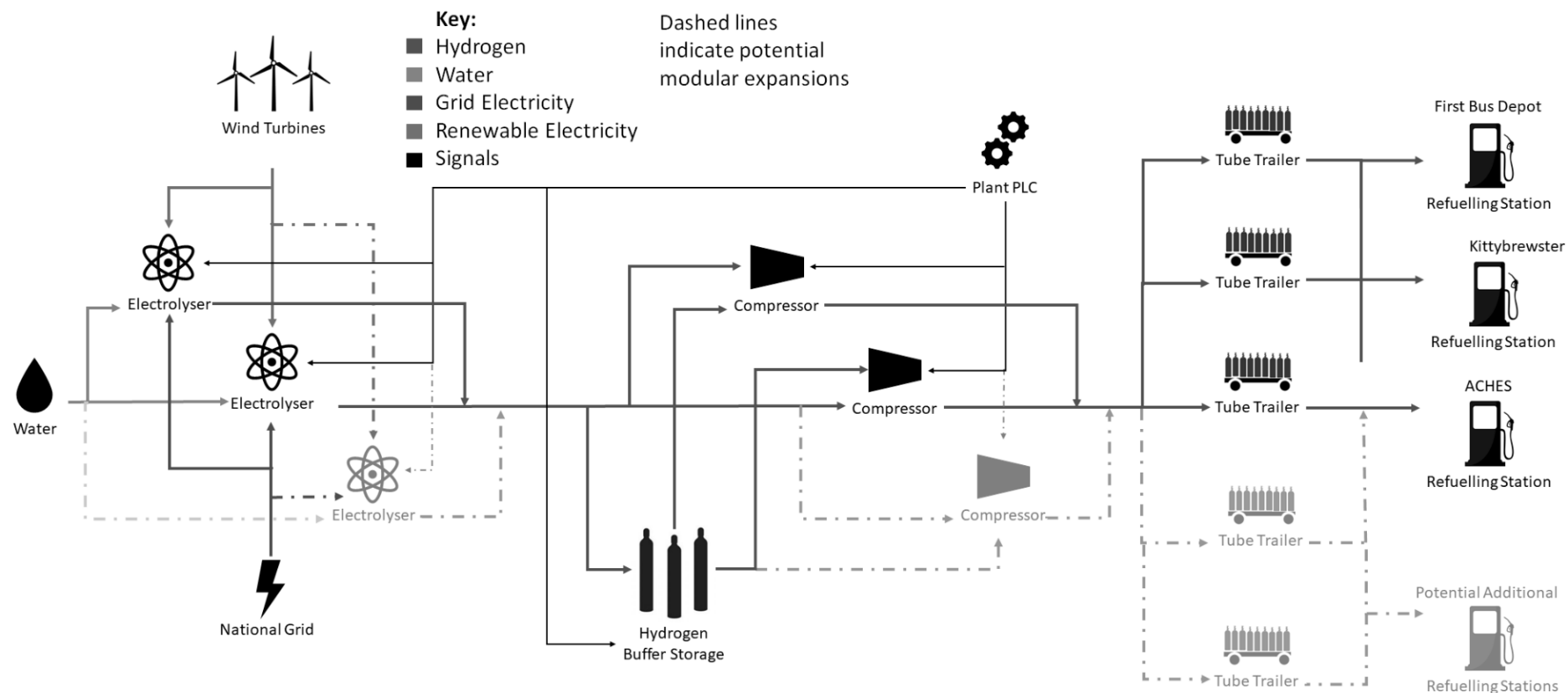
Relative strengths of different supply routes

Supply route	Feasibility of low cost supply	Low carbon credentials	Interest from stakeholders (deliverability)	Scope for expansion beyond 2t/day
1. Reformation of natural gas	Reliability issues at many existing plants	Dependent on biomethane availability	None yet	Promising
2. Grid-connected onsite electrolysis	Challenging	Good	High	Limited
3. Centralised electrolysis co-located with renewable electricity	Promising	Very good	High	Promising
4. Acorn project hydrogen	Promising	Dependent on CCS timescales	High but relatively distant	Critical to this option

- Centralised electrolytic hydrogen production directly coupled to renewable electricity with distribution of hydrogen to the HRS sites has strong potential for low cost supply, provided that there is a demand of **at least 400kg/day**:
 - This could be sufficient to unlock an electricity price of £40–50/MWh (i.e. via a private wire).
 - A high level of demand also limits the additional cost of delivery (assuming 1–3 HRS within 30 miles of the production site).

We have explored a hydrogen supply hub concept based on centralised electrolytic production with distribution of the fuel to existing and new HRS

Components of the Aberdeen hydrogen supply hub



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The demand growth scenario implies a two stage delivery plan (as a minimum) for the Hub infrastructure to meet the growing demand

High level delivery plan for Hydrogen Supply Hub infrastructure

- **Stage 1** (in operation from 2020/21):
 - 2MW electrolyser & compression (high capacity to meet future demand).
 - A new depot-based HRS for the JIVE buses (c.400 kg/day).
- **Stage 2** (in operation from 2023):
 - 6MW electrolyser, in addition to the existing 2MW electrolyser (same site).
 - Two 1,000 kg/day HRS (in addition to the existing HRS).
 - Investment would be contingent on sufficient certainty of future demand.
 - The configuration of the additional HRS capacity (and the extent to which this would involve upgrades to the existing HRS) also depends on the characteristics of the expected future demand; the nature of the vehicles will impact preferences around HRS siting and specifications.
- **Further expansion** - conditional on demand growth but not explicitly modelled.
- The concept for the Hub is based on centralised electrolytic hydrogen production with distribution of the fuel to existing and new HRS. This concept means that at each stage, **separate sites are needed for the electrolyser and the HRS.**

Low cost renewable electricity could be supplied to an electrolyser operator via a private wire from large offshore wind farms in / around Aberdeen

Renewable energy grid connection points

A private wire could be established from the following:

Sub-station for EOWDC*
(93.2MW operational wind farm)

Sub-station for Kincardine (50MW offshore wind farm under construction)



Potential production sites

Bridge of Don

The Event Complex
Aberdeen (TECA)

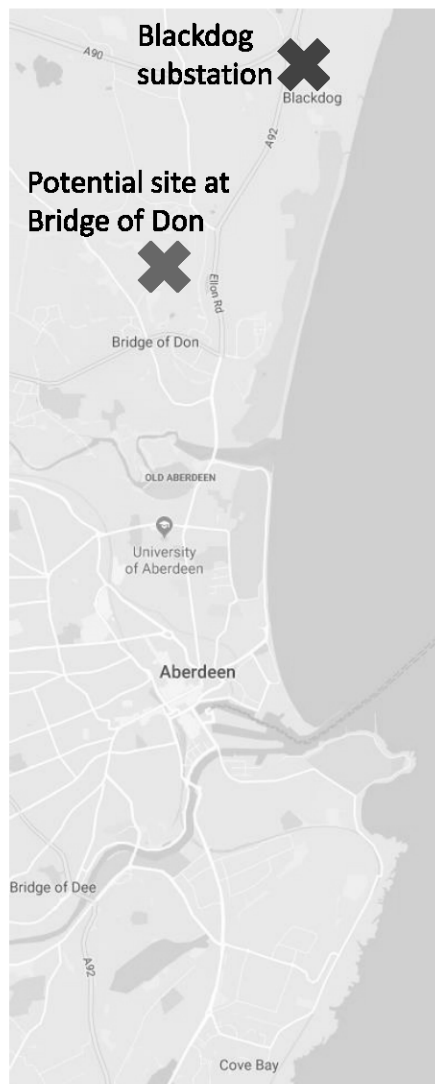
Kittybrewster

South Harbour
Development

Altens Industrial
Estate

ACHES

Vattenfall is exploring options to establish a private wire for electricity from their 93.2MW operational offshore windfarm (Blackdog to Bridge of Don)



Private wire from Blackdog to Bridge of Don

- Vattenfall is exploring the potential for production of hydrogen using electricity from their 93.2MW wind farm (already in operation).
- They are currently assessing the costs associated with a private wire running from Blackdog (the landing point) to Bridge of Don to see if this site would be feasible for hydrogen on the basis of the additional capital costs.
- There are several existing primary sub-stations and a grid supply point near Bridge of Don.
- *Note that an initial search of Council-owned sites within the Bridge of Don area, the only site of a suitable footprint (c.1 acre or greater) is located within a residential area and therefore may not be suitable for electrolytic hydrogen production.*
- Subject to the cost assessments for the private wire, the following conditions could apply for hydrogen production:
 - Electricity price of £45–50/MWh assuming demand follows the windfarm profile.
 - Electrolyser sizing would depend on level of committed demand over time (e.g. through a “take or pay” contract) and level of grant funding to cover the additional capital cost to provide any additional capacity.
- Vattenfall is exploring whether this production model could be eligible for RTFCs, but this is currently uncertain due to the fact that the windfarm is already operational.

The option of a private wire from the Kincardine offshore wind farm has also been explored but further discussions with Statkraft are needed



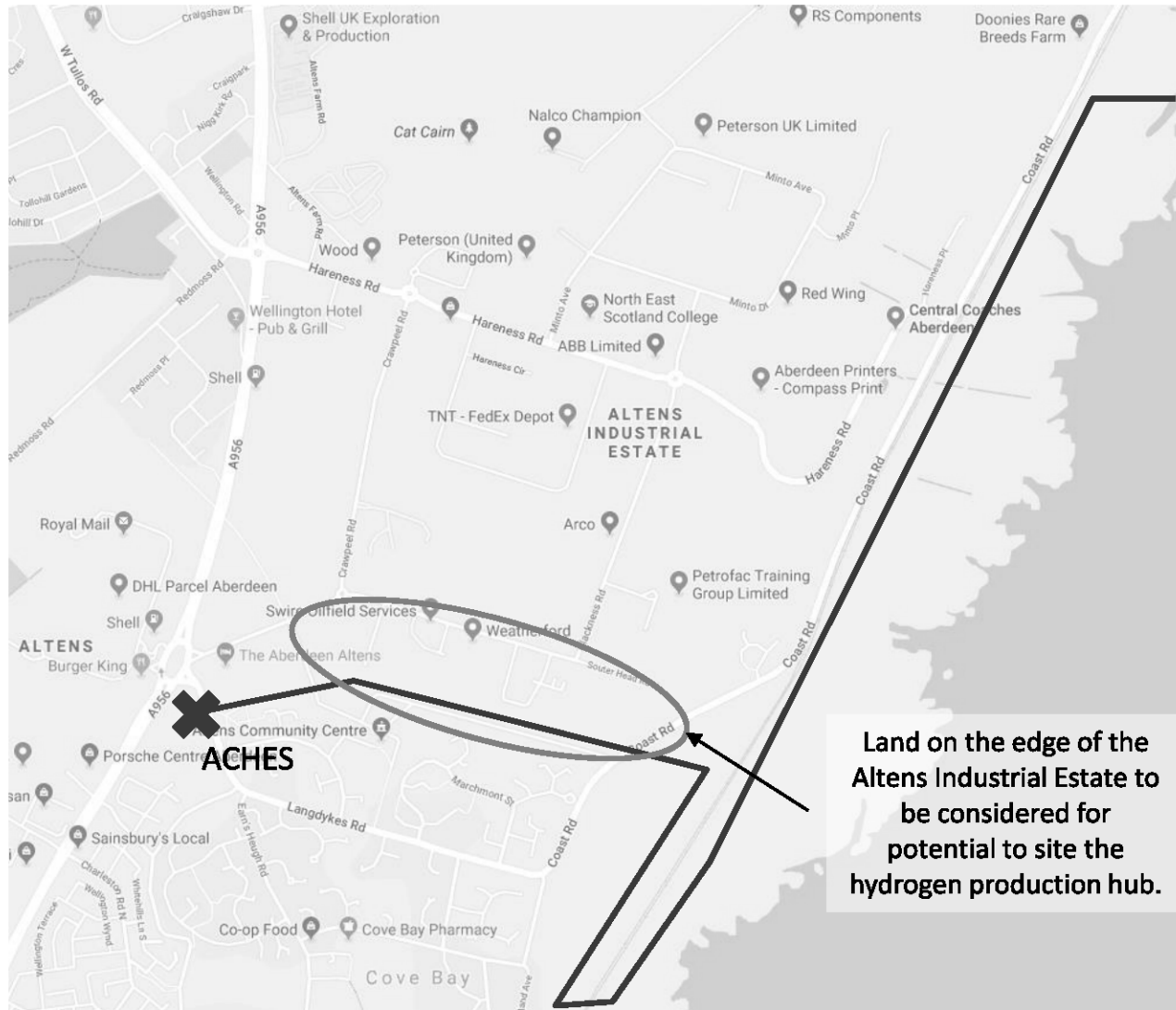
The Kincardine substation is located next to ACHES

- The Kincardine OSW farm (50MW under construction) connects to a dedicated sub-station, next to the ACHES HRS site, via a cable from the landing point (see map on following slide). Note that according to the SSE Generation availability map, the grid supply point status is **constrained** (contracted generation exceeds supply point capacity).
- A (15 year) contract is in place with Statkraft to take power from the Kincardine wind farm.

Discussions with MacAskil Associates

- The potential to use power from the Kincardine wind farm to supply the ACHES site has been considered. However, the current demand levels are too low for this to be of interest to Statkraft.
- With a consistent demand in the low MW scale, there could be some interest. The option of prioritising supply to the electrolyser (to improve the load factor) could be considered.
- MacAskil Associates could not give a firm indication of the likely electricity price but said Statkraft is likely to want at least the “market price” for any electricity supplied.
- Despite repeated attempts to speak to Statkraft representatives, the consultancy team has been unable to make direct contact with the organisation in the context of this study.
- We recommend that the Steering Group considers other approaches to Statkraft to discuss the potential for a private wire connection to a hydrogen hub at / around the ACHES site.

The cable for Kincardine will run from the South Harbour area to a substation next to ACHES, and near to Altens Industrial Estate



Approximate route of cable from Kincardine offshore wind farm to sub-station (located adjacent to ACHES site) shown in red.

There may be a possibility to make a private wire connection, either:

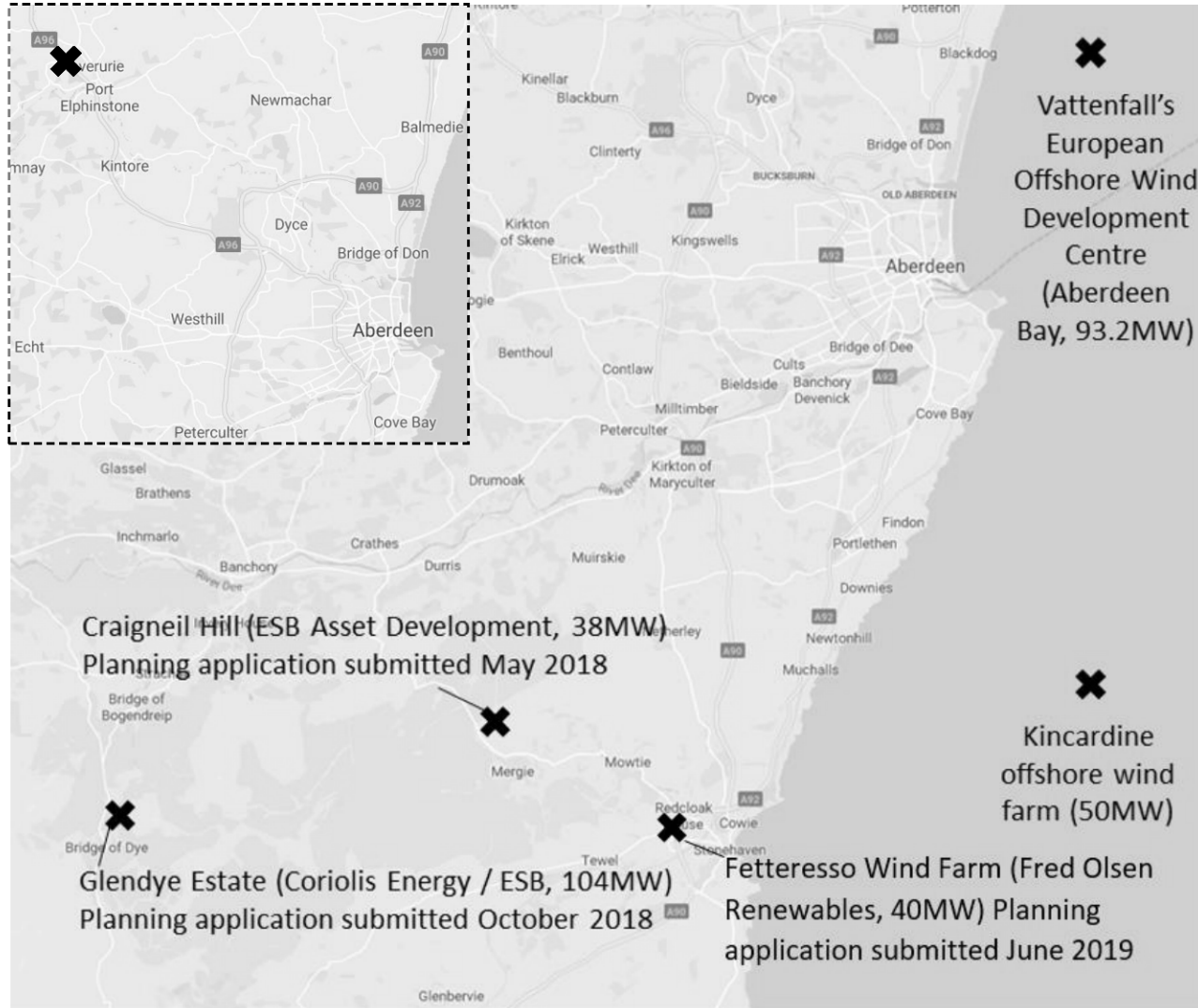
- back from the Kincardine sub-station at ACHES (using the same rights of way as the existing cable), or:
- by making a new connection to the cable at a potential site on Altens Industrial Estate, between the point of landfall and the ACHES site (a new sub-station would likely be needed).

Land on the edge of the Altens Industrial Estate to be considered for potential to site the hydrogen production hub.

Several onshore wind farms in planning stages near Aberdeen offer further opportunities to couple electrolyzers directly to renewable generation

Inverurie Energy Park (currently in planning stages) will include a 30MW Energy from Waste Facility which is due to come online at Inverurie in 2022

Renewable energy developments near Aberdeen (>30MW planned capacity)



Some of the potential hydrogen production sites are also relatively close to several potential HRS sites



Several options exist for refuelling the buses that form the anchor demand for the Hub, with a dedicated depot-based HRS preferred by the bus operator

Options for refuelling hydrogen buses – overview

- There are three main options for refuelling the new fleet of fuel cell buses due to be deployed in Aberdeen as part of the JIVE project. The vehicles will be used by First, whose operations are based at their depot on King Street.
- The table below presents the options and summarises the main pros and cons of each. Note that as part of the stakeholder consultation exercise conducted in this study, First expressed a preference for depot-based refuelling but implied that alternative solutions could be considered for the fleet of vehicles to be trialled under JIVE.

Option	Pros	Cons
1. Continue to use the Kittybrewster HRS (with renewable hydrogen from the production hub delivered to the site).	<ul style="list-style-type: none">• HRS has been successfully operated since 2015.• Minimal investment in new infrastructure (provided BOC agree to continue operating the equipment).	<ul style="list-style-type: none">• Requirement to move buses leading to unproductive hours and dead mileage.• Missed opportunity to demonstrate full benefits of FC buses as solution with minimal operational compromise.
2. Install a new bus HRS at the hydrogen production site and drive buses to the hub for refuelling.	<ul style="list-style-type: none">• Potential cost savings (civils) relative to option 3.• No need to transport the hydrogen (simplifies hub operations, lowers risk and operational costs).	<ul style="list-style-type: none">• Requirement to move buses leading to unproductive hours and dead mileage.• Missed opportunity to demonstrate full benefits of FC buses as solution with minimal operational compromise.• Requires new infrastructure.
3. Install a new bus HRS at the First depot (King Street) with renewable hydrogen from the production hub delivered to the site.	<ul style="list-style-type: none">• No need to move buses for fuelling – demonstrate full potential of hydrogen as a zero compromise ZE solution.• HRS can be designed with scope for expansion and thus facilitate further uptake of FC buses beyond JIVE.	<ul style="list-style-type: none">• Requires new infrastructure.• Requirement to deliver hydrogen to the depot (although it is likely that H₂ logistics will be needed to serve other HRS).

The unproductive costs associated with off-depot bus refuelling are a similar order of magnitude to the costs of delivering hydrogen

Options for refuelling hydrogen buses – economic analysis

- We can gain insights into which refuelling option may be most cost-effective by comparing the *unproductive costs* associated with driving buses away from the depot to refuel with the costs of hydrogen logistics.
- If the bus operator does not have access to a depot-based HRS, the main unproductive costs are:
 - Shunters – people employed to drive the buses between the depot and refuelling site (and to carry out the fuelling).
 - Fuel – the vehicles will consume hydrogen when driving to and from the HRS, which adds to the fuel bills.
 - Wear & tear – adding “dead mileage” (i.e. miles driven with no fare-paying passengers) leads to higher vehicle wear and tear (maintenance) costs.
- Estimates of these costs are presented below.

Cost item	Value per bus per fuelling event	Notes
Shunters	£6.00	Based on cost of £12/hr for shunters and half an hour per refuelling event (10 minutes to drive each way + 10 minutes for fuelling).
Fuel	£2.25	Based on 7.5kg/100km, a round-trip distance from depot to HRS of 5km and hydrogen priced at £6/kg.
Maintenance (wear & tear)	£1.75	Based on a round-trip distance from depot to HRS of 5km and indicative maintenance cost of £0.35/km.*

- Summing the elements above gives a cost of £10 per bus per refuelling event. Assuming each bus is refuelled with c.20kg of hydrogen, this equates to a cost of **£0.50/kgH₂**. This is slightly higher than the variable costs of hydrogen logistics under the assumptions used in this study (costs of moving tube trailers assumed to be £250/trip, with 600kg usable hydrogen gives a variable logistics cost of **£0.42/kgH₂**).

* This consistent with the maintenance cost indicated by the H2Bus project, which applies to large fleets of vehicles (tens to hundreds per site). The maintenance cost of the JIVE buses is likely to be higher.

We have accounted for a depot-based HRS for the JIVE bus fleet in the core business case based on the analysis outlined above

Options for refuelling hydrogen buses – conclusions

- While in practice the unproductive costs associated with moving buses to refuel will depend on several factors (cost of shunters, number needed and scope for optimising operations, distance between the depot (or route ends) and the HRS, etc.), any off-site refuelling of buses represents a change to standard operations. Since fuel cell buses are often promoted as a zero emission solution with no operational compromises it would be preferable to demonstrate this in JIVE with a depot-based HRS.
- For small-scale fleets (around ten buses or below), the costs of moving the vehicles to refuel may be lower than those associated with delivering hydrogen to the depot (and establishing a dedicated depot-based HRS) as the costs of hydrogen logistics (per kg) can be very high when delivering small quantities. However, off-site refuelling for buses is not a scalable solution and hydrogen either produced at the bus depot or delivered to the depot is likely to be a preferable long-term solution.
- The simple economic analysis presented above implies that in the case of the Aberdeen Hydrogen Hub, the variable costs of hydrogen logistics are lower than the unproductive costs of moving buses to refuel. This suggests that a depot-based HRS may well offer lower operational costs, especially if a local hydrogen logistics system is going to be established to serve other refuelling stations in the area. Any depot-based HRS should be designed carefully to meet the needs of the bus operator and ideally should be dedicated to fuelling buses only (i.e. not accessible to the public).
- For the reasons set out above, the core business case assessed in this study is based on a new depot-based HRS at the First depot in Aberdeen. Further work is required to assess the feasibility of installing such infrastructure and to develop an appropriate design, ideally with scope for expansion considered from the outset.

Agenda

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Action plan and milestones for delivering the ten-year vision

Appendix 1 – Action Plan for implementation

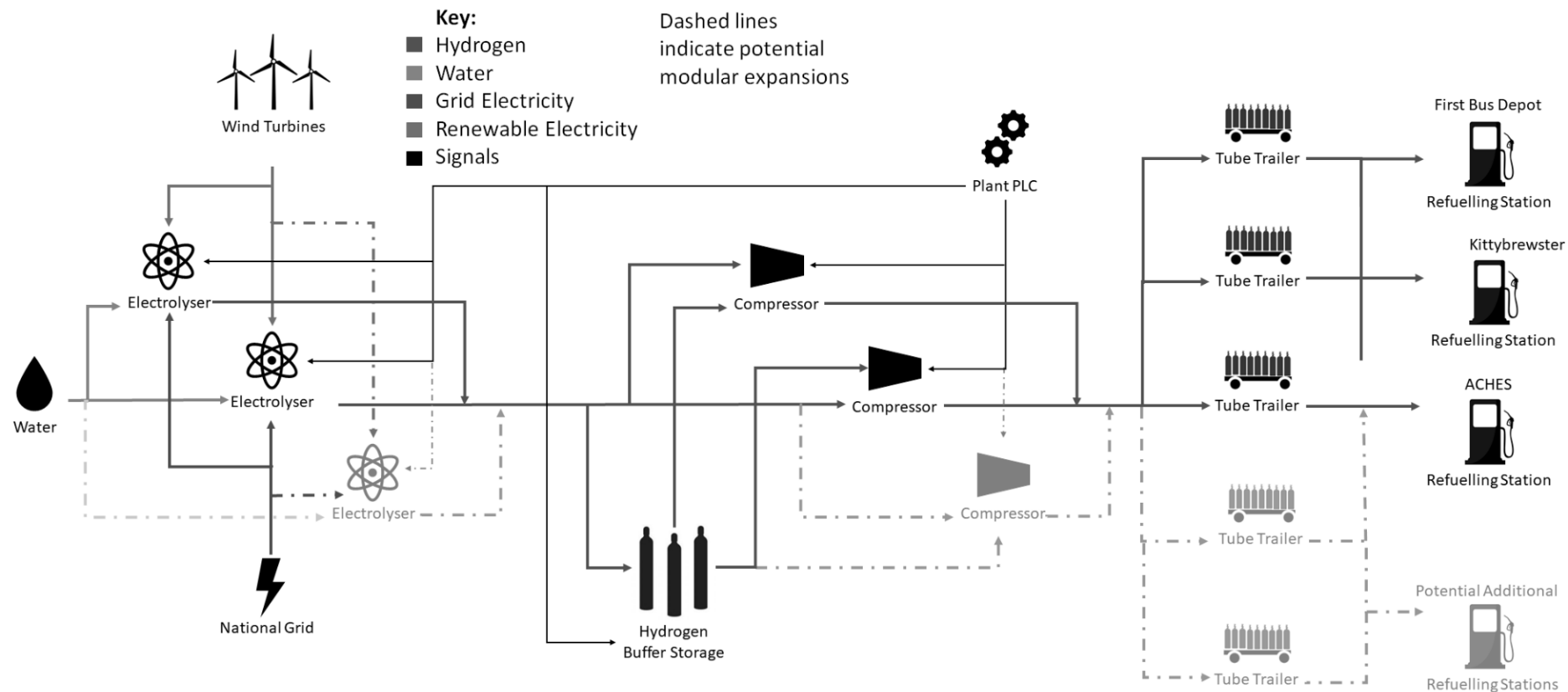
Appendix 2 – Strategy for existing assets

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We have explored a hydrogen supply hub concept based on centralised electrolytic production with distribution of the fuel to existing and new HRS

Components of the Aberdeen hydrogen supply hub



- Costs of renewable electricity generators are not included directly (instead represented by an electricity price).
- A portion (10%) of the electricity for hydrogen production is assumed to come from the grid (representing intermittency of renewable generators).
- We assume that the ACHES HRS continues to operate (but maintenance costs for this site are not explicitly included). We also note the aspiration to keep the Kittybrewster HRS in operation (hydrogen supply for this site could be switched to delivered fuel from the Hub).

Electricity price, RTFC value and hydrogen revenues are all significant for the business case and are still uncertain at this stage

Electricity costs for the electrolyser will be a key component of net cashflows for a Hydrogen Supply Hub

- **Assumptions for business case assessment:** The electrolyser takes 90% renewable electricity (@ £40/MWh) via a private wire close to a substation, and 10% from the grid (@ £90/MWh), leading to an average price of £45/MWh; there is assumed to be no real terms change to this price through time.
- Electricity prices could be affected by the following factors, which are uncertain at this stage:
 - Cost of establishing private wire connections could be high, leading to higher prices (yet to be defined for specific sites);
 - Cost of grid electricity could be higher, depending on agreement with a supplier (yet to be defined for specific sites and demand profiles);
 - Proportion of renewable electricity (depending on the profile & capacity of the renewable generation).

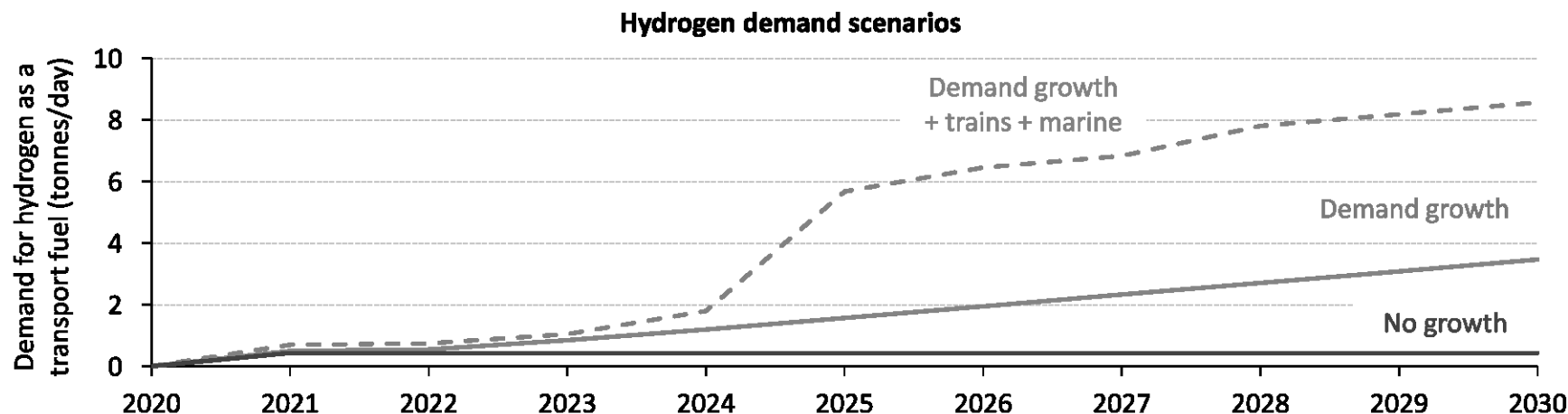
The value of RTFCs (and whether they can be accessed) will also have a significant impact

- **Assumptions for business case assessment:** Hydrogen supply hub operator receives RTFCs for hydrogen sold, at £5/kg in the first two years, decreasing to £1/kg by 2030.
- The maximum value of RTFCs for renewable hydrogen is £7.33/kg (the buy-out price) but their actual market value will depend on the total size of market for RTFCs and the total volume of eligible fuels available in the UK (as well as the demand for these fuels from end users). Based on the current market status, these value assumptions are reasonably conservative (assuming that hydrogen produced by the Hub is eligible for RTFCs over this period; this depends on the conditions, which currently require that the hydrogen generation enables “additional” renewable generation capacity).

Revenues from hydrogen sales depend on the demand and also on the price for different markets

- A successful business case ultimately depends on the hydrogen revenues increasing in line with the expansion in the Hub capacity. There are two key aspects to this: a) the level of certainty around the projected demand, and b) hydrogen sale prices for different markets. Assumptions are set out in the following slides. In each case, **the more certainty there is around the growth of future revenues, the more attractive the investment case will be.**

The business case for the Hub will depend on the level of demand secured, and on the grants and subsidies available



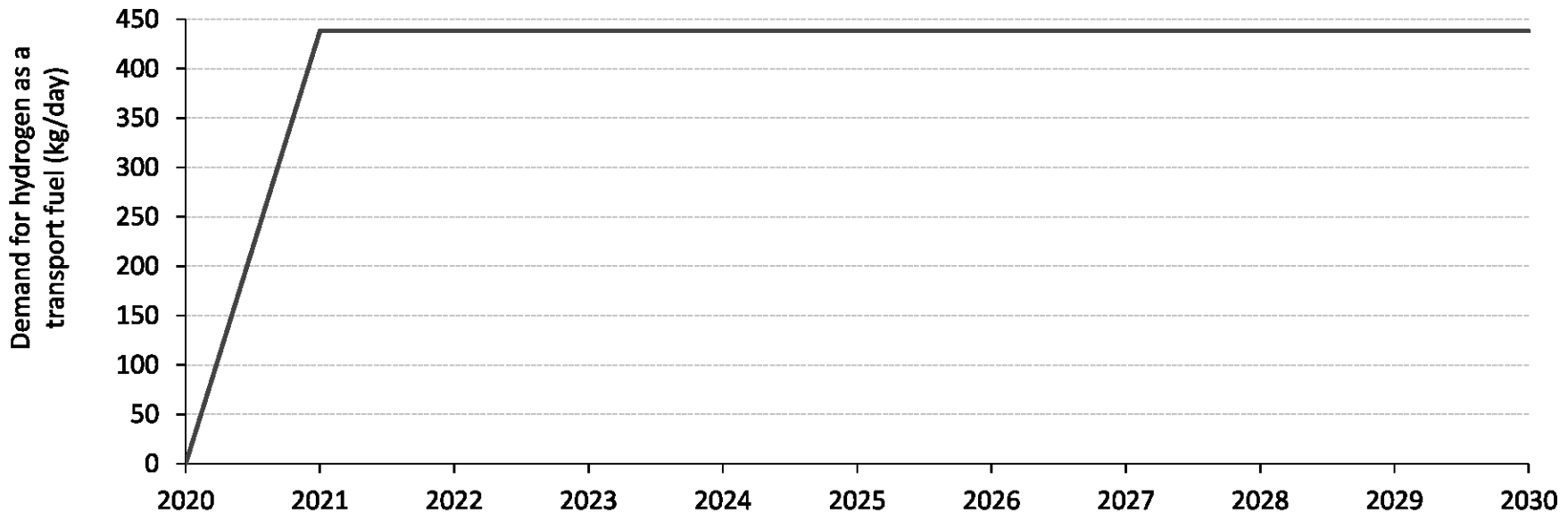
Scenario	Summary	Key transport segments	Level of demand in 2030
No growth	25 buses only; no new demand	Buses	0.4 tonnes hydrogen/day
Demand growth	Gradual transition of public sector fleets & local freight to hydrogen	Buses, cars (e.g. taxis), council RCVs, HGVs	3.5 tonnes hydrogen/day
Demand growth + trains and marine	As above + 10 trains in 2025 + 8 boats by 2028	Buses, cars, council RCVs, HGVs, trains, boats	8.5 tonnes hydrogen/day

- The following slides present cashflow scenarios for the three demand scenarios above. The impacts of access to RTFCs and grant funding on the Net Present Value (NPV) and Internal Rate of Return (IRR) are explored.
- Note that the following assessments are made from the perspective of potential investors in the Hydrogen Supply Hub, and do not include costs associated with vehicle operation.

Under the “no growth” scenario demand from 2021 is c.450kg/day from 25 buses and does not grow beyond this

No growth: 25 buses only

Fuel demands to be met by the Aberdeen hydrogen hub



- Demand from 2021: 25 buses, 17.5kg/day per bus.

We explore the case where this represents the first phase of the Hub, with investments made to allow expansion, but demand does not grow

Summary of the “no growth” scenario

- The following cashflow analysis shows what the business case looks like when:
 - The Hydrogen Hub infrastructure to be installed in 2020 is designed to be expanded in future to accommodate additional demand: the electrolyser is sited somewhere with capacity to be upgraded in future, outside the bus operator depot, and hydrogen is delivered to the bus operator’s depot (tube trailers are required). This provides flexibility for hydrogen to be distributed to any future HRS.
 - Demand fails to grow beyond the initial fleet of 25 fuel cell buses (in contrast to the “Demand Growth” scenario envisaged) and therefore, no expansion of electrolyser or refueling capacity takes place.

Hub infrastructure investment in 2020

- 2 MW electrolyser (to be sited with scope for expansion of capacity, with a grid connection & private wire e.g. for 8 MW).
- 1 new HRS at the First bus depot with sufficient redundancy to meet the high availability requirements for buses.
- 3 tube trailers (to be used as mobile storage at the electrolyser and at the HRS; transport is on a contracted basis).
- Hydrogen production site is separate from the refuelling site. *(Note: it is possible that existing HRS and electrolyser assets could be re-sited and used to meet some of the demand; this could reduce the new investment required. However, the following analysis assumes that all of the assets above are purchased in 2020.)*

Hydrogen revenues (2021–2032)

- Hydrogen demand from 25 buses, 17.5kg/day per bus for 12 years, sold @£6/kg.
- The business case analysis assumes that the demand is present for 12 years. However, it is not a given that the demand is secured over this entire period before the infrastructure investment: given the limited ability of bus operators to guarantee the time period for operating the FC buses, it is likely that investors will need to take the risk. If the demand is secured in some way (e.g. via a take or pay arrangement brokered by ACC) the case for investment becomes much more attractive.

Business case assessment input assumptions (1/2)

Input	Value	Comments / Assumptions
Electrolyser capacity	2 MW	
Electrolyser capex	£2,200,000	£1,100/kW
Other installation costs (WE)	£650,000	Civils, piping, cabling, delivery, installation, commissioning
Compressor capex (installed)	£850,000	Multiple compressor units for redundancy
No. of tube trailers	3	Each with 600kg usable storage
Tube trailer (H2 storage) capex	£1,050,000	£350k per trailer (£583/kg)
Capex of new HRS (installed)	£1,250,000	1 x 400 kg/day HRS (for buses)
Electrolyser load factor	67%	Implied by demand
Electrolyser fixed opex (annual)	4% of capex	
Compressor maintenance	£0.2 per kg throughput	Maintenance required is linked to utilisation
Other fixed opex	£10,000/yr	Allowance for rent (no allowance for business rates or other fixed opex)
Logistics fixed opex	£26,800/yr	Personnel costs + fixed costs such as insurance, servicing, etc.
Logistics variable opex	£250 per delivery	Base case: 100% of H2 is delivered
HRS fixed opex	5% of capex	Equates to £87.5k/yr for a 400kg/day HRS
Other fixed opex for HRS	£11,500/yr	Rent, other fixed opex
Overall fixed opex	£51,000/yr	Insurance, personnel cost, etc.

NB: budgetary cost figures have been used throughout this study. Firmer cost estimates are expected to be obtained during the subsequent (delivery) phase of the project.

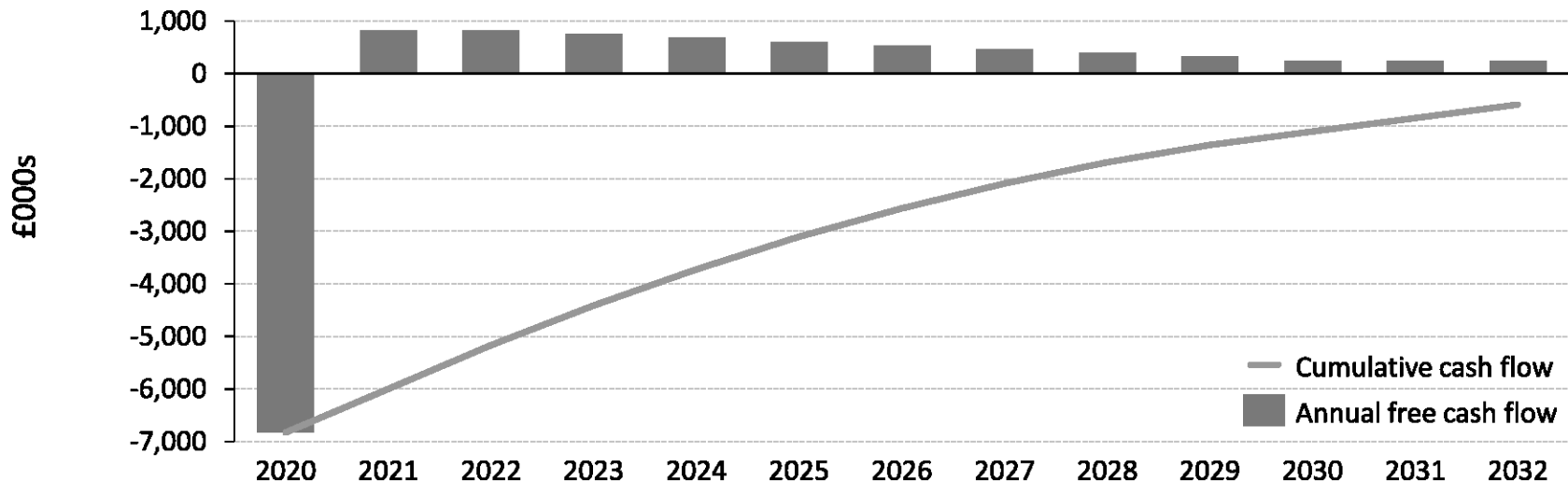
Business case assessment input assumptions (2/2)

Input	Value	Comments / Assumptions
Average WE efficiency	55 kWh/kg	<p>No change through time 90% renewable electricity (£40/MWh), 10% from grid (£90/MWh) => average of £45/MWh</p> <p>Note that the availability of these electricity prices may be partly dependent on the costs of establishing private wire connections (these are yet to be defined for specific sites)</p>
Water demand	20 litres/kg	
Compression electricity demand	2.5 kWh/kg	100% grid electricity @ £90/MWh
Production plant electricity demand	100 kWh/day	100% grid electricity @ £90/MWh
HRS electricity demand	2 kWh/kg	100% grid electricity @ £90/MWh
Hydrogen sale price (buses)	£6/kg	

With no demand growth, a positive business case for the first phase of the hub is challenging, even when RTFC revenues are included

Cash flow (undiscounted) – with RTFCs (£5/kg initially, decreasing to £1/kg by 2030)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: 25 buses



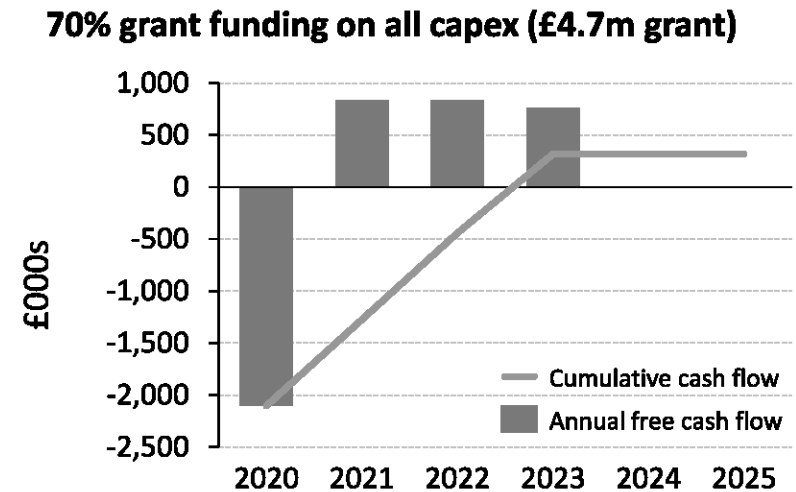
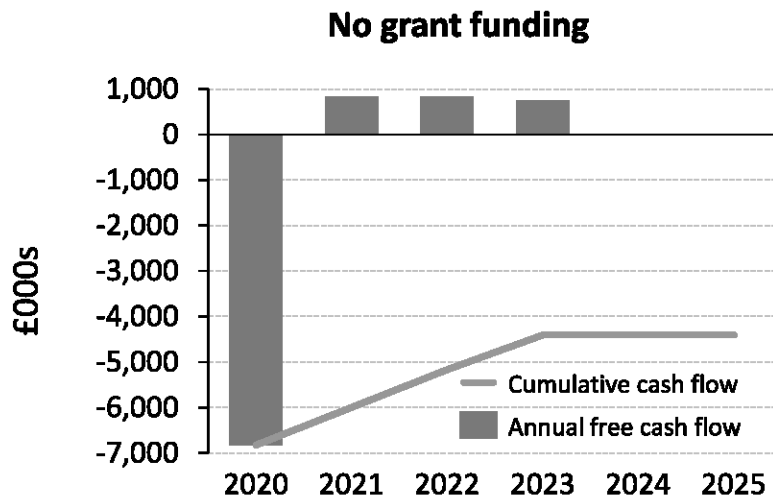
New hardware delivered
1.5MW WE
1 x 400kg/day HRS
3 x 600kg tube trailers

- NPV (to 2032 @8% discount rate) = -£2.3m
- NB: with no RTFCs, NPV = -£5.5m

Even with RTFCs, there is a risk that the £7m capital investment would not be recovered (if the demand drops to zero in 2024)

Cash flow (undiscounted) – with RTFCs (£5/kg initially, decreasing to £1/kg by 2030)

- NPV (over 10 years @8% discount rate) = -£4.4m
- NPV (over 10 years @8% discount rate) = -£0.02m



- Without RTFC revenue, the hub operator is only likely to achieve <£0.5m net revenues over the first few years of operation, which suggests that almost £7m of capital investment is at risk under the “failure” scenario represented here (some residual value could be expected).
- An equivalent result to the grant funding case shown above (right) can be obtained without grant funding and instead increasing the hydrogen sale price to the buses from £6/kg to £16/kg.
 - NB: 438kg/day x 364 days/yr = 159t/yr = 478t over three years. A premium of £10/kg for this period equates to around £4.8m.

The case for supplying hydrogen only to a limited fleet of fuel cell buses would rely on a high level of capex funding and/or RTFCs

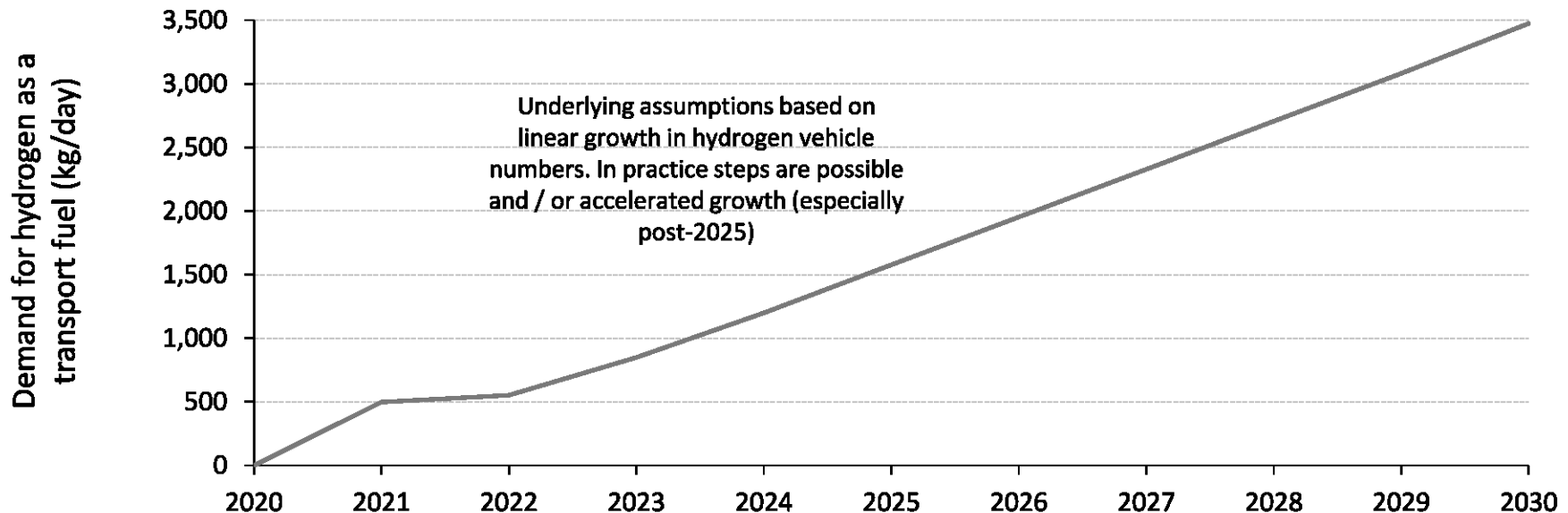
Conclusions for the “no growth” scenario

- If considering the business case for a renewable hydrogen supply hub for buses only (i.e. revenues limited to £6/kg and no other sources of income), the net annual revenues are relatively small compared to the capital investment required.
- Factoring in revenues from RTFCs (with a relatively high value of £5/kg initially) clearly helps the case. However, the analysis above suggests that even with hydrogen sales (at £6/kg) and RTFC revenues, a positive IRR over ten years is unlikely to be achieved without further growth in demand and / or other sources of revenue (e.g. selling hydrogen to other vehicles).
- Furthermore, it is highly unlikely that a bus operator (or any other party) will be able to sign a ten-year supply agreement from 2020/21 and potential revenues from RTFCs are uncertain.
- The “failure cases” considered above suggest that a grant (or perhaps conditional loan) of around £4m – £6m may be required to encourage private sector investment in the absence of other forms of certainty over future revenues for the hub operator. Alternatively, guaranteed higher hydrogen sale prices for a defined period could be used to de-risk the investment (although a key aim is to unlock lower priced hydrogen to stimulate further use of this fuel).
- ACC has an ambition to encourage uptake of hydrogen-fuelled vehicles across a wide range of sectors, hence in the next section we consider the case for the hub supplying other demands.

The “demand growth” scenario represents a positive trial of the FC buses in JIVE and expansion of several fleets of hydrogen-fuelled vehicle types

Demand growth

Fuel demands to be met by the Aberdeen hydrogen hub



- Demands in 2021/22 largely due to the 25 buses and a small fleet of municipal HGVs.
- With the growth scenario presented here the total fleet of hydrogen-fuelled vehicles served by the hub by 2030 includes 800 cars, 145 buses, and c.70 HGVs.

This scenario implies a two stage delivery plan (as a minimum) for the Hub infrastructure to meet the growing demand

Summary of the “demand growth” scenario

- The following cashflow analysis shows what the business case looks like when:
 - The Hydrogen Hub infrastructure to be installed in 2020 is designed to be expanded in future to accommodate additional demand: the electrolyser is sited somewhere with capacity to be upgraded in future, outside the bus operator depot, and hydrogen is delivered to the bus operator’s depot (tube trailers are required). This provides flexibility for hydrogen to be distributed to future HRS.
 - Demand grows sufficiently by 2023 to justify additional electrolyser capacity and installation of additional HRS. The second phase of investment is sized to accommodate significant further growth (mainly in the hydrogen bus fleet).

Hub infrastructure investment in 2020 and 2023

- In 2020:
 - 2 MW electrolyser (to be sited with scope for expansion of capacity, with a grid connection & private wire for 8 MW).
 - 1 new HRS at the First bus depot with sufficient redundancy to meet the high availability requirements for buses.
 - 4 tube trailers (to be used as mobile storage at the electrolyser and at the HRS; transport is on a contracted basis).
 - ACHES is assumed to remain operational; hydrogen could be delivered from the Hub electrolyser to meet demand from cars and any other vehicles.
- In 2023:
 - Additional 6 MW electrolyser (at the same production site).
 - **At least 2 new HRS with an additional 2,000 kg/day refueling capacity** (to meet growing demand from buses, as well as cars and HGVs). The associated investment (an estimated £4.5m) could either cover the costs of a small number of large capacity HRS, or upgrade costs to existing stations along with deployment of new medium capacity HRS.
 - 4 additional tube trailers.
- Hydrogen production site is separate from the refuelling sites.

Business case assessment input assumptions (1/2)

Input	Value	Comments / Assumptions
Electrolyser capacity	2 MW	A further 6 MW installed in 2023
Electrolyser capex	£2,200,000	£1,100/kW (falling to £900/kW in 2023)
Other installation costs (WE)	£650,000	Civils, piping, cabling, delivery, installation, commissioning (initial installation only)
Compressor capex (installed)	£850,000	Multiple compressor units for redundancy (initial installation only)
No. of tube trailers	4 (2020) + 4 (2023)	Each with 600kg usable storage
Tube trailer (H ₂ storage) capex	£350k per trailer (£583/kg)	
Capex of new HRS (installed)	£2,000,000	1 x 400 kg/day HRS (for buses) with redundancy Further HRS installed in 2023 (see below)
Electrolyser fixed opex (annual)	4% of capex	
Compressor maintenance	£0.2 per kg throughput	Maintenance required is linked to utilisation
Other fixed opex	£10,000/yr	Allowance for rent (no allowance for business rates or other fixed opex)
Logistics fixed opex	£26,800/yr	Personnel costs + fixed costs such as insurance, servicing, etc.
Logistics variable opex	£250 per delivery	Base case: 100% of H ₂ is delivered
HRS fixed opex	5% of capex	Equates to £87.5k/yr for a 400kg/day HRS
Other fixed opex for HRS	£11,500/yr	Rent, other fixed opex
Overall fixed opex	£51,000/yr	Insurance, personnel cost, etc.

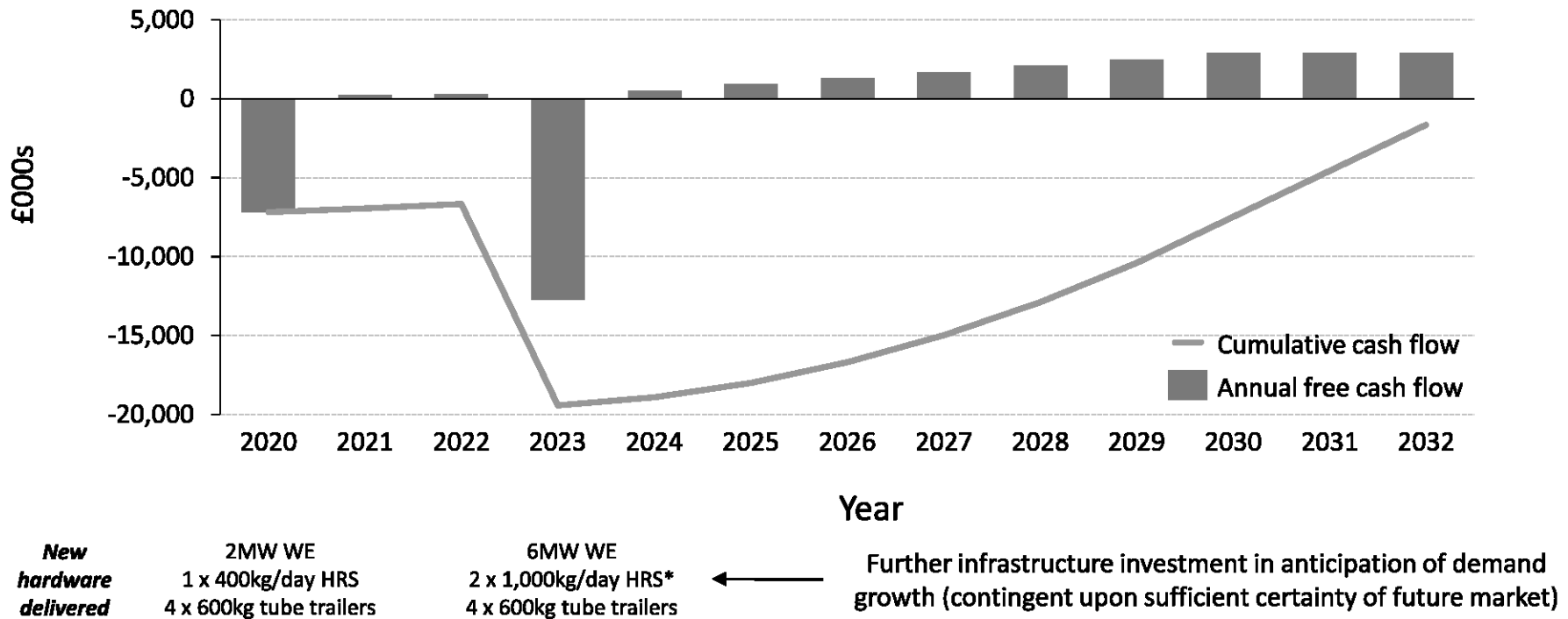
Business case assessment input assumptions (2/2)

Input	Value	Comments / Assumptions
Average WE efficiency	55 kWh/kg	<p>No change through time 90% renewable electricity (£40/MWh), 10% from grid (£90/MWh) => average of £45/MWh</p> <p>Note that the availability of these electricity prices may be partly dependent on the costs of establishing private wire connections (these are yet to be defined for specific sites)</p>
Water demand	20 litres/kg	
Compression electricity demand	2.5 kWh/kg	100% grid electricity @ £90/MWh
Production plant electricity demand	100 kWh/day	100% grid electricity @ £90/MWh
HRS electricity demand	2 kWh/kg	100% grid electricity @ £90/MWh
Hydrogen sale price (buses)	£6/kg	
Hydrogen sale price (cars)	£8/kg	
Hydrogen sale price (municipal HGVs)	£6/kg	
Hydrogen sale price (other HGVs)	£5/kg	

A phased investment approach is likely to be the most appropriate means of delivering and then expanding a hydrogen supply hub

Cash flow (undiscounted) – baseline (no RTFCs, no grants)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth scenario



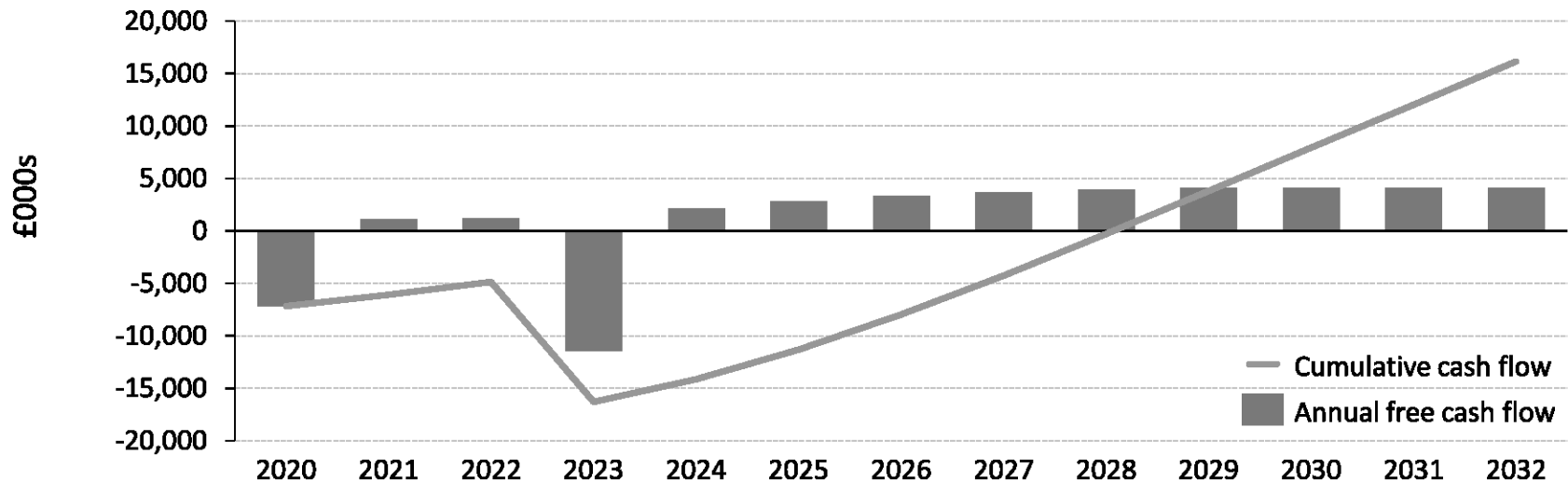
- NPV (to 2032 @8% discount rate) = -£7.3m

* NB: a total investment of £4.6m in new HRS is assumed in 2023. This could cover the costs of a small number of large capacity HRS or upgrade costs to existing stations along with deployment of new medium capacity HRS.

A positive return over 12+ years could be possible with RTFC revenue, but there are significant risks, especially associated with the initial investment

Cash flow (undiscounted) – demand growth (with RTFCs (£5/kg, decreasing to £1/kg by 2030))

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth scenario



**New
hardware
delivered**

2MW WE
1 x 400kg/day HRS
4 x 600kg tube trailers

6MW WE
2 x 1,000kg/day HRS*
4 x 600kg tube trailers



Further infrastructure investment in anticipation of demand growth (contingent upon sufficient certainty of future market)

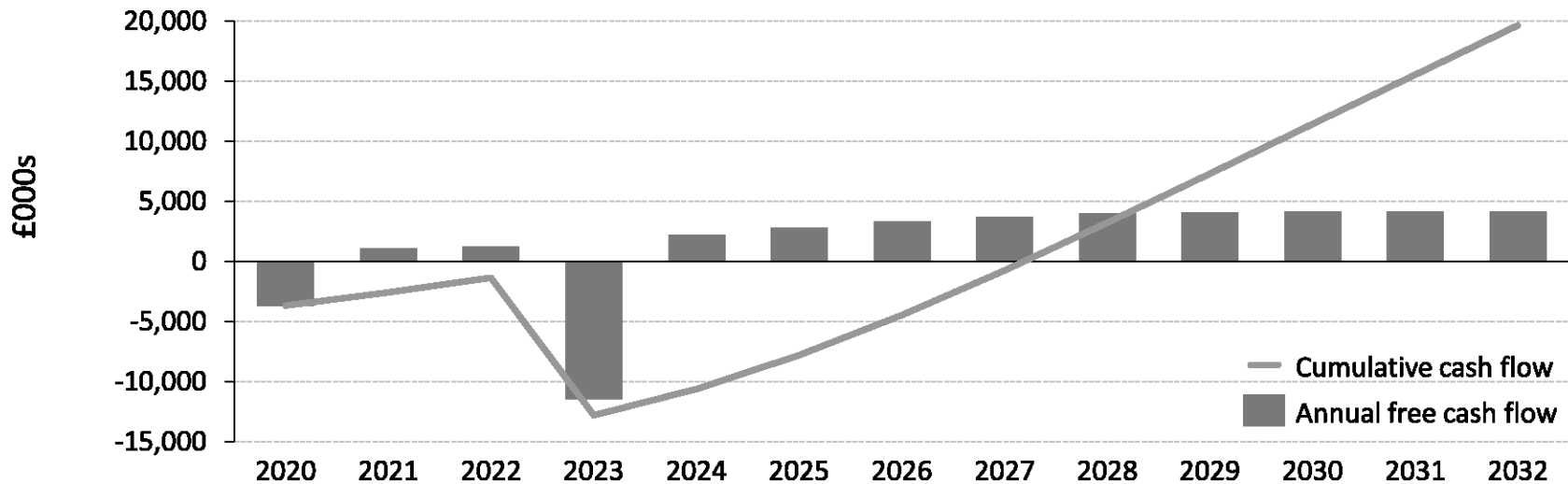
- NPV (to 2032 @8% discount rate) = +£2.9m (11% IRR)

* NB: a total investment of £4.6m in new HRS is assumed in 2023. This could cover the costs of a small number of large capacity HRS or upgrade costs to existing stations along with deployment of new medium capacity HRS.

Including an upfront grant makes the case highly attractive, with an 18% IRR, if RTFCs are also available

Cash flow (undiscounted) – demand growth (with RTFCs + c.50% grant (£3.5m) for initial capex)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth scenario



**New
hardware
delivered**

2MW WE
1 x 400kg/day HRS
4 x 600kg tube trailers

6MW WE
2 x 1,000kg/day HRS*
4 x 600kg tube trailers

Further infrastructure investment in anticipation of demand growth (contingent upon sufficient certainty of future market)

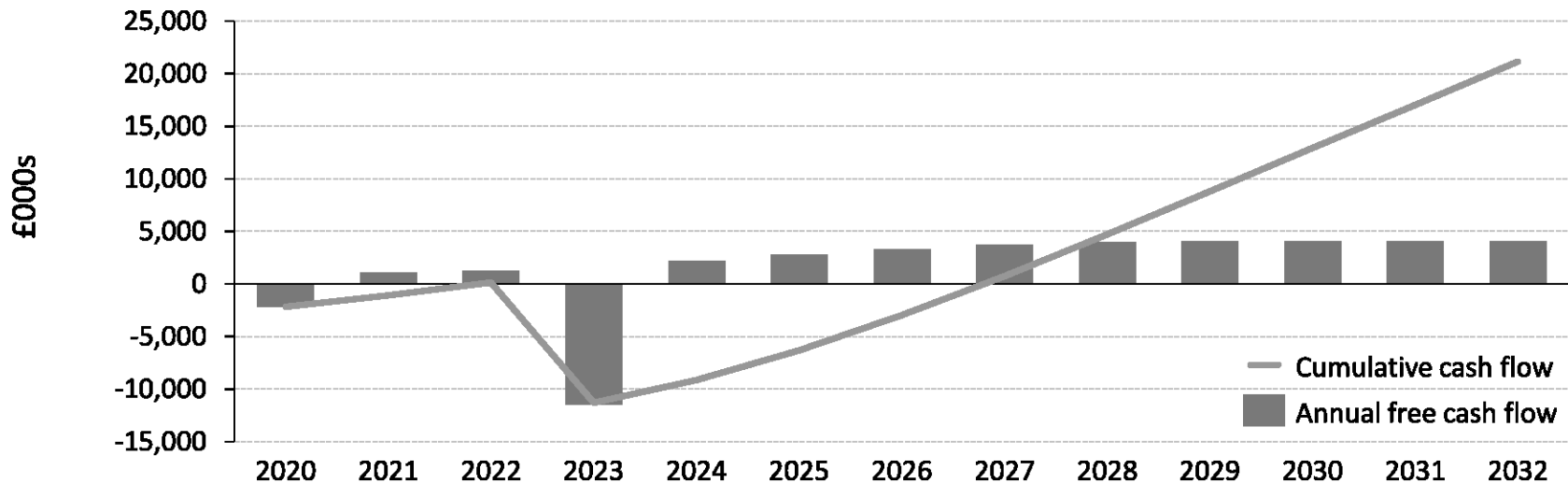
- NPV (to 2032 @8% discount rate) = +£6.1m (18% IRR)
- **Total revenues from RTFCs: £17.8m**

* NB: a total investment of £4.6m in new HRS is assumed in 2023. This could cover the costs of a small number of large capacity HRS or upgrade costs to existing stations along with deployment of new medium capacity HRS.

If the grant was increased to £5m, investment would become even more attractive, with an IRR of 22%

Cash flow (undiscounted) – demand growth (with RTFCs + c.70% grant (£5m) for initial capex)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth scenario



**New
hardware
delivered**

2MW WE
1 x 400kg/day HRS
4 x 600kg tube trailers

6MW WE
2 x 1,000kg/day HRS*
4 x 600kg tube trailers

Further infrastructure investment in anticipation of demand growth (contingent upon sufficient certainty of future market)

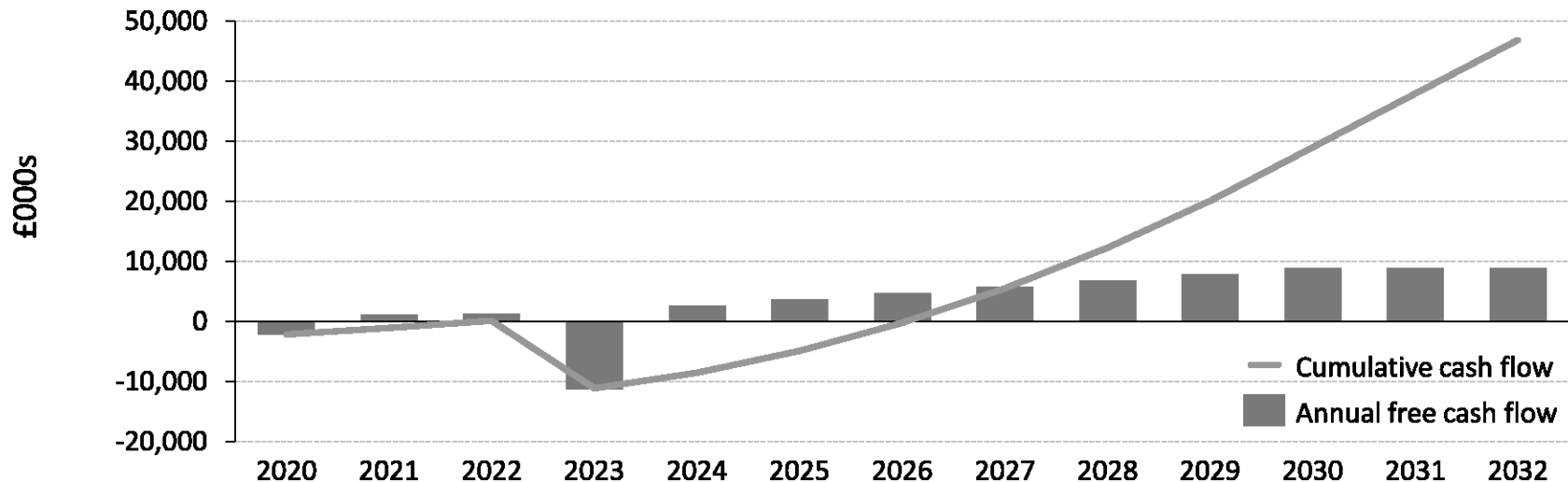
- NPV (to 2032 @8% discount rate) = +£7.5m (22% IRR)
- Total revenues from RTFCs: £17.8m

* NB: a total investment of £4.6m in new HRS is assumed in 2023. This could cover the costs of a small number of large capacity HRS or upgrade costs to existing stations along with deployment of new medium capacity HRS.

The NPV of the Hub would be improved by £11m if RTFCs stay at £5/kg (compared to the case when they reduce to £1/kg by 2030)

Cash flow (undiscounted) – demand growth (c.70% grant (£5m) for initial capex + RTFCs stay at £5/kg)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth scenario



**New
hardware
delivered**

2MW WE
1 x 400kg/day HRS
4 x 600kg tube trailers

6MW WE
2 x 1,000kg/day HRS*
4 x 600kg tube trailers

Further infrastructure investment in anticipation of demand growth (contingent upon sufficient certainty of future market)

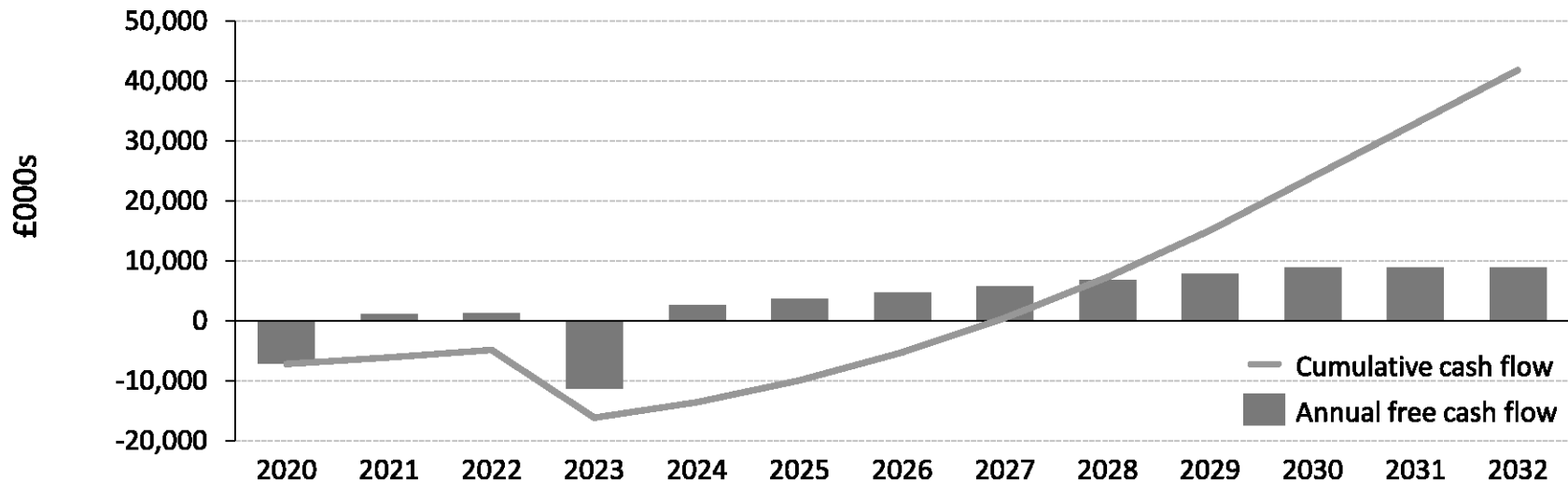
- NPV (to 2032 @8% discount rate) = +£19.1m (35% IRR)
- Total revenues from RTFCs: £43.5m

* NB: a total investment of £4.6m in new HRS is assumed in 2023. This could cover the costs of a small number of large capacity HRS or upgrade costs to existing stations along with deployment of new medium capacity HRS.

With RTFCs staying at £5/kg but no grant funding, the NPV of the Hub would be £14.5m (over 12 years)

Cash flow (undiscounted) – demand growth (no grant, RTFCs stay at £5/kg)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth scenario



**New
hardware
delivered**

2MW WE
1 x 400kg/day HRS
4 x 600kg tube trailers

6MW WE
2 x 1,000kg/day HRS*
4 x 600kg tube trailers

Further infrastructure investment in anticipation of demand growth (contingent upon sufficient certainty of future market)

- NPV (to 2032 @8% discount rate) = +£14.5m (21% IRR)
- Total revenues from RTFCs: £43.5m

* NB: a total investment of £4.6m in new HRS is assumed in 2023. This could cover the costs of a small number of large capacity HRS or upgrade costs to existing stations along with deployment of new medium capacity HRS.

It appears that a positive investment case in the Hub could be possible under certain conditions, but there are various risks (especially early on)

Conclusions for the demand growth scenario

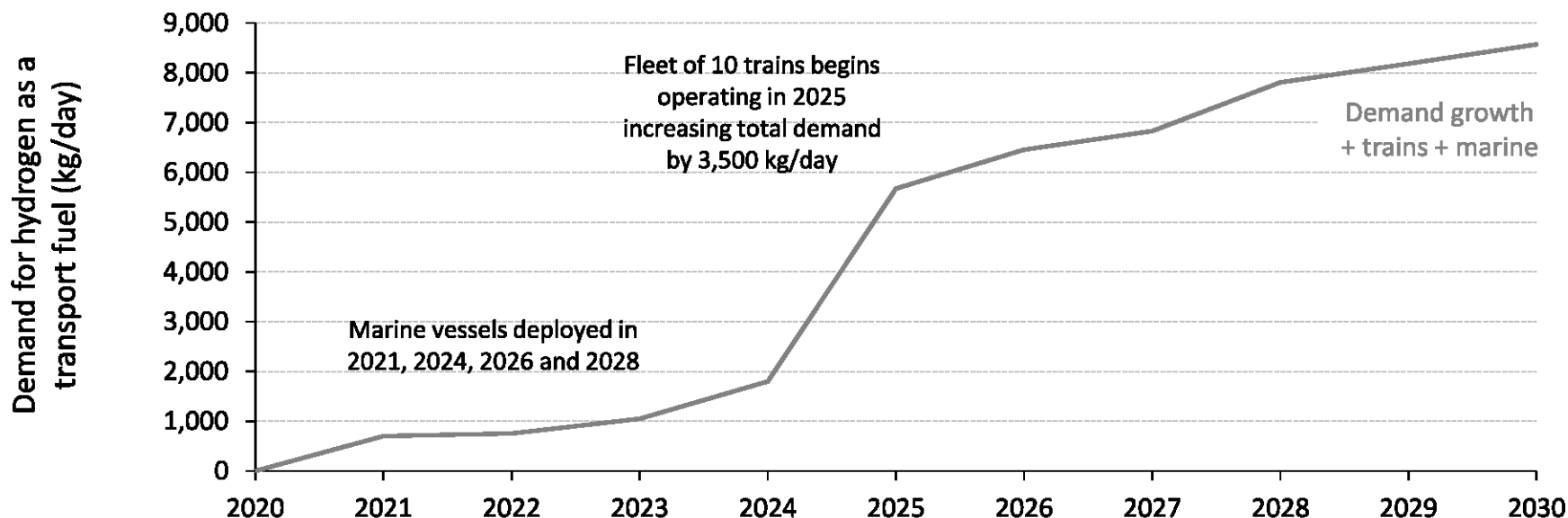
High-level conclusions from the above analysis include:

- There can be a positive investment case whilst providing hydrogen to customers at “acceptable” prices, as long as:
 - Sufficiently low-cost electricity can be accessed (average of £45/MWh in the figures above)
 - Investors are willing to view returns over a sufficiently long period
 - The projected demand growth occurs
 - Additional revenues are available (e.g. RTFCs)
- Clearly, lower than expected future demands for hydrogen or issues obtaining RTFCs present a risk to the business case which it will be very hard for private investors to accept.
- The riskiest time is the first few years as there remains considerably uncertainty over levels of demand growth and limited opportunities to put in place firm supply agreements with hydrogen customers.
- This is where public sector support is likely to be needed to initiate the Hub that can then be expanded in future (ideally with decreasing intervention from the public sector).
- As a consequence, a strategy where the public sector is asked to fund the early stages, with a mechanism for recouping the investment in the event of success in creating demand and accessing RTFCs is recommended.
 - **Some possible examples are explored on p78–80.**

Demand growth scenario + trains + marine: trains and marine applications could require several additional tonnes of hydrogen per day

Demand growth + trains + marine applications

Fuel demands to be met by the Aberdeen hydrogen hub



- Demands in 2021/22 largely due to the 25 buses and a small fleet of municipal HGVs (as per demand growth scenario).
- Boats (each with a demand of 200 kg per day) are assumed to be introduced from 2021, and a fleet of 10 trains begins operating in 2025.
- The total fleet of hydrogen-fuelled vehicles served by the hub by 2030 includes 800 cars, 145 buses, and c.70 HGVs.
- **Note that the benefits of increased demand from boats and trains are limited by lower sale prices for hydrogen in these applications - unless revenues can be “topped up” by subsidies (or a higher willingness to pay for a zero emission option).**

In this scenario, multiple phases of investment would take place to meet the growing demand from different segments

Hub infrastructure is assumed to be built in several phases (including a 4MW electrolyser in 2020)

- The following cashflow analysis shows what the business case looks like with investment in the following infrastructure (clearly, each stage of investment would be contingent on sufficient demand growth):
- In **2020**:
 - **4 MW electrolyser** (to be sited with scope for significant expansion of capacity to meet demand from trains and marine applications as well as buses, with a grid connection & private wire for 18 MW to accommodate later demand).
 - 1 new HRS at the First bus depot with sufficient redundancy to meet the high availability requirements for buses.
 - 1 high capacity marine HRS (this is assumed to use lower pressure refueling, with a lower associated cost than the bus HRS for equivalent capacity)
 - 4 tube trailers (to be used as mobile storage at the electrolyser and at the HRS; transport is on a contracted basis).
 - ACHES is assumed to remain operational; hydrogen could be delivered from the Hub electrolyser to meet demand from cars and any other vehicles.
- In **2023**: 1 new HRS (or capacity upgrade) for additional buses and/or HGVs.
- In **2024**:
 - **Additional 10 MW electrolyser** (at the same production site).
 - At least 2 new HRS with an additional 2,000 kg/day refueling capacity (to meet growing demand from buses, as well as cars and HGVs). The associated investment (an estimated £13.2m) could cover upgrade costs to existing stations, additional medium capacity HRS, and deployment of one very large capacity HRS (for trains).
 - 8 additional tube trailers as mobile storage (total capacity to serve 4–5 different HRS sites).
- In **2026**: **Additional 4 MW electrolyser** (assumed to be at the same production site).
- In **2028**:
 - 1–2 new HRS with an additional 1,000 kg/day refueling capacity in total (to meet growing demand from transport, as well as marine applications). The associated investment (an estimated £4m) could either cover the costs of one large capacity HRS, upgrade costs to existing stations, or deployment of new medium capacity HRS.

Business case assessment input assumptions (1/2)

Input	Value	Comments / Assumptions
Electrolyser capacity	4 MW	A further 10 MW installed in 2024, and 4 MW in 2026
Electrolyser capex	£3,600,000	£900/kW (falling to £800/kW in 2023)
Other installation costs (WE)	£650,000	Civils, piping, cabling, delivery, installation, commissioning (initial installation only)
Compressor capex (installed)	£850,000	Multiple compressor units for redundancy (initial installation only)
No. of tube trailers	4 (2020) + 8 (2024)	Each with 600kg usable storage
Tube trailer (H ₂ storage) capex	£350k per trailer (£583/kg)	
Capex of new HRS (installed)	£2,000,000	1 x 400 kg/day HRS (for buses) with redundancy; mobile refueling solution for boats at £1,000,000 (installed). Further HRS installed in 2023, 2024 and 2028.
Electrolyser fixed opex (annual)	4% of capex	
Compressor maintenance	£0.2 per kg throughput	Maintenance required is linked to utilisation
Other fixed opex	£10,000/yr	Allowance for rent (no allowance for business rates or other fixed opex)
Logistics fixed opex	£26,800/yr	Personnel costs + fixed costs such as insurance, servicing, etc.
Logistics variable opex	£250 per delivery	Base case: 100% of H ₂ is delivered
HRS fixed opex	5% of capex	Equates to £87.5k/yr for a 400kg/day HRS
Other fixed opex for HRS	£11,500/yr	Rent, other fixed opex
Overall fixed opex	£51,000/yr	Insurance, personnel cost, etc.

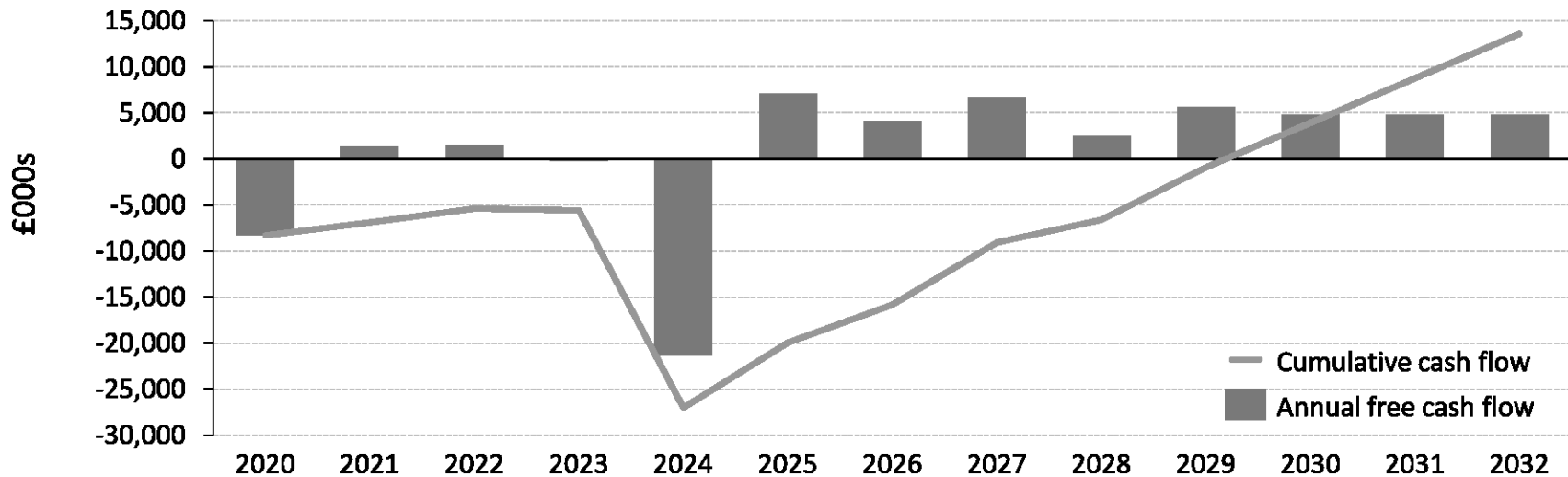
Business case assessment input assumptions (2/2)

Input	Value	Comments / Assumptions
Average WE efficiency	55 kWh/kg	<p>No change through time 90% renewable electricity (£40/MWh), 10% from grid (£90/MWh) => average of £45/MWh</p> <p>Note that the availability of these electricity prices may be partly dependent on the costs of establishing private wire connections (these are yet to be defined for specific sites)</p>
Water demand	20 litres/kg	
Compression electricity demand	2.5 kWh/kg	100% grid electricity @ £90/MWh
Production plant electricity demand	100 kWh/day	100% grid electricity @ £90/MWh
HRS electricity demand	2 kWh/kg	100% grid electricity @ £90/MWh
Hydrogen sale price (buses)	£6/kg	<p>Different sale prices to different applications (based on meeting cost parity with fossil fuel, which varies depending on the level of tax that applies for these applications). Note that this reduces the benefits of increased demand from boats and trains, unless revenues can be “topped up”.</p>
Hydrogen sale price (cars)	£8/kg	
Hydrogen sale price (municipal HGVs)	£6/kg	
Hydrogen sale price (other HGVs)	£5/kg	
Hydrogen sale price (boats)	£3/kg	
Hydrogen sale price (trains)	£3/kg	<p>Note that RTFCs are assumed to be applicable to all applications, whereas today they are only available to road transport.</p>

Without grant funding, RTFC revenues (decreasing from £5/kg to £1/kg) could be just sufficient to make a positive business case over 12 years

Cash flow (undiscounted) – with RTFCs (£5/kg initially, decreasing to £1/kg by 2030)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth + trains + marine



New hardware delivered

4MW WE
1 x 400kg/day HRS
1 x marine HRS
4 x 600kg tube trailers

1 x 1,000kg/day HRS

10MW WE
2 x 400kg/day HRS;
1 x 4,00kg/day HRS*
8 x 600kg tube trailers

4MW WE

2 x 400kg/day HRS

Further infrastructure investment in anticipation of demand growth (contingent upon sufficient certainty of future market)

- NPV (to 2032 @8% discount rate) = +£0.14m (8% IRR)
- NB: with no RTFCs, NPV = -£24.4m

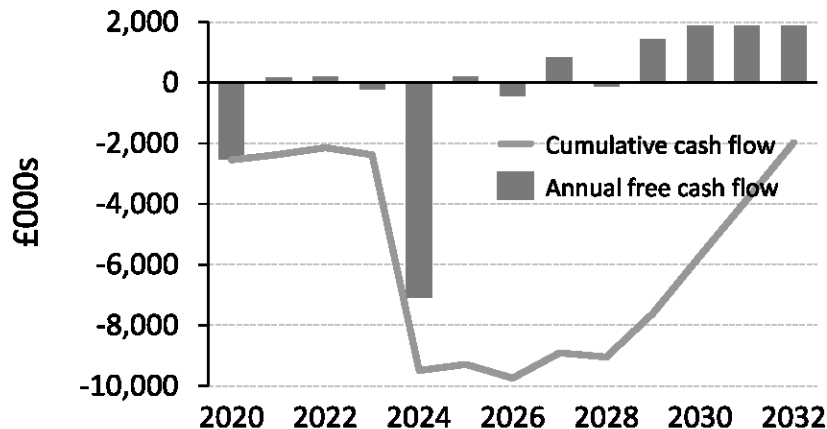
* NB: a total investment of £13.2m in new HRS is assumed in 2024. This could cover the costs of several large capacity HRS; or upgrade costs to existing stations along with deployment of one large capacity HRS (for trains).

In the absence of RTFCs, a 90% capex grant would result in a positive case over a 12 year period

Cash flow (undiscounted) – grant funding, but no RTFC

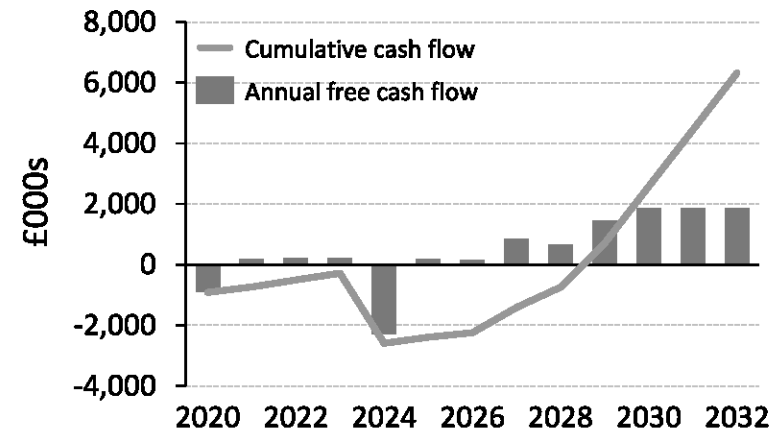
- NPV (to 2032 @8% discount rate) = –£3.9m

70% grant funding on all capex (£29m grant)



- NPV (to 2032 @8% discount rate) = +£2.0m (20% IRR)

90% grant funding on all capex (£37m grant)

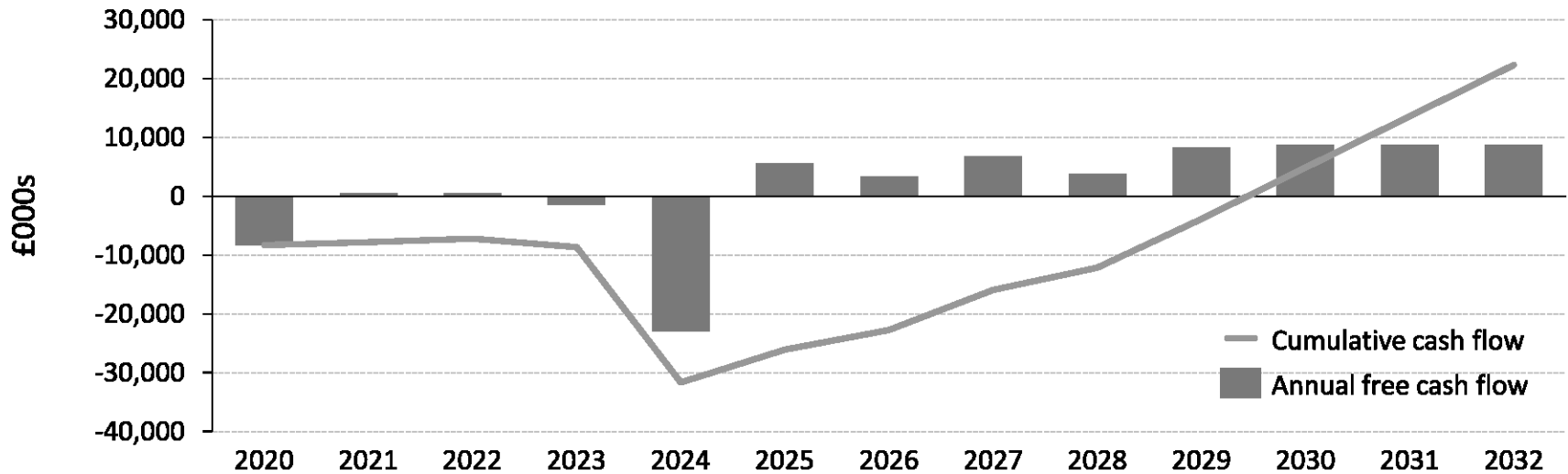


- In the absence of RTFCs, providing a high level of grant funding for all private sector investments would enable a positive business case for investors willing to take a medium term view (i.e. 12 years).
- An equivalent result to the 90% grant funding case shown above can be obtained without grant funding and instead increasing the hydrogen sale price to £6.50/kg across all vehicles (see next).
- The main reason this case is so challenging is that a large share of the demand after 2024 comes from trains and marine applications, which are assumed to have a much lower hydrogen sale price.

Another way to achieve a positive business case without RTFCs would be to access a higher hydrogen sale price: £6.50 per kg, across end users

Cash flow (undiscounted) – no RTFCs, hydrogen sold at £6.50/kg to all end users

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth + trains + marine



New hardware delivered

4MW WE
1 x 400kg/day HRS
1 x marine HRS
4 x 600kg tube trailers

1 x 1,000kg/day HRS

10MW WE
2 x 400kg/day HRS;
1 x 4,00kg/day HRS*
8 x 600kg tube trailers

4MW WE

2 x 400kg/day HRS

Further infrastructure investment in anticipation of demand growth (contingent upon sufficient certainty of future market)

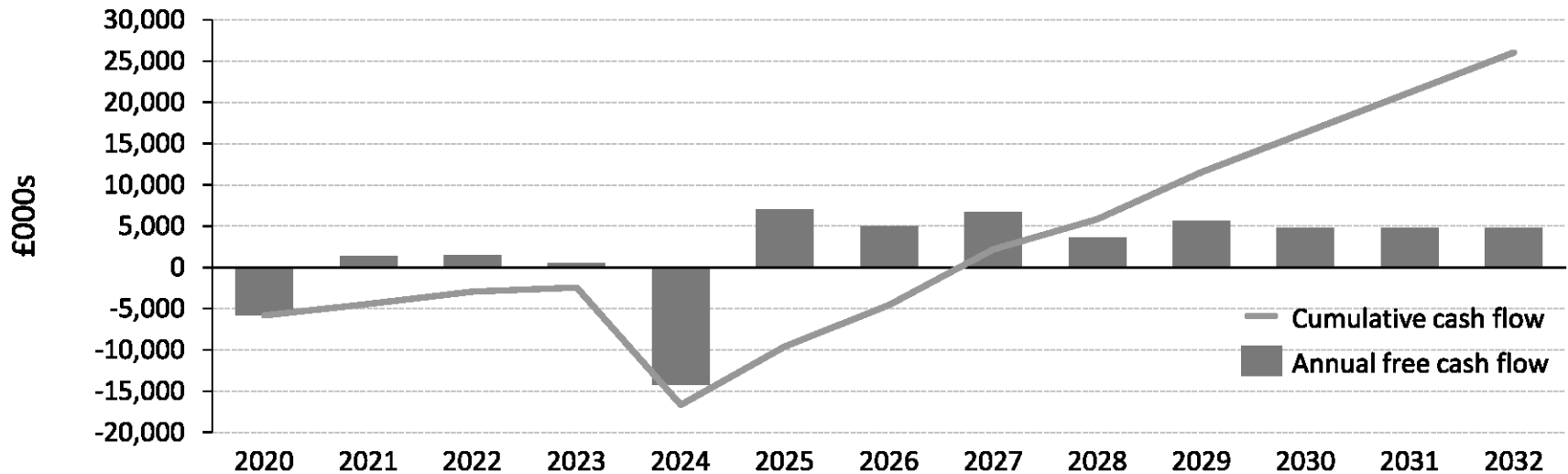
- NPV (to 2032 @8% discount rate) = +£1.8m (9% IRR)
- Total additional cost of hydrogen across end users: £53.4m

* NB: a total investment of £13.2m in new HRS is assumed in 2024. This could cover the costs of several large capacity HRS; or upgrade costs to existing stations along with deployment of one large capacity HRS.

If 30% grant funding (£12.5m) is combined with RTFCs, the Hub could become an attractive investment proposition in this demand scenario

Cash flow (undiscounted) – RTFCs and 30% capex grants (£12.5m in total)

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth + trains + marine

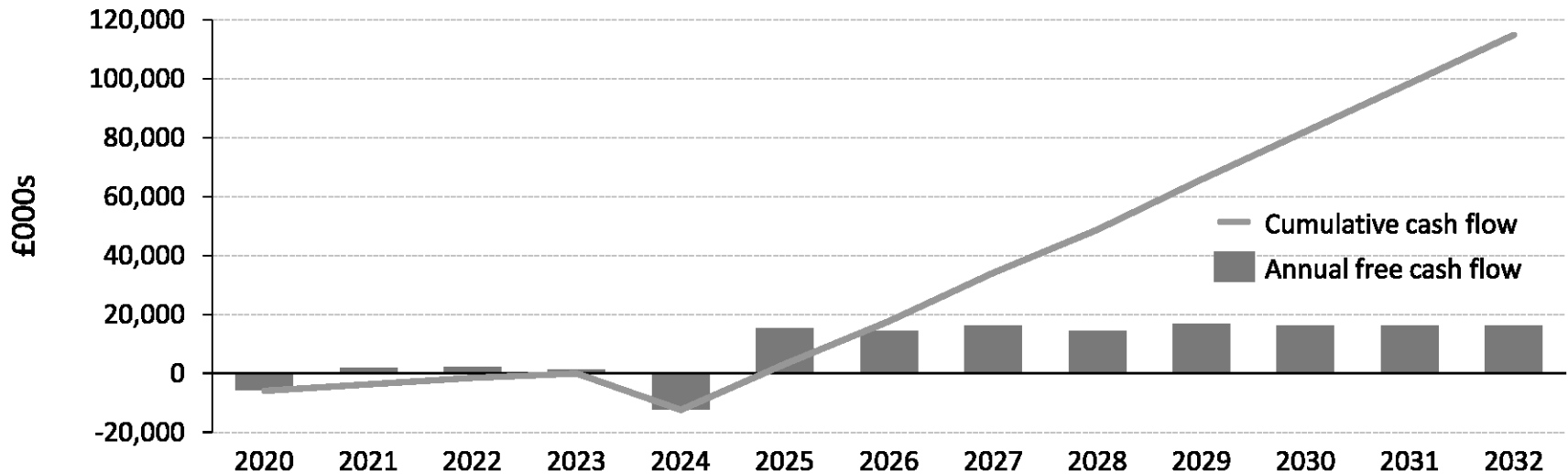


- NPV (to 2032 @8% discount rate) = +£9.0m (20% IRR)
- Total grant: £12.5m (spread across investment years)
- Total revenues from RTFCs: £44.6m

With higher hydrogen revenues as well as RTFCs and capex grants, the potential upside could reach an NPV of £33m in 2030

Cash flow (undiscounted) – RTFCs and 30% capex grants (£12.5m in total) + hydrogen at £8/kg for all users

Cash flow (undiscounted) for a potential hydrogen hub in Aberdeen based on centralised electrolytic production: demand growth + trains + marine



- NPV (to 2032 @8% discount rate) = +£33.2m (49% IRR)
- **Total grant: £12.5m (spread across investment years)**
- **Total revenues received from RTFCs: £44.6m**
- **Total additional cost of hydrogen across all end users (compared to cost with previous sale price assumptions): £88.8m**

Achieving a positive investment case for an ambitious Hub serving lower value markets for hydrogen would require a higher level of public support

Conclusions for the demand growth + trains + marine scenario

- Trains and marine applications are likely to yield a lower price for hydrogen (assuming that operators would be unable to cover the cost premium associated with hydrogen fuel compared to untaxed diesel).
- Supporting the additional markets of trains and marine applications through additional HRS and production capacity would therefore rely on several factors further to those outlined previously:
 - Some form of grant funding to de-risk the additional capacity.
 - A strong level of certainty around demand from markets where hydrogen revenues are likely to be higher (e.g. cars, vans, buses).
 - In the absence of RTFCs, a higher sale price for hydrogen is needed to cover the ongoing operational costs for the production and distribution of hydrogen which are not covered; some operators (or their clients) may be willing to pay for low carbon services (e.g. HGV and marine logistics & services for the oil and gas sector).

There are various possibilities for mitigating the risks of investment in a renewable hydrogen hub

Risks facing investors in renewable hydrogen hub

	Risk	Mitigation options
1	Failure of demand to grow.	Phased approach to investment. Implement long-term supply agreements where possible (take-or-pay). Support market development activities. Grant support or conditional loans.
2	Variable opex higher than anticipated (e.g. electricity prices).	Long-term contracts for key cost parameters. Select site with multiple energy supply options (if possible).
3	Fixed opex higher than anticipated.	Negotiate contracts. Seek fixed prices. Take actions to accelerate demand growth (as fixed opex can be spread over a higher number of customers).
4	Equipment failure (unscheduled downtime and need for additional investment in replacement parts).	Warranties (extended) on key equipment. Build hub with redundancy in design.
5	Other supply solutions with lower cost base come on stream and out-compete the hub.	Implement long-term supply agreements where possible. Seek opportunities for synergies – e.g. Acorn hydrogen feeding the hub for onward distribution to customers.
6	Loss of site for the Hub.	Hub owner / operator to buy land. If not, put in place long-term lease agreement. If not possible, seek alternative sites and / or include budget for relocation if necessary.
7	Unable to access RTFCs / revenue from RTFCs lower than anticipated.	Compliance of any renewable hydrogen production system with the eligibility criteria for RTFCs can and should be checked with DfT. As a market mechanism, the future values of RTFCs is inherently uncertain. It may be possible to hedge this risk via bilateral agreements with other fuel suppliers impacted by the RTFO.

Agenda

Context to the Aberdeen Hydrogen Supply Hub

Assessment of hydrogen demand

Hydrogen supply options

Infrastructure deployment and siting

Business case assessment

Funding, financing and investment requirements

Economic benefits

Environmental benefits

Action plan and milestones for delivering the ten-year vision

Appendix 1 – Action Plan for implementation

Appendix 2 – Strategy for existing assets

Appendix 3 – Assumptions and extracts from stakeholder engagement

Appendix 4 – Market readiness

A combination of private sector investment and public sector funding is the most likely scenario to finance the Aberdeen Hydrogen Hub

Funding and financing options

Private sector investment

Potential suppliers are likely to either use their own funds or bring their own debt providers to finance the initial capital outlay of the Hub. At present a number of companies are expressing a strong interest in investing in this type of novel infrastructure (and in the leasing of alternatively fuelled vehicles). Examples encountered during the project include: Rock Infrastructure, NeOT, Barclays, and John Laing Group plc. The Scottish Investment Bank could also be another source of private sector investment.

Discussions with these specialist financiers suggest a willingness to invest in schemes of this type once backed by bankable contracts (e.g. take or pay arrangements for fuel supply). Generally, these groups are also looking to invest in larger schemes and hence the investments would need to be framed in terms of a planned long term expansion.

These finance suppliers are also interested in developing leasing products for hydrogen vehicles, particularly buses and rail, which can be backed by long term contracts to use the vehicles.

Public sector funding

The “capex support” required to de-risk the initial investment (as described in the previous slides) could be provided by:

- Scottish Government:
 - Low Carbon Travel and Transport Challenge Fund
- Scottish Enterprise:
 - Business grants
- UK Government
 - OLEV (e.g. previously via the Hydrogen Transport Programme)
 - BEIS (e.g. previously via the Hydrogen Supply Competition)
 - Innovate UK
- **Scottish Enterprise should explore options for public sector financing with Scottish & UK Government. This should be done in parallel to the development of the procurement process (to be led by ACC).**

There are several potential options for recouping any public sector financial contribution towards delivering the Hub

Potential public sector funding recouping mechanisms

The aim of the public sector investment is to ensure that the private partner can supply hydrogen profitably even if demand does not pick up and RTFCs are not available. IF these risks do not occur there will be “excess rents” for the private provider (i.e. they will make an over-high profit)

The primary options for recovering the public sector investment in supporting the initial costs involved in establishing the Hub are:

- **Grant** – capital funding could be provided in return for suppliers committing to certain conditions. Most of the hydrogen transport initiatives now underway have been facilitated by significant levels of grant funding, which is often allocated via some form of competition and comes with conditions (e.g. commitment to install and operate equipment for a certain period, provision of data for analysis of the technical / economic performance, etc.). These conditions could include a requirement to repay some of the grant funding in the event that the RTFO (or demand growth) is higher than an agreed baseline.
- **Conditional loan** – up-front funding provided by ACC could be given as a conditional loan. This could be implemented by including a clause that the loan becomes repayable when a certain level of income (per kg or absolute) is exceeded by the project.
- **Co-investment in a special purpose vehicle** – rather than providing funding directly to the selected supplier(s), an alternative option would be to co-invest in a special purpose vehicle, i.e. a new enterprise set up to own and operate the Hub, including the eventual plan for expansion. The concept is that future profits made would be retained by the SPV and some / all could be reinvested in further (higher risk) hydrogen market development activities.

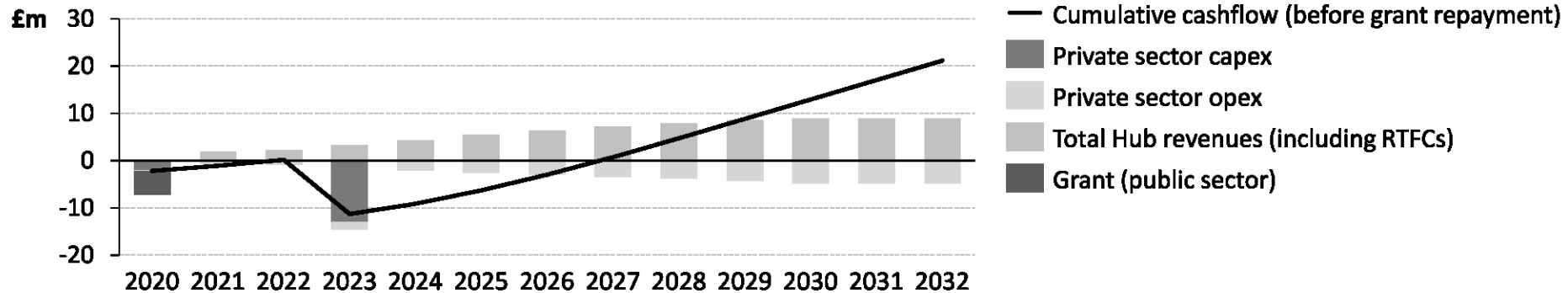
We believe that all of the above options are consistent with a competitive procurement approach (see Action Plan) – i.e. a tender exercise should be used to select the supplier(s), and the mechanism for providing any public sector funding can be developed in parallel.

In the case of a successful second phase of demand growth, the Hub would still be profitable if grant funding is repaid as a low interest loan

Demand growth scenario – case with £5m initial capex grant and RTFCs at £5/kg, reducing to £1/kg by 2030

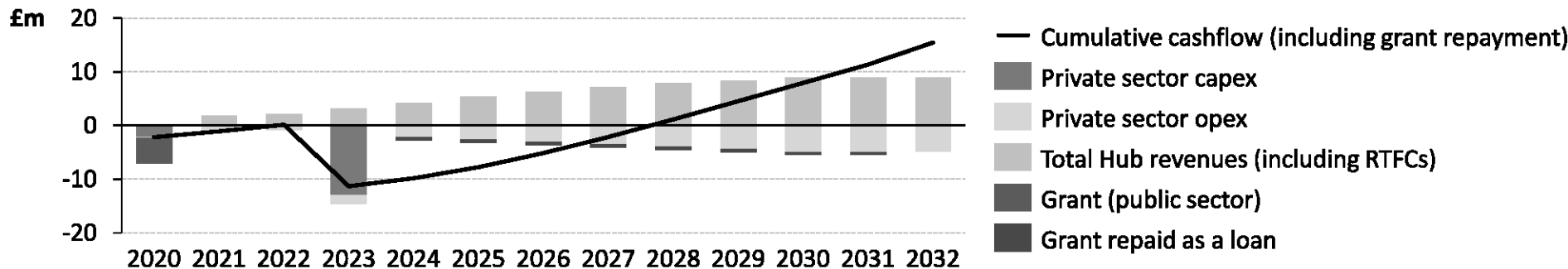
- The private sector could achieve an IRR of 22% and a private sector NPV of +£7.5m with RTFCs and a £5m non-repayable grant:

Private sector cashflow (before grant repayment): 22% IRR, NPV after 12 years: +£7.5m



- The chart below shows the impact on the private investor case when the grant is repaid as a loan (3% interest rate), with repayments starting in 2024 and finishing in 2031. In this case, the IRR is still attractive over 12 years, at 17% (NPV = +£4.5m).

Private sector cashflow (loan @3% interest repaid from 2024): 17% IRR, NPV after 12 years: +£4.5m



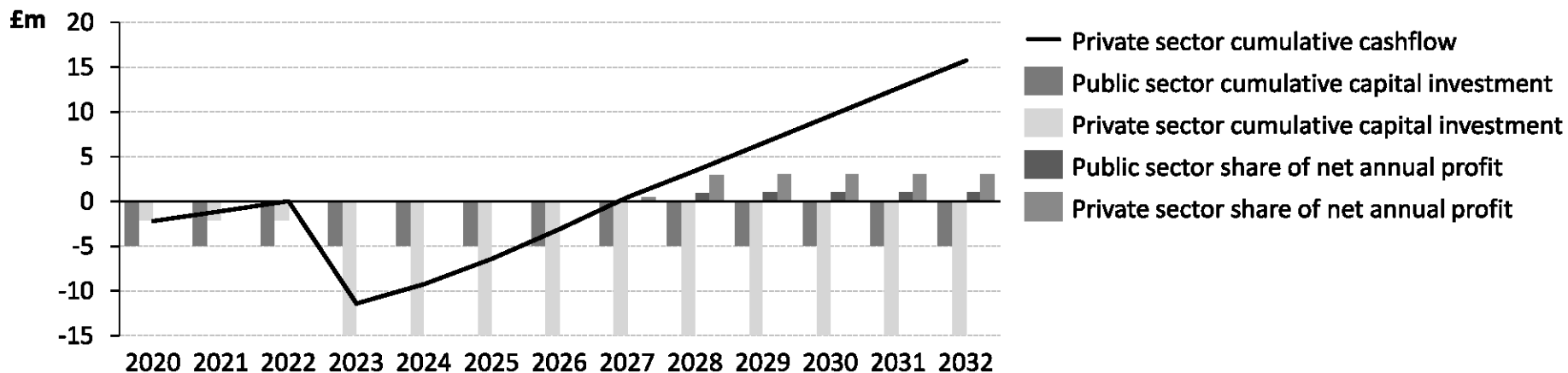
- The repayment of this loan could be conditional on the continued growth of demand (and sufficient revenues, including RTFCs).

A joint venture could be a way of maximising opportunities for growth (i.e. by reinvesting profits into vehicles or infrastructure)

Demand growth scenario – case with £5m initial capex grant and RTFCs at £5/kg, reducing to £1/kg by 2030

- An alternative model to a grant repayment scenario would be a joint venture (or special purpose vehicle), where the profit is shared between the public and private sector parties. The chart below represents how the net annual profit could be split in accordance with the share of the total capital investment. In the case of a joint venture, profits (particularly the public sector share) could be reinvested (e.g. to cover vehicle cost premiums, or additional infrastructure).

Joint venture cumulative capital investments, net annual profit and private sector cashflow – 17% IRR, NPV for private sector: +£4.5m



- A joint venture where the public sector shares ownership of the Hydrogen Supply Hub could provide a stronger demand signal, compared to a “conditional loan” concept, representing the public sector stake in the success of the technology. Public sector contributions to the JV could be financial and/or via provision of land and existing infrastructure (depending on the additional cost associated with moving these to a suitable site).

In addition to low cost hydrogen, vehicle subsidies are needed to allow fleet operators to commit to replacement plans and bring demand certainty

Hydrogen vehicles currently have significant cost premiums, which present a barrier to adoption

- The business case analysis assumes that hydrogen is sold at a price that provides fuel cost parity with incumbent vehicles. For example, in the case of buses, hydrogen is sold at £6/kg. After accounting for the Scottish BSOG (which provides an additional 30p/km subsidy for five years to buses which offer at least a 50% GHG saving vs Euro V) this makes the overall fuel costs broadly equivalent for hydrogen and diesel buses.
- However, to make hydrogen vehicles a viable option for bus operators and other customers in Aberdeen to adopt at scale over the next decade, the additional capital costs of hydrogen vehicles (and in some cases, additional maintenance costs) relative to petrol and diesel equivalents also need to be addressed. This could be achieved via subsidies per vehicle (either at the national or regional level).

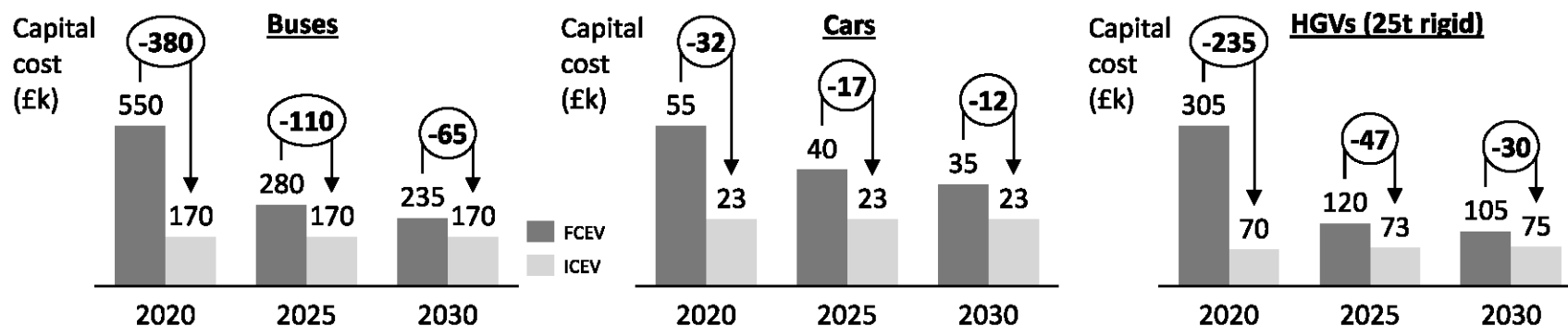
Vehicle subsidies would allow potential Hub customers to commit to adopting hydrogen vehicles

- The next page shows how the capital costs of different hydrogen vehicles are expected to change as the global market grows, and provides an indication of the levels of subsidy that could be provided at different stages of market development to enable the continued adoption of these vehicles in the UK. These subsidies are informed by discussions with vehicle manufacturers, including those that form part of the UK H₂Mobility consortium.
- These subsidy levels are then used to calculate the cumulative vehicle subsidies required to unlock the levels of demand in the “demand growth” business case scenario for the Aberdeen Hydrogen Hub, through to 2032.

A phased approach to subsidy provision would see a decreasing level of subsidy to support vehicle sales through the cost reduction curve

Cost premiums are expected to reduce over time as global production volumes increase

- With growing demand for hydrogen vehicles, global production volumes are expected to increase over the next decade, which will unlock economies of scale for components and for production processes. On this basis, the charts below show indicative vehicle costs over time for buses, cars, and HGVs, and the cost gap relative to incumbent technologies. Initially, cost premiums may also apply for the vehicle maintenance costs, partly due to the absence of established supply chains, but once the supply chain matures, hydrogen vehicles are expected to have lower maintenance costs. Note that both the magnitude of and timescales for cost reductions are indicative and will depend on specific market developments.



Decreasing levels of vehicle subsidy could be provided to support vehicle sales as costs reduce over time

- The proposed subsidy levels shown in the table reflect those proposed to UK Government by the UK H₂Mobility consortium.
- While initial subsidy needs are high, as demand grows and vehicle costs reduce (and the total cost proposition becomes more attractive), lower levels of subsidy could be sufficient to enable continued growth in hydrogen vehicle uptake.

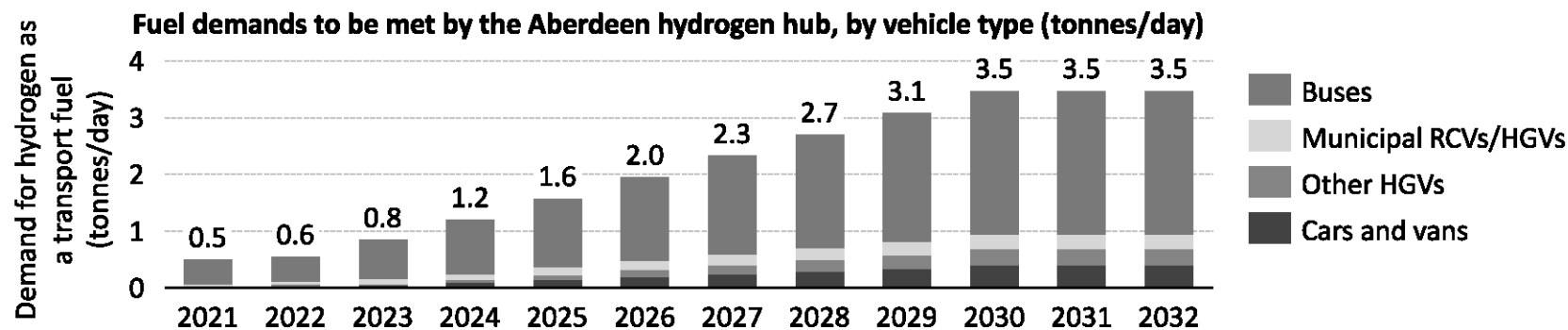
Indicative subsidy levels per vehicle to remove capital cost barrier

Indicative time period	2020–2021	2022–2024	2025–2032
Fuel cell bus subsidy	£350k	£120k	£50k
Fuel cell car/van subsidy	£25k	£15k	£5k
Fuel cell HGV subsidy	£150k	£150k	£50k

The total subsidy requirement to support the level of local hydrogen vehicle uptake in the demand growth scenario would be c.£29m by 2032

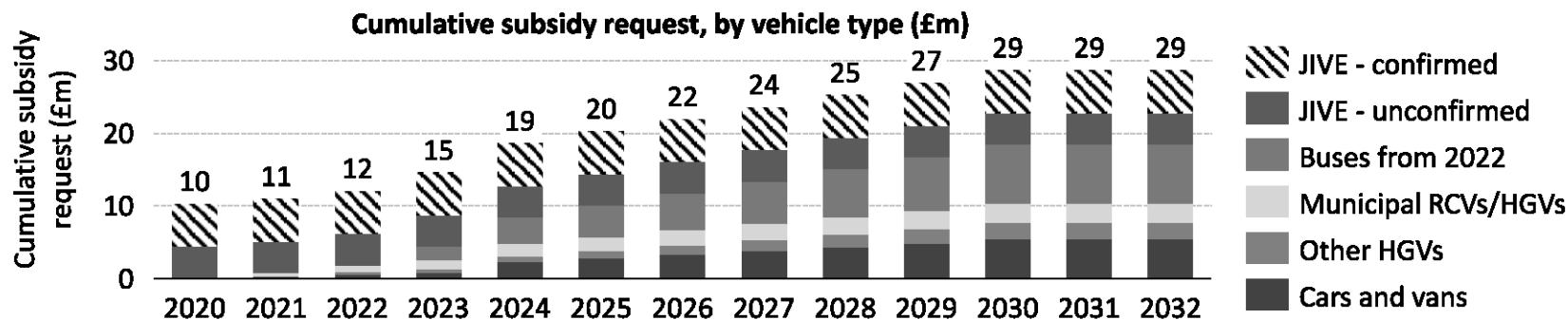
Cumulative demand from hydrogen vehicles (demand growth scenario)

- In the demand growth scenario, by 2032, the fleet of hydrogen-fuelled vehicles served by the hub would include **145 buses**, **800 cars** and **c.70 HGVs**.



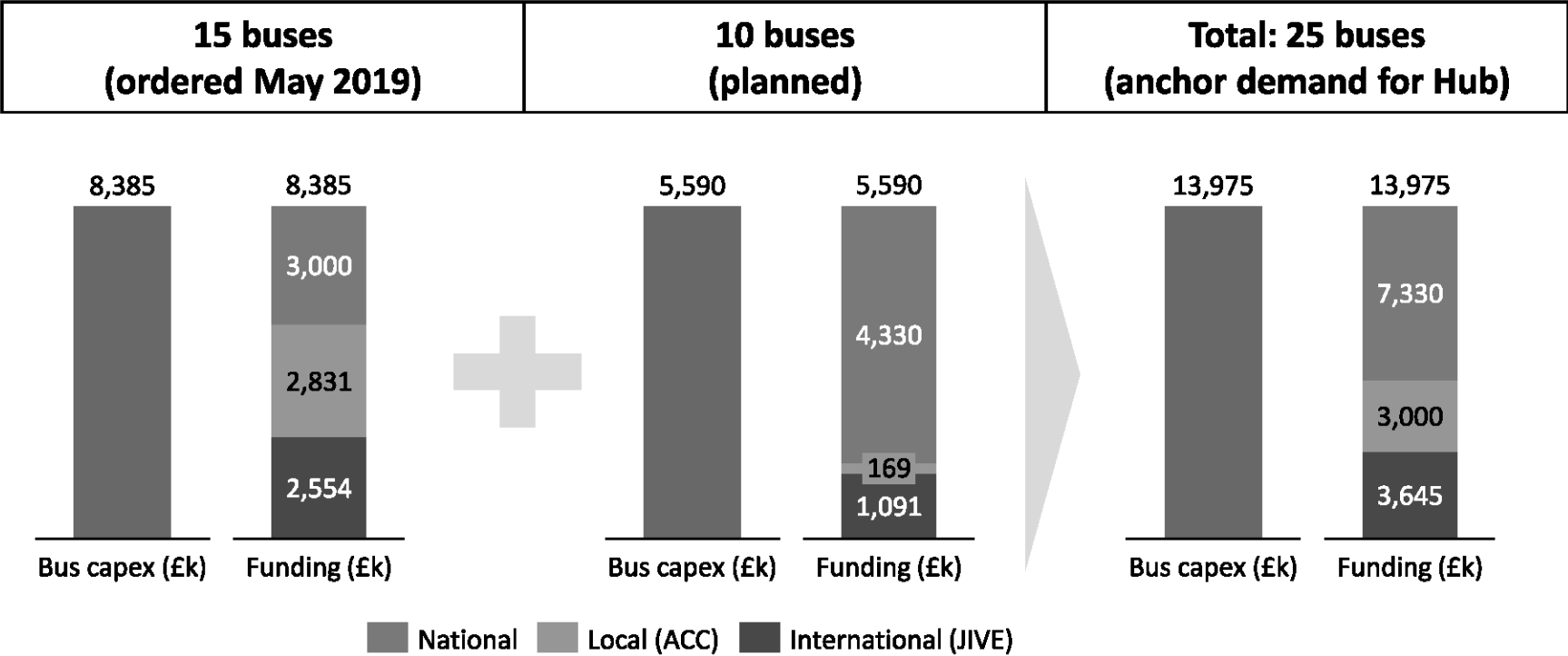
Total vehicle subsidy required to support the demand growth scenario: £29m by 2032 (£6m already in place)

- The total subsidy request, based on the subsidy levels set out on the previous page and the demand scenario above, is shown below. Note that the “JIVE” figures refer to plans to deploy 25 buses under this project (and funding is already in place for the first 15 vehicles). These figures exclude EU funding, against which local / national funding can be leverage (see next page).



EU funding is available to support an expansion of Aberdeen’s JIVE fleet of 25 vehicles – additional public funding from national sources is needed

Funding strategy for initial fleet of buses to be served by the Hub



All funding for the initial fleet of buses is in place (vehicles were ordered in spring 2019 and are due to be delivered in 2020).

There is an opportunity to expand the initial fleet with 10 more buses – funding is to be confirmed (initial indications that JIVE funding could be available).

With this funding strategy, the contributions from each party are well leveraged against those from others.

The vehicle funding requirements to unlock the demand for the Hub are subject to several uncertainties including the impact of other measures

Funding requirements and other measures

- The figures set out above are order-of-magnitude estimates, based on current fuel cell vehicle premiums and cost trajectories based on a range of published data and discussions with manufacturers.
- Vehicle subsidies required will depend on the rate at which technology costs fall, which will be dependent on the rate of global fuel cell (and fuel cell bus) market development as well as specifically on the growth of demand (and production capacity) for European fuel cell buses.
- It may also be possible to reduce the level of subsidies needed via other policy measures. For example, in the case of buses, changes that lead to increased usage (higher fare revenues) combined with regulatory requirements for ZE buses could be an alternative way of achieving the demand growth scenario.
- Other recommended measures to stimulate demand in each segment are set out in the Action Plan.

Contents

Context to the Aberdeen Hydrogen Supply Hub

Assessment of hydrogen demand

Hydrogen supply options

Infrastructure deployment and siting

Business case assessment

Funding, financing and investment requirements

Economic benefits

Environmental benefits

Action plan and milestones for delivering the ten-year vision

Appendix 1 – Action Plan for implementation

Appendix 2 – Strategy for existing assets

Appendix 3 – Assumptions and extracts from stakeholder engagement

Appendix 4 – Market readiness

This section considers the potential short term economic impacts in detail, with a broader overview of the potential long-term impacts, including exports

The assessment of economic benefits resulting from the Hydrogen Hub includes the following:

1) Hydrogen supply chain assessment

- Mapping of hydrogen supply chain: production, distribution, dispensing + vehicle / vessel supply and maintenance
- Relevance to existing industry stakeholders

2) Economic impacts of the Hydrogen Supply Hub

- GVA & employment impacts resulting from hydrogen supply chain activities for the hub **in the region**, to 2030
 - Direct: e.g. initial investment sourced locally / nationally
 - Indirect: purchase of non-labour goods and services resulting from construction and on-going operations
 - Induced: impacts from spending of wages generated directly and indirectly

3) Long-term economic impacts and exports

- High-level assessment of the impacts that could be catalysed by the hub:
 - Potential growth of hydrogen companies that can export hydrogen & related goods / services to countries with fewer offshore renewable resources
 - Potential for transition and growth of existing offshore oil & gas activities to offshore renewables and hydrogen supply

Aberdeen has a strong existing supply chain for renewables and offshore services, but limited activities in other areas of hydrogen production

Upstream: hydrogen production activities	Stakeholders (those with a strong presence in Scotland are in bold)	Strength of current supply chain in Scotland
Carbon capture and storage	Pale Blue Dot, University of Edinburgh, University of Aberdeen, Heriot-Watt University	Strong
Civil engineering	Wood Group, local civil engineering and construction firms	Strong
Renewable electricity generation	Vattenfall, Scottish Power Renewables, SSE, Balmoral Group, Equinor	Strong
Onshore equipment maintenance & life cycle services	Hydrasun, Wood Group, Technip UK	Strong
Offshore maintenance & life cycle services	EC-OG, CHC Scotia, Bilfinger Salamis UK, Windcat, below organisations + others	Strong
Project management, design & engineering	Wood Group, Technip UK, Aker Solutions, Ithica Energy, Offshore Engineering	Strong
Piping & cabling	Hydrasun, transfer of expertise from oil and gas industry (currently much of this is done by existing suppliers)	Strong
Delivery, installation & commissioning		Potential to develop
Reformers	Linde, HyGear, Air Products, Air Liquide	Potential to develop
Compressors	Linde, Howden, Sundyne, NEL, HyET, Hystorsys, Haskel	Potential to develop
Hydrogen storage	Chesterfield Special Cylinders, Hexagon, Luxfer, UMOE	Potential to develop
Electrolysers	ITM Power, NEL, McPhy, Hydrogenics, Siemens	Potential to develop

There is no existing hydrogen distribution supply chain in Aberdeen, but related skills could be transferred from the oil & gas sector

Hydrogen distribution	Stakeholders (those with a strong presence in Scotland are in bold)	Strength of current supply chain in Scotland
Pipeline installation	SGN	Strong
Gas injection to pipelines	SGN	Strong
Consultancy: project management, design & engineering	Wood Group, Technip UK, Aker Solutions, Ithica Energy, Offshore Engineering	Strong
Tube trailers	Calvera, Chesterfield Special Cylinders, CPI, Faber Cylinders, FIBA, Hexagon, Luxfer, NPROXX, UMOE	Potential to develop
Tube trailer maintenance	As above (+ local automotive repair companies e.g. Dingbro)	Potential to develop
Distribution operations	Ryse, BOC, Calor Gas, Flo Gas + local logistics companies	Potential to develop

Similarly, there is significant potential for existing engineering & integration services in the oil & gas sector to transition to hydrogen-related services

Downstream: hydrogen refuelling stations	Stakeholders (those with a strong presence in Scotland are in bold)	Strength of current supply chain in Scotland
Civil engineering	Wood Group etc	Strong
Piping & cabling	Hydrasun, Swagelok	Strong
Consultancy: project management, design & engineering	Wood Group, Technip UK, Aker Solutions, Ithica Energy, Offshore Engineering, Logan Energy	Strong
Dispensers	Linde, NEL, Haskel	Potential to develop
Delivery, installation & commissioning	HRS providers; Hydrasun, potential for oil & gas sector stakeholders to develop expertise	Potential to develop
On-site maintenance	HRS providers; Hydrasun, potential for oil & gas sector stakeholders to develop expertise	Potential to develop
Compressors	Linde, Howden, Sundyne, NEL, HyET, Hystorsys	Potential to develop

Most hydrogen vehicle manufacturers are based outside Scotland, but some new entrants could develop a local base given sufficient demand

Vehicle maintenance	Dingbro (automotive components)	Potential to adapt for hydrogen vehicles
Vehicle maintenance	Dingbro (automotive components)	Potential to adapt for hydrogen vehicles
Buses	Arcola, ADL	Potential to develop
Cars	Toyota, Hyundai, Riversimple, Daimler	Unlikely
Vans	HV Systems, Renault	Potential to develop
HGVs	ULEMCo, Scania, Iveco, Hyundai, HV Systems	Potential to develop
RCVs	ULEMCo, E-trucks	Potential to develop
Trains	Alstom, Vivarail, Siemens	Potential to develop
Boats	CMB Revolve Technologies, Ferguson Marine	Potential to develop
Hydrogen heating appliances	Worcester-Bosch	Potential to develop

To calculate the net economic impacts for Scotland, hub investments are broken down by the share of the additional value attributed to Scottish companies

Step	Description
1. Investment in local economy quantified	<ul style="list-style-type: none">Investment in the Hydrogen Supply Hub is broken down in accordance with the supply chain activities shown on the previous slides. The share of investment attributed to the Scottish economy is quantified based on the strength of the current supply chain in Scotland.¹
2. Costs vs business as usual	<ul style="list-style-type: none">Expenditure related to the Hydrogen Supply Hub is compared to business as usual, to determine where additional value arises (e.g. additional value from FC bus production vs diesel bus production).
3. Direct GVA calculated	<ul style="list-style-type: none">Direct GVA = Additional value invested x % invested in Scottish supply chain.
4. SIC codes assigned	<ul style="list-style-type: none">An area of industrial activity (and associated SIC code) is assigned to each area of activity relating to the Hydrogen Supply Hub; this enables the appropriate multipliers to be identified (for indirect and induced economic impacts).
5. Indirect and induced GVA calculated	<ul style="list-style-type: none">For each project cost, the direct GVA is multiplied by the appropriate multiplier² to calculate the total GVA including indirect and induced effects.

Several scenarios have been considered for the level of local supply chain involvement in the implementation and operation of the Hydrogen Hub

- The potential economic impacts of the Hydrogen Hub implementation will depend on the level of involvement of the local supply chain; several scenarios have been considered, as set out in the table below.
- In Scenario 1, the “local share” of economic activity is assumed to be limited to work that could be carried out immediately by businesses in Scotland. Each successive scenario then assumes that additional supply chain elements move to Scotland and therefore a greater level of expenditure is retained by Scottish companies.

Scenario	Hub components delivered by Scottish supply chain	Justification	Assumed indicative value ¹
1	<ul style="list-style-type: none"> • Civil works, grid connection & piping • Operation and maintenance of refuelling station, electrolyser and tube trailers • Project management 	<ul style="list-style-type: none"> • A number of companies, with expertise from the oil and gas industry are able to provide civil works, piping and grid connection work. e.g Wood group. Spare parts for the current refuelling stations are sourced in Scotland 	<ul style="list-style-type: none"> • Civil capex £500k per electrolyser upgrade and piping/cabling at £50k for electrolyser • 7% of HRS capex in civils and piping • 100% of HRS fixed operating costs 6 FTE on £40k/year for management
2	<ul style="list-style-type: none"> • As per Scenario 1 + installation and commissioning of HRS and electrolysers from 2023 	<ul style="list-style-type: none"> • This is currently carried out by the OEM, here is assumed O&G companies offer these services, or OEMs set up offices in Aberdeen, due to the H₂ Hub. e.g. HydraSun. 	<ul style="list-style-type: none"> • Additional £150k of electrolyser capex • 25% of HRS capex
3	<ul style="list-style-type: none"> • As per Scenario 2 + Bus and municipal HGV retrofit from 2023 	<ul style="list-style-type: none"> • Demand for H₂ vehicles in Aberdeen leads to vehicle retrofitters to open garages in Aberdeen, as Arcola have done for a Liverpool bus deployment. e.g. Arcola, ULEMCo. 	<ul style="list-style-type: none"> • 10% of FC bus capex and £20k per municipal HGV

- The following slides show the estimated GVA and jobs created in each of these scenarios. All scenarios are based on the implementation of the Hub infrastructure and vehicle deployment in the “Demand growth” demand scenario.

¹ Based on Element Energy estimates based on previous project quotes. Indicative breakdown of capex provided in the appendix.

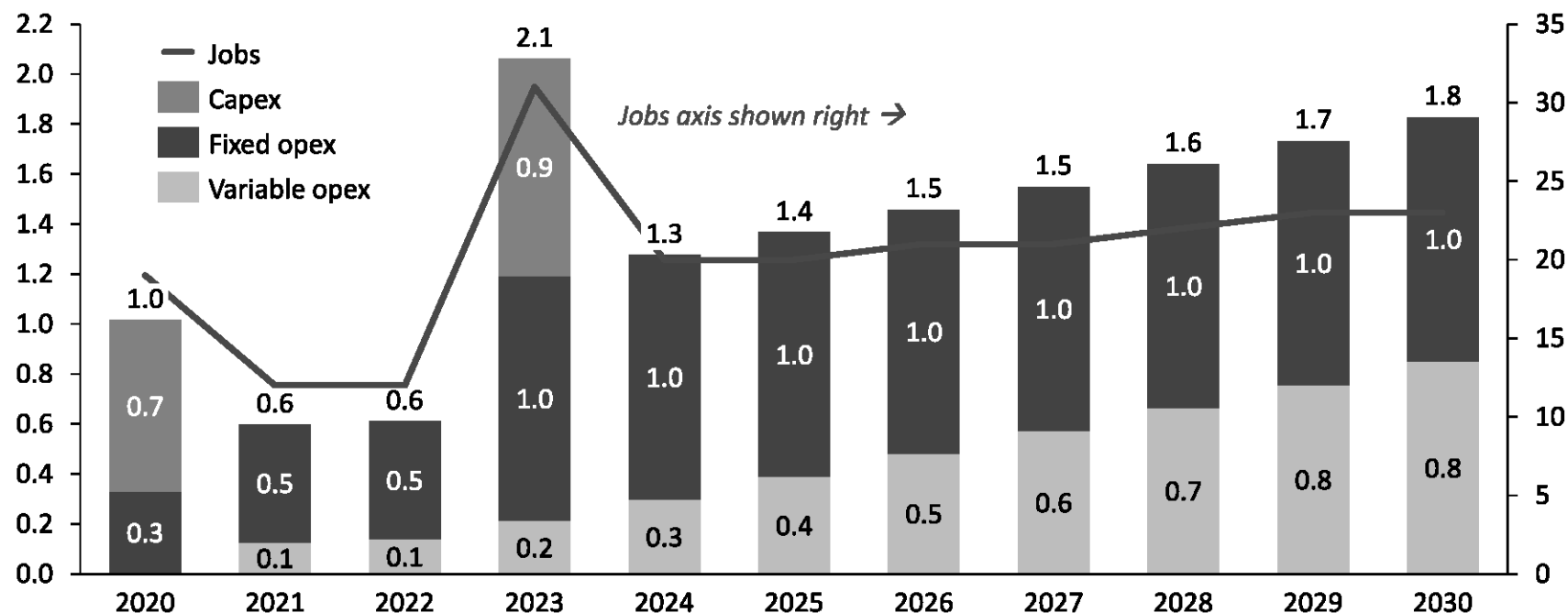
Scenario 1: With a low assumed share of value for the Scottish economy, the total cumulative GVA resulting from Hub activities is £25m by 2030

- In this scenario, long term jobs are largely provided through the operation of the electrolyser, HRS, hydrogen distribution system, and additional wind farm operation and project management. **23 continuous jobs are provided in total.**
- Some short term work (8 jobs for a year at a time) on the civils and piping is required for HRS and production site upgrades.

Economic impact	Cumulative value to 2030 (£m)
Direct GVA	13
Total GVA	25

Direct GVA (£m/year)

Total jobs (FTE)

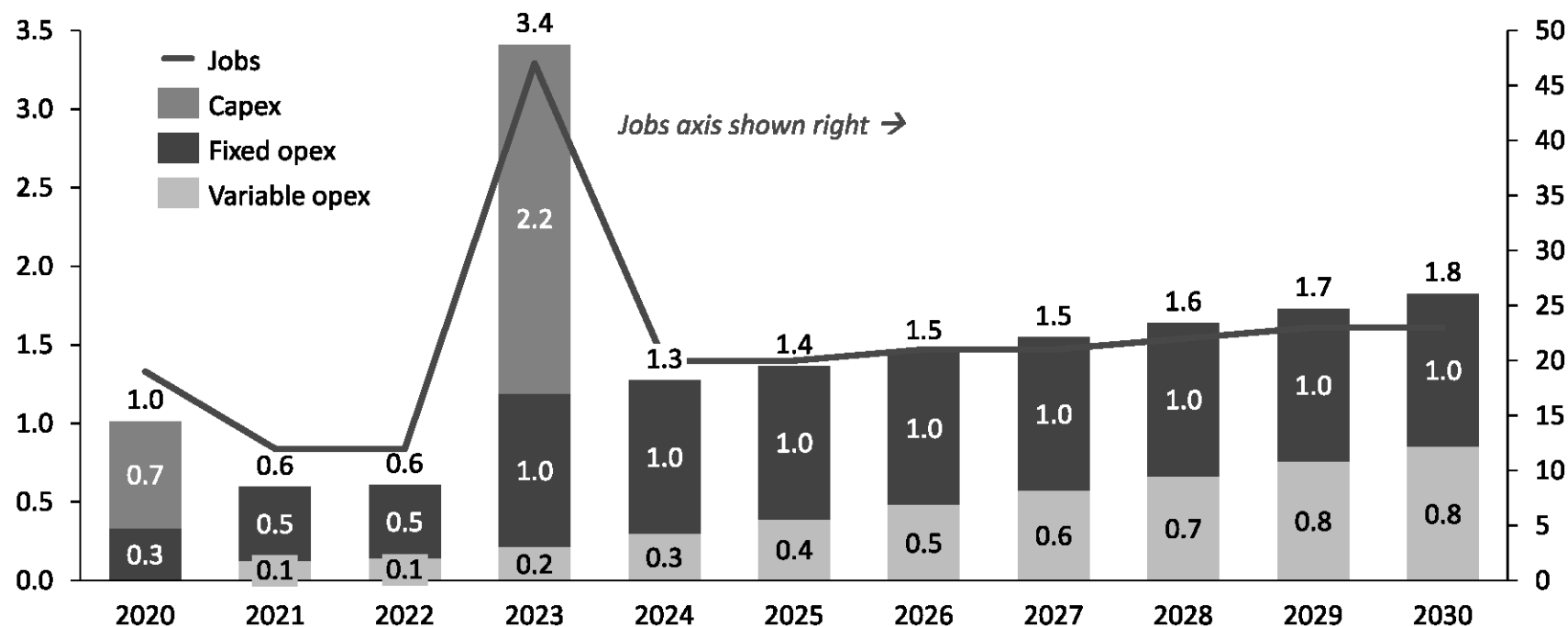


Scenario 2: Including installation and commissioning of the HRS and electrolyzers increases the total cumulative GVA to £28m by 2030

- In this scenario, further short term jobs are generated directly by the supply hub project, in the installation and commissioning of the electrolyser (assumed to be supplied by local companies). The number of temporary jobs for the 2023 upgrade increases to 23, in installation work carried out by a company in Aberdeen.
- If these jobs are maintained through the export of services to or further Aberdeen development 48 jobs are provided in 2030.

Economic impact	Cumulative value to 2030 (£m)
Direct GVA	14
Total GVA	28

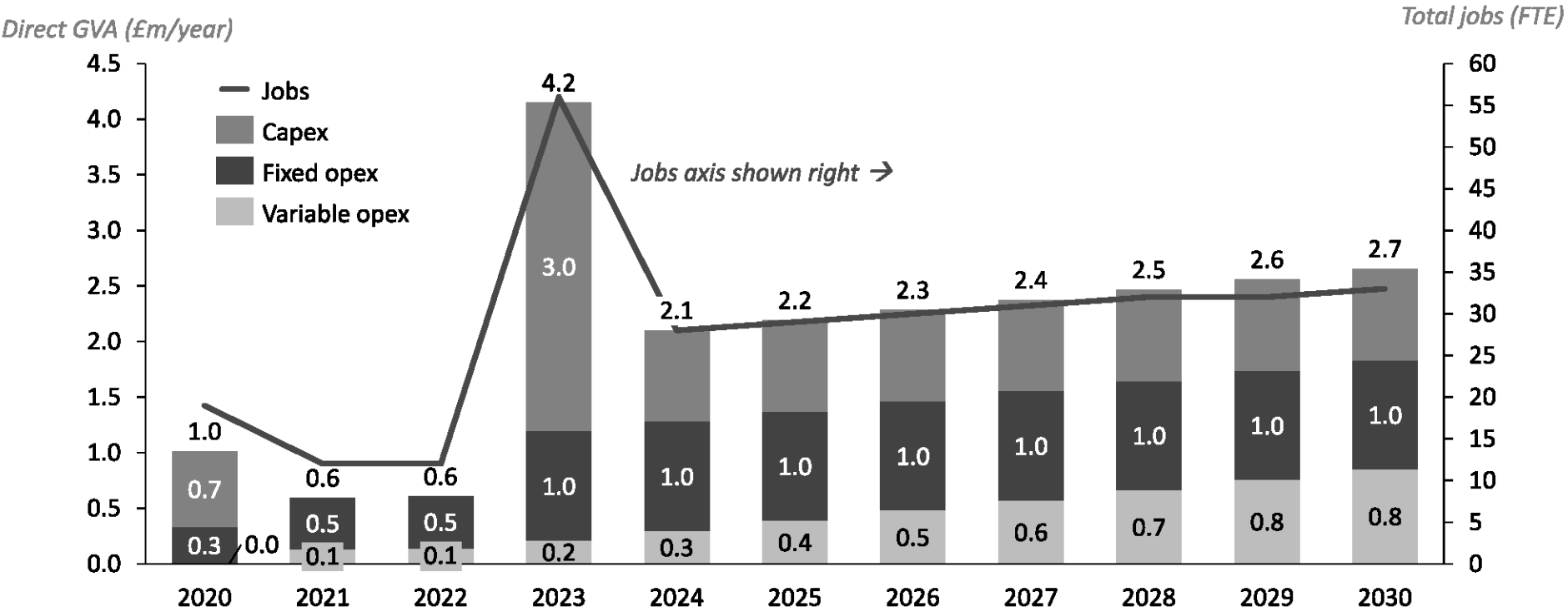
Direct GVA (£m/year)



Scenario 3: Including the bus and refuse truck retrofit work from 2023, GVA resulting from Hub activities increases to £41m by 2030

- In this scenario, the retrofit of vehicles is a regular source of local economic activity, and adds an additional direct GVA of £1.3m/year. **This leads to a total of 33 continuous jobs as a result of activities relating to the Hub deployment.**
- This assumes that from 2025, 15 buses and 5 municipal HGVs are retrofitted each year by local companies.
- If the jobs provided in 2023 in installation and commissioning of HRS and electrolyzers, are maintained to 2030 through export, 56 jobs are provided in 2030 .

Economic impact	Cumulative value to 2030 (£m)
Direct GVA	21
Total GVA	41



* Municipal HGVs

The Aberdeen Hydrogen Hub is expected to result in 23 to 33 FTEs, with the potential for greater impacts with the exportation of services

Resulting GVA and FTEs

- Public and private investment in the Aberdeen Hydrogen Hub is expected to provide **£35m** in GVA for the region by 2030 if business as usual were to continue for H₂ supply chain services in Aberdeen.
- This has the potential to rise to **£41m GVA by 2030** if supply chain elements, that have the potential to locate themselves in Aberdeen, are provided.
 - This compares favourably to the £3m to £20m of public funding (through capex support and RTFCs) paid for the H₂ Hub.
- Including direct and indirect employment effects, the Hydrogen Hub is estimated to provide **23 new full time equivalent (FTE) jobs** via the continuous employment resulting from project work in a business as usual case. This includes the operation and maintenance of the electrolyser, HRS, hydrogen distribution system, and new jobs in wind farm operation and project management. This could rise to **33 FTEs** if local companies are involved in retrofitting or manufacturing of fuel cell vehicles; further temporary jobs will also be created during the installation phases of the Hub.
- While these figures are low compared to the c. 28,000 personnel employed by the oil and gas sector in Aberdeen¹, they relate to the GVA and employment provided by the **core equipment and services** required for the Aberdeen Hydrogen Hub in a reasonable uptake scenario.
- The impact will increase where demand is catalysed in sectors with less certainty, i.e. shipping and rail applications.
- There is also a significant potential for the export of services to other cities / regions / countries.

1 – 'Aberdeen economic policy panel report- 2018', Aberdeen City Council, pg .32 - 40,960 people in primary industries, with >70% employed in oil and gas.

Potential demand from rail and/or marine applications could double the local economic benefits of the hydrogen supply hub

Comparing scale of demand and costs

- Scale of hydrogen demand in initial scenario:
 - 3,500 kg/day by 2030
- Scale of potential demand from trains and boats:
 - 10 trains: 3,500 kg/day
 - 10 boats: 1,500 kg/day (e.g. wind farm support vessels)
- This implies that the **hydrogen demand in a given year would be doubled** with only small growth for these end users when compared to the initial scenario considered.
- These two end users would each require a new refuelling station as well as a substantial increased in the production capacity of the electrolyser and the existing distribution network.
- As a consequence of this increase, investment (and hence economic activity) and employment associated with the production and delivery of hydrogen could also approximately double.
- Growth in these sectors would unlock economies of scale for the hydrogen production components, further improving the business case for this proposition.

Resulting scale of economic impacts

- The deployment of these vehicle types could result in an additional **c. £32m** in GVA and an additional **25 jobs** for the region. This would total **£67–73m** and **48–58 jobs**.
 - This is based upon a doubling of the capacity of the HRS, H₂ production and distribution requirements for the project.
 - The exact increase depends upon the extent of the production and infrastructure upgrades required, and may decrease with economies of scale.
- **The need for the conversion of trains and / or boats based in Aberdeen could create an additional local supply chain** and, hence, local jobs.
- This would become sustainable if a long-term strategy was developed for the conversion of a growing number of boats and / or trains.

Growth of the global hydrogen market offers opportunities to expand local economic benefits by exporting Scottish products and services

Demand for hydrogen is predicted to grow globally, with potential for demand in a range of applications across the energy sector, including:

- Fleet applications of light vehicles
- Heavy duty surface transport applications
- Marine and aviation
- Industry
- Space heating

Many of the potential products and services generated following the establishment of a Hydrogen Hub could be exported, including:

- Renewable hydrogen (e.g. making use of Scotland's significant untapped offshore wind resources)
- Management, engineering & design consultancy services (parallels to the thriving offshore energy services industry)
- Start-ups with new business models (e.g. following up research in Scottish universities)
- More work installing parts (i.e. refuelling stations or vehicle conversions)
- More work specialising in maintenance of hydrogen vehicles
- Parts manufacturing in Scotland

The potential economic value of these service exports has been analysed by examining the potential size of these export markets for these industries.

The production of renewable hydrogen in Scotland offers the potential for up to 440 new jobs in development of the offshore wind and hydrogen production

- Global hydrogen production is expected to reach 117Mt/yr by 2030, compared to 67Mt/yr today¹.
 - Scotland could potentially meet a hydrogen demand of 50 kt/year (137 tonnes/day) by 2030 using offshore wind; only 800MW_e in windfarm capacity would be required to meet this demand².
 - Such a demand would benefit Scotland by a factor of 40 times more than the benefits brought about from the Aberdeen H₂ Hub (3.5 tonnes/day) .
 - The Aberdeen H₂ hub demand scenario provides a total of £2.6m in GVA via electrolyser construction and £1.7m per year via the operation of the electrolyser and windfarm in 2030. This creates 11 continuous jobs.
- ▼
- The potential impact of this in 2030, using the factor of 40, is:
 - Up to **£100 million in GVA** in the electrolyser commissioning and installation and **£460 million GVA** in the offshore wind capacity required to meet this demand. This assumes the same value to Scotland as the 588MW Beatrice offshore wind farm³ (right).
 - Up to **440 jobs** with **£68m/year in GVA** due to the ongoing operation of the electrolyser and wind farm.
 - The GVA and jobs created by delivering these projects could be further increased by siting the electrolyser offshore. In this case, further expertise from the oil and gas sector could be transferred to the electrolyser and pipeline installation.



1 - Hydrogen Council, *Scaling Up* (2017)

2- Assuming FCH JU 2025 target efficiency of 53 kWh/kg, and 37% load factor (average load factor of 2018 UK offshore wind – ‘Offshore wind operational report, January – December 2018’ The Crown Estate

3- ‘Economic Impact of Beatrice Offshore Windfarm Limited, A Report to Beatrice Offshore Windfarm’ Limited, SSE, Bigrar Economics

Becoming an industry leader in offshore hydrogen production could prove to be worth billions in exports, based on the offshore wind industry case

Leveraging Offshore Wind and Oil & Gas Expertise

The UK has the opportunity to lead the way in developing green hydrogen production, replicating successes achieved in the offshore wind sector. There are significant export opportunities to 2030 and beyond for hydrogen production and pipelines, in tandem with these offshore wind opportunities.

- The export of offshore wind expertise is anticipated to be worth £2.6 billion a year to the UK by 2030².
- Scottish companies, in particular oil and gas companies, could provide additional value to the collective hydrogen expertise by offering:
 - Offshore pipeline installation and maintenance.
 - A capital cost of roughly £1.65m per km installed, and operating costs of roughly £39,000/km/year
 - ❖ 15km for a pipeline to the Kicardine windfarm would cost £24m and bring £590,000/year of direct GVA in operation.
 - The impact therefore of a trial pipe could provide (using a SIC code of 35.2-3 and Type II GVA multiplier for gas distribution of 1.8, and employment multiplier of 4.5); £43m in total GVA and 108 job years in construction; and £1m/year and 3 jobs in the pipeline operation.
 - Engineering of hydrogen production capacity offshore.
 - This has yet to be demonstrated, making the potential cost elements for export difficult to quantify.
 - Development of offshore, long-term hydrogen storage facilities in depleted oil and gas fields.
 - This has yet to be technically demonstrated. There is however potential for export in design and geology services.
- The relative immaturity of many of these export capacities makes it difficult to estimate their associated economic impacts.
- However, even if one-tenth of the success of offshore wind export is realised, a GVA of £260 million/year would be realised.

¹ 'Exporting Offshore wind', Offshore wind week, October 2016

²<https://www.renewableuk.com/news/440922/Offshore-wind-is-first-renewable-technology-to-agree-Sector-Deal-with-Government.htm>

Export of HRS installation and commissioning services across the UK could provide £100s of millions in GVA and 100s of jobs to Aberdeen/Scotland to 2030

- The transfer of expertise from the oil and gas sector in Aberdeen companies to refuelling stations, encouraged by the hydrogen hub, will enable companies of this type to export their management, engineering and installation/commissioning/delivery expertise.
- To understand the magnitude of the potential for exporting the installation and commissioning of HRS, the following is assumed:
 - Each 400 kg/day station costs £2 million.
 - Aberdeen based companies will access 25% of the HRS installation and commissioning costs. This would add £1 million of total GVA to Aberdeen (assuming a GVA multiplier of 2) per refuelling station, and provide 8 job years.

**£3 million GVA for
Aberdeen H₂ Hub**



**£100 million and 160
employees for export of
installation services in
UK**



**£1 billion and 1,600 jobs
for export of services
worldwide**


- If these services were offered to 100 refuelling stations across the UK by 2030, this would provide up to **£100 million in GVA and 160 jobs** (assuming ramped up deployment with 20 stations a year in 2030).
 - This is a conservative order size and timeframe when compared with Germany's ambition (and soon to be reality) of 100 HRS by the end of 2019 and plans for 300 more subject to FCEV sales¹.
- A wider global market, of 1,000 of HRS would create **£1 billion in GVA and 1,600 jobs**
 - Once again this is conservative when compared with Hydrogen Europe's 2030 vision of 4,500 refuelling stations installed across Europe by 2030².

1 - Hydrogen Council, *Scaling Up* (2017)

2 - Hydrogen Europe, *Hydrogen, enabling a zero emission Europe* (2018)

The export of project management services could provide up to £14m in GVA and 40 full time jobs to Aberdeen

- Through the development of the hydrogen hub, and building on the skills developed for the JIVE deployments, individuals and companies within Aberdeen will develop exportable skills in the management of hydrogen and fuel cell deployments in other cities.
- An internal estimate of the costs of supporting a new city for the management of hydrogen technology deployments (covering refuelling infrastructure, hydrogen supply and vehicle tendering) is c. £100k (dependent on requirements) for one year. The work should then be passed onto a dedicated team in the local city to continue the development of the project.
 - This provides a total employment (including induced and indirect effects) of two employees for each project, and a total GVA of £140k per project supported.

- 
- If hundreds of refuelling stations are deployed by 2030, this suggests the potential to project manage a similar number of deployments.
 - If a total of 100 vehicle and refuelling station deployments were supported by local companies or the council team out to 2030, an additional **£14m in GVA could be added** with **40 full time jobs** created via project management (assuming a ramped scale-up of project capacity to 20 projects supported in 2030).

The potential export markets catalysed by the Hydrogen Hub could provide significantly greater economic benefits than the Hydrogen Hub itself

Product examples	Estimated global market size in 2030 (new + existing hydrogen applications)	Estimated Scottish market share in 2030	Potential GVA for the region up to 2030
Hydrogen from renewables	117 Mt/year (vs 67 Mt/year in 2015) ¹	50 kt/year offshore production capacity ² (0.05% of global market)	£560m in during wind farm and electrolyser development 440 jobs and £68m/year GVA in operation
Export of offshore energy services related to hydrogen production	Exact market is unclear, but for comparison the export of offshore wind services is anticipated to provide £2.6 billion/year to the UK.		
HRS installation	Thousands in operation	10% for hundreds of refuelling stations in UK	£100m GVA and 160 jobs for 100 refuelling stations across UK
Project management export	Thousands of HRS and deployment projects	10% for 100 projects	£14m GVA and 40 jobs
HGV production and conversions	Thousands per year ¹	e.g. 10% - 100 of conversion per year	£42.5m GVA and 40 jobs

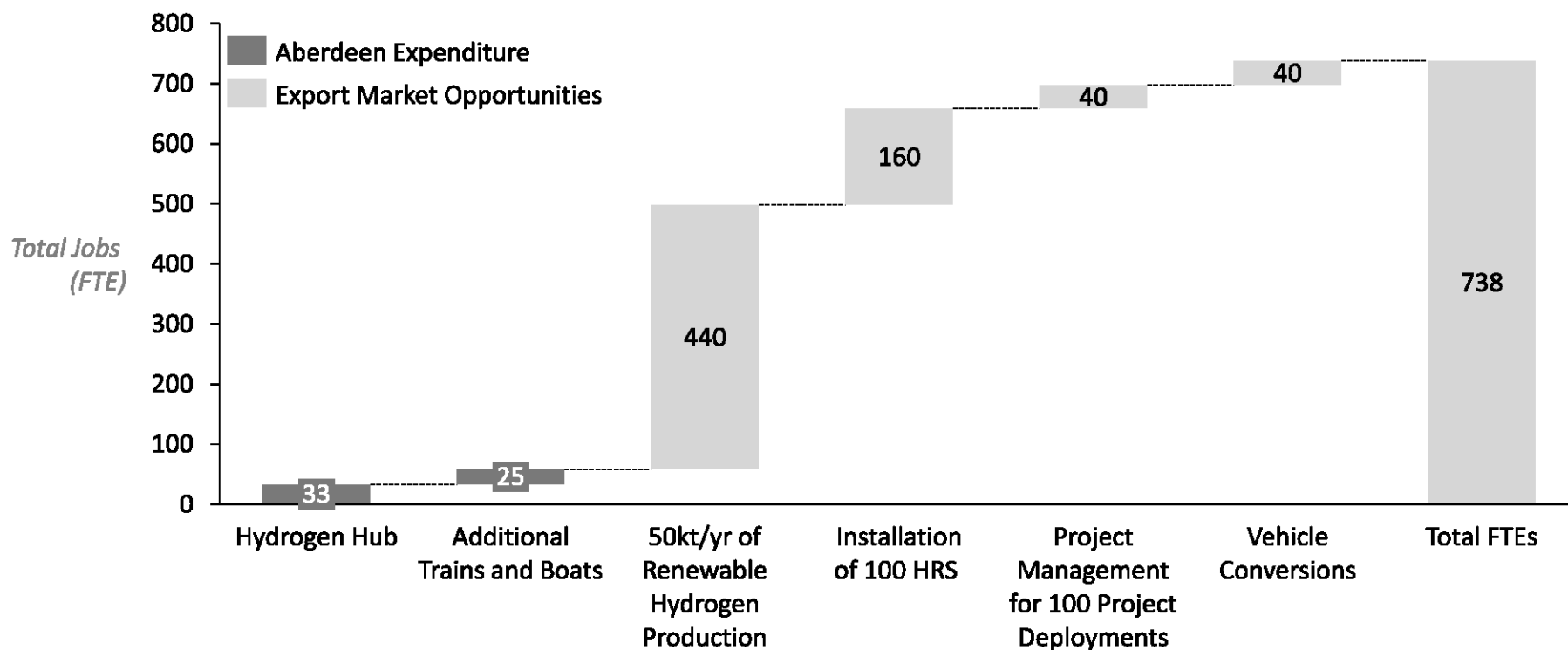
1 - Hydrogen Council, *Scaling Up* (2017)

2 - Based on 300 MW offshore production capacity

3 - Hydrogen Europe, *Hydrogen, enabling a zero emission Europe* (2018)

Export market opportunities are anticipated to result in up to 800 new jobs in the hydrogen industry out to 2030

- The Hydrogen Hub itself adds value that compares well with the funding invested into the project. This is magnified by the potential export markets that are catalysed as a result; these could provide up to 800 jobs by 2030 (excluding temporary jobs in construction of equipment). These exports can provide more than ten times the GVA of the Hydrogen Hub itself.
- Further benefits could be realised via the expansion of the Hydrogen Hub. This could catalyse hydrogen storage projects, a large scale hydrogen distribution network and the export of engineering services worldwide.
- The figure below gives the cumulative FTEs that are brought about due to the development of expertise in the hydrogen sector.



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Delivering a hydrogen hub will facilitate the uptake of hydrogen-fuelled vehicles, bringing emission savings relative to diesel and petrol vehicles

Overview of environmental impacts assessments

- The following pages set out the approach and results of the environmental benefits associated with the Aberdeen Hydrogen Hub. This includes:
 - The **carbon intensity of the fuel production and delivery pathways** for diesel and hydrogen
 - **Well-to-wheel carbon emissions** of hydrogen vehicles compared to diesel incumbents
 - **Total carbon emissions savings** resulting from the uptake of hydrogen vehicles enabled by the Hub
 - **Air quality improvements** in Aberdeen resulting from the uptake of hydrogen vehicles enabled by the Hub
 - **Total avoided societal damage costs** resulting from the uptake of hydrogen vehicles enabled by the Hub
- Emission savings estimates are based on the central demand growth scenario for hydrogen vehicles in Aberdeen out to 2030. This uptake scenario includes passenger cars, buses and heavy-goods vehicles (HGVs).
- Hydrogen-fuelled vehicles are assumed to be procured in place of modern diesel-fuelled alternatives. Thus, the emissions savings from switching to hydrogen can be compared against a benchmark of a fleet of diesel vehicles.
- Significant emissions savings, both with respect to carbon emissions and other pollutants such as NOx, are possible since fuel cell electric vehicles (FCEVs) are zero emission. This means that there are no harmful emissions from the tailpipe. However, some particulate emissions are still present due to tyre wear and brake dust.

Well-to-wheel emissions analysis provides a comprehensive assessment of the carbon emissions associated with vehicle use

- The following analysis considers carbon emissions from a well-to-wheel perspective, i.e. emissions associated with producing/extracting, distributing, dispensing and using transport fuel.
- **Well to tank emissions** depend on the fuel production and distribution method. The table below summarises the possible production and delivery pathways for hydrogen, including the assumed pathway for the Aberdeen Hydrogen Hub.

Fuel	Source of energy	Distribution required?
Diesel	Diesel	Distribution emissions included in diesel emissions factors
Hydrogen from on-site electrolysis	Grid electricity	No – hydrogen produced on-site
Hydrogen from 100% renewable electrolysis	Renewable electricity	Hydrogen assumed to be delivered 10km from point of production
Hydrogen from Aberdeen Hydrogen Hub	90% renewable electricity, 10% grid electricity (to improve electrolyser load factor)	Hydrogen assumed to be delivered 10km from point of production

- **Tank-to-wheel emissions** are the emissions created when the fuel is consumed by the vehicle (i.e. combustion in the case of diesel). For hydrogen, there are no carbon emissions associated with fuel consumption.
- The tables on pages 109–110 show the assumptions used to calculate the well-to-tank and tank-to-wheel emissions, including emissions factors for the different sources of energy, and technology efficiencies.
 - The emissions associated with hydrogen production depend largely on the carbon intensity of grid electricity (when this is used to produce and/or dispense hydrogen). This is calculated for 2020, 2025 and 2030, to account for an increasingly decarbonised grid.



Tube trailer for hydrogen distribution

Emissions analysis assumptions: Fuel emissions factors

Variable	Units	Hydrogen from on-site electrolysis (grid electricity)	Aberdeen Hydrogen Hub Supply (10% grid electricity, 90% renewable electricity)	Diesel
Electrolyser Electricity Consumption @ 100% Load Factor	kWh/H ₂	55.00	55.00	-
Compression Electricity Consumption	kWh/H ₂	4.50	4.50	-
Emissions Associated with Grid Electricity Supply (2020 / 2025 / 2030)	kgCO _{2,e} /kWh	0.29 / 0.22 / 0.13 ¹	10% at 0.29 / 0.22 / 0.13 ¹ 90% at 0	n/a
Fuel Delivery Distance	km	-	10	-
Diesel CO _{2,e} Emissions	kgCO _{2,e} /l	-	2.60	2.60
Trailer Capacity	kgH ₂	-	600	-
Fuel consumption for hydrogen distribution (2020 / 2025 / 2030)	l/100km	-	31.7 / 25.5 / 21.7	-
Total Well to Tank Emissions (2020 / 2025 / 2030)	kgCO _{2,e} /l diesel; kgCO _{2,e} /kg H ₂	17.9 / 13.1 / 7.6	1.8 / 1.3 / 0.8	0.68
Tank to Wheel Emissions (2020 / 2025 / 2030)	kgCO _{2,e} /l	0	0	2.64 ²
Emissions factors per fuel (2020 / 2025 / 2030)	kgCO _{2,e} /l diesel; kgCO _{2,e} /kg H ₂	17.9 / 13.1 / 7.6	1.8 / 1.3 / 0.8	3.3

1: Long-run marginal electricity emissions factors, Treasury Green Book guidance supporting tables, BEIS, 2019

2: GHG Conversion Factors for Company Reporting, BEIS, 2018

Emissions analysis assumptions: Vehicle fuel consumption

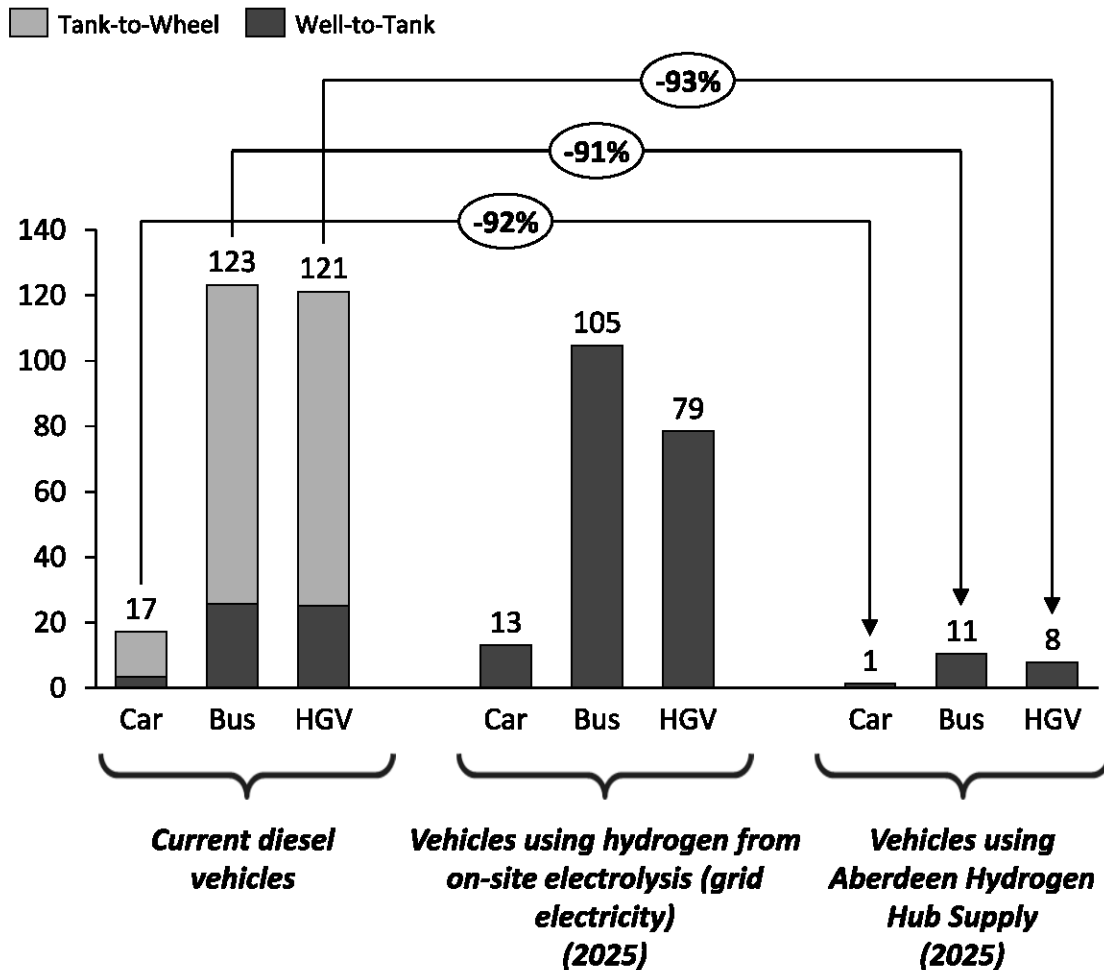
- The fuel consumption and well-to-wheel emissions of the vehicles using the Aberdeen Hydrogen Hub (and the vehicles they are replacing) will vary according to the vehicle type, mileage and type of operations, as well as the year of purchase (likely incremental improvements to efficiency over time mean that vehicles deployed in 2030 could be more efficient than those deployed in 2020).
- However, for the purposes of assessing the emissions benefits, vehicles of the same type are assumed to have the same annual mileage, fuel consumption (based on today's vehicles) and daily fuel demand. These assumptions are set out in the table below. This means that the following emissions savings are compared to current diesel vehicles.
- Note that cars and vans are assumed to be adopted in high-utilisation applications (such as car clubs and taxis) and are therefore assumed to have a higher annual mileage than that anticipated for private car owners.

Variable	Units	Cars and vans	Bus	HGV
Hydrogen Fuel Consumption	<i>kg/100km</i>	1.0	8.0	6.0
Diesel Fuel Consumption	<i>l/100km</i>	5.2	37.5	36.9
Annual Mileage	<i>km</i>	20,000	80,000	50,000
Daily Hydrogen Demand	<i>kg/day</i>	0.55	17.5	8.2

In 2025, each hydrogen vehicle using the Hydrogen Hub would reduce well-to-wheel carbon emissions by over 90% compared to current diesel vehicles

- The chart compares the total emissions **per km** for hydrogen and diesel vehicles in 2025. Two hydrogen pathways are shown: onsite-electrolysis, and the Aberdeen Hydrogen Hub supply route (i.e. distributed renewable hydrogen), which achieves the lower carbon intensity of the two pathways.
- 100% renewable hydrogen would be the least polluting production route, since the only emissions are associated with its distribution from the production site to the point of use. However, it is challenging to obtain a guaranteed supply of 100% renewable electricity from one energy source given the intermittent nature of renewable electricity generation. As such, for the **Aberdeen Hydrogen Hub**, 10% of the electricity is assumed to be supplied by the grid.
- Although there are also some emissions from distribution of hydrogen, the distribution distance is assumed to be very short (10km) and therefore the emissions associated with the grid electricity dominate the emissions for the Hub.

Well-to-wheel emissions by fuel on a per kilometre basis (for vehicles in 2025)
 $\text{kgCO}_{2,e}/100\text{km}$

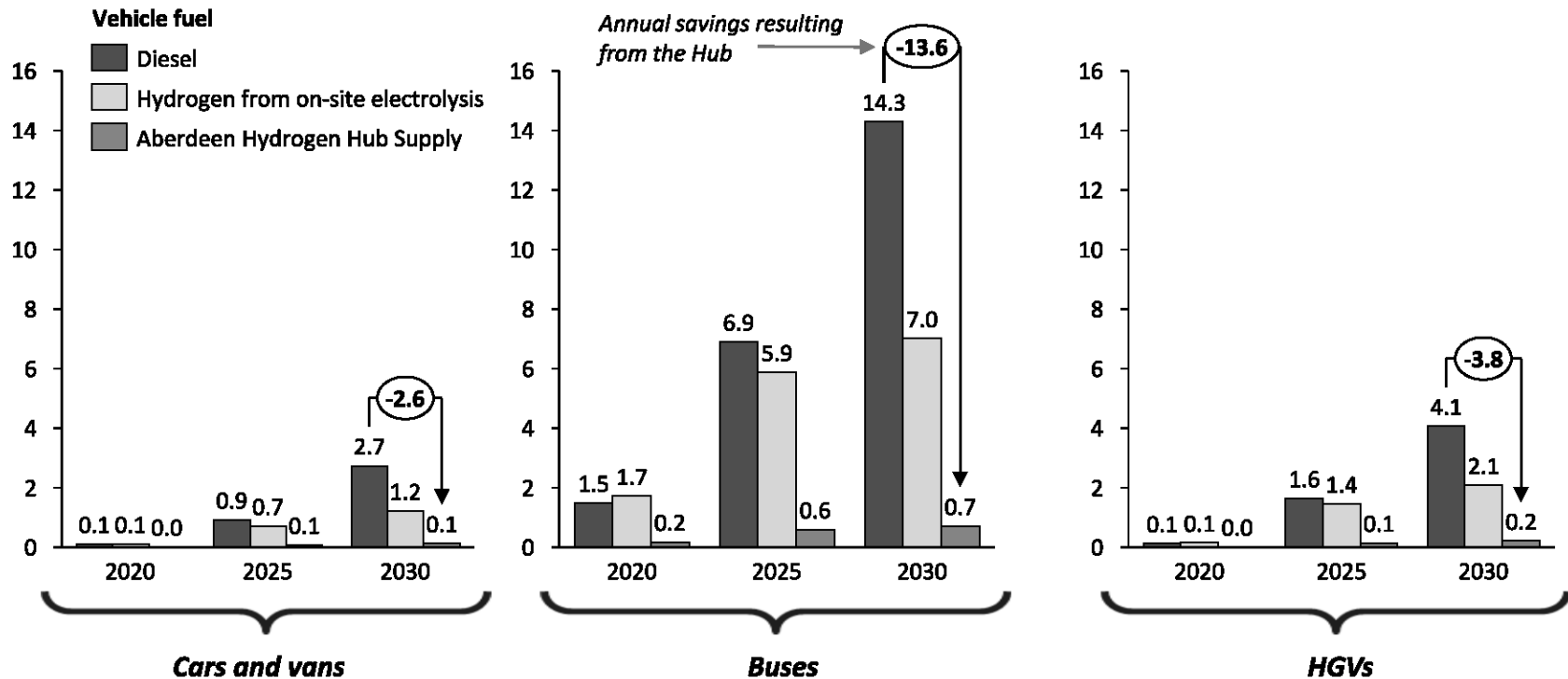


Emissions savings from the buses using the Aberdeen Hydrogen Hub Supply (compared to diesel buses) could reach 14kt/year by 2030

- The charts below show the well-to-wheel emissions associated with the **vehicles adopted under the demand growth scenario**, as a result of the installation and expansion of the Aberdeen Hydrogen Hub. The emissions associated with the equivalent number of diesel vehicles (to be replaced by hydrogen vehicles) are also shown, to quantify the carbon emissions savings that would be achieved in each vehicle segment.
- If the hydrogen was supplied via on-site electrolysis (using grid electricity), the potential well-to-wheel emissions savings would be much lower than for the Hydrogen Hub supply route, due to the higher emissions factor of production.

Annual well-to-wheel carbon emissions of vehicles using the Aberdeen Hydrogen Hub (vs current diesel vehicles)

kt CO_{2,e}/year

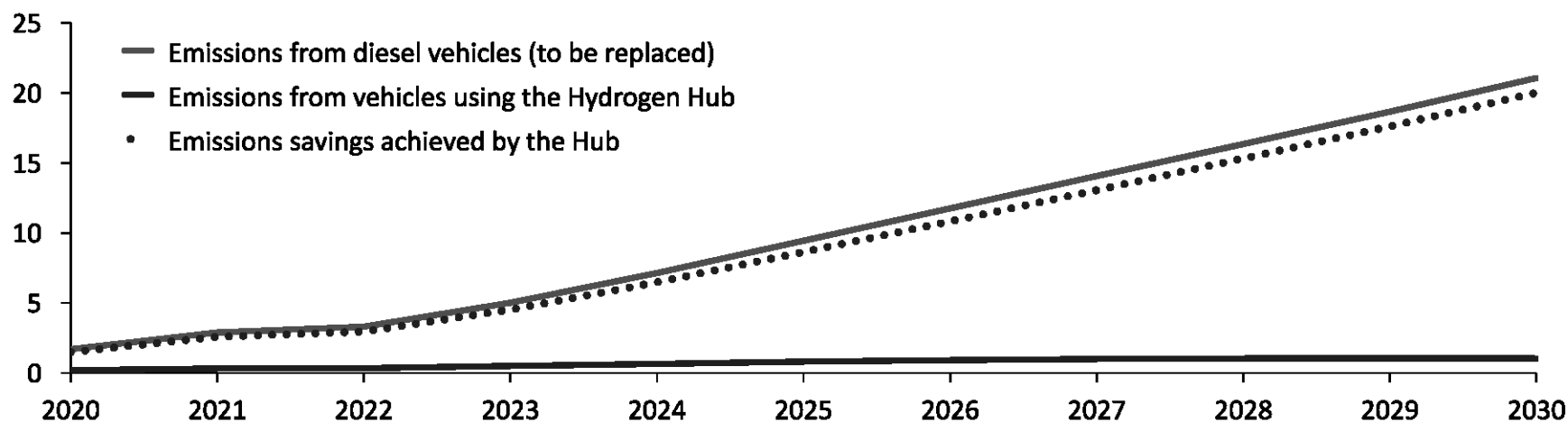


Vehicles using the Hub could achieve well-to-wheel carbon emissions savings of 20 ktCO₂e annually by 2030 compared to current diesel vehicles

- The figure below shows the total well-to-wheel carbon emissions associated with the vehicles adopted under the demand growth scenario, as a result of the installation and expansion of the Aberdeen Hydrogen Hub. The emissions associated with the equivalent number of diesel vehicles (to be replaced by hydrogen vehicles) are also shown, along with the carbon emissions savings that would be achieved as a result of this level of vehicle uptake.
- The well-to-wheel emissions associated with the vehicles using the Aberdeen Hydrogen Hub reach only 1ktCO_{2,e} per year by 2030, representing a total saving of 20 ktCO_{2,e} compared to current diesel vehicles. Using the total transport emissions for the Aberdeen City local authority in 2017 as a benchmark (325 ktCO₂ in total¹), this means that the hydrogen vehicle uptake resulting from the proposed Aberdeen Hydrogen Hub would reduce transport emissions by 6% by 2030.
- The case for this hydrogen supply solution is only expected to improve further with an increasingly decarbonised grid, and it is anticipated that the Hub will catalyse the further adoption of hydrogen vehicles in the area, leading to significant scale-up of these benefits.

Total annual carbon emissions savings as a result of the vehicles using the Hub

kt CO_{2,e}/year



The air quality benefits associated with a successful Hub can be assigned an economic value by considering the avoided societal damage costs

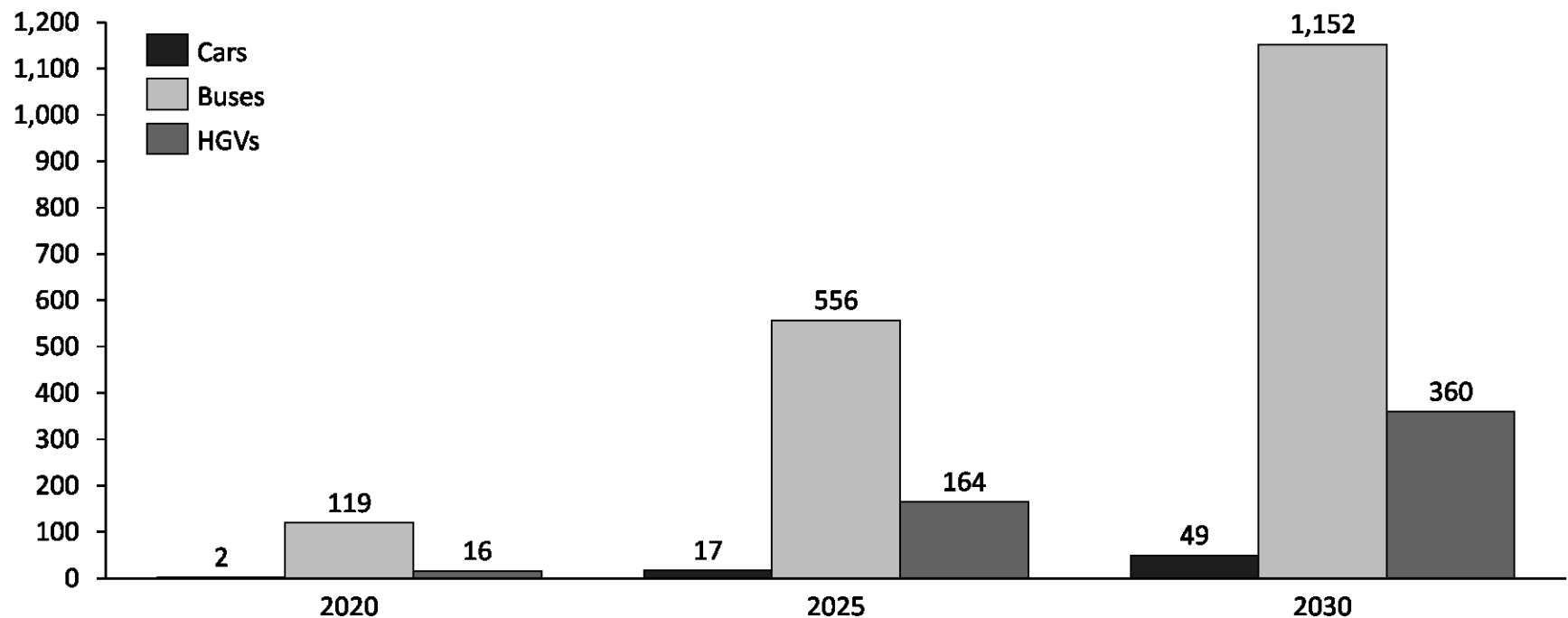
- The impact of emissions that contribute towards poor air quality in the city of Aberdeen can be assessed on a cost basis using DEFRA's air quality statistics. These provide a societal damage cost per tonne of additional pollutant, derived using an impact pathway approach.
- Since there are no pollutants associated with the use of hydrogen as a fuel, these factors only apply to the consumption of diesel. As such, the air quality benefits of the Hydrogen Hub can be measured in terms of the **avoided societal damage costs** associated with the diesel vehicles to be replaced with hydrogen vehicles served by the Hub.
- The table below shows the assumptions used to calculate these avoided costs, including fuel consumption, annual mileage, Euro standards for each vehicle (which define the maximum permitted emissions), and costs associated with different pollutants: particulate materials (PMs) and NOx.

Variable	Units	Cars and vans	Bus	HGV
Diesel Fuel Consumption	<i>l/100km</i>	5.2	37.5	36.9
Annual Mileage	<i>km</i>	20,000	80,000	50,000
Euro 5/V standard (Hydrocarbons / PM / NOx)	<i>g/kWh</i>	0 / 0.005 / 0.23	0.46 / 0.02 / 2	
Euro 6/VI standard (Hydrocarbons / PM / NOx)	<i>g/kWh</i>	0 / 0.005 / 0.17	0.13 / 0.01 / 0.4	
Assumed mix of diesel vehicles in fleet to be replaced	-	Euro 5: 50% of Stock Euro 6: 50% of Stock	Euro V: 50% of Stock Euro VI: 50% of Stock	
PM 10 Societal Cost ¹	<i>£/t</i>		405,280	
NOx Societal Cost ¹	<i>£/t</i>		31,330	
Hydrocarbons Societal Cost ²	<i>£/t</i>		102	

Adopting hydrogen vehicles in place of diesel could avoid £1.6 million/year in societal damage costs by 2030

- The chart below shows the total societal damage costs that could be avoided by replacing diesel vehicles with hydrogen vehicles (in line with the demand growth scenario for the Aberdeen Hydrogen Hub). Hydrogen buses (which form the core demand for the Hub) account for the largest share of the avoided costs.
- By 2030, replacing diesel vehicles with hydrogen vehicles could culminate in avoided societal damage costs of around £1.6m per year.

Avoided societal damage costs associated with emissions from diesel vehicles (to be replaced with hydrogen vehicles using the Hub)
£000s/year



The total avoided costs associated with the emissions savings delivered by vehicles using the Hydrogen Hub could reach £3m by 2030

- In addition to the avoided societal damage costs resulting from improved air quality, a value can be attributed to the carbon emission savings from deploying hydrogen vehicles in place of equivalent diesel vehicles, using BEIS projections of short-term traded carbon values between 2020 and 2030 (a central value of £5/t CO_{2,e} in 2020, increasing to £79/t CO_{2,e} in 2030). The resulting total emissions costs for diesel vehicles assumed to be replaced with hydrogen vehicles are shown in the table below.
- Combining these with the avoided societal damage costs relating to air quality, the **total avoided costs resulting from the adoption of hydrogen vehicles using the Hub** are estimated to be **over £3m per year by 2030**.

		Units	Result of replacing diesel with hydrogen (using the Aberdeen Hydrogen Hub)
Avoided cost of carbon emissions	2020	£/yr	6,850
	2025	£/yr	362,300
	2030	£/yr	1,591,500
Avoided costs of other pollutants	2020	£/yr	136,700
	2025	£/yr	737,200
	2030	£/yr	1,561,500
Total avoided costs in 2030		£/yr	3,153,000

- The bus deployment numbers in the demand growth uptake scenario reflect ambitions to transition to zero emission public transport in Aberdeen. In contrast, the projected uptake of cars, vans and HGVs in this scenario are relatively conservative. It is feasible that the scale of demand – and the associated environmental benefits – for the Hub itself (and unlocked as a result of the scale-up of hydrogen activities in the area) could be an order of magnitude higher than those quantified here.

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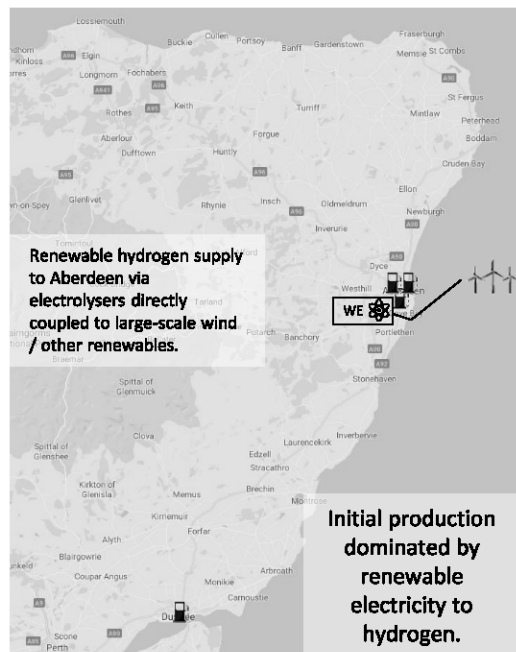
We have developed a vision for how the use of hydrogen in north-east Scotland could grow over the next ten years

Ten-year vision for hydrogen in Aberdeen and the surrounding region – introduction

- We have consulted a wide range of stakeholders throughout this study (>50 calls and meetings held) covering potential suppliers of hydrogen, renewable energy generators, various demand segments, vehicle suppliers, public sector bodies, etc.
- There is a high and growing interest in hydrogen as a clean fuel in many areas of the energy sector, in Aberdeen and beyond, as evidenced by the levels of interest in this study and the number and range of participants at the hydrogen supply chain conference held in Aberdeen in October 2019.
- The analysis undertaken in this study, which has been validated via dedicated meetings with other sector experts, suggests that under the right conditions there are plausible routes to establishing low cost renewable hydrogen delivery systems in Aberdeen, initially mainly for the transport sector but with potential to expand to other applications as technologies and policy develop.
- In this section we describe a vision for hydrogen in energy and transport applications in north-east Scotland over the period to 2030. Delivery of the Aberdeen Hydrogen Hub is an important stepping stone in unlocking further growth in this sector, with the concomitant investments and economic opportunities that will arise. Clearly, there is no guarantee that this vision will be attained, indeed it is highly likely that the eventual level of deployment of hydrogen technologies will differ from the vision articulated below. However, the future scenario described provides useful context to the next steps that are intended to follow this study.

The Aberdeen Hydrogen Hub will accelerate the roll-out of hydrogen and fuel cell technologies, with significant scope for expansion by 2030

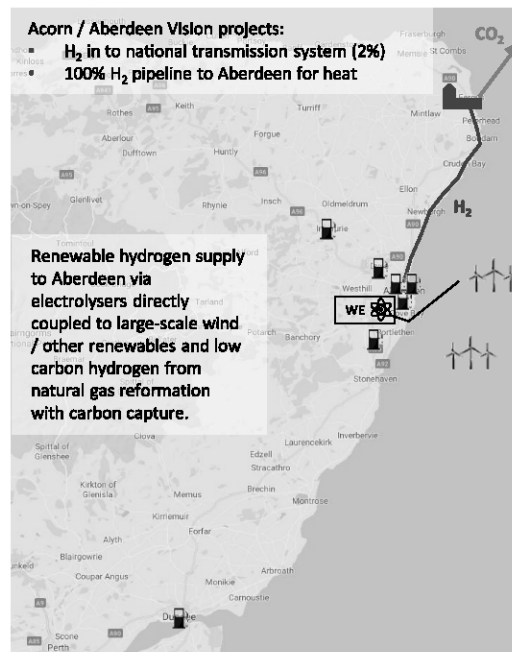
Early 2020s



Hydrogen applications

- Tens to low hundreds of FC cars and vans
- Around 25 FC buses
- Small fleets of dual fuel municipal vehicles
- First deployment of hydrogen-fuelled boats

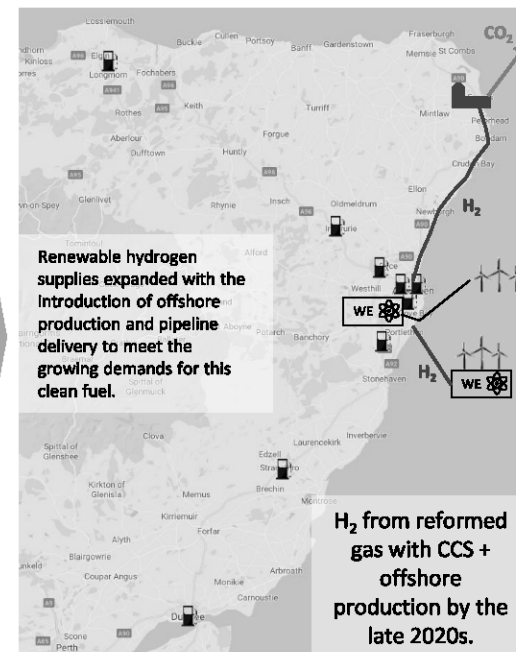
Mid-2020s



Hydrogen applications

- Hundreds of FC cars and vans
- 50–100 FC buses
- Fleets of FC HGVs
- Large fleets of dual fuel municipal vehicles
- FC train pilot
- Fleets of hydrogen-fuelled boats
- Pilots of hydrogen for heat

2030



Hydrogen applications

- Mature hydrogen transport sector: FC cars, vans, urban buses, coaches, HGVs, vessels, trains, etc.
- Hydrogen for heat in Aberdeen's gas network

There are several key milestones on the pathway to delivering the 2030 vision set out above

- ★ Milestone with direct influence of ACC
- ★ Other milestone (related to broader developments in the sector)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydrogen supply	★ H ₂ Hub delivery partners selected	★ H ₂ Hub operational		★ H ₂ Hub expanded (growing demands)	★ Acorn H ₂ available	★ St Fergus to Aberdeen H ₂ pipeline installed	★ Expansion of capacity in Acorn project			★ Offshore H ₂ production at scale	
Light duty transport		★ Additional FC cars available – e.g. second-generation Mirai	★ Launch of ZE taxi mandate policy			★ No new petrol / diesel cars / vans in public sector fleets	★ ZE taxi mandate policy in effect				
Buses & coaches		★ Policies to encourage bus use & ZE bus uptake	★★ Two years of successful JIVE bus operation + bus operators begin purchase of FC buses	★ Begin delivery of 100% H ₂ bus depot			★ FC coaches available on a commercial basis				
Heavy duty transport (non-buses)	★ Form <i>Aberdeen Hydrogen Freight Initiative</i>	★ Strategy for FC HGVs in ACC fleet	★ Pilot FC HGV testing in Aberdeen (oil & gas logistics)	★ Conclusion of HECTOR project (FC RCVs)		★ FC HGV fleet roll-out in Aberdeen (oil & gas logistics)					
Rail	★ Decision on case for FC train deployment (Transport Scotland)		★ FC train pilot demo in Aberdeen		★ Roll-out of fleet of FC trains						
Marine	★ Pilot trial of H ₂ fuelled crew transfer vessel	★ Fleet of H ₂ fuelled crew transfer vessels deployed									Opportunities for wider use of hydrogen in marine applications – e.g. NorthLink Ferries (serving “hotel loads” initially followed by partial and full power operations.
Other applications	★ Study on strategy for H ₂ at the airport and harbour	★ Plan H ₂ for heat trials (following Acorn FID)					★ H ₂ pipeline from St Fergus installed (Aberdeen Vision project)				

NB: timings of milestones are indicative (and in some cases aspirational). List of milestones is non-exhaustive.

FID: final investment decision, RCV: refuse collection vehicle, ZE: zero emission

In addition to the ten-year vision and medium-term milestones, we have defined a set of specific actions to proceed with delivering the Hydrogen Hub

Ten-year vision for H₂ in Aberdeen and the surrounding region and Hydrogen Hub delivery

- Achieving the ten-year vision will rely on actions by a wide range of stakeholders and broader developments in the HFC sector as outlined above, many of which are beyond the direct control of Aberdeen City Council.
- However, given the leading position Aberdeen has established in this area, the city is well placed to help influence broader developments (e.g. accelerate the introduction of wider ranges of commercial fuel cell vehicles), particularly if actors in the city link up with others in the region to create a cluster or *north-east hydrogen coast*.
- Such opportunities should be pursued provided that doing so does not detract from delivering the Hydrogen Hub that is required to deliver the low cost, renewable hydrogen required to facilitate growth in the use of this fuel in the near term.
- We have made a set of recommended next steps for Aberdeen City Council and other members of the Steering Group to follow to progress with implementing the Hydrogen Hub and that will maximise opportunities to continue expanding demands for renewable hydrogen in the city and beyond. These are contained in the *Action Plan* provided as an appendix to the study's main report.

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Action plan for implementation

See separate document.

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Strategy for existing hydrogen production and refuelling assets

Options and recommendations for existing assets

Options and recommendations regarding the existing hydrogen production and refuelling assets in Aberdeen are set out below.

Asset and owner	Options and recommendations
Hydrogen production capacity at TECA (ACC)	<ul style="list-style-type: none">Hydrogen produced at TECA could be made available as an interim or back-up supply for the Hydrogen Hub (with around 400 kg/day capacity), either by:<ul style="list-style-type: none">Siting a refuelling station at the site (subject to suitability as a refuelling location for transport customers). The option for relocating existing refuelling equipment to TECA (dispensers, compressors etc) should be explored further.Delivering hydrogen from TECA to refuelling locations. To explore this option further, the feasibility of loading tube trailers (to transport the hydrogen) at TECA would need to be explored.
ACHES electrolyser & HRS (ACC)	<ul style="list-style-type: none">The ACHES electrolyser and HRS could be re-sited or otherwise used as part of the first phase of the Aberdeen Hydrogen Hub. As such, the provision of this equipment should form part of the offer to potential suppliers.As part of the procurement exercise, ACC should provide potential bidders with details of this equipment and the current site. This should also include details such as remaining lifetime, estimated value, capacity, estimated maintenance costs, and estimated costs associated with re-siting.
Kittybrewster HRS (BOC)	<ul style="list-style-type: none">ACC should aim to keep the Kittybrewster HRS in operation, at least until the new Hydrogen Hub is in operation. The option of re-siting the electrolyser and/or the HRS could be explored with BOC as an option for the future.Initial estimate for fixed opex at Kittybrewster to keep this HRS in operation is £150k per annum in total: this includes ~£60k for electrolyser maintenance, ~£60k balance of plant maintenance and £30k for operation support. Note that this does not include electricity costs and other variable opex.Costs associated with moving the HRS and electrolyser to another site are estimated at £1.5m, which includes site preparation for a new location. Costs associated with moving part of the equipment (or moving the electrolyser and HRS to different locations) would be dependent on engineering work required to isolate different components.

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Other projects and organisations that may be relevant to development and delivery of the Aberdeen Hydrogen Hub

Hydrogen Coast Projects	Project Proponents & Supporters
Aberdeen Vision Project, Aberdeen	SGN and National Grid with Pale Blue Dot Energy and DNV GL
Acorn Hydrogen, St Fergus	Pale Blue Dot Energy, Department for Business, Energy and Industrial Strategy (BEIS), The Scottish Government
Acorn CCS, St Fergus	Pale Blue Dot Energy, EU Innovation and Networks Executive Agency, BEIS, The Scottish Government and Industry Partners
Aberdeen Hydrogen Bus Project, Aberdeen	Aberdeen City Council, EU High Vlo City and Fuel Cell and Hydrogen Joint Undertaking (FCHJU), Innovate UK, Stage Coach, First Group, The Scottish Government, Scottish Enterprise, Scottish Hydro Electric Power Distribution, SGN
The Hydrogen Hub, Aberdeen	Aberdeen City Council, Scottish Enterprise, Opportunity North East
Surf'n'Turf, Orkney	Orkney Island Council, EMEC Orkney, ITM Power, EU, FCHJU, The Challenge Fund, Scottish Government, Local Energy Scotland, Community Energy Scotland
Dolphyn ERM Project, offshore	ERM, Engie, Tractabel Engie and ODE
H100, Fife	SGN
HyStorPor, offshore	University of Edinburgh
BigHit, Orkney	Orkney Islands Council, EMEC
Flotta Terminal, Orkney	OGTC
HyDIME, Orkney	Ferguson Marine, Orkney Islands Council, EMEC, HSSMI
Methiltoune, Fife	SGN
Dundee Bus Project, Dundee	Dundee City Council

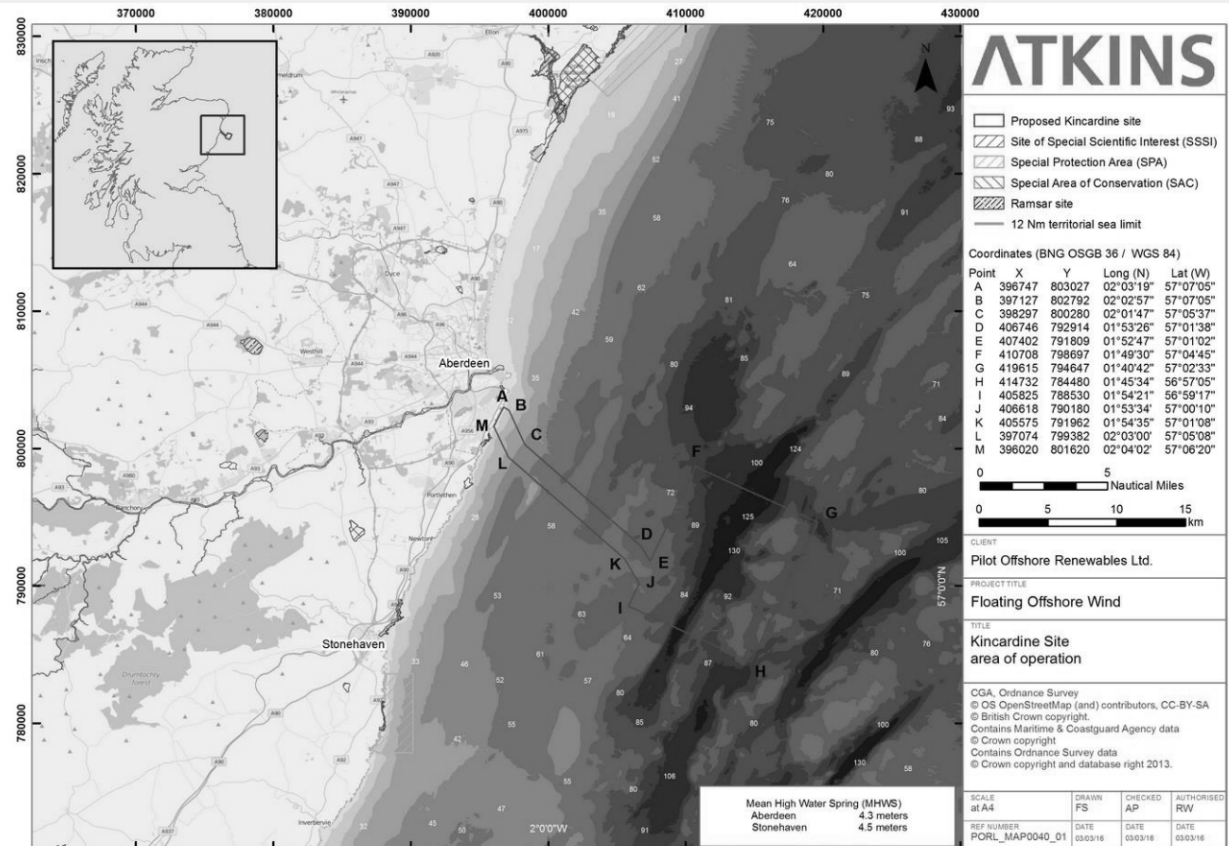
Extract from ***“The Hydrogen Coast – A cluster of projects delivering hydrogen innovation and leadership along the East Coast of Scotland to support net zero carbon emissions targets”***

Source: SGN, National Grid, Pale Blue Dot

The Kincardine offshore wind farm is due to come on stream in 2020

Kincardine offshore wind farm – overview (2019)

- Peak generation capacity: 50MW.
- Turbine 1 (2MW) is already in place.
- The wind farm has a dedicated sub-station situated next to the ACHES site (see below).
- A further 6 x 8.4MW turbines are due to be installed (the first of the larger machines is scheduled to be installed in May 2020).



Total addressable demand and annual sales assumptions and data sources

Vehicle Type		No. of vehicles	Source/Assumptions	Annual sales (veh/year)	Notes
Buses	Aberdeen	187	First, Stagecoach discussions. Breakdown for Aberdeen.	12-16	Assumed 12-15 years lifetime of buses noted by Stagecoach
Coaches		33		2-3	
Buses	Cities within 100 miles of Aberdeen	283	Estimated by population in city compared to Aberdeen, to be updated with Council discussions. Assume FC buses only operate from cities due to infrastructure requirements.	19-24	
Coaches		50		2-4	
Trains		40	Discussion with Scotrail, number of trains on the highland lines that could be well suited to hydrogen.	n/a	
HGVs	Local (Private)	217	Estimate based upon company fleet sizes and primary journey type in ‘An Initial Assessment of Freight in Aberdeen & Aberdeenshire – Nestrans 2018’.	16-31	Assumed 7-14% of fleet replaced each year i.e. 10 year lifetime (Colin Lawson replace 5-10/70 each year)
	Local (Public)	tbd		tbc	
Cars	Taxi+PVH	1,142	Transport Scotland 2018 statistics for vehicles registered in Aberdeen City https://www.transport.gov.scot/publication/scottish-transport-statistics-no-37-2018-edition/sct01193326941-04/#tb14	90	DfT data for Scotland (veh0204 and veh0254) shows new car registrations is 8% of the total registered vehicles. It is assumed that the same holds true for vans.
	Company	4,400		330	
	Private	139,300		6800	
Vans	Company	4,275	Transport Scotland 2018 LCVs registered in Aberdeen City. GB average from DfT data (veh0402) is used for LCV breakdown of company vs. private ownership	320	
	Private	4,725		360	

Assumptions on vehicle H₂ usage

Vehicle Type		H ₂ Usage (kg/day/vehicle)	Annual mileage (km/year)	Notes	H ₂ consumption (kg H ₂ /km)	Notes
Buses		17.5	80,000	Transport Scotland: in 2018, 4,100 buses travelled 330 million km	0.08	JIVE project targets <0.09
Trains		350	180,000	Scotrail assuming 100-120,000 miles/year (270-330 miles/day) for highland lines	0.7	Discussion with Alstom: 10 trains use 3-4 tonnes/day (travelling 450 miles per train per day).
HGVs	Local (Private)	8	35,000	30-40,000 Colin Lawson discussion	0.085	Hyundai truck quoted value
	Local (Public)	8	35,000	30-40,000 Colin Lawson discussion		
Cars	Taxi+PVH	1.1	40,000	Predicted usage for ZEFER vehicles	0.01	Mirai quoted consumption 0.76 kg/km H2ME data 0.012 kg/km
	Company	0.2	9,000	Current H ₂ vehicle in Aberdeen (CW Car Club)		
	Private	0.2				
Vans	Company	0.34	24,000	H2ME Symbio van data	0.005	H2ME Symbio range extended van data
	Private	0.34				

Other potential sources of demand

Demand	Notes on potential demand and requirements for uptake
FC ships	Are a potentially high demand application, for example the HySeas III project would use 250 kg/day of H ₂ . However, technologies for ships are in prototype stages. To realise this demand in Aberdeen, initial successful trials will need to have occurred with the operation of FC ships and refuelling at a harbour.
Materials handling vehicles	Over 20,000 fuel cell MHVs are deployed in America, however only c.100 vehicles are deployed in Europe. We are yet to identify a large fleet of material handling vehicles suitable for conversion to hydrogen (e.g. forklifts) in the Aberdeen area.
Gas grid injection	Capital cost of hydrogen pipelines is high, and the cost of natural gas is low, so hydrogen generated from renewables is not expected to be competitive for injection into the gas grid. If this occurs, it will likely have its own large scale hydrogen production (e.g. Acorn).
Multi-storey car parks and charging	We are awaiting discussions with Siemens, but this is low TRL, and so it is anticipated only trials will happen in the near-term.
Stationary fuel cells for CHP	The delivery costs of hydrogen mean that the widescale adoption of CHP for heating and electricity supply to small-scale users will not be feasible unless H ₂ pipelines are present (as a result of large scale conversion of natural gas to heating). This is hence very uncertain. Large scale demos could happen, for example the 1.4MW _e fuel cell suggested at TECA could have a maximum usage of c. 70 kg/hr ¹

¹Assuming runs at full power all day and FC efficiency of 55% conversion of H₂ (HHV) to electricity

H₂ vehicle demand development

Vehicle type	For reference	
	Total number in fleet	Annual sales (Aberdeen)
Buses – Aberdeen	187	12-16
Buses – cities within 100 miles	283	19-24
Local HGVs (Private)	217	16-31
Local HGVs (Public)	tbc	tbc
Trains	n/a	n/a
Company cars	4,400	330
Company vans	4,275	320
Taxis	1,142	90
Private cars	89,700	6,800
Private vans	4,725	360

Economic impact assumptions: FC vehicle capex assumptions (1/3)

- The capital expenditure on H₂ vehicles deployed is assumed to initially go to supply chains outside Scotland.
 - HV systems (a Scottish company planning to manufacture fuel cell vans and HGVs) and Riversimple (a Welsh company manufacturing small FC cars) are notable exceptions.
 - They are however currently small and so no assumptions are made on their sales.
- A number of UK companies that retrofit vehicles to run on hydrogen also exist. These costs of retrofitting have a high potential to be brought to Aberdeen.
 - e.g. Arcola is opening a facility in Liverpool to support the deployment of FC buses in the city.

Vehicle type	UK-based retrofitter
HGV and RCVs	ULEMCo
Boats	CMB Revolve Technologies
Trains	Vivarail
Buses (+any vehicle)	Arcola ¹
Cars	None
Vans	ULEMCo

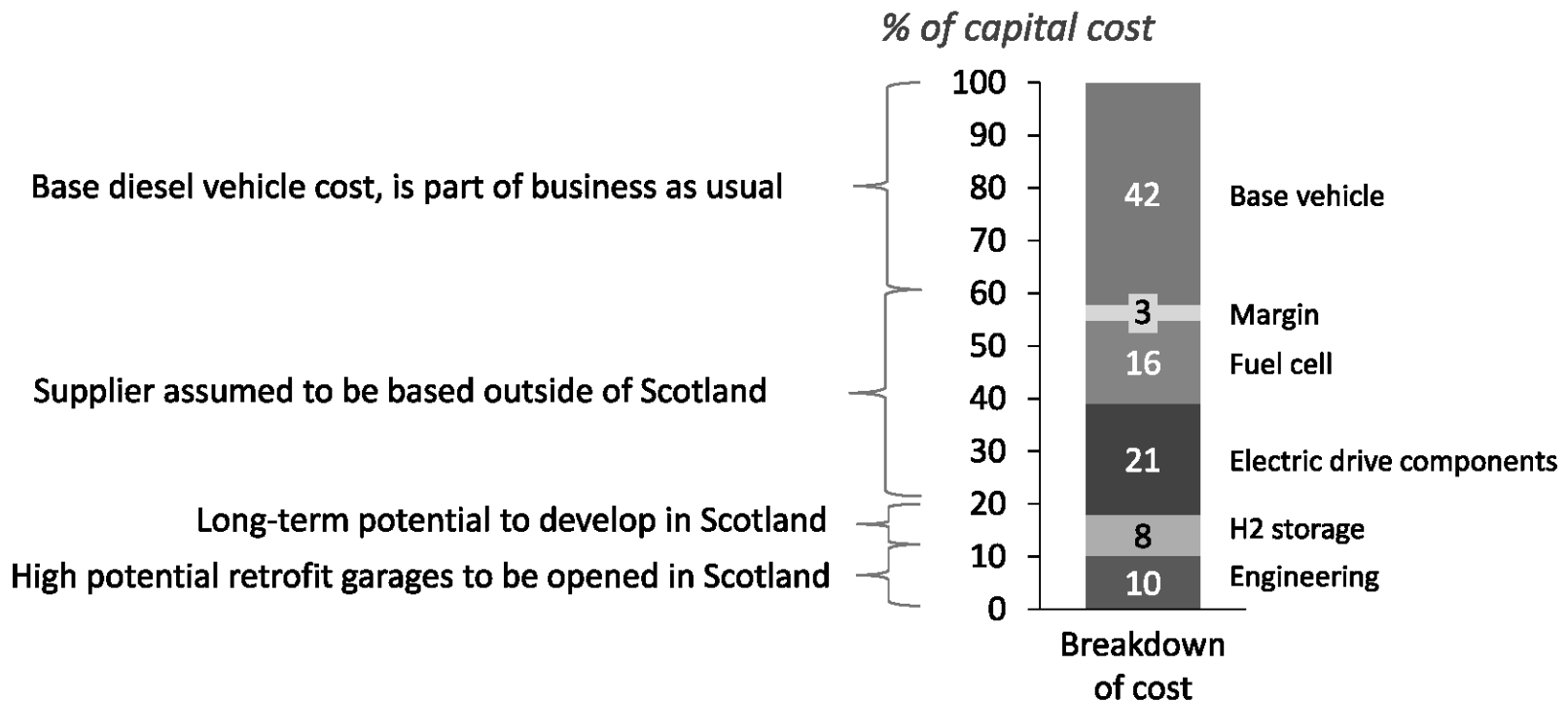
¹Arcola retrofit the buses of ADL, a Scottish company. The base bus is considered business as usual with no net GVA, so that additional GVA arises for the UK company, Arcola.

Economic impact assumptions: FC vehicles (2/3)

- For the retrofitted vehicles outlined on the previous page, the indicative breakdown below is assumed.
- Note ULEMCo differ in their costs, as they produce dual fuel vehicles. They retrofit vehicles for c.£35k. These costs are assumed to be 50/50 parts (non-Scotland) and labour (potential to be local).

Assumption on capital investment of GVA

Indicative breakdown of FC bus capital costs



Economic impact assumptions: FC vehicles (3/3)

- The maintenance costs of the FC vehicles displace the maintenance of petrol and diesel vehicles and so are not considered as adding net GVA.
- The table outlines the assumed share of costs that could be attributed to the Scottish economy.

Vehicle type	Cost component	Assumption	Broad industrial description	SIC code
All	Opex – maintenance	No additional GVA to business as usual	n/a	n/a
All	H ₂ storage	In the future this cost could be retained if manufacturing brought to Scotland, this is c. 8% of capital costs	Manufacture of machinery and equipment	28
Cars, Vans	Capex	No expenditure in Scottish supply chain	n/a	n/a
Buses	Capex – retrofitting	Initially no GVA in Scotland, but from 2023 potential for 10% of capital costs	Motor vehicles	29
Trains	Capex – retrofitting	Potential for retrofit work in Scotland, assumed 10% of capital costs to stay in Scotland and train cost of £5m	Motor vehicles	29
Municipal HGVs	Capex – retrofitting	Initially no GVA, from 2023 potential for 17.5k per vehicle	Motor vehicles	29
HGVs	Capex – retrofitting	Assumed larger manufacturer (e.g. IVECO, Scania). Initial no work in Scotland but potential for 10% of capital costs from 2025	Motor vehicles	29

Economic impact assumptions: Hydrogen refuelling station (1/2)

- An indicative breakdown of the costs for a refuelling station, alongside the potential for a Scottish supply chain to contribute is shown below.
 - Note: Civil costs are site dependent and component costs are dependent upon levels of redundancy required.

Assumption on capital investment of GVA

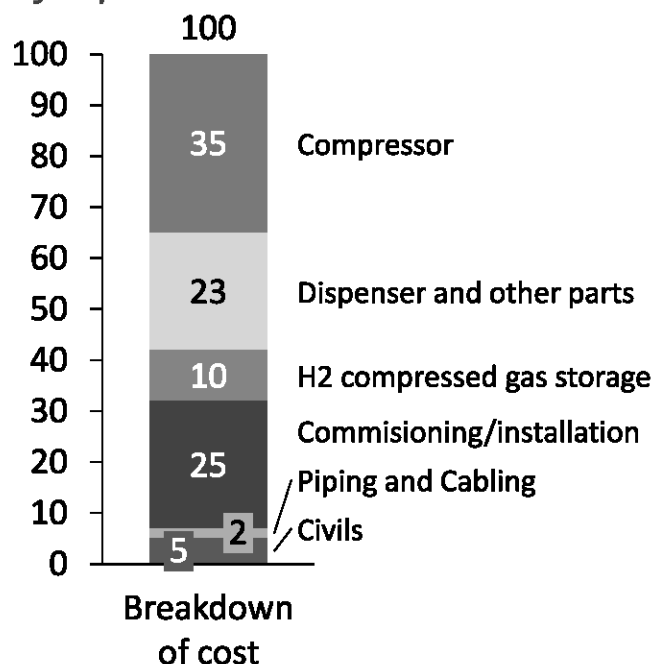
Components manufactured elsewhere in the UK, but could be brought to Scotland

High potential for Scottish supply chain
Commissioning staff currently employed at company locations in the UK, but could be brought to Scotland with sufficient demand

Use local companies – note that this is site dependent

Breakdown of HRS capital costs

% of capital cost



Economic impact assumptions: Hydrogen refuelling station (2/2)

- The assumptions regarding the breakdown of HRS operating costs are listed below.

Cost component	Assumption	Broad industrial description	SIC code
Opex – O&M: labour	Assumed staff employed are local.	Repair and maintenance	33
Opex – O&M: parts	Assumed to be supplied by Scottish manufacturers, which is the case with the current refuelling stations	Manufacture of machinery and equipment	28
Opex – operator margin + land rental	Assumed company is based outside of Scotland and so margin does not add GVA.	n/a	n/a
Compressor, dispenser and compressed gas storage	Cost treated on a refuelling station by refuelling station basis. Assumed to be manufactured outside of Scotland	Manufacture of machinery and equipment	28
Commissioning and installation	Initially assumed to be outside of Scotland, with high potential from 2023 to use oil and gas expertise Scottish employees.	Construction	41-43
Civils	Assumed to be carried out by local companies.	Construction	41-43
Piping, cabling	Assumed to be provided by local companies, with transfer of knowledge from oil and gas sector	Manufacture of basic metals/Manufacture of electrical equipment	24,27

Economic impact assumptions: Electrolyser – capital expenditure

- A capital cost indicative breakdown is displayed below:
 - The exact breakdown of the costs is dependent upon the electrolyser itself and nature of the construction/upgrade
 - The costs of each upgrade are therefore separately considered

Assumption on capital investment of GVA

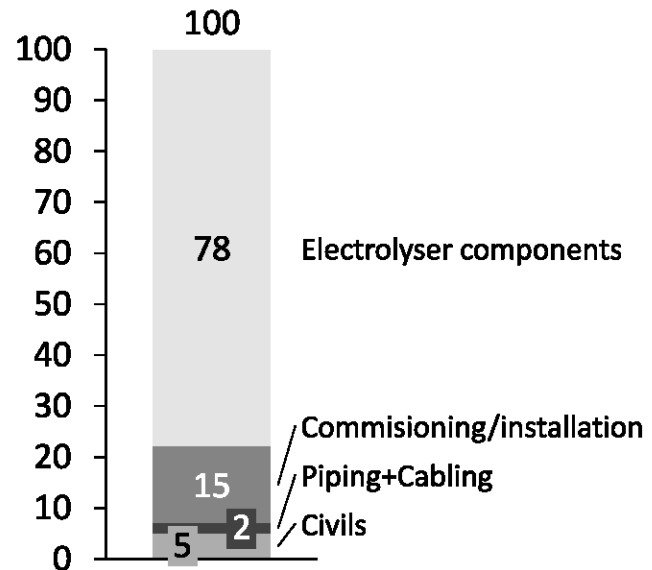
Components manufactured elsewhere in the UK or abroad

Initially goes to UK suppliers, but with potential to use Scottish supply chain

Use local companies

Breakdown of electrolyser costs

% of capital cost



Breakdown
of cost

Economic impact assumptions: Electrolyser – operation

- A key variable operating cost of the electrolyser is the electricity:
 - This is treated as additional capacity that requires operation and maintenance.
 - The Beatrice offshore wind farm (BOW)¹ (588 MW) is found to provide £34 million/year (370 jobs) in GVA to Scotland (£58k/year/MW, 0.62 jobs/MW) on the basis of maintenance & other operating costs.
 - In the short term it is assumed that additional offshore wind generation is not constructed.

Cost component	Assumption	Broad industrial description	SIC code
Opex – electricity from renewables	Facilitates additional utilisation of existing wind farms; adds an additional £58k/year in annual GVA per MW of electrolyser capacity	n/a	n/a
Opex – water and sewerage	Expenditure is within Scotland from the start of the project	Water and sewerage	36,37
Opex – grid electricity	Assumed within Scotland from project start, standard multipliers used	Electricity generation	35.1
Opex – O&M	Currently assumed 50/50 split: cost of parts (UK) and labour (local)	Repair and maintenance	33
Capex – electrolyser components	Assumed to be manufactured outside of Scotland	Manufacture of machinery and equipment	28
Compressed gas, commissioning, civils and piping assumptions as for the refuelling station			

Economic impact assumptions: Tube trailer

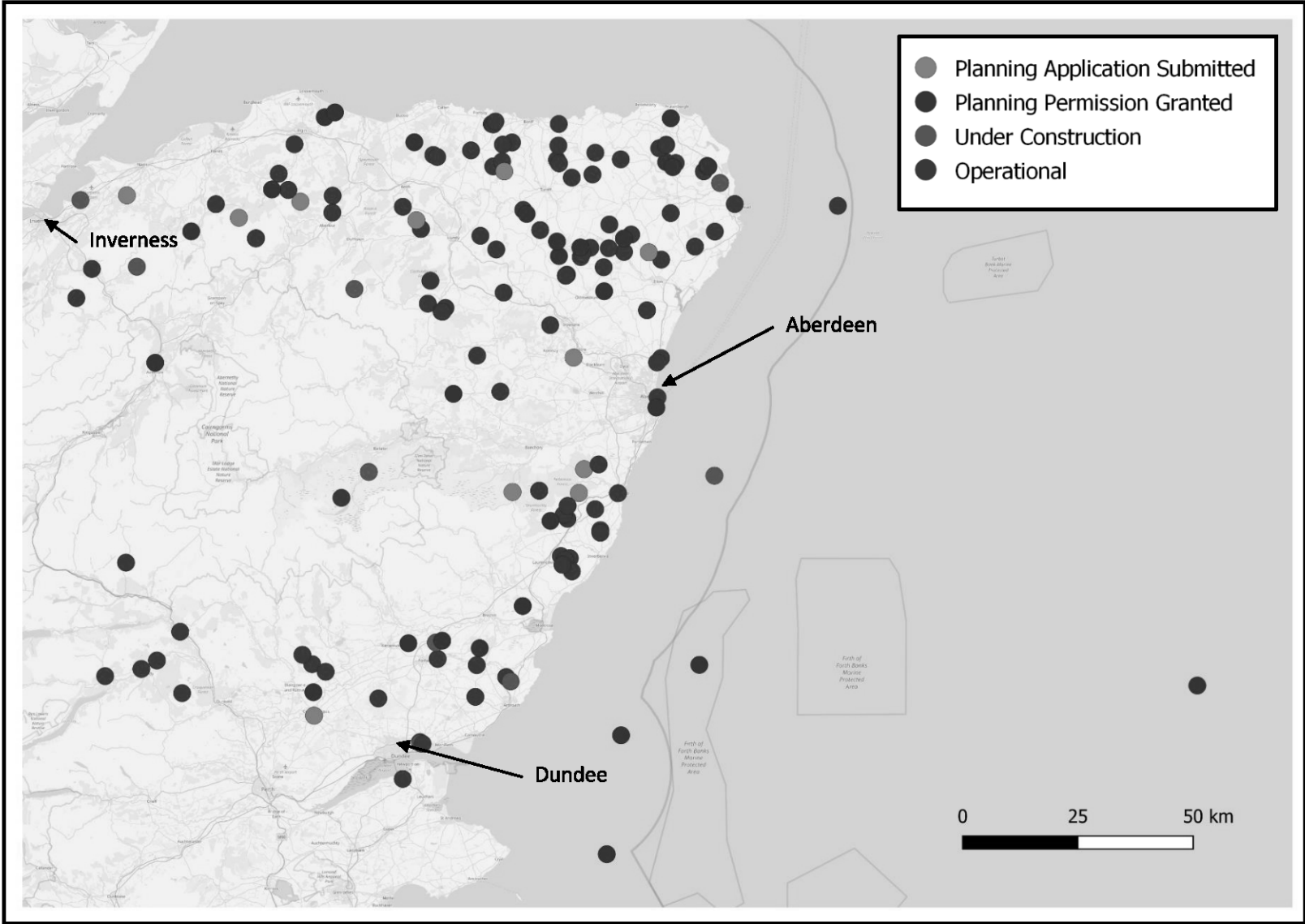
- Hydrogen distribution is assumed to be additional to petrol/diesel distribution:
 - Further details on the assumptions and relevant SIC codes are given below.

Cost component	Assumption	Broad industrial description	SIC code
Tube trailer capex	Assumed to be manufactured outside Scotland, with the potential for wider manufacture in the UK.	Manufacture of machinery and equipment	28
Tube trailer opex – driver costs	Assumed to be carried out by local employees.	Other land transport	49.3-5
Tube trailer opex – fuel	Diesel costs are not considered in GVA analysis, as diesel is business as usual. The tube trailer fuel is considered as an additional potential H ₂ demand	n/a	n/a
Tube trailer opex – O&M - parts	Assumed to be provided by parts suppliers in Scotland	Manufacture of machinery and equipment	28
Tube trailer opex – labour	Assumed to be carried out by mechanics in Scotland.	Repair and maintenance	33

Economic impact assumptions: Project management and consortium

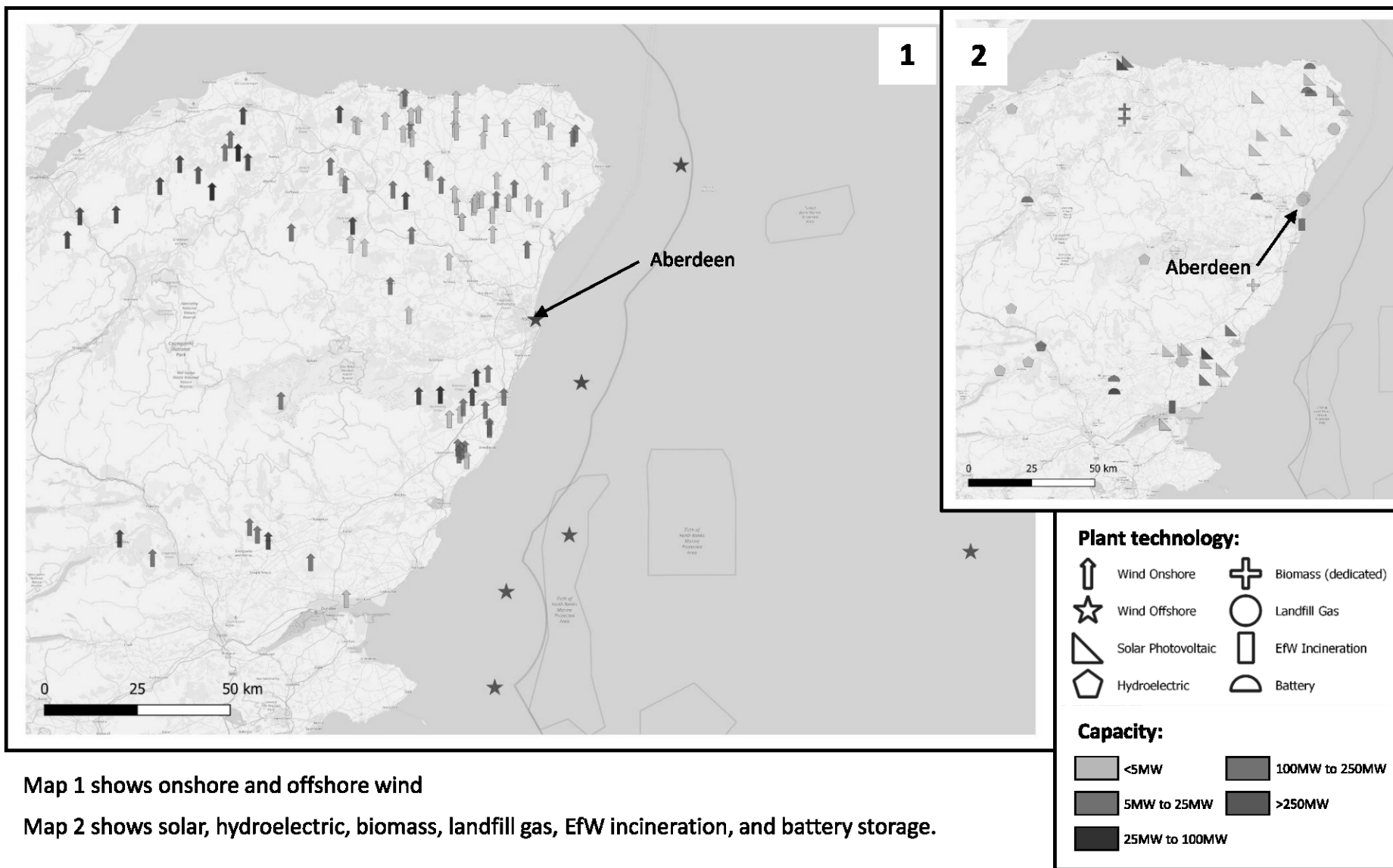
- It is assumed that a consortium of downstream service providers and OEMs is put together as part of the hydrogen hub project, this provides employment in Aberdeen. The employment provided by this is estimated below:
 - The consortium is assumed to include a minimum of one company covering each area required: Hydrogen production, hydrogen refuelling stations, hydrogen delivery, renewable wind generation and an OEM of vehicles is considered.
 - For the basic analysis it is assumed that the equivalent of one FTE is provided for each company, and an additional employee (either from ACC or one of the companies) for the overall project development.
 - This leads to **6 direct** full time employees for the project management in Aberdeen. These employees are considered for the GVA analysis to require a salary of £40k each annually.
- The SIC code used for this work is 70 - Services of head offices; management consulting services.

Renewable energy plants by development stage



Renewable energy plants: operational, under construction, and planned

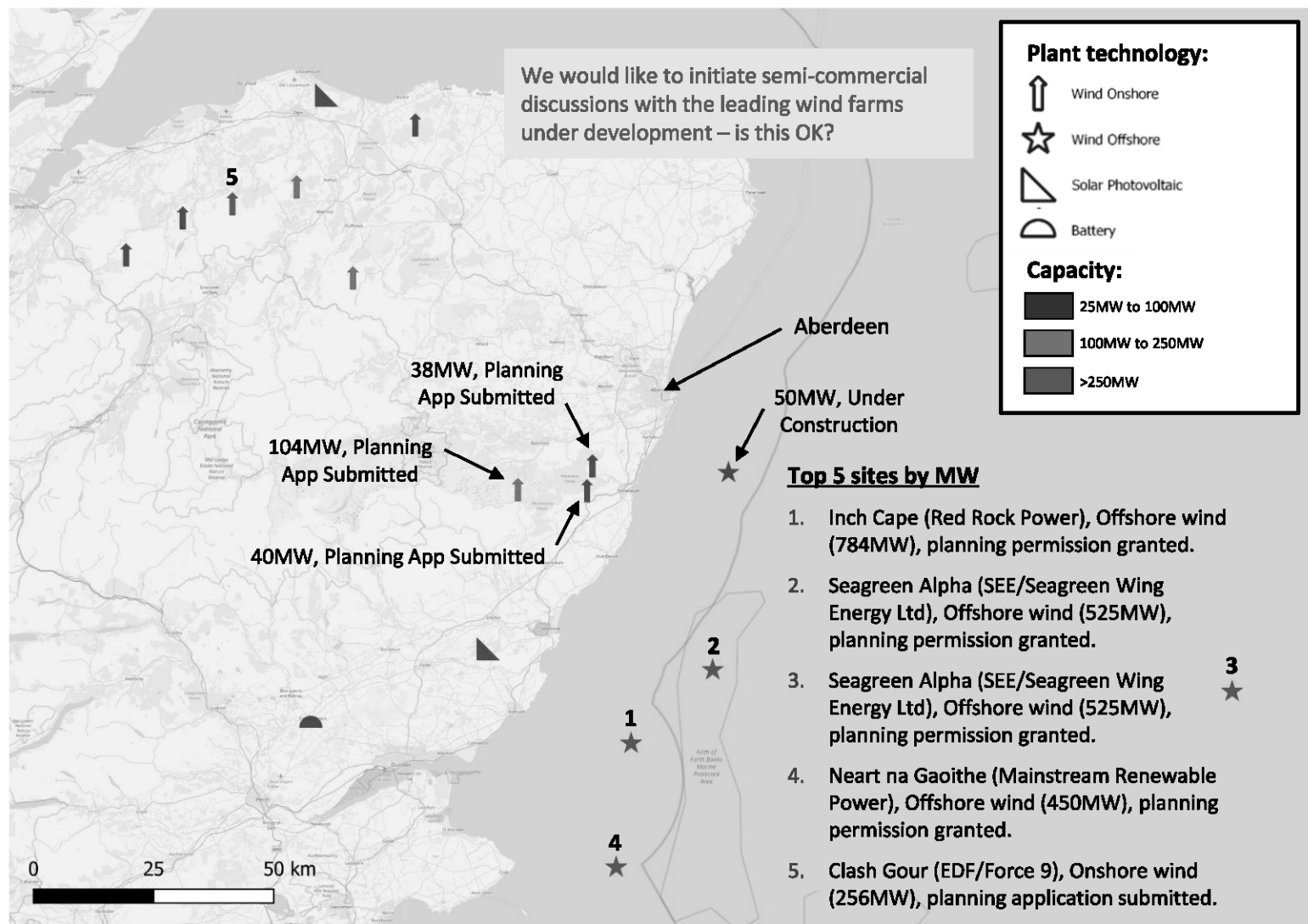
- by technology and installed capacity



Map 1 shows onshore and offshore wind

Map 2 shows solar, hydroelectric, biomass, landfill gas, EfW incineration, and battery storage.

Renewable energy plants >25MW: under construction, and planned - by technology and installed capacity



There has been a very high level of interest in the project from a wide range of potential infrastructure suppliers / owners / operators

Insights from stakeholder discussions – supply chain organisations

- All the potential suppliers / owners / operators of hydrogen production, distribution, and dispensing equipment engaged with as part of this study expressed interest in the project and a willingness to consider contributing towards delivering the vision.
- Some challenged the in-going assumption that it is necessary to aim for hydrogen prices that give fuel cost parity (belief that customers should be willing (or forced) to pay more for ZE solutions).
- Others suggested that capital subsidies do help the business case for private sector investment, but that on-going (opex) support may also be needed (“most hydrogen business cases are killed by opex rather than by capex”).
- There was at least one view that the public sector will need to continue to have “skin in the game” for many years.
- Most potential suppliers appear to place very little (or no) value on possible growth in hydrogen demands – certainty is needed.
- Some cautioned against developing a business case with overly optimistic assumptions (e.g. on the future prices of green electricity or income from RTFCs).
- The need to select partners with the experience and expertise required to operate hydrogen infrastructure in a safe and reliable manner was also raised (beware of suppliers over-promising and under-delivering).

A formal joint venture is a potential delivery model

Joint ventures – overview

- The main rationale for forming JVs is where organisations have complementary skills (and can work together to get synergies) and for mitigating exposure and risk.
- In the context of a hydrogen hub in Aberdeen, a JV could comprise vehicle suppliers*, infrastructure suppliers / operators, and public sector representatives.
- It is important to be clear on the responsibilities and liabilities of each partner in the JV. There would need to be exit clauses and penalties for parties that fail to meet their obligations. It is possible to have the option for new partners to join JVs.
- One option could be to set up a JV with an agreed level of subsidy from the public sector but with review points within the contract where the subsidy would be adjusted / eliminated depending on certain factors (e.g. demand). Thus there would be an incentive for the public sector to help increase demands to the point where subsidies are no longer necessary.
- JVs can take years to negotiate and the more parties involved the more complex this can become. On the other hand, risks can be spread more thinly with more organisations involved.
- Another advantage of a JV approach is that the option to influence national policy once it is established. One view is that for Aberdeen to avoid becoming an island (wrt H₂), scale up in the market is needed and this will only come about via changes to policy at a national level. In theory it is possible for JVs to influence such changes (perhaps more effectively than the companies that form the JV).
- While a JV could be a suitable delivery model, identifying an investable business case for a hydrogen hub remains the priority.

* The vehicle suppliers' main role would be to guarantee a certain level of demand for hydrogen. Vehicle operators could also take this role but it is unlikely that fleet operators would be willing to be part of such a joint venture.

Contents

Context to the Aberdeen Hydrogen Supply Hub

Assessment of hydrogen demand

Hydrogen supply options

Infrastructure deployment and siting

Business case assessment

Funding, financing and investment requirements

Economic benefits

Environmental benefits

Action plan and milestones for delivering the ten-year vision

Appendix 1 – Action Plan for implementation

Appendix 2 – Strategy for existing assets

Appendix 3 – Assumptions and extracts from stakeholder engagement

Appendix 4 – Market readiness

Appendix 4: Market readiness

The following slides show data on the following commercial readiness factors for different transport modes:

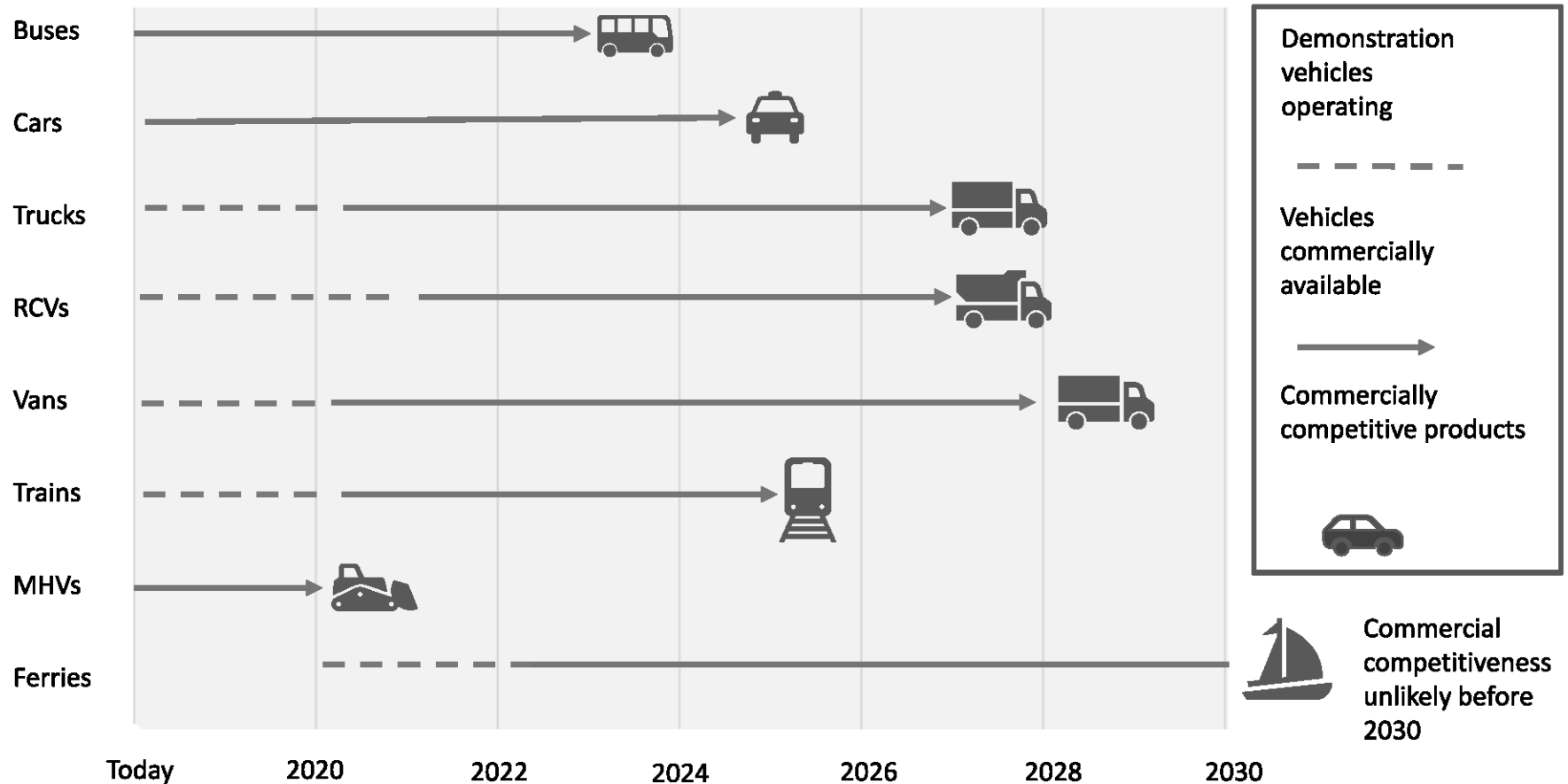
- Current availability of hydrogen vehicles or suitable conversion technologies, and expected release dates for future models.
- Evidence of local appetite for adoption (including information from discussions with potential end users and/or technology suppliers).
- Vehicle cost premiums (representing the approximate level of funding/subsidy needed to make vehicles available at an attractive price) and fuel cost premiums; indicative total cost of ownership analysis is shown for different vehicle types to represent these two factors.
- This data supports the summary table in the main report, which identifies the relative readiness of different vehicle types and informs their inclusion in the demand growth scenario.

Potential adoption by 2030 is informed by the relative commercial readiness of different demand sectors

- The table below provides an indication of the relative levels of commercial readiness for different vehicle types according to the factors set out above. Supporting data on the different readiness factors is shown in the appendix (Market readiness), with a summary of availability and fuel cost factors provided in the following pages.

Vehicle type	Availability	Local appetite	Vehicle cost	Fuel cost	Relative readiness
Fuel cell bus					
Fuel cell car					
Dual fuel RCV/HGV					
Fuel cell RCV/HGV					
Fuel cell van					
Fuel cell train					
Dual fuel boat					
Commercial readiness level →	Highest				Lowest

Multiple hydrogen transport modes could be commercially competitive by 2030, but adoption in the early 2020s is most likely for cars and buses














Note: Commercially competitive products refers to hydrogen transport modes which are competitive with other forms of low/zero emission transport. They may still have a small total cost of ownership premium compared to conventional drive trains.

The next few pages provide more detail of the timelines for availability of different hydrogen vehicles and expected milestones for commercialisation.

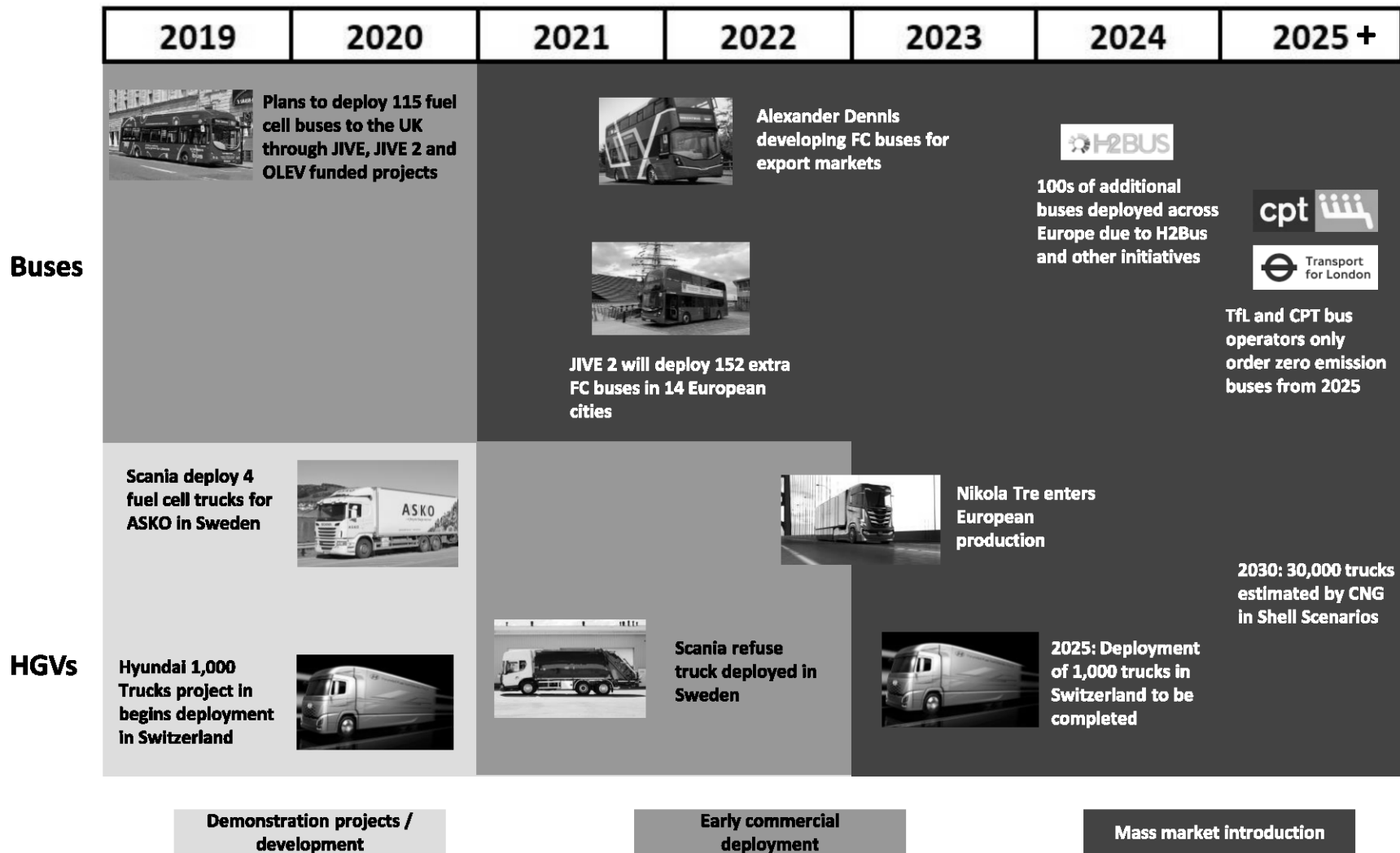
Hydrogen cars could start to be introduced to mass markets in the early 2020s, with vans to follow a couple of years later

Timeline of availability and key national and international milestones for hydrogen cars and vans

	2019	2020	2021	2022	2023	2024	2025 +
Cars	 <p>Deployment begins for 1st gen Toyota Mirai and Hyundai ix35</p>	 <p>Hyundai Nexo starts European deployment</p>	 <p>2nd gen Toyota Mirai begins production of ~30,000 FCEVs per year worldwide</p>	  <p>A range of other cars are being deployed worldwide, likely to come to the UK with the right support regime. Audi, BMW, Honda Daimler, PSA and many Chinese brands all have hydrogen plans in the early 2020s</p>			<p>2025: Planned deployment of 3rd generation mass production Mirai</p>  <p>2025: UK H₂ Mobility target 6,000 FCEVs</p>  <p>Hydrogen Europe aim for 5 million FCEVs across Europe by 2030</p>
	 <p>100s Symbio/Renault Kangoos operating across Europe in 2019</p>	 <p>Renault MASTER ZE Hydrogen available from 2020</p>	<p>Numerous Chinese initiatives to develop FC vans (e.g. SAIC), likely available in Europe in early 2020s</p> <p>787 Symbio/Renault Kangoos planned for EU deployment</p> 	 <p>StreetScooter to produce over 400 Work L vans for DHL and Innogy in Germany</p>			
Vans							
	Demonstration projects / development		Early commercial deployment		Mass market introduction		

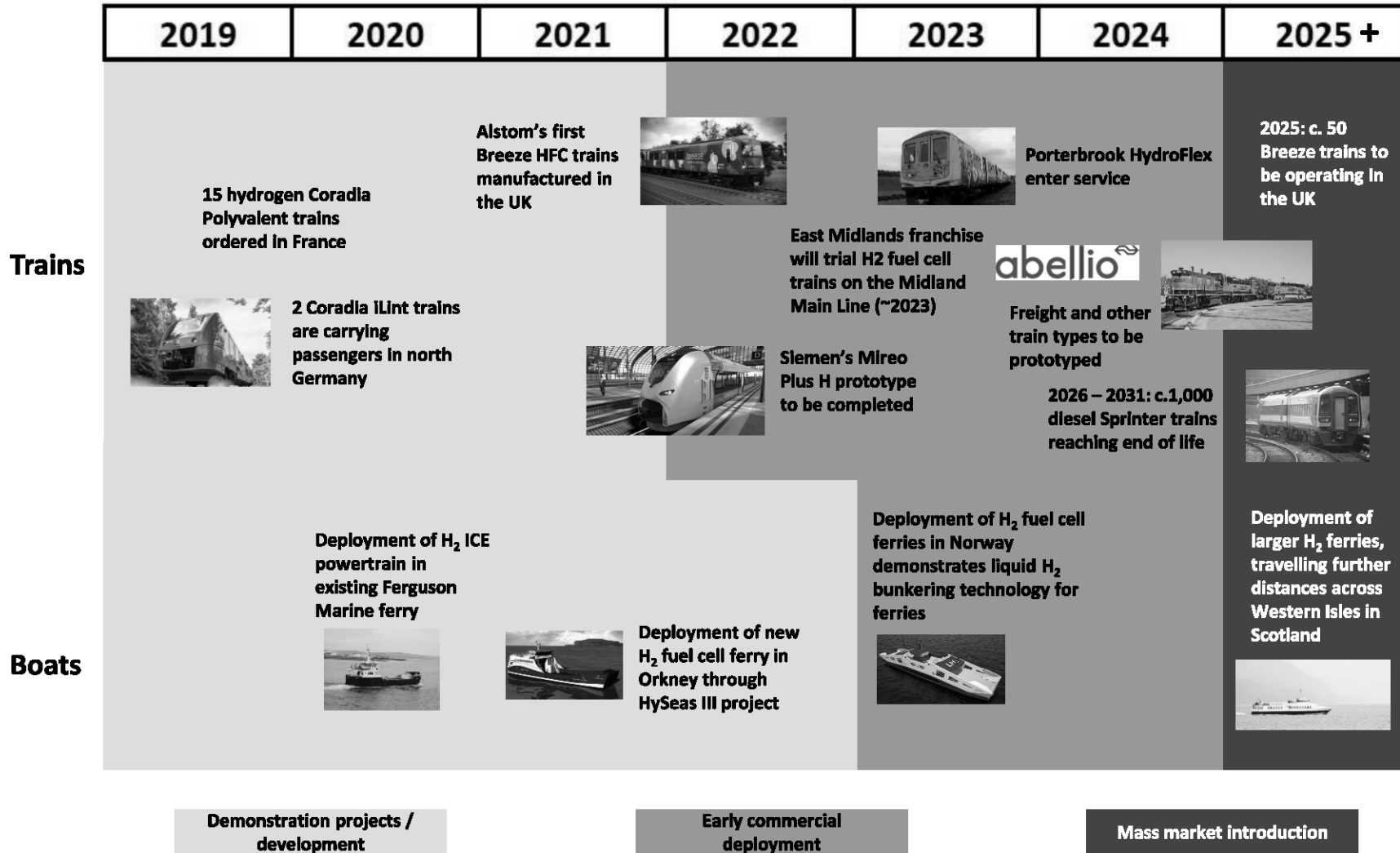
100s of FC buses could be deployed in the UK in the early 2020s, while it is likely that hydrogen HGVs will still be at the trial stage

Timeline of availability and key national and international milestones for hydrogen buses and HGVs



Demonstration of hydrogen trains and boats in the UK could be envisaged in the early 2020s

Timeline of availability and key national and international milestones for hydrogen trains and boats



Most global car OEMs are working on FCEVs, although as of 2018 few have brought vehicles to market



- ix35 Fuel Cell went into production in 2013, hundreds deployed in selected markets globally.
- Nexo launched in 2018.



- Mirai went into production in 2014, c. 5,300 sold globally by Dec. 2017, mostly in N. America (2,900) and Japan (2,100).
- Plans to increase production to 30,000/yr from 2020 (up from c.3,000/yr). Lexus FC car due to be on sale by 2020.



- FCX Clarity produced in small numbers from 2008.
- Replaced by the Honda Clarity – deliveries since 2015/16.

DAIMLER



- First F-Cell based on A Class (c.2002), followed by B-Class F-Cell (c.200 built).
- Latest model is the GLC F-Cell, being produced in limited numbers.



- Pre-production FCEV demonstrated in the HyFIVE project (demo vehicle based on 5 Series Gran Turismo).
- Commercial vehicles expected from early to mid-2020s.
- Many other global OEMs have developed and demonstrated prototype FCEVs – e.g. Audi demonstrated the h-tron Quattro concept FCEV at the North American Auto Show in 2016 and announced it will lead VW Group's FCEV development efforts.

Other car OEMs

In addition to the global automotive OEMs, other innovative companies are developing FCEVs

- **Riversimple** is developing a new microcar concept for leased mobility, based on providing mobility to drivers commuting into towns and cities.
- **Arcola Energy** have a number of vehicle development programmes including a new fuel cell powered van (not yet demonstrated on the road).
- **Microcab** has spent a number of years developing a new microcar concept, which is being produced in small batch runs of vehicles.
- **ULEMCo** is proposing a range extended version of the Nissan ENV-200 (first deployment in 2018).



Riversimple Rasa



Microcab



*ULEMCo Range
extender for ENV-200*

Several fuel cell electric vans have been developed but few are currently available on the market

- **Kangoo ZE RE Renault & Symbio Fcell** – a battery electric van fitted with a fuel cell which can extend its range from c. 100 km to c. 300 km. Low hundreds deployed under funded projects across Europe (sold by Symbio). In October 2019, Renault announced the launch of the **Kangoo ZE Hydrogen** for the end of 2019, and the **Master ZE Hydrogen** for mid-2020.
- **ULEMCo Hydrogen Dual Fuel Van – hydrogen combustion** – ULEMCo carries out retrofit conversions on combustion engine vehicles including vans, heavy duty vehicles (e.g. refuse collection trucks), and ships.
- **Streetscooter** – DHL-owned company building c.100 Work L FC vans by 2020.
- **HVSystems fuel cell vans** – Glasgow-based HVSystems is seeking to “revolutionise the transportation industry” by offering new fuel cell vans and trucks. Pre-orders are now being taken.
- **Hyundai H350 Fuel Cell Concept** – revealed at the IAA in Hannover (2016), a FC van offering c.260 mile range. Not yet available for purchase.
- **VW Crafter HyMotion** – concept vehicle based on the e-Crafter (launched by VW in 2016) that offers a range of c.300 miles (compared to c.100 miles for the electric only version). Not yet available for purchase.



Light duty hydrogen vehicles have been targeted at high usage applications and captive vehicle fleets

- There has been limited uptake of cars and vans so far, with c. 100–200 passenger cars and c.50 vans deployed on UK roads.
- The limited uptake is due in part to the sparse refuelling infrastructure, with 10 publicly accessible 700 bar hydrogen refuelling stations in the UK and current passenger cars priced at c.£66,000.
- Existing vehicle deployments have been targeted at high mileage applications (e.g. taxi fleets and police vehicles). The vehicles have been deployed through funded projects alongside hydrogen refuelling stations, providing a captive fleet (and hydrogen demand) for the station.
- Toyota is developing a next generation fuel cell car (expected in the early 2020s). The production scale of the new model will be increased an order of magnitude relative to the Mirai, which is expected to reduce manufacturing costs per vehicle and lower the price of the vehicle to the consumer.
- Based on current funded projects there are expected to be at least 200 cars on the road by the end of 2020.
- Discussions from industry at UK H₂Mobility have targeted c.6,000 fuel cell vehicles in the UK by 2025, the majority of these are expected to be fuel cell cars, with the main manufacturers targeting to sell c.500 cars/year to 2025.

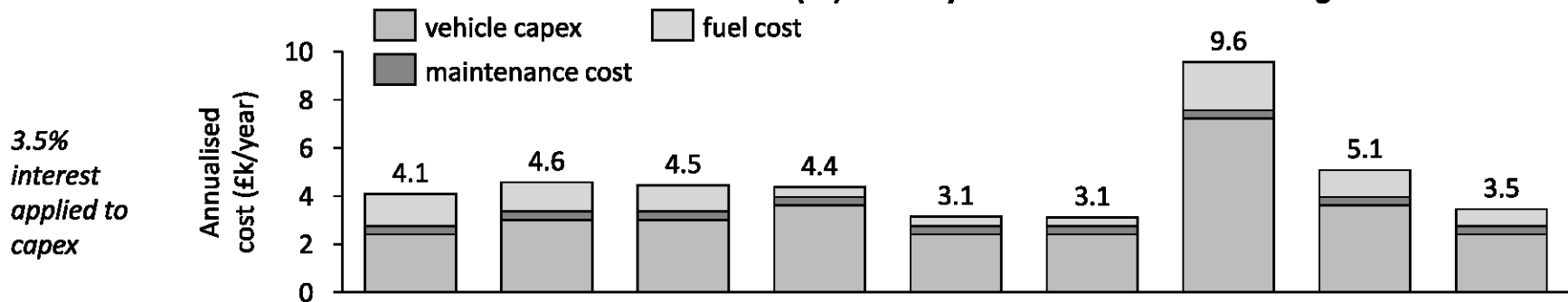


Cost reductions to FCEVs need to be accompanied by low hydrogen prices for cost competitiveness with other technologies

Light duty vehicles

- Fuel cell passenger cars are expected to become competitive with (taxed) diesel on a total cost basis from 2025, with the scale-up of manufacturing of fuel cell cars and increased competition between vehicle manufacturers expected to bring savings in the vehicle capital costs.
- Battery electric cars are likely to be the most cost-effective technology by 2025, with the low fuel cost being a key advantage in cost terms. By 2025, diesel cars are expected to be more costly than electric cars due to the cost of the successive improvements to diesel efficiency required to meet regulatory pressure.
- Fuel cell cars can offer several key advantages: shorter refuelling times and extended range. However, hydrogen fuel costs will need to be very low to compete with battery electric vehicles on a cost basis.

Annualised vehicle costs (£k) over 10 years for different car technologies



Key assumptions	Diesel			Battery electric			Hydrogen fuel cell electric		
	2020	2025	2030	2020	2025	2030	2020	2025	2030
Capital cost (£000)	£20	£25	£25	£30	£20	£20	£60	£30	£20
Fuel efficiency /100 km	6 L	5.5 L	5 L	17 kWh	16 kWh	15 kWh	1 kg	0.8 kg	0.7 kg
Fuel cost	£1.1/L			£0.12/kWh			£10/kg	£7/kg	£5/kg

Assumptions based on a range of published reports and cost projections (including analysis by Bloomberg, Ricardo AEA, Roland Berger and Element Energy) as well as discussions with manufacturers

Prominent bus manufacturers are seeking to ramp up fuel cell bus production in Europe

Fuel cell (FC) buses have been running in London and Aberdeen (and other European cities) for many years. Further deployments are planned across Europe, e.g. the JIVE and JIVE 2 projects which will deploy 291 FC buses.



- Belgium-based **Van Hool** has delivered c.40 FC buses in Europe and the US and is building at least 50 more.

EvoBus

- Daimler's **EvoBus** has demonstrated >50 FC buses in previous projects and plans to offer FC range extender buses, with deliveries expected from 2021.



- **Solaris** delivered two 18m FC buses to Hamburg and 10 FC range extender trolleybuses to Riga. Now focusing on offering its 12m Urbino FC bus (from 2020).



- **Wrightbus** is offering single deck and double deck FC buses. Prototypes of the latest model are undergoing testing and deliveries to customers are expected from 2020.



- The UK's largest bus builder, **Alexander Dennis**, has developed a prototype double deck FC bus in partnership with **Arcola Energy** and **Warwick Manufacturing Group**.

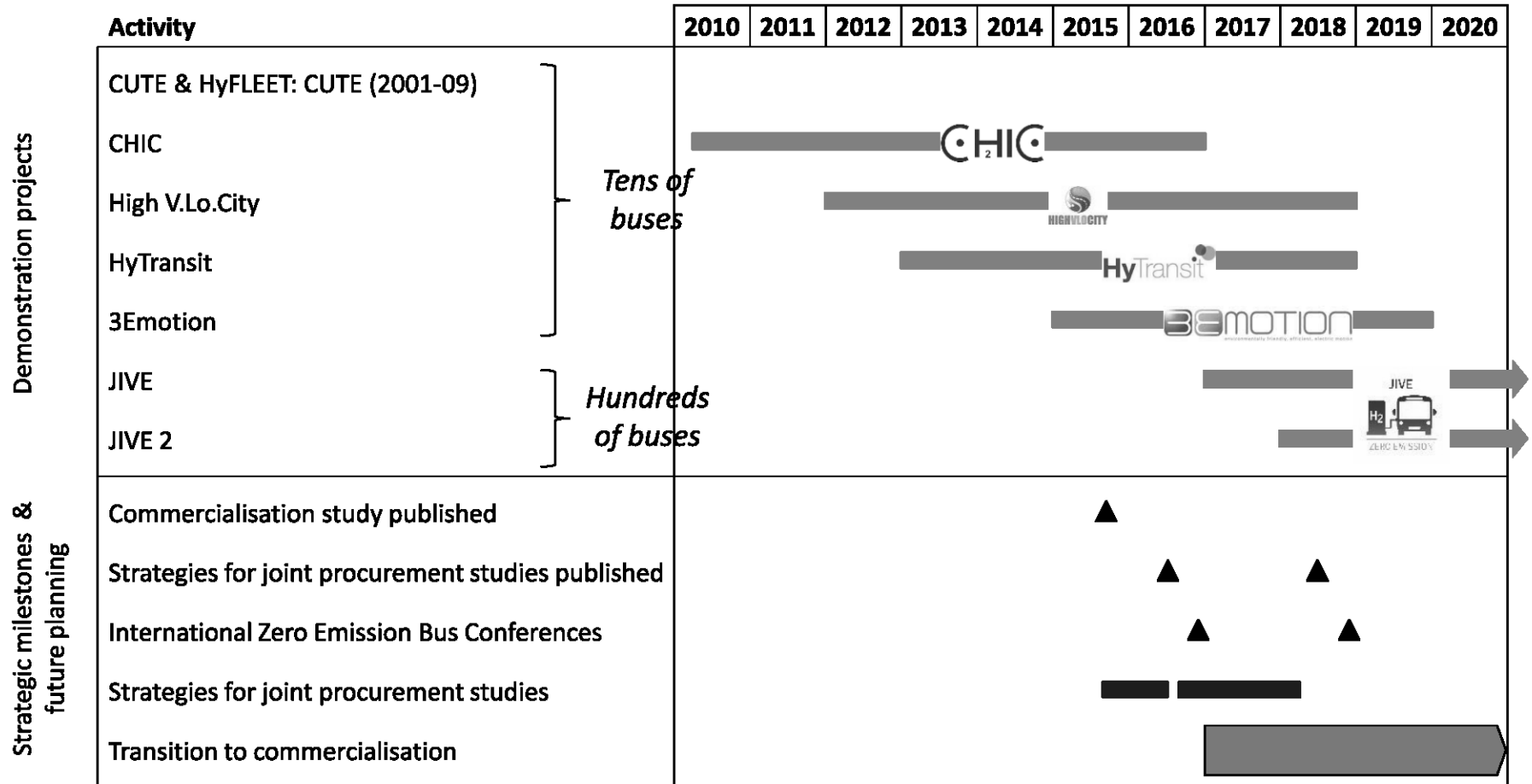


- **VDL** has demonstrated a small number of FC buses and is delivering four vehicles to a Dutch public transport operator as part of the 3Emotion project.



- **Toyota** recently announced plans to supply its H2 technology to **Caetanobus** (Portugal) – prototypes are due in 2019, with scale up in production from the early 2020s.

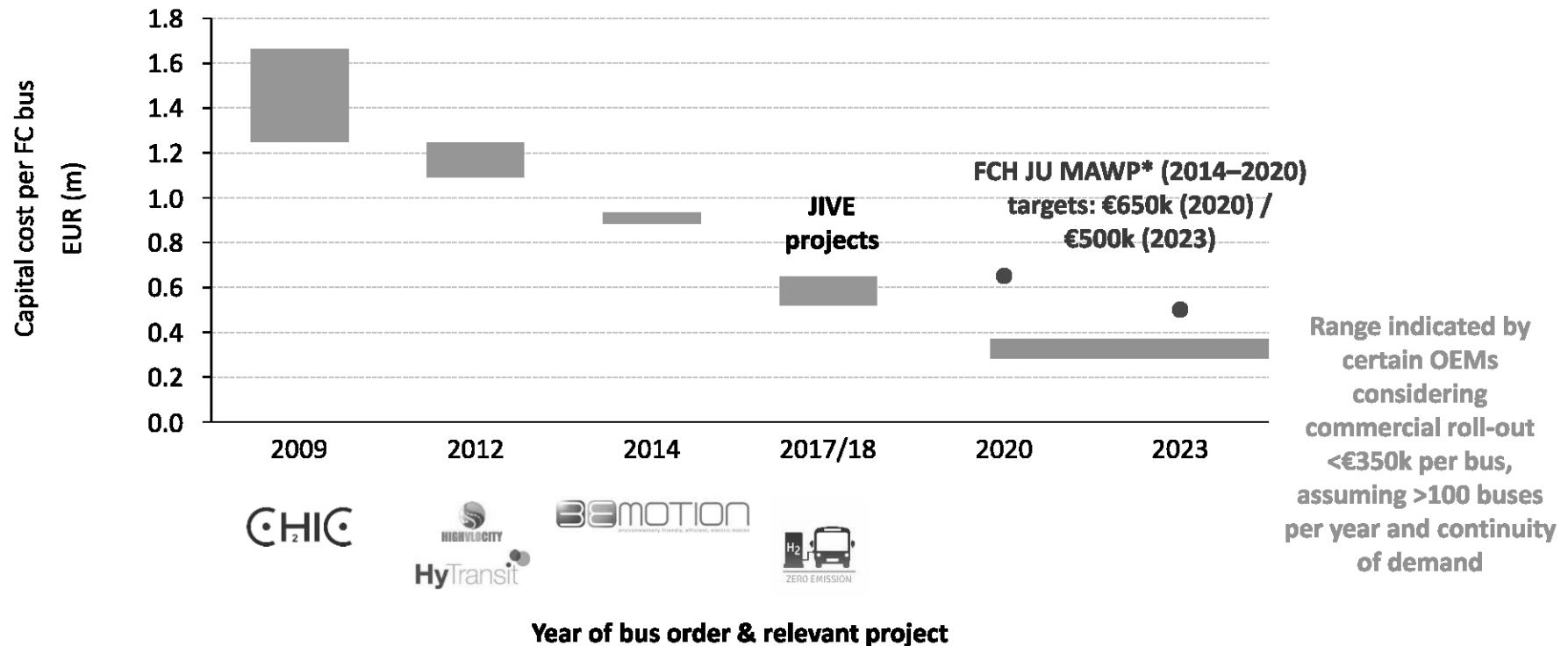
Strategic planning for further deployment of fuel cell buses has been undertaken in parallel to practical demonstration activities



While fuel cell bus costs have fallen significantly in recent years, further reductions will be needed for commercially viable offers

Evolution of fuel cell bus costs in Europe

Capital costs of fuel cell buses ordered in different years (non-articulated single deck buses)



* FCH JU MAWP is the Fuel Cells and Hydrogen Joint Undertaking's Multi-Annual Work Plan, the document that sets out the work plan and strategic targets for the second phase of the FCH JU's programme of research and innovation.

Together, the *JIVE* projects will demonstrate nearly 300 fuel cell buses in over 20 different cities across Europe



Joint Initiative for hydrogen Vehicles across Europe



Objectives

- Deploy large fleets of FC buses and associated refuelling infrastructure
- Achieve a maximum price of €625k for a standard fuel cell bus (JIVE 2)
- Validate large scale fleets in operation
- Enable new entrants to trial the technology
- Demonstrate routes to low cost renewable H₂
- Stimulate further large scale uptake



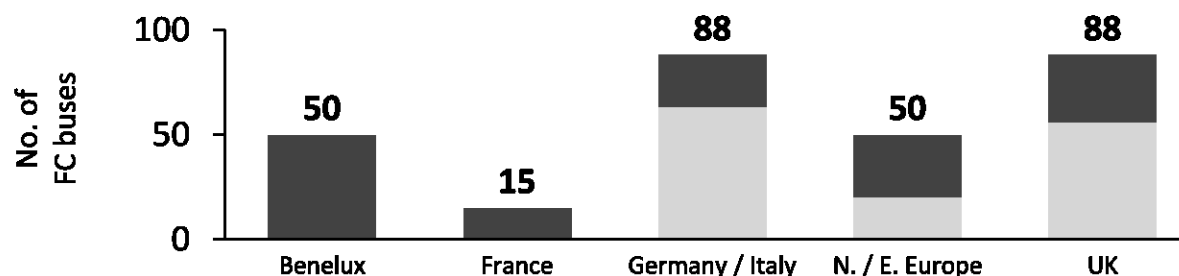
Benelux Cluster
(50 FC buses)

France Cluster
(15 FC buses)

Germany / Italy Cluster
(88 FC buses)

Northern / Eastern Europe Cluster
(50 FC buses)

UK Cluster
(88 FC buses)

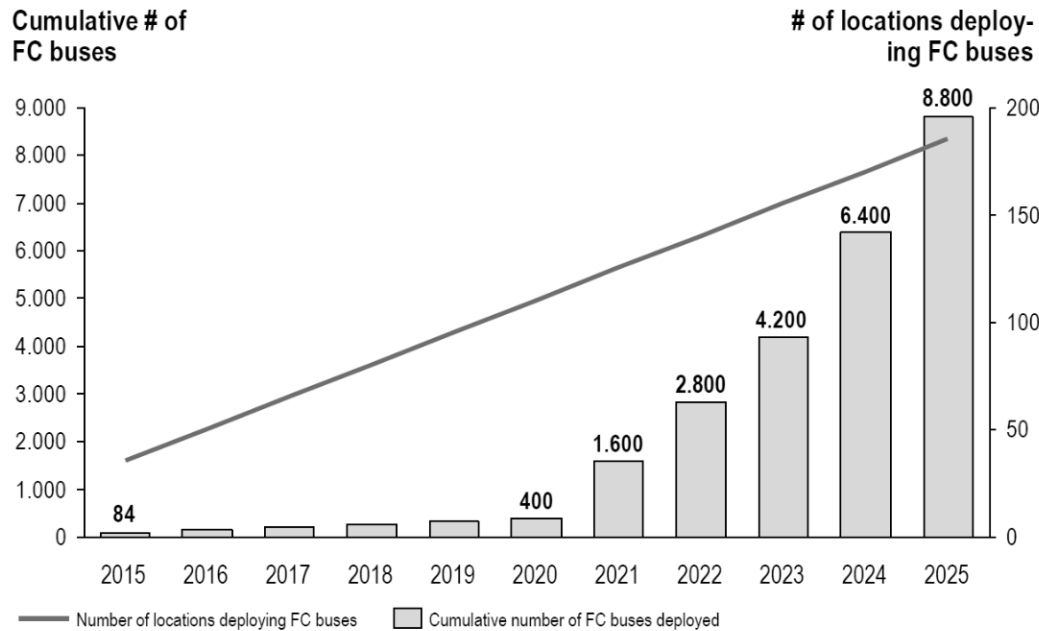


Total = 291 new FC buses for Europe

■ JIVE
■ JIVE 2

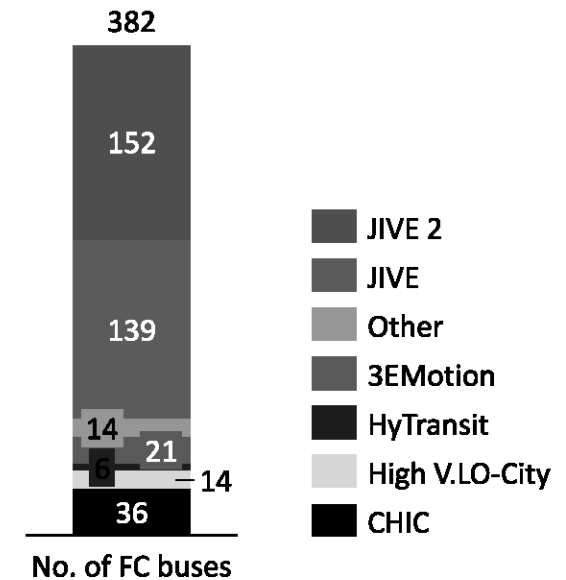
The fuel cell bus commercialisation coalition developed a ramp-up scenario that suggests c.400 FC buses deployed in Europe by 2020

Ramp-up scenario for FC buses in Europe



Source: *Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe*, Figure 29, p.48, Roland Berger for the FCH JU (2015).

Number of fuel cell buses in Europe deployed / planned by project



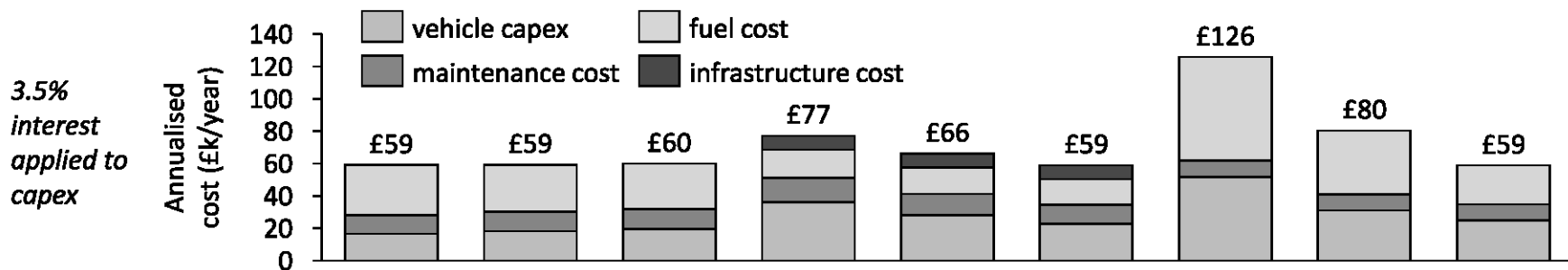
- Existing and planned projects will deliver 350–400 FC buses in Europe by the early 2020s.
- Further scale-up will be required to deliver the vision of the *European ramp up* scenario and to secure the economies of scale needed for FC buses to be offered on a commercial basis.
- For example, the recently announced “H2Bus Europe” initiative seeks to deploy c.600 fuel cell buses in the UK, Denmark, and Latvia. European funding (€40m) has been secured from the CEF Blending Call to support the deployment of new hydrogen refuelling infrastructure and fuel cell buses.

With further reductions in vehicle and fuel costs, FC solutions could be the lowest cost zero emission option for bus operators

Single deck bus

- The capital cost of fuel cell buses has reduced significantly as a result of demand aggregation efforts and increased volume of bus orders per OEM. This trend will continue with the further scale-up of fuel cell bus manufacturing.
- For large bus depots, the scale-up of the refuelling/re-charging infrastructure can become more cost-effective for fuel cell buses, whereas this can increase with the number of battery electric buses (and electric charger installations) with the additional cost of power connection upgrades to the bus depot.
- With hydrogen offered at c.£5/kg H₂ dispensed to the bus operator, hydrogen fuel cell buses could offer the cheapest low emission bus option.
- FC buses will have the added advantage over battery electric buses of no operational compromise compared to diesel.

Annualised vehicle costs (£k) over 12 years for different single decker bus technologies



	Diesel			Battery electric			Hydrogen fuel cell electric		
	2020	2025	2030	2020	2025	2030	2020	2025	2030
Capital cost (£000)	£160	£175	£190	£350	£270	£220	£500	£300	£240
Fuel efficiency /100 km	35 L	33 L	32 L	180 kWh	170 kWh	165 kWh	8 kg	7 kg	6 kg
Fuel cost	£1.1/L			£0.12/kWh			£10/kg	£7/kg	£5/kg

Based on a mileage of 80,000 km/year. Maintenance costs include powertrain overhaul. Assumptions based on a range of published reports and cost projections (including analysis by Bloomberg, Ricardo AEA, Roland Berger and Element Energy) as well as discussions with manufacturers.

Hydrogen-fuelled refuse trucks and other municipal vehicles are also being developed and trialled

Hydrogen refuse vehicles are currently at the trial stage, however, there are significant efforts to bring these to commercialisation underway, including European Funded projects to deploy vehicles (REVIVE and HECTOR). Two of the technologies currently in use / in development in Europe are shown below.

E-trucks platform



- Based on a DAF chassis.
- These increase the range of the pure battery electric version to cope with full daily range.
- Price: ~£600,000 CAPEX – a number of FC providers are available under the new FCH JU backed REVIVE project.
- Maximum speed 70 km / hour; 150 km range (when collecting and compacting).

E-trucks refuse vehicles

ULEMCo – Hydrogen Dual Fuel vehicles

- ULEMCo has converted refuse trucks to dual-fuel hydrogen diesel ICE solutions for Fife council as part of the Levenmouth Community Energy Project (+ others). A road sweeper has also been converted to for Aberdeen City Council.
- The same approach can be applied to heavy goods vehicles and large vans.
- The cost of conversion is c.£40k, but could be c.£20k if carried out at scale (100+).
- The dual-fuel vehicles require refuelling at 350 bar.
- Tailpipe CO₂ emissions are roughly 40% lower (on average) when operating in dual fuel mode than a comparable diesel vehicle.*



ULEMCo Dual Fuel RCVs

Sources: Bilateral discussions with vehicle suppliers.

* Based on amount of diesel displaced, which varies depending on configuration and duty cycle of vehicles.

Heavy-duty H₂ vehicles in Europe are at the prototype / demo phase; European OEMs are yet to announce commercialisation plans

Fuel cell trucks are at an earlier stage of development than cars, vans and buses. Several demonstration activities involving European truck OEMs such as Iveco, Scania and VDL are now starting in Europe. The table below provides some examples of emerging projects and products. New entrants such as Nikola (US) and HVSystems (UK) are also developing hydrogen trucks, and ULEMCo offers conversion to H₂ICE.

Project / product	Coop FC truck demo	ASKO FC truck demo	H2-Share	REVIVE	HVSystems	ULEMCo
Technology	Fuel cell	Fuel cell	Fuel cell	Fuel cell	Fuel cell	H ₂ ICE (100% H ₂)
Vehicle supplier	MAN (ESORO)	Scania	VDL	E Trucks Europe	HVSystems	ULEMCo
GVW	34t	27t	28t	Refuse trucks	44t	44t
No. of trucks	1	4	1	15	TBC	TBC
Demo location(s)	Switzerland	Norway	Belgium, Germany, France, The Netherlands	7 sites	TBC	UK
Dates	2016/17	From 2018	2017–20	2018–21	From 2019 (prototype)	From 2019 (prototype)



Selection of fuel cell heavy-duty vehicle activities in Europe (non-exhaustive). Based on public announcements.

H₂ICE: Hydrogen internal combustion engine

However, there is growing momentum in the FC HGV sector on a global basis, with several international OEMs developing trucks

- **Toyota** – has developed a Class 8 hydrogen fuel cell truck as part of its *Project Portal* programme. A prototype vehicle began transporting goods between depots in the port of Los Angeles and Long Beach in 2017 and will provide data on operating costs, reliability, etc.
- **Kenworth** – recently developed a fuel cell truck with a range of 240 km that will be used for short-haul port operations. The truck is being trialled as part of the *Zero Emission Cargo Transport* (ZECT) demonstration project.
- **Nikola Motor Company** – recently announced a partnership with Bosch for the powertrain development of a series of hydrogen fuel cell semi-trucks that will be built at a new factory in Arizona. Nikola is planning to offer the *Nikola One* and *Nikola Two*, with an anticipated market introduction date of 2021. In partnership with Nel ASA, Nikola is also planning to deliver a network of hydrogen refuelling stations across North America, offering “free” hydrogen for up to 1,000,000 miles of truck operation to its customers.
- **Hyundai** – FC truck to be launched in 2019, and at the IAA Commercial Vehicles show in 2018 Hyundai announced plans to deploy 1,000 vehicles in Switzerland with H2 Energy (2019–2023), subsequently increased to 1,600. The vehicle is 18t (34t with trailer) and has an expected range of 400km.

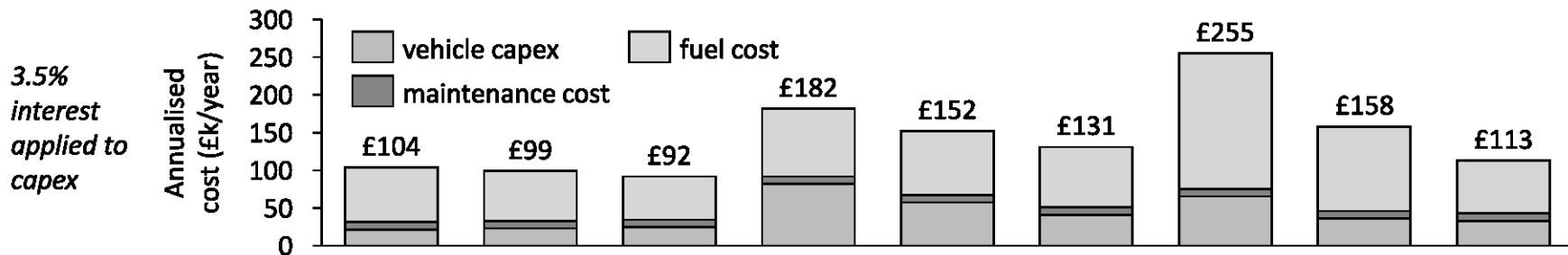


Long haul trucks are sensitive to operational costs: for parity with diesel, operators need access to hydrogen at below £5/kg

44 tonne articulated truck

- The high mileages of long haul trucks mean that the value proposition is very sensitive to the fuel cost and fuel efficiency.
- For battery electric vehicles, the need for ultra rapid charging (and the additional costs involved) for long haul trucks reduces the operational cost advantage.
- Hydrogen at <£5/kg H₂ (and/or legislation making it more costly to operate diesel trucks) would be required for fuel cell HGVs to achieve an operational cost of fuel cell trucks equivalent to diesel.
- Note battery electric and fuel cell 44 tonne trucks are not expected to be commercially available in 2020 – numbers are indicative.

Annualised vehicle costs (£k) over 7 years for different HGV technologies



	Diesel			Battery electric			Hydrogen fuel cell electric		
	2020	2025	2030	2020	2025	2030	2020	2025	2030
Capital cost (£000)	£130	£140	£150	£500	£350	£280	£400	£220	£200
Fuel efficiency /100 km	33 L	30 L	26 L	180 kWh	170 kWh	160 kWh	9 kg	8 kg	7 kg
Fuel cost	£1.1/L			£0.25/kWh			£10/kg	£7/kg	£5/kg

Based on a mileage of 200,000 km/year. Maintenance costs include powertrain overhaul. Assumptions based on a range of published reports and cost projections (including analysis by Bloomberg, Ricardo AEA, Roland Berger and Element Energy) as well as discussions with manufacturers.

The use of hydrogen in marine applications has been limited to date but there is growing interest in this area

Selected examples of hydrogen as a fuel in marine applications include:

Hydrogen fuel cells

- **ZemShip** – in this project a prototype FC passenger ship was built and trialled in Hamburg from 2008.
- **Several initiatives in Norway** – e.g. CMR Prototech announced plans to install fuel cells on the Osterøy car ferry “MF Ole Bull” operating near Bergen, and the HYBRIDShips project which aims to develop a hydrogen-powered ferry to be in operation from 2020.
- **HySeas III** – a project to develop the “world's first hydrogen fuel cell powered ocean-going ferry for passenger and vehicle transport”. The objective is to provide a shuttle service between the Scottish islands of Orkney and Shapinsay with a new type of ship powered by renewable energy sources, beginning in 2021.

Hydrogen-diesel co-combustion

- **Hydroville** – a custom-designed vessel built by UK boat-builder BWSeaCat, commissioned by Belgian marine company CMB, and supported by Revolve (who provided the co-combustion technology and specified the associated hydrogen storage system).
- **HyDIME** – an Innovate UK-funded project to design, integrate and trial a hydrogen / diesel dual fuel conversion system for a 50kW diesel auxiliary power unit on a car ferry in Orkney. The project involves ULEMCo and several other partners and is running from 2018 to 2019.



UK Government has published a plan for decarbonising marine transport and will consider including maritime fuels in the RFTO

Hydrogen powered maritime vessels

- The Clean Maritime Plan was published by the UK Government in July 2019 and sets out a route to zero emission shipping. This includes plans for all new vessels ordered from 2025 (for operation in UK waters) to have zero emission propulsion capacity, and looks at developing clean maritime clusters in the UK, which include bunkering of low or zero emission fuel.
- The UK Government is planning a call for evidence in 2020 on non-tax incentives to support the transition to zero emission shipping and will consult on how the Renewable Transport Fuel Obligation can be used to encourage the uptake of low carbon fuels in maritime¹.



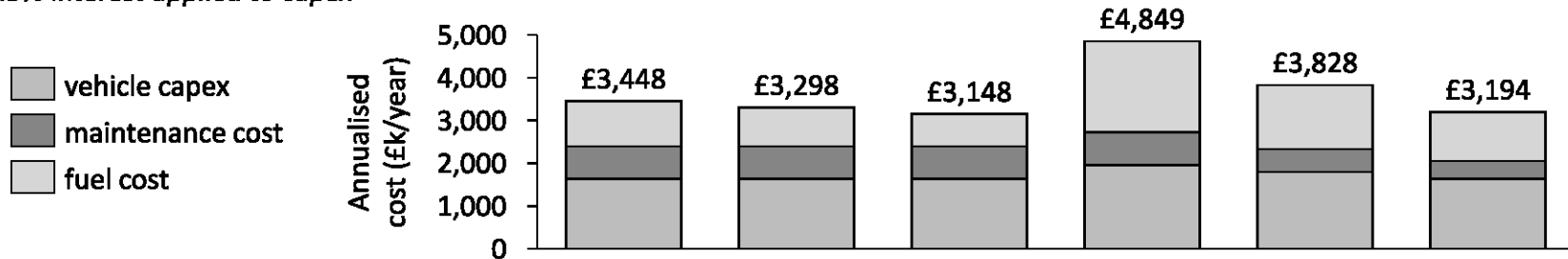
Marine applications also require very low cost hydrogen for parity with marine diesel oil

Hydrogen roll-on/roll-off ferry

- Maritime vessels have operational lifespans of >30 years.
- Fuel duty is not currently applicable for marine diesel oil, which means that to reach fuel cost parity, hydrogen would need to be available below £3.5/kg H₂.
- For vessels travelling longer distances, liquid hydrogen may be required.
- An incentive for zero carbon fuel (such as inclusion in the RTFO for maritime fuels) could help the UK Government to meet decarbonisation targets for marine transport.

Annualised costs per ferry (£k) over 30 years for different technologies

3.5% interest applied to capex



	Diesel			Hydrogen fuel cell electric		
	2020	2025	2030	2020	2025	2030
Capital cost (£million)	£30	£30	£30	£36	£33	£30
Fuel efficiency /100 km	700 L	600 L	500 L	170 kg	150 kg	130 kg
Fuel cost		£0.6/L		£5/kg	£4/kg	£3.5/kg

There is growing interest in hydrogen as a fuel for various railway applications across the world

Notable strategic studies

- A study commissioned by the FCH JU and Shift2Rail JU in 2018 to assess the potential of HFC technologies in the rail sector.
- Feasibility and concept design work for hydrogen-powered trains in Ontario, Canada as part of a major overhaul of the GO Transit service.



Selected examples of hydrogen used in rail applications

- **Alstom's Coradia iLint** was presented at InnoTrans in 2016 and entered commercial service in Germany (Lower Saxony) in 2018. Two trains are now running between the cities of Cuxhaven, Bremerhaven, Bremervörde and Buxtehude.
- In 2018 **Alstom** announced that it is working with **Eversholt Rail** on plans to convert Class 321 electric trains to run on hydrogen by retrofitting fuel cells and hydrogen storage.
- Also in 2018, **Siemens** announced it is working with **Ballard** on developing a FC drive for the Mireo train platform (expected to be ready to enter service in 2021).
- The University of Birmingham unveiled a fuel cell demonstration train (the "Hydrogen Hero") at Rail Live in 2018.
- **Shunting locomotives** – in 2016 the Latvian Railways company (LDZ) signed an MOU with CZ Loko and Ballard to develop fuel cell locomotives. In 2018 Jastrzębska Spółka Węglowa (JSW, coking coal producer) and PKP Cargo (Polish rail cargo operator) signed a letter of intent for joint projects related to the commercial use of hydrogen fuel based on developing new types of hydrogen-powered wagons and shunting locomotives.
- In 2017 a **hydrogen tram** was put into operation in Tangshan, North China's Hebei province.



The UK Government plans to ban diesel only trains from 2040 has spurred the development of hydrogen fuel cell trains for the UK

- The deployment of fuel cell trains has been spurred by the UK Government's plan to ban diesel-only trains from 2040. The operational life of trains is c.30 years, it is therefore not in train operators' interest to purchase new diesel-only trains, and train manufacturers have been developing H₂ fuel cell trains to meet this new market.
 - The rail decarbonisation taskforce estimates that c.1,000 sprinter diesel-only rail vehicles will reach their end of life between 2026–31¹.
- Abellio was awarded the East Midlands franchise in 2019 and announced they would trial hydrogen trains on their route. Alstom, Porterbrook and Vivarail are currently developing fuel cell trains, with Alstom aiming to have the Alstom 'Breeze' operational from 2023.
- Several discussions between Alstom/Eversholt and the Scottish Government rail team have been held regarding the potential to deploy fuel cell trains in Scotland.
- Vivarail is also developing a fuel cell train and is interested in using this on the Aberdeen to Inverness route.
- The Scottish Government aims to decarbonize rail by 2035. Aberdeen is seen as a likely first deployment site for FC trains (within Scotland) due to the existing hydrogen activities and suitable (non-electrified) routes.
- Based on estimates from train manufacturers, UK hydrogen trains will consume c.200 – 400 kg H₂/day/train, dependent on the route and mileage requirements.
- Conditions for a trial:
 - **Certified FC train appropriate for a trial line.**
- Conditions for 10 trains:
 - **Successful pilot demonstration.**
 - **Acceptable business case for FC train fleet and new franchise (from 2025) / franchise variation.**
 - **Early enough decision to allow deployment of FC trains accounting for lead times of vehicles (2 – 2.5 years) and refuelling infrastructure.**



1: <https://www.rssb.co.uk/en/Research-and-Technology/Sustainability/Decarbonisation/Decarbonisation-our-final-report-to-the-Rail-Minister>

2: https://www.raildeliverygroup.com/files/Publications/2018-03_long_term_passenger_rolling_stock_strategy_6th_ed.pdf

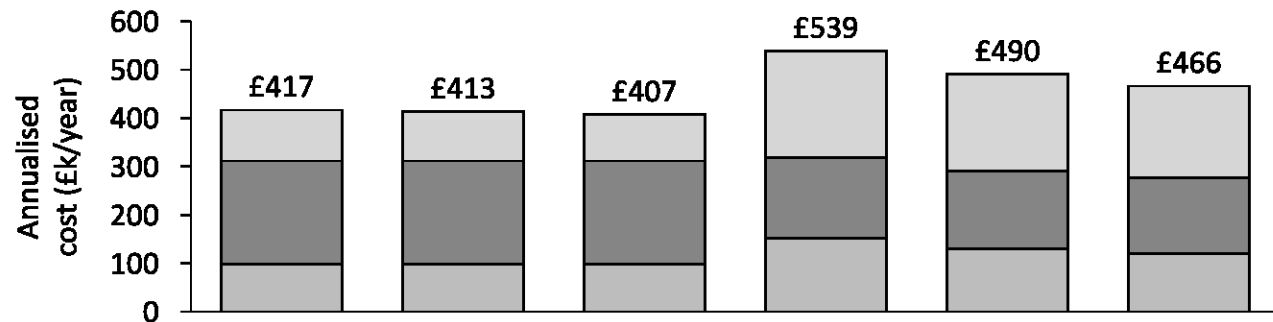
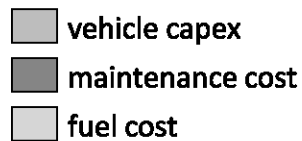
Hydrogen trains will be significantly more costly than diesel trains unless hydrogen can be made cost-competitive with 'red diesel'

<100 mph passenger train (costs per vehicle)

- Trains in the UK typically have an operational lifespan of >30 years, with a mid-life powertrain overhaul. To meet the UK Government's ban on diesel-only trains from 2040, the existing rail stock would need replacing from the early 2020s.
- With significantly reduced fuel duty for trains compared to road vehicles, even if hydrogen was available at £5/kg, the overall costs of operation for hydrogen trains would be significantly higher compared to diesel trains (e.g. by £77k per year, per train, in 2025).

Annualised costs per train (£k) over 30 years for different technologies

3.5% interest applied to capex



	Diesel			Hydrogen fuel cell electric		
	2020	2025	2030	2020	2025	2030
Capital cost (£million)	£1.8	£1.8	£1.8	£2.8	£2.4	£2.2
Fuel efficiency /100 km	88 L	85 L	80 L	22 kg	20 kg	19 kg
Fuel cost	£0.6/L			£5/kg		

Hydrogen revenues per kg from trains and marine applications could be lower than for cars, vans and buses due to the low incumbent fuel costs

The hydrogen price required for “fuel cost parity” can vary between applications

- To achieve fuel cost parity with diesel or petrol vehicles, hydrogen must be sold at a price that is equivalent to the fossil fuel price on a per km basis. What the end user pays for fossil fuel depends on the application; for some transport modes (e.g. trains and marine applications) fuel duty is not applicable (red diesel). This makes the “fuel cost parity” revenues, that the hydrogen supplier could expect to receive per kg of hydrogen sold, significantly lower than those where duty is paid on the incumbent fuel (this assumes that no fuel duty is paid on hydrogen).
- Hydrogen fuel subsidies could be set for different applications to reflect these differences OR users could be asked to adapt their business cases to fundamentally higher hydrogen prices.

