



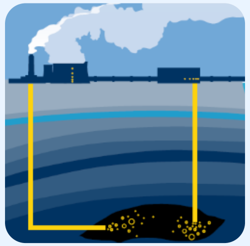



Hydrogen Use in Aviation

Transport and Environment

29/11/2022

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Background – targets have been set for UK aviation to use sustainable fuels

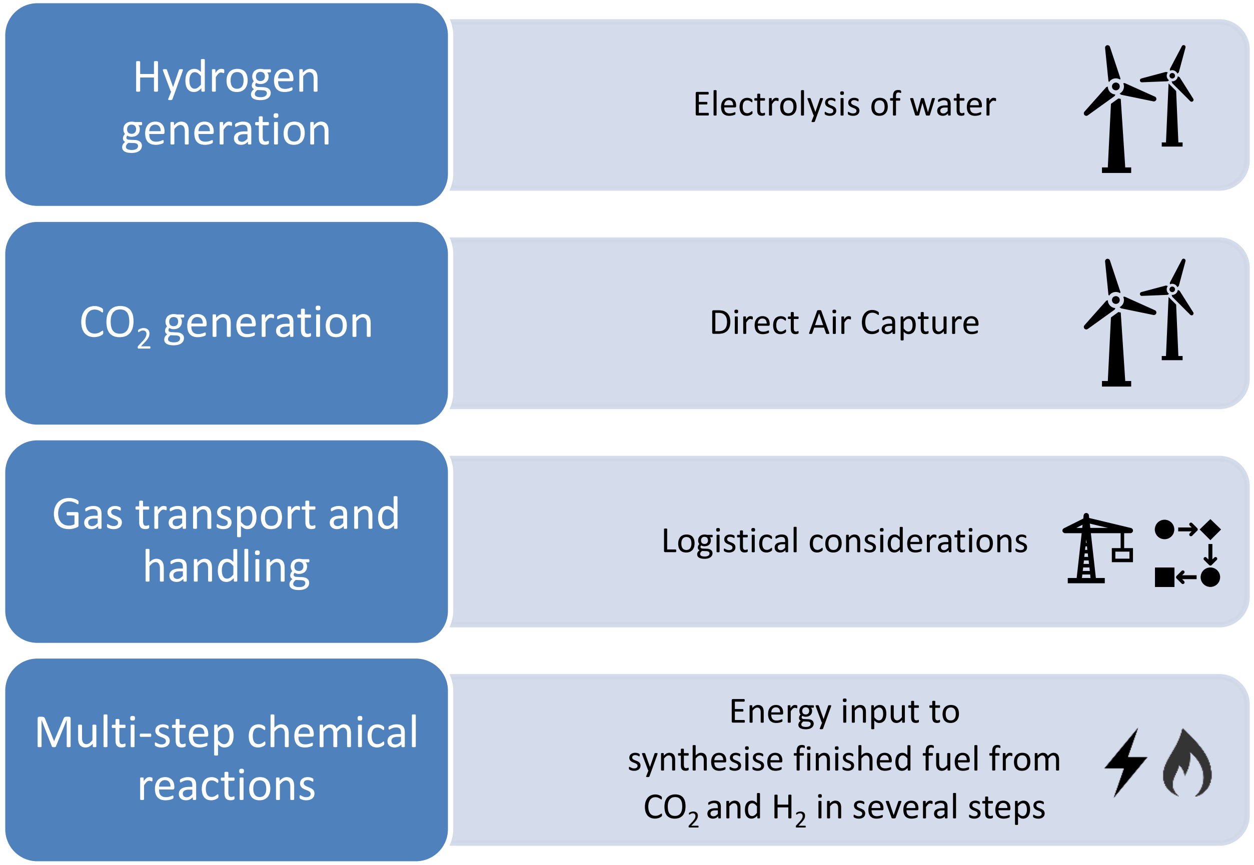
Sustainable Aviation Fuel mandates will necessitate increased renewable energy generation

- The UK government Jet Zero Strategy commits to a target of a minimum 10% Sustainable Aviation Fuel (SAF) by 2030, and the EU has set a target of 5%
  - SAF can comprise Power-to-Liquid (PtL) fuels, waste-derived biofuels and recycled carbon fuels
  - A target of 0.7% of aviation fuel to be PtL fuel has been set by the EU[1], and the UK intends to set a target soon
- PtL fuel is synthesised from hydrogen and CO_2, which in this report is assumed to be generated using renewable electricity through electrolysis
- Synthesis of PtL can be broken down into its component steps
  - Production of green hydrogen via electrolysis of water
  - Production of CO_2 via Direct Air Capture (DAC)
  - Performing the chemical synthesis via one of a number of routes, which may have slightly different energy and material inputs
- We have quantified the total amount of hydrogen and CO_2 in order for an indicative 0.7% of overall UK aviation fuel to comprise PtL fuel, as well as the implied additional electricity generation requirement
- A high level estimate of embedded emissions in new wind turbines and associated infrastructure is also included

1: refueleu_aviation_-_sustainable_aviation_fuels.pdf (europa.eu)

Schematic graphic of PtL fuel manufacturing steps

Energy input is required at each stage



- Hydrogen and CO_2 are assumed to be obtained with renewable electricity
  - We specifically focus on requirements for additional wind energy in this report
- This report does not include quantification of the energy requirements for the following:
  - H_2 and CO_2 handling including compression, transport and storage etc.
  - Reaction steps in the chemical synthesis of SAF
  - Manufacture of new PtL plants and associated handling or transport of this fuel

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Background – 100% hydrogen powered flights will be viable before 2030

UK Government is targeting 100% zero emission commercial flight by 2030

- The UK government Jet Zero Strategy sets out the aspiration for completely zero emission routes connecting different parts of the UK to be operational by 2030
- Technology for 100% hydrogen powered aircraft is under development, and certification of the first models is scheduled by 2030
- The first planes to market will be small turboprop planes, such as the DHC-Twin Otter
  - These planes are currently flying in the UK serving shorter routes such as between Scottish islands and the mainland, and hydrogen alternatives for such planes are scheduled to be available from ~2025
- Slightly larger turboprop planes with up to 80 seat capacity and 500 nautical mile range will be available by the late 2020s
  - These could serve longer UK domestic flight routes
  - Many of these routes are currently served with larger planes operating below full capacity, thus potentially allowing smaller but fuller planes to be viable alternatives
- We have selected three routes which may be able to be served by 100% hydrogen-powered planes and calculated hydrogen and electricity demand, again assuming that green hydrogen made by wind-powered water electrolysis will be used
- We have also calculated the requirements in the event that all UK flight routes currently served by turboprop planes were to be replaced with 100% hydrogen technology, a stretch target nevertheless deemed technically feasible in a best-case scenario
  - There are ~17,000 such flights annually originating in the UK, of which ~13,500 are domestic

1: refueleu_aviation_-_sustainable_aviation_fuels.pdf (europa.eu)

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Background

Electricity and hydrogen demand for power to liquid fuels

Electricity and hydrogen demand for 100% hydrogen powered flight

Results

Electricity and hydrogen demand for power to liquid fuels

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Conclusions and Discussion

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- Background
  - Electricity and hydrogen demand for power to liquid fuels
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- Results
  - **Electricity and hydrogen demand for power to liquid fuels**
  - Electricity and hydrogen demand for 100% hydrogen powered flight
- Conclusions and Discussion

Different estimates of energy inputs to synthesis SAF and its constituents have been made

- Different PtL synthesis methodologies for use as SAF are the subject of ongoing research and development
  - There are a number of studies available looking at the energy and H_2 and CO_2 mass input requirements to synthesise SAF by more than one route
  - Numbers from a recent confidential study have been used to generate the upper end estimates of mass requirements
  - Estimates from a CONCAWE/Aramco study have been used to set the lower end of estimates[2]

- A further key assumption is the efficiency of the electrolysers used to make green hydrogen, where again we have sought to cover the range of literature values from best to worst case
  - For the worst case we have used a study by IRENA[3] which gives an upper and lower bound for 2020 and 2050 values, and using the upper bound we have linearly interpolated between these two points to estimate a 2030 efficiency
  - For the best case we have again used the CONCAWE study referenced above

The quantities of H_2 and CO_2 required per unit of SAF and the energy required for their production can vary significantly

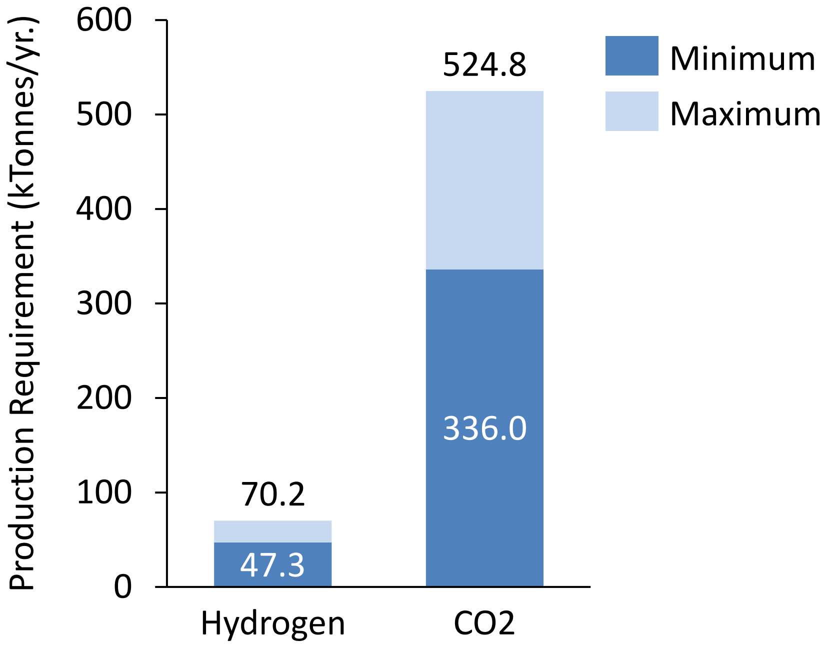
Source	Description	H_2 mass (kg per kg SAF)	CO_2 mass (kg/kg SAF)	Electrolyser energy requirement (kWh/kg H_2)
Confidential SAF synthesis project	Worst case	0.668	4.6	59.3
CONCAWE [1]	Best case	0.45	3.2	49.2

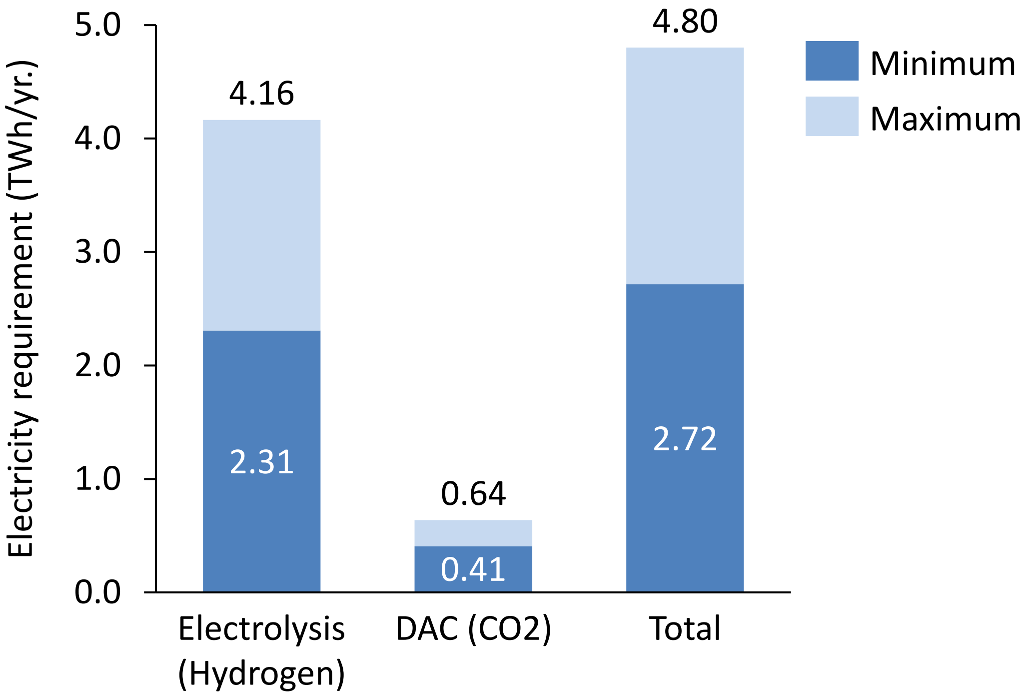
1: UK Jet Zero consultation (theicct.org)
2: E-Fuels (concawe.eu)
3: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Up to 70kt of H_2, 510kt CO_2 and 4.8 TWh of electricity are needed for aviation fuel to be 0.7% PtL

More CO_2 is needed by mass, but H_2 production makes up a large majority of the energy required

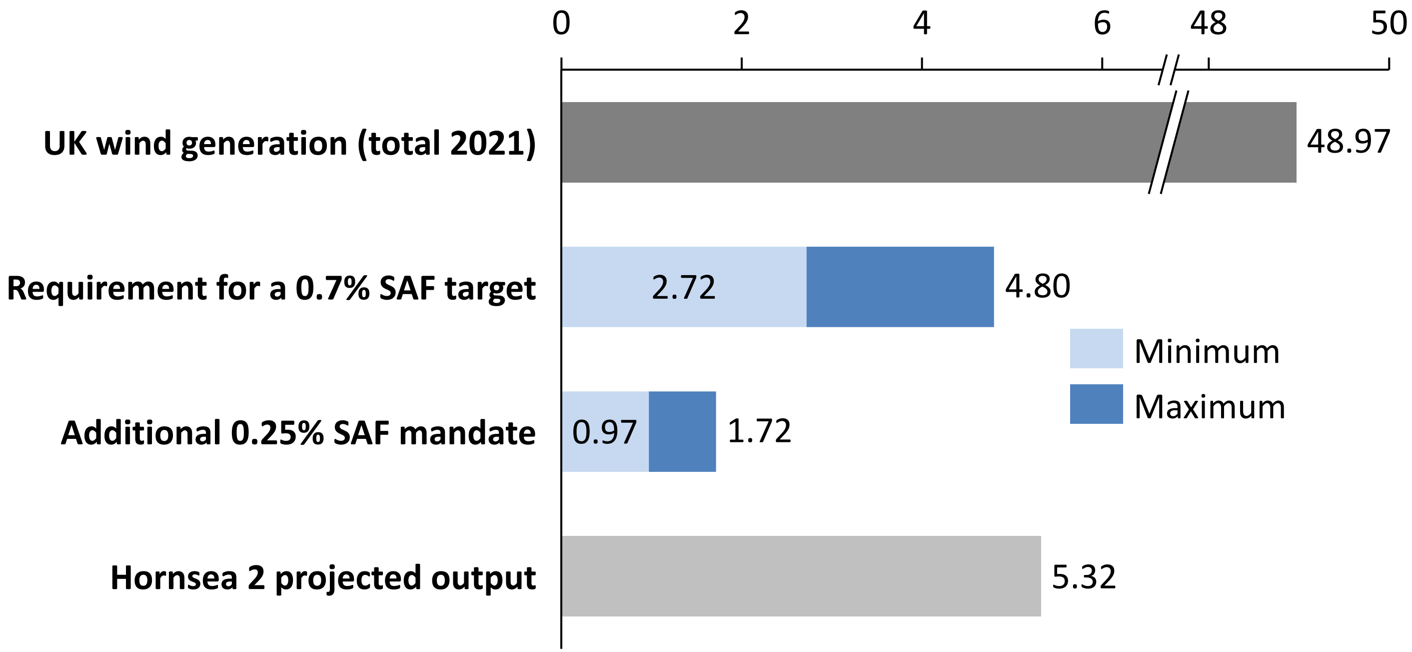
- The charts show the 1-year material and energy requirements to replace 0.7% of 2030 UK aviation fuel demand with PtL fuel
- The values represent an upper and lower bound dependent on the assumptions outlined on the previous slide
- Electrolysis of water to make green hydrogen is the most energy intensive part of the process





The total electricity demand for SAF would be a significant addition to UK generation capacity

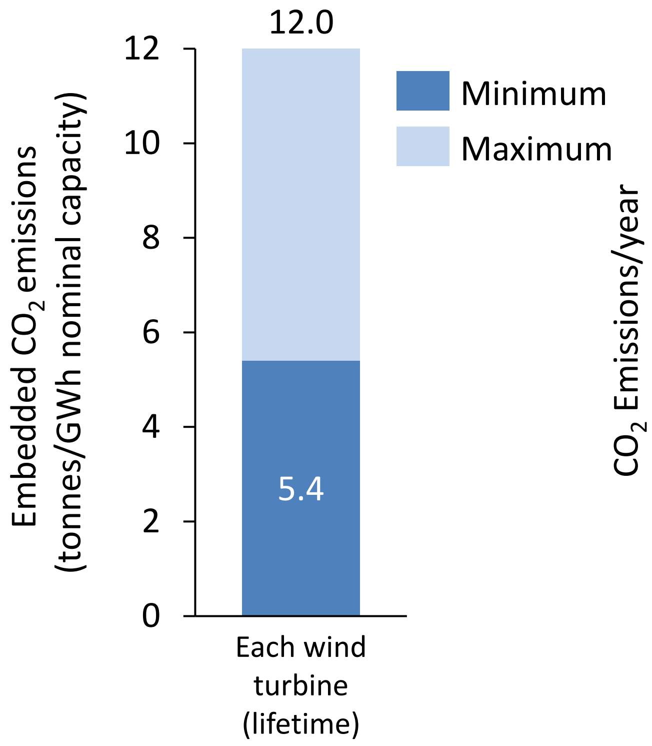
Meeting a 0.7% PtL fuel mandate in 2030 could require a wind farm comparable to the UK's current largest, Hornsea 2

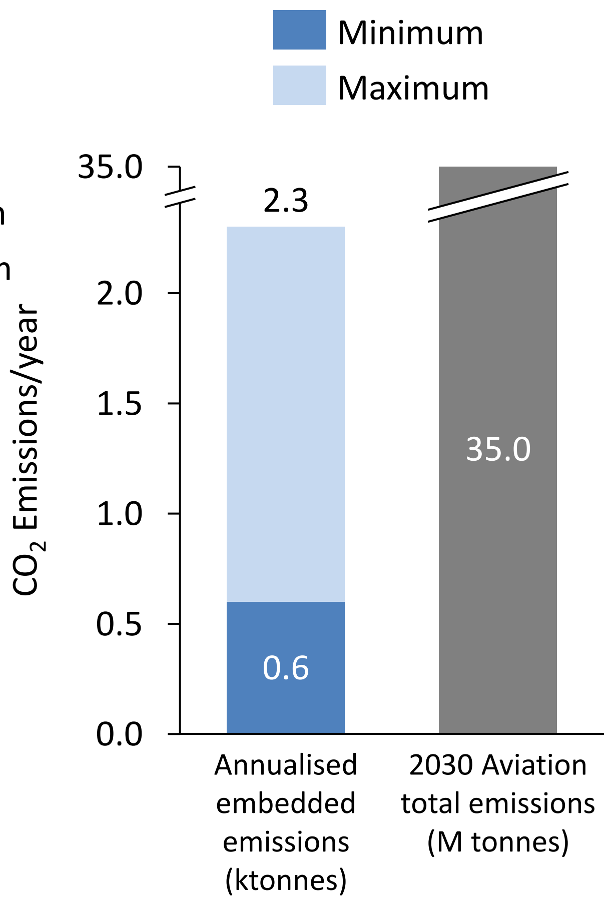


- **2.72-4.80 TWh** of electricity is required to meet a 0.7% PtL mandate for all UK aviation in 2030
- The UK's largest windfarm Hornsea 2, operational from August 2022, uses 165x8MW Siemens turbines, giving an expected average output (assuming a 46% capacity factor, as achieved by sister facility Hornsea 1) of **5.32TWh**
- The wind energy required just to meet a 0.7% PtL target is thus between 50-90% of the capacity of Hornsea 2
  - Or approximately **85-149** x 8MW wind turbines at 46% capacity factor
- Alternatively it would require additional capacity equivalent to ~**6-10%** of all 2021 UK wind generation
- Each extra 0.25% SAF demand will require an additional **0.97-1.72TWh**, or approximately **30-53** x 8MW wind turbines at 46% capacity factor

Embedded CO_2 emissions of wind turbines are up to 12 tonnes per GWh of annual generation output

Up to 58 ktonnes of embedded emissions are implied in the wind turbine infrastructure needed to use 0.7% PtL fuel in from 2030



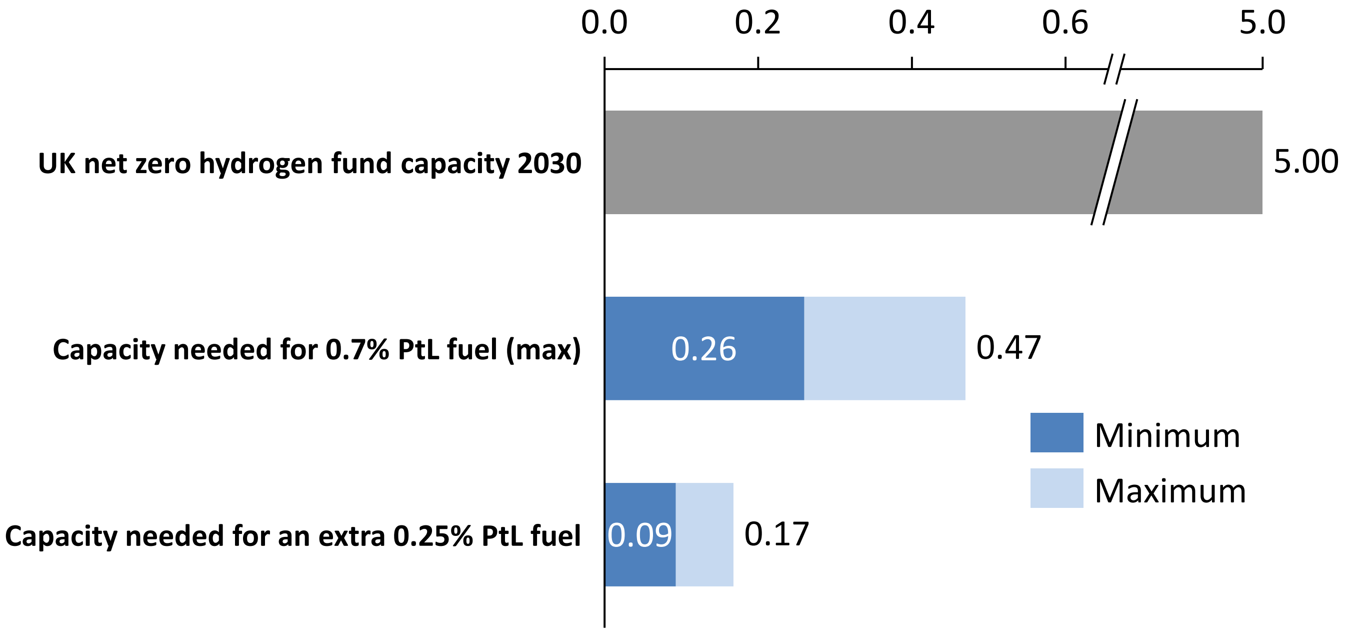


- Embedded emissions for a single wind turbine of 8MW nameplate capacity found in literature from 5 separate studies[1] range from 5.4 to 12.0 tonnes per GWh
  - Generating 4.8TWh in a year therefore has a total footprint of approximately 26-58 kilotonnes
  - The lower estimate of 2.72TWh would have a footprint of ~15-33 ktonnes
- Total embedded emissions of ~15-58 ktonnes are ~0.04-0.16% of expected total 2030 aviation sector emissions of 35 Mtonnes
- Over a typical 25 year wind turbine lifetime this equates to ~0.6-2.3 ktonnes per year, or a maximum of ~0.06% of annual expected emissions, compared to the 0.7% of emissions saved by using PtL fuel
- This value is not usually included as part of the LCA of PtL fuels or the fossil fuels they displace, being a small number
- This analysis also does not include any other emissions associated with new PtL fuel manufacturing capacity, or of handling and transport requirements additional to those associated with standard aviation fuel

1: e.g [What's the carbon footprint of a wind turbine? » Yale Climate Connections]

A 0.7% PtL fuel mandate would consume up to 10% of anticipated green H_2 generation in 2030

UK government net zero hydrogen fund will support 5GW of green hydrogen capacity by 2030



- The government aims to support the production of 5GW of green hydrogen by 2030
  - The exact amount which will be available is uncertain
  - The existence of a PtL fuel mandate may in itself increase this value as PtL fuel manufacturers invest in extra capacity
- The electricity demand for the hydrogen needed for PtL is 2.31 - 4.16 TWh, equivalent to 0.26-0.47GW* of wind generation
- On this basis 6-10% of all anticipated UK green hydrogen in 2030 would need to be dedicated to PtL fuel were it to be made exclusively with UK hydrogen made from UK wind-generated electricity
- Every extra 0.25% increase in the PtL target would require ~1.8-3.4% of all planned UK green hydrogen generation

* Conversion calculation: 2.31 or 4.16x1,000/(24x365). This assumes the green hydrogen production sites run at full capacity all the time. Any downtime in the green hydrogen production facility would mean PtL consumes a greater percentage of total green hydrogen supply

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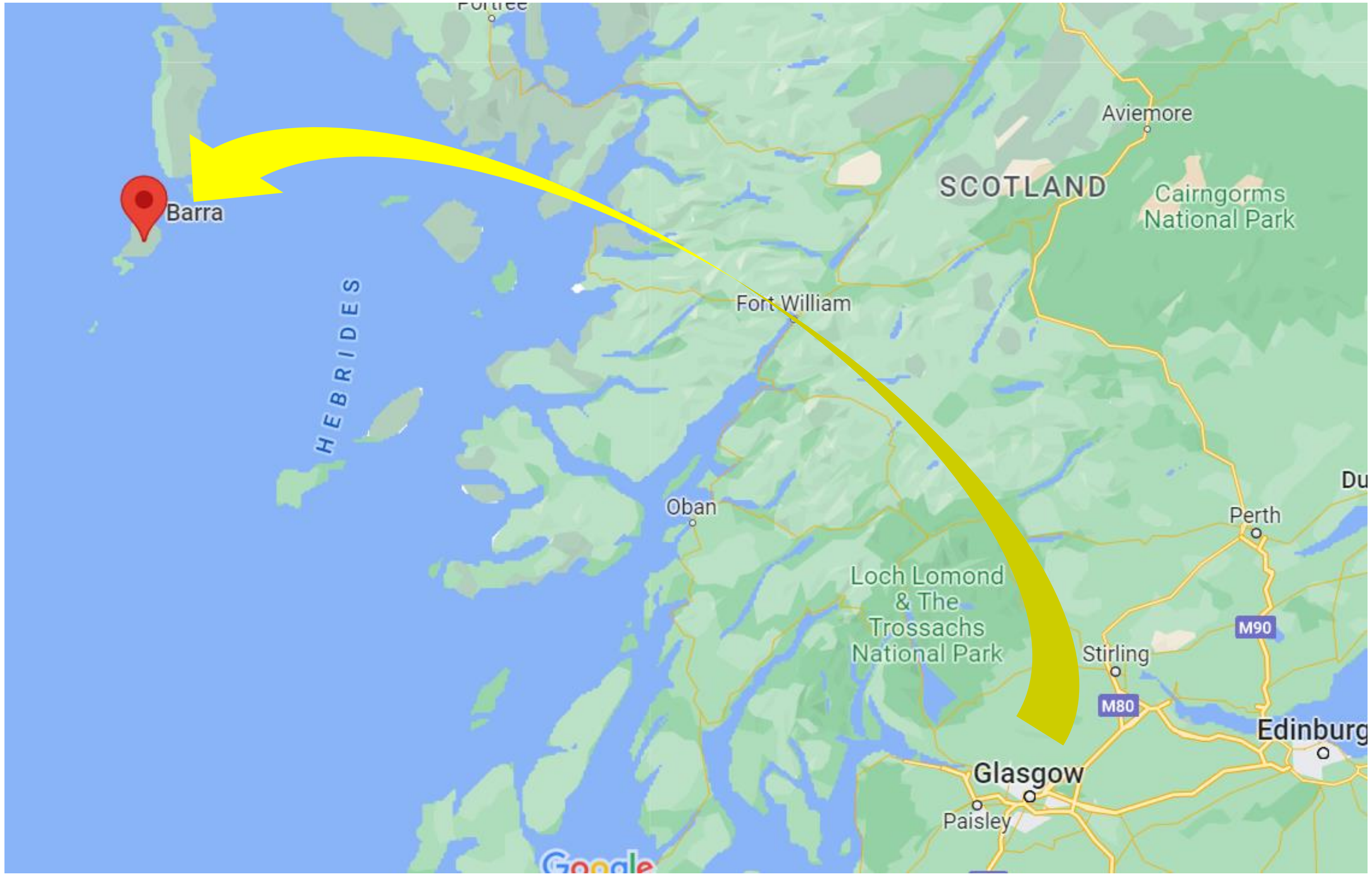
We focused on three flights covering a range of single flight distances and total flights per year

Flights covering a range of technological capability are considered

From	To	Distance (km)	Plane type (potential)	Passenger Capacity	Return flights per year	Hydrogen consumption estimates	
						Per return flight (kg)	Per year (tonnes)
Glasgow	Barra	246	DeHavilland Twin Otter	19	676	100-150	68-102
Dundee	London City	588	ATR72 / DeHavilland Canada-8	50-80	365	600-1000	220-365
Glasgow	Southampton	584	ATR72 / DeHavilland Canada-8	50-80	1248	600-1000	750-1250

- Hydrogen consumption estimates arise from discussions with companies working in the space but are today necessarily based on limited experience and theoretical calculations, leading to inherently high uncertainty
  - This is reflected in the range of estimates used for the hydrogen required for the flights considered
  - We have used the central values for the calculations in this report
- Given the inherent uncertainty in hydrogen consumption data we have also calculated the electricity demand per 100 tonnes of hydrogen
  - This number can be scaled to give an electricity demand for any given flight whose hydrogen consumption is known now or in the future

Short range flight modelled – DeHavilland Twin Otter example aircraft body



- Glasgow to Barra in the Outer Hebrides

Medium range flights modelled – ATR-72 example aircraft body

- Glasgow to Southampton and Dundee to London-City
- ATR-72 (pictured) or Dehavilland Canada-8 are viable options

Assumptions and justifications

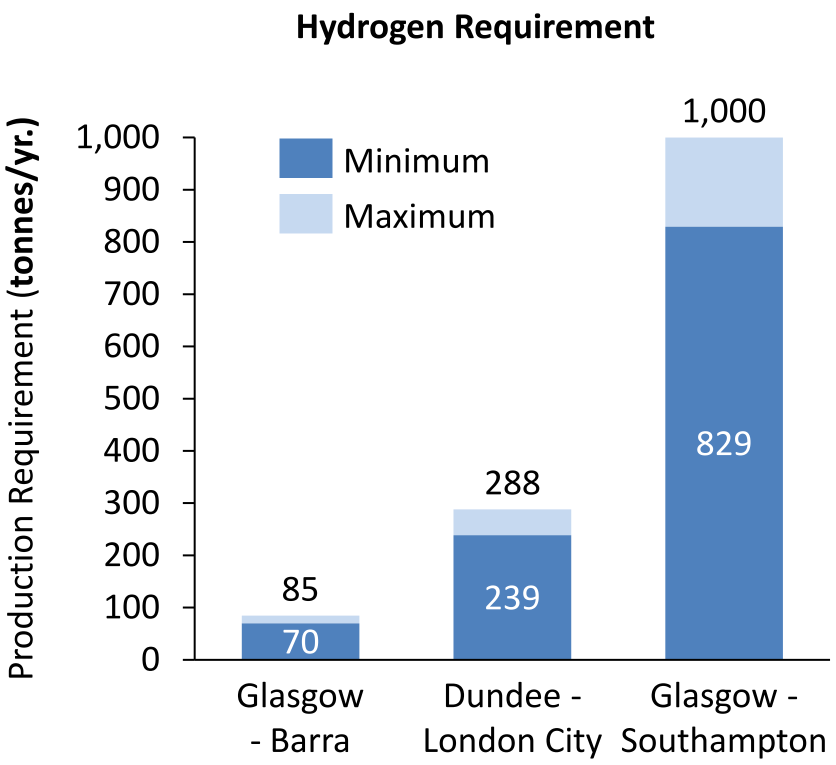
Realistic distances, possible economic drivers and the likely availability of hydrogen were factors

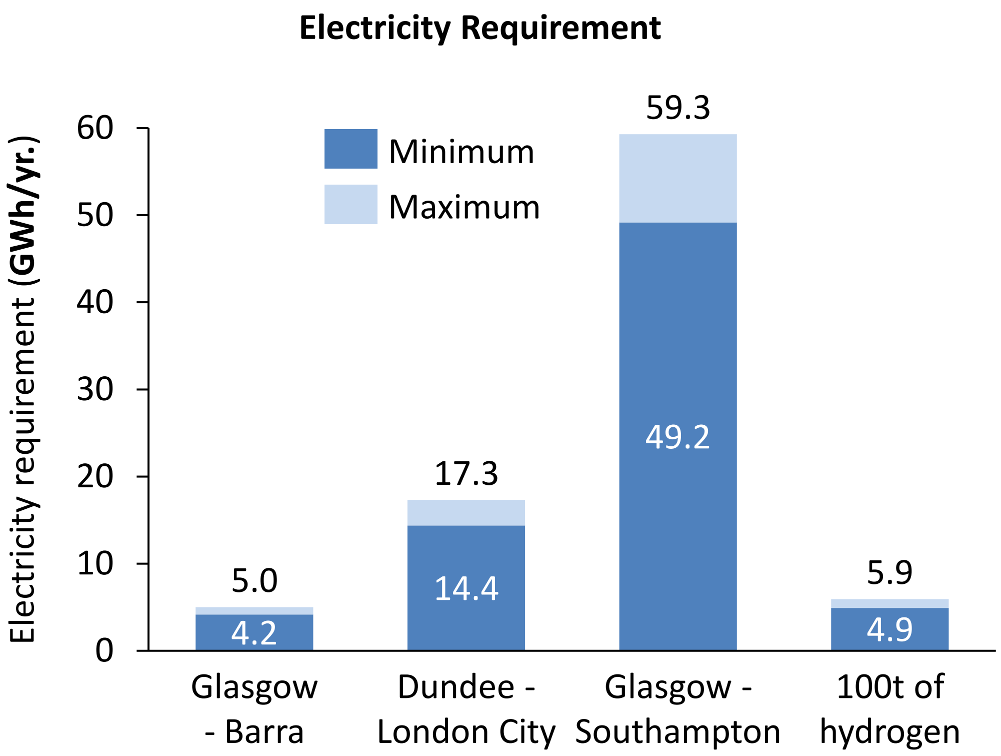
- Dundee to London City and Glasgow to Barra are Public Service Obligation flights part-funded by the UK government, and so any required potential funding to assist in the early adoption of this new technology is judged to be more likely on such routes
- Glasgow to Southampton is a long internal UK flight with high demand which nevertheless could be served by technology projected to be available in 2030, and represents a more ambitious target
- Scotland is developing significant plans for green hydrogen generation and both London, as a major city, and Southampton, with its port and nearby refinery, make them locations where hydrogen will likely be available
- Together the flights studies cover a realistic range of ambition and also of likely hydrogen and thus electricity requirement
- The electricity requirements calculated are dependent on the accuracy of the estimated hydrogen consumption which include a high degree of uncertainty given the current state of the technology

1: Based on discussions with companies developing hydrogen aircraft

Hydrogen demand for individual flights is between ~70 and ~1000 tonnes per year depending on the length of route and size of plane selected

The electricity requirement to generate this hydrogen is between 4.2 and 59.3 GWh

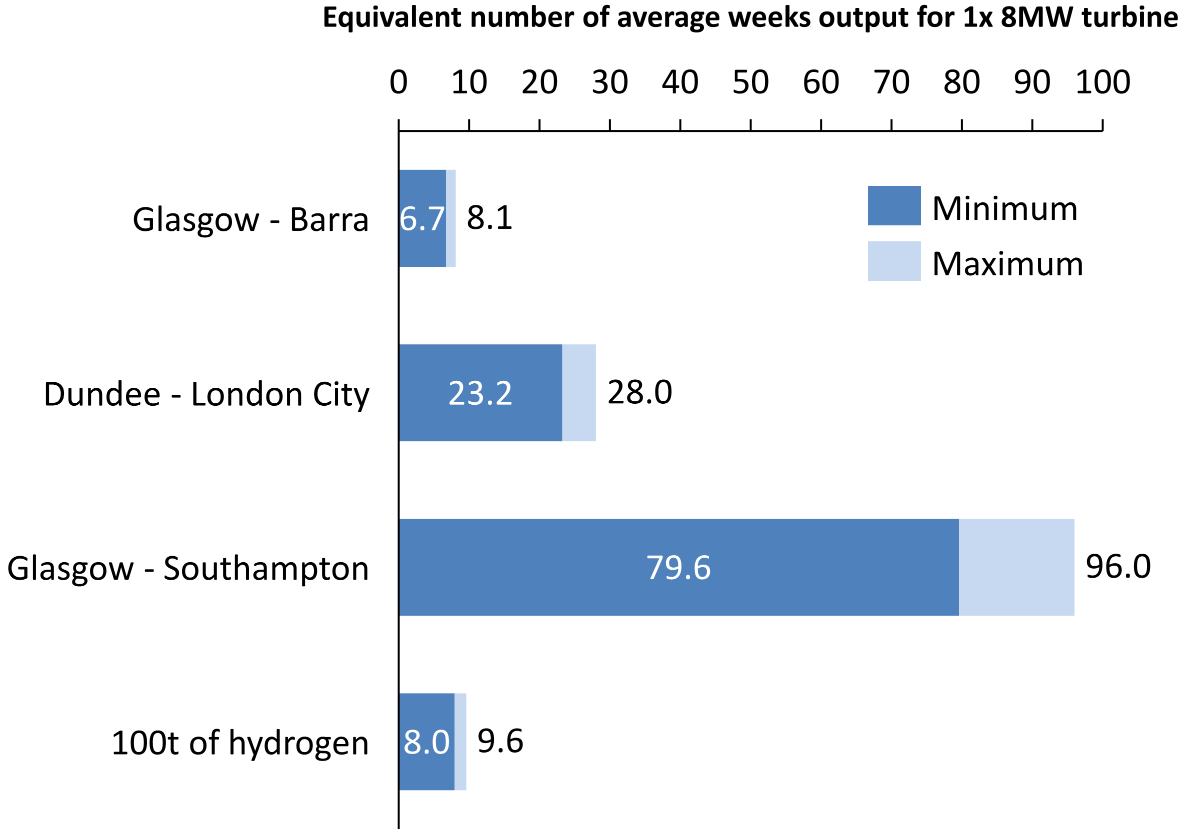




- The values are calculated using the upper and lower bounds for electrolyser efficiency as set out on slide 10

Annual electricity demand for the required hydrogen matches the demand of 1,250-20,000 homes depending on the length of route and size of plane selected

Electricity demand is compared to the equivalent typical weekly output of a wind turbine



- The figures are calculated using average turbine output
  - Based on the OFGEM[1] average for annual UK home electricity use of 2,900 kWh, one turbine could power ~11,000 homes
- The hydrogen required for Glasgow-Barra could be met with ~6-8 weeks of typical generation for 1 turbine
  - Equivalent to ~1250-1700 typical homes’ annual use
- The Glasgow-Southampton route would need ~18-22 months’ operation of one turbine
  - Equivalent to ~17-20,000 typical homes’ annual use
- Each 100t of hydrogen requires between 8-10 weeks output from one turbine
  - Equivalent to ~1700-2000 homes’ annual use

1: Decision for Typical Domestic Consumption Values 2020 | Ofgem

Maximum 2030 hydrogen aviation demand if all feasible flights were operated can be assessed

All turboprop planes could potentially be replaced by 100% hydrogen fuelled alternatives in a best case scenario

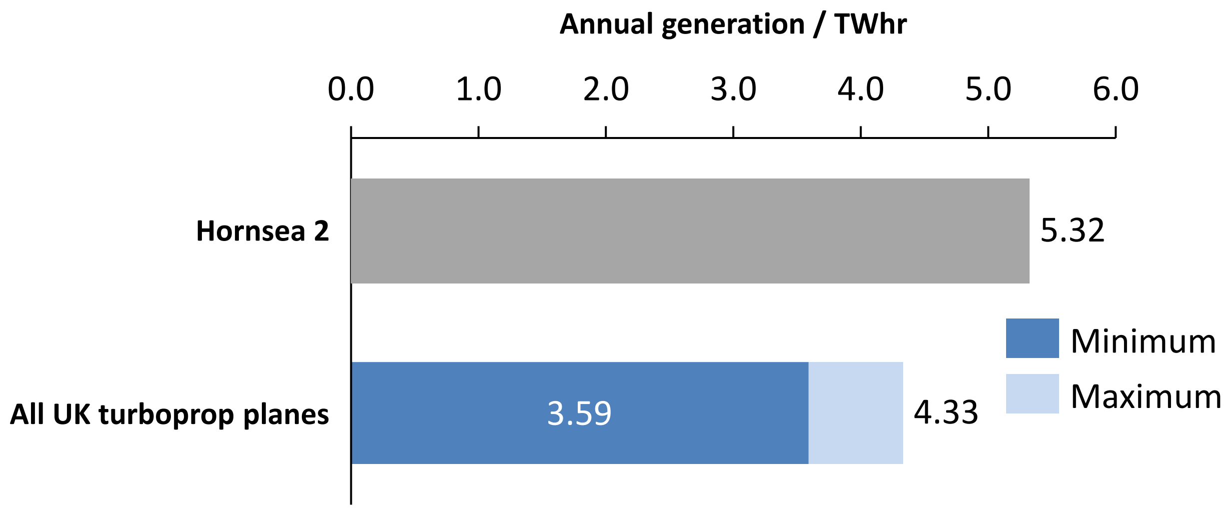
- By 2030 technology to replace all small and medium body planes with turboprop engines with hydrogen alternatives will exist
  - Both retrofitting of existing planes and new builds are viable routes to market

- This is believed to be technically possible but economically challenging and assumes a number of things which are not guaranteed:
  - The continued on-track progress of technology development
  - Successful certification of new planes on schedule
  - Successful scale-up and manufacturing of new technology
  - Acceptance and uptake by the aviation industry
  - Significant upgrades to UK airport infrastructure and hydrogen distribution and logistics
  - Nevertheless this provides an instructive theoretical upper bound in order to contribute to the overall picture for hydrogen and electricity demand in the UK in 2030

- The estimate of the hydrogen demand to replace all turboprop planes is of potentially up to 200 tonnes per day
  - A range for the electricity required for 200 tonnes has been calculated using upper and lower bound electrolyser efficiencies as per slide 10

Replacing all current UK turboprop flights with hydrogen would require much more generation

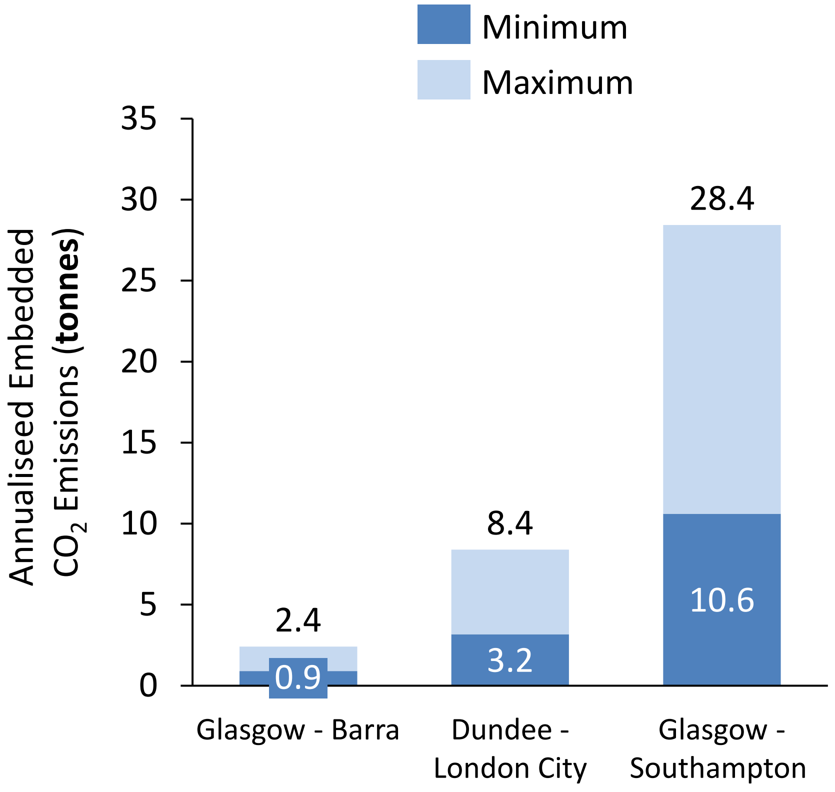
3.59 - 4.33 TWh would be required to generate a hydrogen requirement of 200 tonnes per day

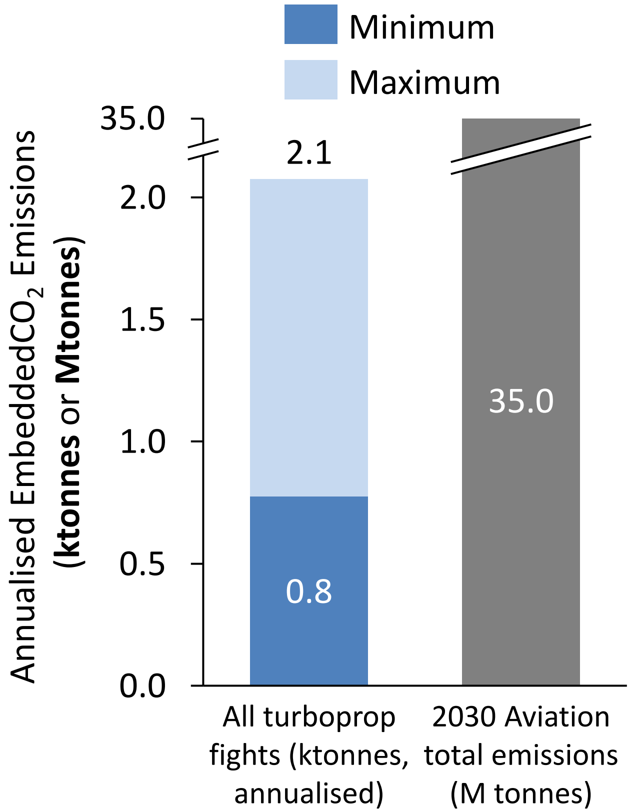


- An upper estimate of 200 tonnes per day for the total requirement of all small and medium turboprop planes in the UK has been used
  - Equivalent to 73k tonnes per year, almost the same as the maximum hydrogen requirement of 70.2 ktonnes for 0.7% PtL fuel
  - For comparison current annual UK hydrogen production is ~550-700 ktonnes
- 73k tonnes per year would require 3.59-4.33 TWh, or the equivalent of approximately 70-80% of the anticipated output of Hornsea 2
  - This is also equivalent to ~1.3 -1.5M typical homes annual use
  - 3.59 - 4.33TWh equates to ~0.4-0.5GW for 1 year and is therefore approximately 8-10% of UK hydrogen production ambition of 5.0 GW for 2030
- This is of the order of the same amount of electricity required to generate hydrogen for 0.7% PtL fuel for all aviation (2.72 - 4.16TWh)
- Significant infrastructure would need to be put in place to deliver hydrogen to all UK airports, this is out of the scope of this report but would present an additional major challenge

Embedded CO_2 emissions of wind turbines for hydrogen flights depend on the scale of ambition

Single flights would generate a small quantity of embedded emissions, replacing all turboprop plane fuel would be more significant





- Embedded emissions shown use the range quoted previously of between 5.4 and 12.0 tonnes CO_2 / GWh of nominal capacity
- The footprint of the turbines required to power individual flights is a maximum of 28.4 tonnes CO_2 per year based on a 25 year lifetime
- The embedded emissions implicit if all turboprop flights were replaced by hydrogen are is ~0.8-2.1 ktonnes per year over 25 years
  - This is of the order of that calculated for a mandate of 0.7% PtL fuel

1: e.g. What's the carbon footprint of a wind turbine? » Yale Climate Connections

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Electricity and hydrogen demand for 100% hydrogen powered flight

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Replacing 0.7% of aviation fuel with PtL fuel requires a significant quantity of electricity

Water electrolysis to generate green hydrogen represents the largest energy input requirement

- Supplying PtL for 0.7% of UK aviation in 2030 will require significant increases in renewable generation capacity
  - Between 2.72 and 4.80 TWh, of which ~90% is for hydrogen generation, with a much smaller amount required for CO_2 DAC
  - Equivalent to 6-10% of total UK electricity generation from wind in 2021
  - Equivalent to approximately 50-90% of the output of the UK's largest wind farm, Hornsea 2

- Each additional 0.25 percentage points increase in the PtL mandate will require an extra 0.97-1.72TWh
  - This is equivalent to the annual output between 30 and 53 of the 8MW wind turbines as used in Hornsea 2

- Building additional wind turbines to provide the required electricity has a relatively small quantity of embedded emissions which are of the order of 0.6-1% of the maximum CO_2 savings expected by the use of PtL
  - It should be noted that this work does not take into account all embedded emissions in the PtL fuel supply chain

Approximately 10% of planned UK hydrogen generation capacity would be needed to supply PtL

PtL would become a significant user of hydrogen in 2030

- The hydrogen requirement to supply 0.7% of all UK aviation fuel would account for ~6-10% of total anticipated UK green hydrogen generation capacity if produced exclusively domestically
  - Every increase of 0.25% on the target would require ~1.8-3.4% of all anticipated hydrogen generation
- Aviation represents ~3% of UK CO_2 emissions[1], so with a 0.7% PtL fuel mandate a maximum of ~0.03% of UK CO_2 emissions would be eliminated by using up to 10% of all green hydrogen generated
- There are expected to be competing demands for hydrogen in 2030 including existing grey hydrogen applications in oil refineries and fertiliser or other speciality chemicals manufacturing
  - Current use of hydrogen is almost entirely in the industrial and chemicals sectors with around 45% used in refineries and 30% being used to make ammonia, chiefly for fertiliser but also as a feedstock for other chemicals
  - Long term decarbonisation of aviation using only PtL fuels would require significantly greater available volumes of hydrogen in future years
  - Current UK hydrogen demand (2021) was ~27 TWh
- The demand implicit in a PtL mandate is however expected to stimulate additional capacity for hydrogen which could increase the overall volume of hydrogen available

1: Progress-in-reducing-emissions-2022-Report-to-Parliament.pdf (theccc.org.uk)

Using 100% hydrogen is feasible at small scale but requires significant extra capacity to do more

If plane technology is delivered on schedule, fuelling all theoretically feasible UK flights will take large amounts of electricity

- Meeting the UK government ambition of a zero-carbon demonstrator flight by 2030 appears feasible
  - The highest demand route studied would need ~49 - 59GWhr, or the equivalent of one 8MW turbine for ~ 18-21 months to generate the required hydrogen
  - The lowest demand route modelled would require 4.2 - 5GWhr or ~6-8 weeks typical output of one 8 MW turbine
  - Embedded emissions of such relatively small extra generation capacity is very limited

- The industry believes that replacing all turboprop planes in the UK may be possible by 2030 in a best case scenario

- If all of these flights were powered with hydrogen the extra electricity requirement would be 3.59 - 4.33TWh, which is similar to the value required for the 0.7% PtL fuel mandate
  - The embedded emissions of this extra generation capacity is between 800-2100 tonnes per year assuming a 25 year lifetime

- The combination of PtL and pure hydrogen demand could amount to a maximum of 20% of expected UK hydrogen in 2030
  - The uncertainty on demand figures quoted here is relatively high, due chiefly to uncertainty about real world hydrogen consumption
  - The effect of aviation demand from 100% H_2 or PtL fuel on stimulating extra H_2 supply above currently anticipated levels is also uncertain
  - Hydrogen generation and distribution, and the airport infrastructure required to deliver it is outside of the scope of this report but must be considered to present a major additional challenge to this level of scale-up by a 2030 timeframe

Range of Annual Electricity Demands

Range of demand to fulfil SAF mandates for all aviation, and for specific flights or all turboprop plane flights to use 100% H_2

Hydrogen use case	Assumed Hydrogen demand	Electricity requirement [1]
All UK Aviation fuel - 0.7% replaced by SAF	47.3 - 70.2 ktonnes	2.72 - 4.80 TWh
All UK Aviation fuel – 0.25% replaced by SAF	16.9 - 25.1 ktonnes	0.97 - 1.72 TWh
100% hydrogen powered flight: All turboprop flights	73 ktonnes [2]	3.59 - 4.33 TWh
100% hydrogen powered flight: Glasgow – Barra	85 tonnes	4.2 - 5.0 GWh
100% hydrogen powered flight: Glasgow – Southampton	292 tonnes	14.4 - 17.3 GWh
100% hydrogen powered flight: Dundee – London City	1000 tonnes	49.2 - 59.3 GWh

1: NB includes CO_2 Direct Air Capture electricity requirement for SAF

2: 200 tonnes per day