WP4: Integrated design optimisation and LCA – method development and application

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- Model architecture overview
- Industrial application
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General information

- Open-source, open-access regional optimisation framework implemented as a mixed integer linear program.

- Open-source software has been developed in a Python-based framework, Pyomo with regional data analysis using QGIS.

- The tool is released under the MIT license enabling users to use, modify and redistribute the software and accompanying data in any form.

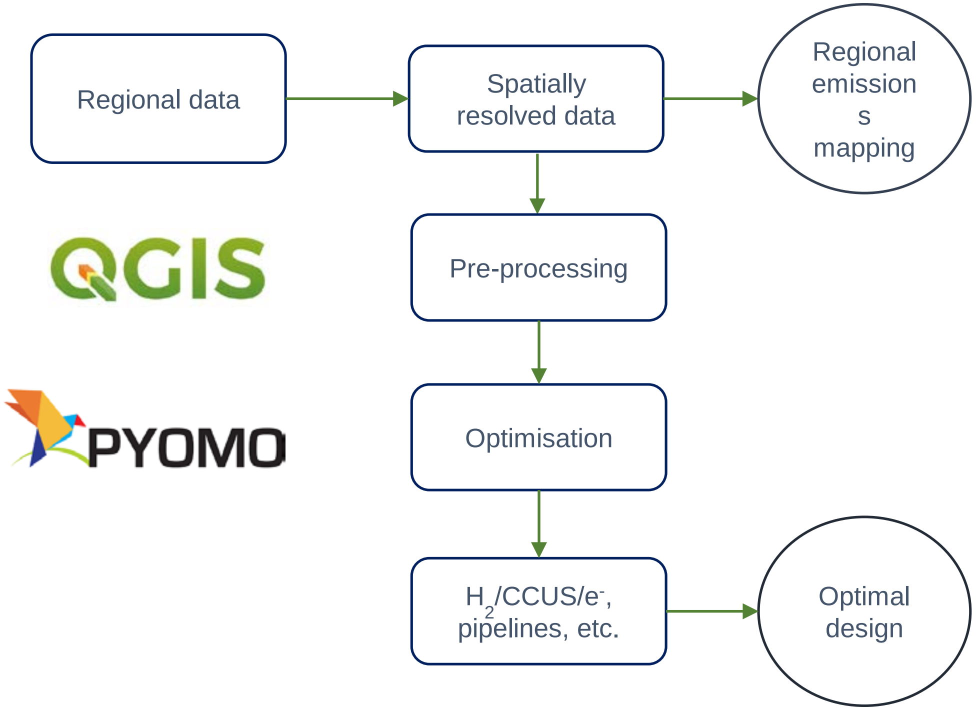
- The chain tool and accompanying datasets can be accessed through the following link: https://github.com/act-elegancy

Model architecture

Regional data processing	QGIS
Optimisation framework	PYOMO
Solvers	GUROBI OPTIMIZATION; IBM CPLEX

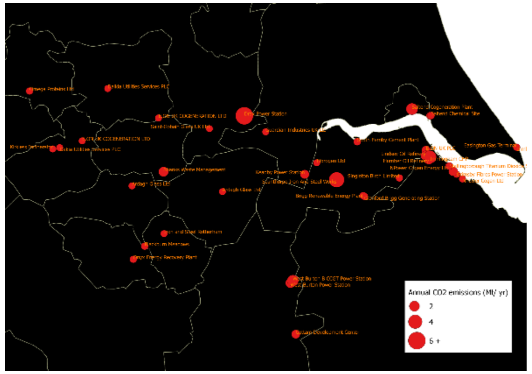
For more details, visit WP4 subsection @ https://www.sintef.no/projectweb/elegancy/publications/

How does it work?



QGIS

PYOMO

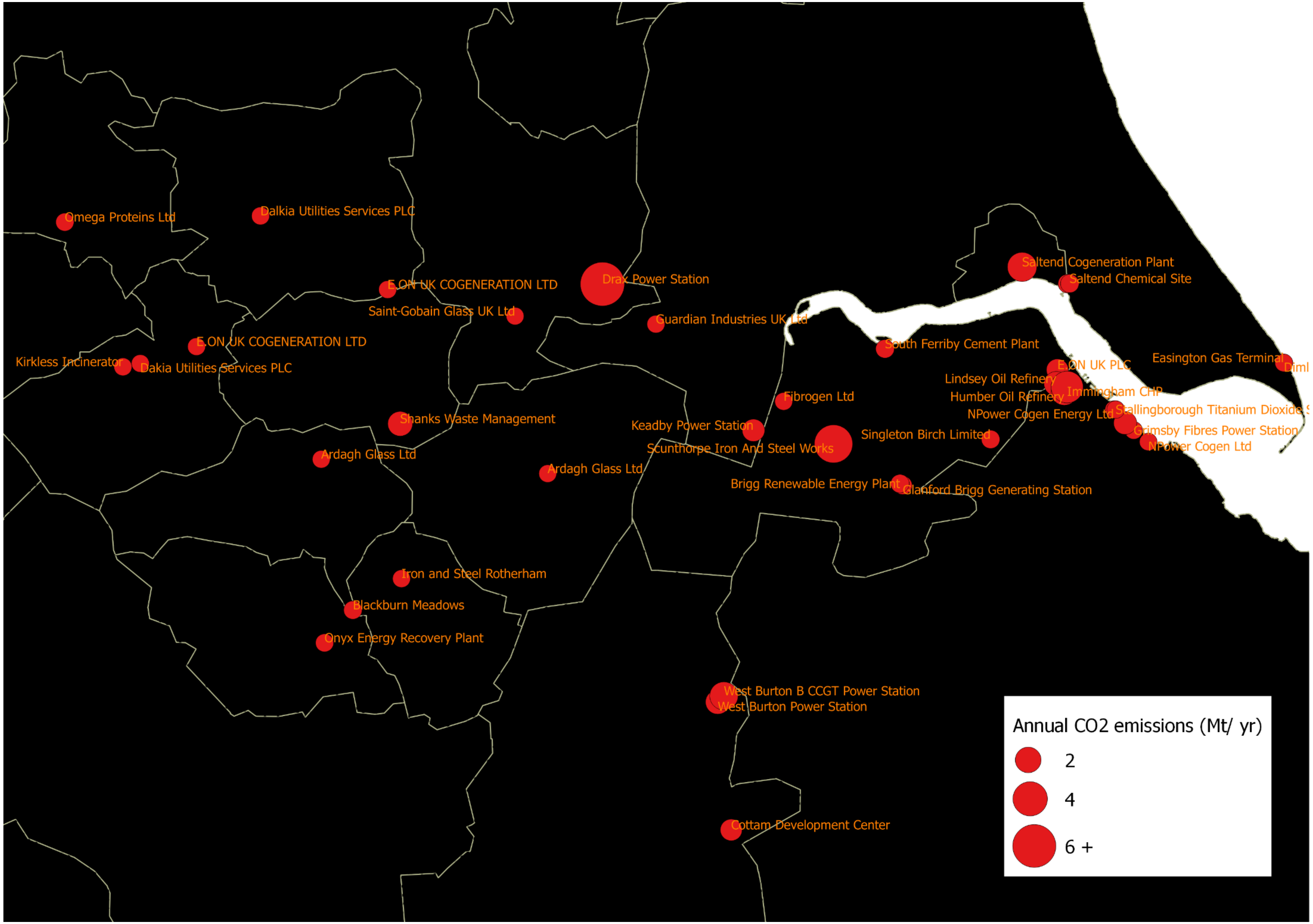


An industrial application

- York and the Humber region.
- A population of 5.5 million people.
- Salamanca was built here in 1812 by Matthew Murray.
- Portland cement was invented here in 1824 by Joseph Aspdin.
- Stainless steel was invented here in 1913 by Harry Brearley.
- GVA of £119bn – 6.5% of UK.
- Key industries are co-located in this region.

The Humber - emission statistics

- Emissions total ~ 37 $MtCO_2\ yr^{-1}$.
- Regional emissions split – heating (14%), process (21%), and power generation (65%) emissions.
- Emissions point concentration of CO_2 vary between 10 – 30 mol% depending on the asset and its operations.


Omega Proteins Ltd
Dalkia Utilities Services PLC
E.ON UK COGENERATION LTD
Drax Power Station
Saint-Gobain Glass UK Ltd
Guardian Industries UK Ltd
E.ON UK COGENERATION LTD
Kirkless Incinerator
Dakia Utilities Services PLC
Shanks Waste Management
Ardagh Glass Ltd
Ardagh Glass Ltd
Keadby Power Station
Scunthorpe Iron And Steel Works
Singleton Birch Limited
Fibrogen Ltd
Brigg Renewable Energy Plant
Glanford Brigg Generating Station
Saltend Cogeneration Plant
Saltend Chemical Site
South Ferriby Cement Plant
E.ON UK PLC
Easington Gas Terminal
Lindsey Oil Refinery
Immingham CHP
Humber Oil Refinery
NPower Cogen Energy Ltd
Stallingborough Titanium Dioxide
Grimsby Fibres Power Station
NPower Cogen Ltd
Iron and Steel Rotherham
Blackburn Meadows
Onyx Energy Recovery Plant
West Burton B CCGT Power Station
West Burton Power Station
Cottam Development Center
Annual CO2 emissions (Mt/ yr)
2
4
6 +

Key CO_2 abatement options?

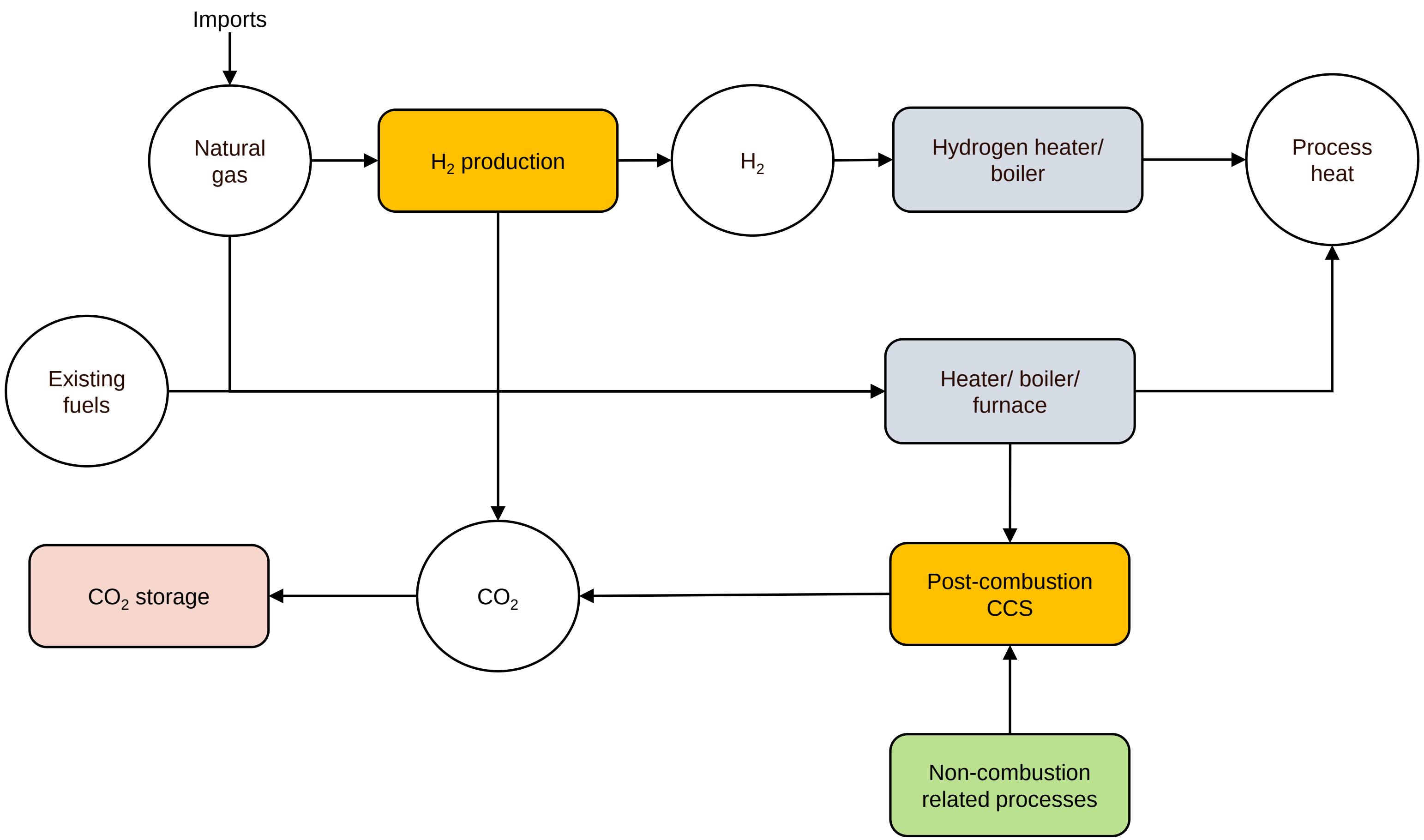
Post combustion CO_2 capture

- Requires, ducts, fans and pumps
- Absorber and stripper requirements
- Requires new on-site processes and workforce
- Additional flue gas desulfurisation units
- Additional CHP plant, cooling water tower, *etc.*

H_2 with CCS

- Additional ATR plant with integrated CCS
- Requires additional piping
- Plant can be located elsewhere
- Furnace and equipment retrofits/ replacements
- Singular point source emission stack

Optimisation superstructure



Core modelling assumptions

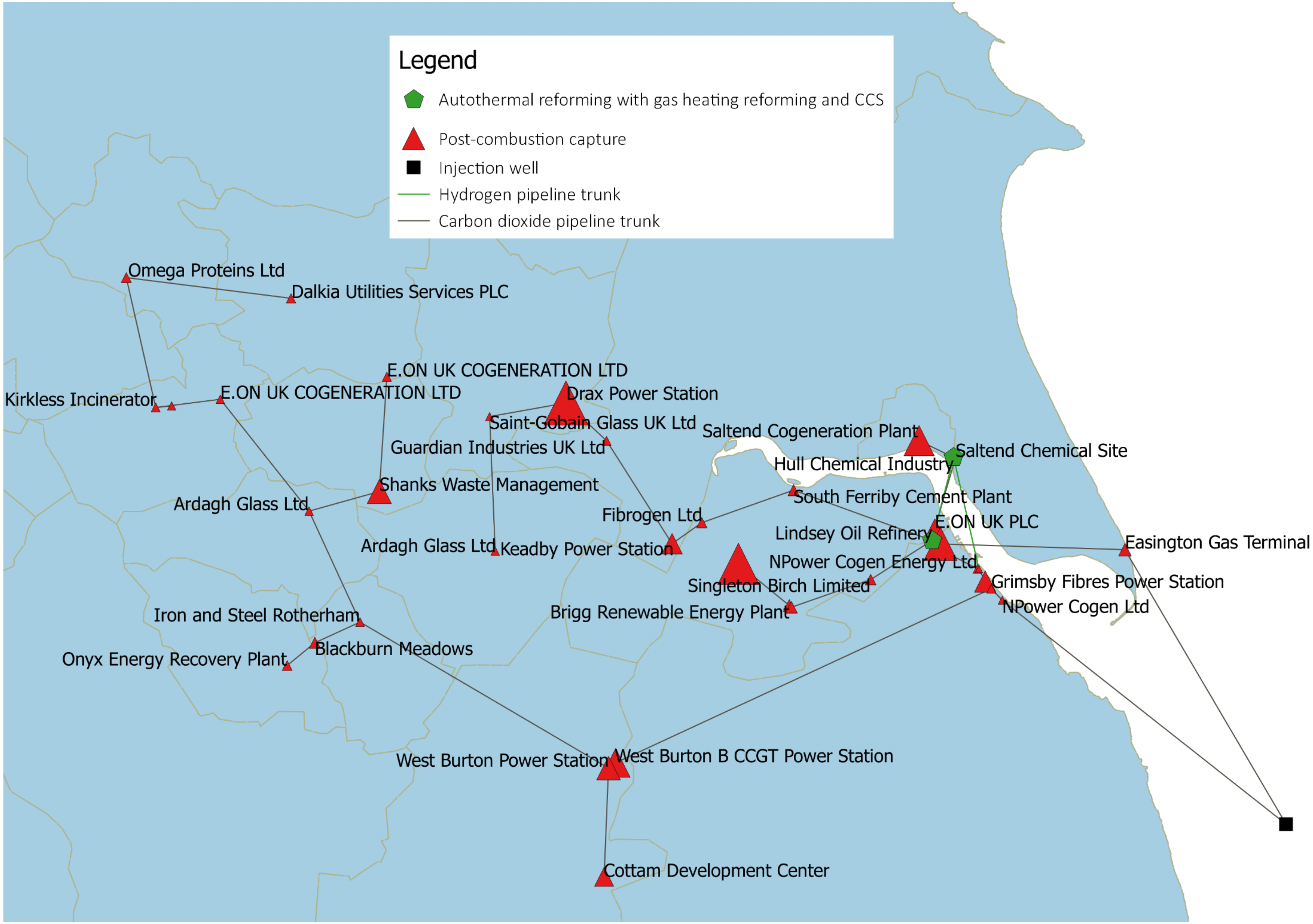
- Natural gas is assumed to be available across the region at £13/ MWh. The emissions intensity of natural gas is assumed to be 225 g CO_2/ kWh.
- Economic lifetime of 25 years and a cost of capital of 11% is used.
- Demand for heat is assumed to be time invariant across an annual timeframe with 90% availability of the processes.

Modelling overview

- Given the distribution of heat, process and power generation emissions, optimise for the least cost network for net-zero CO_2 emissions in the Humber region.

- Capital cost evaluation includes H_2 production plants and their accompanying equipment, H_2 pipelines, H_2 furnaces/ boilers, CO_2 capture facility and CHP, CO_2 piping, ducting and injection wells.

- Key outputs are total CapEx and OpEx, annualised costs, material flows, life-cycle impact indicators, equipment sizes and emission offset requirements.


Legend
Autothermal reforming with gas heating reforming and CCS
Post-combustion capture
Injection well
Hydrogen pipeline trunk
Carbon dioxide pipeline trunk
Omega Proteins Ltd
Dalkia Utilities Services PLC
E.ON UK COGENERATION LTD
E.ON UK COGENERATION LTD
Kirkless Incinerator
Drax Power Station
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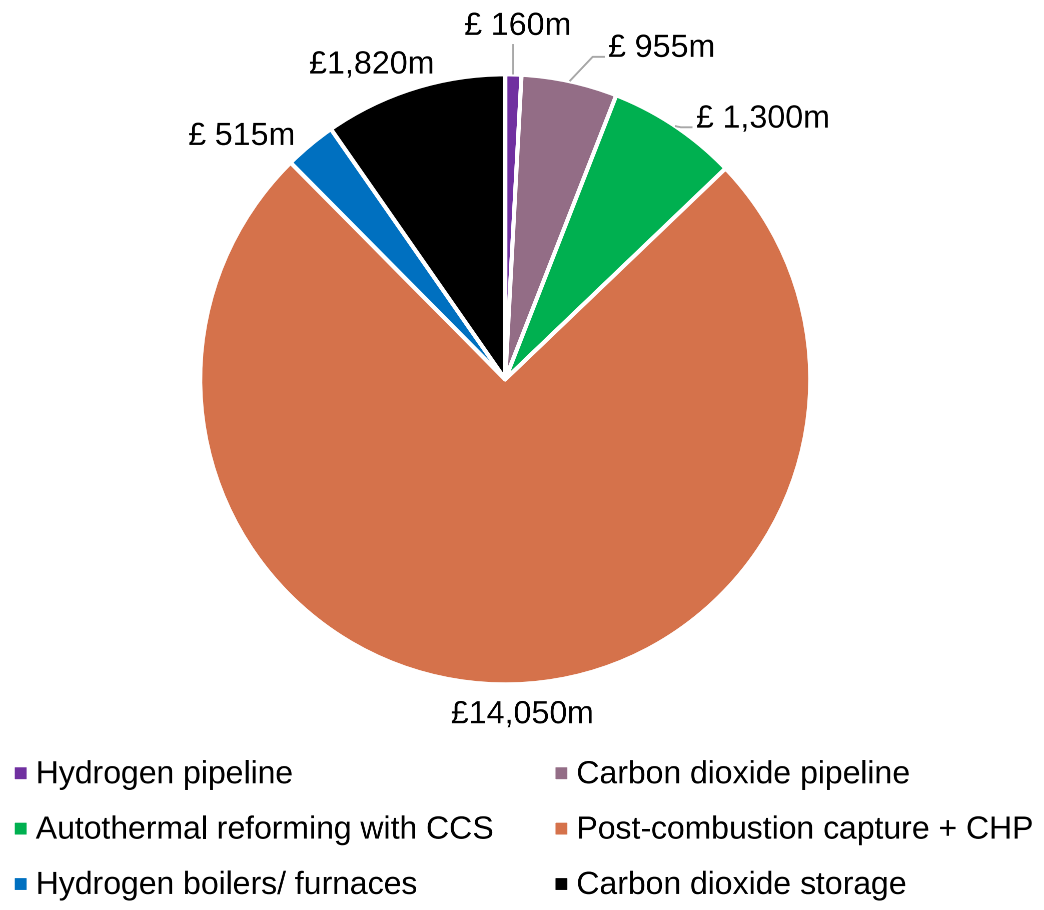
Cottam Development Center

Design statistics

	Optimal design
Total CapEx (£bn)	18.8
Annual OpEx (£m/ yr)	2210
Total annualised costs (£m / yr)	4440
Additional natural gas requirement (TWh/ yr)	65.4
CO_2 stored (Mt/ yr)	43.2
CO_2 avoided (Mt/ yr)	37.2
Emission offsets (Mt/ yr)	4.2
ATR operating capacity (GW)	2
Post-combustion operating capacity (Mt/ yr)	37.3
Overall cost of CO_2 avoidance (£/ ton)	119

CAPEX breakdown - £18.8bn

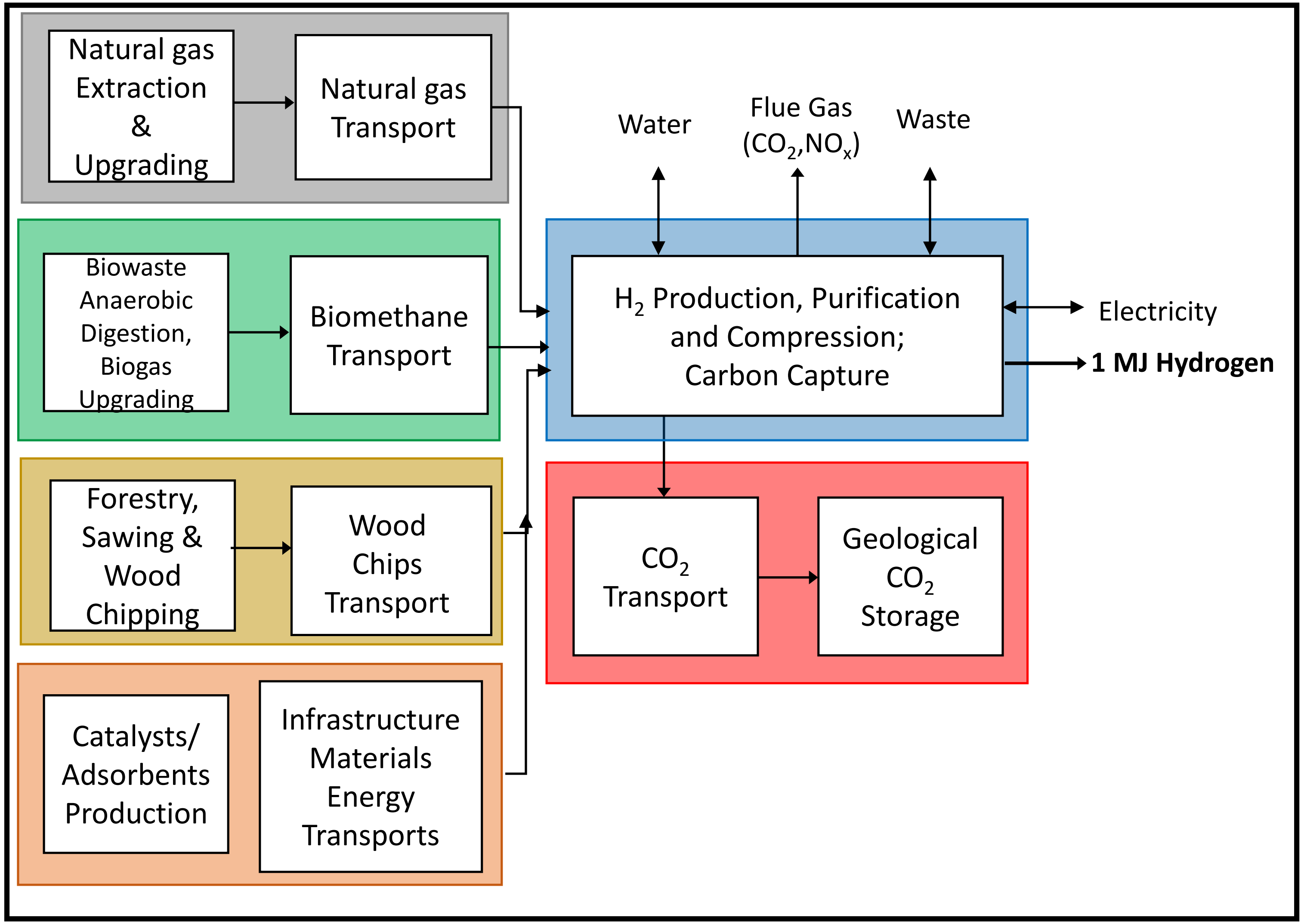


Life Cycle Impact Assessment

Indicator	**Unit**	**x^0**
Climate change	Mt CO_2 eq	2.4
Freshwater and terrestrial acidification	Mmol H^+_{eq}	37.7
Freshwater ecotoxicity	GCTU	2.54
Marine eutrophication	kt $N_{2,eq}$	6.22
Terrestrial eutrophication	Mmol N_{eq}	133
Carcinogenic effects	CTU h	156
Ionising radiation	kt U^{235}_{eq}	438
Non-carcinogenic effects	CTU h	442
Ozone layer depletion	t CFC-11	2.15
Photochemical ozone creation	kt $NMVOC_{eq}$	20.2
Respiratory effects	unit	307
Fossil use	PJ_{eq}	257
Land use	G unit	17.9
Minerals and metals	t Sb_{eq}	42.8

Life Cycle Assessment example: H_2 Production with CCS

- Allows fair benchmarking and identification of trade-offs.
- *Life Cycle Inventory (LCI)*: Datasets with all inputs and outputs related to production of 1 MJ of H_2
- *Life Cycle Impact Assessment:* Translating all LCI flows into environmental impacts/protection areas: 16 indicators on climate change, ecosystem quality, human health, resources
- The chain tool can do optimisation for these impact categories



For details on the technical and LCA modelling of H_2 production, please see recording and slides from the Work Package 1 Webinar on Monday 21st of June or Antonini, Treyer et al. 2020:

Antonini, C., Treyer, K., Streb, A., van der Spek, M., Bauer, C., Mazzotti, M. 2020. Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis. Sustainable Energy & Fuels, 2020, 4, 2967-2986

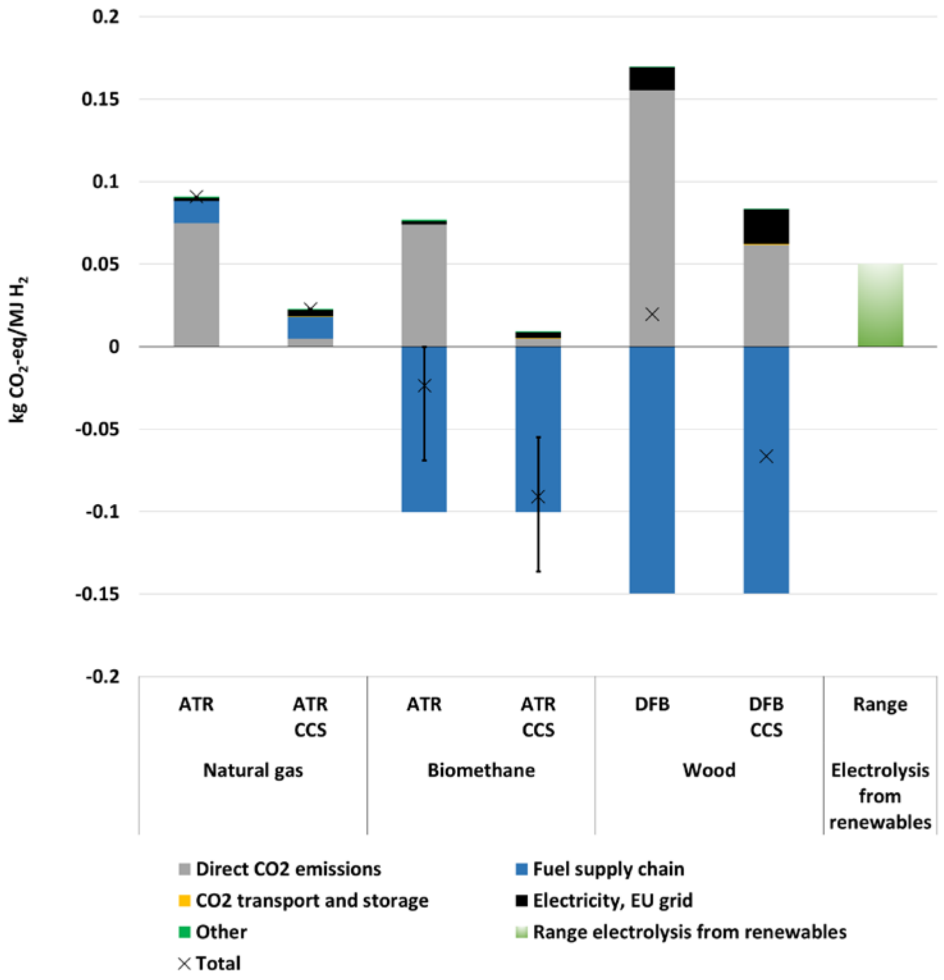
Antonini, C., Treyer, K., et al. (2020)

Life Cycle Inventories

- Foreground data: All technologies/processes/infrastructure present in the chain tool.
  - Datasets from research within Elegancy or previous research at PSI / literature / databases
  - Datasets adapted where necessary to be **consistent with the technological representation in the chain tool** (e.g. technical efficiencies, capacity).
  - E.g.: H_2/electricity/heat production, H_2/natural gas boiler, post-combustion CO_2 capture in natural gas power plant, pipelines, storage

- Background data
  - E.g. input of electricity for production of H_2, input of steel to H_2 production plant
  - Ecoinvent v3.6 database transformed into prospective LCI databases representing conditions in 2020, 2030, 2040, 2050
  - Reference year for this work: 2020

Producing H_2 and achieving zero or negative emissions

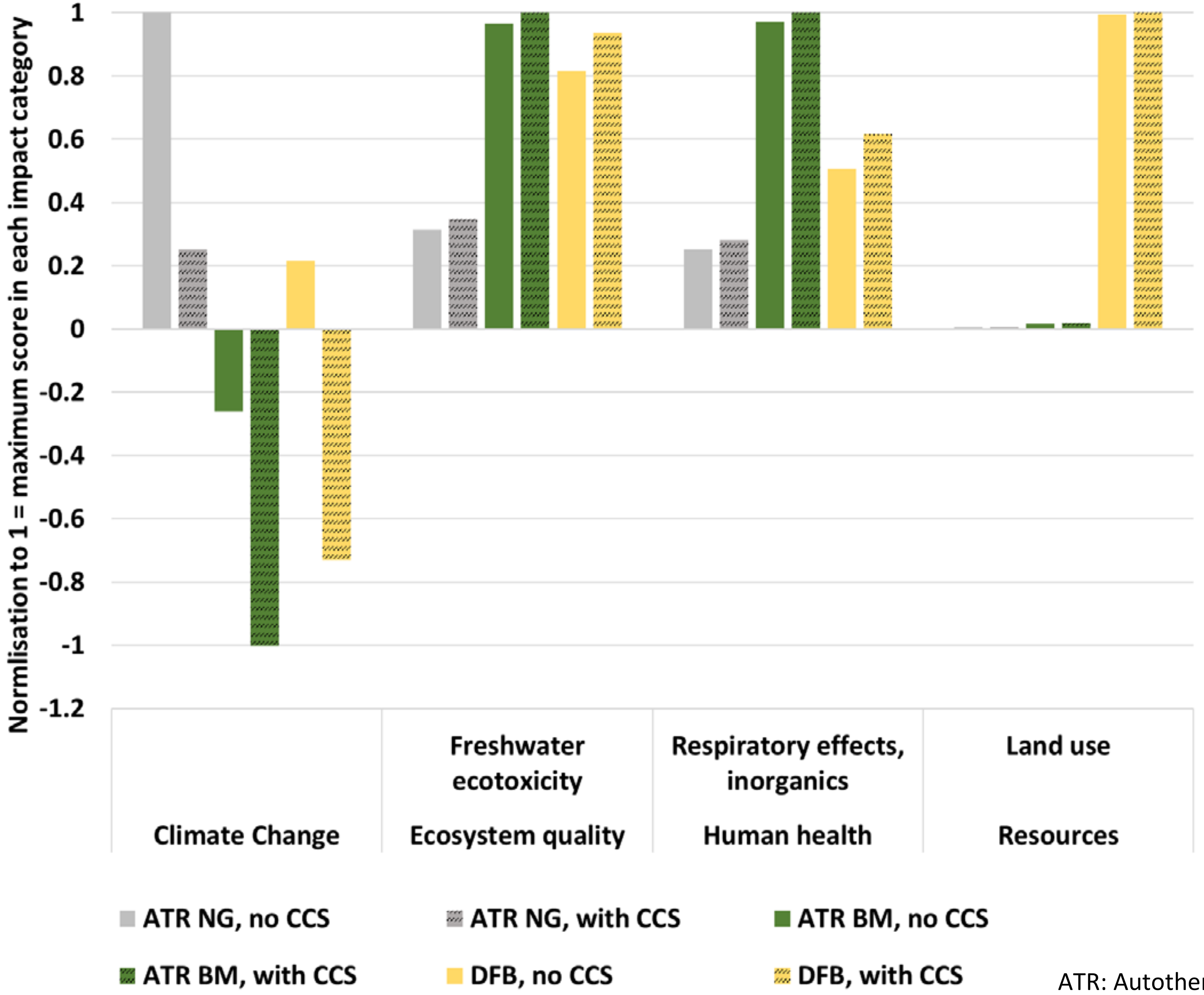


ATR: Autothermal Reforming // DFB: Steam-blown dual fluidised bed gasifier // EF: oxy-fired entrained flow gasifier // CCS: Carbon capture and storage

- Contribution analysis shows us where direct and indirect impacts happen
- **Carbon-neutral or negative emissions H_2 production possible** with both biomethane or wood as feedstock
- Combined with CCS, fossil-based hydrogen («**blue hydrogen**») is low-carbon and environmentally competitive with H_2 from electrolysis.
- A **net zero-carbon H_2 industry** can potentially be achieved by blue&green H_2 combined with negative emissions through biomethane- or wood based H_2.
- H_2 from electrolysis with renewables:
  - Hydropower: ca. 5-30 g CO_2-eq/MJ
  - Wind power: ca. 2-20 g CO_2-eq/MJ
  - Photovoltaics: ca. 20-50 g CO_2-eq/MJ

Antonini, C., Treyer, K., et al. (2020)

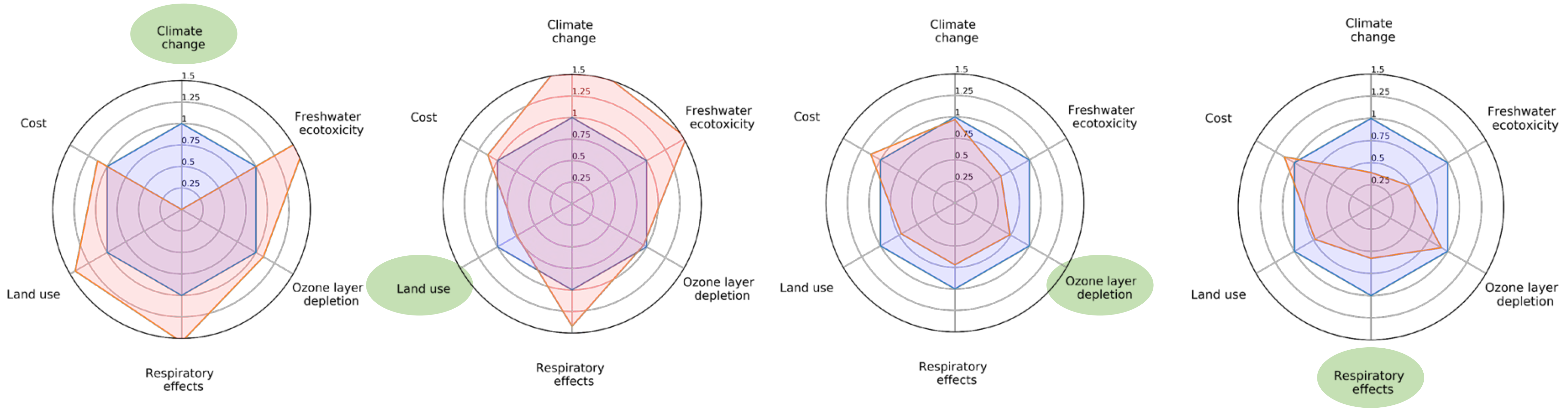
Assessing environmental trade-offs



- **CCS** generally results **in higher impacts in all categories** other than climate change
- Woody gasification (oxEF) reaches high carbon removal while performing well in most other impact categories.
- Differences between production pathways seem to be large
- Broader context of H_2 applications needed to judge the importance of these differences

ATR: Autothermal Reforming // DFB: Steam-blown dual fluidised bed gasifier // EF: oxy-fired entrained flow gasifier // CCS: Carbon capture and storage

Solution space – Humber infrastructure



Legend

- Optimisation Objective
- Cost-optimal
- LCA-optimal

Technology type	Least cost	Least climate impact	Least land use impact	Least ozone layer depletion	Least respiratory effects
Water electrolysis (MW)	0	0	1,300	1,400	400
Autothermal reforming with GHR and CCS (GW)	2	3	3	1	3
Post-combustion CO_2 capture (Mt/ yr)	35.6	31.2	35.3	37.6	35.3
Negative emissions from DFB biomass gasification (Mt/ yr)	5.3	7.5	3.8	3.8	3.8
Cost of CO_2 avoidance (£/ton)	119	131	131	131	131

Summary

- The chain tool can optimise the performance of the H_2-CO_2 system over a range of performance metrics, providing clarity to decision-makers.

- The tool has included a wide variety of features and technologies through the general-purpose programming framework.

- The tool allows including not only direct environmental impacts, but also indirect impacts from the life cycle chain.

- Model instances can be developed with advanced capabilities to analyse the deployment of infrastructure using various levels of public and private investment.

- The integrated region-specific modelling architecture can be extended to account for other processes and existing infrastructure to develop efficient pathways toward net-zero CO_2 emissions.