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Commercially resilient net-zero industrial clusters exploit the system value of low-carbon technologies and infrastructure

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Scale of the problem

- 14 $GtCO_{2,e}$ generated as direct GHG emissions from the industry sector – a quarter of global emissions.
- Indirect GHG emissions from electricity and heat use increase the share to 35% of global emissions, making it the single largest emitting sector.
- The current share of fossil fuels in industrial final energy consumption is 68% according to the latest data from the International Energy Agency.
- The demand for industrial goods is expected to increase with the projected population increases by mid-century.

Observations from literature

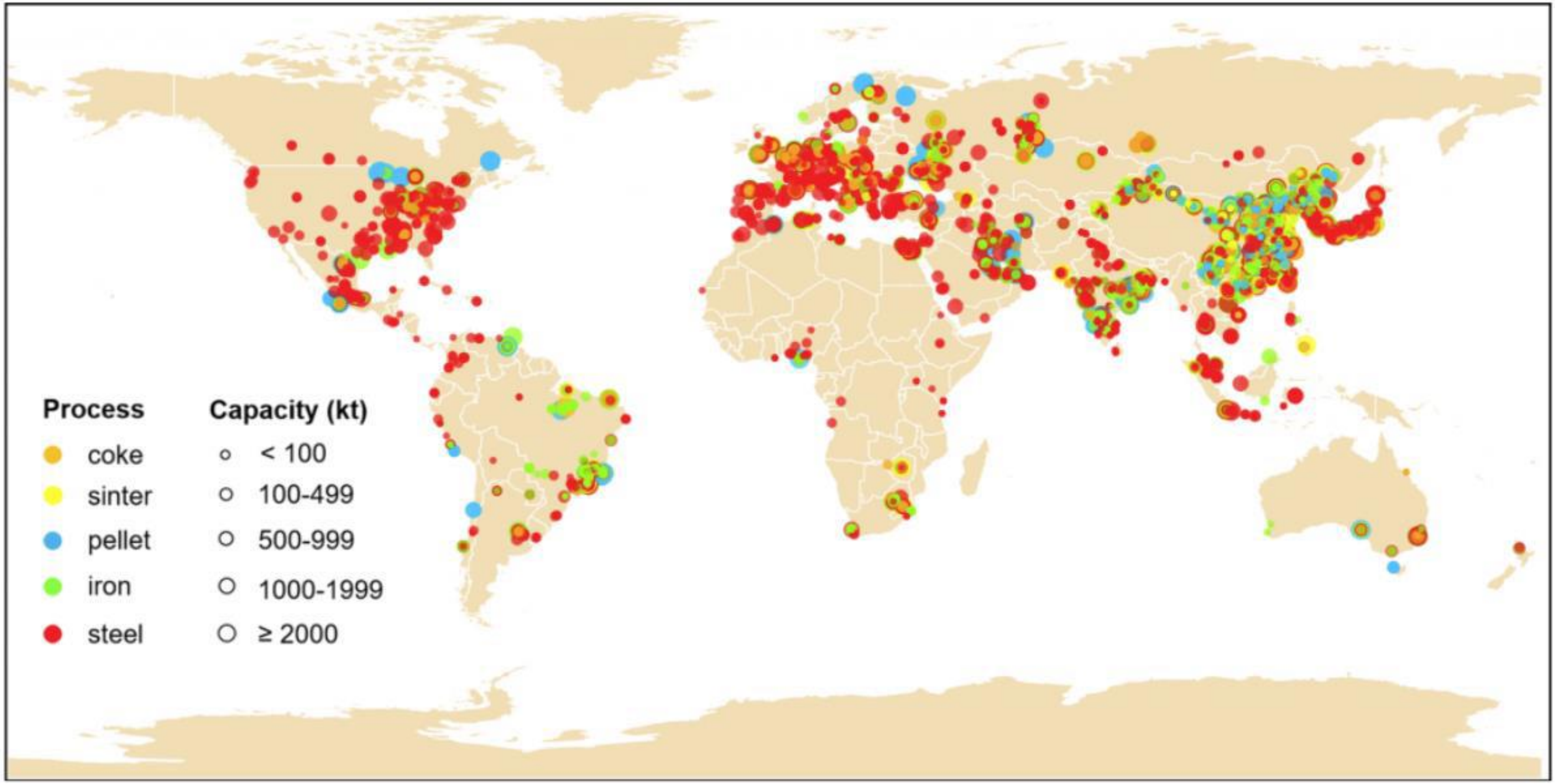
- Some generality across key decarbonisation solutions on a sector-by-sector basis, but solution strategies largely appear to be developed on a sectoral level without being focussed to the region.

- Solutions, such as energy and resource efficiency measures, increased fuel switching with renewables, and CO_2 capture and storage are most widely discussed in the academic and grey literature.

- Energy efficiency improvements can reduce emissions by 10 – 15%.

- Electrification, CO_2 capture, and hydrogen use in industry can account for a significant share of the overall decarbonisation solution depending on the industry type.

- Residual emissions in industry are very rarely discussed and the role of CO_2 removal technologies are poorly defined.



Map of global iron & steel infrastructure (*Global Infrastructure Emissions Database, n.d.; Wang, et al., 2019*)

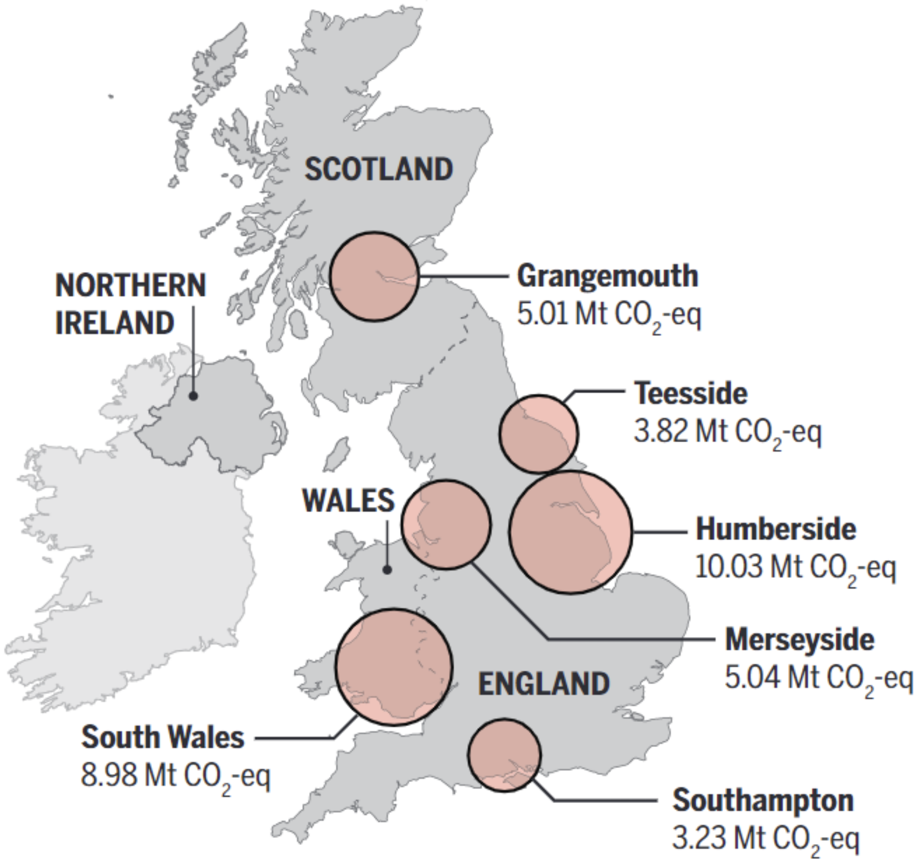
Clusters instead of sectors?

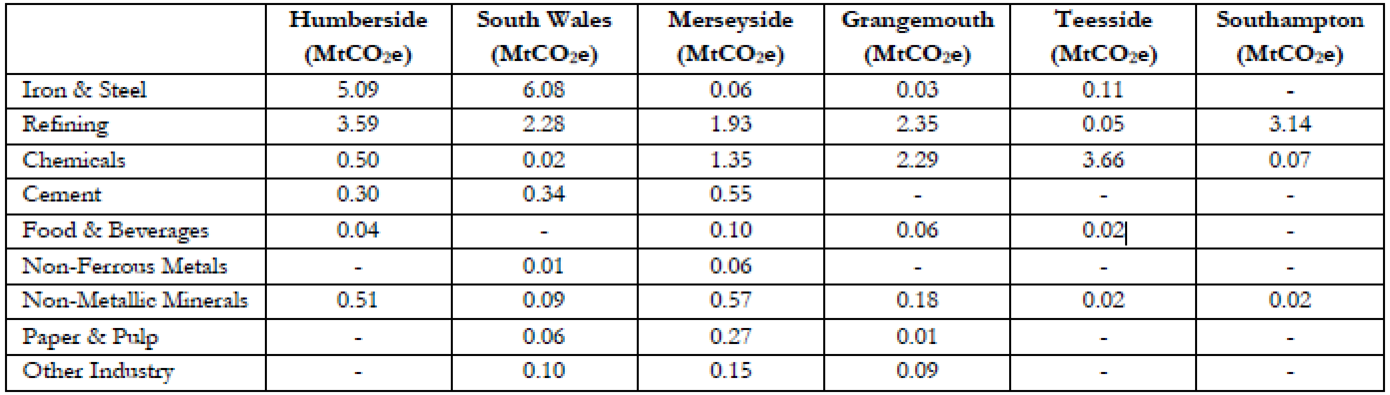
- Clusters of industries (agglomerated in space) offer synergies for decarbonisation.

- Cost-reduction opportunities from cluster-based solutions.
  - Sharing CO_2 transport and storage infrastructure with multiple industrial users.
  - Centralised hydrogen and electricity production plants which leverage economies of scale.
  - Using refinery fuel gases as feedstock for hydrogen production for industrial users.
  - Using industrial waste heat in adsorption DACCS process to reduce energy costs.
  - Using process waste as a feedstock in a circular economy/ symbiosis framework.

- Composition of the cluster and risk tolerance of industrial stakeholders will influence the nature of solution portfolios.

Industrial clusters in the UK





	Humberside ($MtCO_2e$)	South Wales ($MtCO_2e$)	Merseyside ($MtCO_2e$)	Grangemouth ($MtCO_2e$)	Teesside ($MtCO_2e$)	Southampton ($MtCO_2e$)
Iron & Steel	5.09	6.08	0.06	0.03	0.11	-
Refining	3.59	2.28	1.93	2.35	0.05	3.14
Chemicals	0.50	0.02	1.35	2.29	3.66	0.07
Cement	0.30	0.34	0.55	-	-	-
Food & Beverages	0.04	-	0.10	0.06	0.02	-
Non-Ferrous Metals	-	0.01	0.06	-	-	-
Non-Metallic Minerals	0.51	0.09	0.57	0.18	0.02	0.02
Paper & Pulp	-	0.06	0.27	0.01	-	-
Other Industry	-	0.10	0.15	0.09	-	-

UK industrial cluster emissions (Sovacool et al., 2022)

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Clusters are different, as are the solution strategies

How do we decarbonise a cluster?

- We use a mathematical model using process systems engineering principles to evaluate a cost-optimal and resilient pathway to net-zero GHG emissions. It is an adapted mixed integer programming framework, originally developed for task allocation problems by Pantelides.
- Firstly, we identify the emitting facilities and disaggregate their direct emissions based on their origin – industrial processes, or heating and cooling.
- Secondly, we estimate the demand for heating and cooling using the existing portfolio of fuels used by the emitter (using academic literature).
- Thirdly, we explore the performance of different technologies under varying assumptions and identify their implications for reaching net-zero.

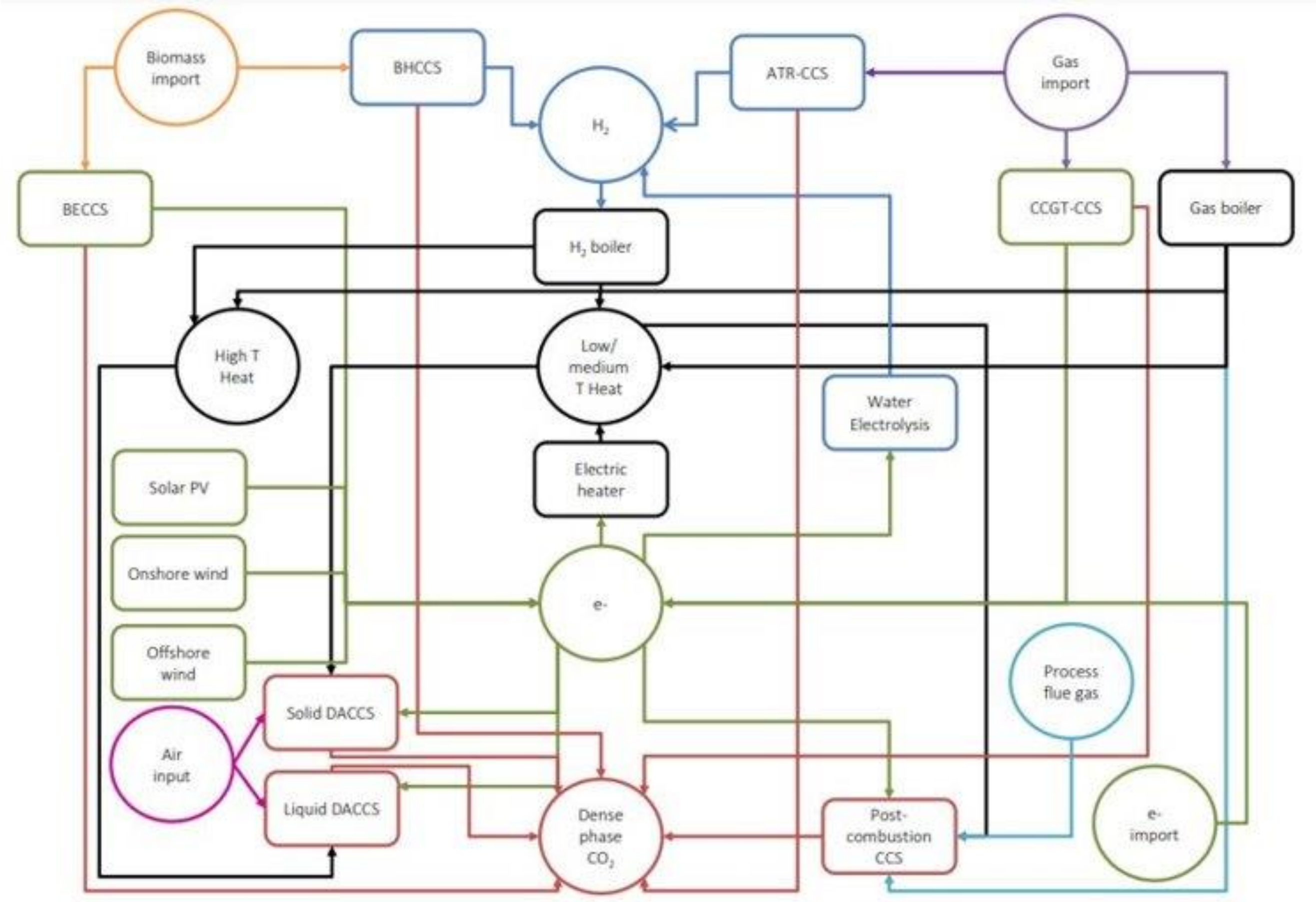
Sunny, N., Bernardi, A., Danaci, D., Bui, M., Gonzalez-Garay, A. and Chachuat, B., 2022. A Pathway Towards Net-Zero Emissions in Oil Refineries. *Frontiers in Chemical Engineering*, *4*, p.4.

Küng, L., Strunge, T., Sunny, N., Nie, Z., Tariq, N., Korre, A., Shah, N. and Van der Spek, M., 2022. An Open-Source Toolkit to Design and Evaluate Net-Zero Pathways for Industrial Clusters. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16).

Model and data architecture

Regional input data	QGIS Renewables.ninja
Optimisation framework	PYOMO
Solvers	GUROBI OPTIMIZATION IBM CPLEX

Model function

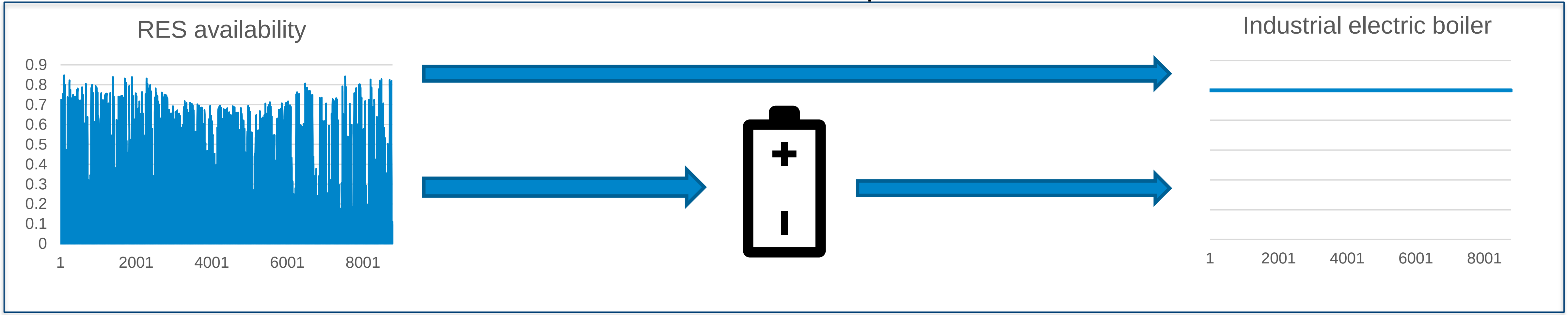


- Input data on the techno-economic performance of all technologies – CapEx, OpEx, efficiency, lifetime, maintenance schedules, etc.

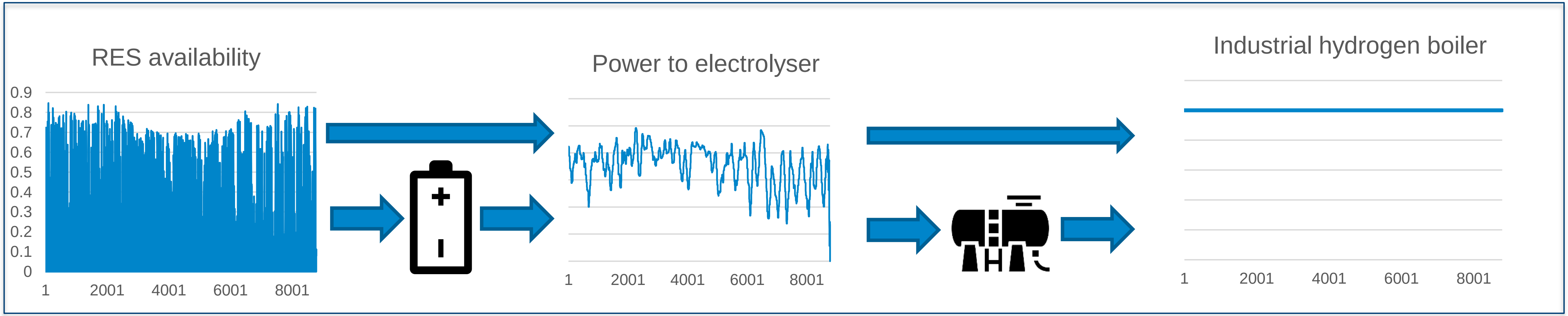
- Key decision variables – size and location of low-carbon technologies, transport, and storage infrastructure. Operation profile of the assets.

- Outcomes – a cluster-specific trajectory to reach net-zero emissions and an investment pipeline for planning.

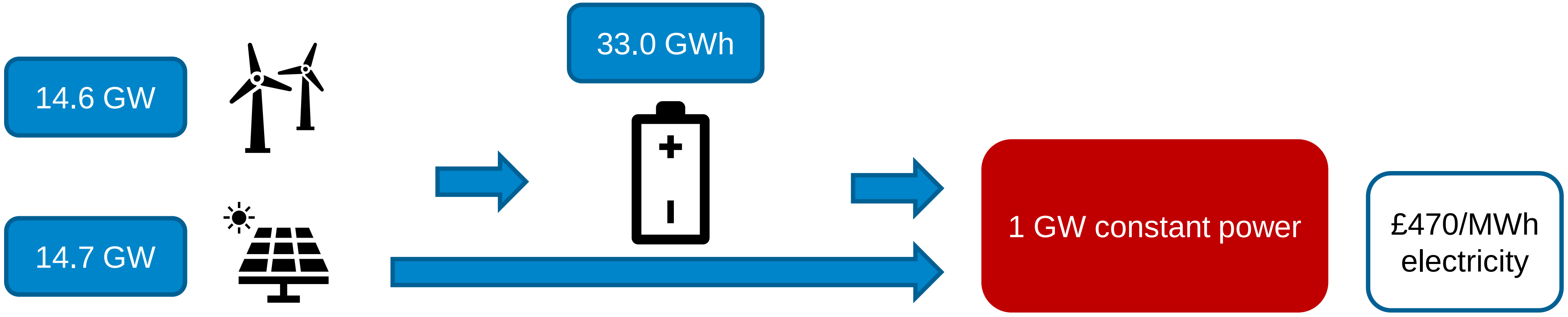
Reliable renewable power



Reliable green hydrogen



Results: Reliable renewable power



14.6 GW

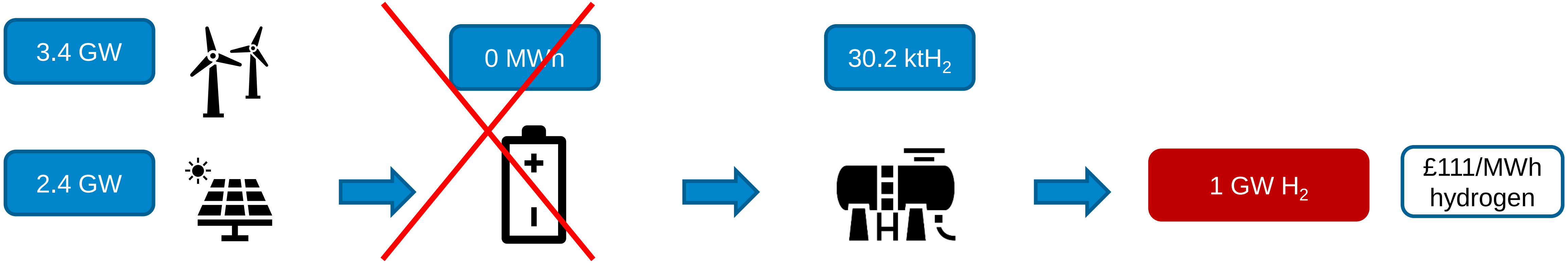
14.7 GW

33.0 GWh

1 GW constant power

£470/MWh electricity

Results: Reliable green hydrogen



3.4 GW

2.4 GW

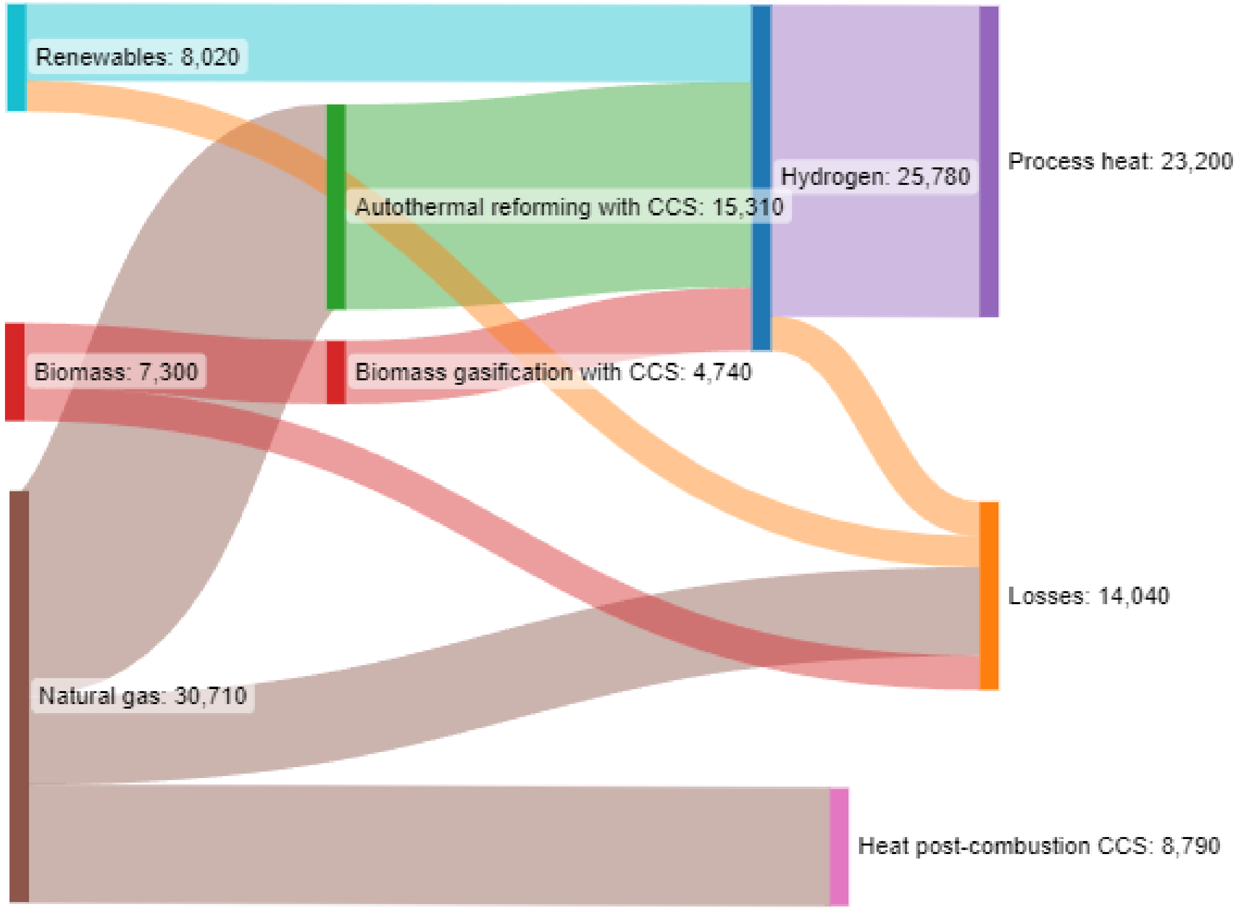
~~0 MWh~~

30.2 ktH_2

1 GW H_2

£111/MWh hydrogen

Results: Cost-effective energy mix (GWh/yr)



- A cost-effective energy mix in a decarbonized Humber cluster relies on post-combustion CO_2 capture for tackling process emissions, fuel switching with hydrogen, and carbon offsets.
- Reforming with CCS dominates the hydrogen supply even at high gas prices. However, the share of hydrogen from gasification increases with the availability of biomass.
- The total final energy consumption increases significantly in a decarbonized future relative to current operation.
- Overall energy losses increase from approximately 3 TWh/yr to 14 TWh/yr, presenting an opportunity for waste heat recovery and industrial integration.

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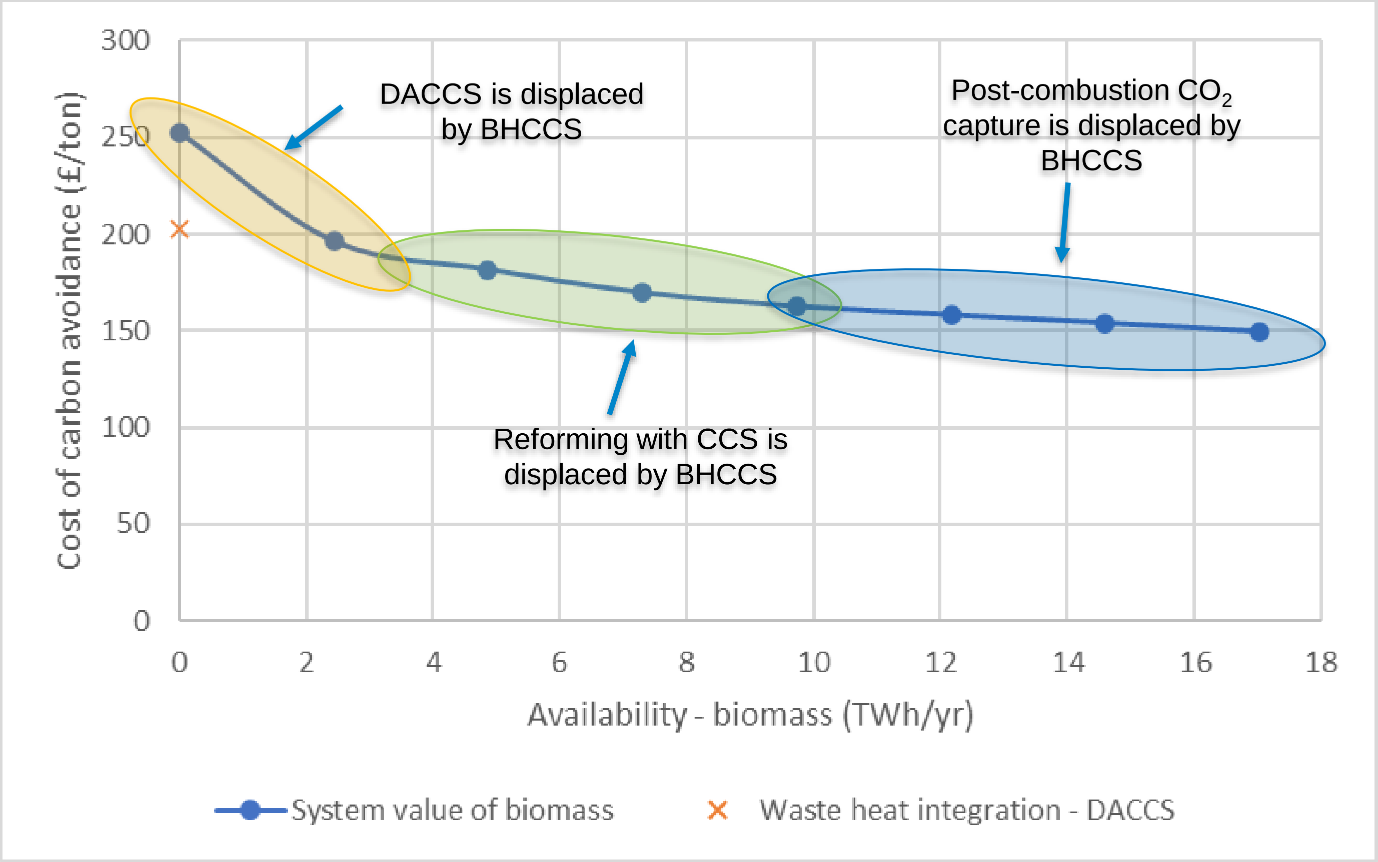
Results: System value of biomass



- Waste heat integration reduces the cost of carbon avoidance (by ~ £50/ton) in the Humber industrial cluster.
- Biomass is highly valuable in industrial clusters as it provides the least-cost route to zero-carbon heating and negative emissions. However, the availability of sustainable biomass is limited.

Summary

- The global industrial sector is highly challenging to decarbonize and will require a highly regionalized solution strategy.

- We have developed a mathematical framework which can be applied to any region with a very high spatial and temporal granularity to solve design problems. The model is flexible and generates insights for all stakeholders involved in an industrial decarbonization project, especially project developers, regional authorities, policy makers, etc.

- A resilient portfolio of solutions combine post-combustion CCS, biomass gasification with CCS, natural gas reforming with CCS, and renewable energy, with associated transport and storage infrastructure.

- The costs of CO_2 abatement could range between £130 - 260/ton depending on the variabilities in fuel prices and system configurations. The lowest costs are achieved in cases where refinery fuel gases are used in autothermal reformers, excess heat is used in adsorption DACCS, and uses low-cost fuels.