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TIMES model industry sector update

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1 Executive summary

1.1 Aims and findings

Scottish TIMES is a whole system energy model of Scotland. It models all key areas of the energy system, from generation, transportation and end use, and all key sectors of the economy. It is used by the Scottish Government as an analytical tool to support the development of climate change and energy-related policies and plans, such as the Climate Change Plan. The industrial sector is a key sector within TIMES as many of its outputs are used by other modelled sectors and are therefore inherently linked. Inaccuracies in the industrial sector data could potentially have large implications for the rest of the model, under- or over-estimating costs and emissions.

The aim of this project was to update and improve the current assumptions in Scottish TIMES relating to the industrial sector. We reviewed and updated key data related to variables such as cost and process efficiency and checked them against the latest sector, industry, or academic research to ensure they are up to date and that they provide an accurate representation of the technologies and processes within the sector. This, therefore, provides an accurate set of data on how much each sector contributes to Scottish greenhouse gas emissions. To do this we reviewed the following sectors: carbon capture usage and storage (CCUS), hydrogen, biofuels, petroleum refining, chemicals, cement, food and drink, iron and steel, paper products, non-ferrous metals (e.g. aluminium and copper), non-metallic minerals (e.g. sand, gravel, limestone, clay, and marble) and other industries.

Note that the scope of this work is only to review the industrial processes parameters and provide replacement data where required/justified. It did not extend to considering the net impact of these changes in any given TIMES scenario or any individual change upon a TIMES solution. This has not been analysed as this falls outside the remit of this work.

The review has led to updating of a range of parameters such as capital and operating cost, process efficiency, expected operational life and technology availability date for the industrial processes across sectors where such data was available. This included data for new and emerging technologies such as CCUS and hydrogen, along with traditional industrial sectors such as oil refining and chemicals. As TIMES is a cost optimised model that selects the lowest cost technology option, updating these parameters could have significant implications on which technologies are selected and how they are operated under different decarbonisation scenarios.

We expected that data on commercially-available technology would be readily available, but we were surprised to find that this was not always the case. In fact, we found it easier to get information on emerging processes and industries that may not be commercially available yet, such as hydrogen production and carbon capture and storage. This could be due to commercial sensitivities around cost and operational data, and to the complexity of certain processes, such as oil refining sites that incorporate a vast range of industrial processes. In cases where we faced such challenges, we engaged with industry and other relevant stakeholders to discuss approximate parameter values and test assumptions.

As well as updating data across the range of industrial processes, our review also identified several new processes for inclusion, such as hydrogen above ground storage, and recommended the removal of others such as hydrogen salt cavern storage, as these are not available in Scotland. The findings from the review suggest that to simplify the TIMES database, some existing processes could be merged, such as some low temperature heat processes, which are based on the same type of technology (e.g. boilers), but using different input fuels (e.g. gas or hydrogen). The review updated data for industrial processes that are common across a range of sectors, such as motor drive (any industrial process that includes a motor), low and high temperature heating, drying and refrigeration.

1.2 Recommendations

This review has successfully updated data and processes within the TIMES database. In many cases, the available data was enough to allow us to successfully update the model. However, relying on publicly available data has limitations.

As a result of our research, we recommend the following:

- A further review to understand how more Scottish site-specific data for specific industrial processes could be used to inform the Scottish TIMES model. This would ensure that the outputs from TIMES are based on accurate assumptions for industrial processes at Scottish industrial sites. This would ultimately build confidence around the TIMES model and its outputs and the decarbonisation scenarios and policies developed from them.
- Further scrutiny and review of the updated parameters once they are incorporated into the model and implications on outcomes are understood. We would recommend focusing on key processes that are important for delivering net zero targets, such as carbon capture, transport and storage. Sensitivity analysis should be conducted around the parameters to establish effects on model results, and further improvement of estimates sought, if deemed necessary.

Contents

2 Glossary

CAPEX	Capital expenditure
CCUS	Carbon, Capture, Utilisation and Storage
CCS	Carbon, Capture and Storage
CHP	Combined Heat and Power
DAC	Direct Air Capture
GHG	Greenhouse gases
NETs	Negative Emission Technologies
NGO	Non-Government Organisation
OPEX	Operational expenditure
TIMES	The Integrated MARKAL-EFOM System

3 Introduction

3.1 Project aim

The aim of the project was to update and improve the current assumptions in Scottish TIMES relating to the industrial sector. We achieved this by reviewing and updating data, and checking against the latest sector, industry, or academic literature. We ensured that the data was current and that it provided an accurate representation of the technologies and processes within the sector.

3.2 Project rationale

Scottish TIMES is a whole system energy model of Scotland. The Integrated MARKAL-EFOM System (TIMES) is a bottom-up energy system-wide model. The TIMES model generator is developed by the Energy Technology Systems Analysis Programme (ETSAP), which is part of the International Energy Agency (IEA-ETSAP, 2022). TIMES has been used widely to analyse different policy questions including decarbonisation scenarios, or the energy system impacts of specific technologies and policies (Calvillo and Turner, 2020). TIMES considers all the processes that transform, transport, distribute and convert energy to supply energy services. The inputs of the model are service demand curves, supply curves (e.g., primary energy resources such as wind power or availability of imports), and techno-economic parameters for each technology/process (e.g., technology efficiencies and availability factors, investment cost per capacity unit, operation and maintenance (O&M) cost per unit of production, etc.). The outputs include energy flows, costs, technology installed capacities and emissions, etc. More detail in the TIMES model can be found in (Calvillo et al, 2017).

TIMES is used by the Scottish Government to support the development of climate change and energy-related policies and plans, such as the Climate Change Plan. It does this by providing up-to-date and accurate information on the greenhouse gases (GHGs) produced across society, and the costs associated with different decarbonisation scenarios, including industrial processes, which are the focus of this project. Accurately representing industrial processes is important because its outputs are used by other sectors and are therefore inherently linked. Moreover, certain industrial processes are important contributors of (GHG emissions. Inaccuracies in the industrial sector data could have large implications for the rest of the model, under or over estimating costs and emissions. Currently, the representation of the industrial sector is highly complex, with a large number of processes. This complicates updating technology assumptions and investigating scenarios results, which is crucial for understanding how decarbonisation targets can be met. Therefore, there is a need to simplify the representation where possible, and check the quality of the data.

TIMES is currently being updated to use for the next Climate Change Plan. This project will help deliver the Scottish Government’s climate change priorities through a more accurate and up-to-date representation of the technologies and processes of the Scottish industrial sector. Improved modelling of this sector will support a more robust analysis and assessment of the options for decarbonisation across the industrial sub-sectors included in the model.

3.3 Policy context

Following the recommendations of the UK Climate Change Committee (CCC) for the 6th Carbon Budget, the UK Government has legislated a new target to cut greenhouse gases emissions by 78% from 1990 levels by 2035 (UK Government, 2021) and reach net zero emissions by 2050. In Scotland, a more ambitious target of reducing emissions by 75% by 2030 compared to 1990 levels was ratified in the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 (Climate Change Act, 2019) along with a net zero target for 2045. In 2018, industrial emissions accounted for 28% of Scotland's emissions and the sector has the second highest contribution after transport. As outlined in the Climate Change Plan Update (Scottish Government, 2020), emissions from the industrial sector need to decrease by 43% on 2018 levels by 2032. As noted in a recent SPICe briefing (Scottish Parliament Information Centre, 2020), this ambitious target is supported by an expectation that the total decarbonisation of the industrial sector will be possible through widespread deployment of carbon capture and storage (CCS), fuel switching (e.g. hydrogen) and negative emission technologies (NETs).

Estimating the emission contributions, investment, and operational costs of systems for industrial decarbonisation in Scotland requires adequate costs models, and detailed information on technology performance and emissions characteristics. This is especially important when emerging technologies and processes such as fuel switching with hydrogen and CCS are envisaged as essential to meet ambitious decarbonisation targets now only decade away. With this information, it is then possible to use energy system models, such as TIMES, to estimate feasible least cost pathways to transition into a low carbon industry and a net zero world. However, confidence in the results that models such as TIMES produce can only be high if the model inputs and the data they are based on are robust. This is where research, such as that proposed in this project specification, can play a crucial role in supporting the evidence base needed to understand the feasible options available for decarbonising.

3.4 Research methodology

3.4.1 Overview of methodology used

The research methodology combined a blend of desk-based literature reviews from publicly available sources, data and cost model analysis and a small number of stakeholder interviews. The literature review focused on relevant available literature, studies, and collection of data from recognised and referenced sources. The list of sources used for the review includes, but is not limited to, the following examples:

- Academic publications and scientific databases such as Science Direct, IEEE Xplore, and Scopus.
- Specialised reports and data from relevant institutions, e.g. the International Energy Agency Greenhouse Gas Research and Development Programme (IEAGHG), and government agencies and non-governmental organisations both in the UK and overseas, such as the Department for Business, Energy and Industrial Strategy (BEIS), National Renewable Energy Laboratory (NREL) and others.
- The University of Strathclyde library database, which has access to millions of books, reports, publications and other relevant sources of information.

Additionally, we consulted with several industry experts and other stakeholders to test and complement the data and/or to flag key processes missing.

The project took a stepped approach, reviewing and updating data and assumptions of one industrial sub-sector at a time, and submitting each sub-sector as it is complete (as opposed to one final submission at the end of the project).

The Scottish Government proposed the list of priorities. They took into account the emission levels as well as dependencies of down-stream processes. As each block was completed, the updated data was reported back to Scottish Goverment for review and inclusion in TIMES at the earliest opportunity. The initial priority sectors for review agreed with the Scottish Government were CCUS, hydrogen, bio fuels and petroleum refining, followed by chemicals, cement and food and drink; and lastly, iron and steel, pulp and paper, non-ferrous metals, non-metallic minerals, and other industries.

Another key part of our methodology was unit conversion. The cost models and data available in the literature use different monetary units (typically USD or EUR) from different years. To allow for a consistent cost updating, all costs were translated to monetary units used by the Scottish TIMES model, which is Pounds Sterling (GBP, £) for the year 2015. We converted these costs using historical exchange rates from UKForex Limited (2021) and translating to the year 2015 using the annual inflation rate from the Bank of England (2021). Similarly, all energy or capacity units were converted to the appropriate units for the Scottish TIMES model, which typically uses peta Joules (PJ)[1] for energy and peta Joules per year (PJ_annum)[2] for power/capacity.

3.4.2 The suitability, robustness and limitations of the methodology

Desk based research and literature reviews are suitable methodologies to find, test and update techno-economic and other performance parameters and assumptions of industrial technologies and processes. The amount of available literature and data online plus the extensive research experience from the project team provide robustness to the methodology. The main potential limitation of the methodology was that data on some technologies may be more limited than others. This potential limitation was addressed by using expert knowledge from relevant industrial stakeholders and/or the use of proxies from other technologies or processes. When this was the case, we discussed the assumptions with the Scottish Goverment.

4 Sector specific updates

This section explains in detail the updates recommended to the Scottish Government in each sector that we looked at. A full list of the sectors we reviews is:

- Hydrogen production, liquefaction, network infrastructure and storage
- CO2 Transport and Storage
- CCS Processes
- Oil Refining
- Chemicals
- Cement
- Iron and steel
- Food and drink

[1] Joules (J) are a typical unit to measure energy, and a peta Joule PJ is $1x10^{15}$ Joules. For reference 1kWh = 3600000J, and 1PJ = 277.78 GWh.
[2] Peta Joules per year or annum (PJ_annum) is used here as a capacity unit for processes. This can be translated as the maximum energy input a process can use per year.

- Pulp and paper
- Non-Ferrous Metals Technologies, Non-Metallic Minerals Technologies, and Other industries

4.1 Hydrogen production, liquefaction, network infrastructure and storage

4.1.1 Sector context

The use of hydrogen in the industrial sector is seen as one of the key options for decarbonising industrial processes and sites. This is particularly true for industries reliant on high temperature processes that currently use furnaces or turbines fuelled by natural gas. The use of hydrogen in industrial processes requires a number of different component parts such as production, liquefaction, network infrastructure to transport hydrogen and storage infrastructure.

4.1.2 Overview of updates to sector

Table 1: Hydrogen sector update summary

Subsector	Update	Reference type
Hydrogen production	Process parameters, including capital and operating costs updated across range of hydrogen production methods including hydrogen from SMR and electrolysis	Government / NGO report Example: Department for Business, Energy & Industrial Strategy. 'Hydrogen Production Costs 2021', 17 August 2021. https://www.gov.uk/government/publications/hydrogen-production-costs-2021
Hydrogen liquefaction	Process parameters, including capital and operating costs updated	Government / NGO report Example: U.S. Department of Energy. 'Current Status of Hydrogen Liquefaction Costs'. DOE Hydrogen and Fuel Cells Program Record. US Government, 9 September 2019. https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf.
Hydrogen network infrastructure	Process parameters, including capital and operating costs updated across range of hydrogen transport options such as transmission network, distribution network and road tanker.	Government / NGO report Example: U.S. Department of Energy. 'Hydrogen Delivery Scenario Analysis Model'. Accessed 16 February 2023. https://hdsam.es.anl.gov/index.php?content=hdsam.
Hydrogen storage	Capital and operating costs updated across a range of	Academic publication Example:

	hydrogen storage methods including gas field, salt cavern and above ground storage.	Epelle, Emmanuel I., et al., ‘Perspectives and Prospects of Underground Hydrogen Storage and Natural Hydrogen’. Sustainable Energy & Fuels 6, no. 14 (12 July 2022): 3324–43. https://doi.org/10.1039/D2SE00618A.

Summary of updates:

- Most of the existing data was successfully updated with recent data sources, including capital expenditure (CAPEX), operational expenditure (OPEX), technical lifetime of the process, start year for new investments (i.e. when the technology becomes commercially available) and technical efficiency of the process.
- We considered three hydrogen electrolysis production technologies (alkaline, proton exchange membrane PEM, solid oxide electrolysis SOE) to compute an average CAPEX and OPEX.
- New hydrogen storage technology (above ground) was found and added.

4.1.3 Challenges, issues and considerations

- Data source for hydrogen production from waste was not found
- Salt cavern storage not available in Scotland, and therefore, not considered

4.2 CO2 transport and storage

4.2.1 Sector context

CO2 transport and storage is a key component of the CCUS sector needed to transport captured CO2 to permanent geological storage sites. CO2 transport and storage could be used to service a number of industrial processes that capture or produce CO2 and require it to be taken offsite to storage. This might include existing industrial processes like cement production, but could also include emerging sectors like blue hydrogen production or direct air capture (DAC). Large scale CO2 transport can take place through pipelines similar to that used for oil and gas, or through shipping. Although CO2 is transported in large scale pipelines in other parts of the world (such as the US) transporting and storing CO2 at large scale is not something currently undertaken in Scotland or the UK.

4.2.2 Overview of updates to sector

Table 2: CO2 transport and storage sector update summary

Subsector	Update	Reference type
CCUS pipeline transport	Capital and operating cost data updated	Academic publication Example: Calvillo, Christian, Julia Race, Enrong Chang, Karen Turner, and Antonios Katris. ‘Characterisation of UK Industrial Clusters and Techno-Economic Cost Assessment for Carbon Dioxide Transport and Storage

		Implementation'. International Journal of Greenhouse Gas Control 119 (1 September 2022): 103695. https://doi.org/10.1016/j.ijggc.2022.103695
CO2 Storage	Capital and operating cost data updated	Academic publication Example: Calvillo, Christian, Julia Race, Enrong Chang, Karen Turner, and Antonios Katris. 'Characterisation of UK Industrial Clusters and Techno-Economic Cost Assessment for Carbon Dioxide Transport and Storage Implementation'. International Journal of Greenhouse Gas Control 119 (1 September 2022): 103695. https://doi.org/10.1016/j.ijggc.2022.103695

Summary of updates:

- CCS transport and storage was not initially included in the subset of processes we were originally asked to review. However, we considered these to be important processes that needed updating, so we included them.
- Current processes were missing CAPEX and OPEX, we have updated this based on relevant literature – considering the pipeline network costs for the Grangemouth cluster and storage sites in the North Sea.
- Pipeline costs update is based on both onshore and offshore pipeline components of the costs available in the literature.

4.2.3 Challenges, issues and considerations

- We have made a suggestion to merge the three CO2 storage types (near shore, offshore, aquifer) into a representative one that considers a cost range. This is motivated from reviewing the literature, where it is apparent that CO2 storage costs are very site specific, with a multitude of factors affecting the cost beyond the shore proximity and/or type of storage (e.g. aquifer or depleted gas fields). For example, the depth to the sea floor, depth of the storage reservoir (for drilling), the number of wells required, and the storage capacity of the site, are likely to have a larger impact of potential storage costs. Therefore, our suggestion to merge the storage processes, considering a cost range, due to lack of detail across the current three types which would allow for a more adequate cost representation.
- We also suggest adding CO2 shipping as an alternative transport option. Recent industrial decarbonisation plans and roadmaps, such as the Scottish Net Zero Roadmap are considering shipping as a transport option for CO2 coming from industries in Scotland, and potentially from the rest of the UK and internationally.
- In our engagement with stakeholders, it was remarked the importance of considering CO2 imports, as a way to reduce T&S costs via economies of scale, making the sector more competitive. We believe that this may be outside the Scottish TIMES model remit, but we wanted to highlight the issue for consideration.

4.3 CCS processes

4.3.1 Sector context

The CCS processes sector in TIMES represents industrial processes linked to carbon capture. Alongside, fuel switching and electrification, carbon capture is a key option for decarbonising industry and can be applied to a range of processes where fuel switching may not be viable. Carbon capture can be undertaken through a range of different technologies and sectors such as power generation, heat production for industrial processes, hydrogen production, and chemicals production. Carbon capture is undertaken at various sites internationally and on a small to medium scale at a number of existing industrial sites around the UK.

4.3.2 Overview of updates to sector

Table 3: CCS sector update summary

Subsector	Update	Reference type
Oil refining with CCS retrofit	Process parameters, including capital and operating costs updated for the CCS retrofit process.	Academic paper Example: Berghout, Niels, Hans Meerman, Machteld van den Broek, and André Faaij. 'Assessing Deployment Pathways for Greenhouse Gas Emissions Reductions in an Industrial Plant – A Case Study for a Complex Oil Refinery'. Applied Energy 236 (15 February 2019): 354–78. https://doi.org/10.1016/j.apenergy.2018.11.074.
Combined heat and power (CHP) with CCS	Process parameters, including capital and operating costs updated	Academic papers and Government / NGO reports Example: Berghout, Niels, Hans Meerman, Machteld van den Broek, and André Faaij. 'Assessing Deployment Pathways for Greenhouse Gas Emissions Reductions in an Industrial Plant – A Case Study for a Complex Oil Refinery'. Applied Energy 236 (15 February 2019): 354–78. https://doi.org/10.1016/j.apenergy.2018.11.074.
Ethanol production with CCS	Process parameters data updated	Government / NGO report Example: IEA GHG. '2021-01 Biorefineries with CCS', 2021. https://www.ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1054-2021-01-biorefineries-with-ccs.
Blast furnaces with CCS for iron and steel production	Process parameters data updated	Government / NGO report Example: West, Kira. 'HISARNA WITH CCS - TECHNOLOGY FACTSHEET'. TNO, 7 September 2020. https://energy.nl/wp-

		content/uploads/hisarna-ccs-technology-factsheet_080920-7.pdf.
Kilns with CCS for cement production	Process parameters data updated	Government / NGO report Example: IEA GHG. '2013-19 Deployment of CCS in the Cement Industry', December 2013. https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1016-2013-19-deployment-of-ccs-in-the-cement-industry.
Biofuels production with CCS	Process parameters data updated	Government / NGO report IEA GHG. '2021-01 Biorefineries with CCS', 2021. https://www.ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1054-2021-01-biorefineries-with-ccs.
Steam cracker with post combustion CCS	Process parameters data updated	Academic paper Example: Ho, M. T., and D. E. Wiley. '28 - Liquid Absorbent-Based Post-Combustion CO2 Capture in Industrial Processes'. In Absorption-Based Post-Combustion Capture of Carbon Dioxide, edited by Paul H. M. Feron, 711–56. Woodhead Publishing, 2016. https://doi.org/10.1016/B978-0-08-100514-9.00028-7.
Steam reformer with CCS for Ammonia or hydrogen production	Process parameters data updated	Academic paper Example: Lee, Kyuha, Xinyu Liu, Pradeep Vyawahare, Pingping Sun, Amgad Elgowainy, and Michael Wang. 'Techno-Economic Performances and Life Cycle Greenhouse Gas Emissions of Various Ammonia Production Pathways Including Conventional, Carbon-Capturing, Nuclear-Powered, and Renewable Production'. Green Chemistry 24, no. 12 (20 June 2022): 4830–44. https://doi.org/10.1039/D2GC00843B.
Direct air capture (DAC)	Process parameters data updated	Academic paper Example: Fasihi, Mahdi, Olga Efimova, and Christian Breyer. 'Techno-Economic Assessment of CO2 Direct Air Capture Plants'. Journal of Cleaner Production 224 (1 July 2019): 957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.

Summary of updates:

- Note that the table above is not exhaustive, as CCS is present in a large number of industrial processes in the Scottish TIMES model

- Updating based on current modelling approach: process specific CCS (we discussed this with stakeholders and agreed that the process specific approach used in Scottish TIMES should be favoured over a generic CCS approach)
- Literature/data available for typical industrial processes with CCS

4.3.3 Challenges, issues and considerations

- In some cases, we had to assume same relative CCS costs for similar processes (where no specific information was available).
- In some processes it was challenging to find specific data for purpose built vs retrofit CCS, in such cases, relative cost difference from other processes was used.
- Data available is normally costed by tCO2 captured, but the model required m£/PJ per annum, which required more analysis and further unit conversion efforts.

4.4 Oil refining

4.4.1 Sector context

Oil refining is a well-established industrial sector in Scotland that predominantly produces transport fuels such as petrol and diesel. The only large-scale refining site in Scotland is located at Grangemouth, with the first hydrocracker refinery being built there in 1969.

4.4.2 Overview of updates to sector

Table 4: Oil refining sector update summary

Subsector	Update	Reference type
Oil refining	Data on existing operations are commercially sensitive, not possible to update. However, the current Scottish TIMES data for these processes was sense checked by stakeholders, and the model can still be calibrated as is and using other publicly available emissions data.	Not available
Oil refining with CCS retrofit	Process parameters, including capital and operating	Academic papers Example: Berghout, Niels, Hans Meerman, Machteld van den Broek, and André Faaij. ‘Assessing

	costs updated for the CCS retrofit process.	Deployment Pathways for Greenhouse Gas Emissions Reductions in an Industrial Plant – A Case Study for a Complex Oil Refinery'. Applied Energy 236 (15 February 2019): 354–78. https://doi.org/10.1016/j.apenergy.2018.11.074.
Combined heat and power (CHP) for oil refining	Process parameters, including capital and operating costs updated	Academic papers and Government / NGO reports Example: Berghout, Niels, Hans Meerman, Machteld van den Broek, and André Faaij. 'Assessing Deployment Pathways for Greenhouse Gas Emissions Reductions in an Industrial Plant – A Case Study for a Complex Oil Refinery'. Applied Energy 236 (15 February 2019): 354–78. https://doi.org/10.1016/j.apenergy.2018.11.074.
Ethanol production processes	Process parameters data updated	Government / NGO report Example: IEA GHG. '2021-01 Biorefineries with CCS', 2021. https://www.ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1054-2021-01-biorefineries-with-ccs.
Biodiesel production processes	Process parameters data updated	Academic papers and Government / NGO reports Example: Feng, Li, Jiajun Liu, Haitao Lu, Bingzhi Liu, and Yuning Chen. 'Techno-Economic and Profitability Analysis of Plant for Producing Biodiesel from Fresh Vegetable Oil and Waste Frying Oil on Large-Scale'. Fuel 323 (1 September 2022): 124304. https://doi.org/10.1016/j.fuel.2022.124304.
Biomass treatment processes, including pelletisation	Process parameters data updated	Academic papers and Government / NGO reports Example: Schipfer, Fabian, and Lukas Kranzl. 'Techno-Economic Evaluation of Biomass-to-End-Use Chains Based on Densified Bioenergy Carriers (DBECs)'. Applied Energy 239 (1 April 2019): 715–24. https://doi.org/10.1016/j.apenergy.2019.01.219.
Pyrolysis and biogas production processes	Process parameters data updated	Academic papers and Government / NGO reports Example: Schipfer, Fabian, and Lukas Kranzl. 'Techno-Economic Evaluation of Biomass-to-End-Use Chains Based on Densified Bioenergy Carriers (DBECs)'. Applied Energy 239 (1 April 2019):

		715–24. https://doi.org/10.1016/j.apenergy.2019.01.219.

Summary of updates:

- Data updated on CHP, bioenergy, and other related processes. Data for most specific process was available, with a small number of exceptions where data from a similar process was used to update the one with missing data. For example, using same values for ethanol from hydrolysis of grass and ethanol from hydrolysis of straw.
- No data available on main oil refining processes. These are very complex sites which are difficult to design and cost in a generic manner and obtain data.
- We discussed with a petrochemicals industry expert about oil refining processes (see below).

4.4.3 Challenges, issues and considerations

- Oil refining in Scotland is one company, not a sector. Therefore, associated data is considered as commercially sensitive information. As a result, data of this sort is not available to update the process in the model. However, the current Scottish TIMES data for these processes was sense checked by stakeholders, and the model can still be calibrated using existing parameters, complemented by publicly available emissions data.
- From discussion with an oil refinery expert, it doesn't seem to be necessary to have in the model the 'high limit' version of oil refining. This high limit process was very similar to the standard process with a slightly larger output range flexibility. However, it was remarked by the expert that the outputs of a refinery are more dependent on the type of crude oil used, rather specific process investments.
- How any future new/additional refining capacity (with CCS) is modelled in TIMES should be considered - in the context of the demand for petrol and diesel after the 2030 ban on new ICE vehicles.

4.5 Chemicals

4.5.1 Sector context

The chemicals industry in Scotland is the country’s second largest exporter, with more than 120 chemical companies operating, with significant concentrations in Forth Valley, Ayrshire, Fife and Dumfries and Galloway.

4.5.2 Overview of updates to sector

Table 5: Chemicals sector update summary

Subsector	Update	Reference
A range of steam cracker processes with different fuel types	Process parameters, including capital and operating costs updated	Academic publication Example: Zhou, Xin, Shangfeng Li, Yuan Wang, Jiewenjing Zhang, Zhibo Zhang, Changgui Wu, Xiaobo Chen, et al. ‘Crude Oil Hierarchical Catalytic Cracking for Maximizing Chemicals Production: Pilot-Scale Test, Process Optimization

		Strategy, Techno-Economic-Society-Environment Assessment'. Energy Conversion and Management 253 (1 February 2022): 115149. https://doi.org/10.1016/j.enconman.2021.115149.
A range of processes related to ammonia production with steam reforming	Process parameters data updated	Academic paper Example: Lee, Kyuha, Xinyu Liu, Pradeep Vyawahare, Pingping Sun, Amgad Elgowainy, and Michael Wang. 'Techno-Economic Performances and Life Cycle Greenhouse Gas Emissions of Various Ammonia Production Pathways Including Conventional, Carbon-Capturing, Nuclear-Powered, and Renewable Production'. Green Chemistry 24, no. 12 (20 June 2022): 4830–44. https://doi.org/10.1039/D2GC00843B.
A range of processes linked to high temperature and low temperature heat for chemicals production	Process parameters data updated	Academic publication Example: Thiel, Gregory P., and Addison K. Stark. 'To Decarbonize Industry, We Must Decarbonize Heat'. Joule 5, no. 3 (17 March 2021): 531–50. https://doi.org/10.1016/j.joule.2020.12.007.
A range of processes linked to drying and separation for chemicals production	Process parameters data updated	Academic publication/ Industry supplier data Example: Thiel, Gregory P., and Addison K. Stark. 'To Decarbonize Industry, We Must Decarbonize Heat'. Joule 5, no. 3 (17 March 2021): 531–50. https://doi.org/10.1016/j.joule.2020.12.007.
A range of processes linked to motor drive for chemicals production	Process parameters data updated	Industry supplier data Example: Acorn industrial services limited. 'Electric Motors', 6 September 2017. https://www.acorn-ind.co.uk/couplings-drives/electric-motors/.
A range of processes linked to refrigeration for chemicals production	Process parameters data updated	Academic publication / Government report Example: BEIS. 'Refrigeration Equipment :: Energy Technology List', April 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/879768/TIL_-_Industrial_Refrigeration_-_April_2020.pdf.

Summary of updates:

- Updated most process data, including CAPEX, OPEX, technical lifetime efficiency, for specialised chemicals processes e.g. steam cracking, steam reforming, etc.
- Also updated more basic processes, e.g. low temp heat, drying, refrigeration, etc. However, it was harder to find specific information for those processes and data is normally reported in ranges.

4.5.3 Challenges, issues and considerations

- The low and high temperature heat processes for the chemical industry are not modelled as specific technologies in the model. Therefore, we assumed these processes consisted of typical technologies able to produce the range of temperatures for low and high heat. For instance, low temp heat processes are based on boiler type processes (exc. Electric low heat, which we assumed to be of electric immersion type technology).
- Similarly, high temp heat and drying based on process heaters/furnaces (exc. Electric version which have more specific information).
- We suggest to merge all these basic processes, since they are basically the same technology with only the input fuel changing e.g. low temp heat; drying ovens/furnaces. We consult this with stakeholders and confirmed that there is little difference between most of these processes (with a few exceptions).
- There was not enough information on the ‘advanced’ version of these processes. We assumed the same parameters of the non-advanced process but with the slightly increased efficiency.

4.6 Cement

4.6.1 Sector context

The main cement plant in Scotland is located at Dunbar, East Lothian, which produces around 1Mt of Portland cement (from raw materials) per year. However, a new Scottish based manufacturing facility that will enable the small-scale production of lower carbon cement products has recently received Government funding.

4.6.2 Overview of updates to sector

Table 6: Cement sector update summary

Subsector	Update	Reference
Cement production processes linked to dry kilns	Process parameters data updated	Academic papers and Government / NGO reports Example: S. Campanari, G. Cinti, S. Consonni, K. Feiger, M. Gatti, H. Hoppe, I. Martínez, M. Romano, M. Spinelli, M. Voldsund, D4.1 Design and performance of CEMCAP cement plant without CO2 capture, 2016. https://www.sintef.no/globalassets/sintef-energi/cemcap/d4.1-cemcap-cement-plant-without-co2-capture_rev2.pdf/

Cement finishing processes: Grinding and mixing	Process parameters data updated	Academic papers and Government / NGO reports Example: S. Campanari, G. Cinti, S. Consonni, K. Feiger, M. Gatti, H. Hoppe, I. Martínez, M. Romano, M. Spinelli, M. Voldsund, D4.1 Design and performance of CEMCAP cement plant without CO2 capture, 2016. https://www.sintef.no/globalassets/sintef-energi/cemcap/d4.1-cemcap-cement-plant-without-co2-capture_rev2.pdf/
Cement finishing processes: Grinding and mixing with increased clinker substitution	Process parameters data updated	Academic papers and Government / NGO reports Example: IEA GHG. '2013-19 Deployment of CCS in the Cement Industry', December 2013. https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1016-2013-19-deployment-of-ccs-in-the-cement-industry
A range of processes linked to Kiln cement production with CCS	Process parameters data updated	Academic papers and Government / NGO reports Example: IEA GHG. '2013-19 Deployment of CCS in the Cement Industry', December 2013. https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1016-2013-19-deployment-of-ccs-in-the-cement-industry

Summary of updates:

- Process data on cement production and processing have been updated. However, for some less common production technologies such as kiln with increased waste utilisation - fluidised bed, it was harder to find information/details.

4.6.3 Challenges, issues and considerations

- We found that the available literature is relatively older than for other sectors
- Where specific data was not available, we have updated using the closer (more similar) process of which we could find data. For example, this was the case on some of the kiln processes.

4.7 Iron and steel

4.7.1 Sector context

There are no large-scale producers of crude steel in Scotland. The largest steel plant, Liberty Steel Dalzell, is located in Motherwell and produces steel plates. Although steel production has traditionally used blast furnaces powered by natural gas and coal, new processes such as production via 'electric arc furnaces' are options for decarbonised steel production.

4.7.2 Overview of updates to sector

Table 7: Iron and steel sector update summary

Subsector	Update	Reference
Iron and steel production processes: Sinter production	Process parameters data updated	Academic publication Example: Ibn-Mohammed, T., C. A. Randall, K. B. Mustapha, J. Guo, J. Walker, S. Berbano, S. C. L. Koh, D. Wang, D. C. Sinclair, and I. M. Reaney. 'Decarbonising Ceramic Manufacturing: A Techno-Economic Analysis of Energy Efficient Sintering Technologies in the Functional Materials Sector'. Journal of the European Ceramic Society 39, no. 16 (1 December 2019): 5213–35. https://doi.org/10.1016/j.jeurceramsoc.2019.08.011.
A range of processes linked to Iron and steel production using Blast Furnaces, Alternative Blast Furnaces and Basic Oxygen Furnaces	Process parameters data updated	Academic publication, Government / NGO report, industry report Example: Hooey, Lawrence, Andrew Tobiesen, Jeremy Johns, and Stanley Santos. 'Techno-Economic Study of an Integrated Steelworks Equipped with Oxygen Blast Furnace and CO2 Capture'. Energy Procedia, GHGT-11 Proceedings of the 11th International Conference on Greenhouse Gas Control Technologies, 18-22 November 2012, Kyoto, Japan, 37 (1 January 2013): 7139–51. https://doi.org/10.1016/j.egypro.2013.06.651.
A range of processes linked to iron and steel production using Electric Arc Furnaces	Process parameters data updated	Academic publication & Government / Industry report Example: Steelonthenet. 'Capital Investment Costs Plant Equipment Electric Arc Furnace', 2018. https://www.steelonthenet.com/capital-investment/eaf.html.
A range of processes linked to Direct Reduction Ironmaking	Process parameters data updated	Academic publication & industry report Example: Lerede, D., C. Bustreo, F. Gracceva, M. Saccone, and L. Savoldi. 'Techno-Economic and Environmental Characterization of Industrial Technologies for Transparent

		Bottom-up Energy Modeling'. Renewable and Sustainable Energy Reviews 140 (1 April 2021): 110742. https://doi.org/10.1016/j.rser.2021.110742.
A range of processes linked to Casting & Rolling Finishing Process	Process parameters data updated, with the exception of some finishing process	Academic publication & industry report Example: Steelonthenet. 'Steel Capital Investment Costs Plant and Equipment Slab Caster', 2018. https://www.steelonthenet.com/capital-investment/slab-caster.html.
A range of processes linked to CHP and boilers	Process parameters data updated	Academic publication & Government / NGO report Example: Thiel, Gregory P., and Addison K. Stark. 'To Decarbonize Industry, We Must Decarbonize Heat'. Joule 5, no. 3 (17 March 2021): 531–50. https://doi.org/10.1016/j.joule.2020.12.007

Summary of updates:

- Process data for sector specific processes has been updated.
- Some processes are deemed the same as of other industries. For example, CHP processes. We have updated these processes, using the same data used in other sectors.

4.7.3 Challenges, issues and considerations

- In some specialised steel and iron making processes, less data is available in academic publications and we had to rely more on industry reports and websites.
- It has also been challenging to get specific information on certain improvement options, and where no specific data was available we have assumed the same data from the improvement on a different process (e.g. heat recovery improvement from an electric arc furnace into heat recovery for a blast furnace).

4.8 Food and drink

4.8.1 Sector context

The food and drink industry in Scotland is comprised of a range of sub-sectors including meat, whisky, seafood, salmon, primary agriculture, dairy, brewing and distilling. The sector relies on a range of common industrial processes such as combined heat and power (CHP), low temperature heat, drying and separation, motor drive, refrigeration and other services.

4.8.2 Overview of updates to sector

Table 8: Food and drink sector update summary

Subsector	Update	Reference type
A range of processes linked to CHP for food and drinks production	Process parameters data updated	Academic papers and Government / NGO reports Example: Slavica, Prvulovic, Micic Ivica, Radosav Dragica, Josimovic Milios, Juric Slobodan, and Novakov Vladislav. 'Testing the Energy Efficiency of CHP Engines and Cost-Effectiveness of Biogas Plant Operation'. IET Renewable Power Generation 17, no. 3 (2023): 555–62. https://doi.org/10.1049/rpg2.12614.
A range of processes linked to high temperature and low temperature heat for food and drinks production	Process parameters data updated	Academic publication/ industry catalogue Example: Wuxi Wiscon mechanical and Electrical Equipment Co., Ltd. 'Heavy Electric Forced Hot Air Circulation Tray Dryer Industrial Drying Oven for Food Dehydrator Vegetable Seafood Fish and Plant Herbal'. Made-in-China.com, 2022. https://powder-equipment.en.made-in-china.com/product/EwbfrAhXJVpU/China-Factory-Price-China-Heavy-Electric-Forced-Hot-Air-Circulation-Tray-Dryer-Industrial-Drying-Oven-for-Food-Dehydrator-Vegetable-Seafood-Fish-and-Plant-Herbal.html.
A range of processes linked to drying and separation for food and drinks production	Process parameters data updated	Academic publication Example: Obeng-Akrofi, George, Joseph O. Akowuah, Dirk E. Maier, and Ahmad Addo. 'Techno-Economic Analysis of a Crossflow Column Dryer for Maize Drying in Ghana'. Agriculture 11, no. 6 (June 2021): 568. https://doi.org/10.3390/agriculture11060568.
A range of processes linked to motor drive for food and drinks production	Process parameters data updated	Academic publication/ industry catalogue Example: Acorn industrial services limited. 'Electric Motors', 6 September 2017. https://www.acorn-ind.co.uk/couplings-drives/electric-motors/.
A range of processes linked to refrigeration for food and drinks production	Process parameters data updated	Academic publication / Government report Example: BEIS. 'Refrigeration Equipment :: Energy Technology List', April 2020.

		https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/879768/TIL_-_Industrial_Refrigeration_-_April_2020.pdf.

Summary of updates:

- Updated all process data. The process in this sector are less specialised more basic processes, including low temperature heat, drying and separation, motor drive, refrigeration, etc.
- We updated these processes using similar data from other sectors, where applicable.

4.8.3 Challenges, issues and considerations

- Due to the similarity of this sector processes with other sectors, the same considerations and assumptions apply (see for instance the Chemicals sector, regarding the assumptions on low temp. heat, drying and separation, etc.).
- Here, we also suggest to merge all these basic processes, since they are basically the same technology with only the input fuel changing.
- Also, we encounter a similar issue with the Other Services processes as in the Chemicals sector, these are undefined residual processes, essentially a calibration item required for modelling purposes. It was not possible to update these processes, and we retained current values.

4.9 Pulp and paper

4.9.1 Sector context

The production of pulp and paper is comprised of three main stages, which include wood handling, fibre processing and drying and packaging. In terms of industrial processes, the production of pulp and paper can include CHP plants, boilers, other production processes such as low temperature heat, pressing, drying and separation, and dry sheet forming.

4.9.2 Overview of updates to sector

Table 9: Pulp and paper sector update summary

Subsector	Update	Reference type
A range of processes linked to CHP for pulp and paper production	Process parameters data updated	Academic papers and Government / NGO reports Example: IEA-ETSAP. 'Energy Supply Technologies Data - Combined Heat and Power', May 2010. https://iea-etsap.org/E-TechDS/PDF/E04-CHP-GS-gct_ADfinal.pdf.
A range of processes linked to boilers for pulp and paper production	Process parameters data updated	Academic publication Example: Thiel, Gregory P., and Addison K. Stark. 'To Decarbonize Industry, We Must

		Decarbonize Heat'. Joule 5, no. 3 (17 March 2021): 531–50. https://doi.org/10.1016/j.joule.2020.12.007.
A range of processes linked to drying and separation for pulp and paper production	Process parameters data updated	Academic papers and Government / NGO reports Example: Laurijssen, Jobien, André Faaij, and Ernst Worrell. 'Benchmarking Energy Use in the Paper Industry: A Benchmarking Study on Process Unit Level'. Energy Efficiency 6, no. 1 (1 February 2013): 49–63. https://doi.org/10.1007/s12053-012-9163-9.
A range of processes linked to pressing for pulp and paper production	Process parameters data updated	Academic publication Example: Laurijssen, Jobien, André Faaij, and Ernst Worrell. 'Benchmarking Energy Use in the Paper Industry: A Benchmarking Study on Process Unit Level'. Energy Efficiency 6, no. 1 (1 February 2013): 49–63. https://doi.org/10.1007/s12053-012-9163-9.
A range of processes linked to dry sheet forming and 'finishing' for pulp and paper production	Process parameters data updated, with the exception of some finishing process	Academic papers and Government / NGO reports Example: Bajpai, Pratima. 'Chapter 10 - Energy Conservation Measures for Stock Preparation and Papermaking'. In Pulp and Paper Industry, edited by Pratima Bajpai, 153–88. Amsterdam: Elsevier, 2016. https://doi.org/10.1016/B978-0-12-803411-8.00010-X.

Summary of updates:

- Similarity on some 'basic' processes as in previous sectors (e.g. CHP and boilers).
- These processes have been updated using the same parameter data.
- Sector specific processes, such as pressing and specialised drying, have been updated. However, considerations have been made where data was not available.

4.9.3 Challenges, issues and considerations

- Same considerations for basic processes as previously reported in other sector.
- Most sector specific processes have been updated with data from the literature. However, there was no available data for some of these specialised processes. In those cases, data from processes of the same type has been used

4.10 Non-ferrous metals technologies, non-metallic minerals technologies, and other industries

4.10.1 Sector context

This last section summarises the process updates linked to the Non-Metallic Minerals, Non-Ferrous Metals, and other industries (not specified). These sectors are modelled in Scottish TIMES as basic processes, including CHP plants, boilers, low and high temperature heat, drying and separation, and others.

4.10.2 Overview of updates to sector

Table 10: Non-Ferrous Metals Technologies, Non-Metallic Minerals Technologies, and Other industries update summary

Subsector	Update	Reference type
A range of processes linked to CHP	Process parameters data updated	Academic papers and Government / NGO reports Example: US Department of Energy. 'Combined Heat and Power Technology Fact Sheet Series - Fuel Cells', July 2016. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Fuel%20Cell.pdf.
A range of processes linked to high temperature and low temperature heat	Process parameters data updated	Academic publication Example: Thiel, Gregory P., and Addison K. Stark. 'To Decarbonize Industry, We Must Decarbonize Heat'. Joule 5, no. 3 (17 March 2021): 531–50. https://doi.org/10.1016/j.joule.2020.12.007.
A range of processes linked to drying and separation	Process parameters data updated	Academic publication/ industry catalogue Example: Wuxi Wiscon mechanical and Electrical Equipment Co., Ltd. 'Heavy Electric Forced Hot Air Circulation Tray Dryer Industrial Drying Oven for Food Dehydrator Vegetable Seafood Fish and Plant Herbal'. Made-in-China.com, 2022. https://powder-equipment.en.made-in-china.com/product/EwbfrAhXJVpU/China-Factory-Price-China-Heavy-Electric-

		Forced-Hot-Air-Circulation-Tray-Dryer-Industrial-Drying-Oven-for-Food-Dehydrator-Vegetable-Seafood-Fish-and-Plant-Herbal.html.
A range of processes linked to motor drive	Process parameters data updated	Academic publication Example: Zhao, Kun, Lin Cheng, Chaohai Zhang, Dexin Nie, and Wei Cai. 'Induction Motors Lifetime Expectancy Analysis Subject to Regular Voltage Fluctuations'. In 2017 IEEE Electrical Power and Energy Conference (EPEC), 1–6, 2017. https://doi.org/10.1109/EPEC.2017.8286230
A range of processes linked to refrigeration	Process parameters data updated	Academic publication / Government report Example: BEIS. 'Refrigeration Equipment :: Energy Technology List', April 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/879768/TIL_-_Industrial_Refrigeration_-_April_2020.pdf.

Summary of updates:

- Updated all process data. The process in these sectors are less specialised more basic processes, including low temperature heat, drying and separation, motor drive, refrigeration, etc.
- We updated these processes using similar data from other sectors, where applicable.

4.10.3 Challenges, issues and considerations

- Due to the similarity of this sector processes with other sectors, the same considerations and assumptions apply (see for instance the Chemicals sector, regarding the assumptions on low temp. heat, drying and separation, etc.).
- Our suggestion to merge all similar basic processes here still stand.
- Also, we encounter a similar issue with the Other Services and Finishing processes as in previous sector, these are undefined residual processes, used as a calibration item required for modelling purposes. It was not possible to update these processes, and we retained current values.

5 Conclusions and recommendations

In our research, we were able to recommend updates to the Scottish TIMES model so that it more accurately reports the performance and potential decarbonisation options for different industrial sectors. This review of current data underpinning TIMES assumptions has successfully updated a range of parameters such as capital and operating cost, efficiency, operational availability, expected operational life and first year of technology availability for the industrial processes included in the Scottish TIMES energy system model. This included data for new and emerging technologies such as CCUS and hydrogen, along with traditional industrial sectors such as oil refining, chemicals, iron and steel, cement, pulp and paper, and food and drink.

Contrary to expectations, our review identified that data was in most cases more readily available for emerging processes such as hydrogen production and CCUS than for some existing sectors, such as oil refining, which was more difficult to find in the public domain. This is due to commercial sensitivities around cost and operational data, but also might relate to the complexity of oil refining sites that incorporate a vast range of industrial processes. As well as updating data across the range of industrial processes, our review also identified several new processes for inclusion, such as hydrogen above ground storage, and recommended the removal of others such as hydrogen salt cavern storage. The review also recommended that existing processes could be merged in order to simplify the TIMES database, such as the hydrogen electrolysis processes. The review also updated data for industrial processes that are common across a range of sectors, such as motor drive, low and high temperature heating, drying and refrigeration.

While this review has successfully recommended updated data and processes for the TIMES database, it is clear that relying on publicly available data has limitations, and in many cases, we relied upon a single data point or reference for different processes. Here, data gathered may also not be specific to sites in Scotland, as references were often only available for international or reference examples. However, we are aware that other projects focussed on industrial decarbonisation, such as the Innovate UK funded Scottish Net Zero Roadmap Project[1], are collecting site specific data that could work to inform the TIMES energy system model and the policy decisions it informs.

Therefore, we recommend that a further review is undertaken to understand how more Scottish site-specific data for specific industrial processes could be used to inform the Scottish TIMES model. This would ensure that the outputs from TIMES are up to date and based on accurate assumptions for industrial processes at Scottish industrial sites. This would ultimately build confidence around the TIMES model and its outputs and the decarbonisation scenarios and policies developed from them.

We also recommend that further scrutiny and review of the updated parameters is undertaken once they are incorporated into the model and any implications on outcomes are understood. This could involve focussing on key processes, such as carbon capture, transport and storage processes, that are important for delivering against net zero targets.

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