Scotland's Net Zero Roadmap Phase 1

Deliverable D4.4

Scoping of industrial energy system modelling: summary report

Paul Guest

Practice Manager

National Energy Systems

Dennis Gammer

Locarb Tech Ltd

3rd July 2020

Document control

ESC programme name	Scotland's Net Zero Roadmap
ESC project number	
Version*	1.0
Status	Draft: Contains preliminary information only. Approved: Contains reviewed and approved content. (delete as appropriate)
Restrictions*	Open / Confidential / Internal use only (delete as appropriate)
Release date	03/07/2020
External release ID	(if project release process requires it)

* Refer to the Information Classification Policy

Review and approval

	Name	Position
Author	Paul Guest Dennis Gammer	Practice Manager – National Energy Systems Consultant, Locarb Tech Ltd
Reviewer(s)	Friedericke Kerr	Project Manager – Infrastructure and Engineering
Approver	Liam Lidstone	Business Lead – Infrastructure and Engineering

Revision history

Date	Version	Comments
03.07.2020	1.0	Initial version

Table of Contents

1. Executive Summary

Many types of roadmap have been published to give structure and credibility to the transitions that are needed to achieve environmental targets to 2050. Cognisant of the implausibility of planning an optimal, definitive pathway 30 years ahead, SNZR has elected to build its industrial decarbonisation roadmap based on the following:

- Good understanding of the current emissions and their cause, at site level, with industry involvement
- Sound engineering assessment of deployable abatement technology options
- Developing a new cluster level model, exploring a range of credible development scenarios to provide a robust and flexible pathway
- Use of national energy system modelling to inform industry about the pace, nature and extent of non- industrial decarbonisation, and the opportunities and challenges it poses

SNZR consider that this approach produces a long-lasting body of work which will develop in the years ahead, engaging industry and providing optimal results.

The cluster-level model will be used to explore selected deployment scenarios, the feasibility of reaching targets, cost-benefit options, and the optimum order of projects, taking into consideration industry constraints. The model will be constructed in such a way that it can be adapted for use with datasets from other clusters. Initially, the model will focus on Scotland's eastern central belt and St. Fergus but will be designed such that an enlarged region could be considered at a later date if required.

This document scopes the development of the energy modelling exercises which form part of the SNZR. Although Scotland has a considerable body of work published on its decarbonization options, assistance is needed from industry in terms of providing insight and data with which to inform the cluster level model. Conceptual studies are required to improve estimation of the cost and performance of abatement technologies such as CCS, fuel-switching and use of renewables. The model will have a library of such technologies from which to choose options, and access to new cost modules for site level interventions. It will focus on assessing deployment as a series of major projects, and will record system costs, infrastructure capability and asset use.

Much less effort is required to bring a national level model to bear as mature models are available, although the depiction of industry could be improved and updated using the cluster level activity above and published data on the generic performance of technologies.

Seven scenarios have been devised to provide assessment of a broad range of options and strategies. These are largely based on dominant technology options, such as CCS and renewables, and their timing. These scenarios will be portrayed in the model as a series of different site-based projects, each consistent with the scenario theme.

2. Introduction

2.1. Project context

The Industrial Strategy Challenge Fund's (ISCF) Industrial Decarbonisation Challenge programme is designed to explore practical methods to decarbonise UK industrial clusters. Within the ISCF Roadmap project, the first phase develops a plan to achieve this in specific areas, to be supported by detailed roadmap development in a second phase. For Scotland's Net Zero Roadmap (SNZR), this first phase is intended to characterise existing emitters (WP1), interview key industrial stakeholders to better understand the viable decarbonisation options considered at industrial sites (WP2), assess technology options required to significantly decarbonise sites (WP3), and assess requirements for appropriate energy (WP4) and economic modelling (WP5) exercises within the second phase.

The current report, satisfying Deliverable D4.4 of the SNZR Phase 1 project, summarises the energy system modelling requirements identified as being critical to deliver a viable roadmap within Phase 2. It includes an outline view of an appropriate modelling framework to be developed further within Phase 2, along with information about data requirements and flows between cluster-level and UK wide plans.

2.2. Industrial decarbonisation: background information

Extensive decarbonisation of the industrial sector has been noted as a key requirement to deliver a Net Zero emissions energy system for the UK [1, 2]. Although successfully delivering on the previous 80% emissions target was already likely to require industrial emissions to reduce by perhaps 50-60% compared with current reported levels [3], it is unlikely that the more onerous Net Zero target will be achievable without even further reducing industry's contribution to greenhouse gas emissions. For example, the Committee on Climate Change and the Energy Systems Catapult envision national aggregate emissions from the industrial sector will be required to total at most 10-20 $MtCO_2e$ to be consistent with a Net Zero energy system.

There is some uncertainty around cluster definitions and specific, measurable requirements for cluster decarbonisation. Examples of key statements provided by relevant stakeholders are:

- To establish the world's first net zero industrial cluster by 2040 and at least one low carbon cluster by 2030 (UK Government, [4])
- To establish a "low carbon cluster" by 2030, Net Zero cluster by 2040 (UK Government, [4])
- Significant volumes of low-carbon hydrogen should be produced at one or more industrial clusters by 2030 (Committee on Climate Change, [5])
- CO_2 transport and storage infrastructure should be operational in at least one industrial cluster by 2026 and available to all major industrial clusters soon afterwards (Committee on Climate Change, [1])
- A network to provide hydrogen to industry outside the main industrial clusters should be established by 2035, or potentially slightly later (Committee on Climate Change, [1])

Techno-economic whole energy system models have contributed significantly to the knowledge base in support of decarbonisation priorities across the whole UK energy system. However, the suitability of such models for understanding specific priority actions at key industrial sites or clusters is less clear-cut. Typically, such models tend to offer fairly generic decarbonisation options split by industrial sector, steered at a high level by a technical evidence base [6,7]. Specific interventions at existing sites are more challenging to extract from this starting point.

A complementary approach to consider is that of supplementing national level analysis with a more detailed site and cluster-level energy system model. Within such a model, specific interventions at a site or even process level can be fully specified and included as options that the model can choose to deploy. Although these options may be similar in ethos to the interventions available within generic models, such as fuel switching (electrification, hydrogen), carbon capture and usage (CCU), carbon capture and storage (CCS) and energy (and resource) efficiency, site-specific information allows practical system transformation to be assessed more directly and realistically. In particular, the consequences for local energy and emissions infrastructure of adopting each specific decarbonisation option can be analysed more clearly at a site level. Local, bespoke constraints that influence the feasibility of reinforcing or building new networks, impractical to include in more generic national-level tools, can easily be included where site-level decisions are the prime focus.

Where this approach is likely to become most compelling is through the hybrid deployment of site/cluster-level models against a realistic whole system, national modelling context. Sites within the industrial cluster are embedded within national energy networks and it is likely that they will continue to consume energy from these sources. A purely cluster-level model needs to include assumptions around the cost and availability of energy sourced from outside the cluster, and it is conceivable that site-level decisions could be made that are inconsistent with national Net Zero trajectories. By setting a credible national Net Zero pathway as the source of the exogenous assumptions (sourced from a national energy system model such as ESME [8]) this will help ensure that the industrial sites aren't calling on more than their "fair share" of available zero-carbon energy carriers and ascribe appropriate costs. An explicit coupling of national and local energy planning has been utilized by tools such as the Energy System Catapult's EnergyPath Networks local area planning model [9], and many of the findings from the development of that tool are applicable to the challenge of industrial cluster modelling.

This document outlines the requirements for such a model of industrial cluster decarbonisation. Although this tool specification is focused on sites included within the Scottish cluster, the framework for such a model is quite generic and thus could be adapted to other clusters should site-level intervention data be available. The document also includes a brief review of the roles of national models in the context of industrial decarbonisation.

2.3. Key features of Scotland's industrial cluster

Scotland's oil and gas industry has put it in an excellent position to progress CCS technology. In addition to accumulating a wealth of valuable information about the geological storage opportunities in the area, the industry can provide opportunity to lower the entry costs of decarbonization by repurposing redundant infrastructure, especially onshore and offshore pipelines. Several of these opportunities have already been studied in detail by several projects, including both conceptual and "FEED" level studies, which have improved the knowledge base on costs and risks. Currently, one live project, Acorn, has attracted European funding (ERA-NET ACT) to progress the definitions of a capture plant at St. Fergus feeding a storage site in the Captain aquifer [10].

Based on SEPA data[1] for the top 25 emitters, much of Scotland's industrial emissions lie in a tight cluster 200 km south-east in the area around Grangemouth, the Forth and Fife (see Figure 1). Therefore, the repurposing of natural gas Feeder 10 for use as a CO_2 pipeline is a key decision in the SNZR solution for Net Zero. A sizeable quantity of research has been carried out into the feasibility and cost of repurposing Feeder 10 to transport CO2 [12].

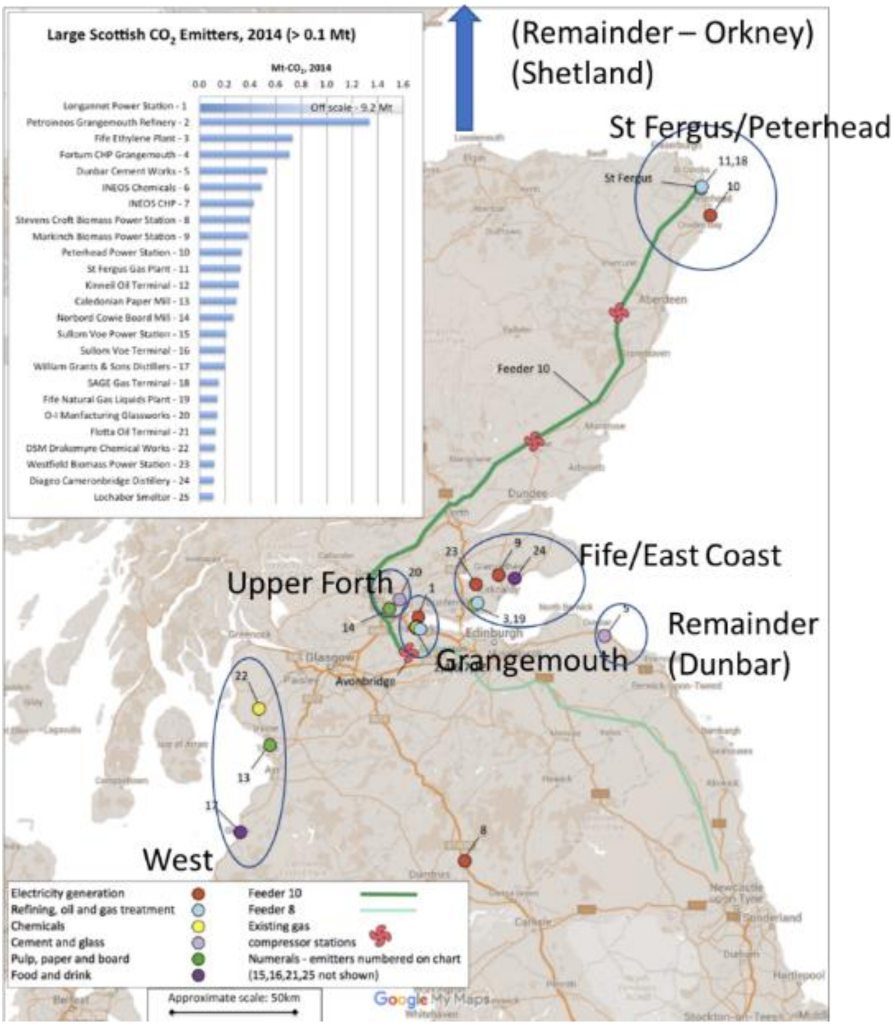

Figure 1: The top 25 industrial emitters in Scotland, with assignment to sub-regions as defined in SNZR WP1 [11]]

As shown in Figure 2, the principal source of industrial emissions (especially non-biogenic emissions) is related to the handling and separation of oil and gases (13% of all emissions) and its subsequent conversion into refinery products (23% of all), monomers and derived plastics (20% of all). Although most of the other sectors have substantially increased the proportion of their

[1] Available via https://www.sepa.org.uk/environment/environmental-data/spri/

emissions originating from biomass feedstocks and so reduced their net impact on the environment, there is still a role to play in both further reductions and the potential to generate negative emissions. This is particularly relevant because some of these sectors emit streams which have a high CO_2 concentration, reducing the penalty for extracting pure CO_2 for storage or use. The top 25 emitters produce 83.7% of site emissions, and similar types of equipment are used across sectors – technical solutions for most emissions are available or under demonstration.

The biogenic CO_2 released by Scotland's top emitters is already over 10% of the total (even excluding EfW and cement). There is therefore an opportunity to create "negative" emissions if this CO_2 can be efficiently captured. Markinch biomass power station and other assets will be well situated to offset emissions in other areas which are more expensive to abate, and more EfW plants are being planned.

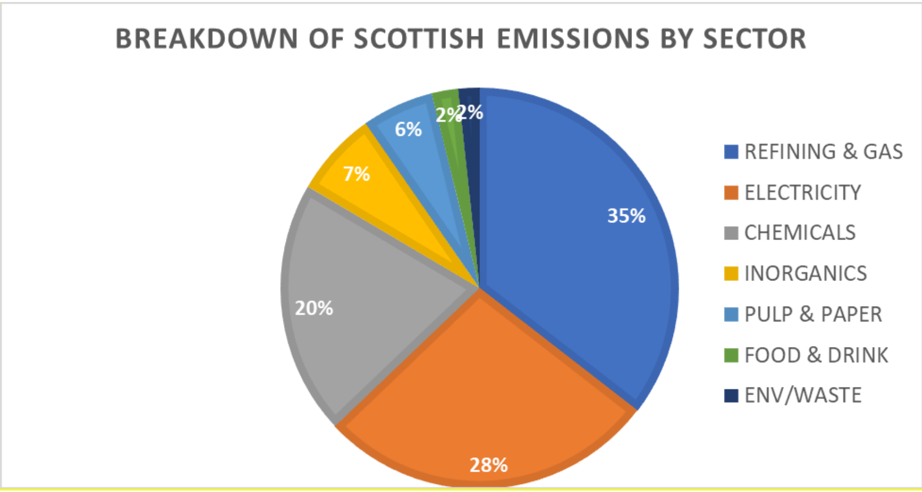

Figure 2: Industrial sector emissions, inclusive of Peterhead power station, from SEPA 2018 statistics

Using the definition of Scotland's sub-regions identified in WP1, emissions from the top 25 emitters (including Peterhead power station) are distributed as shown in Figure 2Figure 3. Focusing on purely fossil derived industrial emissions, over three quarters are from just seven sites – the five Ineos Grangemouth assets, Dunbar cement works and the Fife Ethylene Plant. Thus, in order to make an impactful intervention on Scottish emissions, Grangemouth, St Fergus and Fife regions all need abatement technology. Feeder 10 is a potential conduit for CO_2 from these regions (and much of the other quarter of fossil derived industrial emission as well as others), so it should be no surprise that this pipeline is seen as a key asset in developing scenarios.

Of the "Remainder" of sites (Figure 3), Dunbar is a key large point source emitter (cement and perhaps EfW in the future). The support of the Ineos group of companies in Grangemouth (36% of the top 25 Scottish emissions, and an important part of Scotland's GDP) is clearly key to making an impactful roadmap.

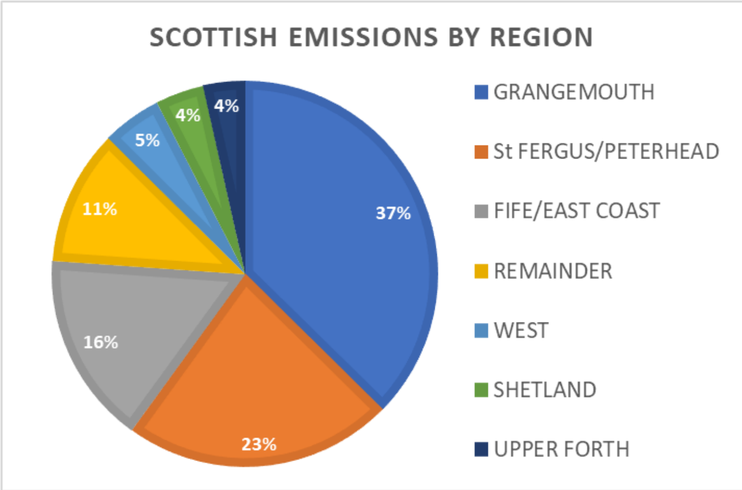

Figure 3: Industrial emissions in regional sub-clusters in Scotland, 2018 (SEPA)

The selected extent of the initial Scottish cluster is shown in dark shading in Figure 4 below:

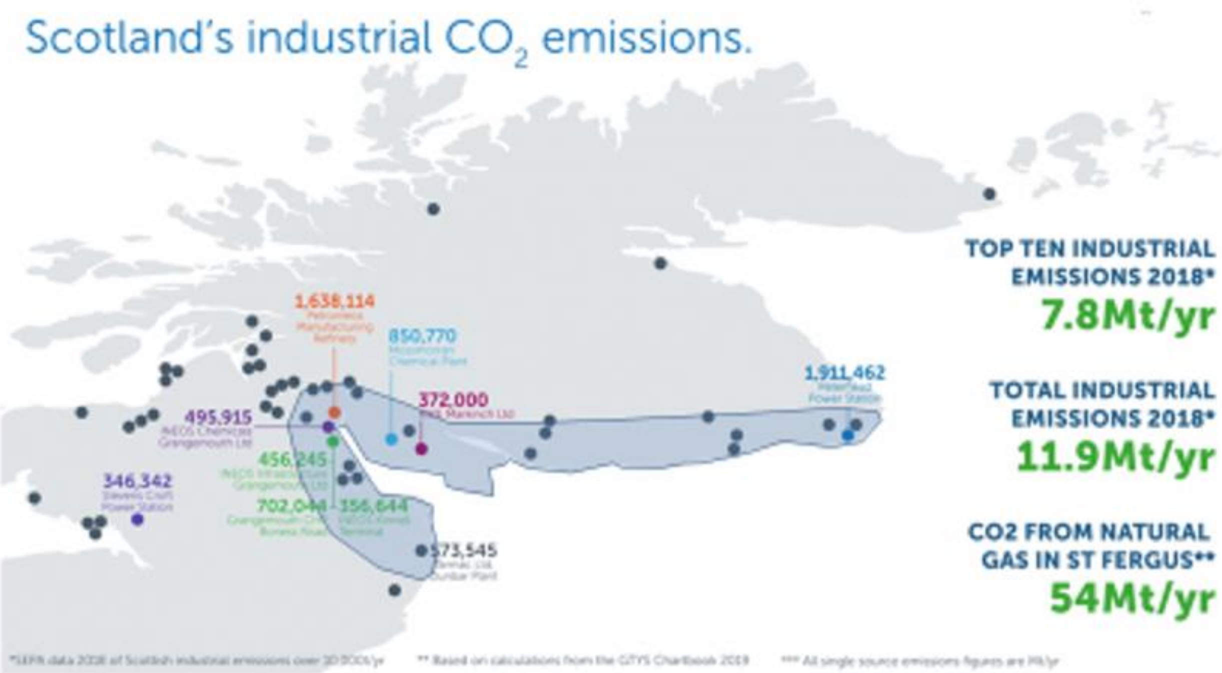

Figure 4: Proposed extent of Scottish industrial cluster. Emissions data from SEPA

2.3.1. Process emissions

CO_2 emissions which must be released as part of a process, as opposed to CO_2 released in the creation of useful energy to support a process or industry, are often called "process emissions". The abatement of this type of emission is almost exclusively assigned to CCU/CCS technology, although demand reduction or efficiency improvements would also potentially assist with process emission reduction. The largest of these are located at Grangemouth Refinery (Fluid Catalytic Cracker and Hydrogen SMR) and the Dunbar cement works. Together, these are individually amongst the largest industrial point sources, thought to contribute over a million tonnes of CO_2 per annum (circa 10% of all emissions) and would form the core of a CCUS "anchor". It is to be anticipated that once CCUS is planned for such emissions, it will also be fitted to other (energy-related) applications at each site, which may be the kernel of a "baseline" scenario for the SNZR roadmap.

Incineration of waste, currently a small part of emissions, will grow in the future. Since the primary purpose of such plants is waste destruction by combustion, not power generation, emissions from EfW plant can also be thought of as a process emission. These emissions are CO_2 rich (c. 12%) and currently have a high biogenic carbon content (c. 50%), so capture offers the potential for negative emissions.

2.3.2. Energy-related emissions

Scotland's oil refining and large chemical and gas handling sites largely meet their own power and heat requirements or have coupled with adjacent "energy centres" and "site service companies" to supply their needs. The use of low value liquid streams for on-site energy use has declined for environmental reasons. Waste gases (inevitable by-products) are used to fire boilers, turbines (CHP) and furnaces, and grid power is typically only used when necessary (at current price sets).

Emissions from these CHP units, boilers and fired heaters are much larger in total than process emissions, and are more prevalent in most sub-regions, although they will be more dispersed across sites. It is therefore prudent to investigate a scenario where industry doesn't wait for carbon capture of process emissions but develops using H_2 generation centres (with CCS) at key sub-regions. Modelling may show that these assets have a higher longevity and better long-term loading factors.

2.2.1 Biogenic carbon emissions

Substitution of fossil fuel by sustainable biomass and biomass derived fuels reduces the rate of accumulation of CO_2 in the atmosphere. Again, Scotland has an inventory of the opportunity in this area [13].

Scenarios will permit the construction of new BECCS plants as options, subject to any constraints on sustainable biomass supply from Scotland. "Smaller" industries also use increasing amounts of biomass. System modelling will give guidance on what the best use is of this material, which is now seeing increases in demand. Work is needed to improve the understanding of datasets in this area.

3. Decarbonisation scenarios

Formation of a robust roadmap involves the exploration of several development pathways for the decarbonisation of Scotland. The base case scenario for Scottish decarbonisation has been developed over many years:

The Base Case Scenario

- Acorn as a minimum viable development project to de-risk CCUS, particularly CNS storage
- Then decarbonisation of the Grangemouth sub-cluster, and repurposing of the Feeder 10 pipeline.
- Then network extension to other sites in Forth, Fife and elsewhere.

This represents an approach that focuses on making maximum “early” impact on today’s emissions, through a manageable number of projects and stakeholder interfaces. Around this base-case, three optional scenarios have been outlined in project working documents:

1. **Soft start**. In this option early progress focusses on simple fuel-switches and on efficiency improvements, and CCUS (other than Acorn) is built later in the pathway.

Arguably this is an extension of current progress. Its investigation allows progress towards Net Zero to be maintained should key CCUS projects in Scotland be further delayed. It may involve lower financial commitment and risk early in the pathways, but less progress towards meeting the target.

2. **Local H_2 Networks**. In this scenario industry focused local (sub-regional) H_2 facilities with CCUS are developed, fed by the NTS, which is largely retained for natural gas, with some re-purposing to CO_2. H_2 is fed to a number of assets for fuel-switching options.

This option mitigates against a risk in the base-case that too much emphasis is placed on investments in a small number of large assets in Grangemouth, in which some sectors face further, extensive contraction.

3. **Hydrogen Economy.** Hydrogen use in heating (buildings), heavy transport and other applications grows rapidly nationwide, and this assists industry in decarbonization.

As noted earlier, current system wide modelling suggests this may occur, even if favoured in specific national regions.

Another two scenarios which were developed during this Phase 1 were:

4. **High Renewables Push.** Investment in renewables and supporting infrastructure continues apace and generation capital costs tumble. Intermittently power is in considerable surplus and can be very cheap in an unaltered wholesale market structure. As well as use of green electricity, green H_2 generation (and optionally O_2) grows and all are available to industry. BECCS is supported by a growth in land use for energy crops and trees.

5. **CO_2 Shipping.** As per Section **Error! Reference source not found.**, investment in Feeder 10 is pitched against the option to ship CO_2 from Grangemouth, Fife and Dunbar.

Optionally, maximum use is made of CNS storage through import of CO_2 from other clusters and Europe through Peterhead harbour

The proposed scenarios list is summarised in Table 1.

Table 1: Levers and drivers for scenarios proposed for SNZR Phase 2

Scenario	Fuel Switching	Efficiency	Process emissions	H_2 production	CO2 transport	Non-industry: heat	Non-industry: transport
Base-case	Baseline	Moderate	CCUS Early	Blue, local, early	Feeder 10, early	Electricity, Hydrogen, DHN	Electric cars, H_2 trucks
Soft Start	Biomass, electricity	High	CCUS Later	Blue, local, early	Feeder 10, later	Electricity, Hydrogen, DHN	Electric
Local H_2 network	Hydrogen	Low	CCUS Later	Blue, local, early	Feeder 10, early	Electricity, Hydrogen, DHN	Electric cars, H_2 trucks
H_2 economy	Hydrogen	High	CCUS Early	Blue, national, early	Feeder 10, early	Hydrogen	H2
Renewables push	Biomass, Electricity, Hydrogen	Low	CCUS Early	Green, national, early	Feeder 10, later	Hydrogen, Electricity, Biomass	Electric
CO_2 shipping	Baseline	Moderate	CCUS Early	Blue, local, early	Shipping, No Feeder 10	Electricity, Hydrogen, DHN	Electric cars, H_2 trucks

4. Cluster energy system modelling

4.1. Introduction

SNZR will be informed by a selection of models, each of which contributes to a broad and complete perspective of Scotland's transition to Net Zero from an energy system perspective. The highest level of granularity, and the most demanding in terms of new data gathering, is the cluster-level model, which will require new conceptual studies of specific site interventions. The proposed cluster-level energy system model is described in this section. This model is designed to soft-integrate with both existing national level models and any future UK wide industrial sector planning developed by Innovate UK during Phase 2 of the ISCF Roadmap project.

As with all modelling tools, a balance needs to be struck between breadth and depth of decision making. A whole system model with high levels of sectoral, temporal and spatial detail is likely to be highly complex and require sophistication in either its computational methods and/or its use practices. The "sweet spot" for a model focusing on industrial clusters is likely to have greatest sectoral detail on industry and supporting infrastructure, with a coarser-grained representation adequate for non-industrial sectors.

Throughout this section, key requirements for model input and model function are drawn out where considered critical to delivery of an insightful tool. These requirements are not an exhaustive list of all data or function, but it is particularly important to source or include these features.

4.2. Definition of industrial clusters

There is no strong definition of an industrial cluster in the UK context. The BEIS Industrial Clusters Mission suggests that "industrial clusters are areas with a number of industrial sites", and that "clusters are key hubs of local economic activity and an important part of the UK economy" [4]. This suggests that any model of an industrial cluster needs to carefully consider:

- The geographical extent of the cluster
- Levels of detail around sector coverage

In the SNZR context the cluster will initially be focused around the 30 highest emitting industrial sites near to the St. Fergus to Avonbridge Feeder 10 gas pipeline and, in particular, the area around Grangemouth and St. Fergus (Figure 4). Data requirements therefore include an explicit list of the key sites to be modelled in detail, as well as the wider geographical area to include. This defines a cluster boundary. Outline data collection to assist computation goes beyond this boundary to allow realistic options to supply energy from outside the cluster in certain scenarios, for example new wind farms (e.g. Viking) or pumped hydro schemes (e.g. Coire Glas).

It is assumed that data to model CO_2 transportation and storage costs will be available from Pale Blue Dot's projects in this area (e.g. Acorn, and potentially Scotland's Net Zero Infrastructure (SNZI) project), and that the initial storage area (Captain Aquifer) will not be filled by the 2040s.

Input Requirement 1: Agreed list of key industrial sites to be included directly

Input Requirement 2: Agreed definition of geographical cluster boundary

Input Requirement 3: Description of energy sectors to be included within the energy system model, along with a proposed methodology for inclusion

4.3.Outline of cluster model features

4.3.1. High-level aim of cluster energy system modelling

The overall aim of the SNZR cluster energy modelling activity is to better understand and compare the implications of specific industrial decarbonisation strategies and scenarios in terms of their overall system cost, impact on greenhouse gas emissions and other metrics, as shown in . the "trilemma" of decarbonisation/sustainability, energy cost/equity and energy security (Figure 5).

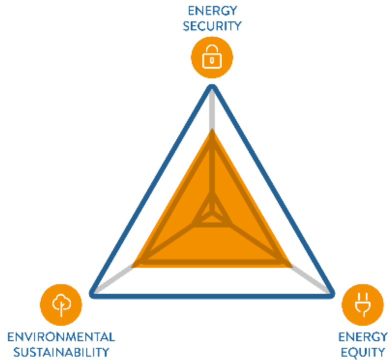

Figure 5: the Energy Trilemma [14]

However, the industrial energy system does not exist in isolation and, especially when considering deep decarbonisation pathways, it may be appropriate to operate industrially-sited energy assets such that they also support the wider non-industrial system through supply of electricity, hydrogen or synthetic fossil fuels to locations beyond the industrial site fence. Therefore, the energy system tool needs to include a representation of energy use within sectors beyond heavy industry and needs to be able to consider import (and export) of useful energy from outside Scotland's cluster boundary.

The tool will be suitable for evaluating a wide variety of industrial decarbonisation scenarios (Section 3) for Scotland's Net Zero Roadmap, taking account of energy sourced from both inside and outside the cluster. Each scenario will consist of a series of projects consistent with the scenario theme. The tool enables the project to deliver insights into the underlying cost and engineering challenges of delivering Net Zero compliant energy systems.

At a functional level, immediate requirements for the model are:

Functional requirement 1: Evaluation and presentation of aggregate emissions reduction pathway for each specifically named scenario, including demonstration of success against the Net Zero targets

Functional requirement 2: Tracking of site and cluster-level system costs in the 2020s, 2030s and 2040s, including capital and operational expenditure, and allowing analysis of the consequences of choosing a specified sequence of decarbonisation interventions

Functional requirement 3: Ability to include common infrastructure needs (e.g. repurposing of the existing Feeder 10 gas pipeline to carry CO_2), to assist with longer term planning

As well as these specific requirements, the model's outputs should permit analysis of the supply-chain implications of following specific, prescribed decarbonisation strategies, and provide the ability to evaluate the system benefits of particular technology and policy evolutions.

More broadly the model will act as a focal point for promoting cluster decarbonization at local and national level, by providing clear, insightful, evidence-based outputs. The level of granularity which can be delivered within the models will be dictated largely by data definition around the industrial sites.

4.3.2. Model structure

Proposed modules within the cluster model are shown in Figure 6. This cluster level energy system model is designed to integrate into both existing national level models and any future UK wide plan modelling developed by Innovate UK and BEIS during Phase 2.

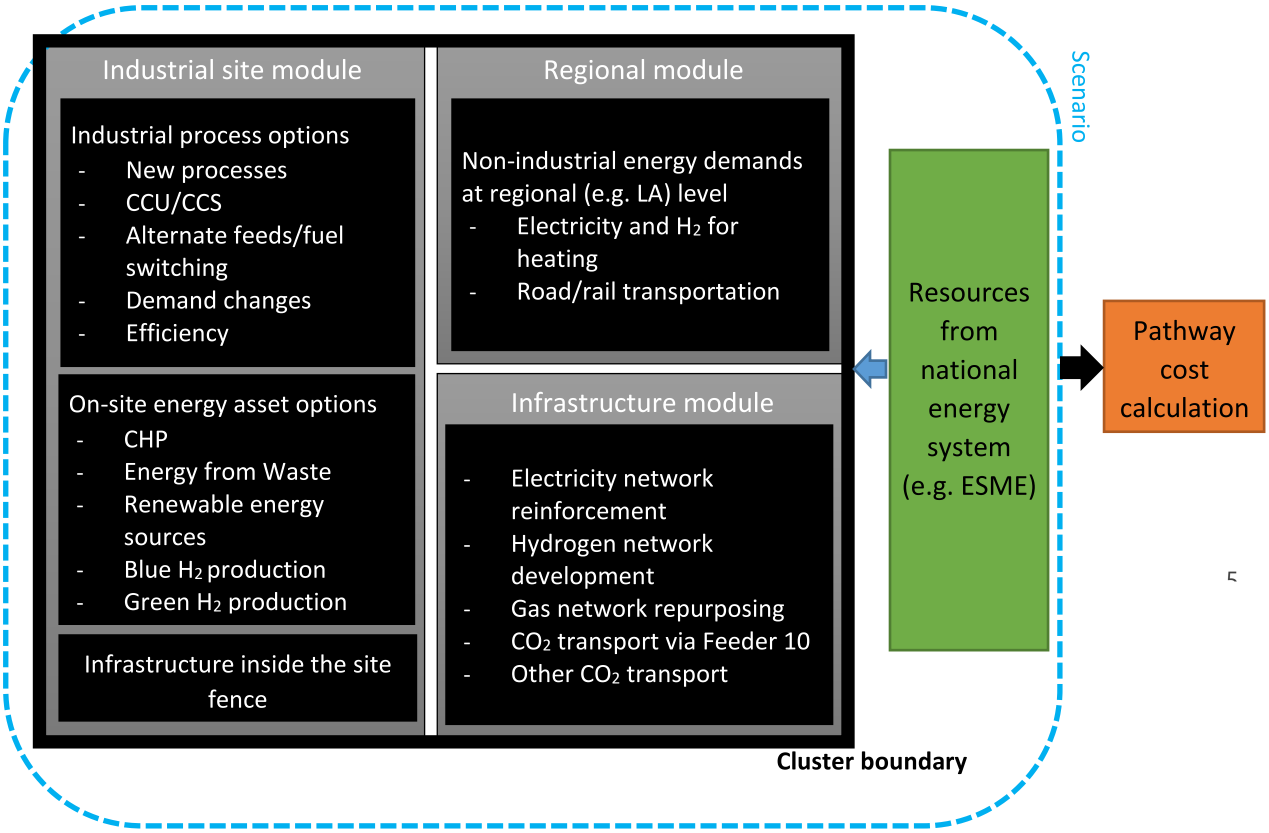

Figure 6: Schematic of cluster model

These modules are combined such that a chosen set of site options lead to the corresponding overall energy supply and infrastructure requirements at a local and regional level.

Industrial site module

Pre-selected industrial sites will be modelled on a project-based approach (where projects are synonymous with site decarbonisation interventions) as detailed in Figure 7, with the construction of these projects being reliant on work carried out in SNZR Phase 2 and the data provided by industrial users.

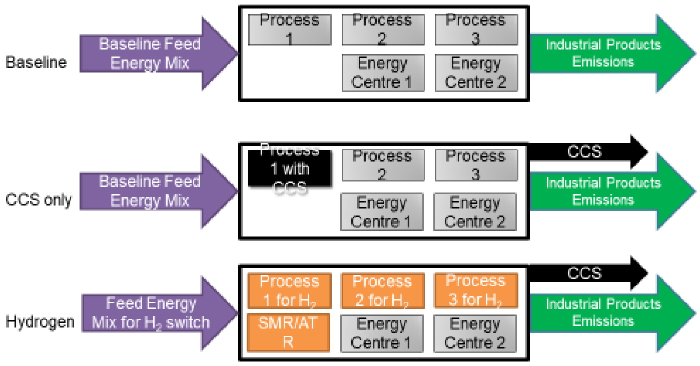

Figure 7: Options for Projects at Individual Sites

The industrial site module is informed by baseline energy and emissions data. The data required to operate the site module can then be divided into a small number of categories:

Input Requirement 4: Characterisation of baseline energy use, emissions, and infrastructure

Input Requirement 5: Future projections of industrial demand and impact of energy efficiency

Input Requirement 6: Characterisation of cost to implement a decarbonisation option at a specific site at given points in time, and hypothetical energy, emissions and infrastructure after such an intervention

Decarbonisation options (energy centres and industrial process changes) will be drawn from a library of interventions developed in SNZR Phase 2.

The output of the site module is thus a separate time-series of current and future feed energy, combustion-based and process emissions for each of the selected sites. Each SNZR scenario contributes a different mixture of site solutions.

Functional Requirement 4: Presentation of specific site-level energy use and emissions projections for each decarbonisation option available for sites

Regional module

The collection of site solutions derived in the site module must subsequently be combined with information about the non-industrial demands in the vicinity of each site to form a regional energy mix. A number of different approaches to forming regional energy requirements are viable, and the data requirements differ depending on the preferred option. An illustration of this choice is provided by considering two extreme cases:

- Fully model-determined decision making for non-industrial sites: In this case, the cluster energy system model makes decisions about the preferred non-industrial decarbonisation strategy, ensuring that SNZR-wide energy demands and carbon targets are met
- Setting of proxy energy demands: In this case, supply characteristics for the non-industry sectors are prescribed rather than determined internally within the model. This is an appropriate method should a strict set of transition scenarios be preferred, and it is likely that support from a national modelling tool would be needed to ensure that scenarios are consistent with national Net Zero emissions trajectories

The second of these options is likely to be most appropriate for an industrial cluster energy system model. In this case, a national energy system tool (proposed to be ESC's ESME tool within the initial stages of Phase 2, transitioning to the prescribed UK-wide planning view as that develops) is required to set the plausible regional mixtures. For the ESME tool, a disaggregation methodology has been developed previously, allowing credible energy balances at local authority level or lower to be determined.

The regional module will also determine whether energy needs to be imported from outside of the cluster at any point in time or, alternatively, exported to support national systems. Cost and availability of import or export energy will initially be sourced either from national energy system models or via forecasts from sources such as BEIS Energy and Emissions Projections; as with regional energy balancing, the tool will be data-driven, enabling a future transition to data sourced from the UK-wide plan.

Input requirement 7: Choice of regional granularity unit

Input requirement 8: Projected mix of energy carrier demands by region for each scenario (or logic to synthesise)

This regional representation will also be useful for selection or attribution of energy centres. Whereas thermal energy centres (e.g. CHP, methane reformers etc) are most likely to be installed at existing industrial sites, alternative energy conversion sources (e.g. onshore wind generation) are likely to be located where production is maximized. Without a sub-national level of spatial resolution such interpretation would not be possible.

Infrastructure module

The infrastructure model collects the total energy requirements from industrial and non-industrial sites to estimate the infrastructure needs for each of the scenarios considered. Elements included in this module are:

- Local industrial site connection requirements. For each of the industrial sites, an estimate of new or reinforced capacity requirements will be produced by combining the energy balance estimates from the site module with GIS-based routing logic from the sites to new or existing networks within the local regional.
- Regional network estimation. Any new, reinforced or repurposed network requirements will be assessed by aggregating energy use profiles at the industrial and non-industrial site via the regional module. Network topology will be estimated using proxy networks where relevant (e.g. where new hydrogen network infrastructure is required, a plausible option is to track the topology of the existing gas network). Where specific, bespoke requirements

are included in the scenario definition – as would be the case, for example, if considering options where CO_2 is shipped from ports to the St. Fergus terminal – new network logic will be synthesized at this stage

- Network costing. Once capacities and network element lengths have been derived, these will be converted into investment cost time-series. This final step allows a full comparison of the whole cluster energy system costs to be carried out and thus enables a detailed comparison of the cluster scenarios

Input requirement 9: Connection capacity requirement for key industrial sites, for each scenario

Input requirement 10: Cost (per metre and per unit energy) to build new, reinforce, repurpose and retire network capacity for each relevant energy/emissions vector

Although design of networks is fundamentally complex and case-specific, some approaches have been developed by modellers such as ESC to support other projects. For example, network routing methods including direct connections to existing DNOs/TNOs and approaches using routing via road and rail networks are included within ESC's EnergyPath Networks (EPN) and emerging Infrastructure Transition Analysis (ITAM) models to assist with design of future energy networks. This experience will be exploited when finalising the model logic within Phase 2 of the project, along with a broader review of appropriate network routing methods.

4.3.3. Sector coverage

In terms of industrial emissions, power, refining, chemicals, onshore oil and gas, EfW, glass, paper and pulp, cement and food and drink sectors will be examined at cluster level. Non-industrial energy use, however, is potentially more challenging to define and optimise.

In national models all major non-industrial sectors (e.g. district heating, commercial and domestic heating), including transportation (including all vehicle powertrain types) are modelled and thus can be fed into the regional module of the cluster. As a minimum, energy use for domestic and non-domestic (non-industrial) heat is expected to be included because of the potential role of industry in supplying key energy vectors to decarbonise these sectors. This will give an insight into the changing demands on primary energy sources and end uses, some of which are constrained in the models, and highlight the opportunities for industry to transition synergistically with other sectors.

This modelling may be used to help show the required size of supply chains needed to support sector transitions across the whole country.

4.3.4. Spatial resolution

The initial footprint of the cluster is shown in Figure 4. Since infrastructure is a strategic enabler, the model will track utilization, used lifetime and unit costs of inter-site infrastructure like pipelines and power lines (mapped approximately via a GIS system). The feasibility of siting large new infrastructure at a local level will also be ascertained. At this level the model's spatial resolution should consider the key industrial sites as independent connected locations (model "nodes"), although some sites may potentially be grouped.

For the non-industrial sectors, a degree of sub-national structure is likely to be required to allow local solutions to be aligned to local industrial requirements, particularly where heat system transition towards hydrogen or district heat is envisioned.

Although the model will need detailed spatial information at site level, it may not be necessary to present this level of detail in the final cluster-level summaries, thus efficient cluster-level aggregation will be included directly.

4.3.5. Temporal resolution

Many national whole energy system models compromise on their level of temporal detail to maintain a computationally tractable problem. ESME and strategically similar models such as UK TIMES tend to adopt a seasonal typical-day resolution, with each typical day being split into four or five diurnal time-slices. This level of detail tends to be sufficient to provide credible insights whilst capturing key features of the energy system such as the electricity and heat diurnal peak and the capacity requirements in cold spells.

Similarly, for the cluster model, the temporal resolution needs to be sufficient to allow capture of the key diurnal demands associated with industry. Should solutions involving a large amount of on-site intermittent renewables be of interest it could be appropriate to consider weekly or fortnightly within-year resolution (wind/solar droughts, summer minimum load) in some elements of the model.

4.3.6. Modelling of uncertainty

The optimal decarbonization pathway can swing on such things as policy support measures (deliberate or not), the emergence of disruptive technology or public pressure – all outside the capability of techno-economic models. It is for this reason that scenario work is adopted – to force the model into exploring levers it would not select "mathematically". Inside the model, uncertainty in the costs and performance of technologies can be dealt with if necessary, e.g. by Monte Carlo analysis, as is already utilized in ESC's ESME and EnergyPath Networks models.

New technologies may offer lower costs than existing ones but carries uncertainties in the terms of risk of project failure, delay, overspend or under-performance which the model does not compute. Without reverting to Monte Carlo techniques, this can be controlled by constraints on adoption rate if required.

4.3.7. Miscellaneous model properties

The model will address several realities which introduce complexity and will require special treatment. The first of these is variability in supply and demand, potentially making use of battery storage systems, pumped hydro, biomass, H_2 and possibly CO_2 storage. In addition, the costs of CO_2 storage may change during the specified period. The second is the use of existing infrastructure, and strategic temporary oversizing of infrastructure, which will need tracking of expiry time and utilization, and different costing lookups. As noted above, large infrastructure will be estimated using a GIS system.

Finally, in one scenario, repurposing of Feeder 10 to form an onshore CO_2 pipeline will not be take place early in the pathway, and a CO_2 shipping option will be explored. This will still potentially require some more limited, bespoke infrastructure estimations via GIS or other means.

4.3.8. Additional requirements and observations

Key observations on the modelling approach outlined are:

1. The baseline reference case definition carried out in WP1 of the current project, including energy and emissions at a site or point-source level, is critical. Reference industrial energy data is available at a UK national level, but this is likely to be of limited use when considering specific sites within an industrial cluster.
2. Characterising the decarbonisation options requires the current industrial sites, non-industrial sites and infrastructure within the cluster to be represented. The module to be developed in SNZR Phase 2 offers a key route to such options for industrial sites.
3. Depending on the level of spatial granularity deemed necessary to support the cluster model, a rich suite of assumptions from national models/plans or other sources is required. These include energy carrier costs, share of resource availability and assumptions on cost-competitive approaches to decarbonising non-industrial sectors.
4. If it is not possible to get data quickly from the sites or from emerging studies within SNZR Phase 2, and safely use it, the library of decarbonisation options could be populated with generic data from published sources, or data purchased from commercial sources or models, though this will carry a greater risk of inaccuracy. There are likely to be gaps in this data – or areas where sub-optimal references need to be used.
5. Development of engaged expert stakeholder reference groups to provide insight from specific sites or sectors into the industrial cluster module option cases is vital. Without appropriate stakeholder group engagement, expertise will be drawn from the SNZR group.
6. Ensuring consistency between the industrial site scenarios and the non-industrial and national energy system designs is potentially challenging. ESC's EnergyPath Networks tool is designed to optimize all such energy system elements simultaneously, but this tool is typically most appropriate when developing insights about heat systems as a local authority scale. At a UK level, it is known that the range of system designs delivering the Net Zero target is substantially reduced compared with the previous 80% target, and thus national-scale energy decisions will need to be considered carefully. The expertise of the Energy Systems Catapult delivery team in national-level modelling with the ESME model and other tools will help achieve this internal consistency and will also signpost the likely requirements for combining cluster models with the eventual UK-wide plan.
7. The infrastructure sizing and estimated proposed within this work package is at a level of detail appropriate for regional estimation. Routing of networks will be simplified but aim to produce costs and capacities that are approximately in line with expectations. Most importantly, they will allow a fair comparison between different scenarios.

4.4. Related existing models

Various stakeholders, including ESC, have experience producing modelled results and using them to provide relevant insights about the energy system transition. It is useful to learn from these case studies both to help shape model logic but also to assess how modelled material might be presented to a range of stakeholders.

4.4.1. ESME

ESME was developed by the Energy Technologies Institute to help identify opportunities for technology innovation. The ESME solution, based on linear programming, finds the lowest-cost UK whole energy system designs which meet stipulated sustainability and security targets, whilst taking account of technology operation, peaks in energy demand and UK geography. Its sectoral scope includes all major suppliers and demands of energy: electricity generation, fuel production, energy use in buildings and industry, and transportation of people and freight. ESME performs a high-level cost optimisation that analyses different combinations of technologies in each sector and selects the combinations which together minimise the total cost while meeting specified targets and constraints. It includes a Monte Carlo function that allows futures associated with different levels of technology innovation success to be explored.

Alternative models are available and utilised by other stakeholders to derive relevant insights. UK TIMES [15] is used extensively by academia, Government and industry; the Clean Growth Strategy [16] is an example of a relevant study supported by UK TIMES.

ESME's regional and sectoral granularity is necessarily coarse but adequate to examine key engineering features of the transition to Net Zero and to allow the trade-offs in emissions success in different sectors to be assessed. Energy is balanced at a UK regional level (former Government Office regions), and industrial sectors are represented at a fairly high level, chosen to be in line with standard energy statistics published by BEIS.

Typically, insights supported by ESME modelling focus on the broad technological and systemic features of the transition to Net Zero. The role of major, significant technologies or families of technologies (e.g. offshore wind, heat decarbonisation etc) are of paramount interest rather than technical detail. For example, ESC's Innovating to Net Zero report [2], published in March 2020, focuses on the key role in meeting Net Zero of technologies such as floating offshore wind and zero-emission vehicles, in addition to changes in behaviour such as diets and international aviation. An example of the system-wide transition in final energy use, supported by these changes in technology and behaviour, is provided in Figure 8.

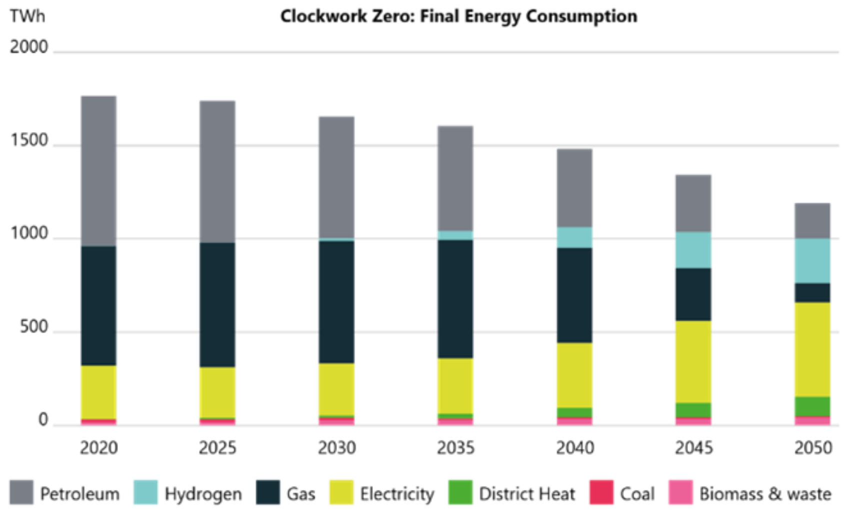

Figure 8: Final energy consumption in Clockwork Net Zero scenario [2]

With regards to industrial decarbonisation, ESME includes generic fuel-switching and CCS options for each industrial sector, drawing on evidence from sources including UKERC [17]. Insights tend to focus on the UK-wide strategic industrial abatement options (CCS, fuel-switching, electrification) rather than on specific, actionable projects at industrial sites; ESME insights are a useful starting point for understanding industrial decarbonisation, and the logic for representing and optimising industrial sites is broadly applicable, but there is insufficient detail in existing modelling studies to draw strong conclusions about specific industrial actions within clusters.

4.4.2. EnergyPath Networks

EnergyPath Networks is an analysis suite designed to help support the planning and design of cost-effective local energy systems for the UK. National whole energy system tools such as ESME necessarily take a relatively simplified view of local features and constraints, and when considering plausible decarbonisation options for a local area these features cannot be ignored. EnergyPath Networks takes a whole systems approach to decarbonisation, incorporating the unique characteristics of the local area including the type of building stock, heating technologies, existing energy networks, electrification of cars, as well as local spatial constraints and opportunities [9].

EnergyPath Networks can be divided conceptually into four main modules as shown in Figure 9, focusing on household options (HOM), spatial analysis (SAM), networks analysis (NAM) and pathway optimisation (POM). These modules assess the characteristics of the local domestic buildings, represent the existing local area (buildings and energy networks), design and cost different energy networks, and produce a specific, optimal pathway. The presence of a sub-national boundary – not present in UK-wide energy system tools – means sourcing of energy from outside the local area is necessary. To align with credible decarbonisation pathways, EnergyPath Networks derives its cost and availability of nationally sourced energy from a related ESME model run.

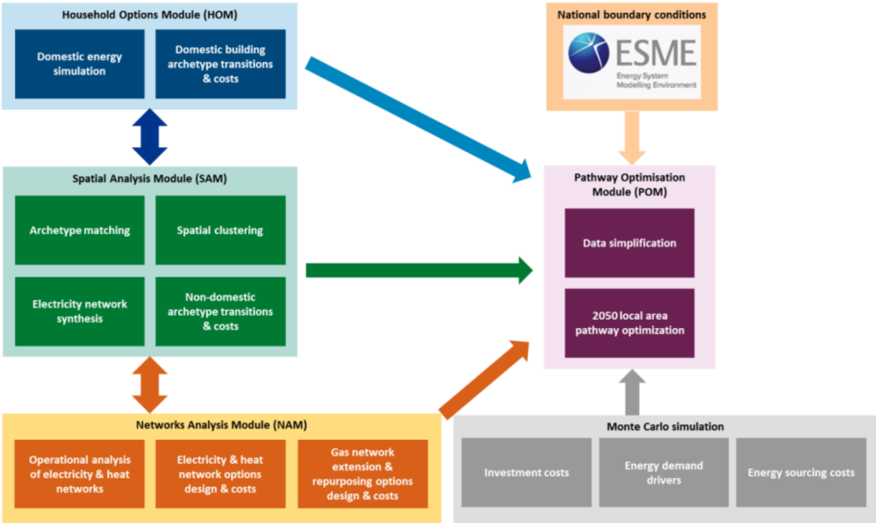

Figure 9: EnergyPath Networks modelling framework [9]

The nature of EnergyPath Networks means that although system-wide features can be produced, such as the cost to decarbonise, the most compelling results illustrate features of the system at a local level, such as the types of domestic heating system employed across a city.

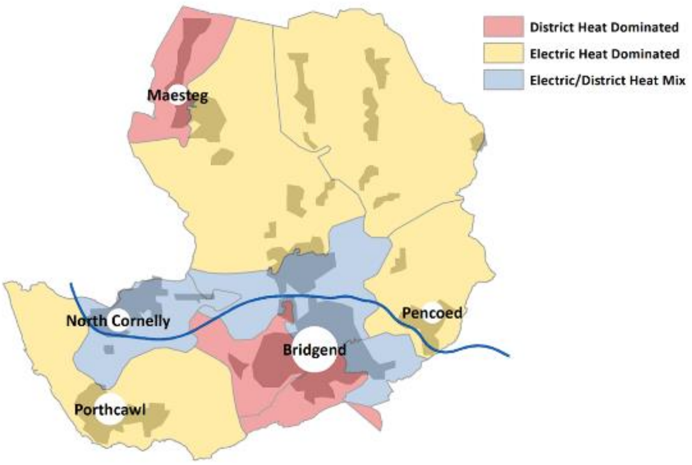

Figure 10: Example EnergyPath Networks results (adapted from [9])

There are similarities between the modelling approach proposed for SNZR and the EnergyPath Networks framework. The role of local availability of energy sources is critical in both cases, as well as the inclusion of energy sourced from outside the area boundary. The modular approach – allowing detailed site-level insights to be included within a larger regional model – is appropriate for both local and industrial cluster level modelling. However, the regional scale of the industrial cluster, combined with the highly specific actions appropriate for industrial sites and for common infrastructure (e.g. CCUS), mean that a simple repurposing of EnergyPath Networks to support SNZR is likely to be inappropriate. Instead, learnings from EnergyPath Networks's modelling methodology and presentation style will be incorporated into the SNZR cluster model where appropriate.

4.4.3. CO2NomicA

This model was developed to provide cost and performance data for conceptual offshore CO2 storage infrastructure, including complex pipeline networks starting at the shore, pipeline networks and platform and subsea systems, starting at several onshore hubs, including St. Fergus.

The model tracks the development of costs of network projects from the shoreline hubs in five-yearly time slots out to 2050 and monitors their capability as the stores fill and pressurise. In order to calculate storage capacity, well numbers, well lengths, platform costs etc it draws on the same storage database that was developed by the UKSAP project[2] and which is now accessible from the British Geological Survey's CO2 Stored program[3]. It provides guidance on pipeline sizing, and offers options regarding choice of store, platform type, spare wells etc.

The computation and presentation of results is in Excel. The tool offers limited graphics (e.g. Figure 11) to portray the layout of pipeline networks. The level of accuracy is suitable for conceptual studies and strategic landscaping.

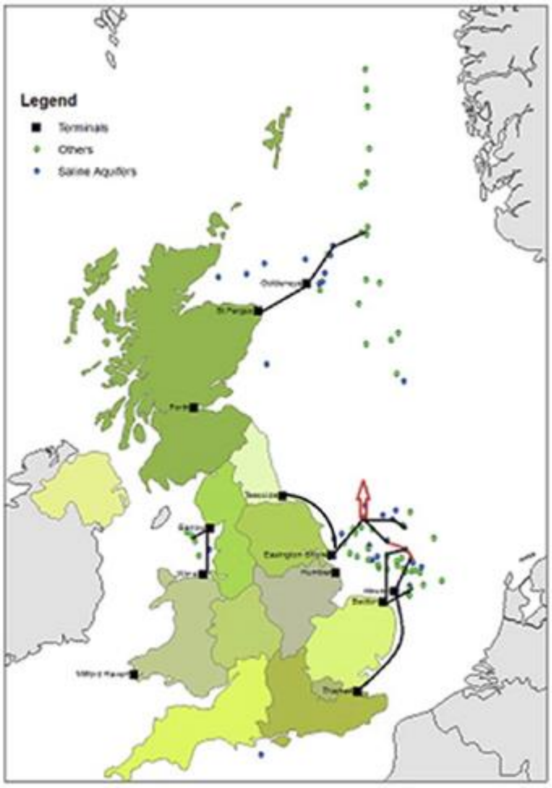

Figure 11: Example visualisations using CO2Nomica

4.5. Summary data requirements

This section summarises the detailed data requirements as provided within SNZR Phase 1 deliverable D4.1. Within this section the indicated reference refers to a known, reviewed source

[2] Information available via https://www.eti.co.uk/
[3] See http://www.co2stored.co.uk/

that contains the specified information. Within the Phase 2 project a wider review of sources and evidence will inform an update of these data – potentially led by Phase 2 workstream 4 – and site studies will provide more specific data where this is required.

Cluster definition

Element	Source
List of industrial sites to include as "primary"	SNZR project decision (Phase 1)
Geographical and sector coverage for non-industrial sites	SNZR project decision (Phase 2)
Approach for modelling non-industrial sites	SNZR project decision (Phase 2)

Baseline definition

Element	Source
Process/site annual energy consumption	Sites/WP1
Process/site diurnal operational profile	Sites/WP1
Process/site GHG emissions from industrial processes	Sites/WP1
Site energy import/export infrastructure	Sites/WP1

Future demand projections

Element	Source
Process/site level demand scenarios	Sites/*Energy and Emissions Projections* [19]
Process/site change in diurnal energy use profiles	Sites/Elexon

Site/process decarbonisation interventions

Required properties of site interventions

Property
Indicative scale of technology
Construction period
Economic life
Technical life
Maximum build rate by decade
Capex and temporal learning rate
Capex and scale-dependency
Fixed cost and learning rate
Variable cost and learning rate
Inputs and efficiency learning rate
Outputs
Losses (including fugitive emissions)
Residual emissions

Process modifications

Site	Source
Site/process properties of fuel switch to hydrogen	Sites/UKERC [17]/Other[4]
Site/process properties of fuel switch to biomass	Sites/UKERC [17]/Other
Site/process properties of fuel switch to natural gas	Sites/UKERC [17]/Other
Site/process properties of fuel switch to electricity	Sites/UKERC [17]/Other
Site/process properties of applying CO_2 capture	Sites/UKERC [17]/Other

Infrastructure

Infrastructure feature	Source
Cost to reinforce electricity networks (£/kW)	ESC [6,19]
Cost to connect to CO_2 networks via pipelines (£/(t/hr)/km)	GIS-based system + ESC [6,19]
Costs and other features of shipping CO_2 to stores	TBC
Cost to build hydrogen networks (£/kW/km)	GIS-based system + ESC [6,19]
Network losses	ESC [6,19]

[4] It may also be possible to build up these properties from a new "SNZR" database included in the model

Energy centres

Energy centre technology	Source
Energy from waste (EfW), moving grate	ESC [6,19]
EfW, moving grate, with CCS	TBC
EfW, gasifier	ESC [6,19]
EfW, gasifier, with CCS	TBC
EfW sorting	TBC
Biomass-fired generator	ESC [6,19]
Biomass-fired generator with CCS	ESC [6,19]
Biomass CHP	ESC [6,19]
Biomass CHP with CCS	TBC
Combined-cycle gas turbine (CCGT)	ESC [6,19]
CCGT with CCS	ESC [6,19]
Open-cycle gas turbine (OCGT)	ESC [6,19]
Small modular nuclear unit	ESC [6,19]
Onshore wind turbine	ESC [6,19]
Rooftop photovoltaics	ESC [6,19]
Utility-scale ground-based photovoltaics	ESC [6,19]
Lithium-ion battery	ESC [6,19]
Flow battery	ESC [6,19]
Natural gas fired boiler	ESC [6,19]
Biomass fired boiler	ESC [6,19]
Large scale heat pump	ESC [6,19]
Hydrogen boiler	ESC [6,19]
District scale sensible heat storage	ESC [6,19]
Steam methane reformer	ESC [6,19]
Steam methane reformer with CCS	ESC [6,19]
Autothermal reformer	BEIS [20]
Autothermal reformer with CCS	BEIS [20]
Proton membrane exchange electrolyser	BEIS [20]
Alkaline electrolyser	BEIS [20]
Solid oxide electrolyser	BEIS [20]
Coal gasification plant	ESC [6,19]

Coal gasification plant with CCS	ESC [6,19]
Synthetic petroleum production plant	TBC

Features from outside the cluster

Element	Source
Cost/cleanliness of electricity from national network	National modelling/*Energy and Emissions projections* [18]
Cost of hydrogen from national network	National modelling
Availability of hydrogen from national network	National modelling
Availability of biomass from UK resources and imports	National modelling/Other

Generic fuel/energy carrier/emission properties

Element	Source
Natural gas delivered price	*Energy and Emissions projections* [18]
Petroleum product delivered price	*Energy and Emissions projections* [18]
Biomass delivered price	ESC [6,19]
Natural gas consumption emissions factor	*DUKES* [21]
Petroleum consumption emissions factor	*DUKES* [21]
Biomass consumption emissions factor	*DUKES* [21]
Biomass production emissions factor	*DUKES* [21]
Global warming potential for other gases	TBC

3.4.1 Industrial site information

In addition to a characterization of baseline fuel use & process emissions, including any extraordinary load patterns and within-day operation & energy vector use, conceptual studies will require physical knowledge of parts of the site, although it is not expected this needs to be recorded in the SNZR models.

3.4.2 Future demand information

It is required to project industrial demand evolution over time, which will be obtained from stakeholders, national modelling and published projections (e.g. BEIS [18]). These will be split by sector or perhaps site or grouped site (BEIS/EEP projections are aggregated).

3.4.3 Industrial interventions

The scope of interventions by fitting new technology is outlined in Figure 12. In addition, efficiency improvements will be included, either through organic development (captured in the learning rate) or by a specific project.

Figure 12: SNZR depiction of technology interventions [22]

3.8.4 Potential data gaps and strategies to fill

As referenced above, credible cost and performance data for new build stand-alone plant for almost all of the major energy transformations and "long length" adjoining infrastructure is available. Some of this data was obtained by commissioning studies from major contractors (Wood, SNC-Lavalin, Costain) or is available from similar work published by IEAGHG or other parties (e.g. [23]).

One weakness for use of these generic sources in cluster level modelling is that it lacks the ability to estimate costs of the bespoke on-site parts of fuel switching projects. Better insight is needed into the costs and schedules for installing on-site piping, ducting and power infrastructure and equipment like H_2 (dual fuel) burners, and large-scale electric heaters (if available).

At a larger scale, a review of recent developments on bioenergy with CCS, synthetic natural gas, hydrogen storage (when caverns are not available) and a study on the inclusion of selected fuel cell options in the models would be beneficial. BEIS has already published some material which can form the basis of these reviews [20].

5. National energy system modelling

5.1.Introduction and history

National energy system models have been used extensively to derive insights about technology innovation, policy and strategy in various countries over the last few decades. In the UK context such models have supported Energy White Papers [25], specific sectoral thinking [26,27] and development of strategies in support of clean economic growth [16]. A variety of models have been deployed to support strategic thinking, each having specific features to ensure adequate simplicity. Key examples are MARKAL, TIMES (including UK TIMES) and ESME. More recently, as computational power has increased, more sophisticated models that balance the need for long-term planning with the requirements for short-term supply and demand balancing (especially when dealing with systems where a high penetration of renewables is a viable outcome) have been developed, such as the ESC's Storage and Flexibility model [28], or Imperial College's IWES model [29] (Figure 13).

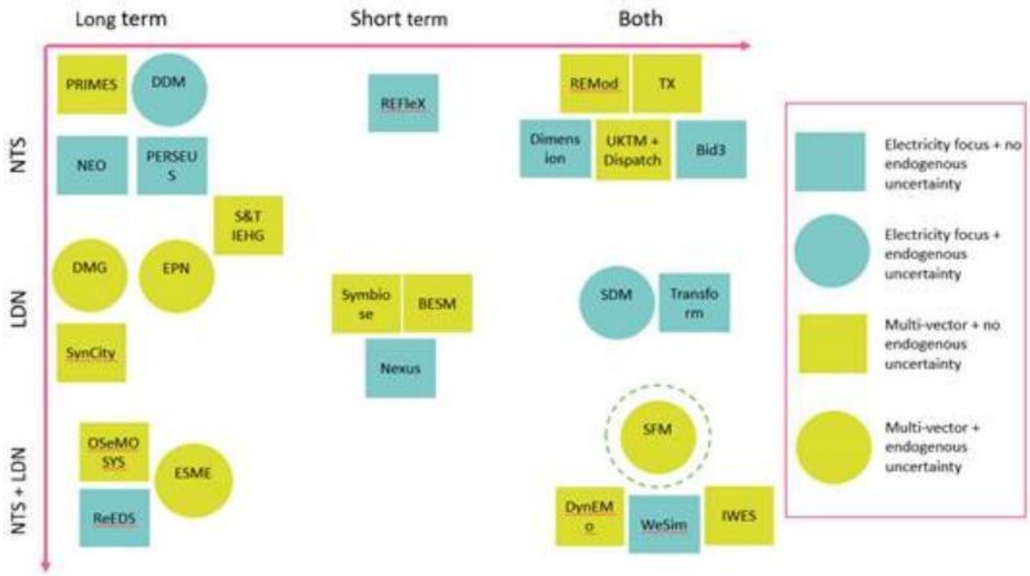

Figure 13: Energy modelling landscape [28])

Historically, with 80% targets, trade-off of emissions was permitted and the residual 20% in could be placed in different sectors. Although some flexibility is still present at Net Zero this residual is much lower, and it is likely that all sectors must go further than 80%.

A study at a national level is of value to individual industrial clusters because it illustrates the possible national sequencing of interventions and any (potential) reliance on national strategy – some industrial decarbonisation actions can be taken without national strategy but not all. It also illuminates us on the carbon content of national grids and gives us a picture of the flexibility in overall emissions requirement for the industrial sector. Some clusters will have a natural resource that may suggest different potential emissions budgets for different clusters.

In addition to a national energy system model, technically informed multi-sector economy system modelling of the kind recommended by the Strathclyde University Centre for Energy Policy and used in HMT NZ modelling offers additional insights. Taking data from whole energy system models and other sources, whole economy models of the UK reveal insights into wide economic issues and social cost benefits. Study of the differing effects of "who pays" for UK decarbonization reveal any disruptions in national budgets and identify where the public and private industry feel the economic effects of what will be designed as a "just transition".

Facets of this form of model are:

- Inclusion of all sectors and markets – drawing information from range of technical, industry, policy sources
- Economic multiplier relationships and metrics
- Simulation framework (more often used for 'what if' or ex ante analyses) – where changes directly impact one or more sectors (e.g. investment spending, export demand, technical efficiency, tax rates), triggers series of economy-wide responses and effects, economy adjusts
- Variation in focus, assumptions and approach, depending on questions being asked (e.g. focus on energy sectors, labour markets, fiscal issues)

This document focuses on the energy system model's requirements – with specific reference to the ESC's ESME model – and highlights potential interactions between a national and cluster-level model. The role of whole economy modelling is outlined in more detail in the SNZR Phase 1 deliverables D5.1, D5.2 and D5.3 and is not expanded upon further in this report.

5.2. Energy system model features

5.2.1. Model formulation

ESME is a data-driven optimisation model that minimizes the total discounted cost of the UK energy system (capital, operating and resources) along the pathway to 2050. It ensures supply and demand are balanced along with deploying adequate supply and flexibility to manage a realistic system operation.

To achieve the required sectoral coverage, a simplified temporal resolution is adopted, with 5 timesteps within-day modelled over two typical seasonal (summer and winter) days. In addition to these typical days, a fully-resolved view of the system in a 1 in 20 cold spell is produced, providing stress conditions against which systems and networks are typically designed.

ESME is built up based upon prescribed end-use demands – e.g. residential buildings, transport km. For a given modelling run, these demands are fixed and inelastic; however, there is no prescription of specific energy carriers (i.e. technologies) to satisfy these demands. The optimal technology deployment mix is selected based on minimisation of system costs.

Supply-chain constraints are included as deployment/year limits. There is also the option to require supply chains to be built up in some cases via so-called exponential uptake constraints.

The greenhouse gas emissions target is a key constraint, and in normal operation the model will not solve if it is not possible to achieve the target emissions level at any point along the pathway.

The latest version of ESME includes full accounting of all significant greenhouse gases in CO_2-equivalent terms, although only CO_2 emitting technologies are considered within the optimisation.

Mathematically, ESME is constructed as a linear programming program. The implication of this is that it is assumed that the spatial granularity is large enough that deployment of energy assets in any given region will be greater than tens of MW scale, thus there is no inclusion of "lumpy investment" or other more sophisticated logic, such as power station output-dependent efficiency.

In typical operation, ESME is structured to provide a policy-neutral view – ESME does not assume that policies that affect (for better or worse) the risk profile of individual technologies are in place. Modelling results thence represent a view of the future energy system as designed by a central architect who has no technological preferences and sees no difference in risk between investing in different energy assets.

This overall formulation is similar, but not identical, to equivalent models such as UK TIMES. Any data exchange between cluster-level models and other national models or plans will be subject to similar requirements to ESME, albeit with some minor adjustments likely in terms of temporal and spatial granularity.

5.2.2. Uncertainty

Future costs and performance characteristics of energy conversion and storage technologies are uncertain. It is not possible to know how successful key innovation projects and global research and development will be, and the influence of consumer acceptance and appeal will strongly influence the ability to drive down technology costs through learning.

A typical approach often taken towards uncertainty within linear models is often to ignore it, and assume prescribed, exogenous assumptions on technology cost and performance. One approach is to use scenario analysis to understand how the energy system might evolve if particular system features (narratives) are observed. Alternatively, some models include logic to endogenise technology features such as cost or performance based on deployment; typically, there are performance implications of taking such an approach, although this has been trialled within TIMES models [30].

In addition to scenario analysis, ESME is capable of adopting a Monte Carlo approach to uncertainty. Commodity prices and technology costs are assumed uncertain but to follow known distributions. ESME also includes variability within biomass resource within its Monte Carlo simulations, reflecting uncertainty in future yields and business models that promote energy crop development over other land use.

Monte Carlo analysis is particularly useful in understanding least-regrets actions: should a named technology play a role in the transition to Net Zero across a range of radically different simulations, it is likely that there is limited regret in pursuing innovation activity to drive the technology to deployment. Monte Carlo also allows the energy system modeller to probe the sensitivity of the energy system to individual technology availability, cost and achievability of emission targets.

5.2.3. Limitations of model

The simplifications applied within national whole energy system models mean that care is needed in interpreting results. For example, the focus on energy balance within typical seasonal days means that some key elements of the energy system – such as wind intermittency – are represented rather simply. It is good modelling practice to test energy systems designed using whole energy system tools using more detailed sectoral models, such as electricity dispatchers. Newer model developments, such as the ESC's Storage and Flexibility Model, balance the sophistication of dispatch and the long-term planning view, but such models tend to be more computationally intensive.

In addition, specific interventions need to be inferred from model decisions made across a region or even UK-wide. Sometimes these decisions represent a single technology installation whereas in others it could represent thousands of distributed technologies. Local constraints are also not usually included within national models except where stark enough to warrant specific attention (e.g. off-gas buildings are sometimes considered specifically).

The Monte Carlo approach has been described previously as a way of managing uncertain future technology properties, and this approach is powerful. However, it is still challenging to determine how to manage the most speculative options that have a very uncertain future and less clear properties. For example, Direct Air Capture of CO_2 is a technology that is of great interest to help remove "hard to treat" emissions within national energy systems. This technology is currently subject to significant research and development but demonstration of the success of this technology at scale, at reasonable cost, has not been fully demonstrated. The Monte Carlo method could be used to probabilistically simulate availability of a technology as well as cost and performance, but this approach is not currently employed wholesale in ESME modelling.

Related to the above, although techno-economic models are, in theory, able to include all technologies (however expensive) and the model should be able to choose techno-economic solutions to satisfy any emissions target, not all technologies and conversion routes have sufficiently robust development to allow cost and performance data to be included.

A final limitation of techno-economic models is in the difficulty of incorporating behavioural change. The natural focus of models like ESME is on technologies and the role they play in decarbonisation. However, the behaviour of individuals, businesses and institutions can also play a significant role in enabling the transition to Net Zero. In particular, the potential for energy users to reduce their demand (e.g. by choosing not to travel or to reduce their comfort requirements within domestic dwellings) offers a route to decarbonisation that is not straightforward to cost in the same way that technologies are. This elasticity within demands is a standard macro-economic feature but ascribing a single, robust cost saving to a reduction in demand and treating it on equal terms to a technology investment is less consistently utilised within national energy system modelling, although there are examples of this in the literature [31,32]. As with some other limitations highlighted in this report, the preferred approach within modelling with ESME is to design or curate scenarios that have plausible and coherent assumptions around demand assumption baked-in; the ESC's Clockwork and Patchwork scenarios are examples of this. It is likely that a scenario-based approach will remain the preferred methodology for the SNZR Phase 2 modelling study.

5.2.4. Industrial and non-industrial data requirements

The ESME dataset is publicly available, fully referenced and contains the data that is included within a standard model run. Many of the assumptions are based on detailed ETI/ESC projects, but as ESME is a data-driven model these can be adapted easily if new evidence emerges. Alternative datasets are held by stakeholders such as BEIS to populate their own national energy models.

With reference to the industrial clusters challenge specifically, the industrial switching logic within ESME is based primarily on the UKERC Usable Energy Database [17], where fuel-switches and CCS availability are characterized at an industrial process level. As previously noted in this report, this logic is adequate to assess the features of industrial decarbonisation at a high level but is unlikely to be directly applicable to specific industrial sites.

A second source of industrial emissions is associated with non-combustion activities within fossil fuel production, including fugitive emissions. There is some variance in the modelling community around how such features are included, with the approach within ESME typically being to treat these as prescribed decarbonisation pathways or scenarios (following trajectories such as those illustrated by the CCC [1], or within BEIS Energy and Emissions Projections [18]). Other models consider specific decarbonisation actions within the model decisioning.

A final source of "industrial" energy use (often treated as industrial consumption within energy statistics) is associated with mobile off-road machinery, such as excavators and loaders. The ESME dataset draws upon detailed study originating in the ETI's Heavy Duty Vehicles programme [33] to include energy use within fossil-fuelled variants of these technologies; Net Zero compliant versions of ESME upgrade these variants to be fuelled by hydrogen or electricity, drawing on methodology suggested within the CCC's Net Zero reports [1].

Currently all CO_2 transport within ESME is assumed to take place via onshore and offshore pipelines. There is not currently the option, for example, to ship CO_2 from selected ports to hubs such as St. Fergus for subsequent transmission to offshore stores, although this would not be technically problematic to implement.

Finally, industrial energy demand forecasts are required. These demands reflect future production levels within individual industrial sites, growth or shrinkage in demand for industrial products (i.e. new or retired industrial sites) and improvements in energy intensity or the impact of resource efficiency.

5.3. Combining national and cluster-level models

The requirement to combine cluster-level insights into a UK-wide plan, as stated in the requirements for the ISCF Roadmaps Phase 2 projects, illustrates the need to understand what features of the cluster model would be fed into a UK-wide model and vice versa. Insights from the national plan to be incorporated into the cluster-level model have been outlined in Section 4.5 of this report, and are expanded upon and visualised in this section. Insights from the cluster-level model to be incorporated into the national plan are more uncertain and will depend on how the UK-wide plan is to be constructed. In this section the integration of cluster-level information into an ESME-like UK whole system model is discussed. It is very likely that many of the data flows described here would be relevant even if the approach chosen for the UK-wide plan was radically different to a modelled approach using a model like ESME.

National data sources for cluster models

Data from national models is likely to be used to characterise energy sourced from outside the industrial cluster boundary. This will include fuels (coal, gas, petroleum products and biomass) and internally generated energy carriers (electricity, hydrogen). The national models will be required to provide costs and availabilities (seasonal and diurnal) of these energy vectors. Another important feature to be passed into the cluster model from outside is a carbon price, if the resulting model is to be based on cluster energy and emissions costing rather than optimisation against a carbon target.

Section 4.5 also indicates several technology characteristics that could be sourced from ESC's ESME dataset. Such characteristics should not be considered as originating from a national model or plan, but rather a reference library of technology properties – these data are used in national models in the same way as they would be in cluster models.

Finally, any regional non-industrial (or small industrial) energy use assumptions need to be sourced from a national transition pathway. This is more initially challenging as sub-regional energy use patterns are not trivial to derive from national pathways. ESC has developed tools and logic to optimise such energy use (via EnergyPath Networks), or to disaggregate national or regional energy use to a finer level of granularity, (within the Future Networks Transition Analysis project [34]); alternatively it may be possible to derive bespoke energy use assumptions at local authority level for each of the scenarios proposed. It is clear that national modelling insights provide a viable starting point for this required regional detail.

The mix of data requirements for cluster-level models are visualised in Figure 14.

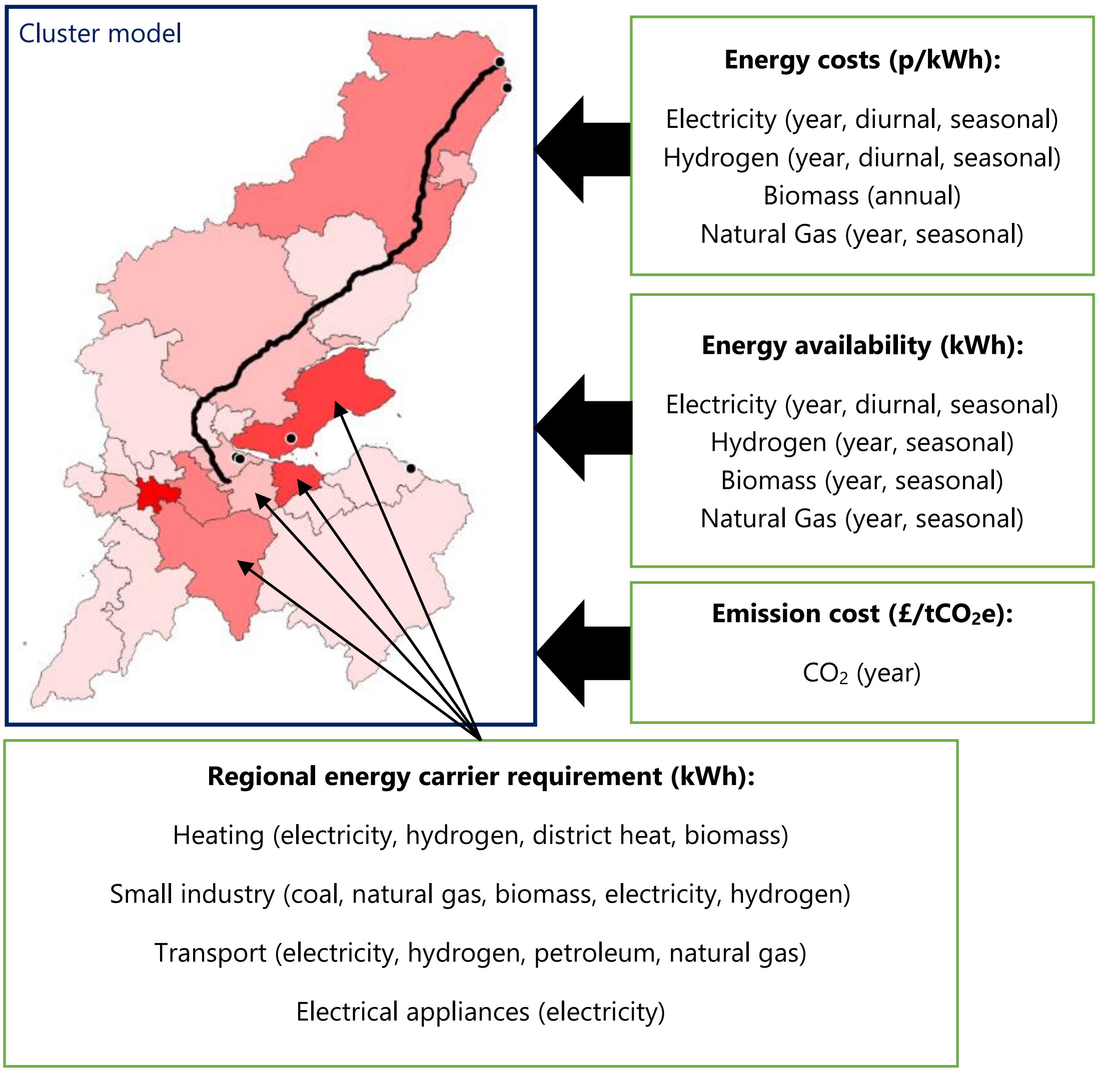

Figure 14: Data requirements for cluster-level model originating in national models/plans

Cluster data sources for national models/plans

As noted previously, the representation of industrial energy use is typically simplified within national whole energy system models, because of the need to provide coverage of the whole industrial sector whilst leaving the model computationally tractable. However, with the availability of a deep dive into specific industrial clusters, a more detailed dataset is potentially available to incorporate into national plans.

The scenario-based approach proposed for SNZR implies that an internally consistent set of industrial energy use profiles (and activities affecting process emissions) will be available for the national plan. Each scenario is comprised of a sequence of specific decarbonisation actions taken at individual industrial sites and thus contributes an emissions pathway for the chosen industrial sites. The cluster-level scenarios will also include a more realistic view on site production demand and energy/resource efficiency and thus should supplant the high-level demand forecasts typically included within UK-wide models.

An important consideration for national models informed by cluster-level analysis is the level of industrial energy coverage. Clusters do not contain the entire balance of energy use in a region or nationally, and thus the UK wide plan requires a methodology to ensure that the whole industrial sector is projected to deliver the required emissions reductions once specified actions within a cluster have been taken. At a basic level this may be done simply by assessing the proportion of regional industrial activity or emissions contributed by sites within the cluster and disaggregating. The national plan then includes a fixed energy use profile for the cluster sites and a separate contribution from non-cluster sites. If such an approach were implemented in ESME, for example, the likely approach would be:

1. Fully prescribe industrial energy (and process emissions) use at the cluster sites as a fixed, exogenous demand (derived from cluster-level modelling)
2. Estimate non-industrial energy use by comparing cluster and national/regional statistics
3. Ascribe the residual (non-cluster) industrial energy use to sub-sectors using national or regional statistics
4. Adopt existing demand/energy intensity assumptions for non-cluster sites
5. Apply existing fuel-switching and CCS options to non-cluster sites based on existing logic
6. Constrain build of energy centres included within cluster-level scenarios

The data flows are summarised pictorially in Figure 15.

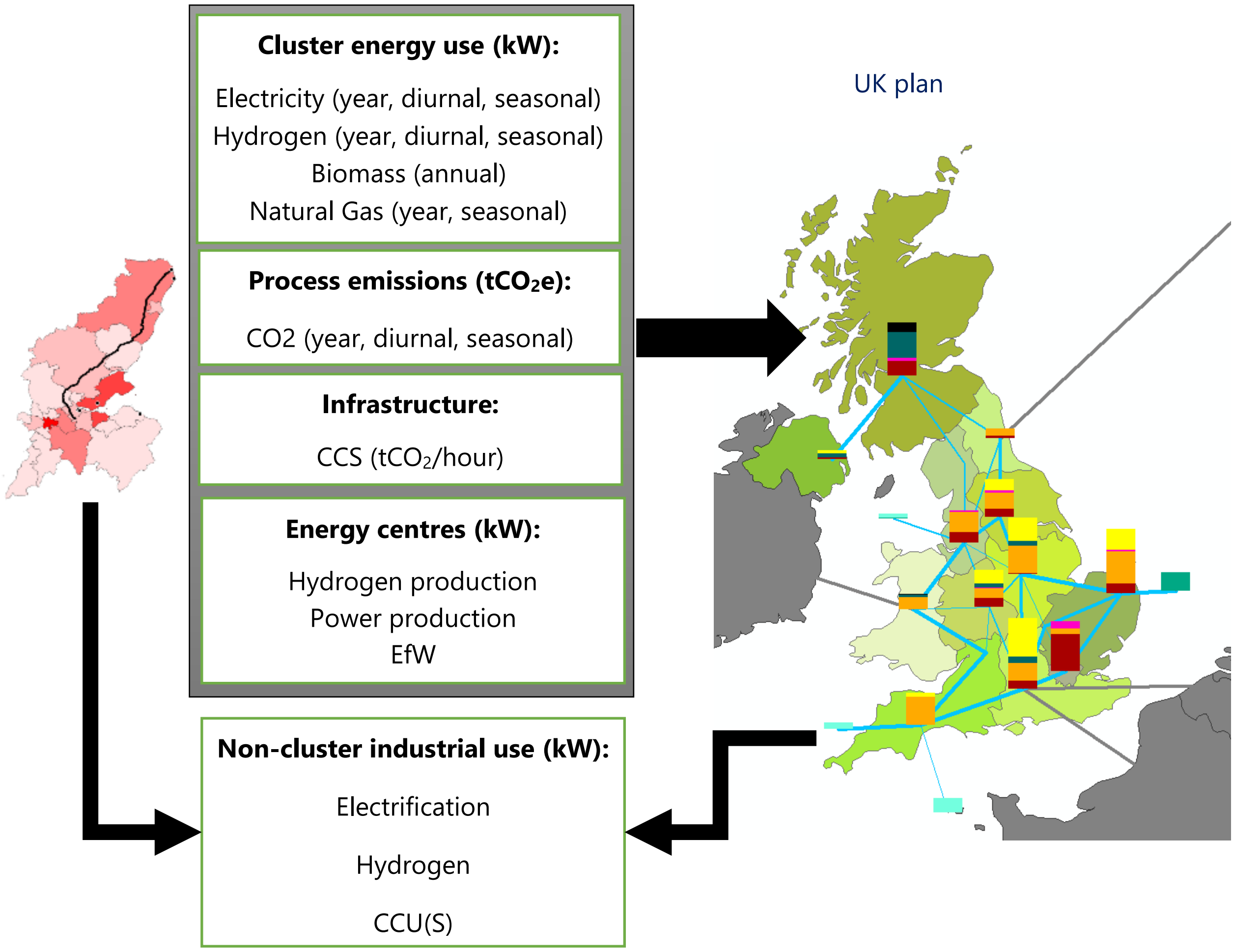

Figure 15: Data requirements for UK-wide plan originating from cluster-level scenarios

6. Conclusions

This summary report presents the key data requirements, prospective model features and appropriate system level scenarios that are relevant when designing a modelling exercise to better understand the potential to decarbonise industry in Scotland. The specific features of Scotland's industry sector – in particular, its historical and current focus on oil and gas production – lend themselves to a series of well-defined decarbonisation interventions that may be readily assessed using modelling tools. Carbon capture and transportation to offshore storage, potentially making use of existing gas infrastructure, is a clear example of common infrastructure that enables some of the key industrial emissions sources to be decarbonised, although other interventions such as hydrogen and biomass fuel-switching have been discussed in initial stakeholder engagements and warrant further attention.

This document highlights seven cluster-level scenarios that should be evaluated in a subsequent phase of this project. These scenarios have been constructed in response to stakeholder feedback in this initial phase, alongside a review of the major research and development activities carried out in Scotland over many years. As an appropriate method of removing industrial process emissions, all scenarios involve the development of CCS infrastructure, although one of the scenarios is designed to test the consequences of major onshore pipelines being unavailable, instead relying of shipping of CO_2 from coastal sites to the St. Fergus hub. At this stage the scenarios are thematic – site-level decarbonisation options, to be developed in the subsequent phase of this project, are required to convert these thematic concepts into specific, actionable site interventions with associated energy and emission profiles.

To understand the consequences of adopting decarbonisation strategies as per each of the scenarios outlined, energy system modelling is required. Although site-level and sectoral models and analytical studies are known to be available, the holistic nature of the Net Zero transition suggests that the role of industry to both support and be supported by the wider energy system nearby cannot be neglected. Therefore, it is proposed that a new modelling framework is developed. This modelling framework, drawing on the Energy Systems Catapult's knowledge and experience with developing tools and national and local level, will allow realistic, high-detail site decarbonisation projects to be combined with broader (i.e. non-industrial) features of the energy system. In particular, this will allow the role of critical infrastructure to be assessed and costed. In the second phase of this project, this modelling framework will be specified precisely and implemented as site and national-level data emerges from within this project and from the UK-wide industrial decarbonisation plan.

Finally, as industrial sites are embedded within the UK's energy system and contribute to the greenhouse gas emission balance which is required to reduce to net zero by 2050 (2045 for Scotland), understanding how cluster decarbonisation interactions with the national energy system is paramount. Therefore, the authors support the development of a UK-wide industrial decarbonisation plan. In this report the interactions and data flows that are likely to be necessary when co-developing local and national plans are outlined, along with some specific requirements if the UK-wide plan was developed using a whole energy system model, such as ESME or UK TIMES. As cluster-level models are likely to require assumptions about energy sourced from the national system, the use of such models (or proxy data) to help inform the cluster model's development is likely to be prudent.

7. References

[1] Committee on Climate Change, Net Zero – The UK's contribution to stopping global warming, May 2019 (via https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/)

[2] Energy Systems Catapult, Innovating to Net Zero, March 2020 (via https://es.catapult.org.uk/reports/innovating-to-net-zero/)

[3] Energy Technologies Institute/Energy Systems Catapult, Options, Choices, Actions Updated, October 2018 (via https://es.catapult.org.uk/reports/options-choices-actions-how-could-the-uk-be-low-carbon-by-2050/)

[4] Department for Business, Energy & Industrial Strategy, The Grand Challenge missions, via https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges/missions

[5] Committee on Climate Change, Hydrogen in a low-carbon economy, November 2018 (via https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf)

[6] Energy Systems Catapult, ESME Data References Book (via https://es.catapult.org.uk/brochures/esme-data-references-book)

[7] B. Fais et al, The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets, Applied Energy 162, 699-712 (15 January 2016)

[8] Energy Technologies Institute, Functional Definition of ETI Energy model, June 2009

[9] Energy Systems Catapult, Asset Guide: Local Area Energy Planning, June 2018 (via https://es.catapult.org.uk/brochures/asset-guide-local-area-energy-planning/?download=true)

[10] Pale Blue Dot, for Acorn ERA-NET ACT, D.03 Basis of Design for St Fergus Facilities, January 2018

[11] Scotland's Net Zero Roadmap Phase 1, Deliverable M1.1, July 2020

[12] Pale Blue Dot, for Acorn ERA-NET ACT, D17 Feeder 10, October 2017

[13] P. Brownsort, Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions, Working Paper for SCCS0188, May 2018 (via http://www.sccs.org.uk/images/expertise/reports/working-papers/WP_SCCS_2018_08_Negative_Emission_Technology_in_Scotland.pdf)

[14] World Energy Council, https://www.worldenergy.org/transition-toolkit/world-energy-trilemma-index

[15] H. Daly and B. Fais, UCL Energy Institute, UK TIMES Model Overview, November 2014 (via https://www.ucl.ac.uk/drupal/site_energy-models/sites/energy-models/files/uk-times-overview.pdf)

[16] HM Government, The Clean Growth Strategy, October 2017 (via https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf)

[17] UK Energy Research Centre (UKERC), Industrial Energy Use from a Bottom-Up Perspective: Developing the Usable Energy Database (https://data.ukedc.rl.ac.uk/browse/edc/efficiency/industry/EnergyConsumption)

[18] Department for Business, Energy & Industrial Strategy, Energy and Emissions Projections (EEP), available via https://www.gov.uk/government/collections/energy-and-emissions-projections

[19] Energy Technologies Institute, ESME Data Book (available via https://www.eti.co.uk/strategy)

[20] Department for Business, Energy & Industrial Strategy, Hydrogen supply chain evidence base, November 2018 (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf)

[21] Department for Business, Energy & Industrial Strategy, Digest of UK Energy Statistics (DUKES), available via https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

[22] Scotland's Net Zero Roadmap Phase 1, Deliverable T3.4 & T3.5, July 2020

[23] IEAGHG, 2017-TR8 Understanding the Cost of Retrofitting CO2 Capture in an Integrated Oil Refinery, August 2017 (https://ieaghg.org/publications/technical-reports/reports-list/10-technical-reviews/819-2017-tr8-understanding-the-cost-of-retrofitting-co2-capture-in-an-integrated-oil-refinery)

[25] HM Government, Meeting The Energy Challenge: A White Paper on Energy, May 2007 (via https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/243268/7124.pdf)

[26] Department of Energy & Climate Change, The Future of Heating: Meeting the challenge, March 2013 (via https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/190149/16_04-DECC-The_Future_of_Heating_Accessible-10.pdf)

[27] HM Government, The UK Renewable Energy Strategy, July 2009 (via https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/228866/7686.pdf)

[28] Energy Technologies Institute/Energy Systems Catapult, Balancing Supply and Demand, September 2019 (via https://es.catapult.org.uk/reports/balancing-supply-and-demand/)

[29] Imperial College London (for Committee on Climate Change), Analysis of Alternative UK Heat Decarbonisation Pathways, August 2018 (via https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf)

[30] W. McDowall, Endogenous technology learning for hydrogen and fuel cell technology in UKSHEC II: Literature review, research questions and data, UKSHEC Working Paper No. 8, 2012

[31] N. Strachan et al, Scenarios and Sensitivities on Long-term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models, UKERC Research Report, February 2008

[32] S. Pye et al, The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. Energy Policy, 73 pp. 575-586, 2014

[33] See https://www.eti.co.uk/programmes/transport-hdv/hdv-programme-overview/ and documents therein

[34] See https://www.eti.co.uk/programmes/energy-storage-distribution/transition-analysis-project/