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A Soft-linking Method for Responsive Modelling of Decarbonisation Scenario Costs

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ABSTRACT

This study presents a methodology that integrates EnergyPLAN and Quintel Energy Transition Model (ETM). Quintel ETM encompasses a holistic view of energy demand and supply from a fixed base year and its user interface enables unparalleled public engagement, but it is constrained by its limited flexibility in updating deeply embedded cost parameters. This shortcoming becomes critical when considering the rapid pace of technological change and market volatility which is characteristic of contemporary energy systems. EnergyPLAN, with its focus on detailed, customizable cost analysis in heating and power sectors, compensates for these limitations by offering a user-friendly interface and a track record of validated costing approaches. This work contributes the 'epnlink' python library for EnergyPLAN – a flexible input-output parser with functionality that extends beyond this study. A soft-linking methodology to map ETM outputs to EnergyPLAN inputs is developed and demonstrated on a case study of Northern Ireland. Alternative pathways to net zero carbon by 2050 are explored, where infrastructure for power and non-industrial heat, and total fuel usage are costed. The demonstrated pipeline has broad applicability as a template to enhance the agility and precision of key cost projections for responsive and strategic energy planning across diverse geographical contexts.

Keywords

Future energy system;
Energy system cost;
Soft-linking;
Quintel;
EnergyPLAN

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1. Introduction

The energy system forms a complex and pervasive underpinning of all modern economic activity. Its components and operations are the subject of techno-economic analysis at all levels and scales, ranging from examining the impact of a single technology on an existing system [1], to assessing projects with regional impact [2], optimising a specific sector for economic operation and expansion [3], and integrated energy system analysis [4]. The climate crisis and unprecedented challenge of total decarbonisation exceeds the utility of narrow-scope analysis because impacts cannot be blithely externalised [5] – in short, the whole equation must balance and optimising one piece will no longer suffice.

A contemporary and visible example of the increasing integration of energy system sectors is electrification increasing the coupling of power, heat, and transport. The inclusion of electrical demand-side response, Power-to-X technologies with dynamic multi-vector energy pathways [6], and cascade interactions which span across an energy infrastructure in flux [7] renders siloed analysis of energy system economics for the net zero transition

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Abbreviations

API	Application Programming Interface
CAPEX	Capital Expenditure
CCUS	Carbon Capture, Utilisation, and Storage
CHP	Combined Heat and Power
Dom.	Domestic (demand sector)
EP	EnergyPLAN
ETM	(Quintel) Energy Transition Model
FEC	Final Energy Consumption
GQL	Graph Query Language
GUI	Graphical User Interface
I&C	Industry and Commercial (demand sector)
LHV	Lower Heating Value
OPEX	Operating Expenses
PES	Primary Energy Supply
PP	Power Plant (EnergyPLAN's terminology for dispatchable thermal power generation)
PV	Photo Voltaic
WINE	"WINE IS Not an Emulator" (Windows API translation layer for POSIX systems)

unhelpfully myopic at best, and dangerously misleading at worst. The literature contains many valid contributions with a narrower scope than the integrated energy system – and these continue to have a place in sectoral planning and optimisation – but transformative planning for decarbonisation requires holistic models [8].

Energy modellers have a wide range of tools available to them, each with its own scope, characteristics, and intended purpose [9]. The different tools and their resultant models have different time scales, spatial resolutions, and represent different aspects of an energy system, such as electricity, heating, cooling, and transportation [10]. Soft-linking is an established approach that allows for a more comprehensive and detailed analysis of an energy system by combining the strengths of different models, or to improve general equilibrium economic models with detailed energy system dynamics [11]. It can also help to reduce the computational burden of running a single comprehensive model by allowing different models to handle different aspects of the energy system [12].

For augmentation of energy system models, previous studies in soft-linking have coupled long-term planning models with short-term optimisation models to explore detailed sectoral dynamics and interactions in future energy systems [13], bridged the gap between detailed bottom-up and aggregated top-down models [14], and applied iterative optimisation using EnergyPLAN and EPLANopt to define a pareto front for costs versus emissions to calculate economic impacts [15]. In this study, soft-linking is used to accelerate the feature maturity of a promising whole-system simulator and energy transition planner - Quintel Energy Transition Model (ETM) – to enable agile economic costing of power infrastructure, non-industrial heat infrastructure, and fuel usage for power, heat, and transport.

The ETM embraces the requirement of integrated energy system modelling for decarbonisation. Furthermore, the platform prioritises the dynamics of energy system transition – offering direct comparison of present and future metrics and describing policies as changes to the status quo. It promotes a paradigm of public engagement and citizen science by providing interactive future scenarios in a user-friendly interface, accessible to anyone with an internet connection. The energy system is complex, and the public debate on decarbonisation is contentious [16] – the ETM offers a level of governmental transparency and ease of public engagement that no contemporary energy planning tools can match.

The target for the soft-linking is EnergyPLAN (EP) – a well-established integrated energy system simulator. While EP is not as accessible to the public as ETM, it is user-friendly and appropriate for system modellers. The literature and open source community has produced several notable EP extensions, including: EPLANopt (genetic optimisation of objective function) [17], EPLANoptMAC (creation of a marginal abatement cost curve) [18], MATLAB integration [19], results visualisation [20], and file parsing [21]. The library contributed by this work, *epnlink*, offers input preparation, output parsing functionality, and comprehensive mapping of EnergyPLAN variables for a full programmatic interface to the program. No existing tools offer end-to-end python integration in this manner.

Soft-linking introduces complexity to the modelling process and that requires a clear statement of purpose [22]. Despite its user friendly interface, ETM has a critical problem that end-users are unable to make updates to fundamental cost components and dynamics. Decision-makers require accurate cost information for scenario assessments and timely updates in response to new technological or sociological developments. This work describes the uni-directional soft-linking of ETM scenario parameters to EP simulations. Soft-linking ETM and EP provides the required information agility by leveraging the strengths of both. Furthermore, even if this gap in ETM is addressed in the future, a full economic assessment of alternative pathways goes beyond the scope of its remit. Therefore, not only is the additional complexity of soft-linking justified in the present; external calculations will be required regardless of future software development.

While the coupling of ETM to EP is application-focused on bridging the costing functionality gap in ETM [22], the benefits also extend beyond addressing cost-related issues. ETM is relatively new software, EP has an established track record with validated calculation pathways and methodologies. ETM scenario result verification using EP's established resources and techniques is unlocked through the soft-linking process. Furthermore, EP offers the advantage of accessible and well-documented settings for detailed scenario parameters (e.g., battery storage efficiency) which are effectively inaccessible to ETM end-users. Adjustment of these additional parameters enables granular sensitivity analysis, amongst other applications.

The net zero transition takes place in a shifting technological, political, societal, and environmental landscape. High levels of uncertainty arise when these circumstances are combined with the long timeframes and large scope of decarbonisation. The Northern Irish strategy to mitigate these challenges is to publish annual progress reports that update decarbonisation actions according to measured progress, and to perform a strategy review every five years [23]. Within a strategy period, various analytical tools are applied to assess contemporary circumstances and forecast outlook, including cost-benefit analysis of scenarios.

Northern Ireland officially legislated to reach net zero carbon by 2050 in the Climate Change Act (Northern Ireland) 2022. The act also specifies that suitable targets for 2030 and 2040 must be set, and that government departments are obliged to produce tailored decarbonisation plans for each sector. Specific goals listed in the document include that, by 2030, emissions must be 48% lower than 1990s baseline levels, at least 80% of electricity must be generated from renewable resources, and that 70% of waste must be recycled [24].

Northern Ireland's Department for the Economy has published the "Path to Net Zero Energy" [23], which lays out the decarbonisation strategy for the energy sector. The scope of the efforts includes powering electrical, heating, and transport applications. They employed scenario-based modelling to propose two alternative decarbonisation scenarios, "Power Play" (prioritising high levels of electrification) and "Flexible Fit" (embracing a heterogeneous mix of regional solutions). There is also a scenario-based plan for development to 2030, called "Road to 2030". These scenarios were built in Quintel ETM [25] to capture characteristics of the alternative policy outlooks [26], and they are used as a case study for the soft-linking methods applied in this work.

Quintel ETM is a fully open-source project [27] developed to aid in the understanding of the energy system and to enable the creation of substantiated plans. The model allows users to explore various energy transition pathways by adjusting sliders to reflect different scenarios for each sector that uses or produces energy. The impact of these choices can be immediately observed through live charts and indicators such as CO_2 reduction, energy savings, and costs. Advanced users can use flexibility technologies like battery storage, pumped hydro, and hydrogen electrolysers to balance supply and demand. ETM models have a scale ranging from a single local neighbourhood up to an entire country.

Quintel Strategy Consulting created the first version of the ETM in 2008, Quintel Intelligence was founded in 2009, and in 2014 its operations became open-source and open-data. The company has established a track record that includes advising the Dutch Council for the Environment and Infrastructure on input to the Minister for Economic Affairs, participating in the International Architecture Biennale Rotterdam to develop a decarbonised energy vision for the Groningen region in the Netherlands [28], and their ETM software was used to perform the calculations for the "Infrastructure Outlook 2050" project on energy scenarios in Germany and the Netherlands [29]. As of 2019, ETM implements support for 9 countries, 9 provinces, 25 regions, 290 municipalities, and 134 Netherlands neighbourhoods [30].

The Department for the Economy in Northern Ireland has built its future decarbonisation models in ETM, and the Republic of Ireland has also developed models on the platform [31]. Decarbonisation of the island of Ireland will require close all-island co-operation and a shared energy system modelling platform supports future collaboration.

EP [32] is an energy modelling tool that is primarily designed to evaluate the energy, economic, and environmental implications of different energy scenarios. In contrast to other approaches whose purpose is to identify the optimal solution based on predetermined conditions, EP is intended for users to propose, compare, and evaluate different energy strategies [33]. EP is focused on the future energy system, with relatively detailed modelling of future technologies and aggregated modelling of present technologies.

The EP model has been in continual development since 1999 and it has a substantial track record in academic and industrial domains [34]. It operates using a fast deterministic algorithm, but there are techniques to incorporate stochastic randomness into an EP workflow [35]. EP includes hourly analyses of the complete smart energy system, including district heating and cooling, electricity, and gas grids infrastructure. A keystone piece of EP documentation, "Finding and Inputting Data into EnergyPLAN" (FIDE), uses Ireland as the example case study and provides a validated analytical pathway that is relevant to Northern Ireland [36].

Soft-linking ETM to EP addresses the critical costing gap in ETM and by enables ETM users to rapidly update costs for their scenarios using a validated tool without resorting to source code compilation or manual scenario rebuild. EP's track record in costing includes assessment of Ireland's energy system [37], and its outputs can provide the accurate financial breakdowns that are required for cost-benefit analysis [38], least-cost generation [39], and policy comparison [40]. These existing methods and pathways for economic assessment using EP further support decision-makers and users in energy system planning.

The contributions of this work are the '*epnlink*' python integration for EP, the development and validation of a soft-linking method to convert ETM scenarios into EP simulations via mapping parameters, and the hands-on case-study demonstration with accompanying dataset of the pipeline in Python. Access to the scientific Python environment greatly enhances EP's capabilities by granting a pathway to the flexibility and power of the world's leading data analysis and machine learning frameworks [41].

The remainder of this paper is structured as follows. Section 2 describes the soft-linking procedure and mapping principles in terms of supply, demand, and flexibility/balancing. Section 3 applies the soft-linking methods to the Northern Ireland decarbonisation scenarios, uses real-world statistics to validate the ETM and EP soft-linking using 2018 base year statistics, and presents the results of EP simulations for future year scenarios in terms of their energy dynamics and costs. Section 4 concludes the study by reflecting upon the strengths and weaknesses of each simulator, considers the advantages and disadvantages of soft-linking EP and ETM, recounts the impact of applying soft-linking to the case study scenarios, and suggests future work to extend this paradigm. A Technical Annex provides detailed information on soft-linking considerations.

2. Methodology

This section introduces the soft-linking methodology, then describes its application in a case study of Northern Ireland's future energy system scenarios.

2.1 ETM model structure and interface

The ETM model employs a tree structure with top-level categories of Demand, Supply, Flexibility, Emissions, Costs & Efficiencies, and Results & Data. Within each top-level category, there are various headings that can be opened to reveal dedicated tabs. Each tab contains subcategories that are fully labelled with instructions detailing the parameters and their role in the simulation. The software also allows user-accessible parameters to be input using a spreadsheet format with documented keys.

ETM simulates its scenarios with energy flows that account for all supply, conversions, and losses in a complex graph format. The internal simulation runs at an hourly resolution, however its outputs are intended to be consumed at annual resolution. ETM scenarios are developed starting from a baseline year. However, it is not possible for users to enter baseline data themselves, as this data must be compiled into the application. While the software is open-source, the process of compiling baseline data is typically impractical for most users. As a result, most customers will contract Quintel Intelligence to develop baseline scenarios.

2.2 EP model structure and interface

EP's interface is a tree-structured tab-based user interface. The top levels of the EP model are Demand, Supply, Balancing and Storage, Cost, Simulation, Output, and Emissions. Each level has a number of different headings that can be opened to reveal dedicated tabs. However, the tab structure in EP is somewhat inconsistent, with some tabs containing sub-areas, some containing subtabs, and the use of rows and columns not being consistent throughout the tool. In some cases, tooltips are provided to explain the purpose and function of various parameters.

When using EP to develop energy scenarios, the user has a high degree of flexibility and control over the input parameters. Scenarios can be fully defined in the graphical user interface (GUI), with a wide range of input options available. Additionally, the developers of EP provide a range of resources, including case study models and a database of costs, to help users develop realistic and effective energy scenarios. However, it is worth noting that the format for inputting parameters via text file is inconsistent and undocumented, which poses challenges for programmatic input and output of parameters and external processing of its results.

2.3 Soft-linking procedure and mapping principles

To link ETM with EP, several different tools and techniques are required as shown in Figure 1. ETM outputs for a given scenario are generated using the built-in Python API and reports, which provides a flexible and customisable way to extract and manipulate data from the model. In contrast, mapping the EP inputs requires unique values to be specified in the GUI for each parameter, manually tracing these back through its scenario parameter text file to map keys to values, and then implementing the *key:value* relationships as a proprietary format encoder.

A Python script is used to read the output from the ETM reports and write the corresponding input parameters for an EP scenario. Costs of fuel and plant are injected into the scenario by querying a graph database that has been prepared with techno-economic parameters and forecasts covering the period of interest. The EP model is run once, the interim results are parsed, feedback calibration of bio-gas production is carried out on the EP scenario, and the final simulation results are produced. Finally, an analysis script is used to translate and aggregate EP outputs into categories that are consistent with ETM and Northern Ireland government energy statistics. Extended technical details of the soft-linking procedure are available in the Technical Annex.

ETM uses energy flows and complex conversion pathways to simulate scenarios. The model features a detailed graph of all nodes and edges that trace energy and material flows. The simulation results are available as polished graphics, tables, and diagrams. Users can query any node or edge of the simulation using GQL, but this requires writing custom code. Additional deep modifications to built-in reports and statistics are feasible through altering the source code.

EP uses demand and supply matching to simulate scenarios. The software includes specific fixed fuel conversion pathways and basic losses. The material flows in the model are summarised in an overall architecture

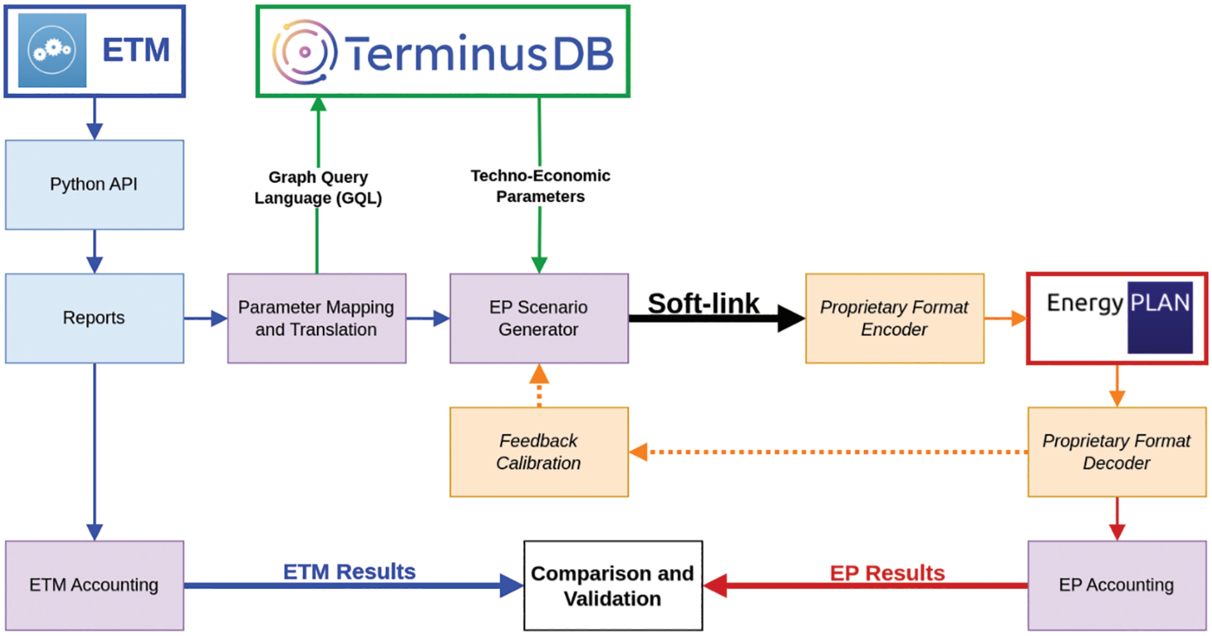

Figure 1: Process flow for soft-linking Quintel Energy Transition Model (ETM) to EnergyPLAN (EP).

diagram. Simulation results are delivered as pre-defined charts or plain text output, but the text output does not follow any documented standard, nor are keys or categories consistent across output options. It is, however, consistent enough to be read by a custom parser. No additional information can be extracted from the software because it is closed source.

In summary, while ETM and EP use different simulation principles, they both provide valuable insights into energy system modelling. ETM offers a more detailed approach, allowing for customised queries and modifications to the source code but it is more difficult to operate and understand. EP provides a simpler approach with pre-defined outputs and has an established track record, but it lacks the flexibility and transparency of ETM because it is closed source.

The simulation output of ETM serves as the basis for defining the inputs of EP. Although the basic data structure is similar, the mapping of demand to demand, supply to supply, and flexibility to balancing is not direct. While there is a significant technological overlap between the two models, there are some differences in the implemented technologies. Notably, ETM has more technologies than EP, but it lacks electro-fuels. However, this study focuses only on the technologies used in the Northern Ireland scenarios which do not make use of electro-fuels.

In integrating the two models, decisions regarding aggregation/disaggregation, translation, and substitution must be made. EP applies a higher level of aggregation than ETM, which means that some technological details may be lost. Care must be taken with figures since both models use a front-end mix of primary energy sources (PES) and final energy consumption (FEC). However, thanks to ETM's API and graph structure, all stages of energy flow are available if required, making it easier to identify and track the flow of energy and losses through the system.

2.4 Parameter translation

This section overviews the approach for soft-linking ETM to EP. Full technical details are available in the Technical Annex and the accompanying codebase.

2.4.1 Demand and supply

The electrical demand input for EP is defined by the total electrical demand from ETM minus the electricity used in transport. For heating electricity, there are two types: heat pump and resistive. Heat pump types are aggregated together, and a single coefficient of performance (COP) is calculated from the total input electricity and heat output. Hybrid heat-pumps have their electrical operation referred to heat pump demand and their combustible operation referred to the appropriate fuel. Resistive heating is summed directly.

All thermal generation from ETM is aggregated into the PP2 plant (a pre-defined EP category that aggregates all conventional thermal power generation), and the generation fuel mix from ETM is used to define the proportions of the variable fuel distribution for PP2 in EP. ETM fuels are grouped into EP fuel categories, and a function is used to calculate EP fuel distributions for each application group by summing the mapped ETM fuel categories. This operation reflects ETM's merit order generator dispatch strategy because fuel usage is mapped instead of installed generation capacity.

Heat demand from ETM is aggregated for buildings and households, for both hot water and space heating applications, and then split by fuel type. All combined heat and power (CHP) technology is aggregated into "District Heating Group 3" (a pre-defined EP supply category). Hydrogen micro-CHP with zero electrical output is used as a stand-in for ETM hydrogen boilers, which are not implemented in EP. Transport fuels are totalised by category and directly mapped to EP fuels. Industrial fuels are placed under the "Industry" category in EP. The "Various" category is available for any remaining fuel demand, but this is not required for the Northern Ireland scenarios.

2.4.2 Distributions and technology efficiencies

Efficiencies for each technology are defined inside ETM, but they are not included in its output reports. However, EP categories aggregate technologies, so the efficiency figure could not be directly applied anyway. To derive efficiencies, ETM aggregator nodes that link useful final demand (FEC) and primary energy supply (PES) are examined, so that application efficiencies can be calculated by taking the total of useful final demand divided by the total fuel input per mapped category. Combi-boilers have an efficiency above 1.0 because ETM uses the lower heating value (LHV) of fuels, however this does not impact the validity of the calculations because the fuel supply must be aligned between the software for costing – not the individual heat demand.

EP uses leap year distributions (i.e., 8784 hours per year), making compatibility with other products challenging. The approach taken when using external distributions is that if a multi-year distribution is available, the first day from the next year is taken, otherwise the first day of the year is repeated at the end of the year. A mean shift can be applied if necessary to prevent a step change in value. Consistency is important to maintain alignment of the distributions in case the impact of holidays is embedded in them (e.g., the time-shifted peak energy usage on Christmas day). Distributions for electrical demand, heat demand, and renewable generation are extracted from ETM and converted by repeating the first day of the year.

2.5 Case study parametrisation

The following actions describe scenario specific settings and translations, however the principles applied are applicable outside the context of Northern Ireland's decarbonisation pathways.

2.5.1 Description of Northern Ireland scenarios

Northern Ireland's Department for the Economy and Quintel Intelligence collaborated to develop 2018 as the ETM's base year scenario. The energy statistics for this year are complete and are available in the annual "Energy in Northern Ireland" report [42]. The approach taken to energy and cost aggregation in this study involved categorising by fuel and sector, following the convention set out in the report which defines I&C (Industry & Commercial) and Dom. (Domestic) for each fuel. Different types of transport are also defined for some fuels in the report, but these are aggregated as Transport in this account.

The published energy statistics are used to validate the ETM parameter extraction and accounting, the soft-linking of ETM to EP, and the EP output extraction and accounting. The scenarios analysed in the study are the 2018 baseline year, Road to 2030 (planned decarbonisation pathway), and the alternative visions for 2050, Power Play and Flexible Fit. The Power Play scenario relies on renewable electricity, with high electrification supported by solar, offshore and onshore wind, marine technology, and enhanced demand-side management. The Flexible Fit scenario emphasises regional differences, with local involvement and varied energy solutions, using electrification, hydrogen, bio-fuels, and decentralised power systems. The future scenarios are represented as Sankey diagrams in Figure 2.

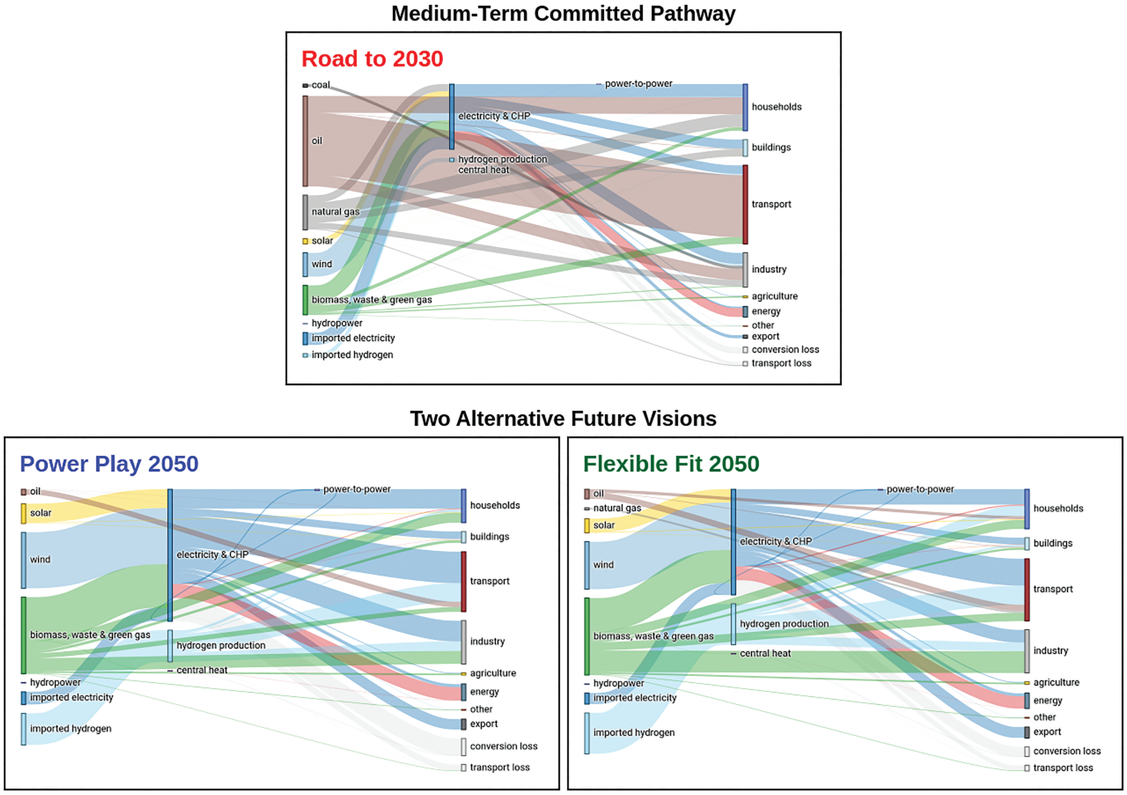

Figure 2: Sankey diagrams generated by ETM for the planned 2030 energy system and future 2050 scenarios, Power Play and Flexible Fit.

These show a large increase in electrification between 2030 and 2050 for both scenarios, as well as the use of biomass and green hydrogen to decarbonise.

2.5.2 Demand and supply aggregation and substitutes

In the Northern Ireland scenarios, all industrial processes are grouped under ETM's "Industry Other" category and are directly mapped to industry fuels in EP. The renewable energy sources used in the Northern Ireland ETM scenarios are onshore wind, offshore wind, solar PV, and river hydro - the other available renewable technologies in ETM are not used. A significant amount of the input to CHPs in Northern Ireland is waste input, which is accounted for and mapped in EP's waste tab. However, the proportional contribution of waste to the energy system is relatively small. The demand for hydrogen import is set equal to the hydrogen demand since the ETM scenarios do not currently specify the use of electrolysers for local production. Transmission line import/export capacity to external electricity markets is fixed at 500MW in all ETM scenarios.

2.5.3 Balancing and storage

In terms of balancing and storage, ETM does not provide specific parameters for grid stability and CEEP (Critical Excess Electrical Production) strategy. CEEP is analogous to curtailment – when too much renewable electricity is being generated, the system must be protected by reducing the output of renewable generators and deliberately not capturing all the energy available to them. The 2018 EP parameters correspond to Northern Ireland's grid stability requirements at that time (translated as 0.35 minimum stabilisation share and 375MW minimum thermal generation). Future scenarios use zero minimum stabilisation share and no minimum thermal generation, because these parameters have not yet been defined for future scenarios and 100% renewable power is a possibility.

The Northern Ireland ETM scenarios only incorporate grid-scale battery storage technologies, but extracting their power and capacity necessitates running the built-in ETM GQueries '*energy_flexibility_mv_batteries_electricity_volume'* and '*energy_flexibility_mv_batteries_electricity_ capacity'*, as these metrics are not included in the pre-defined reports. If additional storage technologies were used, then a custom GQuery may be required. Round trip storage efficiency is fixed at 0.85, a figure which was extracted by inspecting the ETM '*energy_flexibility_mv_batteries_electricity*' node properties, and is consistent with UK government technical assumptions [43].

Wind and solar generation distributions are extracted and converted from a validated Plexos model of the Irish and Northern Irish electrical grid [44] for testing, however it was decided to consistently link the models by using the renewable generation profiles from ETM in the final analysis. For the year 2018, the actual distribution of electricity demand is used. For future years, the demand profile is extracted from ETM and converted into EP format. Since more recent data is not available, a generic heat demand profile is used as a substitute – while this is also sourced from ETM to align the scenarios, it is internally labelled as a generic heating profile for European buildings.

2.5.4 Operational fixes and calibration

Some minor changes were made to the simulation to remove warnings or unwanted behaviour. In EP, hydrogen electrolysers are used regardless of installed capacity or import balancing, so a significant amount of zero-costed hydrogen storage is included in all scenarios to prevent this undesirable behaviour. Biogas production is set in relation to natural gas demand, based on the declared share of biogas in ETM. Carbon capture, utilisation, and storage (CCUS) is disabled because it was causing negative operational costs due to carbon pricing.

EP applies the hydrogen import price without converting from joules to watt-hours (i.e., the unit price is treated as Currency / MWh instead of Currency / GJ) – unlike all other fuel prices in the Cost > Fuel tab. The workaround is simply to input hydrogen prices in Currency / MWh, however this undocumented behaviour has the potential to distort fuel costs by a factor of 3.6 if it goes unnoticed. EP also does not import hydrogen prices from data or cost files, so these must be set manually in the GUI.

Simulations across all scenarios were run to calibrate the outputs of the models using a global set of adjustment parameters. This was focused on aligning renewable generation, aggregated fuel usage, and sectoral demand. EP simulations were adjusted by changing the correction factor for renewable production, heat demand for CHP3, tuning the efficiency of bio-gas and bio-fuel production, and setting a CEEP strategy of "*716*". These changes were based on observation of the simulation output and are designed to be minimally invasive to the soft-linked parameters.

3. Results

In this section, the soft-linking method is validated by examining the known 2018 base year statistics, then the energy balance of each scenario is explored, and finally the case study is completed by applying contemporary cost forecasts to Northern Ireland's future energy system scenarios.

3.1 2018 base year validation

Table 1 and Figure 3 compare the official energy statistics for 2018, the parameters of the ETM base year, and the output of the soft-linked EP simulation. This is a cross-check of the ETM scenarios against official statistics, and then validation of the EP scenarios against the ETM simulation. However, the subject of the validation

Table 1: Validation of ETM and EP scenario parameters against published figures. Delta percentages are given as proportion of the grand total ETM scenario demand.

Type	Category	2018	ETM	EP	ETM-EP Delta (%)
Electricity Demand (TWh)	Domestic	2.90	3.01	–	
	I&C	5.00	5.09	–	
	Other	–	0.33	8.14	
	Transport	–	0.01	–	
	TOTAL	**7.89**	**8.44**	**8.14**	**–0.62%**
Renewable Generation (TWh)	Wind	2.70	2.71	2.83	
	Other	0.51	0.36	0.27	
	TOTAL	**3.21**	**3.07**	**3.10**	**0.06%**
	% of Demand	***40.6%***	***36.4%***	***38.1%***	***1.7%***
Biomass Demand (TWh)	Domestic	1.81	0.26	0.29	
	I&C	4.11	0.28	0.10	
	Other		0.07	–	
	Transport	0.48	0.60	0.86	
	TOTAL	**6.40**	**1.22**	**1.25**	**0.07%**
Gas Demand (TWh)	Domestic	2.74	2.49	4.66	
	I&C	3.54	3.34	1.20	
	Other	–	0.02	–	
	Transport	–	0.00	0.00	
	TOTAL	**6.27**	**5.86**	**5.86**	**–0.01%**
Coal Demand (TWh)	Domestic	0.80	0.76	0.80	
	I&C	1.87	1.77	1.73	
	Other	–	0.00	–	
	Transport	–	0.00	0.00	
	TOTAL	**2.66**	**2.53**	**2.53**	**0.00%**
Oil Demand (TWh)	Domestic	7.46	7.08	7.27	
	I&C	6.84	5.42	5.24	
	Other	1.95	0.00	–	
	Transport	13.56	17.99	17.99	
	TOTAL	**29.82**	**30.49**	**30.50**	**0.02%**
Demand	**Grand TOTAL**	**53.05**	**48.54**	**48.28**	**–0.54%**
	Less Biomass	*46.64*	*47.33*	*47.03*	*–0.62%*

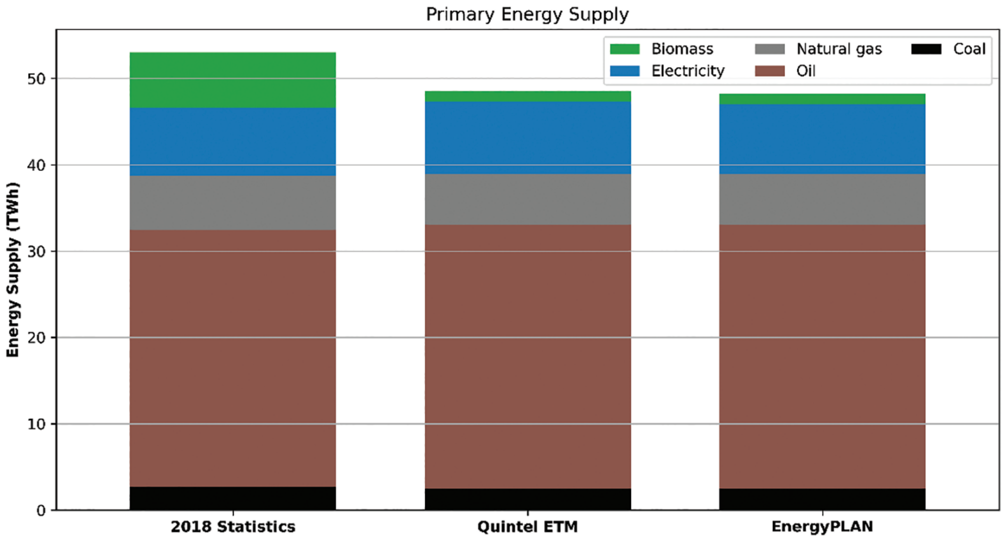

Figure 3: Electricity, gas, coal, oil, and biomass demand in 2018 statistics and simulations.

is alignment of ETM and EP scenarios for future energy system analysis, not calibration against historical statistics. ETM baseline scenario modification is out-of-scope for this study, but the actual statistics are presented for contextualisation of the ETM scenario.

EP outputs closely match the ETM outputs on a fuel-by-fuel basis, differing by less than one percent of the total scenario demand in all cases. However, it is necessary to draw different sectoral boundaries for electricity, biomass, and gas. Where quantities do not exactly match, the EP figures trend slightly towards the actual statistics. When biomass demand is subtracted from the calculation it can be observed that the sum demand matches to the baseline statistics within 1.5% for ETM and 0.8% for EP.

Gas usage is higher in the EP domestic sector because commercial building consumption is referred to households for heat calculations. Only one distribution can be set for *"N.Gas, Other"* in EP, and it will be tailored to industrial patterns in the future. As a result, combining natural gas for commercial buildings (which is largely used for heating) with households is expected to reflect demand patterns better. It should be noted that the sum of I&C and Domestic matches well between ETM and EP.

Biomass accounting is not consistent across models and statistics – sometimes biogas is counted as biomass, sometimes as lower carbon natural gas. Similarly, waste may be counted as biomass in some approaches, whilst others treat it as a separate category. Another confounding factor is that the Northern Ireland statistics include biomass for agriculture which is not accounted for in the same way by the ETM and EP scenarios. These discrepancies create challenges when comparing results between models and highlight a wider need for greater consistency in biomass accounting.

EP achieves a closer figure to reality for renewable generation estimation than ETM, but slightly overestimates biomass demand and does not allow for granular electrical demand categorisation. Given the different dynamical simulation calculations in each software, the linking is remarkably consistent when considered across the aggregate quantities. Recall that the overall objective is costing scenarios – the accurate per-fuel accounting and directly mapped plant deployments enable this objective.

3.2 Future scenario energy balance

Table 2 presents the primary energy supply by fuel for each scenario, while Table 3 and Figure 4 show a comparison between ETM and EP application final energy consumption. Biogas is heavily used in future decarbonised grids, and whilst EP subtracts it from gas usage, ETM counts it directly. The presented metrics differ from the standard EP output because bio-gas and bio-fuels have been referred to their demand sectors as biomass usage. The accounting and conversion calculations for this operation are detailed in the Technical Annex, Section 5.3.2.

Power generation mix is treated separately in the published NI figures, so it was excluded from the

Table 2: Comparison between ETM and EP of primary energy supply aggregated by fuel, including power generation. Delta percentages are given as proportion of the total ETM scenario fuel supply.

	2018 Baseline			**Road to 2030**			**Power Play 2050**			**Flexible Fit 2050**		
	ETM (TWh)	EP (TWh)	Delta (%)	ETM (TWh)	EP (TWh)	Delta (%)	ETM (TWh)	EP (TWh)	Delta (%)	ETM (TWh)	EP (TWh)	Delta (%)
Coal	6.06	5.61	–0.8%	0.61	0.61	0.0%	0.00	0.00	0.0%	0.00	0.00	0.0%
Oil	30.52	30.52	0.0%	17.40	17.40	0.0%	0.82	0.82	0.0%	0.15	0.15	0.0%
Natural gas	13.32	12.06	–2.2%	6.50	8.56	5.2%	0.00	0.00	0.0%	0.00	0.00	0.0%
Biomass	3.18	3.20	0.0%	8.31	7.96	–0.9%	16.73	16.49	–0.7%	19.06	17.60	–4.2%
Renewables	3.07	3.10	0.1%	5.91	5.94	0.1%	10.87	10.88	0.0%	8.82	9.04	0.6%
Hydrogen	0.00	0.00	0.0%	0.74	0.73	0.0%	4.59	4.55	–0.1%	6.33	6.27	–0.2%
Total	56.15	54.48	–3.0%	39.48	41.20	4.4%	33.01	32.74	–0.8%	34.36	33.06	–3.8%

Table 3: Comparison of ETM and EP scenario final energy consumption by fuel type and application category, excluding power generation. Delta percentages are given as proportion of the corresponding ETM scenario grand total. N/C indicates that figures are not comparable due to differences in accounting, where: (1) Biomass, Other does not have a corresponding field in EP; (2) Electricity categories cannot be compared because EP takes a single figure for electrical demand; (3) Electricity, Transport has been calculated for the purposes of this analysis and is not available in the standard EP output format. Dashes indicate unused categories.

		2018 Baseline			**Road to 2030**			**Power Play 2050**			**Flexible Fit 2050**		
Type	Category	ETM (TWh)	EP (TWh)	Delta (%)	ETM (TWh)	EP (TWh)	Delta (%)	ETM (TWh)	EP (TWh)	Delta (%)	ETM (TWh)	EP (TWh)	Delta (%)
Biomass (TWh)	Domestic	0.26	0.29	0.1%	0.86	1.33	1.4%	1.43	1.82	2.2%	1.73	2.13	2.4%
	I&C	0.28	0.10	–0.4%	0.59	0.51	–0.2%	2.51	2.27	–1.4%	3.80	3.92	0.7%
	Other	0.07	N/C	–	0.07	N/C	–	0.09	N/C	–	0.09	N/C	–
	Transport	0.60	0.60	0.0%	1.34	1.30	–0.1%	0.70	0.37	–1.9%	1.61	1.28	–2.0%
	TOTAL	1.22	0.99	–0.5%	2.86	3.14	0.8%	4.75	4.46	–1.6%	7.23	7.33	0.6%
Coal (TWh)	Domestic	0.76	0.80	0.1%	0.00	0.00	0.0%	0.00	0.00	0.0%	0.00	0.00	0.0%
	I&C	1.77	1.73	–0.1%	0.61	0.61	0.0%	0.00	0.00	0.0%	0.00	0.00	0.0%
	Transport	0.00	0.00	0.0%	0.00	0.00	0.0%	0.00	0.00	0.0%	0.00	0.00	0.0%
	TOTAL	2.53	2.53	0.0%	0.61	0.61	0.0%	0.00	0.00	0.0%	0.00	0.00	0.0%
Electricity (TWh)	Domestic	3.01	N/C	–	2.62	N/C	–	2.80	N/C	–	2.21	N/C	–
	I&C	5.09	N/C	–	3.73	N/C	–	4.19	N/C	–	2.92	N/C	–
	Other	0.33	8.13	N/C	0.35	6.39	N/C	0.33	7.02	N/C	0.33	5.16	N/C
	Transport	0.01	0.01	0.0%	1.63	1.63	0.0%	4.55	4.55	0.0%	4.07	4.07	0.0%
	TOTAL	8.44	8.14	–0.6%	8.33	8.02	–0.9%	11.87	11.57	–1.7%	9.52	9.23	–1.7%
Gas (TWh)	Domestic	2.49	4.66	4.5%	2.64	3.98	3.9%	0.00	0.00	0.0%	0.00	0.00	0.0%
	I&C	3.34	1.20	–4.4%	2.58	1.25	–3.9%	0.00	0.00	0.0%	0.00	0.00	0.0%
	Other	0.02	–	–	0.02	–	–	0.00	–	–	0.00	–	–
	TOTAL	5.86	5.86	0.0%	5.24	5.23	0.0%	0.00	0.00	0.0%	0.00	0.00	0.0%
Oil (TWh)	Domestic	7.08	7.27	0.4%	3.10	3.19	0.3%	0.03	0.04	0.1%	0.00	0.01	0.0%
	I&C	5.42	5.24	–0.4%	2.37	2.28	–0.3%	0.01	0.00	*–0.1%*	0.00	0.00	0.0%
	Transport	17.99	17.99	0.0%	11.94	11.94	0.0%	0.78	0.78	0.0%	0.15	0.15	0.0%
	TOTAL	30.49	30.50	0.0%	17.40	17.41	0.0%	0.82	0.82	0.0%	0.15	0.16	0.0%
Demand	Grand TOTAL	48.54	48.02	–1.1%	34.44	34.41	–0.1%	17.43	16.85	–3.3%	16.91	16.72	–1.1%

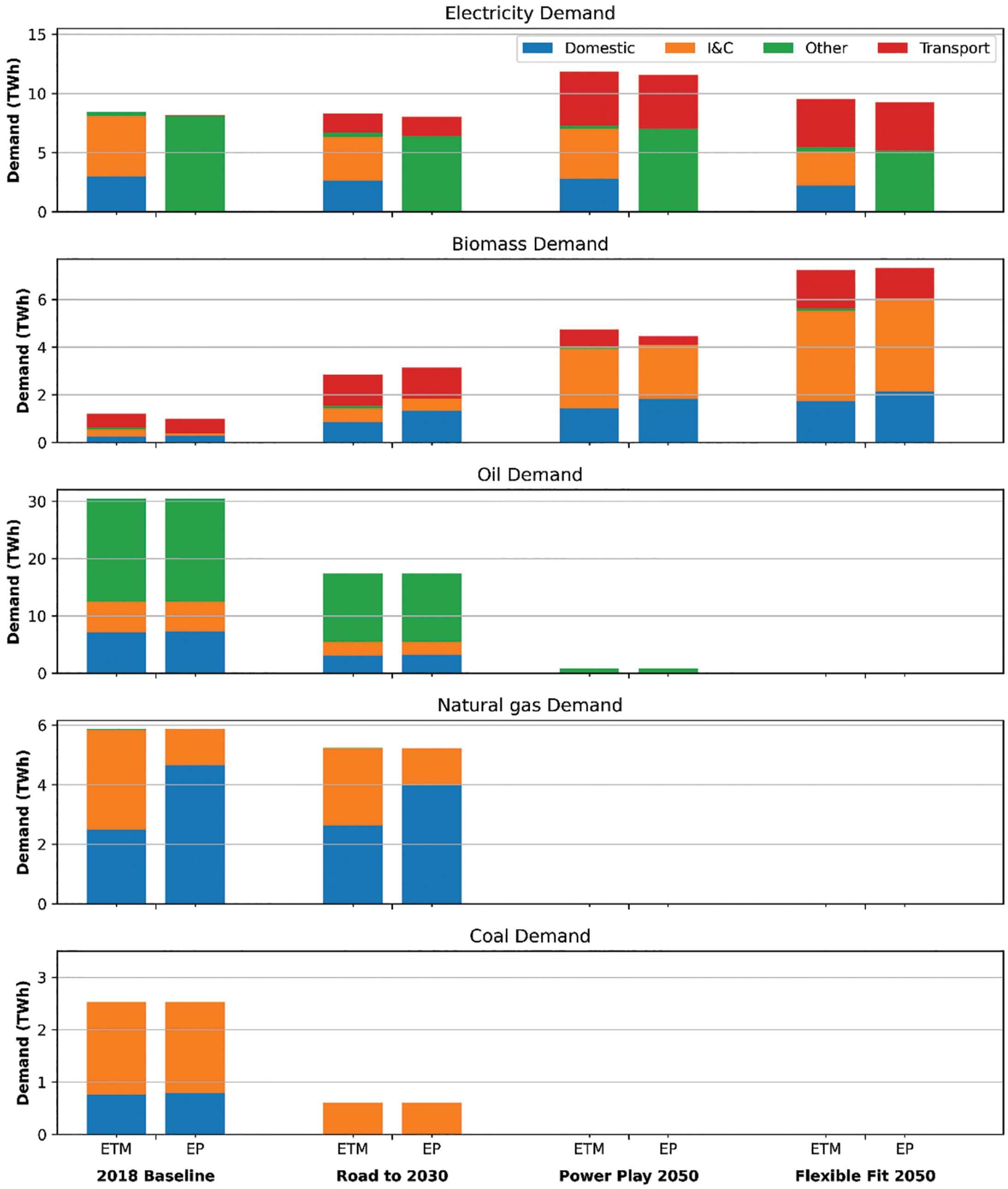

Figure 4: Comparison of sectoral final energy consumption between ETM and EP, with bio-gas (network gas) and bio-fuels (bio-diesel, bio-petrol) referred to biomass.

preceding validation exercise. ETM scenarios include power generation, so it is implemented in soft-linking to EP. The presented energy balances engage with final electricity demand and aggregated primary energy supply rather than power generation mix – however, the dynamical differences between the models and their calibration is detailed in Technical Annex Section 5.5.5. Neither program claims to be a detailed power market simulator, and the discrepancies in their results are centred around electrical generation fuel – observable in the primary energy supply deltas for natural gas and biomass. There is no evidence to show whether ETM's future power system results are more or less accurate than EP.

While it is technically possible to trace primary supply to energy demand in ETM, the complexity of doing would result in a brittle and error-prone analytical pipeline. It is not possible to trace primary supply to final demand with a matching level of fidelity in EP. Given the observable transfer of scenario characteristics from ETM to EP – particularly, the alignment of both primary energy supply and final energy consumption despite differing internal conversion pathways for ETM and EP - the soft-linking is demonstrated to be a success. This supply-demand cross-validation enables confident application of EP's proven costing logic to scenarios defined in ETM.

3.3 Scenario cost forecasts

The targets of this cost analysis are the fundamental costs of fuel, its conversion, and its application. In scope: power generation infrastructure; household heating infrastructure; fuel usage for power, heat, and transport; biomass conversion infrastructure; and CO_2 emissions. The raw fuels evaluated are coal, oil, petrol, diesel, natural gas, biomass, and hydrogen. Out of scope: power distribution and transmission; energy market trading overheads; and energy input required for biomass conversion.

Accurate analysis of power distribution and transmission require more detailed models than ETM or EP can provide. Energy market overheads are particularly infeasible for evaluation because contemporary dynamics are fundamentally unsuited to the very high renewable energy systems under study. Energy requirements for biomass conversion are highly variable for specific plant and processes – however, feedstock losses modelled in ETM have been captured using efficiency metrics to align ETM and EP biomass handling.

Scenario costs were calculated by fusing a variety of sources into a graph database. This approach to knowledge management enables rapid interrogation of heterogeneous data sources via semantic queries. For instance, to explore the cost of electricity generation using wind, the database is asked to provide techno-economic parameters for all technologies capable of converting *"Wind"* into *"Power"*. It will reply using a consistent data structure containing all the matching technologies (e.g., onshore turbines, offshore turbines, large- and small-scale variants). The results of this query are assessed by the modeller, who decides which sources are most applicable to the subject.

This work is focused on prices for Northern Ireland out to 2050, therefore forecasts dealing with UK and EU prices tend to be the most applicable. Table 4 shows the sources selected from the database for the required parameters in the EP simulation. Only the technologies and fuels applied in the scenarios have their prices

Table 4: Sources of techno-economic cost parameters and forecasts.

	Parameter	Source
Commodity	Coal	Fossil fuel price assumptions: 2023 [47]
	Oil	Fossil fuel price assumptions: 2023 [47]
	Gas	Fossil fuel price assumptions: 2023 [47]
	Biomass	EU28 fuel prices for 2015, 2030 and 2050 [48]
	Hydrogen	Hydrogen production costs 2021 [49]
	CO_2 Emissions	Traded carbon values used for modelling purposes [50]
Plant	Aggregated CHP	2017 Techno-economics for larger heating and cooling technologies [51]
	Large PP	Electricity generation costs 2023 [52]
	Wind Onshore	Electricity generation costs 2023 [52]
	Wind Offshore	Electricity generation costs 2023 [52]
	Solar PV	Electricity generation costs 2023 [52]
	Battery Storage	Storage cost and technical assumptions for electricity storage technologies [43]
	Bio-gas Conversion	Average costs of biogas production technologies per unit of energy produced (excluding feedstock) [53]
	Bio-fuel Conversion	Economics of biodiesel production: Review [54]

defined because unused or irrelevant technologies do not affect the financial assessment. The base year, currency, and units of all prices are available in the database and are converted to GBP 2018 prices using annualised EU central bank currency exchange rates [45] and a UK Government GDP deflator [46].

Emissions, biomass, and hydrogen are costed outside EP. Scenario emissions use ETM as the ground truth, so costs are applied to its net calculation rather than using the EP figure. Biomass is priced separately but uses EP quantities - so that direct-use fuel, feedstock for bio-fuel, and feedstock for bio-gas can be separated. Hydrogen is priced per-unit using a levelised cost projection applied to EP quantities. Version 16.2 of EnergyPLAN has a bug where hydrogen cost is not loaded from the configuration file – preventing automation – and when entered in the GUI, it is applied per MWh and not per GJ as indicated.

Waste and food by-product are zero-valued because they are not currently considered in the costing scope. Waste needs to be processed regardless of the energy system, and the contemporary narrative for biomass processing and by-products is one of an endogenous circular economy - therefore it is deemed that monetary valuation is inappropriate for this study [55].

The external electricity market price was set to zero after experimental simulations confirming that this does not affect the validity of the results. The motivation for this change is that Northern Ireland and the Republic of Ireland share one of the smallest synchronous regions in the developed world. Therefore, the capacity for exporting excess power is likely to be extremely restricted – the region will normally be experiencing the 'same' conditions (i.e., renewable overproduction or underproduction).

Following the decision to set the external electricity market price to zero in order to mitigate the illusion of very low running costs due to high renewable exports, a version of each scenario with no grid interconnection was simulated. The loss of interconnection has a strong impact on the proportion of electricity produced by renewables, as shown in Figure 5. There is overproduction in Flexible Fit which produces more than 100% of the electrical demand with renewables, however this is contextualised by the scenario's lower absolute electrical demand from lower electrification. Table 5 shows the absolute sum of wind, solar, and hydro production under the two conditions. Curtailment is significant without interconnection, 1.43 TWh for Road to 2030, 1.96 TWh for Power Play, and 1.91 TWh for Flexible Fit.

Table 5: Renewable production and curtailment in TWh for interconnected and islanded circumstances.

	Road to 2030	**Power Play 2050**	**Flexible Fit 2050**
Interconnected	5.94	10.88	9.04
Islanded	4.51	8.92	7.13
Curtailment	**1.43**	**1.96**	**1.91**

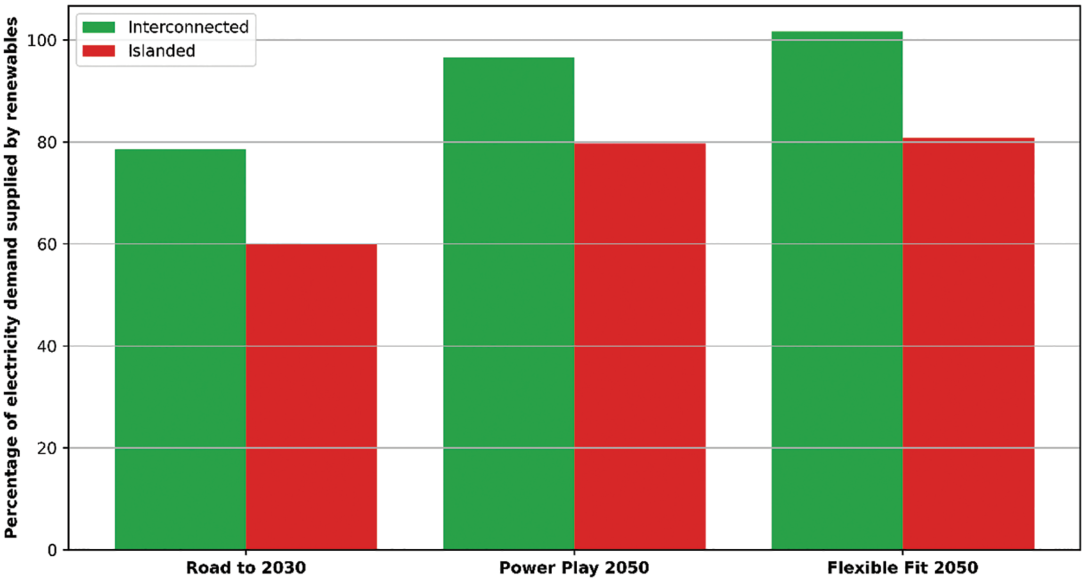

Figure 5: Percentage of electrical demand met by renewable generation with and without interconnection.

Table 6 and Figure 6 show the final cost figures for the future scenarios and the baseline. The Northern Ireland Department for the Economy estimates that the region's energy spending in 2018 was £8.7BN; £3.2BN purchasing energy, £1.1BN maintaining vehicles and boilers, and £4.4BN investing in transport, buildings, energy supply, and industry [23]. The official cost estimate is subject to uncertainty, does not yet have a rigorously defined scope, and is a market-based calculation – whereas this assessment focuses upon the fundamental costs of energy supply and usage. The EP analysis produces a figure of £3.1BN for the same period – however, this figure does not include transport infrastructure, vehicle maintenance, or energy supplier profits. In absolute terms, this model captures approximately 36% of the quoted total energy system cost estimate.

Table 6: Energy scenario costs in Millions GBP (2018) using fusion of UK and EU techno-economic forecasts.

	NI 2018	**Road to 2030**	**Power Play 2050**	**Flexible Fit 2050**
Power CAPEX	246	222	392	321
Power OPEX	116	99	166	135
Heat CAPEX	364	401	499	461
Heat OPEX	163	179	224	206
Conversion CAPEX	0	31	223	189
Conversion OPEX	0	15	100	85
Coal Fuel	61	9	0	0
Oil Fuel	216	60	0	0
Diesel Fuel	1,145	442	10	1
Petrol Fuel	291	108	20	5
Natural gas Fuel	252	177	0	0
Hydrogen Fuel	0	89	528	729
Biomass Fuel	54	106	106	152
Biofuel Feedstock	20	45	15	51
Biogas Feedstock	0	41	336	285
CO_2 Emissions	**165**	**481**	**0**	**0**
Total Variable (Fuel)	**2,038**	**1,076**	**1,016**	**1,223**
Total OPEX	**279**	**293**	**490**	**426**
Total CAPEX	**610**	**654**	**1,114**	**971**
Grand Total	**3,092**	**2,505**	**2,620**	**2,620**

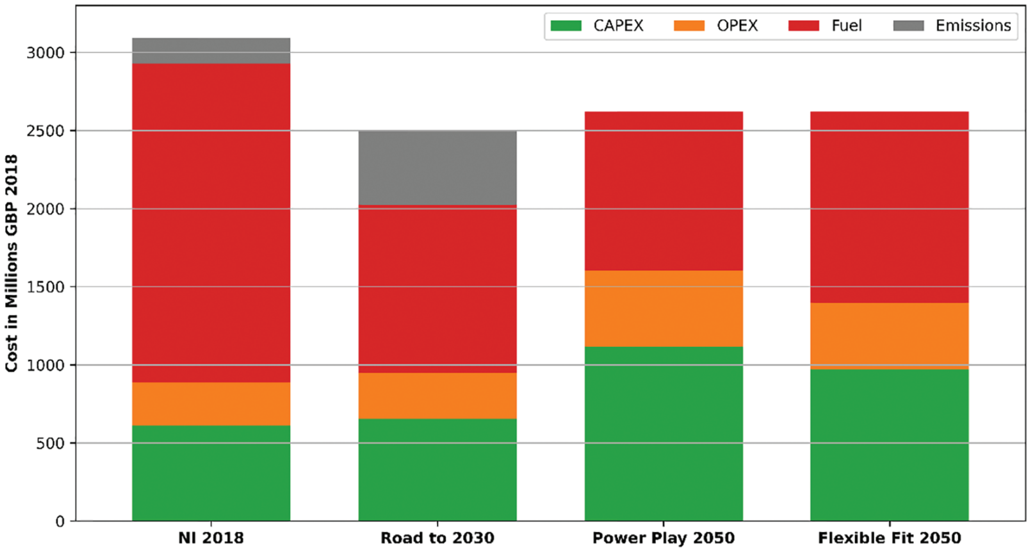

Figure 6: Scenario costs using fusion of UK and EU techno-economic data.

Although the categories of expenditure do not map directly, some observations can be made. Of the quoted £1.1BN spent on vehicles and gas/oil boilers, this study estimates £163M spent on household heater maintenance, or 15% relatively. £4.4BN is quoted as investment across all energy-related activities – which corresponds to CAPEX – this study has a total of £610M, or 14% relatively. Purchase of energy is quoted at £3.2BN, and the remainder of the study costs are £2.3BN, or 72% relatively. These are plausible ratios, considering the cost of vehicle maintenance relative to boilers, the narrower scope of capital assessment, and the exclusion of market-based overheads (i.e., middlemen profits in the chain from raw fuel to final use), respectively.

The variable costs of the energy system are forecasted to shrink under all pathways, an effect which is attributable to the decoupling of the system from commodity markets and the reduced requirement for fuel. This paradigm is also reinforced when comparing the Power Play 2050 scenario, which has lower operational costs and implements widespread electrification powered by renewable generation, and Flexible Fit 2050, which implements a wider range of technologies that make use of different fuels. However, the total cost of each pathway is the same, as they balance a trade-off between investment in equipment and ongoing running costs. The price of fuels and technologies promises to remain volatile, and whilst these scenario costs were seeded by a state-of-the-art graph database, EP enables end-users to update specific parameters for a soft-linked ETM scenario without needing to write or run any code.

4. Conclusion

This work firstly developed a method to soft-link ETM to EP, and secondly demonstrated its application through a case study costing Northern Ireland's future decarbonisation scenarios. Although the scenarios are originally defined in ETM, they are successfully translated to EP and costed using up-to-date sources. This newfound capability empowers ETM users to comprehensively examine the implications of different cost scenarios and technological developments. The *epnlink* library also provides a general purpose python interface to EnergyPLAN.

4.1 Soft-linking ETM to EP

The soft-linking procedure takes a world that is built in ETM and describes it to EP. However, EP and ETM simulate that world differently, producing expected variations in their outputs. Some aspects of the ETM simulation dynamics are hinted to EP during the translation, for instance merit order dispatching is reflected in the PP2 fuel distribution - whilst EP is left to its own devices in other respects, such as deciding when to charge and discharge storage technologies. Despite these variations, the soft-linking procedure extends ETM's functionality without requiring a new model to be built.

ETM's API enables the extraction of any scenario parameter, while its graph view provides detailed insight into the model's operation. Although some parameters remain difficult to understand, the open-source nature of the code allows for inspection and further comprehension. Programmatic automation of EP requires custom code and reverse engineering. However, despite this drawback, its deterministic results are stable for a given simulation, and this is helpful for developing output parsers and tuning translators. Compared to ETM, updating cost parameters in EP is quick, the software boasts a large community, and it has a strong track record in energy system costing.

The decoupling of the cost database from the ETM scenario brings forth significant benefits in investigating cost changes. Unlike ETM, where costs are tightly integrated into the source code and require compilation for modifications, EP provides a user-friendly environment for adjusting system component parameters and properties. The ability to perform sensitivity analysis by sweeping different costs and fundamental system parameters is gained through soft-linking, a task that is impractical within the confines of ETM – and a procedure that is essential for rigorous system assessment.

4.2 Costing Northern Ireland's ETM decarbonisation scenarios in EP

Based on the analysis of the base year scenario, it was found that scenario translation from ETM to EP was accurate and that energy demand and generation figures were realistic. The 2050 scenarios of Power Play and Flexible Fit have similar total costs, with the electrification scenario demonstrating lower operational costs in trade for higher investment costs, reflecting the widely accepted dynamics of electrification. The 2018 baseline scenario accounts for approximately 36% of the estimated energy spend and therefore the future scenarios are also partial estimates – but, with a crisply defined scope. While it is not possible to make a direct projection, Power Play will structurally account for more of the energy system cost due to electrification encompassing a larger proportion of energy usage. The unaccounted energy spend, even if it was identical per-unit in the two scenarios, could introduce a significant delta in actual costs between the scenarios despite their apparent equivalence.

Experimental removal of the system interconnector caused a negative impact on renewable generation as expected, and this highlights the potential need for greater storage and flexibility in the future energy system scenarios. This observation becomes especially acute when recalling that the primary interconnection with the Republic of Ireland will most likely be experiencing similar grid conditions (i.e., it will probably not have the capacity to absorb over-supply, nor can it provide energy during periods of renewable under-production). An alternative mitigation is to ensure strong interconnection to external synchronous regions in mainland Europe and Great Britain.

4.3 Future work and limitations

Operational fixes and mitigations in EP should be carefully formalised, and ideally automated, to ensure that the parameters used in the simulation are consistent with ETM parameters, and to prevent the need for mitigation parameters like large hydrogen storage to prevent electrolyser operation. There is also a need for more thorough consideration of grid stability requirements (e.g., maximum system non-synchronous penetration, minimum spinning reserve), which have not yet been formally defined in the future scenarios – as underscored by the zero-interconnector simulation results.

The use of a graph database to store techno-economic parameters and forecasts enables a tighter synthesis between ETM and EP – for instance, the database can expand to hold the ETM scenario parameters, the EP translation information, and even the simulation results. The graph-based approach could be used by energy modellers to create, maintain, and analyse unified multi-model scenarios with rapid source data ingress, formatting, and re-use.

One potential solution for addressing parameters that cannot be calculated a-priori is bi-directional soft-linking, which is a key enabler for algorithmic optimisation of scenario parameters. Greater linking of distributions and profiles such as electric vehicle smart charging and industrial activity would provide more detailed demand profiles that improve the accuracy and pairwise consistency of the simulations. ETM has implemented initial support for external model coupling that would facilitate further development [56].

Finally, deeper automation also enables exploration of scenario sensitivity to costs and technological parameters at a granular level. Visual representations, such as bar charts with error/uncertainty bars, and sensitivity input-output functions, can be employed to provide stakeholders with a comprehensive understanding of the implications of different cost scenarios.

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Disclaimer

The views and opinions expressed in this paper belong to the authors, and do not reflect upon the views and opinions of their institutions and or funders.

5. Technical Annex

5.1 Open source code artifacts

This study is accompanied by Electronic Supplementary Information (ESI), which contains:

- *epnlink* Python library
- ETM scenario outputs
- EP simulation inputs
- EP distributions
- EP cost parameter files
- EP simulation outputs
- Soft-linking demo script

Code is not provided for the external costing operations, cost-file generation, and automation stack – the ESI is provided to demonstrate the use of *epnlink* rather than as an exhaustive replication of the study. Additional data can be made available upon request. The *epnlink* library is also available online at https://github.com/Atinoda/epnlink.

5.2 Software environment

This study can be explored using an interactive Python (iPython) scientific computing environment, and an installation of EnergyPLAN. Quintel Energy Transition Model is optional, but access to it will aid in understanding the principles of the study.

The online version of ETM is not the same as the one used in this report because the software is updated regularly, but it is suitable to get an impression of the user interface. For consistent analytical work, the version must be frozen, and Quintel maintain versioned docker images that enable this. Therefore, any users seeking to implement this pipeline for their own scenarios should deploy a local instance of ETM set to a fixed release – however, it is not essential for the purposes of exploring the pipeline used in this study or understanding the soft-linking method.

5.2.1 EnergyPLAN (EP) bottles

The EP version used in this work is 16.2, and it is running on a Linux host via WINE [57] managed with the Bottles [58] interface. No *winetricks* or dependencies are required for EP, and it runs perfectly except for some minor graphical glitches that have no effect on functionality. Ensure that the provided distribution files are loaded into *Data/Distributions* before running the simulations. For automation, ensure that the EnergyPlan Data folder is accessible to the overseer program – cli-based EnergyPLAN simulations cannot read configuration or settings files that reside outside the Data structure.

5.2.2 Quintel energy transition model (ETM) docker

The ETM instance used in this work has been frozen at version tag 2022.12, is running in development mode, and is deployed locally using docker containers [59] on a Linux host. Instructions for configuration are available at: https://docs.energytransitionmodel.com/contrib/running-with-docker/. Ensure that any API-based queries are directed to the correct local IP address because the ETM API defaults to Quintel's hosted instances.

5.2.3 Python miniconda and data management

The Python environment is managed by Miniforge [60] and Mamba [61] (permissively licensed and accelerated versions of Anaconda [62] tooling), and the graph database is implemented using TerminusDB [63]. Full details of TerminusDB for techno-economic energy data is subject to future publication – its contribution in this work is management of sources and citations for cost metrics.

5.3 Biomass accounting

Biomass accounting is problematic in official figures, across government departments, and each software handles it differently. For the purposes of this soft-linking work, there are three categories of biomass – biomass as fuel, biogas feedstock, and bio-fuel feedstock. The conversion processes have an associated efficiency which is empirically set and validated by simultaneously tuning a shared figure that aligns fuel usage across differing scenarios.

5.3.1 Bio-fuel feedstock calibration

ETM implicitly models losses in bio-fuel conversion, however these are difficult to observe in the energy flow and application demand variables. EP models energy input and losses (efficiency) for bio-fuel conversion, however it does not report these losses in a separable manner in its outputs. This study uses a single efficiency metric for bio-diesel, bio-petrol, and bio-JP production. Bio-fuel efficiency is empirically calibrated by simulating a range of scenarios, adjusting the production efficiency across a range of feasible values, and observing the biomass fuel balance between the models.

5.3.2 Bio-gas feedstock calibration

ETM implicitly models losses in bio-gas conversion, however it is difficult to observe in the energy flow and application demand variables. An efficiency metric can be derived by observing the user interface chart tooltips, and this corresponds to 56.3%. This efficiency is set in the EP key *Input_BiogasUpgradeEff*, however the production in TWh, *input_Biogas_prod*, must be set to zero because the quantity is subject to a feedback calibration operation detailed in Section 5.5.7.

5.3.3 Biomass as fuel

Biomass as fuel is generally referred to as '*wood_pellets*' in ETM, and these are assigned across individual heating, power generation, and industry – the latter of which serves as a catch-all for any unassigned fuel usage. No efficiency calibration or adjustments are applied to these metrics.

5.4 Hydrogen accounting

Hydrogen is treated as pure import and costed separately. This is achieved by setting the EP key *input_HydrogenImport* to the totalised hydrogen demand *ef_fds_fuels_totals_ep['h2']*. Hydrogen storage is set to a very large number and the cost is set to zero. A levelised cost of green hydrogen, including production, storage, and transport is applied to assess the scenario. While EP does offer the ability to specify hydrogen production in some detail, the hydrogen ecosystem is under rapid evolution and is a current topic of debate. Therefore, it is more suitable to capture the dynamics in a levelised cost rather than the prescriptive dynamics of EP.

5.5 Soft-linking technical notes

This section of technical notes explains the details of mapping and conversion of specific parameters and dynamics between ETM and EP. The reader is strongly encouraged to read the accompanying '*demo_softlink_ni.py*' example script to understand the details of the linking and the properties of the data structures. For this reason, equations will prefer to use program variable names rather than standard mathematical notation. The provided code is heavily commented to provide a rapid route to replication and extension. These notes are not exhaustive explanations, they are a conceptual overview of the required procedures accompanied by highlights of key considerations.

5.5.1 ETM data processing

ETM offers a range of pre-configured reports that can be downloaded as .csv files. The software uses *gqueries* internally to generate these reports, and also to create the diagrams and metrics displayed in its GUI. The user can download the pre-configured reports, run any of the pre-configured gqueries, and specify custom gqueries by modifying *etsource*. Scenario instantiation, simulation, and outputs are available via the ETM API.

This soft-linking workflow downloads the entire set of available pre-configured reports and several of ETM's pre-defined gqueries that are required for soft-linking, e.g., '*share_of_greengas_in_gas_network*'. The simulation outputs are provided as ESI, and the reader is encouraged to examine the provided files and to consult the ETM documentation for additional context at https://docs.energytransitionmodel.com/main/intro/.

The variable naming schema in ETM is descriptive and consistent, and this property is leveraged to create several views of the output data that parametrise the scenarios in terms of fuel and sectoral boundaries. The *demo_softlink_ni.py* script retains development objects to assist users with replication and exploration of the data. While the code is heavily commented, there are three key variables to focus on – the Sankey flow object '*sk*', the energy flow object '*ef*', and the application demand object '*ad*'.

The data objects contain *primary_demand_** and *final_demand_** variables, which are analogous to primary energy supply and final energy consumption, respectively. In most applications, *input_of_** and *output_of_** correspond to fuel input and end-user demand. For some quantities, there may be several inputs – like a heatpump with *input_of_ambient_heat* and *input_of_electricity* – so the user must carefully parse the interaction of the quantities. Variable keys including '**_aggregator*' in the name should be treated with care, as they combine other variables which can lead to double counting. Several iPython cells titled with '*[...] EXPLORER*' are provided to help visualise these interactions with dense matrix variables, where rows and columns with all zero values have been removed.

5.5.2 EP data processing

EP uses a key-value structure as a text file for its scenario inputs. Simulation outputs can be printed to screen as plaintext, copy-pasted to Excel, or run to an ascii file. This study uses an automation pipeline that calls EP from the cli, loads a configuration file, saves the results to .ascii, and parses the ascii to *pandas* dataframes. The data handling is performed by the *epnlink* library, created by the author and available as ESI and on Github. The code to call EP and run the simulation are out of scope because they are only required for full automation, rather than soft-linking.

The *epnlink* library includes tools to load and parse EP settings text files, save EP settings text files, map variables described by their path in the GUI to the correct key, and parse EP ascii outputs to machine readable dataframes. The code provided as ESI demonstrates the use of these features and includes the datasets used in this study. The library code is heavily commented to explain its functionality and operation, and this is treated as key documentation. Guidelines to install EP on Linux are provided in Section 5.2.1 and automation is an exercise for the reader, should they require it.

epnlink is a programmatic interface to EP – its goal is not to explain the operation of EP, nor to document the interaction of variables or the principles of EP modelling. Therefore, the library should be used in conjunction with the EP documentation, and with reference to the instructions provided in the EP GUI.

5.5.3 Hourly distribution extraction and conversion

Hourly distributions for electrical demand and household heat are extracted per-scenario from ETM, processed, and inserted into the EP simulations. Renewable generation curves are extracted from the ETM base data set, processed, and used for all EP simulations. ETM uses 8,760 hour years, while EP uses 8,784 hour years (leap years).

All ETM distributions are processed by max-scaling to 1.0 and replaying the first 24 hours of the year at the end of the year. For each scenario, hourly distributions are extracted from the pre-configured reports *household_heat* and *merit_order* for electricity and heating demand, respectively. Globally shared renewables generation distributions are available via the ETM Dataset Manager > Hourly Curves > Default curves at: https://data.energytransitionmodel.com/datasets/UKNI01.

5.5.4 Demand, fuel, and efficiency calculations

EP uses a mix of fuel demand (e.g., oil boilers) and application demand (e.g., heat pumps) to define scenario parameters. ETM is a demand-led simulator, and rarely uses fuel input as a specification. When considering fuel input and application demand, there are positive or negative losses in the conversion. A positive loss is an efficiency less than 1.0, which is the case for almost all technologies. Heat pumps have an efficiency above 1.0, and a negative loss, because they capture ambient heat. Strictly speaking, their efficiency is not higher than 1.0 – however, environmental ambient heat is not normally accounted for in this way.

EP needs a mix of fuel inputs and demand inputs, so this information must be extracted from ETM. Furthermore, it is required to specify the conversion efficiency to align the fuel usage of the models. The fundamental formula, *Fuel x Efficiency = Output*, is used for these calculations. While this is apparently simple, consider households and buildings in ETM - it is necessary to aggregate the fuel inputs of these categories for EP, and to calculate an aggregate efficiency for each fuel, respecting the weighted mix of technologies using each fuel.

The aggregation categories, and the polarity of the calculations seeking either fuel input or application demand, are detailed in the accompanying code. The reader should consult the soft-linking code for details, however several subtleties are highlighted: hybrid heat pumps have conventional mode operation assigned to the appropriate fuel, and their electrical mode operation assigned to the heat pump aggregator; hydrogen boilers are proxied to H_2 micro CHP with zero electrical output; and condensing boilers have an efficiency above 1.0 because ETM uses the LHV of fuels in its calculations.

5.5.5 Power generation dispatch and renewable curtailment

ETM and EP use different power system dispatching algorithms – no direct alignment between them is feasible. Therefore, the goal is to align the fuel mix of the power generation and the production of renewables. ETM scenarios include a wide range of dispatchable power sources which must be aggregated in EP simulations. All ETM thermal generation is aggregated to PP2 in EP, and the fuel mix of this aggregate group is inserted to Supply > Fuel Distribution > PP2. Northern Ireland scenarios also use distributed CHP, which is aggregated to CHP3 in the same manner, with the caveat that waste input is entered into Supply > Waste > Group 2. Renewable generation capacities and distributions can be mapped directly from ETM to EP.

Due to the different power grid management algorithms, electrical production may not align between the models. Renewable under-production in EP can be adjusted using the provided correction factor, over-production can be augmented by increasing the stabilisation share in Balancing and Storage > Electric grid stabilisation requirements > Minimum grid stabilisation share, and the curtailment strategy is defined in Balancing and Storage > Critical Excess Electricity Production (CEEP) regulation. The calibration was performed empirically in this study by comparing the renewable generation in ETM and EP across different parameter values.

Power generation tends to over-dispatch in EP compared to ETM, and the CHP3 aggregator tends to use too much fuel. Reducing grid stabilisation share and Minimum PP can help to reduce the power dispatch but care should be taken not to invalidate the model with regards to actual system operation.

However, stability is treated as deferred to ETM so the constraint is not as direct as for a standalone simulation. CHP3 fuel reduction is achieved by proportionally reducing heat demand for district heating. This compromise is acceptable for Northern Ireland because the CHP is treated primarily as electrical generation – and the quantity of interest is its fuel usage, not its heat output.

The calibration factors, their effects, and their justifications are provided as adjustments at the end of the example soft-linking script.

5.5.6 Individual heat demand calculation

EP uses a nominal heat demand per household to define the count of deployed individual heating boilers, while ETM specifies the total number of residences and shares of technology deployment. The models are aligned by dividing the total individual heat demand in EP by the number of residences in the ETM scenario as shown in the following equation:

$$\text{input\_Heatdemand\_PerHouse} = \frac{\text{ep\_individual\_heat\_demand\_sum}}{\text{ql\_number\_of\_residences}}$$

5.5.7 Bio-gas feedback calibration

ETM specifies network gas using a percentage mix of green-gas. The same relationship between network gas and bio-gas exists in EP however, the mix must be specified in absolute terms. Although the soft-linked scenario parameters are aligned, EP is responsible for thermal power dispatch and renewable curtailment in its simulation. This independence leads to different absolute usage of network gas for power generation, meaning that bio-gas production cannot be specified a-priori using ETM scenario parameters. The following formula is applied:

$$\text{input\_Biogas\_prod} = \frac{\text{Fuel Balance}\left(\text{N.Gas,Total}\right)\times\text{share\_of\_greengas\_in\_gas\_network}}{\text{Input\_BiogasUpgradeEff}}$$

Where, the total network gas usage from fuel balance '*N.Gas, Total*' in EP is observed, and the ETM green gas percentage – yielded by the '*share_of_greengas_in_gas_network*' gquery – is used calculate the corresponding absolute production of bio-gas for the EP scenario. The efficiency of biogas production must be applied, which is stored in the EP key '*Input_BiogasUpgradeEff*'. The resulting figure is set in the EP key '*input_Biogas_prod*'. Unfortunately, this doubles the time taken for each simulation – however, EP simulation runs are measured in seconds of duration, and the introduction of a mandatory feedback loop increases the robustness of the soft-linking pipeline.

The provided ESI includes before-and-after bio-gas calibration settings files designated as *A0_{scenario}.txt* and *A1_{scenario}.txt*, respectively.

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