Review of the Scottish TIMES energy system model

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February 2021

Executive summary

Aim and context

The Scottish TIMES energy system model is built using the TIMES platform, which is developed by an International Energy Agency (IEA) technology collaboration programme and used in 63 countries. It contains a detailed and up-to-date depiction of all Scottish energy flows and greenhouse (GHG) emissions, and explores the potential future benefits of a wide range of low-carbon fuels and technologies.

The Scottish TIMES model has provided influential evidence to inform Scottish Government climate policy in recent years. Yet as a complex economic model, with more than 60,000 data points, it is difficult for stakeholders to understand the quality of the evidence that the model produces. This report presents the findings of a technical review of the Scottish TIMES model. The work comprised a review of the model inputs and a number of diagnostic tests based on running the model with a test scenario. The review does not extend to considering whether the model has been used appropriately to support Scottish Government climate policy.

Summary conclusions

Review of model inputs

- The Scottish TIMES team have put considerable time into developing the model and keeping the data up-to-date, and have consulted a range of experts as part of this process.
- The team operates good quality assurance processes, but it would be good practice to formalise these and to use a version control system.
- A number of issues should be investigated further. These include the need for a reassessment of model boundary conditions, particularly for the GB electricity system, and some technology assumptions could be updated.

Outcome of the diagnostic tests

- The diagnostic tests identified a number of minor model data issues to investigate. At worst, these would make the existing model more conservative, by preventing some low-carbon technologies from being deployed.

- The greenhouse gas emission accounting system (i.e. how greenhouse gases are counted across the economy) could be more robust.

Overall, it is clear that Scottish TIMES is a solid and well-designed model that is suitable for informing Scottish climate policy if used appropriately.

Potential model development

The model could:

- Have improved greenhouse gas emissions accounting.
- Provide more value through a wider range of uses, for example by exploring future uncertainty.
- Be used more efficiently if a system were developed to produce the output data and analyses that stakeholders require.

For the model to continue contributing high-quality evidence to inform Scottish policy, there is a need to ensure that there is sufficient technical modelling capacity within the Scottish Government.

Detailed recommendations

More information about each recommendation can be found in the relevant report section.

Section	
Commodity trade assumptions	
3.1	Consider how the influence of international fossil fuel trade on the price of Scottish resources for Scottish consumption can best be represented.
3.1	Consider representing hydrogen exports and ammonia imports and exports.
3.2	Consider how electricity exports to England/Wales are likely to vary throughout the year.
Energy system data assumptions	
3.1	Revise the representation of municipal solid waste for energy purposes.
3.2	Update onshore and offshore wind generation capital costs and capacity factors.
3.2	Consider increasing the electricity peak reserve capacity margin.
3.2	Consider whether the electricity system that the model constructs by 2050 could be operated reliably.
3.3	Review electrolyser cost and efficiency assumptions.
5.2	Edit the industry technologies to remove negative emission counters and rerun the technology operation check to identify any further issues.
6.1	Update energy service demand load curves.
Other modelling assumptions	
4	Consider wider use of dynamic growth constraints for new technologies.
4	Review the industry sector constraints in the "IND_FuelSwitch" scenario to ensure that they are comprehensive.
5.1	Address, as far as practicable, all of the model issues identified by VEDA-FE and TIMES.
6.1	Use a consistent timeslicing approach for each commodity unless there is a clear justification for an alternative approach.

	Emissions accounting
3.8	Consider whether the bunker fuel approach is appropriate to allocate UK international shipping and aviation emissions to Scotland.
5.3	Consider editing the GHG accounting to record net emissions of each GHG at whole system and sectoral levels.
5.3	Remove the ETS emission accounting scheme.
5.3	Estimate the error in emissions accounting caused by using IPCC AR4 instead of AR5 global warming potentials for combustion emissions to confirm that it is not substantial.
5.3	Set the minimum net emission for each counter to –infinity.
	Using the Scottish TIMES model
6.3	Use oblong and levelised annual costs, and mid-year discounting, for all Scottish TIMES scenarios.
6.4	Create a system to efficiently extract and analyse model outputs in a format suitable for stakeholders.
	Quality assurance
6.6	Consider adopting a formal QA system for Scottish TIMES, for example based on the BEIS quality assurance system for Excel workbooks.
6.6	Move Scottish TIMES to a version control system such as Git.
6.8	Consider the potential benefits of a cross-governmental energy system modelling group.

Contents

1 Introduction

The Scottish TIMES energy system model has provided evidence to underpin the Scottish Government's climate policy in recent years. In this review, I consider whether the model is suitable for this role by examining model inputs and outputs in some detail, and I make recommendations for future model development.

1.1 Use of TIMES energy system models for policymaking

TIMES is a model generator that is used to build models of economy-wide energy systems. It is developed by the ETSAP technology collaboration programme of the International Energy Agency (IEA),[1] and is used in 63 countries. In addition to Scottish TIMES, there is a UK TIMES model that is used by a range of stakeholders including the UK Department for Business, Energy and Industrial Strategy (BEIS).

TIMES is a least-cost optimisation model. Given information about energy flows across an energy system, future energy demands, and future technology costs, it identifies the lowest-cost technology transition to meet energy goals such as net zero greenhouse gas (GHG) emissions. The starting point for each scenario is a description of each energy technology and energy flow in the economy in a "base year". It is a bottom-up model, as each technology is represented separately. For each new technology, the user must specify the capital and operating costs, lifetime, and energy conversion efficiency. The model then calculates commodity market prices, including a carbon price, for each time period in the model horizon, and uses these to identify the lowest-cost investment in new technologies in the future that meet all energy demands. It uses an assumption of perfect foresight, which means that it understands all future costs and demands when making investment decisions.

TIMES models help us to understand potential future energy flows through the economy, and the impact of environmental and other constraints (e.g. moving to a net zero energy system). They are valuable for policymakers because they can systematically identify a range of methods to meet policy goals at low cost, and can identify technologies that are both very likely, or very unlikely, to have a role in a transition. As they represent whole economies, they can be used to explore trade-offs between emission cuts in different sectors, and to understand when and where emissions are best cut at each stage of the transition. They can also provide evidence that energy transition scenarios will plausibly meet emission targets.

TIMES models do not predict the future. They calculate what the future might resemble if all of the assumptions about future demands and technologies are accurate, and if decarbonisation decisions are based only on minimising the total cost of the energy system transition. In reality, there is uncertainty about future demands and technologies, and investments in new technologies reflect many other concerns in addition to cost.[2]

The broad nature of energy system models also tends to mean that they have low spatial and temporal resolution, and only a high-level representation of end-use sectors in particular. These weaknesses can be minimised through careful model design, and can be at least partially be addressed by linking energy system models with high-resolution electricity system models, and with building and transport stock models.

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[1] https://iea-etsap.org/

[2] The public and private sectors consider many factors when planning investments, including energy security and equity, governance arrangements, the roles of various actors in the energy system, industrial growth opportunities, and the quality of the energy service provided by each technology.

1.2 Scope of this review

The Scottish Government provided Scottish TIMES v2.05 for this review. It is similar to the version used for their Update to the Climate Change Plan, which was published in December 2020.[3] The residential and service building sectors are currently being revised, and that process had only partially been completed in this version.

In this review, I examined the model inputs and I carried out a number of diagnostic tests on the outputs from a test scenario. I did not review how the model has been used to support Scottish Government climate policy. In this report, I focus on potential issues that I have identified, rather than praising the many areas of good practice in what is a solid and well-designed model that is appropriate for informing Scottish climate policy.

In Section 2, I provide a brief overview of the version of the Scottish TIMES model that I reviewed. I review the model inputs in Sections 3 and 4, and identify issues from the diagnostic runs in Section 5. I conclude by identifying a number of areas for future model development in Section 6.

2 Overview of the Scottish TIMES model

Scottish TIMES represents Scotland using a single region (i.e. with no spatial resolution). The residential sector is an exception, as urban and rural dwellings are treated separately.

The base year for Scottish TIMES is 2015. The model time horizon extends to 2052, and 10 representative time periods are defined over that horizon. These cover 2015 to 2017 individually, and then 5-year carbon budget periods (2018–2022, etc.). It is also possible to extend the time horizon to 2067.

The model objective function minimises the total discounted cost over the entire time horizon. Discounting in years after the base year follows Treasury Green Book recommendations (3.5% for first 30 years, then 3%).[4]

Scottish TIMES defines 16 "timeslices" to represent variations in energy demand and energy flows through the year. These timeslices represent a single typical day in each season. These typical days are split into four unequal parts that are based on electricity demand in 2010 to represent the overnight low, daytime, evening peak, and late evening. Only electricity and heat flows are examined in this way, with other commodity balances being calculated only annually.

Scottish TIMES v2.05 represents 1260 energy commodities, and 2235 processes (i.e. technologies) that produce commodities or meet demands. There are 236 general "user constraints", which are used across all model sectors to limit new technology uptake, define relationships between technologies, set GHG emission limits, etc. In total, Scottish TIMES has more than 60,000 data points.

An early version of the UK TIMES model[5] was used as the starting point for Scottish TIMES. Over the last few years, the two models have diverged substantially. For example, UK TIMES has a different base year (2010), and the residential and service sectors in Scottish TIMES have a different building archetype structure. Yet many new technologies are defined in similar ways in each model.

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[3] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/
[4] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent
[5] https://www.ucl.ac.uk/energy-models/models/uk-times

TIMES is built in the GAMS programming language. The proprietary VEDA software is used to process the Scottish TIMES model data, run cases, and analyse the model results.

3 Review of the model reference energy system

Given the large number of data points in Scottish TIMES, I did not check each individually. Instead, I took a targeted approach in four steps:

1. Reviewing the modelling of a number of key technologies that have an important role in a 2050 net zero energy system.
2. Scanning technology input tables for inconsistencies that might point to errors.
3. Producing diagrams of the reference energy system to identify potential issues such as "orphaned" technologies.
4. Checking whether some errors that were in the version of UK TIMES that was used as a base for Scottish TIMES were still present.
5. Analysing unexpected model outputs (Section 5 contains details about the diagnostic model runs).

The model splits the energy system into eight sectors. I discuss each in turn below. Overall, it was clear that the Scottish TIMES team have put considerable time into developing the model and keeping the data up-to-date, and have consulted a range of experts as part of this process.

3.1 Resource sector

The resource sector represents domestic production, imports and exports of a range of energy commodities, including fossil fuels, biomass and hydrogen. It provides boundary conditions for Scottish TIMES, with the choice of prices and limits on availability substantially affecting the scenario outputs. The range of commodities is similar to other energy system models and is appropriate.

Scottish TIMES implicitly assumes that only domestically-produced crude oil will be used in Scottish refineries in future, and that the oil price is based on production cost rather than a global market price. In reality, oil is traded globally and the price for refineries would be close to the international market price, as producers would otherwise sell their oil on the international market. A similar assumption is made for natural gas, yet gas is traded extensively across Europe. While the approach captures the economic benefits of extracting oil and gas to the Scottish economy, it has the disadvantage of ignoring international markets and potentially of assuming higher fossil fuel consumption than would be likely due to unrealistically low prices. An alternative approach would be to separate domestic production from consumption and to assume that consumers would pay prices similar to the international price for domestically-produced resources.

Recommendation: *Consider how the influence of international fossil fuel trade on the price of Scottish resources for Scottish consumption can best be represented.*

In the test scenario, by 2050, all domestically-available and imported biomass is consumed, which means that biomass availability assumptions substantially influence the model outputs. Hence constraints on biomass availability should be justified, and uncertainties in these constraints considered.

Scottish TIMES can import liquid hydrogen at a high price, and cannot export hydrogen. Given the recent focus on green hydrogen exports from Scotland, and the global interest in the trade of ammonia as a hydrogen energy carrier, perhaps it would be a good time to review these assumptions.

Recommendation: Consider representing hydrogen exports and ammonia imports and exports.

The model assumes a negative cost (i.e. an income) for using municipal solid waste. This leads to it taking this waste, to realise the income, but then to not using part of it in the energy system as it is expensive to process compared to other fuels. This "stockpiling" strategy is not plausible. Waste would ideally be treated as a liability that can be used for energy purposes or disposed of elsewhere. The model assumes fixed waste GHG emissions in the future that result from a waste disposal scenario, and the energy uses of municipal solid waste should reflect that scenario. An alternative approach would be to represent waste emissions dynamically, with the model disposing of wastes to minimise the total cost to the Scottish economy.

Recommendation: Revise the representation of municipal solid waste for energy purposes.

3.2 Electricity generation

Scottish TIMES represents options for a wide range of electricity generation technologies, including fossil fuel and biomass combustion (with and without carbon capture and storage - CCS), hydropower, wind, solar and marine renewable generation, nuclear power, hydrogen turbines, and Combined Heat and Power (CHP) in industry and heat networks. Interconnection with England/Wales and other electricity systems is represented. Energy storage technologies include pumped hydro and batteries.

Overall, I think the representation of future electricity generation options is appropriate.

Wind generation assumptions

Both onshore and offshore wind capital cost assumptions appear high to me, particularly when compared with the strike prices from the most recent capacity auctions.

Onshore wind capacity factors assume that all turbines are located in the windiest UK locations, which might not be realistic given the high deployment rate in the test scenario. In contrast, offshore wind capacity factors for new deployments are more representative of existing turbines than the larger turbines that will be built in the future, and assuming higher capacity factors for these would be more appropriate.

Recommendation: Update onshore and offshore wind generation capital costs and capacity factors.

Nuclear power

Scottish TIMES assumes that new nuclear plants will not be built in Scotland, and hence that current Scottish Government policy will be continued by all future administrations over the next 30 years.

Electricity system stability

In the test scenario, onshore wind generation reaches 88% of total generation by 2045. The only controllable electricity plants are Combined Cycle Gas Turbines (CCGTs) and biomass plants, and since both use CCS, they might not be able to provide variable load operation. Moreover, the system reserve capacity is set very low at 10% of peak generation – for comparison, for the same 16 timeslices in Scottish TIMES, the UK TIMES model uses a reserve capacity of 23%. It is not clear to me that such a system design could operate reliably in practice.

Recommendation: Consider increasing the electricity peak reserve capacity margin.

Recommendation: Consider whether the electricity system that the model constructs by 2050 could be operated reliably.

Electricity transmission system

The transmission system is modelled as if the whole network were constructed in 2015, with annualised capital costs charged over the full model time horizon. This is unrealistic as most of the network capital costs will have been repaid. In contrast, distribution networks are assumed to have no historic capital costs.

Electricity imports and exports

Representing the Scottish electricity system is a challenge because it is integrated into a single system serving Great Britain. Although transmission capacity between England/Wales and Scotland has been limited historically, new capacity is gradually being deployed, with Scottish TIMES assuming 3.5 GW transmission capacity in 2017, rising to 13 GW from 2030. Since Scottish TIMES only represents electricity generation and demands within Scotland, it is necessary to decide how the Scottish part of the system will interact with other parts in the future, and particularly what level of imports and exports will take place, and when. Similar decisions are required for trade with other electricity systems, for example the Irish Single Electricity Market and the continent. Four broad methods are available, which range from fully fixed to fully dynamic modelling:

1. Fixed trading flows are assumed, ideally based on other models that run scenarios which are consistent with the Scottish TIMES scenarios.
2. Electricity prices in other markets are estimated for each timeslice in each time period, again from other models, and Scottish TIMES optimises imports and exports according to the difference between those prices and Scottish generation prices.
3. Non-Scottish electricity systems are represented in the model as separate small region(s) that decarbonise over time and trade with Scotland.
4. Scotland is represented as a region of a larger energy system model that also has GB and perhaps other regions with which it can trade.

Scottish TIMES currently uses the fixed trading flows method. Scotland is assumed to export electricity to England/Wales at a constant year-round rate of 2.7 GW in 2020, rising to 4.7 GW from 2030. Scotland is assumed to not export to other electricity systems, and to not import any electricity. This is important because around half of total Scottish electricity generation is exported to England/Wales in the test scenario.

While the potential for Scotland to develop a substantial offshore renewable industry is widely acknowledged, it seems unlikely that it would export at a constant level and that there would be no imports at all. Moreover, since the seabed is shallower in many places off England than Scotland, it is not clear that Scottish renewable generation would be able to undercut English renewable generation.

The import and export network capacities are different in Scottish TIMES but they are presumably representing the same power lines so should be equal. User constraints would ideally be created to ensure that the same power lines are not importing and exporting at the same time.

Recommendation: *Consider how electricity exports to England/Wales are likely to vary throughout the year.*

3.3 Process sector

The process sector represents fuel transformation for fossil fuels (e.g. oil refineries), biomass and hydrogen, as well as carbon capture and storage systems. It is broadly similar to the UK TIMES model.

The role and design of oil refineries in a low-carbon energy system is an area requiring research. Four types of oil refinery are defined in Scottish TIMES. Three have successively more flexible fuel outputs, with increasing costs, while the fourth has CCS. In the test scenario, there are investments in several of these technologies in order to produce both fuel flexibility and emissions capture. In practice, however, oil refineries are only economic at scale and Scotland is unlikely to have more than one. The TIMES "lumpy investment" option could be used to require a minimum refinery size of a particular type to be constructed.

Hydrogen is produced from biomass and natural gas rather than renewable electricity in the test scenario, despite the focus on green hydrogen exports from Scotland. Electrolyser costs are higher than assumed in UK TIMES, and energy conservation efficiencies are lower, so perhaps these should be reviewed.

Recommendation: *Review electrolyser cost and efficiency assumptions.*

3.4 Agriculture sector

The agriculture sector covers energy use and emissions from agriculture and land use. Many of these emissions are not energy-related, and a range of mitigation options are defined for these based on a marginal abatement cost curve. The model uses the most recent Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) emissions accounting and considers peatland emissions. The approach is more sophisticated than most TIMES models and a good example of best practice.

Tractors account for a substantial amount of agricultural expenditure in UK TIMES. In the absence of data, hydrogen and compressed natural gas (CNG)-powered tractors are assumed to cost double that of existing tractors in 2016, falling to 1.25x the cost in 2050. In reality, a 1.5x cost factor is applied in 2050. I think it would be more appropriate to assume lower costs for gas fuels, on the basis that the powertrain is a lower part of the total cost than for other vehicles. Moreover, electric tractors have been developed (both with and without batteries, but are assumed unavailable in the model. Finally, the share of bio-diesel tractor fuel is limited to 34%, but I think this is unrealistic as tractors have been developed (e.g. by John Deere) that can use 100% biodiesel.

3.5 Industry sector

Scottish industry is categorised into eight sectors. Energy-intensive industries that use relatively homogenous processes (e.g. iron and steel; cement; chemicals; paper) are represented in detail, with a range of low-carbon alternatives to existing processes. Other industry sectors are represented using generic demands (high-temperature heat; low-temperature heat; drying; motor drive; other). These approaches are commonly used elsewhere, are consistent with national statistics, and are appropriate.

Several GHG emission sources cannot be mitigated in the model. It would be useful to systematically identify those emissions and to consider whether there are emerging technologies that could mitigate them (e.g. direct iron reduction using hydrogen, and bio-based synthetic fuels to replace petroleum products).

3.6 Residential sector

Six dwelling archetypes are used to represent the Scottish housing stock: urban flats; urban houses; and rural houses, for buildings already existing in 2015 and for those built after 2015. All heat and non-heat energy service demands are separately defined for each dwelling archetype. An appropriately-wide range of low-carbon heat and other technologies are defined to meet these demands, including heat networks. Energy conservation measures can be deployed to reduce demands.

The residential sector can only use biomethane by constructing a new gas distribution network. I recommend enabling biomethane injection into the existing gas network, as for other sectors. One challenge is that biomethane has a lower calorific value than natural gas, so is normally mixed with propane prior to injection. In UK TIMES, biomethane is assumed to be mixed with LPG prior to injection in the short term, and you could consider a similar approach for Scottish TIMES.

The residential sector in Scottish TIMES is currently being revised. I comment on how conversion of the gas networks to deliver hydrogen could be represented in Section 6.1.

3.7 Service sector

Heating energy service demands in the service sector are split into four categories covering private and public buildings with high and low energy demands. This approach to splitting between private and public buildings is good practice that is increasingly being adopted elsewhere. Further disaggregation would be difficult as a result of a lack of data about the sector.

A range of energy conservation measures are represented in the sector. Scottish TIMES assumes a fixed level of deployment of conservation measures in the future, with the choice of measures cost-optimised. At present, the portfolio of measures that is deployed is not plausible. It would be useful to add deployment constraints on each individual measure to improve the plausibility of the scenarios.

The service sector can only use biomethane by constructing a new gas distribution network, following a similar approach to the residential sector, and I recommend enabling biomethane injection into the existing gas network as for the other sectors.

3.8 Transport sector

Car, motorcycle, light goods vehicle (LGV), heavy goods vehicle (HGV), bus, passenger and freight rail, and shipping and aviation are separately represented in Scottish TIMES. Demands for each of these are forecast to 2050 and any mode switching is included in those demands.

Both domestic and international shipping and aviation demands are based on Scottish bunker fuel consumption. For domestic demands, this seems appropriate. For international demands, there is a question about the extent to which Scotland uses other parts of the UK as a hub (e.g. linking to international flights from London, or ports in England). International shipping and aviation demands are only 4% and 5% of UK demands in 2015, respectively, despite Scotland having 8% of the UK population.

Recommendation: *Consider whether the bunker fuel approach is appropriate to allocate UK international shipping and aviation emissions to Scotland.*

Refuelling infrastructure represented in the model includes refuelling stations and battery car charging stations. These are represented separately for each fuel and it would be better to group fuels where appropriate (e.g. petrol, diesel, ethanol and biodiesel).

4 Review of core user constraints

In TIMES models, "user" constraints can be defined across technologies and commodities to affect scenarios (e.g. to force a reduction in the use of coal in industry over time, or to limit the speed of deployment of new technologies). Scottish TIMES has a total of 212 user constraints, which is within an order of magnitude of similar models.

User constraints are often the most challenging part of a TIMES model to implement. The Scottish TIMES team follows a process in which each change to a user constraint is

verified by a second team member, which I consider to be good practice. I encourage the team to verify the equations that are produced by GAMS as well as verifying the equation data inputs.

I formed a small number of recommendations during my review of the user constraints:

- Make wider use of dynamic growth constraints for new technologies, as innovation theory shows that deployment rates often depend on the existing capacity.
- A number of industry sector constraints in the "IND_FuelSwitch" scenario did not work properly. I was not convinced that this scenario was comprehensive, particularly for energy-intensive industry sectors in which processes rather than generic energy demands are defined.
- Avoid using constraints based on process activity, where possible, as activity is defined differently for different types of processes. For example, CHP devices can measure activity in terms of just electricity or both electricity and heat outputs, and storage processes specify activity as the total stored energy. In most cases, activity can be replaced by commodity flows.
- Add descriptions to the user constraints to aid users in understanding the purpose of each constraint.

Recommendation: *Consider wider use of dynamic growth constraints for new technologies.*

Recommendation: *Review the industry sector constraints in the "IND_FuelSwitch" scenario to ensure that they are comprehensive.*

5 Diagnostic model runs

The Scottish TIMES team provided a typical net zero scenario on which I carried out diagnostic model runs. In the test scenario, Scotland achieves net zero emissions by 2050 under Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) global warming potentials.[6] The scenario includes all of the user constraints in the standard version of the model. I took particular interest in the model GHG emissions accounting and the energy system costs. The investigations are described in the following sections.

5.1 Automatic error checks

TIMES models undergo three automatic error checking stages:

1. The VEDA software carries out a range of checks when loading the model data into a single database. It identified ~1800 issues in Scottish TIMES – for example, entries in tables that produce no model data.
2. The TIMES code contains a series of QA data checks for the compiled model scenario. It identified ~800 issues in Scottish TIMES, of which most were warnings of potential minor errors with single technologies.
3. The GAMS language generates warnings if model discrepancies are found. It identified ~3000 issues in Scottish TIMES that were caused by obsolete data interpolation options not being removed. I addressed and removed all of those issues.

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[6] Global warming potential (GWP) is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere.

Most of the issues identified by VEDA-FE and TIMES were related to an unfinished revision of the residential sector, and should be resolved in time. I identified no issues that I thought would have a substantive impact on model results. Most led to processes becoming unavailable, making the model solution more conservative. It would be good practice to systematically address all of these issues.

Recommendation: *Address, as far as practicable, all of the model issues identified by VEDA-FE and TIMES.*

5.2 Technology operation check

I ran a scenario in which the model was required to construct and operate every technology that is defined.[7] This test identifies any technologies that had been defined in such a way that conflicting equations are created if the technology is deployed, so the technology is never used in model scenarios.

The test identified a number of industrial technologies with CCS that could not be constructed when the "Accounting" scenario was being used. The issue is caused by emission counters recording negative emissions, which is sometimes permissible in TIMES but is generally bad practice.[8] This could be avoided by, for example, using the emission counter as an input to the process rather than an output.

The impact of this issue is to make Scottish TIMES unnecessarily conservative, as it implicitly assumes that these technologies could not be deployed in practice. While it might therefore be possible to achieve net zero a little more cost-effectively than assumed in existing net zero scenarios, this issue does not affect the validity of those scenarios.

Recommendation: *Edit the industry technologies to remove negative emission counters and rerun the technology operation check to identify any further issues.*

5.3 Emissions accounting

Scottish TIMES counts GHG emissions across the Scottish economy, from both energy and non-energy sources, and represents a range of mitigation options for these emissions. Since there are a large number of emission counters, the risk of introducing counting errors is substantial. Using a system inherited from the UK TIMES model, emissions accounting takes place on three layers:

1. When fuels enter or leave the Scottish economy, GHG emissions are recorded for the whole system using counters that assume that the fuel will be combusted (e.g. CO2TOT).
2. Fuels that are combusted in each sector are recorded by sectoral counters (e.g. AGRCO2). Any non-fuel emissions in each sector (e.g. agricultural or industrial process emissions) are recorded by both sectoral and whole system counters within the sector.
3. Sectoral emissions are allocated to a further set of GHG counters depending on whether they are covered by an emission trading scheme (ETS).

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[7] This was achieved by setting a minimum activity constraint for each technology in the year 2040.
[8] Recording negative emissions is possible if the emissions are counted only by the commodity balance (EQ_COMBAL) equation (e.g. for process ALUFOR01). However, if other emission accounting is specified then TIMES creates a VAR_FLO variable for the emission flow and relates this to the process activity using a transformation (EQ_PTRANS) equation. VAR_FLO variables are defined as positive GAMS variables in TIMES, and activity variables must also be positive, so if the emission coefficient is negative then the transformation equation cannot be balanced and the process cannot be constructed.

The first advantage of this approach is that the whole system counters are less likely to have errors as they are produced from a small number of processes, and errors can be identified by comparing the whole system and sectoral counters. The second advantage is that the sectoral counters enable a straightforward comparison of the net emissions in each sector that can be easily traced back to the individual processes producing the emissions.

In Scottish TIMES, the whole system counters are not used systematically so do not provide useful information. The sectoral counters do not always record net emissions; for example, reductions in agricultural emissions are counted as positive net emissions in the sectoral counters, but negative emissions in the GHG counters as they should be. This means that sectoral counters do not represent net emissions from each sector.

I have identified only one minor issue with the emissions accounting for the overall GHG emissions constraint, so these issues with the whole system and sectoral emissions do not affect the net zero scenarios that have been used to support Scottish Government climate policy. Nevertheless, I believe there is an opportunity to improve the usefulness of the emissions accounting by recording net emissions from each GHG at whole system and sectoral levels.

Recommendation: Consider editing the GHG accounting to record net emissions of each GHG at whole system and sectoral levels.

ETS emission accounting

Scottish TIMES has a deprecated ETS emissions accounting system that might no longer be consistent with the new UK ETS scheme. Since it is no longer used, it would be good practice to remove this accounting system to avoid confusion in future.

Recommendation: Remove the ETS emission accounting scheme.

Emissions accounting for IPCC AR5

The scenario that updates the methane (CH_4) and N_2O emission factors to IPCC AR5 equivalence (Scen_Update_GWPs_to_AR5) does not update the emissions from combustion that are recorded in ~COMEMI tables. Since combustion is a minor source of CH_4 and N_2O, I expect the resulting accounting discrepancy to be small. A longer-term solution would be to count actual quantities of each emission rather than counting in CO_2 equivalent terms, and then using appropriate AR4/AR5 factors to sum the emissions.

Recommendation: Estimate the error in emissions accounting caused by using IPCC AR4 instead of AR5 global warming potentials for combustion emissions to confirm that it is not substantial.

Negative emission boundaries

Some Scottish TIMES emission counters will be negative in order to achieve net zero emissions across the economy in 2050. The TIMES model has a default assumption that commodities must have zero or positive values. In Scottish TIMES, a very large negative minimum for each emissions counter (e.g. –100 $MtCO_2$) is defined to address this issue. Unfortunately, using such large numbers creates numerical stability issues for the model optimisation solver. I recommend instead that you set the lower limit of each emission to –infinity in all time periods, which is achieved by setting the limit type to "N" and the limit to "-1" in the BY_Trans file.[9]

Recommendation: Set the minimum net emission for each counter to –infinity.

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[9] Further details: https://iea-etsap.org/forum/showthread.php?tid=113&highlight=negative+emissions

5.4 Energy system cost analysis

TIMES minimises the total discounted cost of supplying energy and other demands over the entire time horizon. I extracted the undiscounted costs of each technology and commodity for the years 2020, 2030, 2040 and 2050 in the test scenario to examine the balance of costs between sectors, and to identify and further investigate any costs that were higher or lower than I would have expected.

Table 1 shows the breakdown of undiscounted costs by sector. Electricity generation and other fuel production costs are accounted for in the supply sectors (resources; upstream; electricity; process). End-use sectors account only for fuel distribution and for capital and operating costs of end-use devices. Overall, the costs were broadly consistent with my expectations. I identified several areas for further consideration:

- Resource costs are negative in 2040 and 2050 because exports, which provide income, exceed the costs of imports and domestic fuel production. In 2050, 94% of export income is derived from electricity export to the rest of the UK, and this is discussed in Section 0.
- I was surprised that resource costs were so low, which I think partly reflects the use of extraction costs rather than market prices for domestic fossil fuels. Section 0 discusses the ramifications of this choice.
- Electricity costs were a little higher than I would have expected, which I believe is due to wind generation costs being too high (Section 3.2).
- The low industry costs are consistent with the UK TIMES model. They effectively assume that fuel switching accounts for the majority of the cost of decarbonisation for industry. We do not have a good understanding of industry transition costs and it is possible that the capital costs are underestimated.
- The high transport costs are consistent with the UK TIMES model, and are caused the whole powertrain costs of vehicles being included in the capital costs. The cost of cars accounts for 70% of the total transport cost in 2050.

I identified 14 technologies for further investigation. Where necessary, I have commented on these in Section 3. None of these would undermine the net zero emission scenarios that have been produced by the model.

Table 1: Breakdown of undiscounted costs by sector for the test scenario.

	2020	2030	2040	2050
Resources	1%	2%	-1%	-2%
Upstream	0%	0%	0%	0%
Electricity	10%	14%	17%	17%
Process	2%	3%	3%	5%
Agriculture	2%	4%	6%	5%
Residential	20%	21%	16%	15%
Service	7%	6%	6%	6%
Industry	1%	2%	2%	2%
Transport	57%	48%	51%	51%

6 Areas for future model development

Scottish TIMES, like all energy system models, evolves over time through incremental improvements. In this section, I suggest a number of potential improvements to the design and use of the model. I also discuss quality assurance processes and practical issues around model development.

6.1 Model design

Timeslicing

Natural gas and hydrogen are modelled using seasonal timeslices in the resource sector (i.e. demands vary seasonally but not between day and night). However, other sectors do not take a consistent approach and often model these commodities on an annual basis. The model would ideally have a consistent approach for each commodity.

Recommendation: Use a consistent timeslicing approach for each commodity unless there is a clear justification for an alternative approach.

Each energy service demand has a load curve, and these are generally based on load curves from an old version of UK TIMES. UK TIMES has since transitioned to new load curves that are based on high-resolution electricity and gas demand data. Scottish TIMES could similarly benefit from updating demand data, particularly if disaggregated data were available for Scotland rather than Great Britain.

Recommendation: Update energy service demand load curves.

One weakness of many energy system models, including Scottish TIMES, is low temporal resolution that does not resolve electricity system balancing needs very well. One approach to address this weakness is to increase the number of timeslices. Some models have developed a flexible timeslicing approach, in which the base model is annual only and the required timeslicing data is input through scenarios. This approach also increases the efficiency of model development as the annual only version solves very quickly and produces a much lower quantity of outputs for analysis. The Scottish TIMES team might wish to consider the potential benefits of adopting a flexible timeslice approach.

Gas network conversion to hydrogen

Decarbonising heat by converting the gas distribution networks to deliver hydrogen has received much attention both in Scotland and in the wider UK in recent years. I was asked by the Scottish TIMES team to comment on how conversion could be modelled in Scottish TIMES.

It is challenging to implement conversion in an energy system model in a way that accurately captures the costs of conversion and the benefits of repurposing existing infrastructure.[10] I use two approaches to modelling conversion: either it is mandated by government, and the whole network is assumed to be converted over a multi-decadal period, or the level of conversion (if any) is optimised by the model. For each of these approaches, I assume either that all converted homes would use hydrogen for heating, or that homeowners would choose the cheapest technology following conversion to minimise their long-term heating costs (which might not be hydrogen). This means that I use four scenarios in total.

The broad approach in each scenario is to limit the deployment of hydrogen pipes to the same level as existing natural gas pipes. User constraints prevent both gas and hydrogen being used in the same pipes. The costs of building hydrogen pipes are

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[10] See Dodds & Demoullin (2013) Conversion of the UK gas system to transport hydrogen.

removed and replaced with the conversion costs (for example for new appliances in homes) to ensure that conversion costs are levied only once. Beyond this broad framework, each of the four scenarios is specified quite differently in the model, and I will separately provide further details about the approach in each scenario.

I noted that all micro-CHP technologies are disabled in Scottish TIMES. If the gas networks are converted to hydrogen then fuel cell micro-CHP might become a valuable technology in the future.

6.2 Running model scenarios

The scenario I was provided examines the transition to a net zero Scottish economy by 2050. It does not consider whether net zero could be sustained beyond 2050, and I suggest considering scenarios that extend to the year 2060.

Energy system models can be used to demonstrate whether a preferred scenario meets net zero (or other policy goals), for which user constraints would be used to create the scenario in question in the model. An alternative approach, at the other end of the spectrum, is to use the model as a tool to help identify the best scenario(s) and to explore the implications of different scenarios and the importance of uncertainties. Given the weaknesses of the TIMES model, in terms of both technical limitations (e.g. temporal resolution) and the paradigm (cost-optimal perfect foresight) it is unlikely that Scottish TIMES would identify the most appropriate scenario for Scotland. It could, however, provide much valuable information to consider in developing that scenario, particularly if the implications of uncertainties are explored systematically (e.g. looking at parametric and structural uncertainty, and removing the perfect foresight assumption).

In order to gain the most value from the model, it would ideally be used in an exploratory mode at first, and then constrained to examine the final scenarios. The model structure should ideally reflect such different model uses, with constraints for a particular scenario applied separately to other constraints. It would also ideally be designed to enable uncertainty studies to be carried out, for example by collecting data ranges for key parameters for use in Monte Carlo uncertainty analyses.

6.3 Choice of TIMES model variant

TIMES has a number of objective function variants. One issue with the standard variant is that the capacity-related costs are not completely synchronised with the corresponding activities, which may cause distortions in the accounting of costs. It is then challenging to calculate the total discounted objective cost from the undiscounted costs – in my experience, the discrepancy is often around 3%. An "OBLONG" option is available in TIMES that causes all capacity-related cost to be synchronised with the process activities (which are assumed to have oblong shapes), so the objective function can be calculated from the undiscounted data. I will send you information about this calculation. I recommend that you use the OBLONG option. It is also necessary to use levelised annual costs by choosing "ANNCOST 'LEV'" in the RUN file.

In the standard objective formulation, both the investment payments and the operating cost payments are assumed to occur at the beginning of each year within the economic/technical lifetime of technologies. This approach is often called beginning-of-year discounting. However, it leads to an underestimation of the costs, because in reality the investments can be paid back only after getting some income from the investment. An alternative approach is to use end-of-year discounting. As a good compromise between these two approaches, mid-year discounting can be used, and I recommend that you adopt it for Scottish TIMES.

Recommendation: Use oblong and levelised annual costs, and mid-year discounting, for all Scottish TIMES scenarios.

6.4 Analysing model outputs

The TIMES community uses numerous approaches to analysing model outputs. A standard approach has not yet been developed for Scottish TIMES. Now that the Scottish TIMES team has gained experience of using the model outputs with stakeholders in the Scottish Government, it would be a good time to create a system to efficiently produce the outputs that internal stakeholders require.

Recommendation: Create a system to efficiently extract and analyse model outputs in a format suitable for stakeholders.

6.5 Improving model performance

The CPLEX barrier solver requires aggressive scaling in order to converge to a solution, as it otherwise needs to use simplex and this is very slow. Solution time could be improved by optimising the model data for the solver. The principal approach is to remove as many large and small numbers as possible (i.e. $<10^{-6}$ or $>10^{6}$). For example, the dummy import prices could be two orders of magnitude lower without impeding their operation.

When more than one commodity is used by a process, it is good practice to not include a flow share constraint for each of the N commodities as rounding can cause infeasibilities. Instead, include share constraints for only N-1 commodities.

6.6 Quality assurance processes

There has been a strong focus on improving the quality assurance of analytical models in the UK Government in recent years, as exemplified by the recent energy white paper.[11] Their approach is set out in the AQuA book.[12]

The Scottish Government does not have similar formal quality assurance standards. The Scottish TIMES team have adopted a number of processes:

- Model changes are documented in the model input spreadsheets.
- When different team members change the model, the objective functions of each version are compared, differences are identified, and a decision is made on changes to the synchronised version.
- Every user constraint change is checked by a second person.

This is a very good basis for quality assurance. Nevertheless, I encourage the Scottish TIMES team to review the BEIS approach to quality assurance for Excel workbooks.[13] I also recommend that the model is moved to a version control system, such as Git, to better enable model changes to be formally documented and identified, and to enable model branches to be created.

Recommendation: Consider adopting a formal QA system for Scottish TIMES, for example based on the BEIS quality assurance system for Excel workbooks.

Recommendation: Move Scottish TIMES to a version control system such as Git.

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[11] https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future
[12] https://www.gov.uk/government/publications/the-aqua-book-guidance-on-producing-quality-analysis-for-government
[13] https://www.gov.uk/government/collections/quality-assurance-tools-and-guidance-in-decc

6.7 Minimum technical specialist capacity

TIMES is a complex modelling system and new users tend to require a six-month learning curve, in my experience, to usefully use a model. Further experience is needed to understand the intricacies of a sophisticated model such as Scottish TIMES and to implement substantive updates and improvements. If Scottish TIMES is to continue making an important contribution to Scottish energy policy, then sufficient technical specialist capacity will need to be cultivated in order to provide continuity. This is a particularly important consideration when specialists are civil servants that tend to move to new positions frequently.

It has been said that any model needs three specialists working on it at any one time: one learning to use it; one experienced modeller as the foundation of the team; and one that will soon move to a new position. Scottish TIMES has recently been used in some Scottish universities, and this will help to build some wider capacity. However, the transient nature of university research means that it will not provide the core capacity that the Scottish Government will need in the future, and sufficient internal resource will likely be required.

6.8 Coordination with other UK administrations

During this review of Scottish TIMES, I have noted a number of areas in which the UK TIMES and Scottish TIMES teams could benefit for each other's experience. The Welsh and Northern Irish Government departments are also interested in developing a TIMES capacity. It might be useful to convene a cross-governmental group that could:

- Review model structural developments.
- Review new data assumptions.
- Promote good quality assurance processes.
- Discuss and identify best practice for model applications.
- Develop a shared model output analysis system.

Recommendation: *Consider the potential benefits of a cross-governmental energy system modelling group.*

7 Conclusions

The Scottish TIMES energy system model has made a prominent contribution to Scottish Government climate policy in recent years by exploring potential transitions to net zero emissions in Scotland. It is built using the TIMES platform, which is developed by an IEA technology collaboration programme and used in 63 countries. It contains a detailed depiction of all Scottish energy flows and GHG emissions.

I have reviewed each part of the model, carried out a number of diagnostic model runs, and considered areas for future model development. I have made 24 recommendations for the Scottish TIMES team to consider. I particularly encourage a review of model boundary conditions, particularly for electricity trading, and that the emission accounting issues are addressed.

The small number of minor errors and inaccuracies that I have identified are not uncommon in a model of this complexity, and I do not believe they would undermine the key conclusions taken from the model for Scottish policy. It is clear that the Scottish TIMES team have put considerable time into developing the model and keeping the data up-to-date, and have consulted a range of experts as part of this process. Scottish TIMES is a solid and well-designed model, with cutting-edge features in some areas, that is suitable for informing Scottish climate policy when used appropriately.

Report author

Paul Dodds is Professor of Energy Systems at University College London. He has led the development of the UK TIMES energy system model since its inception. He has published a number of methodological papers on energy system modelling, and often represents the UK at the "Energy Technology Systems Analysis Program" (ETSAP) of the International Energy Agency, which is an IEA technology collaboration programme that develops the TIMES modelling system.

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