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Introduction

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Energy futures in Scotland and the UK

Niels Bohr is supposed to have said that prediction is very difficult, especially when it is about the future.

This is certainly true about attempts to understand how the UK energy system might evolve, under the simultaneous pressures of the need for deep reductions in carbon emissions, aspirations for greater energy security, and the imperative to maintain cost-competitiveness and develop new sources of competitive advantage. Add the evolving relationship between Scotland the rest of the UK to the mix, and the boundary between the known and unknown unknowns starts to dissolve. This is the situation into which this Special Issue of the Fraser Economic Commentary seeks to generate some insights.

Thinking through models

It does so by reporting on the results of applying in sequence three very different but sophisticated models.

The first, a mature energy system model developed by University College London's Energy Institute under the auspices of the UK Energy Research Centre (UKERC), plots out different scenarios under which the UK and Scotland, separately or together, could meet their various carbon emission reduction and renewables targets. The energy systems that result from these scenarios turn out to be significantly different in a number of interesting ways that raise important policy issues for both Scotland and the UK.

The energy system model used for the first part of the analysis has only a rudimentary representation of the transmission system, especially that between Scotland and the rest of the UK. Yet this transmission system is known to require reinforcement if Scotland's abundant renewable energy resources, especially in the north, are to be made available to the demand centres in central Scotland and in England. A new transmission system model, developed by the University of Strathclyde, addresses itself to this issue, mapping out the new transmission capacity that will be required for the various low-carbon and high-renewables scenarios generated by the energy system model. The results suggest that none of the scenarios are infeasible from a transmission point of view, though current experience suggests that actually putting in place the transmission infrastructure will present challenges.

Neither new renewables nor transmission capacity comes cheap, but the nature of the expenditures required mean that they can be viewed as both costs and investments. It is clear that even without ambitions for decarbonisation of the power system or the exploitation of Scotland's and the rest of the UK's abundant renewable energy resources, very substantial investment in the UK energy system would be required. The incremental cost of making the new generation infrastructure low-carbon is not insignificant, but it has the advantage of using indigenous and non-depletable energy resources with very low marginal costs of exploitation once the generation and transmission infrastructure has been installed.

Understanding and trying to represent the economic implications of such a transition to a low-carbon energy system is fraught with difficulty, because the outcomes depend so heavily on such imponderables as the world prices of fossil fuels and the rate of technological progress in the various renewable technologies that the governments of both Scotland and the UK are seeking to install.

This is the task undertaken by the third of the modeling exercises reported here, using a model of the Scottish economy also developed by the University of Strathclyde. It has represented the economic incentives for installing renewables through the imposition of a carbon tax through to 2020 such that the 2020 Scottish carbon emissions reduction target is achieved. The model generates a range of insights about the macroeconomic impacts of this, which depend crucially on how the revenues from the carbon tax are recycled. Further differences in economic outcome are revealed by the model depending on whether economic agents anticipate future events, with the results indicating the importance of long-term policy credibility.

Modelling limitations

This Commentary combines the insights of three different models on the same set of issues and the results indicate a rich set of possibilities for the evolution of the energy systems of Scotland and the UK under the impact of policies introduced to meet their governments' carbon emission reduction and renewable targets.

But models are not truth machines. In simplifying complex realities, they often miss out key issues or considerations, and give a crude representation of those they do include. For example, the energy and transmission system models assume that energy systems evolve according to optimality, which they clearly do not. The macroeconomic model can only give a very limited idea of how innovation might drive renewable developments in Scotland, with its possible benefits of new supply chains, increased employment and competitive exports. And none of the models even begin to capture the political complexities around policies for carbon reduction and support for renewable, or around the Scotland/UK relationship, which will be crucial influences on how these issues actually play out.

But even with these limitations in mind, these modelling results shed new illumination on issues that are acknowledged to be of major importance both north and south of the border.

Insights into Scotland's climate and energy policies from energy systems modelling

Will McDowall, Gabrial Anandarajah and Paul Ekins, UCL Energy Institute

Energy system models are powerful tools for examining the dynamics of a transition to a sustainable energy system. Here, we report the first application of a two-region version of the UK MARKAL energy system model that explicitly represents Scotland and the rest of the UK as distinct regions. We use this model to examine the implications of Scotland's carbon and renewable energy targets, in the context of the targets legislated for the UK as a whole.

Climate and renewable energy targets in Scotland and the UK

Both the UK and Scotland have legislated long-term targets for the reduction of greenhouse gas emissions. Through the Climate Change Act (2008) the UK has committed to reducing emissions by 80% from 1990 levels by 2050, with an interim target of 34% by 2020. In Scotland, the Climate Change (Scotland) Act 2009 sets out a similar target of 80% by 2050[1] and a deeper 2020 target of 42%.

Renewable energy is an important means of reducing emissions, and both the UK and Scotland have established renewable energy targets, both to drive emissions reductions and because renewable energy is associated with other benefits. Under the European Renewable Energy Directive, the UK has signed up to a target that 15% of final energy must be renewable by 2020, across heat, power and transport. This is likely to mean that at least 30% of UK electricity must be renewable by this time. Scotland's targets are more ambitious, aiming to produce renewable electricity equivalent to 100% of Scottish electricity consumption in 2020.

In this modelling exercise, we examine the implications for the Scottish energy system of both UK and Scottish climate and renewable energy targets.

Modelling Scotland's energy system: development of two-region MARKAL

The UK MARKAL model is a well-established analytic tool that has been used to support a number of UK energy policy processes, including the 2003 and 2007 Energy White Papers and the Committee on Climate Change's suggested carbon budgets and the government's responses to them. MARKAL was developed by the International Energy Agency in the 1970s, and the UK version of the model was mainly developed by the modelling team now at the UCL Energy Institute in the years since 2003 as part of the work programme of the UK Energy Research Centre (UKERC), building on an earlier version of the model, which was also used for policy analysis.

MARKAL is an optimization model of the entire energy system. It includes explicit representation of the UK's energy resources (such as oil and gas, and bioenergy resources), imports, and over 5000 technologies including conversion and processing technologies (power stations, refineries etc), infrastructures (gas and electricity grids) and end-use technologies (spanning vehicles, household appliances, industrial energy use, and energy-efficiency measures). The model is given a set of forecasted energy service demands, and it calculates the least-cost[2] way of meeting those demands based on the technologies and resources available in the model database, subject to constraints such as carbon targets.

The two-region version of the model was developed by disaggregating UK MARKAL into two regions: Scotland and 'rest of the UK'. Data on the Scottish energy system was largely derived from the Scottish Energy Study (Scottish Government, 2006). The model is described in more detail in working papers on the UKERC website[3], while more details of the modelling work reported here are contained in a paper that is currently being reviewed for publication in an academic journal.

Results: Carbon targets

We ran a scenario in which the UK meets UK-wide carbon targets[4] at least cost. In this scenario, Scotland reduces emissions faster and deeper than the rest of the UK, making reductions beyond both UK and Scottish 2020 targets (See Figure 1). Adding Scotland's targets as an additional constraint on the model makes no difference to the decarbonisation trajectory of either region, as the Scottish target is satisfied when the model meets UK targets at least cost. Our results therefore suggest that Scotland's emissions targets may not imply any additional abatement activity beyond that which would be required if the UK were to meet UK-wide targets in the most cost-effective way.

The cheaper abatement opportunities in Scotland arise partly because of planned closure of existing fossil fuel plant (such as Cockenzie power station, due to close in 2013), and partly because Scotland has a large portion of the UK's lowest cost renewable energy potential. Cheap early abatement in Scotland in the model is also in part a result of our allocation to Scotland of offshore oil and gas resources and emissions, which are in decline (see 'upstream' emissions, which include emissions from offshore oil and gas, in Figure 2)[5].

Figure 1: Shows the emissions pathways for Scotland, the rest of the UK (England, Wales and Northern Ireland), and the UK as a whole to meet UK and Scottish targets. 100 = 1990 emission levels

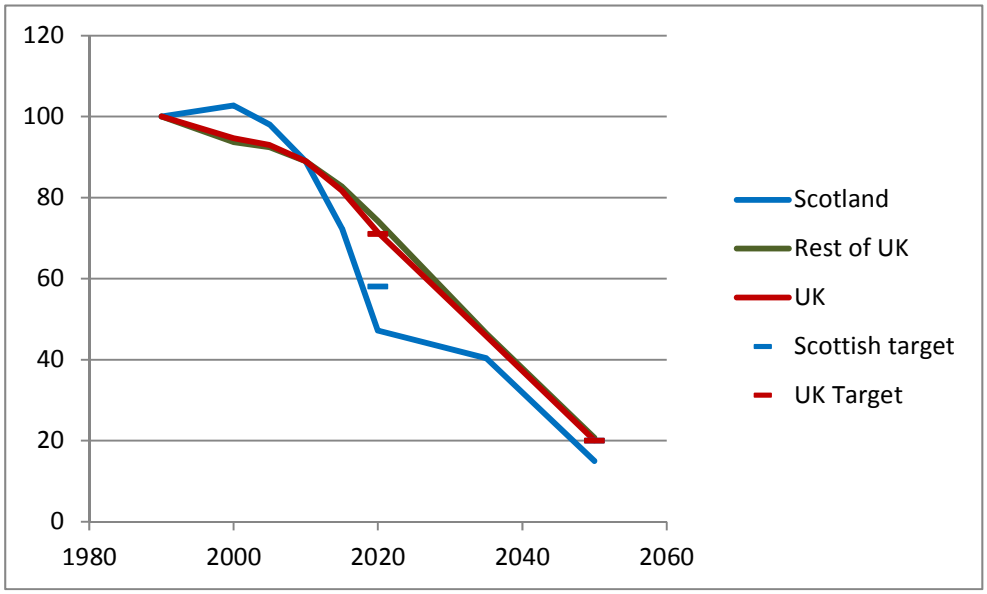
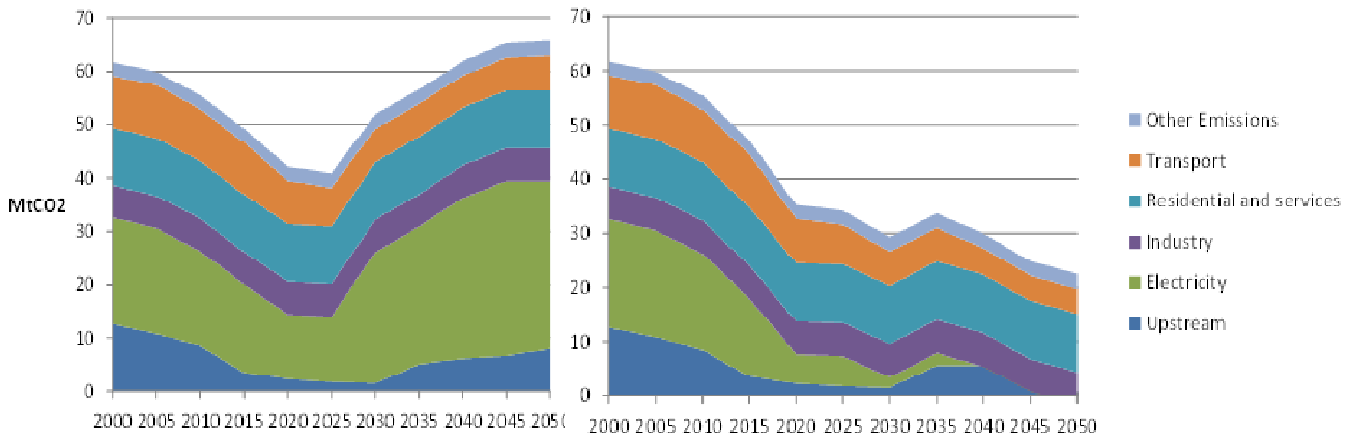


Figure 2. Scottish CO2 emissions in the reference case in which no carbon targets are applied (left panel) and the low-carbon case (right panel)



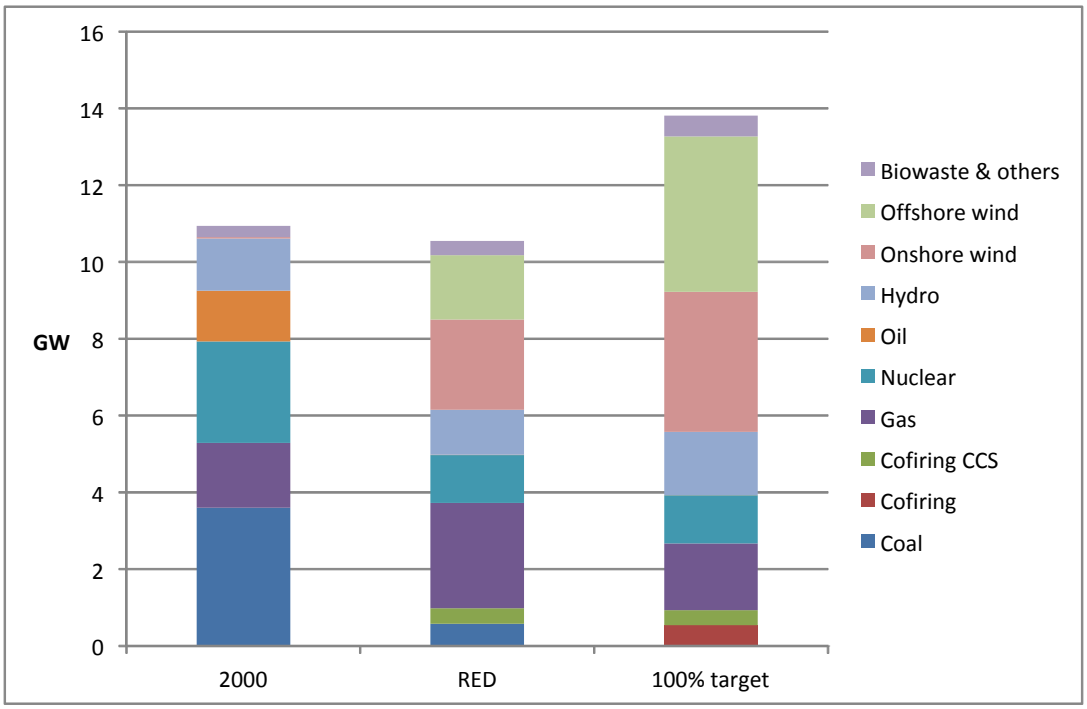
Results: Scotland's renewable targets

We ran two scenarios to examine the implications of renewable energy targets in Scotland. First, we ran a scenario in which the UK meets its obligations under the Renewable Energy Directive (RED) at least cost, with the model free to deploy renewable energy in Scotland or the rest-of-the-UK depending on where the cost is lowest. Second, we ran a scenario that meets the RED targets and also meets Scotland's 100% renewables target. Both of these scenarios are also required to meet carbon targets.

The effects of Scotland's targets on the Scottish power generation mix in 2020 are shown in Figure 3. From the figure, one can see that the 100% target drives greater uptake of both onshore and offshore wind compared to the RED scenario, and also drives replacement of coal generation with biomass co-firing.

In the RED scenario the proportion of renewable energy in Scotland as a share of Scotland's final electricity consumption is 55%. This clearly misses Scotland's 100% target. In the second scenario we require the model to meet Scotland's 100% target, in addition to meeting UK-wide RED targets. The result is that there is no increase in overall renewable energy across the UK. Instead renewable energy investment and deployment is shifted from the rest of the

Figure 3: Installed power generation capacity in Scotland in the year 2000, and in two 2020 scenarios. In the RED scenario, the UK deploys renewable energy at least cost to meet the UK's obligations under the Renewable Energy Directive. In the 100% target scenario, Scotland produces renewable electricity equivalent to 100% of its consumption



UK to Scotland. Requiring the model to meet Scottish renewable energy targets in addition to UK RED targets adds to the overall costs of the energy system, equivalent to a total discounted cost of about £15 per person in the UK, assuming that the additional costs are spread across all UK consumers.

An important assumption underlying this finding of higher costs is that the policy actions of the Scottish government make no difference to the actual installed costs of renewable energy. It does not take into account, therefore, the fact that a more favourable planning system in Scotland for onshore wind, for example, could reduce the costs associated with renewables deployment. Nor does it account for the possibility that, with the higher targets in Scotland, the renewables supply chain there might develop and reduce its costs more quickly. Either of these factors could reduce the costs we have calculated.

Note also that the model does not take into account the possible political constraints on actually installing the lowest-cost renewables in the UK, much of which is onshore wind in England. It is very possible that it will not prove politically feasible to harness much of this resource, in which case the extra installed capacity in Scotland driven by the Scottish renewables targets may make a crucial difference as to whether the UK-wide renewables targets are met or not, or the degree by which they are missed.

Insights for policy

The scenarios examined in this work have generated two principal findings. First, we find that Scottish carbon targets do not lead to additional abatement beyond that which is required under a least-cost path to meeting UK targets. Second, we find that Scotland's renewable energy targets lead to a shift in investment and deployment from the rest of the UK to Scotland, leading to a higher overall cost for the UK as a whole. We discuss the implications of each of these in turn.

Since Scotland reduces emissions beyond its own targets under a scenario constrained only by the UK targets, one might be tempted to draw the conclusion that Scotland's targets are unnecessary. However, we believe that would be a mistake. The value in Scotland's targets is not necessarily that they drive additional effort over and above that which should be happening in response to UK-level targets, but that they play a supporting role, augmenting action to meet the UK target. Several authors have noted the additional value of complementary targets within a multi-level governance regime (e.g. Goulder and Stavins 2010), arguing that complementary targets strengthen investor confidence in future carbon constraints, and bolster the political consensus on the need for action. In the context of Scottish carbon targets, Reid (2009) argues that it was the ambition of Scotland that led to the stringent UK-level carbon targets, highlighting the important role that

Scotland's carbon targets have played even if they can be described as less ambitious in terms of the marginal abatement costs of meeting them, as our model suggests.

The situation with renewable targets is different. Unlike with carbon targets, Scottish renewable energy targets do require additional deployment in Scotland over and above that which would occur in a least-cost pathway to the UK's Renewable Energy Directive target. This additional deployment in Scotland results in additional costs for the UK as a whole, equivalent to a total discounted cost of around £15 per UK citizen. Current policy and market structures mean that this additional cost would be borne by consumers across the UK. We have noted that it is possible that the model overstates the size of this additional cost, because it ignores the fact that the target is accompanied by other efforts to encourage renewable energy which may decrease the costs of deployment (such as streamlined planning approvals). However, assuming that this finding of additional costs is real, one might ask why UK consumers should pay for renewable energy deployment to be focused in Scotland.

One possible justification is that Scottish renewable targets provide greater investor confidence, and in doing so they make it more likely that the UK will actually meet its RED targets. The model does not take into account the possibility that the UK may fail to meet its targets, but in reality we know that this is possible, and perhaps even likely. Given the on-going resistance in many parts of the UK to deployment of onshore wind, one might argue that Scotland's targets act as insurance against the risk that the rest of the UK will fail to deploy renewable energy fast enough to meet targets. Note that failure to meet targets is not cost-free. Aside from the implied political cost of missing statutory targets, and the environmental cost if this results in higher emissions, the European Commission may apply financial penalties to member states that fail to live up to their commitments.

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Endnotes

[1]The Scottish target has a broader scope than the UK target, e.g. it includes international aviation and shipping.

[2]The cost that the model minimizes is the total discounted energy system cost. This is the discounted stream of all the fuel costs, investments and operating and maintenance costs required to meet energy service demands from 2000-2050.

[3]See http://ukerc.rl.ac.uk/UCAT/cgi-bin/ucat_query.pl?URadio=P_12&GoButton=Find+Publications

[4]We conducted this analysis before the Government's response to the fourth carbon budget, and hence the model results reflect targets in 2020 and 2050.

[5]In our model, allocation of offshore oil and gas resources, and hence emissions, follows that in the Scottish Energy Study, i.e. resources are allocated to the region in which they are landed. However, in the real world emissions occurring in the UK Continental Shelf are not allocated to Scotland, and reductions here thus do not count towards Scottish targets. Our allocation of emissions was necessary for this work because of the way in which offshore activities are represented in the model, but the result is an overstatement of the ease with which Scotland meets its 2020 carbon targets. However, we believe this overstatement does not affect the overall finding that Scotland meets targets in a UK least-cost decarbonisation scenario.

Network reinforcement requirements for Scotland and the rest of the UK (RUK) – and possible solutions for this

Malcolm Barnacle and Graham Ault, Strathclyde University, Institute of Energy and Environment

A novel multi-objective transmission expansion planning (MOTEP) tool has been developed to analyse, on a comprehensive geographical scale, the reinforcements required to a base case electrical transmission network following application of a chosen future energy scenario, and to generate optimal network expansion plans, designed to alleviate these areas of strain, for a range of crucial network planning objectives. Here, we report the application of the MOTEP tool to a base case predicted 2014 GB transmission network (thereby including already planned reinforcements such as the Beauly to Denny line) under heavy strain from three 2020 energy scenarios developed by the two-region UK MARKAL energy system model. Reinforcement requirements for Scotland and the RUK beyond 2014, along with optimal network expansion plan options, are examined.

A snapshot of the current situation of the GB transmission network

At present the GB transmission network is under strain where there are no generation connection opportunities in Scotland, Wales or the North of England (National Grid, 2009) and as such there is a need for major transmission reinforcement in these areas. The predominant power flow in mainland GB is from net generation in the North (Scotland) to net demand in the South (England) and this is going to increase as wind farms are connected in the North where there is a more abundant fuel source. This net southerly flow is currently across transmission circuits that are already operating at their maximum capability (ENSG, 2009), hence, the GB transmission network needs to be reinforced and expanded to accommodate increased renewable generation penetration needed to achieve the CO2 emissions target of a 34% reduction by 2020. Parallel to the emissions objectives, for 2020 and 2050, future network developments need to be planned optimally in order to reduce grid connection charges and consumer electricity bills.

Construction has already begun on the crucial 220km, 400kV, 4740MVA capacity overhead line between Beauly and Denny in Scotland with expected completion in 2014. This is a major reinforcement to enhance network capability for the future connection of renewable energy in the North of Scotland (6,176MW capacity of accepted renewable generation is awaiting the inclusion of the Beauly to Denny line for grid connection (Scott, 2009)). Although the inclusion of this reinforcement, along with other planned reinforcements by 2014, greatly alleviates network strain, there is no cast iron network plan beyond 2014 to achieve the 2020 emissions target.

The newly developed MOTEP tool is implemented here for three 2020 scenarios; the low carbon scenario (LCS), the renewable energy directive scenario (RED) and the RED scenario including the Scottish 100% renewables target (RED & 100%). The generation mix for each scenario was generated via the two-region UK MARKAL model.

The MOTEP tool

The MOTEP tool has recently been developed to apply a future electricity supply generation mix to a base case transmission network for creation of an optimal set of expansion plans to resolve predicted areas of network strain. Each expansion plan is evaluated against five key objectives in transmission planning for analysis into the objective trade-offs of each plan. Over successive generations of optimisation inside a genetic algorithm, expansion plans are created before being assessed on these objectives for whether each plan can continue into the next generation of solutions or be scrapped due to poor fitness in relation to the other plans. The MOTEP tool therefore uses an iterative optimisation process until a final set of expansion plans is obtained where each plan on this set is optimal, for the multi-objective problem, in its own unique way. This complex multi-objective optimisation, among often conflicting goals, is preferred to a linear cost optimisation for better understanding of the problems likely to be faced in the future, and the difficult decisions required to be made in regard to these trade-offs. Further multi-objective analysis allows for trade-offs to be made between cost and non-cost objectives. The five key objectives chosen for plan evaluation are:

- Network Investment Cost (total capital cost of the transmission plan using build and upgrading costs);
- Network Constraint Cost (total constraint costs saved by the transmission plan under peak and base demand conditions using an optimal market analysis program);
- Outage Cost (total cost of outages needed to accommodate the plan construction);

- Transmission Losses (MW's saved from 'variable' I2R heating losses); and

- Minimum CO2 emissions intensity (from a network capability assessment of each plan's ability to cope with increasing levels of renewable generation).

The MOTEP tool is novel in its use for full spatial analysis of a realistic multi-voltage transmission network. Due to the large scale network base case used, the MOTEP tool employs a static DC power flow simulation of the network at peak demand. This means that the focus of MOTEP lies with active power planning where each expansion plan generated must adhere to thermal line limits (MVA line capacity) but not to voltage and reactive power limits associated with an AC power flow. Due to the study occurring at peak demand, this also means that each generated plan must adhere to the deterministic security criterion of N-1 (loss of one circuit component) and N-D (loss of a double-circuit component).

The MOTEP tool is also novel in its creation of a transmission expansion plan. The MOTEP tool includes two methods for reinforcement and/or expansion of a thermally overloaded line. The first method is through the addition of a line by adding either a single circuit or double circuit configuration. The second method is by upgrading the existing line through re-conductoring, adhering to pre-defined voltage level line capacity limits. The inclusion of line upgrading in the plan creation process is crucial to allow a minimum capital investment cost for each generated expansion plan to be achieved due to the reduced associated cost of re-conductoring compared to line addition.

More details regarding the MOTEP tool are contained in a paper that is currently being reviewed for publication in an academic journal.

Results: Areas of network strain under all three scenarios and optimal expansion plan solutions

Here the three scenarios of LCS, RED and RED & 100% are applied to a predicted 2014 GB transmission network base case that includes the Beauly to Denny line amongst other expected network reinforcements and expansions. A maximum line load condition that a power flow must not exceed before being treated as an overload was set to 84% of the line capacity. This line load condition percentage was determined from a DC power flow peak demand study of the 2009 GB transmission network. It was found that no power

Table 1: Shows the location and severity of thermal overloads for each scenario as modelled by MOTEP The zones refer to Figure 1

Zone	Line (node 1 – node 2)	Overhead Line / Underground Cable Length (km)	Voltage (kV)	Line Capacity (MVA)	Overload Percentage (%)
LCS Scenario base problem					
5	442 – 739	5.72 / 0	132	132	103.87
9	222 – 262	11.32 / 0.32	400	2090	86.97
15	36 – 782	18.69 / 0.5	275	860	90.55
18	276 – 781	34.91 / 0	400	1560	84.32
RED Scenario base problem					
5	442 – 739	5.72 / 0	132	132	97.15
9	222 – 262	11.32 / 0.32	400	2090	85.03
11	657 – 898	35.78 / 0.17	400	1160	100.54
13	897 – 898	0 / 5.71	400	1220	95.59
13	818 – 897	9.94 / 0.43	400	1160	100.54
14	685 – 755	43.3 / 0	400	2150	84.74
15	36 – 782	18.69 / 0.5	275	860	89.36
RED & 100% Scenario base problem					
4	658 – 871	0 / 3.7	132	120	84.85
5	442 – 739	5.72 / 0	132	132	117.59
11	657 – 898	35.78 / 0.17	400	1160	98.56
13	897 – 898	0 / 5.71	400	1220	93.72
13	818 – 897	9.94 / 0.43	400	1160	98.56
15	36 – 782	18.69 / 0.5	275	860	85.6

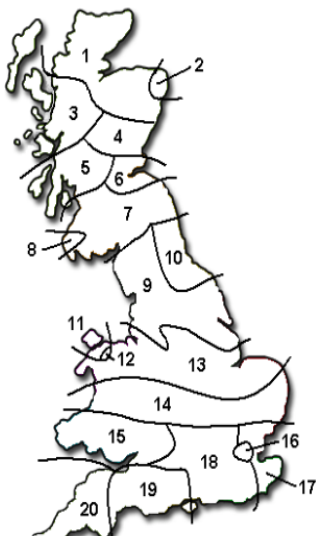

Figure 4. Generation use of system tariff zones used in 2009.

flow exceeded 84% of the associated lines capacity, therefore this was set as the condition required of the GB transmission network in 2020. The areas of network strain determined by MOTEP for all three scenarios are detailed in Table 1.

It appears from Table 1 that the LCS scenario requires the least network reinforcement of all three scenarios with only 4 lines failing the pre-set line load condition. The RED and RED & 100% scenarios require a similar level of reinforcement (RED has one more overload), however the RED & 100% scenario requires two reinforcements in Scotland as opposed to just one. All other network reinforcement requirements are located in central England and in the North and South of Wales. The Welsh overloads are due to the predicted location of new onshore wind farm developments in these areas, added to achieve RUK scenario targets. It is clear from Table 1, when observing the severity of the overloads and the length of these strained lines, that there is not a significant amount of reinforcement required to the 2014 GB transmission network in order to cater for the three 2020 scenarios. Nonetheless, a multi-objective optimisation was carried out by MOTEP to locate and assess a set of optimal network expansion plans for all three scenarios. Allowance was made for the possibility of connecting a double-circuit line and a single-circuit line to an existing route, enabling a wide range of line addition/upgrade combinations for each thermally overloaded line, thereby enabling the exploration of a wide range of expansion plans.

All generated expansion plans are designed to fully eliminate 2020 network constraint costs at peak demand for all three scenarios. MOTEP has calculated that during a one hour simulation at peak demand in 2020 a constraint cost saving of £725 for the LCS scenario, £1219 for RED and £3288 for RED & 100% can be achieved by full reinforcement. The extent of this saving (particularly for the RED & 100% scenario) under this one hour operational setting, provides a good further incentive for continued network expansion beyond 2014 when considering the lifespan of new transmission assets. The constraint cost at base demand was found to be zero for all three scenarios, without the need for reinforcement. Hence the base demand constraint cost could not be included in the multi-objective analysis. Figure 2 details the output from the multi-objective analysis of the most demanding scenario RED. Table 2 shows the most interesting optimal expansion plans from this multi-objective analysis.

Figure 2: The multi-objective analysis output of the RED scenario as modelled by MOTEP

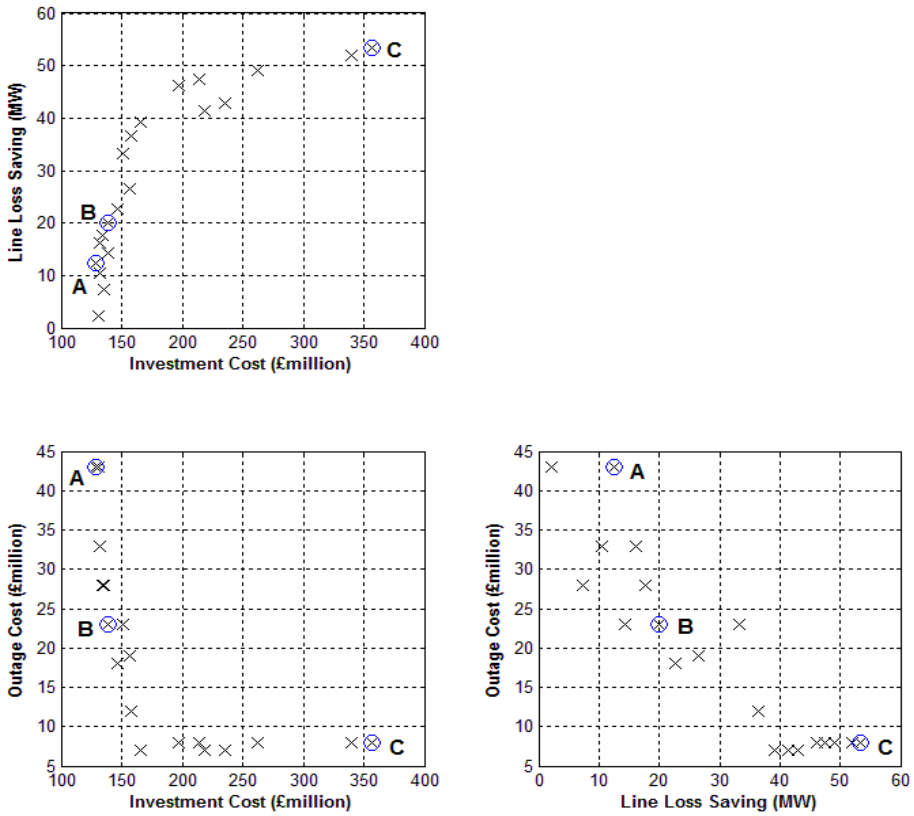

Table 2: Shows the three most interesting optimal expansion plans from the multi-objective analysis detailed in Figure 2. The circuit layout of the plan along with the objective evaluations is detailed

Expansion Plan	No. of Double-circuits / Single-circuits / Upgrades	Capital Investment Cost (£million)	Outage Cost (£million)	Line Loss Saving (MW)	Minimum CO2 Emissions Intensity (g/KWh)
A	2 / 1 / 4	128.54	43	12.44	320.47
B	4 / 1 / 2	138.72	23	19.96	274.89
C	5 / 4 / 1	356.42	8	53.34	314.88

From table 2 it is clear that expansion plan B is a good option for the RED scenario. Expansion plan A has the lowest investment cost but comes with a large outage cost. The increase in around £10 million in capital investment for plan B comes with a £20 million reduction in outage cost from plan A. Further plan B has a low CO2 emissions intensity, according to the objective evaluation, which suggests a good location of transmission assets for future grid connection of large scale renewable generation.
Concluding Statements from the MOTEP tool analysis

MOTEP's analysis shows that only one reinforcement, on a small 6km overhead line, is required beyond 2014 for Scotland's electrical transmission network to cope with the 2020 LCS and RED scenarios. An added reinforcement on a 4km underground cable is required for application of the RED & 100% scenario. All other expansion requirements are located in central England and southern Wales. The minimum capital investment cost required for an expansion plan, to eliminate thermal overloads and maintain current deterministic security criterion, for the RED scenario is £128 million. This is around 3 times greater than the minimum capital cost of an expansion plan for the LCS scenario. It is clear that according to the MOTEP tool simulations, all three 2020 scenarios require minimal network reinforcement beyond the predicted 2014 GB transmission network. The largest capital investment for an expansion plan occurred in the LCS scenario simulations; £475.5 million. This would still represent a modest investment on top of the now predicted £600 million capex for the proposed Beauly to Denny line. This is due to the short line route lengths and low thermal line ratings of the new MOTEP proposed lines for required expansion beyond 2014. The longest and largest line requiring reinforcement, which occurs under the RED scenario (see Table 1), is a 43.3km line rated at 2150MVA. This is over half the capacity rating of the proposed Beauly to Denny line and a fifth of the line length.

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The impact of the introduction of a carbon tax for Scotland

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Introduction

Since devolution, the Scottish Government has progressively adopted a distinctive environmental and energy policy (Allan *et al*, 2008). This is expressed in two forms: first through setting emissions and renewables targets that differ from those set in the rest of the UK, and second by developing specific policies within the non-reserved powers at its discretion.

The Climate Change (Scotland) Act includes a target to reduce CO2 emissions to 42% below 1990 levels by 2020. This is stricter than the 34% CO2 emissions reduction adopted by the UK Government. Moreover, the corresponding Scottish Government target for renewable electricity generation in 2020 is equivalent to 100% of electricity consumption in Scotland and preliminary data suggest that the interim 2011 target of 31% was exceeded by 4 percentage points.

The powers under the Scottish Government's control that it can use to affect energy outcomes include the judicious use of the planning system and additional funding for alternative renewable technologies in pre-commercial scales, such as the Wave and Tidal Energy Scheme (WATES), The Saltire Prize, and the Scottish Community and Households Renewables Initiative.

Nevertheless, the Committee on Climate Change report into Scottish emissions targets concluded that with current policies and the current cap on emissions under the EU ETS, the Scottish Government's target of a 42% CO2 reduction will be missed, with emissions only falling by 38% on 1990 levels.

It is clear that whilst Scotland has adopted challenging targets, many key policy instruments are reserved to the UK Government (Allan *et al*, 2008; McGregor *et al*, 2011). At present the main "green" elements of the tax system remain under Westminster control. This includes fuel duties, air passenger duty and the climate change levy. Also reserved to the UK Government are: the tax-transfer system; powers over the structure of the electricity market; Renewable Obligations Certificates, the Renewable Transport Fuels Obligation and the Renewable Heat Incentive; Climate Change Agreements; and the Carbon Reduction Commitment.

Many economists regard a carbon tax as the most efficient way to reduce carbon emissions (Tullock, 1967; Pearce, 1991). It is therefore of interest to consider the possibility of the Scottish Government's adopting such a tax. This is particularly relevant given the present discussions concerning fiscal autonomy that are taking place around the Scotland Bill and the impending independence referendum in Scotland. In this paper we use an energy-economy-environmental model of Scotland to simulate the impact of a Scottish specific tax on carbon emissions. The model quantifies the effect on carbon emissions and the level of aggregate economic activity in Scotland.

Section 2 outlines the arguments for a carbon tax and introduces the notion of the double dividend. Section 3 briefly describes the Scottish simulation model that we use. Section 4 gives the specific simulation set up. Section 5 reports the simulation results and Section 6 is a short conclusion.

General arguments for carbon tax

Firms, households and governments generate emissions of CO2 that impose a cost on present and future generations in the form of global climate change[i] However, those who directly emit CO2 do not directly bear the cost of their own emissions. That is to say, they are not forced specifically to take these costs into account when they make production and consumption decisions. These costs are known generically as externalities and the notion that they can be internalised by the governments' setting a tax equal to the marginal cost imposed on others was first suggested by Pigou (1920). Coase (1960) persuasively argues that imposing appropriate property rights can also solve this problem. In this case, the owners of the right to pollute the atmosphere would charge for allowing individuals and organisations to emit CO2. This is the basis for the use of tradable permits for controlling emissions. However, the principles behind carbon taxes and carbon trading are fundamentally the same[ii]. A price should be set for emitting carbon, either through a specific tax or the requirement to acquire a permit.

Essentially, the arguments that favour treating externalities in this way are similar to those that favour the use of free markets in general. They are an effective means of decentralised decision making. In this specific case, the government has set targets for the level of carbon emissions. However, this decentralised approach should lead to these targets being met at minimum cost in terms of consumption foregone. Setting a price on carbon emissions generates an appropriate set of incentives: individual governments, firms and consumers can decide how best to adjust to the increase in price. If there are possibilities to reduce the inputs of carbon then it is optimal for agents to

seek out and implement these reductions. Therefore firms will seek to adopt less emission intensive production techniques. The price of products that embody carbon emissions will rise. Therefore consumers will tend to consume less of these products. There is an increased incentive for technical change that involves reducing carbon emissions in the future. Therefore more resources will be channelled into generating sustainable technologies.

However, there is an additional potential benefit from the use of carbon taxes. Carbon taxes (or tradeable permits, if owned by the state) are sources of revenue for the government[iii]. This additional revenue can be used to reduce other taxes that generate distortions in the operation of the economy, thereby producing a so-called 'double dividend'. Here, not only are CO2 emissions reduced (the first dividend), but the efficiency with which other elements of the economy operate can be simultaneously improved (the second dividend). There is an extensive literature concerning the possible nature of this second dividend and the conditions under which it exists[iv]. The most popular formulation suggests a cut in the taxes on employment. The reduction in the price of labour to the firm produces a net reduction in costs to labour intensive firms, and encourages the substitution of labour for other inputs in all production. This may increase employment and in almost all economies such labour market improvements are highly valued, particularly under present circumstances.

Table 1: Impact of implementing a £50 per tonne carbon tax in Scotland on key macro-variables: Percentage change from base year values

	Externally recycled		Internally recycled Public expenditure		Internally recycled Income tax	
	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run
CO2 Emissions	-32.66	-39.34	-32.55	-38.84	-31.83	-37.49
GDP	-0.30	-2.68	-0.14	-1.37	0.26	0.83
Unemployment Rate	4.08	0.00	1.79	0.00	-3.77	0.00
Total Employment	-0.45	-2.60	-0.20	-1.27	0.42	1.06
Nominal Gross Wage	-0.60	0.81	0.24	0.81	-0.88	-1.43
Real Wage After Tax	-0.45	0.00	-0.20	0.00	0.43	0.00
Replacement Cost of Capital	-0.26	0.63	0.50	0.63	0.07	-0.36
Labour Supply	0.00	-2.60	0.00	-1.27	0.00	1.06
Household Consumption	-0.90	-1.68	-0.56	-0.87	1.18	1.45
Govt. Consumption	-	-	4.66	3.97	-	-
Income Tax Rate	-	-	-	-	-6.16	-5.37
Capital Stock	0.00	-2.82	0.00	-1.53	0.00	0.40
Export	0.14	-1.23	-0.55	-1.23	-0.29	0.05

The AMOS model for Scotland

In this paper we explore and quantify the impact of introducing energy taxation to reduce carbon dioxide (CO2) emissions in Scotland. To do this we use AMOSENVI, a multi-sectoral energy-economy-environment computable general equilibrium model for the Scotland developed for policy analysis by the Fraser of Allander Institute. The model has 17 industry sectors: 13 are energy sectors, of which 9 are forms of electricity generation. Production is characterized by cost minimization with standard, well-behaved production functions. Firms sell output in competitive markets and household consumption is dependent on the population level, average income and consumer prices. In the simulations performed here wage setting follows a bargaining procedure where the real wage is inversely related to the unemployment rate.

When the model is run in a period-by period mode, the population and the capital stock are upgraded between periods. We incorporate flow equilibrium migration, where net immigration is positively related to the Scottish real wage and negatively related to the unemployment rate. Investment is determined by profit maximizing behaviour, with an assumed internationally integrated capital market. The model can be solved in either myopic or forward-looking mode. In the first case agents use adaptive expectations so that they abstract from future periods, while in the second case firms and consumers have perfect foresight and react optimally to anticipated future events. Except where explicitly stated the model is run here with perfect foresight.

Simulation set up

The simulations impose a tax on carbon emissions generated in production. This is achieved by introducing an

Figure 1: The short and long-run percentage change in sectoral output for a £50 per tonne tax on CO_2 emissions with revenue recycling through a reduction in income tax

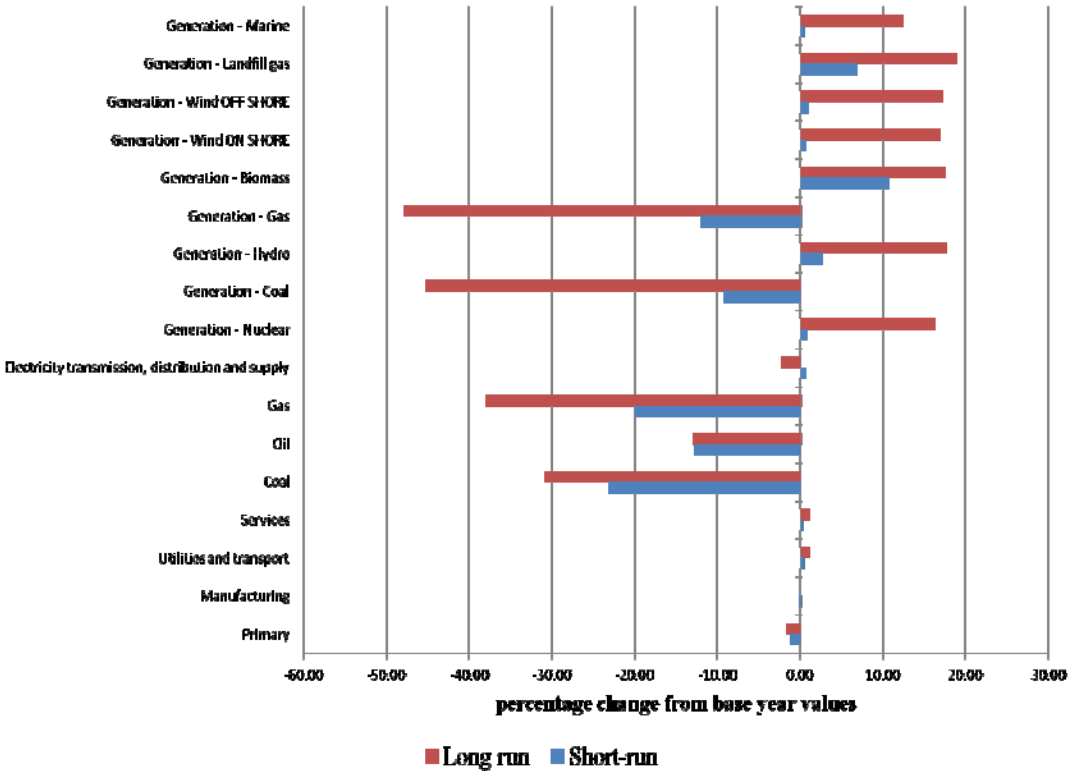
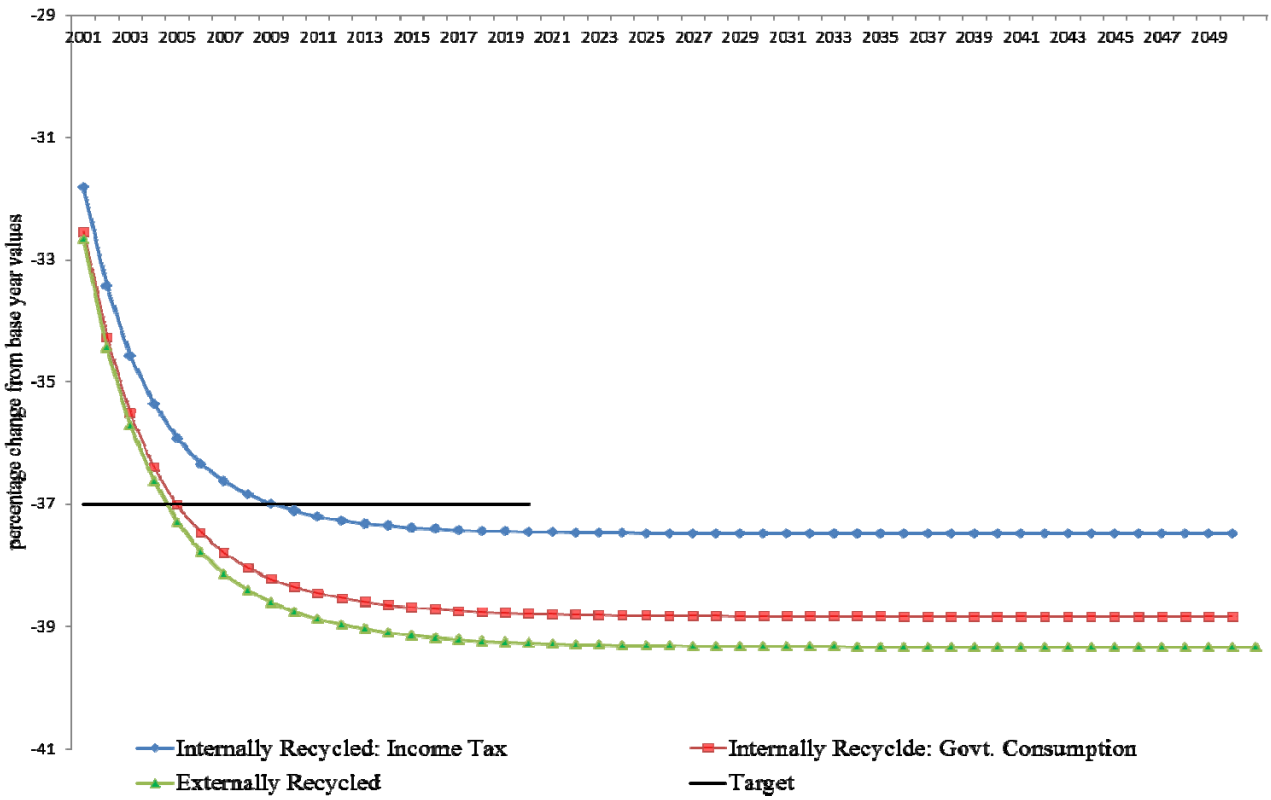


Figure 2: Change in total CO2 emissions for a £50 per tonne tax on carbon emissions for all three forms of revenue recycling



differentiated according to the carbon content of each fuel. The tax is imposed in the first period and maintained at a constant rate. The model is run forward with no other changes until we reach a new long-run equilibrium.

The tax generates revenue for the public sector. We run three simulations that differ in the way in which these funds are recycled. In one simulation the revenues revert to the UK Government and are spent outwith Scotland. In the other two simulations, the funds are used in Scotland. In one the revenues are recycled through an expansion in government expenditure. In the other the revenues are used to reduce the tax on labour.

The Scottish Government's target is to reduce CO2 emissions by 42% in 2020, compared to the total in 1990. Our model is calibrated for the year 2000. Because there had already been some reduction in emissions in the decade leading up to 2000, to achieve the Scottish target requires a 37% reduction of CO2 emissions in the 20 years to 2020. By trial and error, simulation indicates that the target can be met by a carbon tax of £50 per tonne of CO2.

Simulation results

Table 1 reports results for key economic variables for the simulations with each of the three forms of revenue recycling. Figures are presented for the short and the long run. The short-run results give the impact in period one. In this period capacity constraints are imposed so that both capital and labour supplies are fixed to their base-year value. The long-run results apply where all supply constraints are relaxed, so that both capital and the labour supply are free to adjust totally. In all three cases the introduction of the carbon tax is able to substantially reduce CO2 emissions. The 37% CO2 reduction target is met with a very rapid adjustment even in the first period. However, the impacts on the aggregate activity variables, GDP and total employment, are much smaller and their sign depends on how the tax revenues are recycled.

Where the tax revenue is externally recycled the carbon tax clearly has a depressing effect on the Scottish economy. The cost of fuels used in production has increased and this has a contractionary impact. Initially this contraction is generated by a fall in household consumption, and there is actually some crowding in of exports. However, in the long run there is an increase in nominal wages as workers attempt to maintain their real wages and exports fall, together with household consumption, as competitiveness is reduced. The GDP decreases by 0.3% in the short run and 2.68% in the long run. Employment initially declines by more than GDP, as labour is more flexible than capital in the short run, thereby producing a short-run rise in unemployment of 4.1%. But the impact of outmigration, triggered by the adverse local labour market conditions, means that in the long run the unemployment rate moves back to its original level. However, in this time interval the labour force, and therefore also employment, has been reduced by 2.6%, just less than the fall in GDP.

For the case where revenues are recycled through increased Scottish Government expenditure, the net effect on aggregate economic activity is again contractionary. In this simulation there is an increase in public expenditure of 4.66% in the short-run and 3.97% in the long-run, funded by the additional carbon tax revenues. However, this expenditure stimulus is not able totally to offset the negative supply side effects of the increase in energy taxation. In this case the long-run fall in GDP and employment are 1.37% and 1.27% respectively. The increase in public spending only goes some way to mitigating the adverse supply side effects of the tax. However, it is important to remember that in this case the Scottish population do benefit from an increased supply of public goods.

A qualitatively different outcome for the overall economy is obtained if the carbon tax revenues are used to reduce the tax on labour. In our model this takes the form of a reduction in income tax, which falls in both the short and the long run by 6.16% and 5.37% respectively. This would be within the range of income tax variation proposed in the Scotland Bill. The net impact on the Scottish economy is positive, resulting in an increase in GDP and household consumption in both time periods. The expansion in economic activity reduces unemployment in the short run by 3.77%. The resulting immigration increases the labour supply, again pulling the real wage and the unemployment rate back to their base year value.

This result indicates that under the circumstances assumed in this simulation, the implementation of such a revenue-neutral set of tax changes not only reduces CO2 emissions but also stimulates economic activity and jobs. Employment increases by 0.42% in the short run and 1.06% in the long run. In this scenario the percentage change in employment is greater than the percentage change in GDP in both of the time frames shown here. The increase in the real wage in the short run stimulates household consumption, with some crowding out of exports. However, in the long run nominal wages fall, with the labour supply and competitiveness rising, so that increased household consumption and exports drive the expansion in the economy.

In Figure 1 we report the short and the long-run changes in sectoral output where the revenue is recycled through reduced income taxes. Of course the introduction of the carbon tax directly increases the price of coal, oil and gas when these are used as an input in production. The demand for these fuels falls, reducing dramatically their production and import levels. Electricity supply increases in the short run, as a result of the small increase in economic activity. However, in the long run, when there has been a full adjustment to the new prices, electricity supply falls. There is, however, a significant increase in electricity generated from renewable energy. The share of electricity generated by renewables increases in the long run by slightly more than 42%, reflecting also the large fall in output in the coal and gas electricity generation sectors. As for the non-energy

Figure 3: % reduction in total CO2 emissions for a £50 per tonne tax with revenue recycling through a reduction in income tax. A comparison between myopic and perfect foresight agents

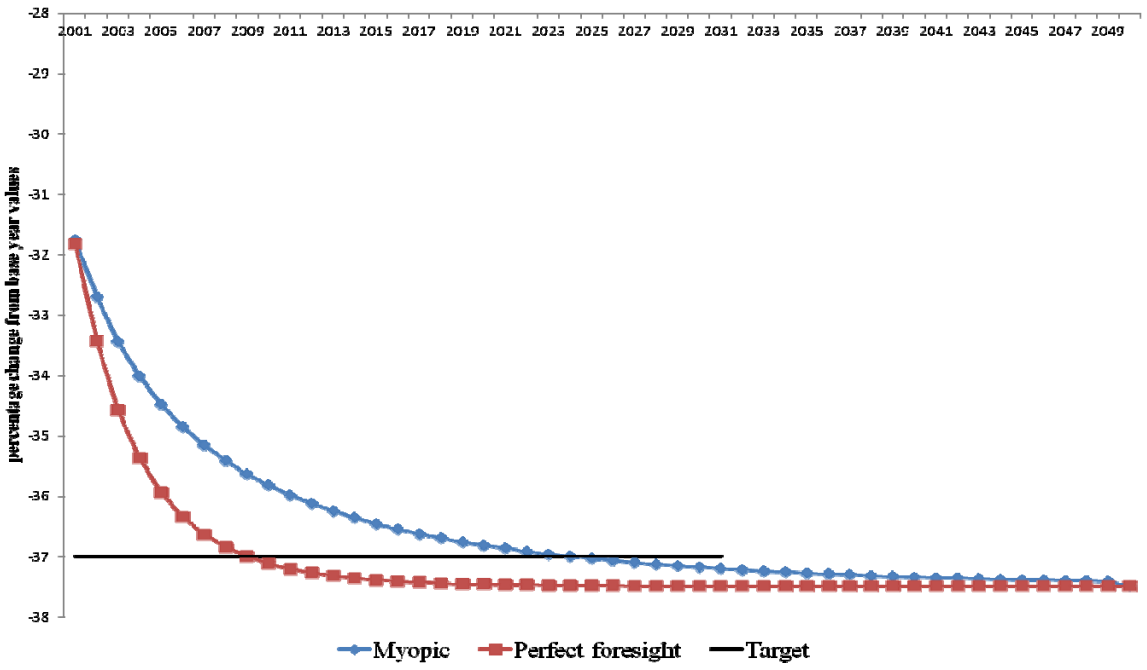
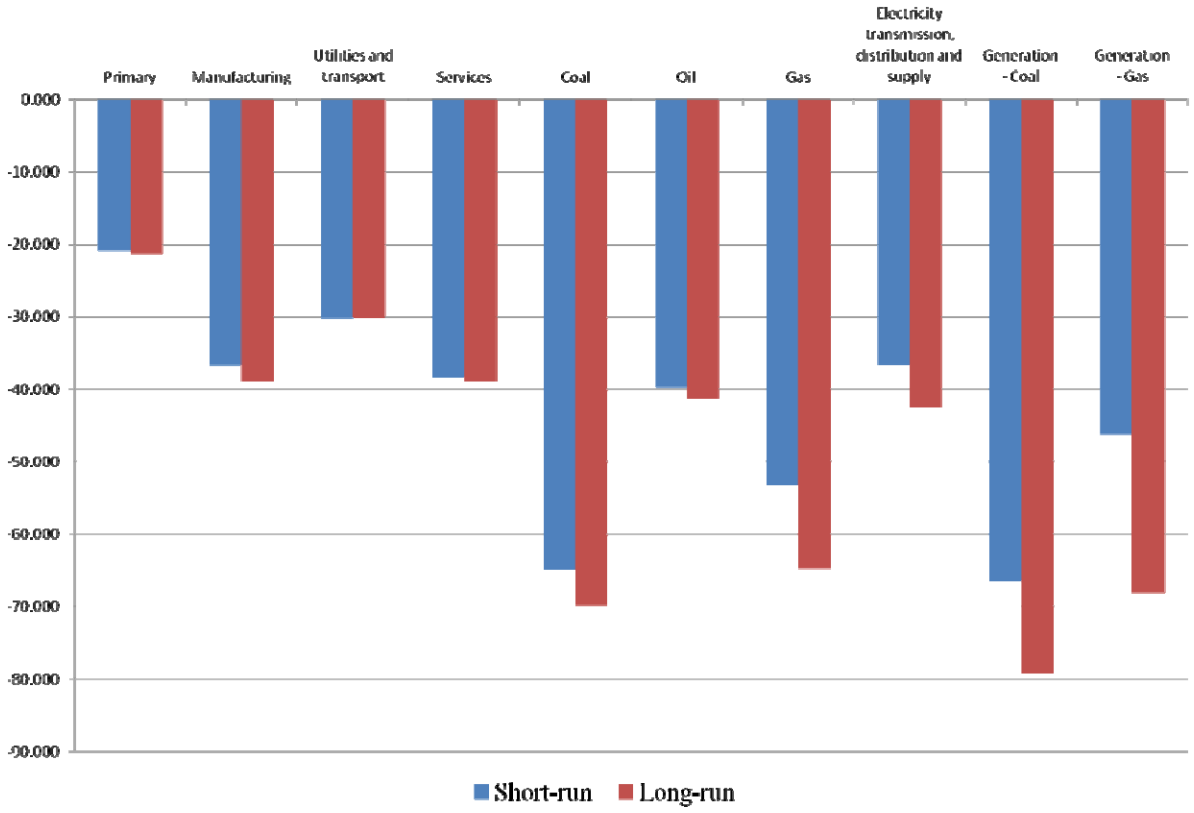


Figure 4: The short and long-run % reductions in sectoral CO2 emissions for a £50 tonne tax with revenue recycling through a reduction in income tax



sectors, only the primary sector shows a long-run reduction in output.

In Figure 2, we show the period-by-period reduction in CO2 emissions from the base period. Note that for all three shocks the carbon tax is able to achieve the 37% target emissions reduction by the year 2020. This target is met after only 5 years when the revenue is either externally recycled or used to increase public expenditure within Scotland. With revenue recycling through a reduction in Scottish income tax, the target is achieved after ten years.

All the simulations reported up to now have incorporated forward-looking behaviour on the part of all agents. In Figure 3 we compare the period-by-period impact of the carbon tax on the level of CO2 emissions under both forward looking and myopic assumptions. Again we report the percentage change from base year values of total CO2 emissions for the simulations where the carbon tax revenue is used to reduce income tax. As we would intuitively expect, both the myopic and forward-looking model reach the same long-run equilibrium, regardless of the dynamic structure. However, whilst with perfect foresight the target is achieved in less than ten years, with the myopic model we are only able to reach the target by 2025.

This has implications for the need for credibility in the implementation of the environmental policy by the Scottish Government. In order that agents can optimally adjust to policy by anticipating its future effects, those agents must believe that the policy will be maintained in the future. In the myopic case, the agents have adaptive expectations. They adjust only with respect to present prices and outputs. The adjustment is much slower without this commitment to the future.

In Figure 4 we show the short-run and long-run change in CO2 emissions at the sectoral level (for those sectors that emit carbon). Note that there are huge reductions in emissions in all energy sectors. In the long run, the reductions in the coal and the coal electricity generation sectors are 70% and 79% respectively. As for the non-energy sectors the biggest reductions in emissions are in the manufacturing and the service sectors, which are the most energy-intensive sectors.

Conclusions

There is no doubt about the level of ambition of the Scottish Government's emissions targets; but there must be some doubt about whether it has sufficient policy instruments under its direct control to induce households and firms to behave in a way that ensures these targets are met. Yet this is the challenge that the Scottish Government faces in the context of liberalised energy markets. While credibility is enhanced by enshrining emissions targets in a legal framework, this is generally insufficient to ensure their satisfaction (McGregor *et al*, 2011).

The debate on constitutional change continues to gain momentum in the run up to the referendum on independence. However, regardless of the outcome of that debate, the Scottish Government is destined to benefit from a significant enhancement in the extent of its fiscal powers. Against this background, it seems natural to consider the possibility of a Scottish-specific carbon tax. It seems natural because: this would be a genuine option under both devo max and independence. Such a tax is focused on the "bad" of emissions directly and if implemented in a fiscally neutral way offers the potential of a double dividend if the revenues are used to subsidise (or more realistically reduce the tax on) the "good" of employment. Our simulations demonstrate that a carbon tax could simultaneously stimulate employment while reducing emissions: the double dividend.

We end on a cautionary note. Our analysis is still in a preliminary stage, and we plan more extensive systematic analysis of the factors that govern both the direction and the scale of the Scottish economy's response to a carbon tax. Furthermore, extensions to explore the impact on the economy of the rest-of-the UK would also be of considerable policy interest. However, the estimates we present here are by no means an upper bound for the potential beneficial impacts of the tax for, in the longer term, we would expect the tax to stimulate innovation in low-carbon technologies, a positive effect that is absent from our current analysis. Furthermore, in current circumstances, it may be thought desirable to focus the good news by recycling revenues to subsidise employment among the younger age groups who have been most adversely impacted by the recession and its aftermath. We believe that our initial investigations are sufficiently promising to merit more extensive analysis of a Scottish carbon tax.

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Endnotes

[i]We do not question the science here. For a robust rebuttal of the climate change sceptics, see Nordhaus (2012).

[iii]Weitzman (1974) discusses the cases where these approaches differ under uncertainty.

[iv]A key role of the government is to produce public goods: goods that provide freely available services where it is difficult to exclude individuals from benefiting from these services. These goods are provided inadequately by the private market. The classic example is defence.

[v]See Fullerton and Metcalf (1998) for a clear account of the issues and Bosquet (2000) for an survey of the double dividend literature on environmental taxes.

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