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What are the costs of Scotland's climate and renewable policies?

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HIGHLIGHTS

- ► Scottish climate policy is less stringent than UK policy.
- ► Scottish targets would complement UK targets if UK policies fail to meet UK targets.
- ► The possible conclusion here is that Scottish carbon targets are unnecessary.
- ► Scottish renewable policy is more stringent than UK policy.
- ► As expected, this increased stringency leads to additional costs.

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ABSTRACT

The UK government has established ambitious policies to address climate change and promote renewable energy, and has set targets both for reducing carbon emissions and for deploying renewables. Scotland, a constituent nation of the UK, has also set its own targets for climate change mitigation and renewable electricity. This paper analyses the energy, economic and environmental implications of carbon and renewable electricity targets in Scotland and the UK using a newly developed two-region UK MARKAL energy system model, where Scotland (SCT) and rest of the UK (RUK) are the two regions. The paper shows that meeting Scotland's carbon targets does not require additional decarbonisation effort if the UK meets its own targets at least cost; and that Scotland's renewable energy ambitions do imply additional costs above the least cost path to the meeting the UK's obligations under the EU renewable energy directive. Meeting Scottish renewable electricity targets diverts investment and deployment in renewables from rest of the UK to Scotland. In addition to increased energy system cost, Scottish renewable electricity targets may also require early investment in new electricity transmission capacity between Scotland and rest of the UK.

1. Introduction

The UK government has set a ground-breaking target of reducing the UK's greenhouse gas emissions (GHGs) by 80% from 1990 levels by 2050 and 34% by 2020 (CCC, 2008). The UK has also committed to increase the share of final energy consumption from renewable sources to 15% by 2020, as part of the wider EU renewable energy directive (European Parliament, 2009).

Scotland, a constituent nation of the UK, has introduced its own climate change mitigation and renewable electricity targets. Scottish climate change mitigation targets require deeper GHG reductions than the UK, requiring reductions of 42% in 2020 and 80% in 2050 from 1990 levels, including emissions from international aviation and shipping (Scottish Parliament, 2009). In recent years, Scotland has also introduced increasingly ambitious renewable electricity targets, with current proposals increasing the Scottish renewable electricity target to 100% for the year 2020 (Scottish Government, 2011).

Considerable effort has gone into understanding the costs and energy system implications of the UK's carbon and renewable targets. However, less is known about the costs and implications of decarbonisation pathways for Scotland, or how Scottish targets and policy ambitions interact with UK targets. In particular, it is not clear whether Scottish targets imply additional effort (and costs) in achieving decarbonisation and the development of UK-wide renewable energy supplies over and above the efforts required to meet UK targets.

This paper analyses energy, economic and environmental implications of Scottish climate and renewable electricity targets in Scotland and the UK using a new two-region UK MARKAL energy system model, where Scotland (SCT) and the rest of the UK (RUK) are the two regions. This model enables detailed analysis of Scotland's decarbonisation pathway, the costs of meeting renewable energy targets, and the interactions between UK and Scottish policy ambition.

The paper first sets out the policy context for Scottish and UK carbon and renewable targets, and the economic theory relevant

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to such targets in a multi-level governance context in Section 2. Then, Sections 3 and 4 introduce, respectively the MARKAL modelling framework generally, and the assumptions used to develop the UK two-region model (henceforth abbreviated as "UK2R MARKAL"). Sections 5 and 6 set out the scenarios analysed with the model and their results, and Section 7 discusses the implications of these results and draws conclusions arising from the analysis.

2. Scotland's energy and climate goals in a multi-level context

2.1. Carbon targets in Scotland and the UK

The UK has a quasi-federal governance structure, with its constituent nations (England, Scotland, Wales and Northern Ireland) having different levels of jurisdiction over energy and climate policy.[1] Responsibility for climate policy is not always clear, since climate policy is a new and cross-cutting area involving energy, environment and other policy areas (Reid, 2009). Nevertheless, Scottish policymakers have legislated carbon targets for Scotland in addition to those legislated for the UK as a whole.

Federal or multi-level governance structures exist in many nation states, and regional or sub-national entities frequently have some control over climate policy. Several authors have discussed the relative merits of centralized versus multi-level governance structures for climate policy, and the implications of interactions between national and regional targets (e.g., Goulder and Stavins, 2010; Lutsey and Sperling, 2008).

From a theoretical economic perspective, two possibilities are clear in a multi-level governance context in which both a national and regional entity set quantity-based (as opposed to price-based) carbon reduction targets. If regional targets can be met at a lower marginal abatement costs than national targets, they could be argued to be ineffectual, because they are superseded by the national target (i.e., they imply no additional abatement activity over and above that required to meet the national target). On the other hand, if regional targets require higher marginal abatement costs than national targets, they raise the costs of meeting the national target, without leading to any additional reductions. Extra efforts expended in the sub-national region will allow less effort in the rest of the country, leading to an identical outcome at higher cost (Goulder and Stavins, 2010). There may be additional benefits to regional policies, particularly from a political perspective, and these are raised in Section 7.

The Scottish Government and the UK Committee on Climate Change have both argued that the Scottish greenhouse gas (GHG) emissions reduction target of 42% by 2020 from 1990 levels is 'ambitious' when compared with the overall UK target, of 34% GHG (29% CO_2) reduction by 2020 from 1990 levels (CCC, 2010; Scottish Government, 2010). While it is unequivocally the case that Scotland's carbon reduction targets are deeper than those of the UK, it is not immediately clear whether they are more ambitious, in the sense that it is possible that they may be met at a lower marginal abatement cost than UK targets. If marginal abatement costs are lower in Scotland than they are in the UK as a whole, Scotland would be expected to achieve higher percentage reductions than the rest of the UK even without any targets of its own. Deeper quantitative reductions are not necessarily the same as greater ambition if marginal abatement costs vary across different regions.

This paper therefore explores a scenario in which UK2R MARKAL is constrained to meet UK carbon targets at least cost, and examines Scotland's progress towards its own targets. If Scotland's targets turn out to be met in scenarios in which the UK meets UK targets, then Scotland's targets could be argued to be redundant, since they would imply no additional abatement activity over and above that required to meet UK targets in a cost-effective way. If, on the other hand, Scotland's targets indeed require abatement in Scotland over and above that which would occur in a least-cost pathway to meeting UK targets, this raises important political and economic questions. Who is likely to bear the costs of that additional Scottish ambition?

2.2. Renewable energy policy and targets

As established in the EU renewable energy directive (RED), the UK has committed to meet 15% of gross energy consumption, including heat, power and transport, from renewable resources by 2020. The government has indicated that it expects to meet this target with 30% of electricity supplies coming from renewable sources in 2020 (HM Government, 2009). The principal rationale for pursuing such ambitious renewable energy targets is carbon reductions, but policymakers support renewables for other reasons too, including reducing other environmental impacts, diversifying energy supplies, and a belief that investments in renewable energy may establish domestic industries that can export such technologies. All of these reasons have been invoked by policymakers at the UK and Scottish level (HM Government, 2009; Scottish Government, 2009). As a result, policy targets exist despite evidence that renewable energy may not be the least cost decarbonisation option. Anandarajah and Strachan (2010) show that the UK's renewable energy targets may raise the overall costs of decarbonisation, though there is substantial uncertainty in the future costs of both capital plant (renewable and otherwise) and fossil fuels, both of which are important in determining final costs (Usher and Strachan, 2010).

Scotland itself has also introduced increasingly ambitious renewable electricity targets for the year 2020. Although the Scottish government has limited jurisdiction over energy policy,[2] Scottish ministers have been keen to set out a vision of Scotland's clean energy future (Winskel, 2007). In particular, Scottish politicians have argued that Scotland can realise substantial economic benefits through the development of its renewable energy resources (see discussion in Allan et al., 2008a). Scotland's first renewable energy target, of 40% renewables by 2020, was set in 2003. This target was revised upwards in 2007, 2010 and 2011, so that the current target is that Scotland should, in any given year, generate renewable electricity equivalent to 100% of its electricity consumption by 2020 (Scottish Government, 2007, 2010, 2011).

The possible costs and benefits of meeting Scottish renewable energy targets have generated recent controversy (e.g., Mackay, 2011; Marsh and Miers, 2011; Scottish Parliament, 2012), but have received relatively little treatment in the academic literature. Bergmann et al. (2006) provided a valuation of various renewable energy options for Scotland using a choice experiment framework, and Allan et al. (2007, 2008b) have assessed economy-wide effects of renewable energy in Scotland using input–output and computable general equilibrium analysis. However, no previous analysis has applied a technologically-detailed bottom-up energy system model to assess Scotland's renewable policy targets.

As with carbon targets, Scotland's renewable energy target appears more ambitious than the UK-wide target. But as with carbon targets, since marginal costs differ across the UK, it is not *a*

[1] Both the UK and Scotland are 'nations'. For clarity, this paper uses the term 'national' to refer to UK emissions and policies, and 'regional' to refer to Scottish emissions and policies.

[2] Energy policy is formally 'reserved' by the UK government, but Scotland has some powers under the 2000 Utilities Act.

priori obvious that these targets do indeed imply additional deployment above that expected in a least-cost pathway to meeting UK-wide RED targets. UK2R MARKAL is therefore run with UK-wide renewable energy targets, and Scotland's progress towards its own targets are assessed in a scenario in which the UK meets UK targets at least cost.

3. Energy system modelling of renewable and climate change policy

3.1. Energy system modelling

Different models covering bottom-up (integrated energy system simulation models and dynamic optimisation models), top-down (input–output, macroeconomic or computable general equilibrium models) and hybrid categories have been used to study the energy system implications of renewable energy and climate change mitigation policies. The model classes differ mainly with respect to whether emphasis is placed on the comprehensiveness of endogenous market adjustments or on the technological details of the energy system (Bohringer and Rutherford, 2007). While significant efforts have been dedicated to the development of hybrid models (Hourcade et al., 2006), no model fully meets the competing requirements of an ideal energy system modelling approach: technological explicitness, microeconomic realism, and macroeconomic completeness (Bataille et al., 2006). Instead, the research question determines the most apt model to generate insights, with an inevitable trade-off in the focus of the model used. For analysis of competing CO_2 emissions and renewable energy policies at national and regional level, the technological, regional and country specific detail of the UK2R MARKAL model makes it an appropriate choice.

3.2. MARKAL modelling

MARKAL (MARKet ALlocation) is a technology-rich bottom-up cost optimization modelling framework. In simple terms, this means that the model draws on a large database of energy technologies and resources to meet a set of energy service demands that are specified exogenously. The model uses linear programming to find the least cost energy system (resources, technologies and their usage) to meet those energy service demands, and can do so subject to policy constraints (such as carbon targets) or taking into account policy measures such as subsidies, taxes and so on (Fishbone and Abilock, 1981; Loulou et al., 2004). For detail on the MARKAL model framework and its conceptual strengths and weaknesses, the interested reader is referred to the documentation for the MARKAL family of models (Loulou et al., 2004) and the literature on MARKAL modelling, much of it published in previous issues of this journal (e.g., Anandarajah and Strachan, 2010; Rafaj and Kypreos, 2007.

MARKAL is very widely used at global, national and regional scales to investigate energy system impacts of renewable and/or climate change policies in different countries (see, e.g., Ichinohe and Endo, 2006; Chen et al., 2007; Strachan and Kannan, 2008). In the UK, the single region UK MARKAL model has provided a major analytical underpinning to UK energy policy (including the energy white paper (BERR, 2007) and the climate change bill (DEFRA, 2007). A comprehensive description of the UK model is given in the model documentation (Kannan et al., 2007), with recent peer reviewed publications including Strachan and Kannan (2008), Ekins et al. (2011), and Anandarajah and Strachan (2010). Anandarajah and Strachan (2010) analysed interaction and implications of climate and renewable policies for the UK, and the present analysis builds on that work by examining the implications of climate and renewable policies across Scotland and the rest-of-the-UK.

It is important to be clear about the meaning of 'costs' in the MARKAL modelling presented in this paper. The model identifies the energy system with the lowest discounted *energy system cost* that meets energy service demands across the time-period (2000–2050). This cost is the sum of discounted capital costs (for new and renewed capital stocks, such as replacement power stations and new cars), operating and maintenance costs, and resource costs (both domestic production costs and imports).

3.3. Multi-regional energy systems modelling with MARKAL

Multi-regional versions of MARKAL have been used for many years (see, e.g., Stocks and Musgrove, 1984; Kanudia and Loulou, 1997), although most early MARKAL models focused on a single region (Seebregts et al., 2001; Fishbone and Abilock, 1981). The multi-regional feature is now a fully enabled option within the standard MARKAL code made available through the International Energy Agency's ETSAP programme (Loulou et al., 2004).

This multi-regional capability was developed in order to provide a flexible basis for developing multi-region models, with model users free to determine the appropriate spatial boundaries and scale at which regions are defined. As a result, multi-regional MARKAL models have been developed in which the regional units are defined at widely differing spatial scales. Many multi-region energy-system models have used countries or multi-country regions (such as the EU) as the appropriate spatial units (Rafaj and Kypreos, 2007; Gül et al., 2009). Others have defined intra-country regions, in the US and Canada (Shay et al., 2008; Goldstein et al., 2008; Loulou and Kanudia, 1999), Australia (Stocks and Musgrove, 1984; Naughten, 2002), and Norway (Rosenberg et al., 2010). Clearly, the appropriate scale for regional disaggregation will depend in part on the questions that the model is designed to address (Short, 2007), but in selecting an appropriate scale it is also important to consider the way in which multi-regional MARKAL represents different regions, and the implications this has for the insights that can be drawn from the analysis.

Regions in multi-regional MARKAL models are represented as separate but linked energy systems, with fully implemented trading of all energy carriers (electricity, gas, oil products etc.) as appropriate for the regions in question (i.e., the availability of electricity trading will depend on whether or not electricity transmission between the regions is feasible). It is intuitively clear that this is an appropriate way of representing regions that correspond to independent sovereign states, since it makes sense that these can be typically be considered as independent energy systems linked by trade.

It is less immediately obvious that this independent-but-linked regional representation is applicable for a model representing regions within a given country, since one might expect this to poorly represent the integrated energy markets typically found within nation-states. This concern might particularly apply to a two-region UK model, since Scotland is closely integrated into the energy system of the wider UK, with single UK-wide markets operating for electricity, gas and other fuels. However, if no restrictions are applied to trade of energy carriers between regions in a multi-regional MARKAL, the two (or more) regions' energy systems effectively operate as a single system to meet energy service demands spanning all regions. This is because the marginal unit of energy service demand in one region can be supplied by either 'domestic' production within that region, or from imports from the other region, whichever is cheapest.

4. Two-region UK MARKAL model development

4.1. Introduction

UK2R MARKAL has been developed by breaking out Scotland from the single region national UK MARKAL model, so that Scotland

(SCT) and rest of the UK (RUK) are defined as the two regions in UK2R MARKAL.

UK2R MARKAL is calibrated in its base year (2000) to data (for SCT and RUK) of resource supplies, energy consumption, electricity output, installed technology capacity and CO_2 emissions, as described below. The model then optimises via 5-year increments through to 2050. The single region UK MARKAL is well documented and published in different journals (Strachan and Kannan (2008), Anandarajah and Strachan (2010)), this paper discusses the development of UK2R MARKAL model and presents data and assumptions for Scotland. In particular, this section discusses the basis for disaggregating final energy demand, base year installed power generation capacity, and various resources.

The two-region MARKAL model follows MARKAL modelling convention in representing the energy systems as separate but linked by trading of energy carriers. There is one respect in which this approach to disaggregating the Scottish and rest-of-the UK regions may distort the dynamics of an integrated power system, and that is in the model's requirements for each region to satisfy peak margin capacity requirements domestically. As a result, both regions must have sufficient capacity to provide margin over peak demand, whereas in fact one might imagine a scenario in which one region or the other contained sufficient peak capacity to provide margin for the other region's needs. This assumption is common to other multi-regional MARKAL models, and its implications for the results of the UK2R MARKAL model are discussed in Section 6.5.

4.2. Data and assumptions

4.2.1. Final consumption

The base year (2000) for the single region UK MARKAL model was calibrated to the DUKES (2006) data. Final energy consumption of the both regions in UK2R MARKAL has been calibrated in the base year to actual data for each energy-service demand by fuel type. For each sector, Scotland's share of final consumption (i.e., the proportion of UK final consumption that occurs in Scotland) has been identified.

Transport sector energy consumption by fuel and mode for the SCT region is taken from BERR (2008). Scotland's share of fuel consumption is used to calculate the fractional share of transport service demand for Scotland. Scotland's share of UK road transport sector energy consumption varies among the modes: shares of bus, car-petrol, car-diesel, motorcycle, heavy goods vehicles and light good vehicle demand are 10.5%, 8.0%, 7.9%, 5.5%, 7.8%, and 8.5%, respectively.

Residential sector data are taken from the BRE domestic energy fact file (BRE, 2008), which reports that 9% of UK households are in Scotland. Gas and electricity consumption data for Scotland and the UK (data from Energy Trends 2004) show that about 8.23% of gas and 10.03% of electricity is consumed in Scotland, i.e., close to 9% of total energy (gas and electricity) is consumed in Scotland. Therefore, the total residential energy service demand in the UK single region MARKAL model is disaggregated such that 9% of total UK demand is assumed to be in Scotland. Electricity and gas consumption by Scotland in the base year is kept to 10.03% and 8.23% of the total UK consumption, respectively.

Services sector data are taken from Scottish Energy Study (2006) which reports Scotland's share of UK final consumption as 11.6%. Agriculture sector energy consumption data are taken from DECC (2008). Scotland consumes 18% of the UK's petroleum demand for agriculture.

Industry sector data are taken from Scottish Energy Study (2006). Scotland's share of final consumption for chemical, iron and steel, non-ferrous metals, pulp & paper and other industry is 8.0%, 0.7%, 1.0%, 20.2% and 9.9%, respectively. The fuel mix in each industry sub-sector, to which final consumption is calibrated, is presented in Table 1.

4.2.2. Installed power generation capacity

Scotland's installed power generation capacity in the base year was about 9.5 GW. Scotland produces more electricity than it consumes, and electricity is exported to England and Northern Ireland. Existing installed capacity and electricity generation data for Scotland are taken from Scottish Energy Study (2006) for gas, coal and nuclear plants (Table 2). Retirement of the existing capacity over the years is also modelled based on the retirement data in the Scottish Energy Study. Installed capacities for renewables (wind, landfill gas, bio-fuels) are taken from BERR (2009).

4.2.3. Wind resource data

Since off-shore wind is expected to be the main future contributor to renewable electricity supplies, a detailed spatial representation of off-shore wind resource data has been used in UK2R MARKAL (Dalvit, 2009). Off-shore wind resource data are divided into five concentric bands, each of which is 30 km wide, representing tranches of wind resource at increasing distance from shore (i.e., 0–30 km, 30–120 and >120 km offshore). These concentric bands have been further subdivided into different zones on a geographical basis as shown in Fig. 1. Further assumptions on feasible water depths (the data assumes no regions deeper than 50 m will be developed), spatial data on wind speeds, and exclusion of conservation areas and shipping lanes have provided a supply curve for offshore wind specific to each offshore zone. The total possible resource available to the model is 416 GW at a minimum wind speed of 9 m/s.

On-shore wind resource data are taken from Enviros (2005) which reports that maximum UK onshore wind capacity is about 20 GW of which 8.66 GW is available in Scotland. However, no additional data on differential wind regimes in Scotland vs. the rest of the UK has been applied in this analysis, a weakness which is likely to be addressed in future work. In general, onshore wind in Scotland has higher capacity factors than in the rest of the UK, and therefore delivers power at a lower levelized cost. The treatment of onshore wind in this paper, which does not account

Table 1
Scotland's industrial fuels: patterns of consumption across sub-sectors.
Source: Scottish Energy Study (2006).

Industry sub-sector	Coal (%)	Oil (%)	Natural gas (%)	Electricity (%)
Chemical	11.4	1.9	27.3	9.1
Iron and steel	0.4	1.0	2.2	1.6
Non-ferrous	0.4	0.1	0.1	0.1
Pulp and paper	8.5	4.8	16.4	22.60
Other industry	79.1	92.2	54.0	66.7
Total	100	100	100	100

Table 2
Installed capacity in Scotland in the year 2000 and assumed closure date in UK2R MARKAL.

Station	Type	Capacity (MW)	Assumed closure date
Chapelcross	Nuclear	200	2005
Cockenzie	Coal	1200	2010
Hunterston B	Nuclear	1190	2010
Longannet	Coal	2400	2020
Peterhead	Gas	1524	2025
Torness	Nuclear	1250	2025
Several	Hydro	1609	–
Several	Wind	149	–
Total		9522	

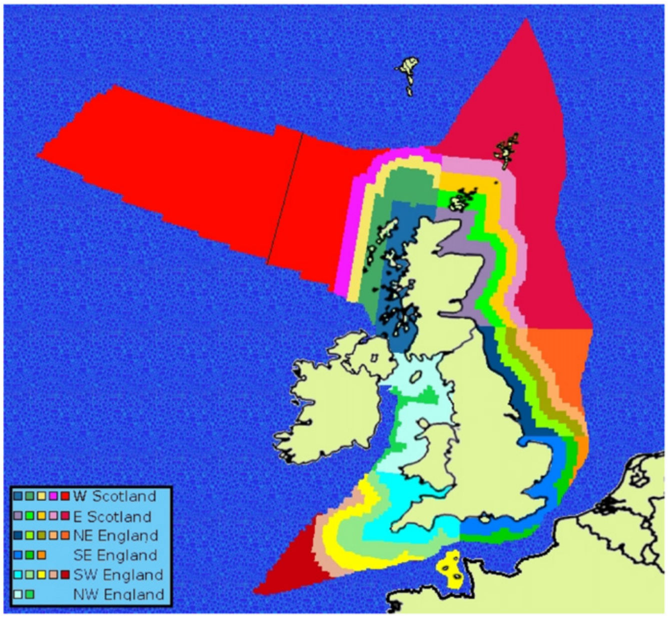

Fig. 1. Offshore wind resource regions in UK2R MARKAL.

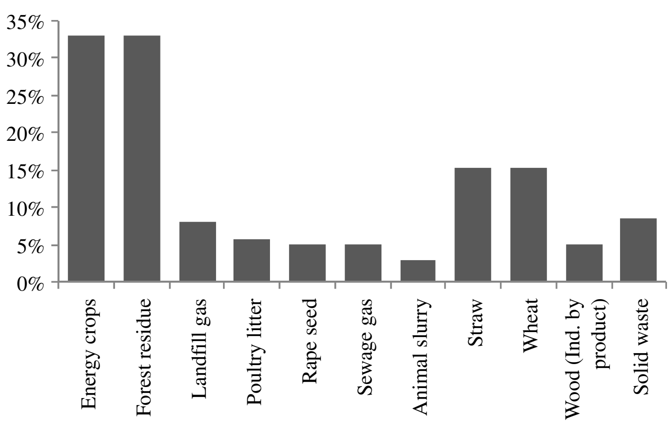

Fig. 2. Scotland's assumed share of UK bioenergy resources.

for this difference, will therefore tend to overstate the costs of deploying onshore wind in Scotland relative to the rest of the UK.

4.2.4. Biomass resource

Biomass resource availability in Scotland is mainly taken from Scotland's renewable resource (SRR, 2001). Data for energy crops and forest residue is taken from Andersen et al. (2005) and data for all other biomass resources are taken from the SRR report (SRR, 2001. Scotland's share of UK biomass resources are presented in Fig. 2. Scotland's energy crop and forest residue resources are relatively high because of Scotland's greater land area.

4.2.5. Treatment of energy and emissions in the UK continental shelf

A considerable portion of the UK's oil and gas resources are extracted offshore, from the UK continental shelf (UKCS). Unlike the territorial waters, which extend 12 nautical miles from the coast, the UKCS is not a part of any constituent nation of the UK, but rather is an exclusive economic zone where the UK has oil and gas exploration rights. For this work, UKCS oil and gas activities, and their associated emissions, were allocated to either Scotland or the rest of the UK, based on the shares outlined in the Scottish Energy Study (2006), which assumed that resources are 'indigenous' to the region in which they come ashore. This allocation of offshore oil and gas resources was necessary given the rather aggregated representation of oil and gas production processes in the model and in available statistics, and because of the significant effort that would be required to disaggregate this set of industrial processes such that a clear division of emissions from UKCS, territorial waters and onshore terminals could be applied in the model.

Note that Scotland's real-world emissions inventory does not include any emissions that occur in the UKCS, and thus Scotland's legislated targets do not apply to these emissions. Our allocation of such emissions to each region introduces a source of error to which we return in the discussion.

Offshore renewables that lie outside the limit of the territorial waters of any constituent nation of the UK are allocated to either Scotland or the rest of the UK, based on a straight east–west line running out to sea from the land border (as illustrated in Fig. 1).

4.2.6. Emissions inventories, baselines and targets

The carbon reduction targets for both Scotland and the UK are based on the six greenhouse gases covered under the Kyoto Protocol, and are expressed as a percentage reduction from 1990 levels by 2050. The UK MARKAL model represents only energy-related CO_2 emissions. It is therefore necessary to make assumptions about how best to apply the real-world policy targets in the model framework, since the scope of the model differs from the scope of the policy targets. In this work, these economy-wide GHG targets are applied as targets for energy-related CO_2. If in reality it is more costly to reduce non-energy emissions, and emissions of non-CO_2 gases, then this work will understate the costs of meeting targets.

Emissions data used to establish a 1990 baseline, and hence 2050 target for Scotland and the rest of the UK, were taken from Thomas et al. (2011). Carbon dioxide emissions associated with oil and gas extraction in the UK continental shelf were allocated to Scotland and RUK in the baseline in proportion to the share of oil and gas activity given in the Scottish Energy Study (2006).

The Scottish GHG targets include emissions from international aviation and shipping. This work excludes those emissions, as the basis for allocating emissions to either Scotland or RUK is not clear. However, it is likely that abatement of these emissions will be more expensive, and excluding international aviation and shipping is thus likely to understate the costs of decarbonisation. The Committee on Climate Change estimate that meeting the overall Scottish target of a 42% reduction in GHGs by 2020 will require a 44% reduction in sectors other than international aviation and shipping (CCC, 2010).

4.2.7. Scottish nuclear policy

The Scottish Government's policy is that no new nuclear plant will be built in Scotland, a position that has been endorsed with a vote in the Scottish Parliament (Anon, 2008). For the purposes of this study, the model is able to build nuclear plant in Scotland should it form part of the least cost model solution, and sensitivity runs have been carried out to examine the implications of Scotland's no nuclear policy.

5. Scenarios

The following five scenarios are defined for analysing climate and renewable electricity policies:

- Reference (REF) Scenario: CO_2 emissions are not constrained. Existing policy measures as of Energy White Paper 2007 (i.e., UK-wide renewables obligation of 15% and Renewable

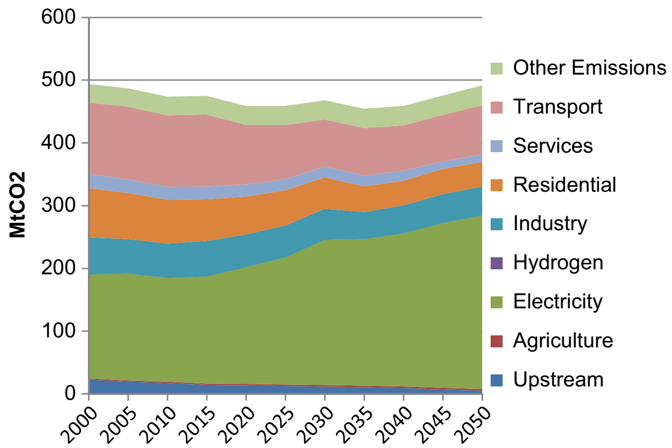

Fig. 3. Sectoral CO_2 emissions in rest of the UK in REF.

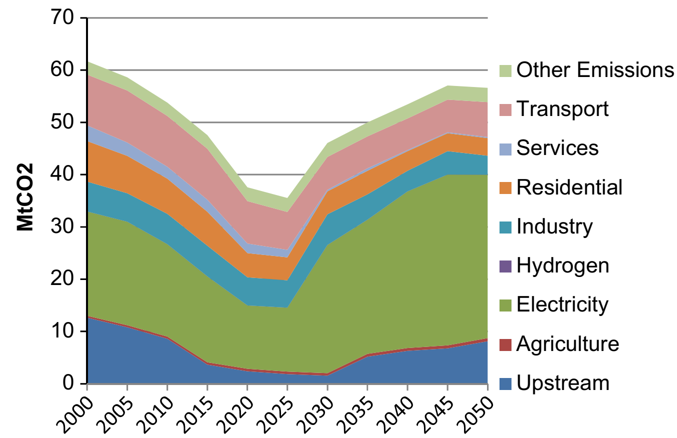

Fig. 4. Sectoral CO_2 emissions in Scotland in REF.

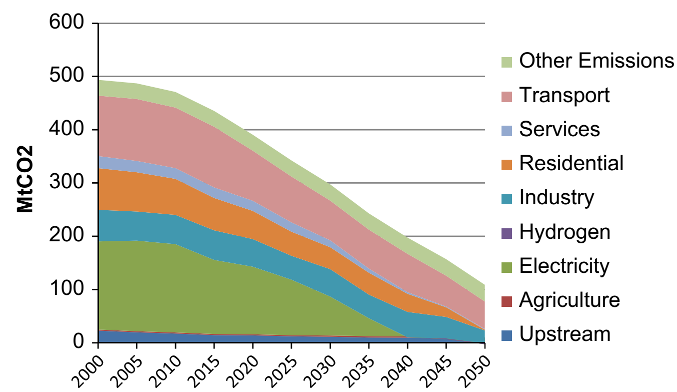

Fig. 5. Sectoral CO_2 emissions in rest of the UK in LCS.

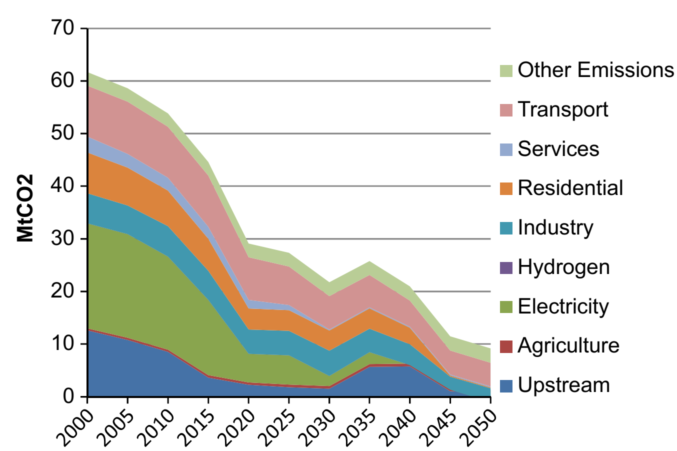

Fig. 6. Sectoral CO_2 emissions in Scotland in LCS.

Transport Fuel Obligation of 5%) are applied. Modelling period is 2000–2050.

- Low Carbon (LC) Scenario: The model is constrained to meet reductions in CO_2 emissions in line with targets, i.e., by 29% in 2020 and 80% in 2050 over 1990 levels. All other conditions are same as in the REF Scenario. The target can be met by mitigating emissions from both regions depending on where it is cheaper to do so.
- Renewable energy strategy (RES) Scenario: The Renewable energy strategy (RES) is applied to the UK at national level. We use the 'lead scenario' in the UK government's Renewable Energy Strategy (HM Government, 2009) to illustrate how the UK might meet the renewable energy directive: 30% renewable electricity, 10% renewable fuels in transport and 12% renewable fuels in heating. This scenario is also required to meet UK carbon targets.
- Scottish renewable policy (SRP) Scenario: Scottish renewable electricity target is set to 80% by 2020, i.e., An amount equivalent to 80% of Scottish electricity consumption must be generated from renewable sources in Scotland, on an annual basis. All other conditions are same as in the RES.
- Scottish High renewable policy (SHRP) Scenario: An amount equivalent to 100% of Scottish electricity consumption must be generated from renewable sources in Scotland, on an annual basis. All other conditions are same as in RES.
- Sensitivity scenarios have been run with a 'no nuclear' policy for Scotland on three of the above scenarios (RES, SRP and SHRP).

6. Results

6.1. CO_2 emissions

Regional CO_2 emissions in the Reference (REF) Scenario, where no climate policy has been applied, are presented in Figs. 3 and 4 for rest of the UK (RUK) and Scotland (SCT), respectively. Despite the fact that demand for energy services increases over the period, existing policies (renewables obligation [RO] and renewable transport fuel obligation [RTFO]) along with genuine efficiency improvements of power and end-use technologies can keep the emissions below the base-year (2000) emissions during the period. Among the sectors, the power sector dominates and its share increases over the period in both regions due to an increased share of coal generation (Figs. 7 and 8). In part due to the allocation of offshore oil and gas emissions used in the model (see assumptions in Section 4), Scotland has a large share of the UK's upstream CO_2 emissions.[3] Scotland also exports electricity to RUK. The dip in Scottish emissions in 2020–2025 is explained by reductions in upstream processes (as a result of declining oil and gas production in the North Sea, and declining refinery activity in Scotland) and power sector emissions (as Cockenzie and Longannet power stations reach the end of their lives, and are not fully replaced in Scotland, as the model instead installs additional capacity south of the border). In the longer term, these trends are

[3] 'upstream' refers to industrial activities associated with the extraction and processing of oil and gas resources.

Table 3
CO_2 emissions in selected years under different scenarios in Scotland and rest of the UK.

Sector	2020				2035				2050			
	LCS	RES	SRP	SHRP	LCS	RES	SRP	SHRP	LCS	RES	SRP	SHRP
Rest of the UK (RUK)												
Upstream	13.8	12.8	12.8	12.8	9.9	9.7	9.5	9.9	7.1	7.1	7.1	7.1
Agriculture	2.1	2.1	2.1	2.1	2.4	2.4	2.4	2.4	2.8	2.8	2.8	2.8
Electricity	126.9	139.2	139.9	140.9	33.7	40.5	39.8	39.9	−12.9	−12.4	−10.1	−7.2
Hydrogen	0	0	0	0	0	0	0	0	1.8	1.8	1.8	1.9
Industry	52.0	52.6	52.6	52.5	44.4	45.3	45.2	45.3	24.1	25.8	25.9	25.8
Residential	52.8	52.6	52.3	52.4	41.3	40.8	41.4	40.9	1.5	1.5	1.5	1.5
Services	19.0	19.2	19.4	19.3	7.8	7.7	7.8	8.0	1.5	1.5	1.5	1.5
Transport	94.3	79.0	78.8	78.7	73.1	66.7	66.7	66.7	51.6	50.3	50.1	49.6
Others	29.9	29.9	29.9	29.9	30.6	30.7	30.7	30.7	31.4	31.4	31.4	31.4
Total	**391**	**387**	**388**	**389**	**243**	**244**	**243**	**244**	**109**	**110**	**112**	**114**
Scotland (SCT)												
Upstream	2.3	2.1	2.1	2.0	5.7	5.4	5.7	5.3	0.7	0.7	0.7	0.7
Agriculture	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Electricity	5.4	10.0	9.6	8.9	2.3	2.6	2.3	1.7	−2.3	−2.9	−5.1	−8.0
Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0
Industry	4.6	5.9	5.7	5.2	4.4	4.3	4.4	4.5	2.7	3.0	2.9	2.8
Residential	4.0	4.1	4.3	4.6	3.9	4.0	4.2	4.4	0.1	0.1	0.1	0.1
Services	1.6	2.1	2.1	2.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Transport	8.1	5.2	5.2	5.3	6.2	5.5	5.5	5.8	4.5	3.9	3.9	4.5
Others	2.6	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Total	**29**	**32**	**32**	**31**	**26**	**25**	**25**	**25**	**9**	**8**	**6**	**4**

reversed, as higher oil prices lead to renewed extraction from the North Sea (from 2030 onwards), and rising electricity consumption leads to a new round of installation of coal power generating plant.

In climate change mitigation scenarios (i.e., all the scenarios that include a carbon constraint), a UK-wide CO_2 emissions constraint is applied. In other words, UK emissions are constrained and the target can be met by reducing emissions from SCT and RUK, with more mitigation wherever it is cheaper. In the Low Carbon Scenario (LCS), decarbonisation is foremost in the power sector till the middle or end of the projection period (Figs. 5 and 6). Major efforts then switch to the residential, transport and service sectors in both regions. The Scottish power sector decarbonises more rapidly as compared to that of RUK in the short-term (2020). Due to the increased share of wind generation in the Scottish power sector, closure of existing fossil plant, and declining emissions from North Sea oil and gas, Scotland's share of total UK emissions decreases over the period in the LC scenario from 11% in 2000 to around 8% during 2020–2050. Scotland emits only 9 Mt-CO_2 while RUK emits 109 Mt-CO_2 in 2050.

Detailed sectoral CO_2 emissions under different climate change mitigation and renewable electricity policy scenarios are presented in Table 3 for Scotland and rest of the UK regions. The RES scenario, which significantly increases the deployment of renewables in both regions, has perhaps counter-intuitive impacts on emissions in the power sector in 2020. In RES, in both regions the power sector emits more than in the LCS while the transport sector emits less, due to the high renewable heat and transport requirements, which divert bioenergy from the power sector to transport and heat. In both regions, by 2050 selection of co-firing with CCS brings down power sector emissions to negative values[4] (Table 3).

[4] Bioenergy is considered to have net zero emissions when combusted; if these emissions are captured and stored, the result is net negative emissions, since the carbon absorbed from the atmosphere during plant growth is removed from the atmosphere and stored.

6.2. Are Scottish carbon targets met in a scenario constrained to meet UK carbon targets?

In a scenario in which the UK meets its own 2020 carbon targets at least cost (the LCS scenario), Scottish CO_2 emissions are reduced by 52% as compared to 1990 levels in 2020, which meets and goes beyond Scottish targets. In other words, no additional, Scotland-specific constraints are required in this scenario for Scotland to meet its targets. Indeed, all climate change mitigation scenarios meet the Scottish targets (see Table 4). This might be argued to imply that Scottish carbon targets are redundant, a question which is addressed in the discussion.

It should be noted that the allocation of offshore oil and gas resources and emissions, described in Section 4.2.5, means that the results are likely to overstate the ease with which Scotland meets targets, since these emissions are expected to fall in response to declining activity in the UKCS.

6.3. Electricity generation

Figs. 7 and 8 show the generation mix in Scotland and rest of the UK regions, respectively in the REF scenario. Electricity generation increases to 2050 in RUK, while total generation in Scotland fluctuates due to varying net electricity flow from Scotland to the rest of the UK. There is a dip in Scottish generation in 2020 when the net electricity flow from Scotland to rest of the UK is at its lowest level due to retirement of part of the coal and nuclear capacities in Scotland by 2020. Net flow of electricity from Scotland to RUK is 29 PJ, 32 PJ, and 25 PJ from Scotland in 2000, 2005, and 2010, respectively (Figure 14). Since new capacity is built in RUK to meets its electricity demand, electricity import is reduced to 16 PJ in 2020. Both regions invest in wind, in order to meet the renewables obligation requirements.

Electricity generation in the low carbon scenario (LCS) is much higher than that in REF especially during latter part of the period for both regions (Figs. 7–10). End-use sectors are decarbonised by shifting to low carbon electricity during the latter part of the

Table 4
CO_2 emission reductions from 1990 levels in Scotland, rest of the UK, and the UK as a whole in 2020 and 2050.

Scenario	2020			2050		
	SCT (%)	RUK (%)	UK (%)	SCT (%)	RUK (%)	UK (%)
LCS	52	26	29	85	79	80
RES	47	27	29	86	79	80
SRP	47	27	29	90	79	80
SHRP	49	26	29	94	78	80

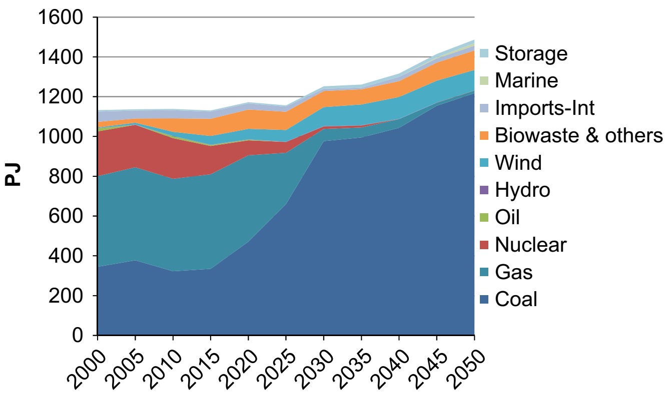

Fig. 7. Generation mix in rest of the UK in REF.

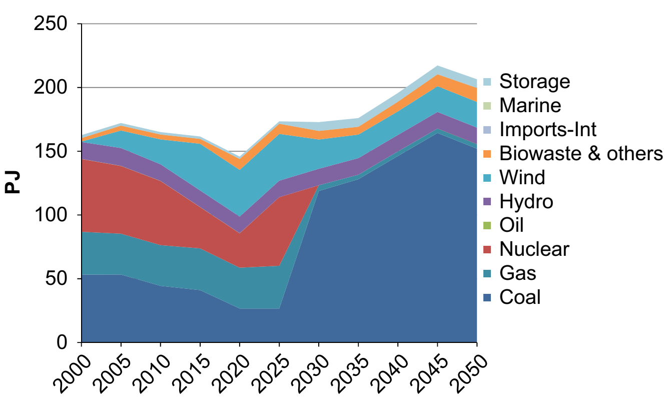

Fig. 8. Generation mix in SCT in REF.

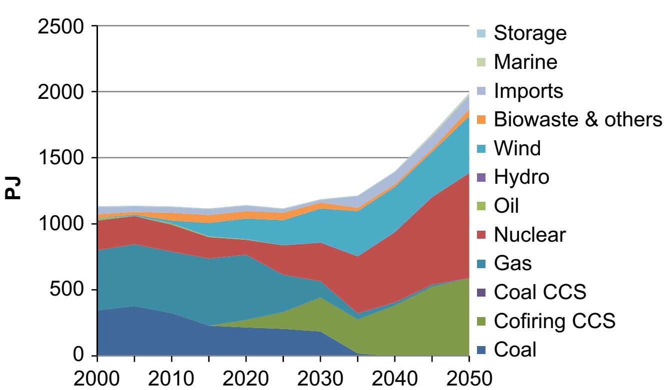

Fig. 9. Generation mix in RUK in LCS.

period leading to higher electricity demand in the mitigation scenarios. In LCS, both regions invest in CCS (with co-firing) from 2020 and in nuclear from 2025. UK-wide renewable electricity is modest before 2020, but both RUK and SCT regions invest

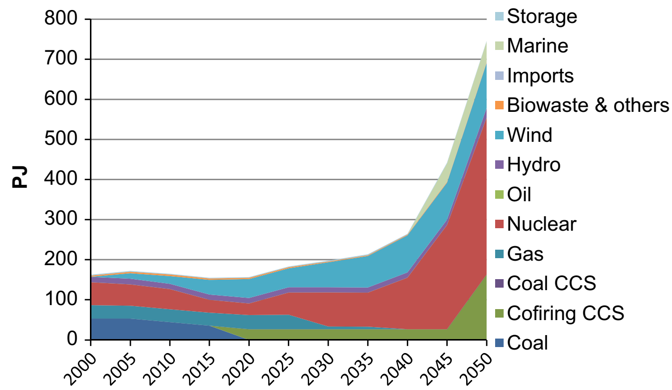

Fig. 10. Generation mix in SCT in LCS.

significantly in wind plants from 2025 and 2015, respectively. The cost-effectiveness of off-shore wind and marine technologies in Scotland increases the net flow of electricity from Scotland to rest of the UK (Figure 16) during the latter part of the period in the LCS. Marine technology becomes cost-effective from 2045. The very end of the period (2050) sees a steep increase in Scottish generation from nuclear and co-firing with CCS, in response to high marginal abatement costs[5] .

Both regions invest in wind in the renewable energy strategy (RES) scenario to meet the UK renewable electricity target of 30%. Wind replaces co-firing and nuclear generation in RUK and co-firing in SCT.

The capacity mix of each low carbon scenario in each region is shown in Figs. 11 and 12 for the years 2020, 2035 and 2050. The increase in capacity is notable, reflecting the shift to fuel switching to electricity in other sectors, and reflecting the greater generation capacity required with larger proportions of intermittent renewables, which require back-up generation (which explains the large gas capacity in 2050, despite relatively little gas-based generation, since this is used as back-up plant).

6.4. Does the least-cost path for meeting UK renewable targets satisfy Scottish renewable targets?

The MARKAL scenario analysis suggests that it is cost-effective to generate an amount equivalent to 57% of Scottish electricity consumption from renewable resources in Scotland in 2020 in a scenario that meets the renewable energy directive and carbon targets at least cost. This does not meet Scottish renewable electricity targets. Constraining UK2R MARKAL to meet Scottish targets (either 80% or 100%) shows that these targets lead to more renewable capacity being constructed in Scotland, and less in the rest of the UK. UK-wide renewable generation is not increased in SRP and SHRP scenarios as compared to RES scenario in 2020 (see Fig. 13). For example, in Scotland in 2020, wind capacity increases from 4GW in RES, to 7.7GW in SHRP, while in RUK the capacity of wind falls from 17.5 GW in RES to 12.7 GW in SHRP.

6.4.1. Economic implications of Scotland's renewable electricity targets

Constraining the model to increase Scottish renewable electricity targets (i.e., in the SRP and SHRP scenarios) has significant

[5] The sharp rise in nuclear in Scotland after 2040 is a result of constraints on the assumed possible rate of nuclear construction in both regions. It was assumed that neither region can deploy more than 5 GW of new nuclear per period (5-year). The constraint becomes binding in the rest of the UK during the 2030s, leading to an expansion of the modelled nuclear build programme into Scotland, with electricity exported south.

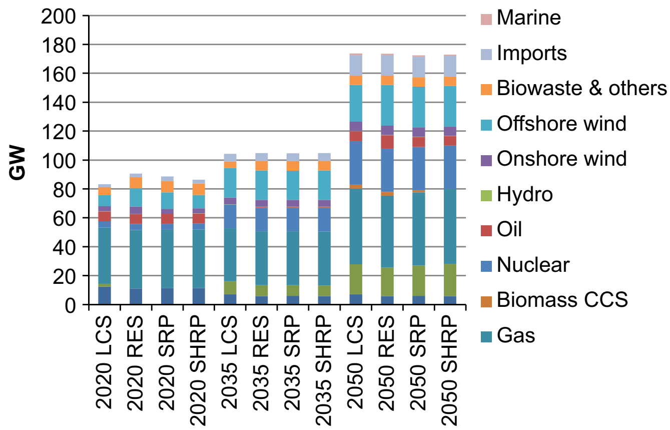

Fig. 11. Generation capacity mix in RUK in climate change mitigation scenarios in 2020, 2035 and 2050.

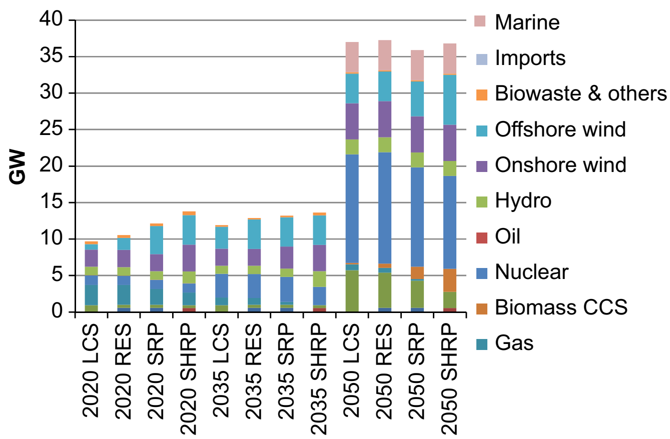

Fig. 12. Generation capacity mix in SCT in climate change mitigation scenarios in 2020, 2035 and 2050.

effects on energy system costs. The effect of the SRP and SHRP scenarios is to reduce energy system costs in RUK and increase energy system costs in Scotland. In RUK, the discounted energy system cost (over the planning period of 2000–2050) decreases by £537 million[6] and £904 million in SRP and SHRP scenarios, respectively as compared to that in RES. In Scotland, the increases in energy system cost are £1,066 million and £1,822 million, respectively. For the UK as a whole, energy system costs increase by £529 million in the SRP and £918 in the SHRP. This is because the model's deployment of renewables at the UK level is driven by the renewable energy directive requirement of 30% renewable electricity. The additional targets in Scotland result in a deviation from the least-cost solution to meeting that target, such that when constrained to meet Scottish targets the model deploys renewables in Scotland that are more expensive than the renewables it would have deployed in the rest-of-the-UK.

Our analysis suggests that meeting Scottish renewable energy targets in 2020 would add to the costs of meeting the UK's obligations under the renewable energy directive, with an increase in the total discounted energy system cost of £918m. This figure should be regarded with caution for several reasons. First, the representation of onshore wind, a key renewable resource, does not take into account Scotland's higher average wind speeds. Second, the model assumes that the delivered costs of renewable energy are not brought down in response to Scottish policies introduced to support the target, such as a more favourable planning approvals system, or support for the development of a supply chain. Both of these factors mean that the size of the costs may be overstated in these results.

However, if this finding of additional costs implied by Scottish targets is real, this begs the question of who would bear those additional costs. Under current policy mechanisms and market structure, the additional costs of renewable energy support are borne by consumers across the UK. If this remains the same, the additional costs of deploying renewables in Scotland rather than wherever they are cheapest would result in a transfer of wealth from the rest of the UK to Scotland, since consumers across the UK would bear the additional costs, while Scotland would receive the additional investment.

6.4.2. *Transmission from Scotland to the rest of the UK*

Focusing renewables development in Scotland through higher Scottish renewables targets (SRP and SHRP) increases net flow of electricity from Scotland and to rest of the UK (Fig. 14). The net electricity flow from SCT to RUK in 2020 under RES is about 40 PJ, slightly more than the present value of about 30 PJ. Net electricity flow in 2020 will be 50% higher under SRP (65 PJ) and more than double under SHRP (85 PJ) as compared to RES, requiring early upgrading of transmission capacity between the regions. Since MARKAL is not a network model, we are unable to quantify additional investment costs associated with those upgrades.

6.5. *No nuclear scenarios for Scotland*

Sensitivity analysis has been carried out in RES, SRP and SHRP scenarios to examine the implications of Scotland's 'no nuclear' policy. Running the UK2R MARKAL model with no new nuclear plants for the Scotland shows a medium-term increase (to 2035) in renewable electricity generation compared to the scenarios that allow building new nuclear plants in Scotland, but the effect of excluding renewables on nuclear is small, and has disappeared by 2050 in these runs. Under no nuclear scenarios, nuclear generation in RUK slightly increases while Scottish nuclear generation is replaced by co-firing (coal + biomass) CCS, and there is a small rise in the UK-wide energy system cost. However, the findings here may be influenced by the way in which multi-regional MARKAL represents separate regions. The apparent trade-off between nuclear and co-firing CCS may be a result of the requirement for each region to satisfy peak margin requirements domestically. It would therefore be unwise to draw strong conclusions about the trade-offs between nuclear and other technologies from these sensitivity scenarios.

7. Discussion and conclusions

This paper analyses the energy, economic and environmental implications of UK and Scottish climate change and renewable energy targets using a newly developed UK2R MARKAL model.

The analysis suggests that Scottish climate policy is less stringent[7] than UK climate policy in terms of the marginal costs implied by the UK target. A possible conclusion here is that Scottish carbon targets are unnecessary. Alternatively, we can understand the value of Scottish carbon targets as augmenting UK targets, by providing additional confidence for investors in carbon reductions in Scotland. Scottish targets can thus be seen as

[6] All costs are given in year 2000 Pounds Sterling.

[7] The term 'stringent' is used here in the sense of how tightly a target or constraint binds on a system. Tight targets that are more difficult to meet are more stringent, targets that are easier to meet (i.e., at a lower marginal cost) are less stringent.

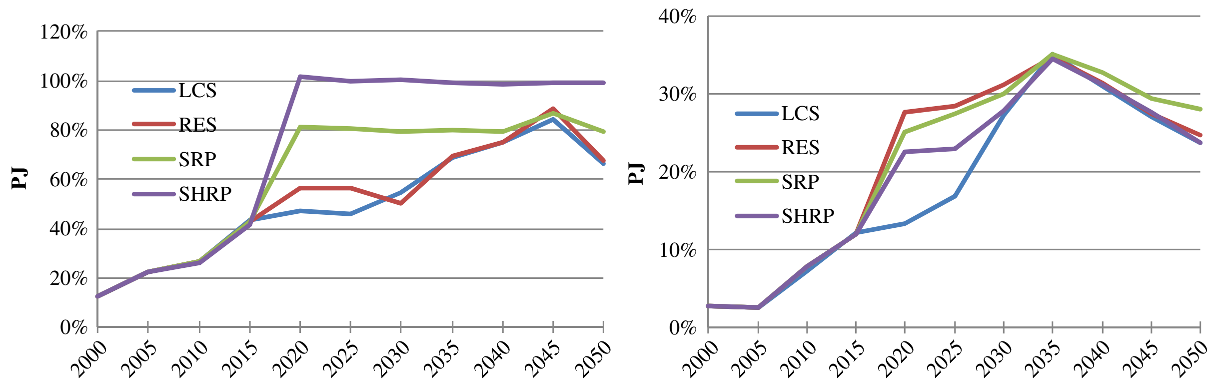

Fig. 13. Share of renewables in SCT and RUK in different scenarios.

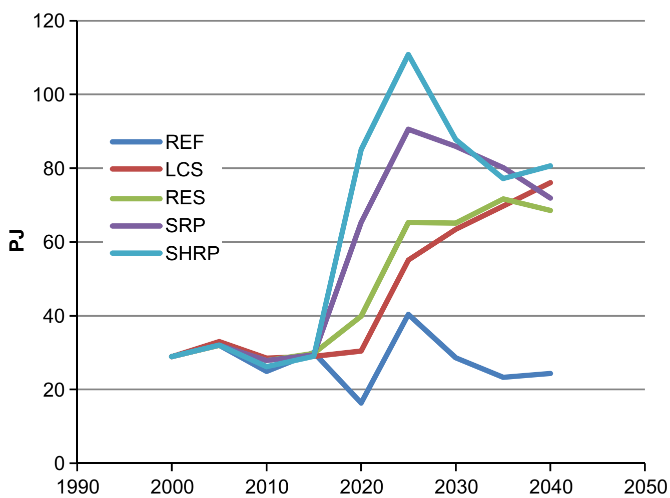

Fig. 14. Net annual electricity flow from Scotland to rest of the UK (2000–2040).

reducing the risk that UK-level policies fail to meet UK targets. The political effects of Scotland's deeper quantitative ambition may also be important, and indeed it has been argued that Scotland's draft climate change act was instrumental in the UK raising its ambition from 60% to 80% in the landmark 2008 Climate Change Act (Reid, 2009). Rather than being redundant, Scotland's targets can thus be seen as complementary.

Results on renewable electricity targets suggest that Scottish renewables targets are more stringent than UK targets. As expected, this increased stringency leads to additional costs. As well as these extra costs, the results show that there is a reduction in renewables deployment in the rest-of-the UK when Scottish renewables targets are met. Scottish renewable electricity targets simply divert investment in renewables from rest of the UK to Scotland. In addition to increased energy system costs, meeting Scottish renewable electricity targets seems likely to require early investment to increase electricity transmission capacity between Scotland and rest of the UK, given the increasing power flow between regions.

However, there may be strong reasons why these additional costs are justified, because of other, off-setting benefits from more-stringent sub-national policies (Goulder and Stavins, 2010). In particular, the potential for sub-national experience and policy to further improve and strengthen national-level policy is highlighted. Furthermore, it should be noted that the model does not take into account the possibility that the UK may fail to meet its renewable energy directive obligations, a failure that could incur substantial penalties from the European Commission. Seen in this light, one can perhaps see the additional costs of meeting Scottish targets as a form of insurance against the risk of missing targets.

As a bottom-up model, MARKAL is unable to analyse the impact of policies on economic output as a result of increased investments in different regions (which would require a macroeconomic model), or the investment costs required for upgrading electricity transmission capacity between the regions, which requires network analysis. These are highlighted as areas for future work.

Finally, it should also be noted that the results presented here are subject to considerable uncertainties of the kind explored by Usher and Strachan (2010) and discussed throughout the paper, and more research is required to show the sensitivity of these results to such uncertainties and model assumptions.

Acknowledgement

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