Ricardo Energy & Environment

Renewable energy in Scotland in 2030

Final Report

Report for FoE Scotland, RSPB Scotland and WWF Scotland

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Executive summary

Ricardo Energy & Environment and UCL were commissioned by FoE Scotland, RSPB Scotland and WWF Scotland ("the clients") to answer the question:

"*What level of renewable energy across sectors is consistent with Scotland's legally binding greenhouse gas emissions target for 2030?"*

The emissions target for Scotland in 2030 is as specified in the Climate Change (Scotland) Act 2009, and works out to be around 28.1 million tonnes of CO_2e.

To answer this question, we used the well-known MARKAL model[1] to find the minimum cost approach to Scotland meeting its targets. MARKAL is an optimisation model which looks for the least cost path to meeting an emissions objective, given constraints on energy demand and supply (such as limits on how much fuel can be imported, or how much demand will grow in future). We used a MARKAL model that splits the UK into two regions: Scotland and the rest of the UK. Because the two regions have a highly connected energy system and policy regime, the model looks at the best solution *for the UK,* consistent with Scotland's emissions targets. We have also, because the ultimate objective is emissions in 2050, optimised over the period to 2050, not 2030.

We ran a number of scenarios and calculated the level of renewable energy in each scenario for electricity, heat and transport. Since MARKAL does not include international aviation, land use or forestry, all of which are covered by Scotland's emissions target, we adjusted the emissions target that MARKAL had to achieve to reflect this. We also calculated an overall renewable energy target although as discussed later, there are issues with this.

The results of any model are only as good as its inputs, and so a major part of our work was to update the model's inputs. Our sources are listed in the text but we drew heavily on published technology costs from the Department of Energy and Climate Change (DECC), the Committee on Climate Change (CCC) and Ricardo-Energy & Environment's work on the Renewable Heat Incentive. We have also reviewed the existing literature on Scotland's future energy, covering all energy producing sectors. This includes Scottish Government publications such as the Second Report on Policies and Proposals (RPP2)[2] and its Draft Heat Generation Policy Statement[3] and publications by Transport Scotland[4] and Element Energy[5] on the future uptake of electric vehicles.

We also consulted on these inputs, the scenarios and draft model outputs, at a stakeholder workshop in Edinburgh. This included individuals with expertise in all types of renewable technology, individuals from the Scottish Government, and others with expertise in emissions scenarios. A key lesson from the stakeholder sessions was the need to take account of the time it takes for the stock of buildings and vehicles in a country to change. We are very grateful to them all for their freely given time and input. More details on their comments can be found in the main body of our report.

Before proceeding to the results, there are two important caveats to state, which to some extent apply to all modelling results.

First, it should be said that our MARKAL model is an approximation of the real Scotland, and cannot capture all the complexities and rich detail of the country – no model can. The real Scotland in 2030 will no doubt present a more complex energy picture than is shown in this report, and the inclusion or exclusion of a particular technology in our results does not mean that it must, or cannot, be part of that picture.

[1] Specifically, the 2R MARKAL model developed by UCL, which covers the UK with Scotland shown as a separate region. 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, the 2008 Climate Change Act and the Committee on Climate Change's suggested carbon budgets and the government's responses to them.
[2] Scottish Government, 2014, Low Carbon Scotland: Meeting our Emissions Reduction Targets 2013-2027: The Second Report on Proposals and Policies
[3] Scottish Government, 2014*, Towards Decarbonising Heat: Maximising the Opportunities for Scotland*. Draft published for consultation at: http://www.gov.scot/Publications/2014/03/2778
[4] Transport Scotland, 2013, *Switched-On Scotland: A Roadmap to Widespread Adoption of Electric Vehicles*. http://www.transportscotland.gov.uk/sites/default/files/documents/rrd_reports/uploaded_reports/j272736/j272736.pdf
[5] Element Energy, 2009, *Electric Vehicles in Scotland: Emissions Reductions and Infrastructure Needs* http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/05/EVs_in_scotland_final_report_Nov.09.pdf

A model is also not a crystal ball, and it does not show how the future *will* or *must* be. The results that a model produces are best seen as *possible* pathways which show how Scotland *could* achieve its 2030 emissions target.

With those caveats in mind, we now turn to look at the three scenarios developed for this study, in consultation with the clients (i.e. FoE Scotland, RSPB Scotland and WWF Scotland). These are shown in table E1 below.

Table E1: Scenarios

Scenario	Description	Key assumptions
Baseline	Emissions set to follow the trajectory set out in RPP2	All RPP2 policies (but not proposals) deliver their full expected emissions reduction Note that the 2030 Climate Change (Scotland) Act target is *not* achieved under this scenario
RPP Optimistic	Assumes all RPP2 policies are achieved and then the least cost set of additional measures is chosen to meet the 2030 target	• Policies in RPP2 are achieved • Oher policies are chosen to achieve the 2030 emissions target at least cost • Electricity emissions in 2030 are 50g CO_2/kWh • There is one 400MW CCS unit. No other new fossil fuel generation • Biomass limited to levels that can be sustainably produced in Scotland[6] • 5% biofuels in transport
RPP Realistic	As RPP Optimistic, except some of the policies in RPP2 are assumed to only partially deliver, and some emissions in other sectors are higher than expected. This means that additional emissions reductions are needed, over and above those in "RPP Optimistic"	As above, except: • Only half of expected savings from increased tree planting are achieved • 70% waste recycling target achieved in 2030 rather than 2025 • International aviation emissions grow in line with UK Government central forecasts rather than staying flat • Smart meters, Green Deal and ECO deliver half expected savings in domestic sector • Heavy Goods Vehicles do not convert to compressed natural gas (CNG)

A fuller description of our scenarios is in section 5.

[6] Which we calculate to be around 22 PJ per year. This is around 1.2 million oven-dried tonnes (odt). It is based on our estimate of what could be supplied from Scottish forestry and energy crop sources, and works out to something less than 10% of final energy demand, which is the sustainability figure produced by the CCC and by DECC's 2012 Bioenergy review. We also allow the use of waste for bioenergy.

Research questions

In commissioning this study, the clients set out a number of research questions for us to answer. We list these below, and provide summary answers which are expanded on in the text.

What is the relative role of renewable energy consumption in transport, heating and electricity in 2030?
Renewables account for 40% of heat demand, 18% of transport demand, and around 145% of electricity demand. The electricity figure is driven by the decarbonisation of the electricity generation sector, which is already on trend in Scotland, and much of the output is exported to the rest of the UK as now. The major change in our results is the significant increase in renewable heat, to a level consistent with the Scottish Government's ambition of significant progress on renewable heat by 2030.

What proportion of total energy consumption must be from renewable sources if Scotland is to meet at least a 60% (below 1990) ghg emissions reduction by 2030 and be on the least cost path to at least an 80% reduction by 2050?
Our "RPP Optimistic" scenario shows 44%, while "RPP Realistic" shows 48%, calculated on the same basis as the Scottish Government's 2020 renewable energy target. See Annex 3 for a detailed discussion.

What is the role of energy demand reduction in achieving the transition required by the question above scenario?
Energy demand falls by around 20% from 2010 levels, on an approximately straight line trend (approximately 1% per year). Energy demand in Scotland reduced from 2005-07 to 2010 by 6.2%[7], which is faster than the trend in our results.

What level of renewable energy consumption will be achieved under a business as usual growth trajectory?
Our analysis suggests around 31% - that is, slightly beyond the Scottish Government's 2020 target of 30%.

What are headline macroeconomic effects of the proposed target vs the BAU scenario?
We see significant increases in renewable electricity, and studies suggest[8] that around one net job is created for every GWh per year from wind, which would imply around 14,000 additional jobs in our "realistic" scenario compared to the baseline. We also see a significant reduction in imports of fossil fuels, particularly petrol and diesel, which is likely to improve energy security.

There is little difference in net cost to the Scottish economy between our scenarios.

What are the main co-benefits of the target (i.e. what are the wider societal benefits from the transition)?
Apart from the increased employment and reduced import dependence noted in the previous answer, we can expect significant improvements in air quality with the reduction in the use of petrol and diesel. This will have significant health and quality of life benefits. Reductions in traffic noise, because electric vehicles are quieter, is also likely.

What are the key environmental constraints (e.g. risks to wildlife) on achieving the target and how can any risks be minimised?
We expect these to be very limited, with careful management. There is sufficient wind energy already consented or operational to achieve the onshore wind output required in our scenarios. Other renewables can have minimal impact, provided they are well-sited.

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[7] Source: RPP2, page 104
[8] UKERC, 2014, *Low carbon jobs: The evidence for net job creation from policy support for energy efficiency and renewable energy* http://www.ukerc.ac.uk/publications/low-carbon-jobs-the-evidence-for-net-job-creation-from-policy-support-for-energy-efficiency-and-renewable-energy.html

What are the critical policy steps required by UK and Scottish Governments to secure the energy system transformation identified under Q1 above and to what extent are these spelt out in the Scottish Government's Report on Proposals and Policies?

The first critical step is to decarbonise the power sector. This (specifically, a 50g/kWh target) is set out in the Electricity Generation Policy Statement and mentioned in RPP2. Continued support for renewables deployment, both as subsidy and through action to facilitate planning and grid connection, is likely to be required. Our analysis suggests achieving the 50g target is not compatible with new unabated fossil fuel power stations.

The steps in the heat sector relate to deployment of heat pumps at wide scale – to the extent that they are the standard heating technology. This will require continued subsidy (although possibly not for the whole of the 2020s). The Renewable Heat Incentive is included in RPP2, but it is not clear that it is funded into the 2020s. Long term policy certainty is important. Additional policies to overcome consumer lack of awareness or reluctance around heat pumps will be important. It is not clear that these are included in RPP2. Further pushes on building energy efficiency will be needed to maximise the benefits of heat pumps. The RPP2 does not show the Scottish Home Energy Efficiency Programme continuing beyond 2017.

In the transport sector, the key steps are those to encourage electric and hybrid vehicles, particularly in the non-domestic vehicle sector. The main barriers to such vehicles are high upfront cost, lack of charging network, vehicle range and consumer acceptance. These barriers are lower where vehicles travel many miles per year, where they charge at the same place on a regular basis, and where their range is relatively limited.

RPP2 includes a Green Bus Fund, which supports the uptake of low carbon buses in Scotland. It is not clear what the lifetime of this fund is, or how it will support the move beyond demonstration stage. RPP also includes the objective to have an EV charging network in cities by 2020. This should support decarbonisation of vehicles that only travel within cities, but a wider network is needed to support widespread electric vehicle uptake. Other policies could focus on the benefits of EVs – particularly where they reduce emissions such as from diesel engines. Charges on more polluting vehicles (e.g. a congestion charge) or creating zones where only vehicles with very low emissions can enter, can also be considered. These are not discussed in RPP2.

What are the critical assumptions underpinning the required growth in renewable energy?

The first assumption is that all the GHG reduction policies deliver, not just the policies that will help deliver renewable energy. Those policies, and renewable energy policies, will together deliver the 2030 Climate Change (Scotland) Act emissions target. If the policies that are not about renewable energy do not deliver as expected, the renewable energy policies will need to deliver greater reductions.

The second relates to probably the key renewable energy technology in our results – heat pumps. Installing them in around half of Scotland's homes will require, in effect, all heat system installers to be qualified to specify and install heat pumps and recommend installing them. This may need policy support (e.g. for training).

Finally, while electric vehicles can be cost-effective, particularly for high-mileage vehicles, user acceptance will be important in driving uptake.

What role do decentralised and community-owned renewable generation play in achieving this 2030 RES target and how can this contribution be maximised?

Our results do not distinguish between community, decentralised and other electricity generation. We note that significant additional renewable heat and transport are required, and a community focus on these might help to drive necessary uptake.

A review of the literature suggests that communities need to see clear benefits in participating in renewable energy projects, and that partnerships between communities, developers and municipal authorities can be beneficial. It also notes that barriers around electricity grid connections and becoming a licensed electricity supplier can be off-putting. There are fewer barriers for community-owned heat and transport projects, due in part to fewer regulations and licence requirements.

Results - detail

We now discuss the detail of our results starting with the renewable energy figures.

As noted in table E1 above, we ran three scenarios, "Baseline", an "RPP Optimistic" and an "RPP Realistic". The renewable energy figures for each by sector are shown in table E2 below.

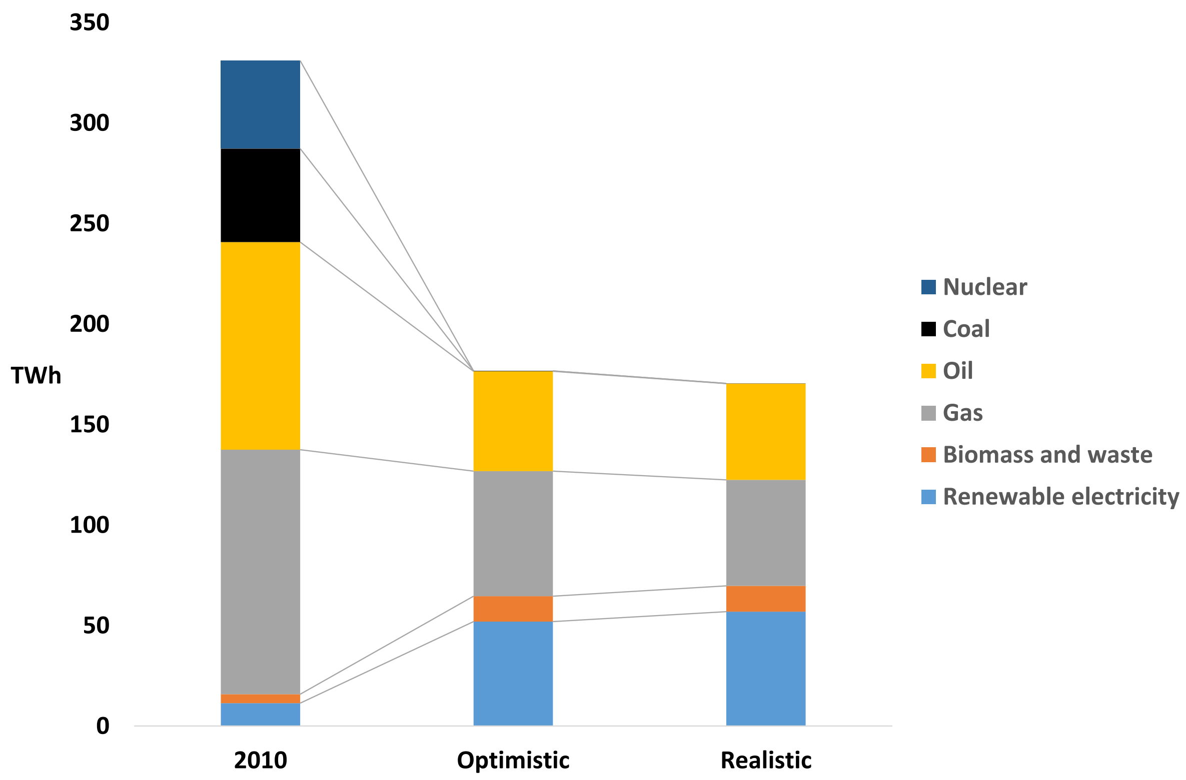
Table E2: Renewable energy targets by sector in 2030[9]

Scenario	Overall	Electricity	Heat	Transport
RPP Optimistic	44%	145%	36%	11%
RPP Realistic	48%	143%[10]	40%	18%

By contrast, in our Business As Usual scenario we see around 31% renewable energy by 2030.

Figure E1 shows how Scotland's fuel mix changes between 2010 and 2030 in our scenarios.

Figure E1: Primary energy demand by fuel



[9] In the RPP Optimistic scenario less renewable energy is needed as policies for other GHG reductions make a greater contribution, for RPP Realistic the reverse assumption applies.

[10] This figure is the ratio of supply to demand for electricity. It is slightly lower than in the "optimistic" case because while there is more renewable electricity supply in the "realistic" case, there is also more demand from more electric vehicles. The net effect is to slightly reduce the %, although the difference is very small as can be seen.

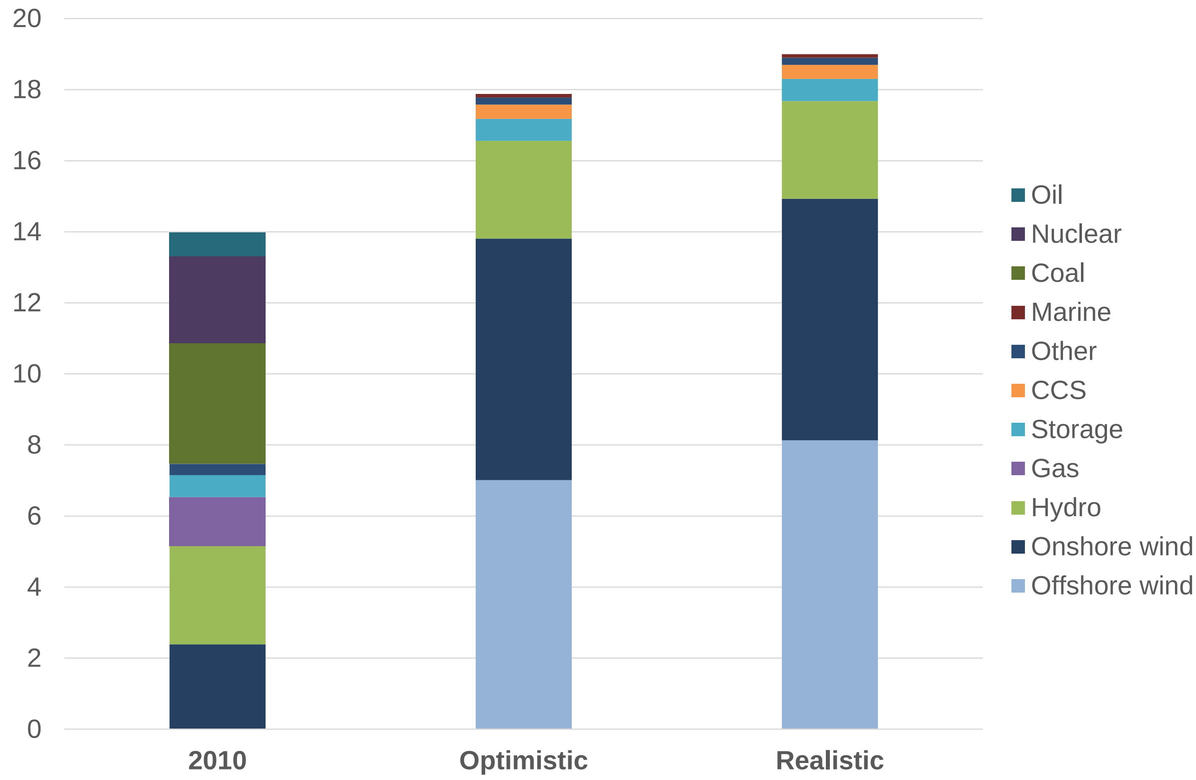
This shows nuclear and coal demand disappearing, as expected. Demand for oil also shrinks[11]. Demand for gas reduces, although not as much as oil does, since gas is still used for heating particularly in the industrial and domestic sectors and in an abated gas fired power station. The major increase is from the supply of renewable electricity, in blue above. This increases by a factor of around five over the 15 years that we consider (2015-2030). As a comparison, supply more than doubled in the five years between 2010 and 2015.

This increase in renewable electricity reflects the fact that the "RPP Optimistic" and "RPP Realistic" scenarios are both highly electrified. We now consider the electricity sector in more detail; similar sections for the heat and transport sectors follow.

Results: electricity

The electricity sector consists almost entirely of renewables, with a small amount of CCS and significant interconnection. The electricity mix is shown in Figure E2 below.

Figure E2: Installed electricity generation capacity in GW[12]



We do not dwell on the electricity generation mix here since it has been comprehensively covered in a recent report[13] by DNV GL for WWF Scotland, which looked at the implications of this level of renewable electricity and how it is consistent with security of supply. We summarise key conclusions of that report in Box 1 below.

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[11] For reasons of clarity, we have not shown the small negative energy figure for "refined oil". This is negative since Scotland is a net exporter of oil, as shown in its official energy balance figures (Scottish Government, 2015, *Energy in Scotland 2015.* The table in Annex A shows "Primary Demand, Petroleum products" as negative 2.7 million tonnes of oil equivalent)
[12] 2010 figures are sourced from the Scottish Government: http://www.gov.scot/Publications/2012/05/8985/3
[13] DNV-GL, 2014, *Analysis of Implications of a Decarbonised Power Sector in Scotland by 2030*
http://www.gl-garradhassan.com/assets/downloads/Technical_Report_WWF_Scotland_-_Nov_14.pdf

Box 1: Selected conclusions of DNV-GL study into electricity in Scotland in 2030

> The study looked at whether electricity supply in Scotland would be secure, if decarbonised by 2030. It concluded:
>
> "*Electricity supply in Scotland will be secure if the combined GB system is secure. National Grid studies for high-renewables cases show that this is achievable"*
>
> Another possible challenge to our scenarios is that they contain only 400MW of gas (with CCS), and the system needs more gas generation to be stable. The DNV-GL report concluded:
>
> "*With the transmission capacity to the rest of the GB currently existing or planned, there is little or no need for conventional generating capacity in Scotland to maintain security of supply, even in periods of low renewables production*"
>
> The study also looked at what additional infrastructure or generation would be needed. It concluded:
>
> *"No additional infrastructure is needed for the scenarios investigated in this study beyond that already planned, except (in some cases) some further transmission reinforcement…with strong efforts on energy efficiency and demand reduction in Scotland, the volume of renewable generation already existing or under construction will get Scotland close to the target of 50g/kWh well in advance of 2030"*

This is a significant increase in currently installed wind generation. However, there is already significantly more (20GW) of renewables either operational, under construction or with planning consent in Scotland. It is also important to note that our scenarios show more generation than is required to satisfy *Scotland's* electricity need, because from a UK perspective, making use of Scotland's excellent wind resources to satisfy UK demand makes economic sense at UK level and offers supply chain economic opportunities in Scotland.

This point is important, and so needs clarifying. Our MARKAL model is a UK model, which shows Scotland as a separate region. Since many of the electricity policies in place cover the whole of the UK (such as the CFD FIT) it makes sense to consider the UK as a whole when deciding where renewable electricity generation is sited. As is the case today, our scenarios show Scotland having more than its share of renewable electricity generation in the future, and being a net exporter of electricity. This could represent an economic opportunity – an opportunity for supply chain businesses.

It should also be said that not all of the renewable generation in our scenarios needs to be built to satisfy Scotland's electricity demand. Since renewable generation in our scenarios supplies nearly 1½ times what Scotland needs (on an annual basis), around one-third of it could be removed and Scotland could still meet its annual electricity demand from renewables, on average. This latter position is of course the Scottish Government's ambition for 2020.

Turning now to the demand side, it should also be pointed out that electricity demand only grows by around 11% (RPP Optimistic scenario) because of higher efficiency in the demand sectors.

In fact, if we consider the overall picture for a moment, overall demand for energy falls by around 20%[14]. Some of this is driven by the fact that electric heat pumps and electric vehicles are both around three times as efficient as their fossil fuelled counterparts, and some by increases in other energy efficiency measures such as insulation.

This fall in demand is not a surprise. Recall that the objective set for the MARKAL model was to reduce carbon emissions by 2030 at least cost. There are essentially four ways to do this:

- Reduce demand (e.g. reduce passenger-km)
- Energy efficiency (LED lighting)
- Switching to lower carbon fossil fuels (i.e. gas)
- Renewables

[14] 18% in "RPP Optimistic", 21% in "RPP Conservative"

MARKAL does not reduce demand – indeed passenger-km increase. It projects a good deal of energy efficiency improvement, reflecting the fact that this is often at low or negative lifetime cost. It also pushes some fuel switching particularly in the industrial sector. Renewables are therefore only part of the emissions reduction story. However, since MARKAL is likely to be optimistic on energy efficiency, since it looks at lifetime cost which is not how consumers make choices, it is likely to be if anything conservative on the level of renewable energy required. Our results should therefore be seen as representing the minimum level of ambition required.

Turning now to the heat and transport sectors, the key measures are heat pumps and electric vehicles respectively. We discuss each of these in turn.

Results: heat

Deep decarbonisation of the heat sector is driven by the roll-out of heat pumps (either stand-alone or hybrid - a combination of a gas boiler and a small electric heat pump). These become widespread in domestic and other non-industrial buildings, providing around half of domestic heat and slightly more than that for commercial and public buildings. For industrial heating, we see some uptake of biomass but there is less of a shift.

It should be noted that even in the “business as usual” run, MARKAL calculates that heat pumps would be economic in many buildings in the 2020s. This is consistent with the CCC’s view in its fourth carbon budget[15]. We return to this in our policy recommendations section.

Results: transport

In the transport sector, the picture is more complex. We show lower levels of renewable energy, but transport demand falls by around a third (in heat, it falls by around a fifth, even though there is more renewable energy). Part of this is from the increased efficiency of hybrid vehicles. These are not[16] renewable, but they do reduce emissions since they use much less petrol or diesel per km. As fully electric vehicles enter the fleet, these also have increased efficiency, but will in effect be fuelled from zero or very low carbon generation (renewables or CCS).

In terms of vehicles, the majority of light goods vehicles and buses are hybrids by 2030. These are high mileage vehicles, and so the higher initial cost of a hybrid can be offset by the lower running costs compared to standard petrol or diesel buses and vans. We see a limited number of electric passenger cars in the “RPP Optimistic” scenario, but in the “RPP Realistic” scenario around 20% of passenger cars are battery vehicles. Battery buses start to make major inroads from the mid-2020s.

In summary, we see some level of renewable transport vehicles in the 2020s, but there is less than might be expected because of the increased efficiency as a result of hybridisation and electrification.

In the next section, we look at the major impacts of our scenarios, starting with costs.

Costs

We calculated the cost of the scenarios as a net cost, compared to the “base” scenario. This involved looking at total cost and discounting the annual cost from 2015 to 2050 at the standard 3.5%[17] real social discount rate.

Our analysis shows that the costs are less than the value of carbon saved.

Macro-economic impacts

As far as overall macro-economic impacts are concerned, we see a shift away from the need for petrol and diesel retailers, and towards renewable fuel vendors. Increased employment in the electricity sector is also likely. A study by UKERC suggests that the levels of renewable electricity in our scenarios could lead to an extra 14,000 jobs from wind. We also see significant reduced net imports of petrol and diesel, since demand falls by 40%.

[15] CCC, 2010, *The Fourth Carbon Budget - Reducing Emissions Through the 2020s.* http://www.theccc.org.uk/publication/the-fourth-carbon-budget-reducing-emissions-through-the-2020s-2/
“*We estimate [the] average cost of heat pumps from -£18 per tonne of CO_2 abated (i.e. heat pumps reduce costs) for ASHP to £7 for GSHP*”

[16] Except plug-in hybrids, which can be partially powered by renewable electricity

[17] Source: HM Treasury Green Book

This is similar to the analysis by Cambridge Econometrics[18] which looked at the UK's fourth carbon budget. It estimated that there would be an additional 190,000 jobs created across the UK, and that around £8.5 billion would be saved annually in reduced fuel imports.

Environmental impacts

We also considered environmental impacts in a qualitative way. Since the major infrastructure development in our results is new wind generation, at levels not much above what is already in the planning process in Scotland, the *additional* environmental impact of our scenarios should be low.

We expect a number of positive environmental benefits to flow from the scenario. The main one would be improved air quality in cities as a result of the 40% drop in the use of petrol and diesel. This is likely to have health benefits, although these are not possible to quantify accurately without a more detailed, spatial, model. Cambridge Econometrics, in the study referenced in the previous section, estimated UK-wide healthcare savings of between £96m and £288m per year. Reduced traffic noise (since electric vehicles are quieter) is also likely, as noted by Transport Scotland in its report[19].

Community and decentralised energy

We also considered the role of community and decentralised energy. Our results suggest that while there is scope for additional community renewable *electricity* projects, as the demand for renewable electricity in Scotland is significant, there is already significant other renewable electricity in the pipeline, compared to requirements. However, a more interesting and less explored area is community renewable heat or transport projects – community-owned heating networks, or community vehicles that are hybrids or EVs. So the role for community electricity could be to supply heat or transport. This would be an interesting area for further study, and potentially demonstration projects.

[18] http://www.wwf.org.uk/what_we_do/tackling_climate_change/how_we_re_tackling_climate_change/our_climate_work_in_the_uk/the_value_of_a_low_carbon_britain/

[19] Transport Scotland, 2013, *Switched-On Scotland: A Roadmap to Widespread Adoption of Electric Vehicles*. http://www.transportscotland.gov.uk/sites/default/files/documents/rrd_reports/uploaded_reports/j272736/j272736.pdf

Policy conclusions

Our conclusions are divided by sector.

Electricity

In our scenarios, we have assumed that the 50g target is met, with increased renewable electricity and one 400MW CCS unit. Given the renewable energy pipeline in Scotland, the level of renewable capacity installed in our scenarios is achievable given ongoing policy support and investor confidence.

One implication of this 50g target is that new unabated fossil fuel generation makes little sense. In early runs we found that it is very difficult to both achieve a 50g target and have unabated fossil fuel generation, unless it runs at exceptionally low load factors (effectively zero).

Electricity security of supply was a frequent question in our work. We point again to the work by DNV-GL referenced in our bibliography, which notes that "*Electricity supply in Scotland will be secure if the combined GB system is secure….with the transmission capacity to the rest of the GB currently existing or planned, there is little or no need for conventional generating capacity in Scotland to maintain security of supply…*".

Heat

Our analysis indicates that heat pumps (or hybrid heat pumps in the domestic sector) are economically attractive without subsidy in many cases in the 2020s. However, to get to the levels of renewable heat required in our scenarios, some support is required. This support would be to improve housing stock to make heat pumps effective, to overcome consumer barriers to uptake (such as the hassle factor, and unfamiliarity with heat pumps) and the higher upfront cost of heat pumps compared to gas boilers.

We suggest that policy here could be a combination of financial support and demonstration/ leadership. For the former, a long term continuation of the RHI would seem most appropriate given its familiarity. For the latter, the Scottish Government should consider the option of installing heat pumps in suitable public buildings.

Transport

The story here is about efficiency and a move to electrification (which our results indicate could well take off in the 2030s). Different policies are likely to be useful in the two cases.

The key difficulty with hybrid, and plug-in hybrid, vehicles from a purchaser's point of view is the higher initial cost. This needs to be balanced against the lower running costs – in some cases, this can already have a reasonable[20] payback period of under five years (e.g. for so-called "mild hybrid"[21] buses). This period, under our assumptions, becomes shorter over time as hybrid technology improves.

There are already policies in place, such as the Scottish Green Bus Fund, to help with the cost of electric vehicles. Extensions of this could particularly focus on organisations with high mileage or vehicles with a duty cycle that is particularly suitable for hybridisation or electrification. As it has previously suggested, the Scottish Government could lead by example. Other options include a leasing model, which would spread the high upfront cost more evenly over the lifetime of the vehicle. This could benefit from policy support.

The delivery of a charging network, as already envisioned by the Scottish Government, will also be crucial. Element Energy's report on this for the CCC notes that at current rates of deployment (including from funding from the Office for Low Emission vehicles (OLEV)), they anticipate around 160,000 UK charging points by 2020, against 260,000 BEVs on the road by 2020. They note that this "*...suggests a steep acceleration in domestic/depot [charging point] installation will be necessary to support the EV pathway…of around 40% being required*"

[20] See for example http://www.ricardo.com/Documents/PRs%20pdf/PRs%202013/Preparing%20a%20low%20CO2%20roadmap%20for%20buses.PDF
[21] This includes, typically: engine stop/start; regenerative braking; torque assist; and limited electric only mode.

Finally, HGVs present an interesting situation. Our figures show that both CNG conversion, and plug-in hybrids, are economic by 2030. Unconstrained, MARKAL shows significant uptake of both. However, given the practical issues associated with converting internationally mobile vehicles such as most HGVs, we have conservatively assumed limited conversion to these technologies. Since, in MARKAL, "HGV" represents any van over 3.5 tonnes, this may be overly conservative. The Scottish Government could consider policies to promote low or zero-emission vehicles particularly those in cities, such as low-emission zones or charging points at appropriate sites for logistics operators.

Other sectors

We have not focused on sectors not covered by the MARKAL model, such as international aviation, agriculture and land use and forestry in this report. However, Scotland's emissions will be determined by the total action across all sectors, including these ones. Therefore, the less that is achieved in these, the more that will need to be done in the heat, electricity and transport sectors to achieve the Scottish Government's targets. We have tried to make realistic assumptions about the future pathways of those, based on the RPP2 report and other sources. However, even those assumptions in the "RPP Realistic" scenario are by no means a worst case. This suggests that aiming only for 44-48% renewable energy risks missing the emissions target in the Climate Change (Scotland) Act.

Conclusions

Our analysis sets out possible futures for Scotland that are consistent with the Climate Change (Scotland) Act 2009 target for 2030. We show a Scotland which is powered to a very large extent by renewable electricity, generated in Scotland from its abundant wind resources. Around one third of this renewable electricity is exported to the rest of the UK. The level of wind power leads to thousands of new jobs.

In buildings, heat pumps provide nearly half of Scotland's heat in 2030, and are a common sight in homes and (particularly) commercial and public buildings. Electric vehicles are commonplace – indeed, most new cars are electric – and public and city logistics are heavily decarbonised, with the attendant benefits for air quality, noise and health. Total costs are limited, and easily justified by a carbon price well below the social cost of carbon.

We also see a much more integrated energy system. Electricity is used much more widely across the economy to provide both heat and transport. Management of this demand is likely to be increasingly important in future. In that regard, we note that MARKAL has chosen to use hybrid heat pumps in homes. They have a number of potential advantages. One in particular is the fact that, compared to a stand-alone heat pump, the electricity demand from a hybrid heat pump is lower. Since heating will be heavily used at peak electricity demand times (winter), it has the potential to add significantly to the electricity peak demand, which would require additional generation, transmission and distribution expenditure. Hybrid heat pumps could lessen this. On the transport side, the potential for electricity storage in vehicles, while not covered by our model, should be considered in any demand management scenario. The different duty cycles of different vehicles should also be considered, and it may be sensible to give priority to electrification for vehicles which do not necessarily get charged at peak times.

Table of contents

1 Introduction

This is the final report for the project conducted by Ricardo Energy & Environment, in conjunction with University College London (UCL), on renewable energy targets for Scotland for 2030.

The project was for WWF Scotland, Friends of the Earth Scotland and the RSPB Scotland, ("the clients") and this report is addressed to them.

The key question for this study was "*What level of renewable energy is consistent with Scotland's legally binding greenhouse gas emissions target for 2030?"* We answered this using the MARKAL[22] model, a well-known bottom-up optimisation model that has been extensively used for long-term energy system planning in the UK[23] and elsewhere.

The rest of this report is structured as follows. We start by describing the context to this project, such as the existing climate change and renewable energy targets, goals and ambitions in Scotland, the UK and Europe. We then describe our methodology, including the use of the MARKAL model and how we tested the draft results coming from the model with stakeholders. MARKAL uses a very wide range of assumptions, and the next section sets out the key assumptions that we set specifically for this project. We also describe the three scenarios that we considered. We then move on to describe our key results, including the overall renewable energy figure, how that is divided between electricity, heat and transport, and some of the implications of our scenarios. Finally, we present our overall conclusions. There are also a number of supporting annexes including additional detail on assumptions, results and the operation of the MARKAL model, as well as a list of references.

Finally, we would like to thank FoE Scotland, RSPB Scotland and WWF Scotland, for commissioning this very interesting and valuable project and providing valuable guidance, and all the stakeholders who generously gave their time to comment on early draft results from our work.

[22] Documentation for MARKAL can be found on the International Energy Agency's website, under the IEA's Energy Technology Systems Analysis Program, at: http://www.iea-etsap.org/web/Markal.asp . This also includes lists of the countries which use MARKAL (over 40, at the last count).
[23] See for example: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48072/2290-pathways-to-2050-key-results.pdf

2 Background and context

This section sets out the context for our work, particularly the policy context for renewable energy and greenhouse gas emission reduction targets. We start, however, by briefly considering where Scotland is today – where does its power, heat and transport fuel come from?

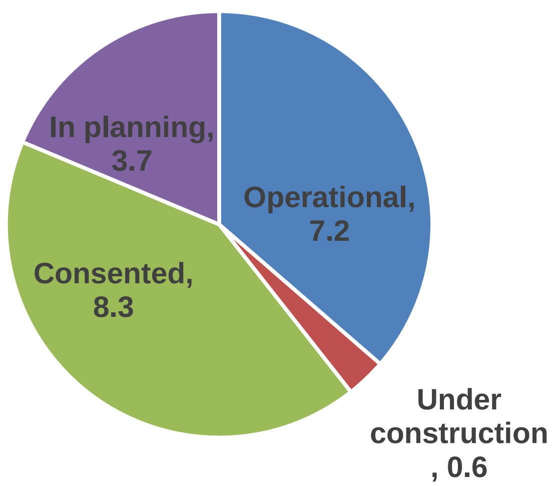
2.1 Current situation

The following sections cover, respectively, the current electricity, heat and transport energy situation for Scotland.

2.1.1 Electricity

In 2014, renewables in Scotland provided 18,959 GWh[24], which is estimated as 49.6% of Scotland's total electricity consumption. Scotland's current renewable electricity generation pipeline[25] is as shown in Figure 1 below.

Figure 1: Scotland's renewable electricity generation pipeline (figures in GW)



As at the end of 2013, Scotland also has a number of fossil-fuel and nuclear power stations, as set out in Table 1 below.

Table 1: Non-renewable capacity in Scotland[26]

Fuel	Capacity in MW	Output in 2013 in GWh
Nuclear	2,289	18,498
Fossil fuel	4,118	16,990

By 2030, the policy as set out in RPP2 is to have an emissions intensity of no more than 50g of CO_2 per kWh. The Scottish Government notes that this represents an 83% reduction in carbon intensity from 2011 levels (289g)[27].

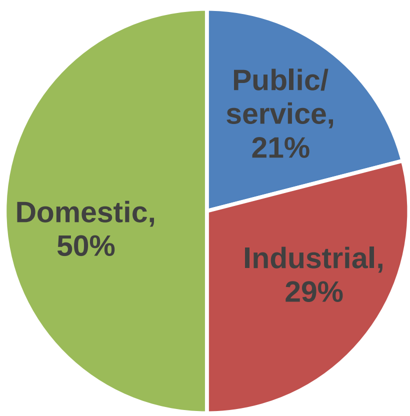
[24] Scottish Government, March 2015 , *Renewable Energy Statistics for Scotland* http://www.gov.scot/Resource/0047/00474200.pdf
[25] ibid
[26] Source: Digest of UK Energy Statistics, table 5.7. Transmission Entry Capacity (TEC) as at December 2013, adjusted for closure of Cockenzie. Includes Longannet. Output figures from Scottish Government energy trends: http://www.gov.scot/Topics/Statistics/Browse/Business/TrendData
[27] Source: RPP2

On the demand side, the Scottish Government is committed to a 12% *energy* demand reduction by 2020. Scottish domestic electricity consumption has fallen sharply since 2005, but is still slightly above the UK average at around 4.6MWh per person per year.

2.1.2 Heat

In Scotland fuel used for heat makes up about 50% of overall energy demand, underlining the importance of heat in meeting emissions reductions and renewable energy targets. The breakdown of heat use by sector is shown in Figure 2 below.

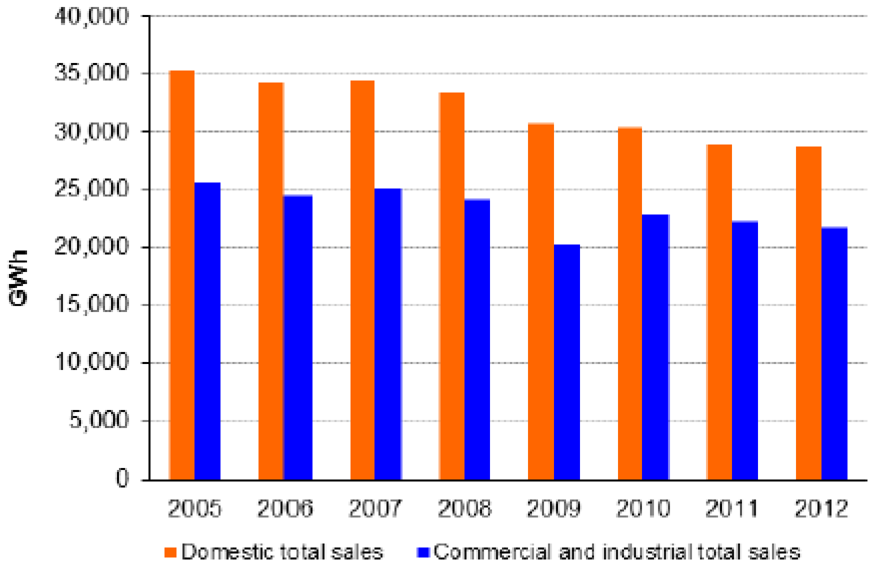
Figure 2: Split of heat demand in Scotland



While the majority of this is fuelled by gas, there is important use of oil and LPG in rural areas, as well as electricity in rural areas and flats, with an increasing use of biomass and other renewable fuels.

Figure 3 below shows the trends in Scottish gas consumption.

Figure 3: Gas consumption in Scotland[28]



[28] Source: Scottish Government, 2014, *Energy in Scotland 2014*
http://www.gov.scot/Resource/0044/00444530.pdf

This shows a flattening of both domestic and non-domestic gas usage in recent years, despite energy efficiency policies.

As far as renewable heat is concerned, in 2013, an estimated 0.662 GW of renewable heat capacity was operational in Scotland, producing an estimated 2,904 GWh of useful renewable heat[29]. The Scottish Government estimates that the current level of renewable heat is 3% of demand.

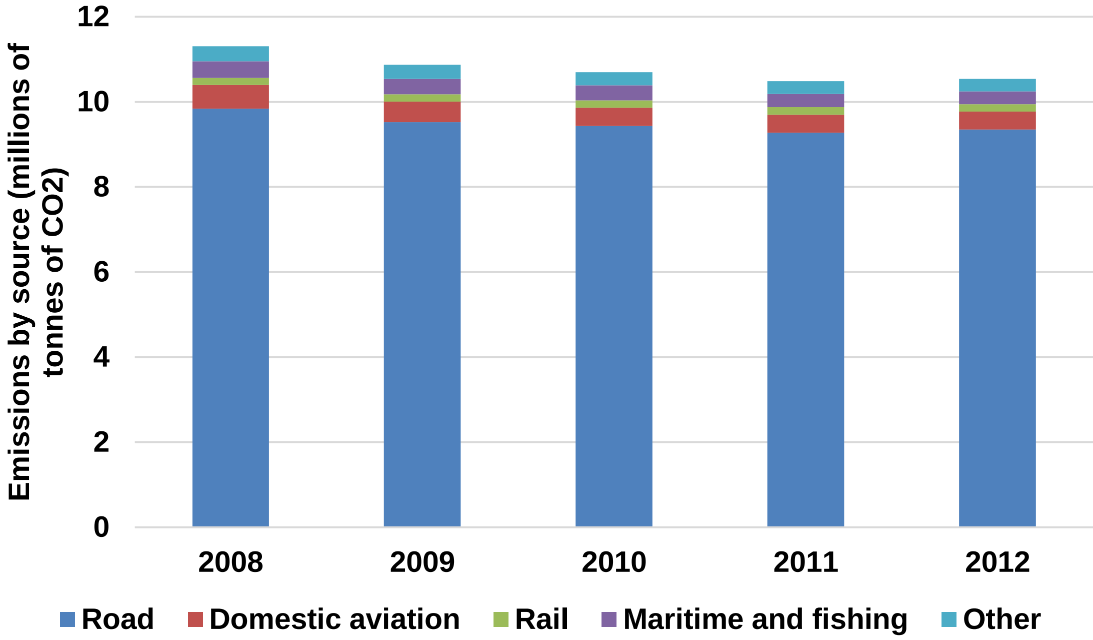
The Scottish Government's objective, as set out in the RPP, is for heat to be "*largely decarbonised*" by 2050, with "*significant progress*" by 2030. These objectives are in the RPP. However, it is not clear what "largely decarbonised" means. WWF's report on renewable heat in Scotland[30] set out three scenarios including a "high abatement" scenario of 50% renewable heat in the domestic sector by 2030 (which is more than the CCC's estimate). In the shorter term, there is a policy for 11% of demand for heat to be met from renewable sources by 2020.

2.1.3 Transport

Road transport energy consumption in Scotland per head is similar to that for the UK as a whole at around 0.55[31] tonnes of fuel per person per year. Fuel use by domestic users has fallen in recent years, while freight use has risen. The vast majority of this is fossil fuel based (biofuels account for around 3.1% at a UK level).

Further data on current transport emissions is available from the National Emissions Inventory, produced by Ricardo Energy & Environment for DEFRA. This[32] shows emissions in Scotland by type of transport – see Figure 4 below.

Figure 4: Greenhouse gas emissions by sector 2008-12



This shows road transport emissions as the major contributor, responsible for nearly 90% of greenhouse gas emissions from transport as a whole. The overall trend is a slow decline, except for rail which shows a slight increase over the period.

For transport, the ambition in the RPP is to make "significant progress" towards "almost complete decarbonisation" of transport in Scotland by 2050.

[29] Source: Renewable Energy Statistics for Scotland
[30] WWF, 2014, *The burning question: what is Scotland's renewable heat future*
http://assets.wwf.org.uk/downloads/rh_web.pdf
[31] ibid
[32] http://naei.defra.gov.uk/reports/reports?report_id=799

Again, it is unclear what "significant progress" means. A key study in this area is the 2013 work[33] by Element Energy for the Committee on Climate Change on pathways to high penetration of electric vehicles in the UK. This includes a "high uptake" pathway, which assumes "*60% market share [PHEVs and EVs] by 2030*" (that is, 60% of vehicles purchased in 2030 are PHEVs or EVs). This is equivalent to having 13.6 million PHEVs and EVs on the road in the UK by 2030.

This concludes our discussion of the current context and ambitions. We now turn to Scotland's greenhouse gas targets.

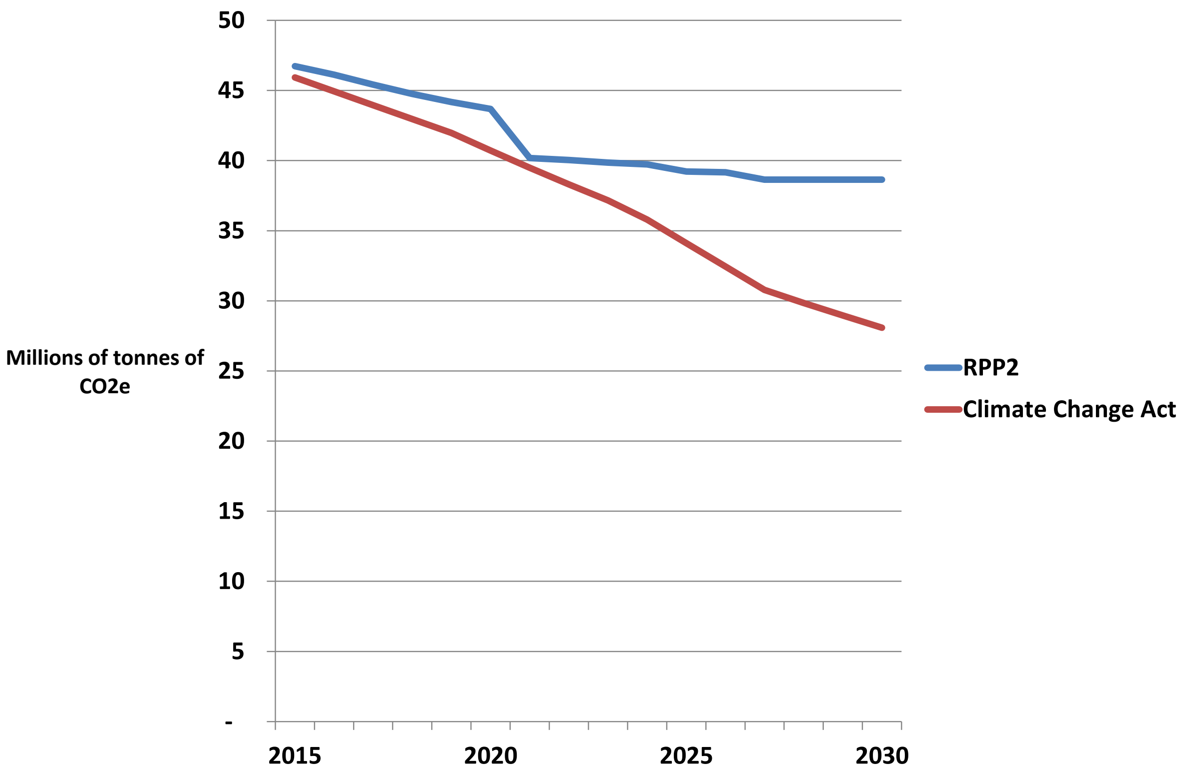
2.2 Greenhouse gas emission reduction

In this section we look at Scotland's plans, targets and policies. We start by discussing the Climate Change (Scotland) Act 2009, which sets the overall trajectory for Scotland.

2.2.1 Climate Change (Scotland) Act

This Act sets out annual targets for Scotland. The target for 2030 is 28,089,337 tonnes[34]. The key policies for achieving these targets are set out in Scotland's Second Report on Proposals and Policies (RPP2)[35]. Figure 5 below compares the impact of the policy measures in RPP2 with the requirements of the Climate Change (Scotland) Act.

Figure 5: Emissions trajectory for RPP2 policies versus required trajectory under Climate Change (Scotland) Act[36]



As this graph shows, there is a remaining gap which expands as we move towards 2030, with a total gap of over 10 million tonnes by that year. However, the RPP2 line only takes account of existing firm policies, and does not include the emissions reductions attributed to the proposals in RPP2.

[33] Element Energy *et al*, December 2013, *Pathways to high penetration of electric vehicles: Final report for the Committee on Climate Change*
[34] Source: RPP2, table 2.1, with figures beyond 2027 based on minimum 3% reduction per year as required by the Act
[35] Scottish Government, 2013, *Low Carbon Scotland: Meeting our Emissions Reduction Targets 2013-2027. The Second Report on Proposals and Policies.* Available at : http://www.scotland.gov.uk/Publications/2013/06/6387
[36] There is a significant drop in the RPP2 line from 2020, which appears to be due to a change in how emissions from sectors covered by the EU Emissions Trading System are accounted for.

2.2.2 Targets and policies

There are a number of key targets and policies are in place that will have an important influence on energy use in Scotland, across electricity, heat and transport.

We can also ask how Scotland's ambitions compare to those in the UK and the rest of the EU. This is summarised in Table 2 below.

Table 2: Targets, recommendations and estimates for 2030[37]

Item	European Union	United Kingdom	Scotland
Emissions (weighted to CO_2 equivalent)	40% reduction (EC target)	60% reduction, to 310 $MtCO_2e$ (CCC recommendation)	60% reduction (Scottish Government estimate, to meet legal obligation for 2050)
Renewable energy	27% of energy consumption (EC target[38])	40-60% of electricity generation (CCC analysis)	No figure
Renewable electricity	45% of electricity production (EC estimate to meet other targets)	No figure	No figure
Demand reduction, energy efficiency	25% reduction (EC estimate to meet other targets)	No figure	No figure
Heat	>50% of heat demand (external modelling)	No figure	'Significant progress' made towards total decarbonisation of heat sector by 2050
Transport	20% GHG reduction compared to 1990 levels (EC estimate to meet other targets)	No figure	'Significant progress' made towards total decarbonisation of transport sector by 2050

2.3 Conclusion

In summary, Scotland has already made some progress towards a decarbonised power sector, and has sufficient capacity in the pipeline to almost entirely decarbonise it. While this will need continuing support to ensure it is delivered, the decarbonisation of the electricity sector is further advanced than that of heat and transport. There is therefore a need to look harder at the latter two sectors, where Scotland has set out ambitions, but these are largely unquantified for 2030. A key purpose of this project is to start to quantify them – in particular, by showing the minimum level that they *must* reach to be consistent with Scotland's legally binding emissions targets.

[37] Source: DNV GL, 2014, *analysis of implications of a decarbonised power sector in Scotland by 2030, Scenarios Report*
[38] http://ec.europa.eu/energy/en/topics/renewable-energy

3 Methodology

This section describes how we delivered this project, using the MARKAL energy system model. This has been modified by UCL[39] to consider Scotland separately. The model has also been updated to reflect the latest assumptions in key sectors, such as technology cost, and recalibrated to match actual historic emissions and generation capacity in 2010[40].

3.1 Models vs reality

Before discussing how the model was developed, we should make it clear that, like any model, MARKAL is an imperfect representation of the real world. It is best understood therefore as a decision support tool, suggesting how Scotland *might* increase its level of renewables rather than predicting how it *would or must do so*. MARKAL results should be taken as showing that an objective is possible rather than predicting how it will be achieved.

We also note that MARKAL takes decisions about what to deploy based on the minimum lifetime cost to society as a whole. This is not how most purchasers make decisions, and so its results need to be used with judgement.

Finally, it needs to be remembered that MARKAL is a *cost-optimisation* model. It looks for the cheapest technology to deal with any given energy demand. This means that it tends to install only one technology for any given demand, unless the user inputs some constraint on the level of deployment of that technology. This is called "penny switching".

More detail about the model can be found in

[39] Anandarajah and McDowall, *Two Region UK MARKAL model documentation* https://www.ucl.ac.uk/silva/energy-models/models/uk-markal/uk-markal-two-region-version-documentation
[40] 2010 generation data sourced from Scottish Government. See table 3.1 at http://www.gov.scot/Publications/2012/05/8985/3

.

3.2 Particular modelling issues

The choice of model always involves trade-offs, and MARKAL is no exception. There are a number of issues which it does not model well, or at all, and we describe three key ones here: district heating, electricity networks and storage.

District heating is difficult to model in MARKAL because it is highly-location specific. MARKAL takes a whole country view and does not consider location at all. For this reason, it can only provide a very approximate view of the attractiveness of district heating.

In our work we have assumed that district heating grows in line with current Scottish Government ambitions. Our stakeholder discussions suggested that there were a number of practical issues to overcome for widespread district heating roll-out and so showing a relatively low level might not be unrealistic.

Second, MARKAL does not consider the need for any upgrades of electricity transmission or distribution networks. While we recognise that transmission and distribution issues remain (for example, on the Scottish islands), and it is important that planned transmission improvement proceeds, we do not see it as a major limiting factor in the long term for our study, referring to the DNV-GL report which noted that planned upgrades were sufficient to deliver sufficient interconnection for Scotland. This also limits any need for additional storage in Scotland.

Looking at electricity generation first, the level of generation already consented[41] is sufficient for our scenarios. Further details can be found in the DNV-GL report for WWF[42]. On the demand side, we show relatively limited electrification of transport (around 10% of vehicle fuel demand from electricity). Heat pumps have the potential to put increased load on the electricity distribution system, but our results show many as hybrid pumps, which potentially have a smaller electricity load particularly at peak times.

Finally, we have not modelled energy storage in any detail (pumped hydro storage is included but MARKAL does not model it on a half-hourly basis). However, in practice energy storage is used as a way of providing security of electricity supply. As the DNV-GL work points out, the Scottish electricity system is an integrated part of the GB system, and if the GB system is secure, the Scottish one will be as well. It may well be argued that our results underrepresent the benefits that storage could offer Scotland, but this would require further work to confirm, and in any case suggests that we are being conservative.

This concludes our discussion of the model methodology. We now turn to our assumptions.

[41] Clearly not every consented project is built, but 2030 is still 15 years away, and the fact of the projects being consented indicates that availability of sites is unlikely to be an issue.
[42] DNV-GL, 2014, op. cit.

4 Assumptions

This section sets out the basis of our assumptions, where these are common to all scenarios. Our scenarios are described in section 5 .

Our data was sourced from a review of the existing literature on emissions reduction and renewable energy, with a particular focus on Scotland. Key documents included the Second Report on Policies and Proposals (RPP2), the Scottish Government's Heat Strategy, and publications by DECC and the Committee on Climate Change on technology costs.

4.1 Electricity generation

We start with the costs for electricity generation. Our figures are based on those from DECC's December 2013 generation costs update[43].

MARKAL requires inputs in year 2000 prices, and in £/kW or £/GJ as appropriate (for costs based on capacity or energy respectively). We therefore converted the DECC costs to this basis.

This leads to a very long list of technologies and so for reasons of space we only show significant technologies where there have been material changes in Table 3 below. Note that the table shows current prices, except where otherwise specified. Our expectations on future technology trends are discussed later in this section.

Table 3: Updated assumptions for electricity generation

Generation type	Technology	Upfront costs (£/kW)	Fixed operating and maintenance costs (£/kW/year)	Variable operating and maintenance costs (£/GJ)
CCS	New GTCC[44] with capture in 2030	906	17	0.38
	New IGCC[45] with capture in 2030	2,281	92	0.38
Nuclear	Combined E-PWR and AP1000 (URN) – 2020	2,935	49	0.57
Wind	On shore T6 (6.5 m/s) >5MW	1,089	25	-
	Off shore New T2- Scotland East (assumed equivalent to offshore Round 2)	1,750	43	0.38
	Off shore New T4- Scotland East (assumed equivalent to offshore Round 3)	1,842	48	n/a – use existing figure
Hydro	Pumped Storage	2,353	17	1.13
	Small (1.25–20MW)	2,145	30	1.89
	Micro (<1.25MW)	3,064	71	-

[43] https://www.gov.uk/government/publications/electricity-generation-costs-december-2013 . We note that the recent Contract for Difference (CfD) allocation round has suggested lower costs in many cases
[44] Gas Turbine Combined Cycle
[45] Integrated Gasification Combined Cycle

Generation type	Technology	Upfront costs (£/kW)	Fixed operating and maintenance costs (£/kW/year)	Variable operating and maintenance costs (£/GJ)
Marine[46]	Wave energy technology T2	3,139	67	-
	Tidal stream	1,839	98	0.19
Geothermal	District heat low temp heat generation	3,228	24	1.89
PV	Commercial (building mounted)	681	15	-
	Residential (roof mounted, <4kW)	1,294	16	-

Costs for CCS and nuclear are included since, although they do not affect the model directly, they do affect the cost implications of excluding CCS and nuclear. Based on the above, these implications are very limited. If CCS and nuclear were significantly cheaper than renewables, ruling out CCS and nuclear could increase overall costs significantly. However, this is not the case and so excluding them should not make much, if any, difference to costs.

We also note the relatively low cost of PV, which has fallen significantly in recent years, driven by global reductions in PV panel prices. Per kW installed, PV is now significantly cheaper than onshore wind. However, when installing any technology MARKAL looks at the cost per kWh. Because of Scotland's climate, PV has a relatively low load factor of just over 9%[47] – much lower than that for onshore wind, which can reach 30%. This means that in practice, MARKAL does not install any.

This is not to say that no PV will be installed in Scotland – the MARKAL model is only an approximation of reality and cannot consider all factors that will drive PV uptake. When we look to the future, with increasing use of electric vehicles and heat pumps, and a more integrated energy system, there is a case to be made for rooftop solar from the perspective of individual consumers.

We also note that PV costs continue to fall rapidly, and it may well be that cost reductions will be sufficient to drive significant uptake in future.

[46] Figures for marine are for 2025 introduction – assumed not to be commercially deployed in significant volume before then
[47] Source: DECC analysis of load factors under the Feed-in Tariff. Figures for Scotland in table 3 range from 9-9.3%: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/386897/FiT_load_factor.pdf

The DECC report also provides cost estimates for 2020, which are shown in Table 4 below.

Table 4: Comparison of cost estimates between 2016 and 2020 for electricity generation technologies[48]

Generation type	Technology	CAPEX (£/kW)		Fixed O&M (£/kW/year)		Variable O&M (£/GJ)	
		Current	*2020*	Current	*2020*	Current	*2020*
Wind	On shore T6 (6.5 m/s) >5MW	1,089	1,021	25		0.95	
	Off shore New T2- Scotland East (assumed equivalent to offshore Round 2)	1,750	1,614	43	37	0.38	
	Off shore New T4- Scotland East (assumed equivalent to offshore Round 3)	1,842	1,706	48	39	-	
Hydro	Pumped Storage	2,353	2,489	17		1.13	1.51
	Small (1.25–20MW)	2,145	2,281	30		1.89	2.27
	Micro (<1.25MW)	Not given – assume no cost reduction					
PV	Commercial (building mounted)	681	613	15		-	
	Residential (roof mounted, <4kW)	1,294	1,089	16		-	

This shows slight reductions in onshore wind costs, with more significant reductions in offshore wind. Costs for hydro increase slightly (most likely a reflection of the need to use more marginal sites) while costs for PV show further reductions.

Given the potential for significant levels of offshore wind for Scotland in future, we have also reviewed the work by the Offshore Wind Reduction Cost Task Force[49] which was based on work by Arup[50] for DECC in 2011.

The Arup report included estimated capital and operating costs for offshore wind, and noted that at current costs in Scottish territorial waters, those translated to a levelised cost of £139/MWh in 2015[51]. A reduction of 30% would therefore take us to around £100/MWh, which is an industry target for 2020.

Costs to 2030 are inherently less certain. The figures used by the CCC in its assessment[52] of the costs and benefits of DECC's Electricity Market Reform programme give a 34-35% reduction by 2030, which implies some although very limited cost reductions beyond the 30% reduction assumed by 2020.

These figures are broadly consistent with the analysis done by Pöyry[53] on technology learning, which suggested that costs for offshore wind would "*…approach [but do not reach] £100/MWh by 2030…*", and that for onshore wind "*the potential for future cost reductions…is much lower [than for offshore]*". The original Arup report for DECC suggested that costs for offshore wind in Scottish waters might fall

[48] Figures for nuclear, marine and CCS are not shown since they are assumed to not be deployed until at least 2020
[49] See the June 2012 Offshore Wind Cost Reduction Task Force report, available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66776/5584-offshore-wind-cost-reduction-task-force-report.pdf
[50] Arup, October 2011, *Review of the generation costs and deployment potential of renewable electricity technologies in the UK*
[51] Ibid, table on page 50, "medium 2015" figure
[52] CCC, May 2013, *Next steps on Electricity Market Reform – securing the benefits of low-carbon investment*, data underlying figures 1.1. and 1.3, available at http://www.theccc.org.uk/publication/next-steps-on-electricity-market-reform-23-may-2013/
[53] Pöyry, 2013, *Technology supply curves for low-carbon power generation: a report to the CCC*

to £91/MWh. We note that the bids in the recent Contract for Difference (CfD) auctions for offshore wind were £79.23 and £114.39/MWh, showing wide variation in expected cost.

For wave and tidal, we assume limited commercial deployment before 2025. Technology cost reductions beyond that date are highly uncertain, but some estimates are available from analysis done by the Carbon Trust[54]. This suggested that given certain assumptions about global deployment levels, the levelised cost of wave and tidal could be reduced to £170-190/MWh[55] by 2030. This is of course still significantly higher than the cost of wind – offshore or onshore – and as a result MARKAL is likely to deploy little to no wave or tidal. This is consistent with the DNV-GL scenarios[56].

Given the uncertainties, and the likely low contribution of wave and tidal, we propose making the conservative assumption that there is no reduction in costs between 2025 and 2030, to avoid having the project's overall results challenged by stakeholders on a relatively small part of the generation mix.

Finally for PV, we have reviewed the trends in the Parsons Brinckerhoff report[57] for DECC on future PV costs. This suggests that in the "central costs/ fast" scenario, costs for domestic installations will be around £1,000 (2012 prices) in 2030. We will assume that the same percentage reduction applies to commercial installations.

In summary, our assumptions about the percentage reduction in costs by technology from the present day to 2030 are shown in Table 5 below.

Table 5: Cost reductions by 2030 for electricity generation technologies

Technology	Reduction in 2020	Reduction in 2025	Reduction in 2030
Onshore wind	2%	4%	5%
Offshore wind	15%	30%	30%
PV	8%	16%	22.5%
CCS demonstration		0%	
Nuclear		0%	
Marine		0%	

We also validated key assumptions by reviewing them with stakeholders, as discussed below.

4.1.1 Other assumptions

The question of our assumptions on new and existing power generation were discussed in the stakeholder workshop and with our clients. Following those discussions, we have made the following assumptions for the power sector:

- No new nuclear (in line with existing Scottish Government policy)
- No life extensions (at all) for existing nuclear[58]
- No CCS units except one 400MW demonstration unit at Peterhead
- No other fossil fuel generation
- In our two high renewables scenarios (that is, scenarios other than the baseline) we have also assumed that the emissions intensity of electricity is no more than 50g of CO_2 per kWh, both in Scotland and in the UK as a whole. For the baseline, we have assumed that electricity emissions are in line with the scenario shown in RPP2[59].

As noted earlier, we have assumed based on the DNV-GL report that there is sufficient interconnection between Scotland and England to ensure that electricity demand is met at all times.

[54] Carbon Trust, 2011, *Accelerating Marine Energy: the potential for cost reduction* http://www.carbontrust.com/media/5675/ctc797.pdf
[55] The Carbon Trust report expressed this in p/kWh – 17-19p/kWh is equivalent to £170-190/MWh
[56] DNV-GL, 2014, op.cit.
[57] PB, 2012, *Solar PV Cost Update* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/43083/5381-solar-pv-cost-update.pdf
[58] Assuming that Torness and Hunterston close in 2023
[59] http://www.gov.scot/Topics/Environment/climatechange/scotlands-action/lowcarbon/meetingthetargets

4.2 Heat assumptions

This section sets out our assumptions on heat costs. Unless otherwise stated these are based on Ricardo Energy & Environment's previous work on the Renewable Heat Incentive.

The previous Ricardo Energy & Environment work is a detailed set of data on the typical size, capital cost, operating cost (excluding fuel), load factor and seasonal efficiency for a range of renewable heat technologies including biomass boilers and district heating and different types of heat pumps. For the residential sector costs are specified separately for three different types of housing (detached, semi-detached and terraced, and flats) location (rural, suburban, urban) and building age (solid wall, pre-1990, post 1990 and new build), as each of these factors not only determine which renewable heat technologies are suitable for the dwelling, but also aspects such as size of system required and cost of installation.

For the MARKAL modelling however, only average values for existing and new build for the whole of the residential sector are required. The Scottish Housing Condition Survey (SHCS) provides a breakdown of the housing stock by type (detached, semi-detached, terraced, tenement and other flats), age and urban or rural location. The percentage of housing stock in each category from the SHCS was therefore applied to the more detailed data to calculate weighted average values for each technology when used in existing or new buildings that were representative of the total Scottish housing stock. The proportion of new build located in urban and rural areas, and proportions of different types of new build were assumed to be the same as for existing stock.

We present the costs as current (2010) costs, plus a trend showing expected cost reductions over time. We also show expected efficiency improvements for heat pumps.

Starting with current costs, Table 6 shows our assumptions by technology, comparing capital, operating and maintenance costs for domestic installations in new buildings. Costs for heat pumps and solar thermal are higher in existing buildings where they have to be retrofitted.

Table 6: Current costs for heating, domestic installations

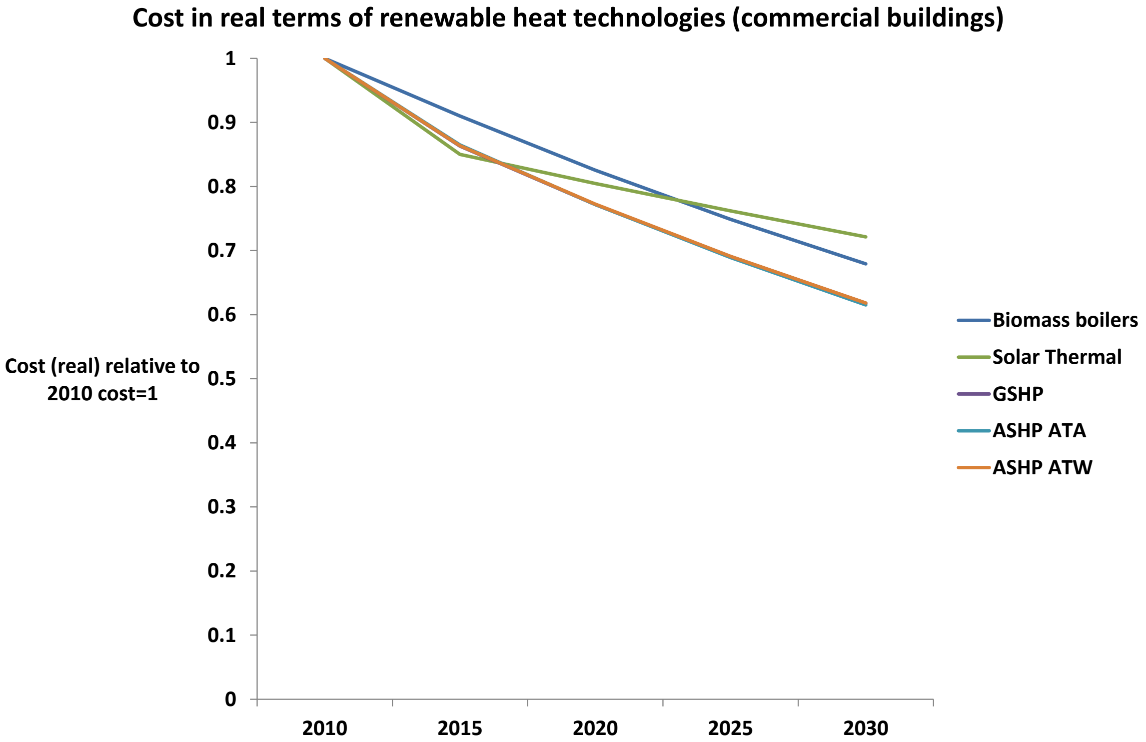
	Typical size (kW)	Capital cost (£)	Operating cost excluding fuel (£/year)	Seasonal efficiency	Load factor
Biomass boilers	8	5,880	230	85%	11%
Biomass district heating[60]	1,200	914,078	22,852	51%	14%
Solar Thermal	2.6	3,947	46	50%	8%
Ground Source Heat Pump	6	1,135	54	373%	14%
Air Source Heat Pump (Air to Air)	4	1,615	55	172%	11%
Air Source Heat Pump (Air to Water)	6	7,057	53	314%	13%
Liquid biofuels	20	3,586	188	93%	4%
Electric heating	4	738	0	90%	8%
Gas	20	3,025	188	94%	4%
Oil boiler	20	3,026	188	93%	4%

Note also that these figures relate to domestic installations in new homes. Commercial and industrial installations tend to be larger and so the cost per kW will tend to be lower, because of economies of scale. Data for commercial and industrial buildings were also derived from the RHI data set for industrial and commercial heating.

[60] Cost for boiler and heat network. The seasonal efficiency is lower than for individual boilers due to heat losses from the network. Over the summer when heat loads are low as the system is only supplying hot water, these losses can be relatively high compared to the heat delivered and lead to a lower system efficiency

As far as future costs are concerned, we have assumed that the cost of renewable heat technologies[61] will reduce over time, as the technologies mature and develop. The cost reductions are based on the modelling work we have carried out for DECC on the Renewable Heat Incentive. Figure 6 below shows our assumptions for the installation costs of those used in commercial buildings – the profiles for domestic installations are identical.

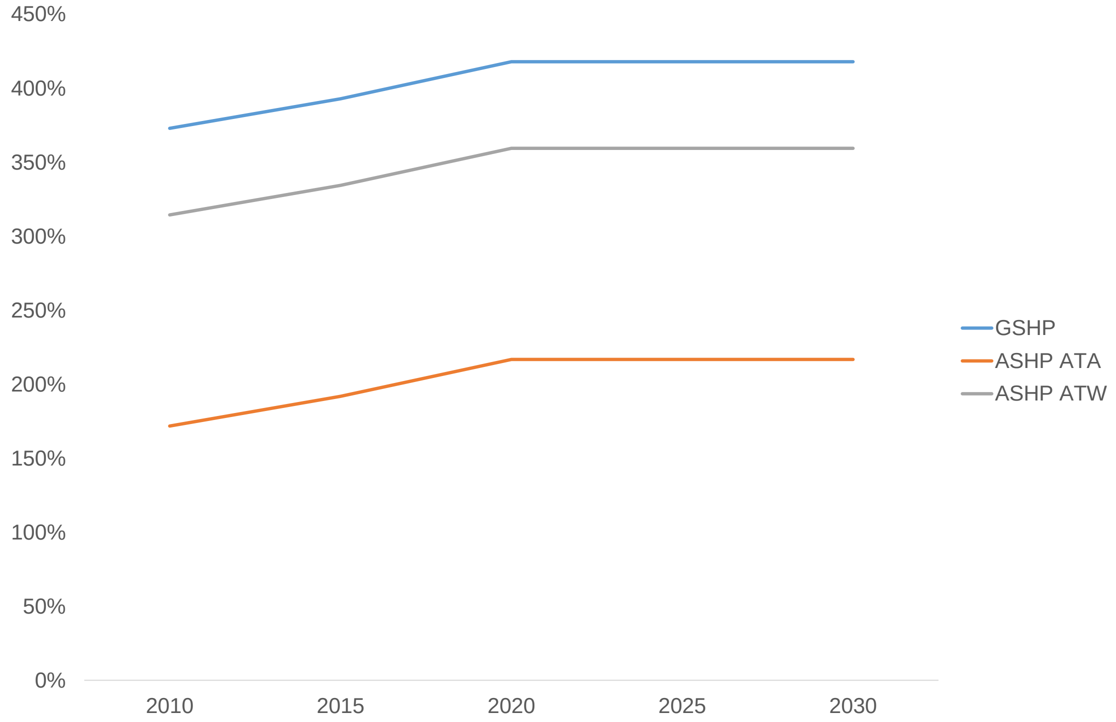
Figure 6: Cost trend for renewable heat technologies



We also assume that heat pump technologies become more efficient over time, providing more heat out for the same energy input. These assumptions are based on RHI modelling work carried out for DECC and modelling work carried out on decarbonising the residential sector in Europe by Ricardo Energy & Environment for the European Gas Forum. The increase is shown in Figure 7 below; the figures are the same for both commercial and domestic installations.

[61] Except liquid biofuel boilers, which are essentially oil boilers and so a relatively mature technology

Figure 7: Heat pump efficiency trends assumed

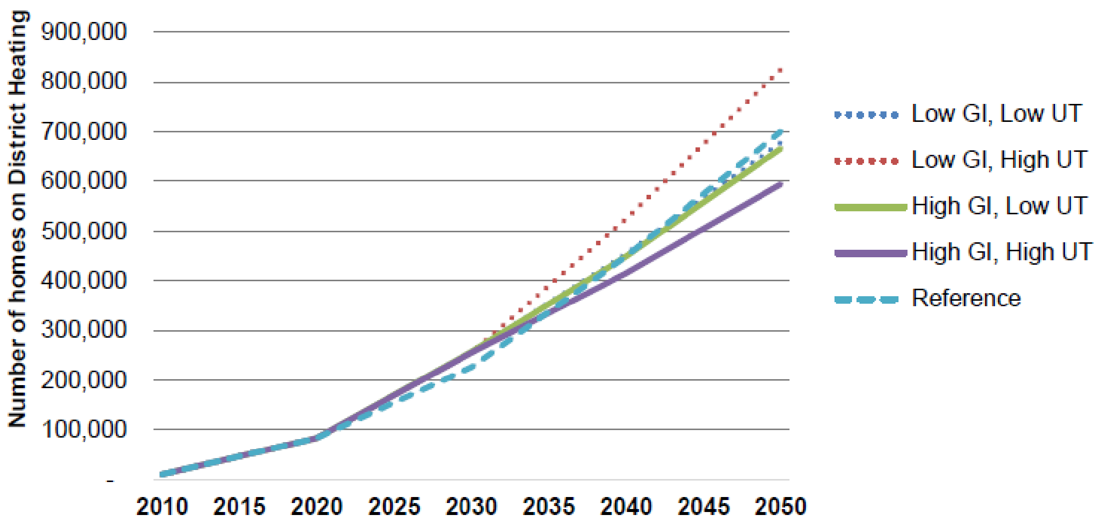


We cross-checked these figures against a study[62] by Delta-EE for the Electricity Networks Association. This study showed co-efficients of performance for Air Source Heat Pumps equivalent to 300% efficiency by 2025.

4.2.1 Other heat assumptions

We also considered whether there were other factors driving the likely uptake of renewable heat. We noted that the Scottish Government has set out a Heat Scenarios report[63] which contains a number of different uptake scenarios for district heating. These are shown in Figure 8 below.

Figure 8: Scottish Government district heating uptake scenarios



[62] http://www.energynetworks.org/modx/assets/files/gas/futures/Delta-ee_ENA%20Final%20Report%20OCT.pdf
[63] http://www.scotland.gov.uk/Topics/Business-Industry/Energy/Energy-sources/19185/Heat/HeatScenariosReport

Bearing in mind the priority attached to district heating in Scotland, we have therefore assumed a certain level of uptake: 1.5TWh by 2020. MARKAL can decide to install more district heating if it is cost-effective compared to other decarbonisation technologies (see next paragraph for a discussion of district heating's carbon impacts). We noted earlier the issues with modelling district heating in MARKAL and why its results on district heating should be treated with caution.

There is also the question of how the heat for this district heating is generated. Leaving aside the option of waste heat from an industrial site, the options are essentially gas, heat pumps or biomass. Our results show in almost all cases that gas is installed – in one scenario there is some limited biomass district heating by 2030. Retrofitting district heating with biomass is more straightforward than retrofitting a number of installations in individual properties.

This is also consistent with our overall approach on biomass (see later, in our section on scenarios). At our clients' request, we have limited the available biomass to what we assume can be sustainably produced in Scotland. We take this to be 1.2m oven-dried tonnes (odt)[64] or around 22PJ, plus waste.

For building demand levels, we calculated representative values for domestic buildings based on the Scottish Housing condition survey (see bibliography).

4.3 Transport assumptions

Our analysis of transport costs follows the same approach as for heat. We have looked at base year costs and efficiencies, and then projected future trends in both. Unless otherwise stated, these figures are based on our previous work for the Committee on Climate Change.

Table 7 below shows our assumed current costs by vehicle type.

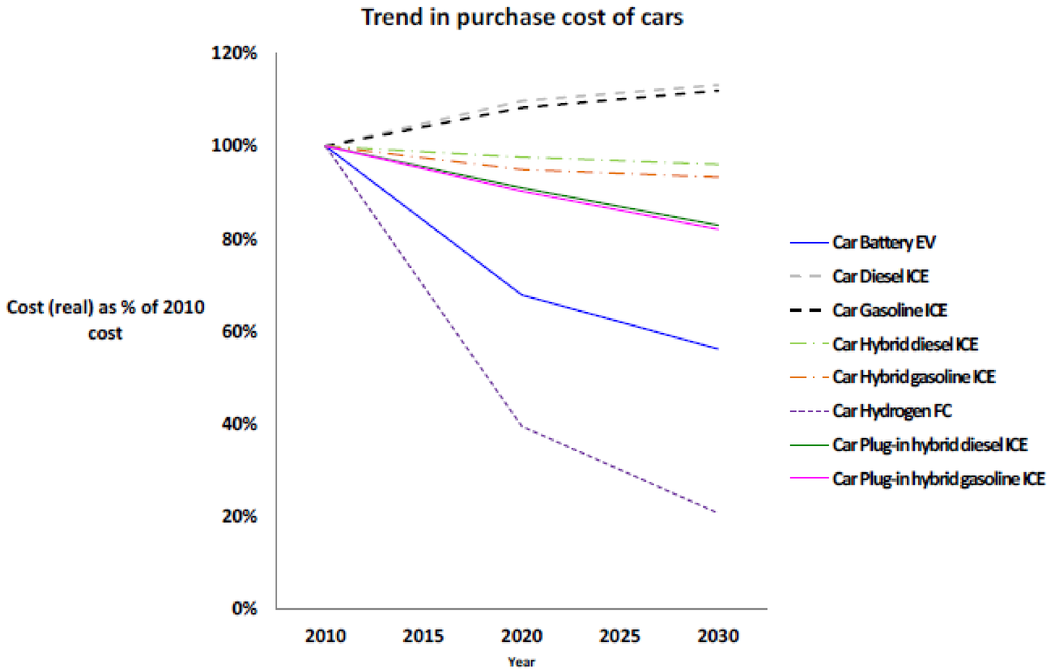
Table 7: Assumed current vehicle purchase costs (£, current prices)

	Diesel	Petrol	Hybrid diesel	Hybrid petrol	Plug-in hybrid diesel	Plug-in hybrid petrol	Battery EV
Bus	187,948	-	203,547	-	374,726	-	319,642
Car	16,323	15,702	18,396	18,103	27,864	27,610	32,514
LGV	18,614	17,298	21,240	19,948	28,811	27,718	37,365
HGV	80,478	-	94,788	-	129,064	-	-

[64] This is based on an estimate of 0.8 million tonnes from forestry and 0.4m tonnes from sawmill residues, based on:
Sustainable Development Commission, 2005, *Wood fuel for warmth, a report on issues surrounding the use of wood fuel for heat in Scotland*.
Ricardo-AEA, 2013. *Biofuels: Scottish feedstock summary and potential biofuel opportunities for Scotland. Report for Scottish Enterprise*

As for heat, we have assumed future cost profiles. The profile for cars is shown in Figure 9 below.

Figure 9: Purchase costs of passenger cars – assumed trends to 2030

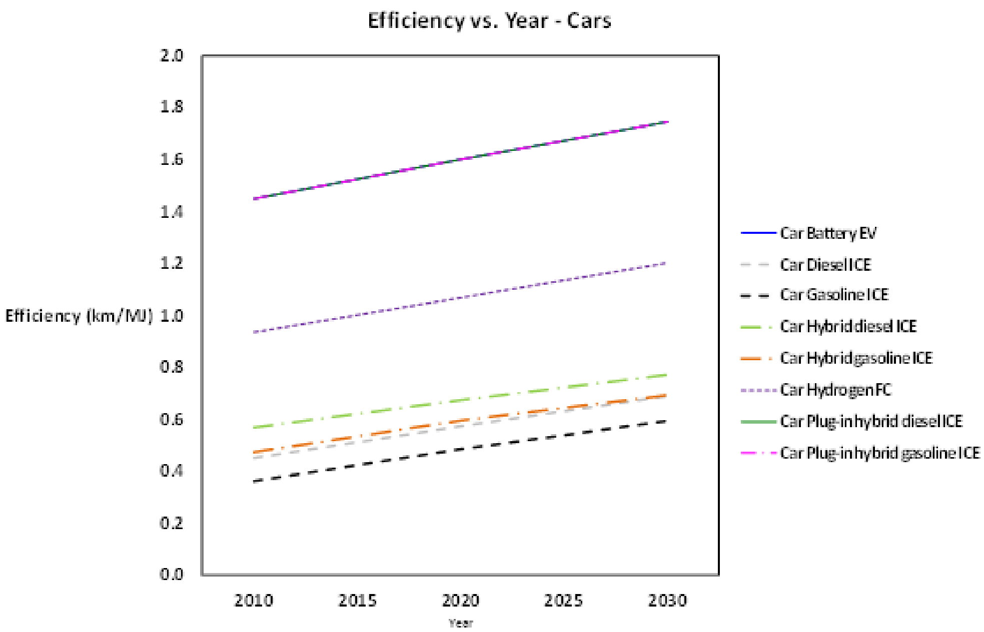


This shows slight increases in the cost of conventional diesel or petrol-powered vehicles, and very substantial falls in the costs of EVs. The cost of hydrogen fuel cell vehicles shows the largest fall but this is from a very high starting level (our assumption is that a typical fuel cell car would cost £50,000 in today's prices).

4.3.1 Efficiencies

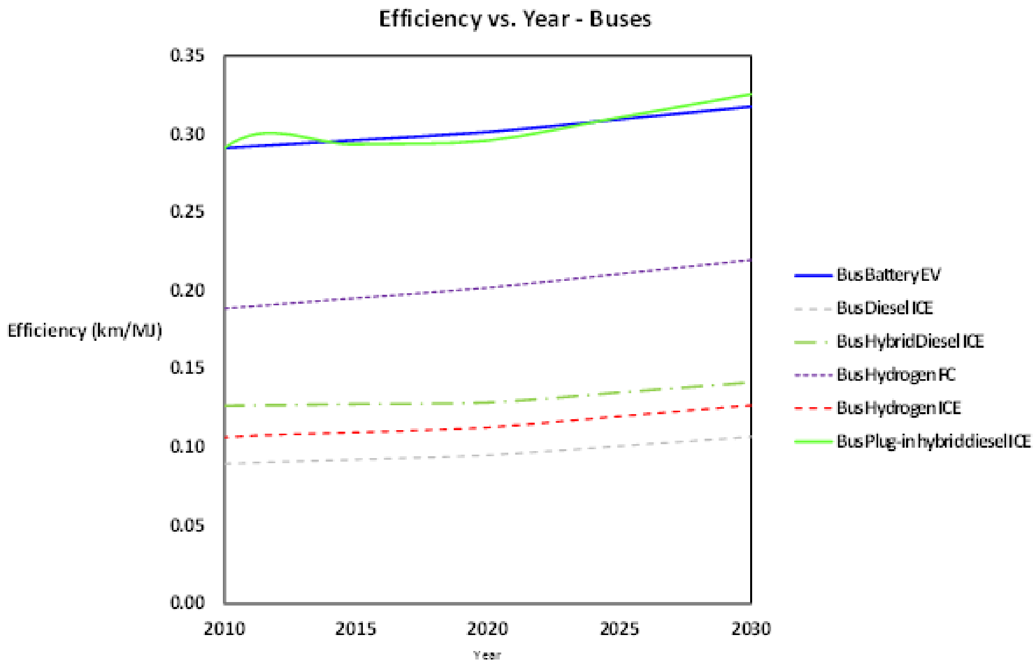
We have projected the efficiencies (measured in km per MJ – distance travelled per unit of energy in) for cars, buses, LGVs and HGVs. The two charts below show our estimates of future efficiencies for cars and buses (fossil fuelled, electric and fuel cell vehicles) relative to today.

Figure 10: Fuel efficiency of cars to 2020



The important point from this chart is the big jump in efficiency from the dashed lines in the lower half (fossil fuel vehicles) to the lines at the top (electric vehicles). This shows the relatively high efficiency of electric and plug-in electric vehicles compared to fuel cells and hybrid vehicles. Conventional petrol and diesel vehicles are the least efficient (lower black and grey dashed lines). The picture is similar for buses, as shown in Figure 11 below.

Figure 11: Fuel efficiency of buses to 2030



For the majority of vehicles, the future trends in efficiency were obtained from work performed for the CCC[65]; these future improvements were applied to the existing efficiencies in MARKAL for the year 2010. For PHEV vehicles, the future trends were derived as the average of those for PHEV and REEV vehicles (as REEVs are not included as a separate vehicle type in MARKAL). Data for PHEV buses and HGVs were obtained from a more recent unpublished study by Ricardo Energy & Environment as they had not been included in previous studies.

It should be noted that the efficiency values provided to MARKAL for PHEVs are those for when the vehicle is operating on battery power (and, hence, tend to be the same as those for BEVs). Other elements in the MARKAL input data then specify the reduction in efficiency which occurs when the vehicle is operating on its internal combustion engine (ICE). The updated values for this parameter were derived from the detailed data used in the study for the CCC.

Tables showing the values behind these graphs are in Annex 2.

[65] AEA Technology *A review of the efficiency and cost assumptions for road transport vehicles to 2050* AEA/R/ED57444, 2012

4.4 Stakeholder workshop

We tested our initial assumptions with a stakeholder workshop. Those organisations represented at the workshop are listed in Table 8 below. We would like to thank all those who attended and participated.

Table 8: List of attendees at stakeholder workshop

Organisation
Scottish Renewables
Scottish Government
Energy Savings Trust
University of Edinburgh
IET
Urban Foresight
CHPA
Scottish Hydrogen and Fuel Cell Association
National Grid
Scottish Power
WWF
RSPB

For confidentiality reasons, we have not named any of the individuals at the workshop, and comments are not attributed to any specific organisation.

At the workshop, we presented our key assumptions (particularly on technology costs) and two ‘test’ scenarios showing how the carbon emissions targets could be achieved through only focusing on heat (at the expense of transport) or vice versa. These scenarios were known as “clean heat” and “clean transport” respectively. They were deliberately challenging scenarios designed to test assumptions about potential deployment and retirement rates and about the need for particular new technologies.

The messages that we received in the workshop can be grouped into a number of high-level categories, as below.

4.4.1 Deployment rates

There was a general message that the “clean heat” and “clean transport” scenarios were extreme. The deployment rates shown – and the retirement rates, particularly of petrol cars – stretched credibility. We identified a number of areas where they might need adjusting, as set out below.

Table 9: Assumptions adjusted as result of stakeholder workshop

Area	Adjustment to assumptions
Vehicle retirement	The average scrappage age is 14[66] years, so showing all vehicles of a certain type being removed within that timescale is unrealistic.
Boiler replacement rates	A realistic rate might be 5% per year based on an assumed lifetime of 20 years[67].

66 Society of Motor Manufacturers and Traders (SMMT) suggests current figure is 13.5 years and on upward trend. http://www.smmt.co.uk/sustainability/environmental-performance/end-life-vehicles/
67 Source: DECC (renewable heat incentive)

Area	Adjustment to assumptions
Wave/ tidal	We should assume that the 100MW identified in the UK's Electricity Market Reform (EMR) programme comes forward in Scotland. Deployment beyond that was felt to be unlikely, in part because of a lack of offshore networks being developed.
Air quality limits	These might impose significant limitations on the use of biomass in urban areas. We considered whether to restrict biomass use to the 18%[68] of the population that are in rural areas, and to prevent its use in non-domestic buildings, on the assumption that these are almost exclusively in urban areas. However, it was felt that a more appropriate option would be to include the cost of abatement technology in the cost of biomass boilers, and not restrict their deployment in this way. We also considered the option of thermal gasification of biomass at a rural location and injection of the resulting gas into the gas grid. But while this has been demonstrated, it is not yet a commercial technology. Injection of biomethane (from anaerobic digestion at present) is already included in MARKAL.
District heating	For deployment, we have taken the figures from the Scottish Government's heat scenarios. This shows around 250,000 homes connected by 2030, out of a total of 2.3m in Scotland. As noted elsewhere, district heating is difficult to model in MARKAL. We have therefore constrained MARKAL to have at least 11% of domestic heating from DH by 2030.
Use of imported power	We will follow the same approach as in the Arup heat study for the Scottish Government, where power consumed in Scotland is assumed to have the carbon emissions intensity of the GB grid[69]
Domestic insulation	We will use the assumptions from the latest DECC National Energy Efficiency Data (NEED) report[70]. This suggests, based on installations in 2011, that average[71] savings from cavity wall insulation are 7.7%, from loft insulation 2.0% and from solid wall insulation 13.8%.
2015 costs for Fuel Cell cars	We have assumed a figure of £50,000 in 2015. This is consistent with manufacturers' estimates, and with the overall trajectory assumed by CCC and others. It is still somewhat speculative since there is limited experience with FC vehicles.
Alternative fuel buses	Based on our understanding of current plans by the bus industry in Scotland, we expect limited take-up of buses other than standard diesels before 2020 (we understand that some have already been deployed on a trial or pilot basis). As a simple conservative assumption we have constrained MARKAL to only allow non-diesel buses to be purchased from 2020.
Gas/ heat pump combination boilers	We have included these in the model, using a fixed split between gas and electricity, and an averaged efficiency factor.
Gas boiler costs	After comparing our figures against other published sources[72], we propose reducing them by 10%.

[68] Source: Scottish Government National Statistics 2011, combining "remote rural" and "accessible rural" populations http://www.scotland.gov.uk/Publications/2011/09/29133747/2
[69] Arup, 2014, Scenarios for Scottish Heat. "*For calculating the emissions from electricity consumed in Scotland, the average grid intensity of the GB system is used as Scotland is part of an integrated GB grid…*"
[70] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/323939/National_Energy_Efficiency_Data-Framework_2014.pdf
[71] Defined as the mean reduction in gas usage
[72] We compared to figures from Arup, from DECC's 2050 calculator, and from the Delta-EE report for the Energy Networks Association

4.4.2 Additional technologies

The workshop participants identified a number of additional technologies, including deep geothermal and gas/ heat pump hybrid systems.

The British Geological Survey has looked[73] into the potential for deep geothermal and suggests that from abandoned mine workings alone there could be up to "*12GW [which could] theoretically provide [approximately] one third of Scotland's heat demand*"[74]. However, not all of this is likely to be realised in practice. We have used the currently assumed potential in MARKAL which is of the order of 100MW by 2030[75].

We have added in costs[76] for gas/ heat pump hybrid systems, as in National Grid's Future Energy Scenarios.

We also considered micro-CHP. Ricardo Energy & Environment reviewed this technology for the European Gas Forum (EGAF) study and concluded that there were a number of constraints (e.g. siting requirements, degradation in fuel cell based systems) to overcome. Even after allowing for significant cost reductions by 2030, costs were too high, compared to other options, for it to take any market share. We have therefore not included it for the current study.

4.4.3 Other issues

The meeting also identified some other issues for us to consider, including:

- Wind repowering (already included in MARKAL)
- Increases in diesel/ petrol vehicle costs (down to improvements in vehicle specification, and consistent with CCC work)
- Decreases in PV costs (our figures are consistent with DECC's).

This concludes our key assumptions that are common to each scenario. In the next section we discuss the scenarios that we ran.

[73] http://www.bgs.ac.uk/research/highlights/2013/ScotlandGeothermalPotential.html
[74] http://www.scotland.gov.uk/Publications/2013/11/2800/2
[75] MARKAL limit is 0.6PJ, which at 20% load factor is around 100MW
[76] Source: Delta-EE, 2014, op. cit.

5 Scenarios

We ran a number of initial scenarios in order to test the limits and other assumptions in the MARKAL model, and discussed the results with stakeholders. This led to the model's assumptions being updated. Those were deliberately extreme scenarios intended to test uptake rates and limits on potential and we do not discuss them here.

Following discussion with our clients, it was agreed that the final three scenarios would be a **baseline** scenario, an **RPP Optimistic** scenario and an **RPP Realistic** scenario. These are described below.

5.1.1 Baseline

The baseline scenario reflects the current firm plans of the Scottish Government, as shown by the policies (but not proposals) in RPP2. Our assumptions on overall emissions are taken directly from that document. While there are questions about the extent to which the expected emissions reductions in RPP2 will be achieved (we return to this later), we consider that it represents a sensible starting point for a discussion about what more needs to be done to deliver emissions reductions. The overall emissions figure for 2030 in this scenario is set to the baseline in RPP2 (38.6 million tonnes), less emissions from rural land use which are not captured by MARKAL, an energy-only model. We have also calibrated overall emissions from the electricity sector to those in the Electricity Generation Policy Statement, and emissions from transport and residential sectors are calibrated to those in RPP2 (the remainder will be industrial and other emissions).

This baseline scenario is mainly used to show where effort beyond RPP2, and what is cost-effective, is required.

5.1.2 RPP Optimistic

The second scenario is a "cost-optimal" one. One of the key objectives of energy policy is to minimise costs to consumers. This is important in managing fuel poverty, and in building consensus for the low carbon transition. We therefore ran a scenario in which, within the cost and deployment parameters specified, MARKAL looked for the lowest cost pathway to 2030, consistent with the required emissions reduction. In this scenario, we assumed that Scotland achieves its 2030 emissions target as required by the Climate Change (Scotland) Act, and indeed its targets for the entire 2020-2050 period.

We also assume that electricity emissions in 2030 are no more than 50g of CO_2 per kWh, and that comparable policies are followed in the rest of GB so that overall GB grid intensity is 50g or less by 2030. For the purpose of calculating the carbon intensity of Scottish electricity consumption, some of which may be imported from England, we allow MARKAL to determine the cost-optimal (i.e. cheapest) approach. This applies limits reflecting current policy and constraints on potential and rate of uptake of new technologies (e.g. build rate, maximum replacement rate for vehicles and boilers). It should be underlined here that MARKAL does not – and cannot – include every constraint that applies in reality, particularly geographical environmental constraints, and so its results should be interpreted with this in mind.

It is important to point out that "cost optimal" here means "cost optimal to 2050". While the focus of this project is on renewable energy for 2030, that must be consistent with a pathway to the ultimate objective of the 2050 emissions target. Optimising only to 2030 would also mean that only five years' worth of the benefits from any measures taken in 2025 would be counted. Since renewable energy tends to be more expensive initially, but have lower running costs, optimising to 2030 would significantly skew the results.

This raises the question of what costs we have assumed beyond 2030. Conservatively, we have assumed no changes to technology costs beyond 2030. In reality, there may be significant reductions particularly in the newer technologies such as wave and tidal, and EVs. However, projecting technology cost savings 15 or 20 years into the future is risky, and so we have taken the simple and cautious approach of assuming no further cost reductions beyond 2030. For fossil fuel prices, we have used DECC's central scenario and again assumed no change beyond 2030.

It should also be pointed out that "cost optimal" means "least cost to society as a whole" rather than "least cost individual consumer decisions". So some individual choices may not be the best for individual consumers. For example, it might make sense as a society to drive the uptake of a particular technology – such as renewable heat - even if individual consumers would not make the decision to install it themselves because it is currently more expensive than the alternative gas boiler technology, before carbon costs are considered. However, the combination of choices should be what is best for society as a whole, which is consistent with the question that this project asks.

This difference between the decision that is best for society as a whole, and individual consumer choice, can point to useful policy instruments. Put simply, where it is in society's interest for consumers to switch to a particular low-carbon technology, but for some reason consumers are reluctant to do so, it can make sense to offer incentives or to use other policy instruments such as minimum efficiency standards.

We have also constrained emissions in each year to 2030, because of the need to limit cumulative emissions. A pathway that was only limited at 2030 might show high annual emissions until 2025 and then a sudden drop, which would leave cumulative emissions too high and might be seen as requiring unrealistic deployment rates.

The emissions target is set at the Scottish Government's statutory target (28.1 million tonnes in 2030) less emissions from rural land use and from international aviation. The rural land use emissions are assumed to be those from RPP2 (5.6 million tonnes), and those from international aviation are assumed to be 2.5 million tonnes. Conservatively, we assume that emissions from international aviation are held at current levels, based on their allocation of carbon allowances under the EU Emissions Trading System.

The result is that MARKAL is constrained to an emissions level of 20 million tonnes in 2030.

We have also, following discussions with our clients, made a number of other assumptions about uptake over the next fifteen years. These are listed in Table 10 below.

Table 10: Key assumptions in "RPP Optimistic" scenario

Sector	Assumption	Rationale
Transport	No biokerosene for aviation	Appears economically attractive but expert judgment is that it will be very limited to 2030
Transport	5% of vehicle fuel will be biofuel	Progress at EU level, and sustainability, suggests that this will be limited to a relatively low level
Transport	At least 9% of cars are PHEVs or BEVs by 2030	Consistent with the business as usual case from the Element Energy report on electric vehicles
Electricity	No new fossil fuel generation	MARKAL, if unconstrained, builds new CCGTs in Scotland which have a negligible load factor by 2030. They are unlikely to be commercially viable in practice.

On biokerosene, we note the CCC's view that "*…concerns about land availability and sustainability mean that it is not prudent to assume that biofuels in **2050** could account for more than 10% of global aviation fuel"*[77].

5.1.3 RPP2 Realistic scenario

In the previous scenario, we assumed that all policies in RPP2 are achieved, and that international aviation emissions are held to current levels. A reasonable case can be made though that some of these assumptions – and others - may not be realised. Table 11 below shows where we have made a relatively more pessimistic assumption.

[77] CCC, 2009, *Meeting the UK Aviation target – options for reducing emissions to 2050.* http://www.theccc.org.uk/publication/meeting-the-uk-aviation-target-options-for-reducing-emissions-to-2050/

Table 11: Assumptions underlying RPP Realistic scenario

Change	Basis	Impact ($MtCO_2e$)
International aviation emits 31% more than today	The Department for Transport's central emissions forecast[78], which shows emissions from flights from UK airport of 33.2 million tonnes in 2010 and 43.5 million in 2030 – an increase of 31%. Emissions from international aviation 0.8$MtCO_2e$ higher (31% of 2.5$MtCO_2e$, current emissions from international aviation in Scotland).	0.8
Scotland achieves 70% recycling target by 2030, rather than 2025	The EU is discussing a 70% target by 2030, so this assumes that Scotland is in line with the possible EU average. Scotland currently has lower recycling rates than Wales or England, so only achieving the average is not unreasonable. The table on page 239 of RPP2 shows savings from Zero Waste Policies and the Zero Waste Plan. Emissions from waste in 2030 are therefore 0.075[79] $MtCO_2e$ higher than expected.	0.075
Smart meters, Green Deal, ECO and domestic retrofit measures deliver half the expected savings in domestic sector	A WWF report[80] on investment in domestic energy efficiency says that "*…the…ambition set in the RPP would require 2.7 times the investment [likely to be available]*". There are likely to be diminishing returns to investment, so a shortfall by a factor of 2.7 does not mean that delivery will be 2.7 times lower than expected. Conservatively, we assume it will only be half what is expected (i.e. half of 0.598$MtCO_2e$, based on RPP2 page 236).	0.3
Afforestation delivers only 50% of expected savings	Afforestation policy in RPP2 assumes an average planting rate of 10,000 hectares per year[81]. The Scottish Parliament has expressed concern[82] that this is unlikely to be achieved with current budgets. It cites the Forestry Commission Scotland as saying that it *might* achieve 5,000 hectares in 2015[83], although it expects to achieve 3,000. It is possible that this rate would continue, which would be half the rate assumed in RPP2, and so deliver half the savings. This means a saving of 50% of 687$ktCO_2e$ (expected savings in RPP2)=0.343$MtCO_2e$	0.343
No HGVs convert to CNG	The Low Carbon Vehicle Partnership produced a report[84] which said that CNG/LNG for HGVs is economic now (payback time of around 3 years). But there are barriers particularly refuelling infrastructure (which since HGVs travel across borders, means EU infrastructure). So preventing HGVs from taking up the CNG/LNG option is reasonable. The exact impact is unknown but could be significant.	Unknown
TOTAL IMPACT		>1.52

[78] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223839/aviation-forecasts.pdf, table G2
[79] Expected abatement in 2027 of 1,161ktCO2e vs expected abatement in 2025 of 1,086ktCO2e. Assuming no further abatement beyond 2027
[80] WWF, 2012, *Mind the Gap: Funding Home Energy Efficiency to Deliver Scotland's Climate Change and Fuel Poverty Targets*
http://assets.wwf.org.uk/downloads/fuel_poverty_funding_3__2_.pdf
[81] RPP2, page 240
[82] http://www.scottish.parliament.uk/S4_RuralAffairsClimateChangeandEnvironmentCommittee/Reports/ru15-DraftBudget.pdf
[83] Ibid, paragraph 56
[84] TTR for Low CVP, 2011, *Biomethane for Transport – HGV cost modelling*
http://www.lowcvp.org.uk/assets/reports/LowCVP%20Biomethane%20Report_Part%201%20Final.pdf

The net impact of this is that the scenario has an emissions constraint of just under 18.5 million tonnes in 2030. From a renewable energy perspective, we expect that more renewable energy will be required to hit this emissions target.

Renewable energy is not the only option – energy efficiency is also a possibility. However, as we will see in the next section, even this relatively modest shortfall increases the renewable energy required significantly.

6 Results

This section shows the results of the scenarios. We start with the overall renewable energy targets, and then present detailed results by sector, including a discussion of the drivers for those results. We then compare to other reports.

6.1 Overall targets

Table 12 below shows the renewable energy percentages for the RPP Optimistic and RPP Realistic scenarios, and compares these to stated Scottish Government targets and ambitions by sector.

Table 12: Renewables percentages

Sector	Baseline	RPP Optimistic	RPP Realistic	Scottish Government
Electricity[85]	129%	145%	143%	100% renewable by 2020 50g of CO_2 per kWh by 2030
Transport	8%	11%	18%	Significant decarbonisation by 2030 but no target.
Heat[86]	27%[87]	36%	40%	Significant progress by 2030 towards largely decarbonised by 2050 but no target
OVERALL	31%	44%	48%	30% by 2020 – no 2030 target

The overall figure is calculated as the total percentage of final energy consumption from renewables, divided by the total final energy consumption.

Table 13 below shows the reduction in emissions by sector for the "optimistic" and "realistic" scenarios, compared to the baseline.

Table 13: Emission reductions by sector (millions of tonnes of CO_2e)

Sector	RPP Optimistic	RPP Realistic	Baseline emissions for comparison purposes
Electricity	2.8	2.8	3.0
Transport	2.2	3.0	11.8
Heat	4.7	5.7	16.2

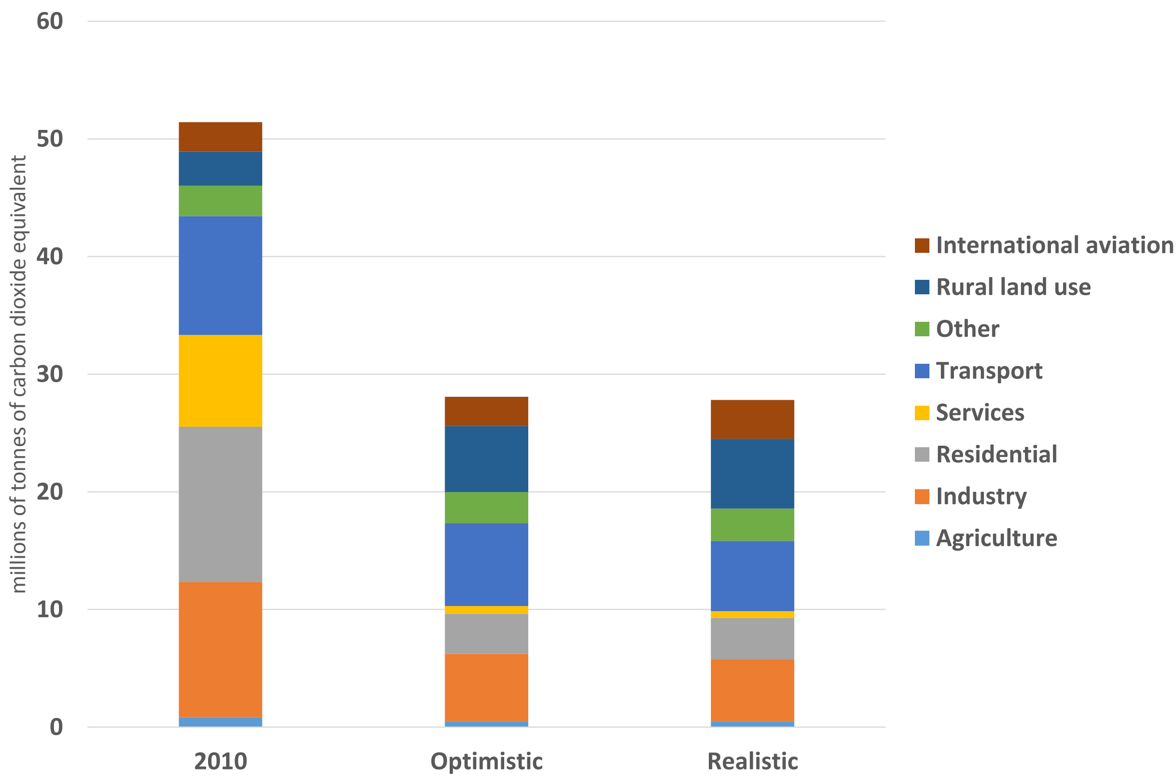
In terms of overall trend, this is consistent with messages from other studies. Decarbonisation of the power sector happens first – a clear message from the CCC – and we then address heat and transport. Heat decarbonisation levels are again broadly consistent with the CCC's fourth carbon budget report, which suggests up to 42% renewable heat by 2030.

[85] Measured as the ratio of electricity generated to electricity consumed over the year
[86] Aerothermal and geothermal heat from heat pumps is included, in line with the Renewable Energy Directive. They have been added to both numerator and denominator.
[87] Note that we have constrained renewable heat here to the levels shown in the 2011 Element Energy work for the CCC (RHI to 2030, baseline scenario)

The picture for renewable transport is of most interest and is discussed in more detail below. At this stage we would highlight that while the level of renewable energy used in transport is still relatively low compared to heat and power, *emissions* from transport fall dramatically - by 43% in our "RPP Realistic" scenario compared to 1990 levels[88]. This is not because of demand reduction (indeed vehicle km increase) but because of increasing vehicle efficiency – particularly the high efficiency of electric vehicles compared to internal combustion vehicles, and the benefits of hybrid vehicles, which count as efficiency rather than renewables. Reductions based on policies designed to support transport modal shift – such as incentives to use public transport, improved cycle paths and facilities, and penalties for car use such as congestion charging – could all add to this reduction in emissions.

This is illustrated in Figure 12 below which shows emissions by sector.

Figure 12: Emissions by sector for base year and for 2030 in RPP Optimistic and RPP Realistic scenarios



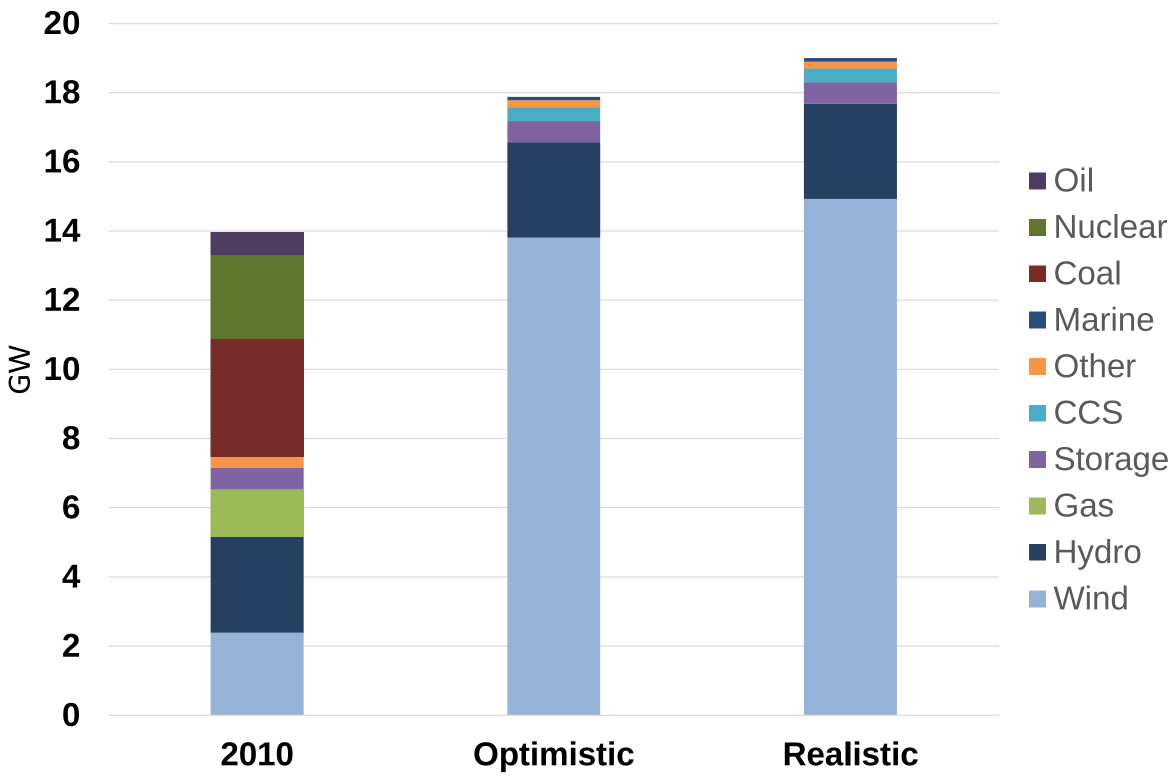
We now present more detailed results.

[88] 10.5 million tonnes – source: National Atmospheric Emissions Inventory

6.1.1 Detailed results: electricity

Figure 13 below shows the level of renewable electricity capacity installed in our scenarios.

Figure 13: Installed capacity by scenario, in GW



The figures behind this and other charts are in Annex 2.

This pace of development is feasible. As DNV-GL note in their report[89]: "*DECC statistics show that onshore wind generation in Scotland increased by an average of 680 MW [per year] over the period 2011-2013*". If this rate continued, there could be an additional 10.2GW by 2030. We also note that there is around 20GW of renewable energy already operational, under construction or with planning consent in Scotland[90].

In summary, the level of renewable electricity shown here is entirely achievable and within the range of published estimates.

Finally, around one-third[91] of the electricity generated in Scotland is used in the rest of the UK. Achieving the decarbonisation shown in our scenarios is therefore not contingent on all the wind generation shown being built.

Why is more renewable electricity being built than is needed to meet Scotland's requirements? The answer is that MARKAL is optimising at a UK level. Because Scotland has abundant renewable energy resources, more than Scotland's share (on a population basis) of renewable electricity is built in Scotland. This is similar to the current situation.

6.1.2 Detailed results: heat

We now turn to renewable heat. This is a more complex picture than for electricity.

The tables below shows the fuel split, and the percentage of renewable energy, by sector. The first table shows the "RPP Optimistic" scenario and the second shows the "RPP Realistic" scenario.

[89] DNV-GL, 2014, op.cit.
[90] Source: Scottish Government, 2015, *Energy in Scotland*
http://www.gov.scot/Resource/0047/00475681.pdf
[91] In the "realistic" scenario it is 32.9%

Table 14: Heat demand in "RPP Optimistic" scenario (petajoules)

	Residential	Commercial and public buildings	Industrial heat (all types)
Gas	30	12	56
Heat pumps			
Gas demand	27	-	-
Elec demand	11	9	-
Heat supplied	59	28	-
Electricity	4	2	11
Coal	-	-	0
Oil (including fuel oil)	3	-	9
Biomass	3	3	1
District heating	10	-	-
Other	2	1	0
Of which renewables on energy input basis	*20%*	*52%*	*16%*
Of which renewables on heat output basis	*36%*	*72%*	*16%*

Table 15: Heat demand in "RPP Realistic" scenario (petajoules)

	Residential	Commercial and public buildings	Industrial heat (all types)
Gas	27	12	52
Heat pumps			
Gas demand	27	-	-
Elec demand	11	9	-
Heat supplied	59	28	-
Electricity	5	2	15
Coal	-	2	15
Oil (including fuel oil)	3	-	-
Biomass	1	-	7
District heating	10	2	4
Other	2	1	-
Of which renewables on energy input basis	*19%*	*51%*	*24%*
Of which renewables on heat output basis	*36%*	*72%*	*24%*

The figures for heat pumps need some explanation, because of a slightly complex energy accounting issue.

In most cases, the energy supplied for heating is roughly the same as useful heat energy produced. Modern gas boilers for example are over 90% efficient. This is not the case for heat pumps, which since they use electricity to transfer heat from the outside air into the home, can have "efficiencies" of well over 100%, where efficiency is defined as heat supplied to the home divided by electricity input to the heat pump. A further options is hybrid heat pumps, which have a gas boiler and a heat pump in combination.

For this reason, we calculated the renewable percentage on two bases. The first basis looks at the energy input – supplied. For the second basis, the percentage of heat output from renewables, is how the Renewable Energy Directive calculates renewable heat from heat pumps. It is therefore the definition we use when calculating the renewable energy percentages for our overall results. More detail on the renewable heat, and overall renewable energy percentage calculations, is in Annex 3.

Returning to the results themselves, there are a number of points to note.

The first is that while there is significant heat decarbonisation in the residential sector, it is overshadowed by that in the commercial/ services sector. We also show relatively limited renewable heat in the industrial sector, although somewhat higher in the RPP Realistic case. Decarbonising many industrial processes, at a UK level, is expected to rely on CCS, which we have assumed[92] will not happen in Scotland by 2030.

The other important question is what proportion of buildings have renewable heat equipment (heat pumps or biomass boilers). For the services sector, this is a relatively simple question to answer – around 72%, based on the level of renewable heat. For the domestic sector, the figure is complicated by the fact that we are installing hybrid heat pumps. These produce some renewable heat and some non-renewable heat. We therefore need to look at the total heat output from heat pumps, as a percentage of the total heat demand, to reach this figure. This turns out to be 56% - in other words, over half of Scottish homes have a heat pump. This is consistent with the figure in the "High Government intervention High Uptake" scenario in the *Scenarios for Scottish Heat* study done for the Scottish Government by Arup, which used the Scottish Housing Condition survey as a basis for assessing the potential for applying "*novel heat technologies*".

Achieving this level of heat pump uptake, at a reasonable level of efficiency in terms of heat delivered, will be contingent on improving household insulation. Our results show very significant efficiencies in the household sector, with residential heat demand falling by around 30% over the period. This is consistent with a view from an academic energy efficiency expert, who commented to us[93] that to 2030, the best case for demand reduction might be 2% per year. Should this not be achieved, total heat demand would be higher and so total emissions would be higher, meaning that the renewable energy percentage would have to *increase*. This again indicates that our figures for the renewable energy percentage are conservative.

As a comparison, the Scottish Housing Condition Survey[94] shows that energy consumption in Scottish homes for heating and hot water (of which heating is the significant majority) fell by 27% in the two decades between 1991 and 2010.

We also note that hybrid heat pumps could be helpful in reducing the impact of heat pumps on peak electricity load in Scotland, since the gas capability of the hybrid could be run at that time. They could also be useful in improving the overall co-efficient of performance of the heat pumps, which tends to fall as the outside temperature falls. The presence of a gas boiler for use at times when it is very cold outside would mean that the heat pump would tend to be run at times when outside temperatures are higher, making it more efficient.

[92] Our basis for this is that there are no CCS demonstration units in the UK at present, and a recent IEA workshop on CCS (http://www.iea.org/media/workshops/2013/ccs/industry/cem_workshopreport.pdf) discussed possible industrial demonstrations by 2020. We have therefore taken the conservative approach of not relying on industrial CCS for significant abatement in our work.

[93] Private conversation

[94] Scottish Government, 2012, *Energy Use in the Home: Measuring and Analysing Domestic Energy Use and Energy Efficiency in Scotland.* http://www.gov.scot/Resource/0039/00398667.pdf . Figure used is median energy consumption

Why are we seeing these results? Heat accounts for around 50% of energy demand in Scotland, and so any credible pathway to the 2030 emissions target must involve both high energy efficiency and significant decarbonisation of heat. The options for decarbonising heat are essentially electrification (i.e. heat pumps) or the use of biomass. As discussed elsewhere, we have limited the use of biomass because of sustainability concerns, and much of the biomass supply is used in transport. There is therefore little alternative but to show significant roll-out of heat pumps. Hybrid heat pumps are chosen partly on cost grounds and partly because of their better load profile at peak times (that is, they add less to the peak electricity demand than a stand-alone heat pump). As the CCC noted, heat pumps are expected to be cost-effective without subsidy in many cases in the 2020s, and indeed we saw significant uptake in the base case.

It should be said that this is one instance where MARKAL is presenting a more extreme result than is likely in practice. In reality, it is very unlikely that only *hybrid* heat pumps will be installed in domestic buildings. However, because stand-alone heat pumps would produce a higher emissions reduction than a hybrid heat pump (since they do not rely on gas), any use of stand-alone heat pumps will reduce the percentage of domestic buildings that will need to have heat pumps installed in order to meet the renewable heat objective. Taking the other extreme, to achieve the same emissions savings in the domestic sector using only stand-alone heat pumps would require them to be installed in around 28% of Scottish homes, under our assumptions. In other words, the 56% figure above may well be a significant over-estimate of required domestic heat pump penetration in Scotland.

We now turn to our results for the transport sector.

6.1.3 Detailed results: transport

Our scenarios show a relatively lower level of renewable transport than renewable heat. This is quite similar to other analyses, which tend to show power decarbonising first, then heat and then transport. In particular, heavy goods vehicles (HGVs) are felt to be difficult to decarbonise by 2030.

Our overall results – in terms of what fuels are used for transport - are shown in Table 16 below. We look at vehicle types later.

Table 16: Transport fuel demand (petajoules per year)

Fuel	2010	RPP Optimistic	RPP Realistic
Petrol/ Diesel	139	88	82
Electricity	3	7	14
Jet fuel (domestic aviation only)	3	5	5
Bio-diesel/kerosene	2	5	5
Compressed natural gas (CNG)	-	14	-
Ethanol/methanol	2	1	1
TOTAL	*149*	*120*	*107*

The first thing to note is that this shows a significant drop in transport fuel demand – by 28% in the "Realistic" scenario. There is a drop of just over 40% in petrol and diesel[95] use in the "Realistic". Demand for electricity increases, but the absolute increase of 11PJ is not as large as the drop in petrol/ diesel of 57PJ in the base case.

[95] Because diesel vehicles are slightly more efficient, and so cheaper, MARKAL keeps them in preference to petrol vehicles. In reality, there is likely to be a more balanced shift away from diesel vehicles. It therefore makes more sense to consider the petrol/ diesel figures together

This is mainly because of the greater efficiency of electric vehicles (an electric vehicle today travels about three times further than a petrol vehicle of a similar size, for the same energy input), and also partly about increasing efficiency of all vehicles over time. Note that we have used the CCC's efficiency assumptions, but if these turn out to be optimistic, we would need more electric vehicles to achieve the emissions reductions required.

The "CNG" row is also interesting. When we ran the "RPP Optimistic" scenario through MARKAL, it assumed that a significant proportion of HGVs would switch to CNG. This has emissions savings, and a report by the Low Carbon Vehicle Partnership calculated that it has a payback period of around 3 years. However, because the duty cycle of many HGVs is international – that is, they travel outside Scotland regularly – the decision for HGV owners about switching to CNG is not only determined by Scottish policy. In addition, the fact that the switch is not being made now, despite it being economic, suggests there are other barriers than cost. We therefore removed this option in the "RPP Realistic" run.

As well as the fuel demand, the other important result is what percentage of vehicles are electric (or hybrid, or PHEVs). This is shown in Table 17 below ("RPP realistic" scenario only).

Table 17: Vehicle types by fuel in 2030 (%)

Vehicle	Petrol/ diesel	Hybrid (including PHEV)	Battery EV
HGVs	95%	5%	-
LGVs	24%	66%	10%
Buses	52%	-	48%
Cars	65%	4%	31%

While the exact figures should be interpreted cautiously, the clear message here is that public transport, and lighter goods vehicles, will be heavily electrified. At the household end, there is significant taken up of EVs, although in practice MARKAL may tend to overestimate EV uptake at the expense of PHEVs because it does not take maximum vehicle range into account, and it focuses more on lifetime cost than the average consumer does. By contrast, lifetime cost is likely to be a better representation of how businesses – such as LGV and bus owners – make decisions, and so the figures here may be closer to reality. HGVs are, conservatively, shown as being only mildly hybridised. In early runs, we saw significant hybridisation, suggesting that it would be economic, but our transport experts considered this to be unrealistic.

The figure for buses is particularly striking. While the reality may be that there is more use of hybrids (particularly plug in hybrids), electric buses are already being used in Scotland – for instance, from Stranraer train station to the ferry[96], and more are planned for Inverness[97]. We note that RPP2 suggests that we could "*…see low carbon buses accounting for half of the Scottish bus fleet by 2027*", and "*By 2030…over 30% of car and van fleet will be plug-in hybrid (PIH) or battery EV and hydrogen fuel cells*", which is essentially what our results show (although RPP2 assumes some uptake of hydrogen, which MARKAL does not show – we note that there is a pilot project in Aberdeen).

Why has MARKAL decided on these vehicle choices? Again, because of limits on biomass, the choices for transport decarbonisation are electric vehicles, hybrid vehicles or hydrogen vehicles. MARKAL does not show any of the latter since they are more expensive, under our assumptions, than electric vehicles. The decision between electric vehicles, hybrids and PHEV is likely to have largely been based on mileage. As is well known, electric vehicles tend to be more expensive than other vehicles to buy, but have lower running costs. They will tend to be more attractive, therefore, for vehicle types with high mileage, such as buses. The picture is more mixed for LGVs, which have been pushed towards the hybrid option, and we see the lowest level of uptake in passenger cars.

[96] http://www.optare.com/news/2014/6/25/minister-launches-scotlands-first-electric-bus-service
[97] http://www.stagecoach.com/media/news-releases/2014/2014-10-23.aspx

It should be said that the EV market shares shown above are challenging. To give a sense of what this would mean in practice, we can use a standard approach to looking at the take-up of a new product called the Rogers Adoption curve. This looks at different segments of the population, by their openness (or not) to new products. At the 60% level (assumed in RPP2 and by the CCC, and consistent with our results), uptake is driven by "*peer pressure, social norms or economic necessity…most of the uncertainty around [the product] must be resolved…*"[98]. In short, it would mean that purchasing a PHEV or EV has become utterly mainstream. It also means that PHEVs & EVs cannot be confined to those in the larger cities whose typical journeys are relatively short. This implies that a national charging network is needed.

The charging network was discussed in a report by Element Energy for the CCC. It assumed that: "*A national rapid (40kW+) charging network extends across all UK regions by 2030…The cost of the rapid charging network is estimated at £300-£530 million (capital and installation), representing around 20,000 units over 2,100 sites by 2030. This compares to around 8,600 liquid fuel stations in the UK currently*". This cost is a UK-wide cost, so needs to be scaled for Scotland, although we note that Scotland's relatively dispersed population might mean that the cost per head of a charging network might be higher in Scotland than the UK average (assuming that the network is rolled out across the country rather than say focusing on the central belt, which is likely to be required to achieve a 60% market share for the reasons stated earlier on the need for PHEVs and EVs to be mainstream).

We have assumed that the cost for Scotland is proportional to *road miles* rather than population, so the average distance between charging points – which is what drivers are concerned about – would be the same in Scotland as the rest of the UK. The Office for National Statistics estimates that around 15%[99] of total GB road miles are in Scotland. This suggests that the Scottish proportion of the road charging network would be around £45-80 million; we have taken the mid-point figure of £62.5m.

In the transport sector, MARKAL chose hybrid and electric buses and light goods vehicles in preference to hybrid or electric cars. The decision here is likely to have been based on mileage. As is well known, electric vehicles tend to be more expensive than other vehicles to buy, but have lower running costs. They will tend to be more attractive, therefore, for vehicle types with high mileage, such as buses.

6.1.4 Renewable energy as one option for decarbonisation

While these figures are similar to those from other reports (as we will see in the next section) it is useful to ask why MARKAL has chosen the pathways that it has. We have discussed this for individual sectors above. But why has the given level of renewable energy been chosen?

To understand this, we need to return to the overall objective – reduce emissions in line with Scotland's legal obligation under the Climate Change (Scotland) Act 2009. This can be achieved in the following ways:

1. Energy efficiency
2. Reducing demand
3. Switching from coal or oil to lower carbon fossil fuels
4. Renewable energy
5. Other low carbon energy e.g. nuclear and CCS

In fact, our scenarios do not show any of (2), and we have removed option (5) by assumption, apart from 400MW of gas with CCS. We have also limited (3) in the transport sector by capping biomass and preventing HGVs from using CNG, in our "Realistic" scenario.

Therefore, MARKAL uses a combination of energy efficiency, fuel switching and renewable energy to achieve the 2030 emissions target.

What is the relative contribution of each? Recall that the 2030 target is a reduction of a little over 60% reduction in emissions from 1990 levels by 2030. What we see is that energy efficiency in its various forms gives a 20% reduction in economy-wide demand over the period, and that there is some limited fuel switching in industry. This leaves, broadly, a further 40% reduction to be achieved by renewables, from a 1990 starting point with essentially no renewables apart from some hydro. It is therefore not a surprise that our headline result is a little over 40% renewables across the economy.

[98] Ryan and Gross, 1943, *The Diffusion of Hybrid Seed Corn in Two Iowa Communitie*s, Rural Sociology
[99] Source: ONS https://www.gov.uk/government/publications/road-lengths-statistics-in-great-britain-2011

Put another way, MARKAL achieves the emissions reductions through one-third efficiency and two-thirds renewable energy. MARKAL is generally assumed to be if anything over-optimistic on energy efficiency, for example because it looks at lifetime cost which is not how consumers make decisions (at least without significant policy interventions). So we can reasonably expect that the level of renewable energy is at the lower end of what is required for the 2030 targets.

We note that electricity demand is actually about 18% *higher* in our core and conservative scenarios than in the baseline, where demand is 34.2TWh. This is because of the increased electrification of heat and transport.

6.2 Comparison to other reports

In this section, we compare the results from above to four key reports:

- The CCC's report on the 4th carbon budget. While that focused on the mid-2020s, it did give indicative figures for 2030
- The Ecofys study on renewable energy in Europe[100]. While that study focused on the EU-27 as a whole, it does provide a helpful benchmark to see if the results of our study would see Scotland out of line with the EU average
- The study by Element Energy on electric vehicles in Scotland
- The Transport for Scotland study "Switched On Scotland" on electric vehicles to 2050

A summary of our results, compared to those reports, is shown in Table 18 below.

Table 18: Comparison of results with other studies

Source	Renewable Heat	Renewable Transport
Current project	36-40% renewable heat Half of building heating from heat pumps	11-18% renewable transport Nearly half of buses are electric Majority of LGVs hybrid 31% battery cars by 2030 (RPP Realistic case, lower in RPP Optimistic)
CCC	Up to 42% renewable heat[101] Heat pumps account for c. 70% of emission reduction potential. Some biomass in homes but focus is on district heating and industrial	No overall figure 60% of new cars and vans in 2030 being electric (mostly plug-in hybrids), 50% of buses being fuelled by hydrogen, and a fall in emissions from petrol or diesel vehicles to 80g CO_2/km
Ecofys	35% renewable heat	36% renewable transport
Element Energy	n/a	Business as usual – 9% of cars as PHEVs or EVs by 2030 "Upper" scenario[102] - 31% of cars as PHEVs or EVs by 2030
Transport Scotland: Switched On Scotland report	n/a	By 2030, half of all fossil-fuelled vehicles will be phased-out of urban environments across Scotland. 60% of new vehicles will be PHEV or EV by 2030[103] "*Achieve essentially CO2-free city logistics in major urban centres by 2030*"

We now discuss the comparison in more detail, starting with heat.

[100] ECOFYS for WWF, 2012, *Renewable Energy: a 2030 scenario for the EU.* http://www.ecofys.com/files/files/ecofys-2013-renewable-energy-2030-scenario-for-the-eu.pdf
[101] Table 5.1, fourth carbon budget report
[102] Defined in the report as a reasonable upper bound on EV uptake
[103] See figure 5 of the report

6.2.1 Comparison to other reports: heat sector

This level of renewable heat is in line with that in the CCC's fourth carbon budget. That showed up to 10 million homes with heat pumps by 2030 (40% of UK stock), and notes that the "*key option for supply side [heat] decarbonisation is heat pumps*". It also showed some use of biomass which we do not show, partly because heat pumps are cheaper and partly because we have limited biomass use such that it goes mainly to transport. The CCC also limited it for domestic buildings, but the driver there was a concern about local air quality. Our overall results on the level of renewable heat in homes (around half) are consistent with the CCC's fourth carbon budget (see figure 5.9 of that report in particular).

A report for the Scottish Government[104] also looked at the potential for heat pumps in Scotland, and concluded that with a high degree of Government intervention and user acceptance, 57% penetration of heat pumps might be achieved. We have used this limit in our analysis.

To test the importance of high penetration of heat pumps, we did run two variant scenarios that had only 40% of domestic heating from hybrid heat pumps. As expected, the level of renewables in transport increased to compensate for reduced renewable heat, although by under 1% in the "RPP Optimistic" scenario and by only 3% in the "RPP Realistic" scenario – indicating that the level of heat pump penetration in our scenario is not required to hit the emissions target.

It should also be noted that MARKAL has focused on hybrid heat pumps here. In reality it is likely that some homes would install "pure" heat pumps, which produce all of a home's heating from electricity rather than hybrids which produce only some. This would reduce the number of homes that need to install heat pumps to achieve any given level of renewable energy.

We have also shown a level of district heating that reflects the Scottish Government's level of ambition. The CCC's view is that there is a "*…limited role for district heating, reflecting uncertainties around technical and economic aspects of this option, with the possibility of deeper penetration as uncertainties are resolved.*"

The CCC also shows higher use of renewable heat in the commercial sector than in the domestic. For industry, it suggests "*…use of biomass and biogas…account for around 25% of total heat demand by industry in 2030*". This is very similar to the figure in our "RPP Realistic" scenario, of 24%.

Finally, we note that our overall renewable heat figure – of 40% - is in line with the assumption in Friends of the Earth's "*Power of Scotland – Secured*" report[105] as to what "reasonable progress by 2030" towards decarbonising heat means. It is also very similar to the figure for the EU as a whole from the Ecofys study (35%).

We now turn to the transport sector.

6.2.2 Comparison to other reports: transport sector

The CCC's report suggests that by 2030, we might see 60% of new cars and vans in 2030 being electric (mostly PHEVs), 50% of buses being fuelled by hydrogen, and a fall in emissions from petrol or diesel vehicles to 80g CO_2/km.

This is comparable to our results. If we assume a gradually increasing uptake trend to 60% of new cars EVs by 2030, we find that around 30% of the car fleet is an EV. This is also comparable to the 60% of new cars as hybrids or EVs shown in the "Switched-On Scotland" report (figure 5 of that report). It is at the upper end[106] of the feasible range in the Element Energy report on EVs in Scotland (see below).

The figure for LGVs is higher than the CCC's, although we show them being hybrids of one form or another. Like the "Switched On Scotland" report, we show a major shift of goods vehicles and buses away from petrol and diesel (we assume this is what "city logistics" refers to). We also show a 40% reduction in petrol and diesel demand.

By contrast with the CCC, we do not see any uptake of hydrogen vehicles of any type, for reasons of cost (the CCC figures are from 2009).

[104] Arup, 2014, *Scenarios for Scottish Heat: Heat Pathways Scenarios Model Factual Report* http://www.gov.scot/Resource/0045/00451939.pdf
[105] http://www.foe-scotland.org.uk/sites/www.foe-scotland.org.uk/files/possv6final.pdf
[106] Assuming a smooth progression from minimal EV sales today to 60% by 2030, one might expect that the car fleet would be around 30% electric,

Comparisons to the Ecofys study are more difficult. That study showed significant use of biomass for transport fuel – up to 36%, beyond the level that would be sustainable if Scotland alone is considered. In our scenarios, the limited biomass available was used for industrial and district heating, with only around 5% biofuels in transport. Given the issues with biomass sustainability, we consider 36% to be a very high figure.

6.2.3 National Grid Future Energy Scenarios[107]

As a further cross-check, we compared our results across all sectors to those from National Grid's Future Energy Scenarios report, and in particular the "Gone Green" scenario. Note that figures shown are for 2035, and for the UK as a whole, rather than 2030 figures for Scotland, so are not directly comparable to our results. Based on relative population size[108], we might expect UK figures to be around 12 times those for Scotland and unless otherwise noted we have divided the National Grid figures by 12 to reach a "scaled to Scotland" figure.

These are shown in Table 19 below.

Table 19: National Grid "Gone Green" scenario key statistics

Figure	2035	Scaled to Scotland	Our figure (RPP Optimistic scenario)	Our figure (RPP Realistic scenario)	Comments
Total electricity generation capacity (GW)	163	13.5	18	19	Likely relatively higher percentage of wind power in Scotland, and Scotland's role as net exporter of power, means our figure should be higher than a simple 1/12 share of the total
Residential heat pumps (millions)	10	1.0[109]	1.4	1.4	National Grid's figure is the same as the CCC's figure for 2030
Electric vehicles (millions)	5.4	0.45[110]	0.27[111]	0.84[112]	Our figures bracket National Grid's figure
Annual gas demand (TWh)	705	59	52	47	We see higher electrification of heat, which would tend to reduce gas demand
Renewable energy %	32	32	44	48	32% is only slightly above the Scottish Government's target for 2020, so likely an underestimate for Scotland

[107] http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Future-Energy-Scenarios/
[108] Scotland accounts for a little over 8% of the UK's population, i.e. about 1/12.
[109] Scotland has around 2.5 million households. Source: Housing Statistics for Scotland http://www.gov.scot/Publications/2014/08/2448/downloads
[110] Strictly, Scotland has fractionally more cars per head than the UK as a whole, but the difference is small.
[111] 10% of cars are BEVs or PHEVs in 2030
[112] 31% (RPP Realistic scenario) of Scotland's stock of 2.7 million vehicles

We are therefore in a similar position on electric vehicles, and more aggressive on heat pumps and reductions in gas demand. Our overall percentage of renewable energy is higher, reflecting our focus on renewables and our exclusion of nuclear and CCS. By contrast, National Grid's Gone Green scenario shows a small increase in nuclear capacity.

6.3 Other impacts including cost

In this section we look at other impacts of our scenarios. Cost is an important impact, but we also consider:

- The overall energy mix – where does Scotland's energy come from, by fuel?
- Environmental impacts
- Community and decentralised energy
- Longer term trends

6.3.1 Costs

We calculated the cost of the scenarios as a net cost, compared to the "base" scenario. This involved looking at total cost and discounting the annual cost from 2015 to 2050 at the standard 3.5%[113] real social discount rate. This total cost includes the cost of building, operating and fuelling all electricity generation in Scotland, the cost of every vehicle (purchase cost, operating cost, fuel cost) and of every heating system (installation, operating/ maintenance and fuel). It includes import costs where appropriate.

First, we calculate the cost before carbon. This is, discounted, around £25-26 billion, compared to the baseline. We note that the cost of Scotland's 2020 renewable electricity target was estimated at £35 billion[114].

We compared this to the net benefits, using DECC's carbon valuation toolkit[115]. This gave a benefit of around £25 billion. We note that this calculation involves valuing changes in emissions from electricity generation at the EU ETS price, rather than at the social cost of carbon, so is an underestimate of the damage cost of emissions. This is summarised in Table 20 below.

Table 20: Comparison of costs and benefits

	Costs	Benefits	Net benefit/ (cost)
Cost of core/ conservative relative to baseline	£25-26 billion	£25 billion	Zero (within the margins of error of our analysis)

So, our analysis suggests that using the UK Government's current carbon pricing appraisal approach, our "optimistic" and "realistic" scenarios have a comparable cost to the "base" scenario. This conclusion would be strengthened if all reductions were valued at DECC's estimate of the social cost of carbon.

We note that Scotland would have to, in effect, pay these carbon costs directly in the "base" scenario. This is because that scenario does not achieve Scotland's legally binding emissions targets. To remain compliant with the legislation, Scotland would have to buy carbon allowances on the international market (assuming that they were available). Assuming DECC's carbon price forecasts are correct, the cost of this, together with the loss of the savings from energy efficiency shown in our scenarios, would be the net benefit shown by the carbon valuation toolkit – that is, around £25 billion.

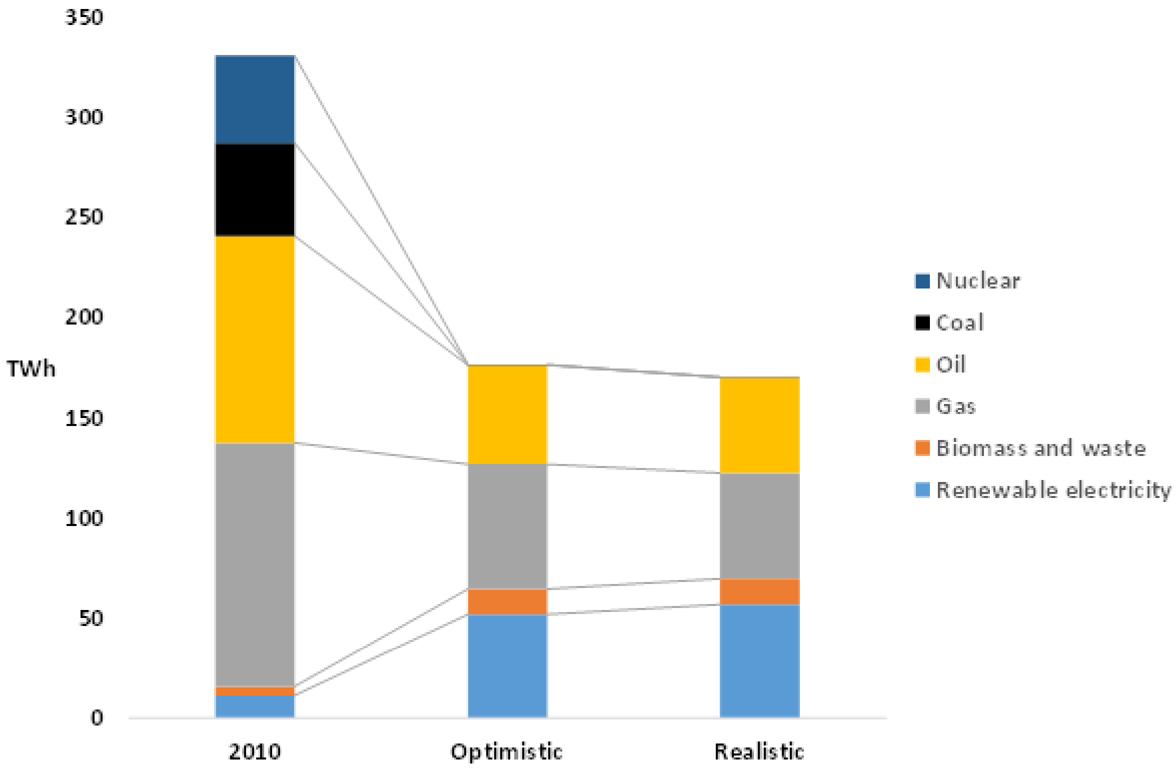
[113] Source: HM Treasury Green Book
[114] SKM, 2011, *Scottish Generation Scenarios and Power Flows*. Section 5.2 http://www.gov.scot/Resource/0039/00393483.pdf
[115] Available at: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal . We made a minor adjustment to the tool to allow it to cope with a variation in electricity carbon intensity. This involved calculating the change in greenhouse gas emissions off-model and inserting them in row 6 on the "TS_CO2" sheet.

In other words, there is little apparent difference in cost between our scenarios. But this does not take account of all impacts. For example, as far as overall macro-economic impacts are concerned, we see a shift away from the need for petrol and diesel, and towards renewable heat installers. Increased employment in the electricity sector is also likely, as noted elsewhere – of the order of 14,000 additional jobs.

6.3.2 Where does Scotland's energy come from

Figure 14 below shows Scotland's primary energy supply by fuel.

Figure 14: Primary energy supply in Scotland in 2010 and in RPP Optimistic and RPP Realistic scenarios for 2030



The angles of the lines show the trend in fuel use for each fuel. Starting from the top, nuclear reduces to zero as expected. Coal demand virtually disappears as well (a small percentage remains in industry, but this may be a model artefact).

Oil and gas demand are also squeezed, particularly oil demand. Gas demand falls by around half, but because of fuel substitution effects, the 400MW gas with CCS power station and the use of hybrid heat pumps, it does not fall as much as might be expected.

The major growth is in renewable electricity, which increases to around five times the level in 2010.

6.3.3 Environmental impacts

We also considered environmental impacts in a qualitative way. Since the major infrastructure development in our results is new wind generation, at levels not much above what is already consented in Scotland, the *additional* environmental impact of our scenarios should be low. However, it is important to recognise that not all consented generation will be built, and that not everything in the planning process will be determined to be environmentally acceptable.

We expect a number of positive environmental benefits to flow from the scenario. The main one would be improved air quality in cities as a result of the 40% drop in the use of petrol and diesel. This is likely to have health benefits, although these are not possible to quantify accurately without a more detailed, spatial, model. Cambridge Econometrics, in the study referenced in the previous section, estimated UK-wide healthcare savings of between £96m and £288m per year.

Reduced traffic noise (since electric vehicles are quieter) is also likely, as noted by Transport Scotland in its report.

6.3.4 Macro-economic impacts

As far as overall macro-economic impacts are concerned, we see a shift away from the need for petrol and diesel retailers, and towards renewable fuel vendors. Increased employment in the electricity sector is also likely; a study by UKERC suggests that the levels of renewable electricity in our scenarios could lead to an extra 14,000 jobs from wind alone[116]. We also see significant reduced net imports of petrol and diesel, since demand falls by 40%.

This is similar to the analysis by Cambridge Econometrics, which looked at the UK's fourth carbon budget. It estimated that there would be an additional 190,000 jobs created across the UK, and that around £8.5 billion would be saved annually in reduced imports.

6.3.5 Community and decentralised energy

We also considered the role of community and decentralised energy. Our results suggest that there is scope for additional community renewable *electricity* projects, as the demand for renewable electricity in Scotland is significant.

In addition, a number of community renewable heat and transport projects are in existence. Indeed, DECC's Community Energy Strategy Update[117] notes that "*Community heat projects often face lower costs and fewer challenges than electricity projects, and their scale is often inherently at the size of a community*". The Aberdeen Heat and Power district heating scheme, while not renewable, shows the potential for community heating schemes (although it was set up by the city council rather than the community).

On transport, the Fintry Energy Efficient Transport[118] car club, for example, offers those in Fintry the option to share three community cars, one of which is electric. The Fetlar Electric minibus, a community owned electric vehicle, is another example. It will be important to ensure that support programmes recognise this need to decarbonise energy demand (such as heat and transport) as well as energy supply. In the Fetlar case, for example, the community applied for funding through the CARES programme to install wind turbines to generate electricity to fuel the vehicle. The funding for the vehicle itself, however, came from a number of sources – making it a more complex process than if the funding had been from a single one.

However, while there are some community energy schemes in existence, real barriers remain. We have reviewed a number of studies (listed in the bibliography) to identify what these are, and how they might be overcome.

The first issue identified is a lack of knowledge. While in some cases, this may be that the community is simply unaware of the potential for community energy, it can also mean a lack of knowledge about how to go about developing a community energy scheme. Organisations such as Local Energy Scotland[119] provide advice and support to help overcome this barrier. It also provides support on accessing funding, such as the CARES scheme.

The second barrier identified is around the regulatory arrangements. It can be complicated to connect to the electricity network, and the processes for doing so are often designed around industry professionals. Some[120] take the view that "*'License Lite', the current framework for licensing smaller decentralised energy supply, maintains too many administrative burdens and reinforces the dominant position of big energy utilities*". It also takes significant time and effort for a community group to become a licensed electricity supplier.

[116] This includes jobs at all stages of the supply chain, not all parts of which may be in Scotland
[117] DECC, 2015, *Community Energy Strategy Update* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/414446/CESU_FINAL.pdf
[118] http://www.fintrydt.org.uk/how-can-we-help/feet-car-club/
[119] http://www.localenergyscotland.org/about/
[120] http://www.communitypower.eu/en/uk.html

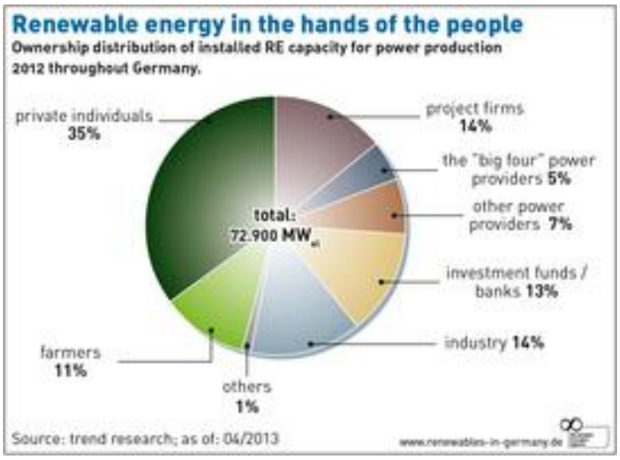
Again, the CARES toolkit provides advice on getting a connection to the electricity grid[121], but the reality is that the process can be "*long, complicated and costly*". Further assistance in this area (perhaps including working with DNOs and Ofgem to streamline or simplify the process for communities) may be helpful.

Additionally, there appears to have been an issue with the Financial Conduct Authority not registering some proposed community energy co-operatives. The grounds for this need to be further investigated but this may merit policy action.

Many of these barriers relate more to electricity, which (for a number of reasons including safety and network stability) has relatively complicated arrangements. Energy projects dealing with heat and transport may be simpler, as DECC notes.

We also note that the experience in other countries has been quite different. As Figure 15 below shows[122], there is very significant ownership of renewable electricity by private individuals in Germany.

Figure 15: Renewable energy ownership in Germany



It has been suggested[123] that a key reason for this difference is the simplicity of the FIT in Germany, including for larger schemes, compared to the RO or (now) the CfD FIT.

6.3.6 Longer term trends

Finally, we take a brief look at the trends beyond 2030. These need to be treated with caution, as the model was set up to look at 2030. However, we can discern some general qualitative trends for the 2030s and 2040s.

Overall, there is a continuing focus on electrification and increasing renewables generation installed. Demand continues to fall particularly in transport although overall demand falls more slowly than before.

In transport, we see the elimination of standard diesel buses and an increasing number of battery buses. Diesel LGVs and HGVs remain, although over time they are replaced with hybrid models. HGVs are eventually switched to hydrogen. While this may not be realistic in a world where other vehicles are being electrified, it can be taken as an indication of the difficulty of decarbonising the HGV sector.

In heating, gas starts to reduce and electricity to increase in the industrial sector, and significant additional reductions in emissions are seen. The service sector continues to see a reduction in gas heating (and interestingly, less efficient wood heating is replaced by more efficient heat pumps).

It would be wrong to read too much into these results. However, they do indicate where the "next" sectors of interest for decarbonisation after 2030 might be.

[121] http://www.localenergyscotland.org/funding-resources/resources-advice/cares-toolkit/project-development/grid-connection/
[122] Source: Renewables-in-germany.com. http://www.unendlich-viel-energie.de/media/image/1136.AEE_Erneuerbare_Energien_in_Bu%E2%95%A0%C3%AArgerhand_april13_en-01.jpg
[123] http://www.communityenvironment.org.uk/cms/wp-content/uploads/2013/08/Community-owned-energy-generation-Alan-Simpson.pdf

7 Conclusions and policy recommendations

Based on the results and assumptions in the previous section, we can draw a number of conclusions. These are summarised in Box 2.

Box 2: Key conclusions

1. Electricity decarbonisation (50g CO_2/kWh) is achievable given the current renewables pipeline, and compatible with security of supply. We see around 145% renewable electricity.
2. Energy efficiency could see Scotland's energy demand fall by a fifth over the next 15 years. Without this, much more effort is needed on renewables
3. Heat decarbonisation is key: 40% renewable heat by 2030
4. Transport emissions may be reduced more by efficiency (hybrids, EV efficiency compared to ICEs) than renewables. Transport shows 18% renewable energy, but a 28% fall in energy.
5. Petrol/ diesel demand could drop by 40%, bringing benefits in terms of improved air quality and health
6. Gas will continue to play a significant role in the economy, although how and when it is used will change – more use in industry to substitute for other fuels, less use in electricity generation and in heat
7. Additional costs are outweighed by the value of the carbon reductions alone, using DECC figures. Many of the measures will be cost-effective in the 2020s.
8. Additional policies are needed to support the transition, and many existing ones need to be made longer term and more certain

What our analysis shows is a picture that is consistent with the high level messages sent out by the Scottish Government on future levels of renewable electricity, heat and transport. "*Significant progress on renewable heat by 2030*", for example, should mean around 40% on a straight line trajectory to decarbonising heat by 2050. However, many of those messages have not yet been quantified, and the policies to achieve them are incomplete.

One of the aims of this report is to provide quantified levels for renewable heat, transport and electricity, consistent with the Climate Change (Scotland) Act target for 2030. While they are not the only possible future, they do provide internally consistent, cross-economy, pathways that deliver the 2030 target. Alternative proposed futures that show less ambition in a particular area than our scenarios must show where they will demonstrate greater ambition, in order to hit the overall 2030 emissions target.

Finally, we underline again that the additional costs are balanced by the value of the carbon saved. This also does not take into account other benefits such as improved air quality, reduced energy imports and employment benefits. This picture is consistent with analysis[124] done on the UK's fourth carbon budget, which showed how it would be overall beneficial.

[124] Such as the work by Cambridge Econometrics – see bibliography.

7.1 Recommendations

We can identify a number of barriers to achieving the scenarios set out in this report. These are discussed, by sector, below. We also provide policy recommendations.

7.1.1 Electricity

Decarbonising the power sector is crucial for electrification of other sectors to have maximum carbon benefit. While there is enough wind power already operational, consented or in planning to deliver the scenarios here, if it is all built, there is no guarantee that it will be. This could be because of future limited subsidy, or because of objections during the planning process. We also see that allowing unabated fossil generation is very difficult to reconcile with a 50g target.

Our recommendations for wind are:

- To continue to provide appropriate levels of subsidy
- To support strategic planning of renewables development to steer development towards the most appropriate sites
- To support a higher degree of community involvement
- To work with the Distribution Network Operators and Ofgem to overcome barriers around grid connection.

7.1.2 Heat

The key feature of the heat component of our scenarios is the widespread deployment of heat pumps to the extent that they are the standard heating technology. The barriers to this include the need for subsidy (at least until the 2020s), consumer acceptance, and the potential load on the electricity grid. While there is existing subsidy (the Renewable Heat Incentive), funding for this is not guaranteed to 2020. Building efficiency will also be important, and we note that the RPP2 does not show the Scottish Home Energy Efficiency Programme continuing beyond 2017.

Our recommendations for heat are:

- To provide longer term financial support for renewable heat
- To increase the rate of energy efficiency improvement
- To demonstrate the benefits of heat pumps, possibly through public sector leadership
- To investigate the potential grid benefits of hybrid heat pumps

7.1.3 Transport

In the transport sector, the key success factors are the widespread deployment of electric and hybrid vehicles, particularly in the non-domestic vehicle sector. The main barriers to such vehicles are high upfront cost, lack of charging network, vehicle range and consumer acceptance. These barriers are lower where vehicles travel many miles per year, where they charge at the same place on a regular basis, and where their range is relatively limited.

Our recommendations for transport are:

- To continue to provide financial support for the purchase of electric cars and other vehicles
- To investigate leasing or loan models for vehicles
- To push harder on a charging network, particularly in cities
- To look at options for making high emissions vehicles less attractive, such as congestion charging or low emissions zones

Appendices

Annex 1 - Description of the 2R MARKAL model

The MARKAL model

The MARKAL modelling framework is used worldwide as a key tool of energy policy analysis, and was originally developed by the International Energy Agency (IEA) under the Energy Technology and Systems Analysis Programme (ETSAP). MARKAL, and its recent successor TIMES, has been used in over 100 countries. An international community of modellers continues to use MARKAL and TIMES models around the world, supported by the IEA-ETSAP.

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, the 2008 Climate Change Act and the Committee on Climate Change's suggested carbon budgets and the government's responses to them. Different variants of the model have been used in these processes, incorporating macro-economic feedbacks (MARKAL-MACRO and MARKAL Elastic Demand) and incorporating analysis of uncertainty (Stochastic MARKAL). The current UK version of the MARKAL model was developed by the modelling team based at the UCL Energy Institute, with funding from the UK Energy Research Centre.

The two-region version of the model used in this project 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, published by the Scottish Government in 2006[125]. The assumptions used to develop the two-region model are described in more detail in Anandarajah and McDowall (2012)[126]. Much of the data and many of the key assumptions in the two region model are unchanged from the full UK model, documentation for which is published by the UCL Energy Institute[127]. Some of the technology data in the 2R model has been revised under this project and the changes have been documented in the main body of the report.

Model paradigm

MARKAL is an optimization model of the entire energy system from resources to conversion to end-use sectors to energy services. It includes explicit representation of the UK's energy resources (such as oil and gas, solar radiation and bioenergy resources); energy trade (fossil fuels, electricity, biomass, etc.); and energy 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). As such, it is a bottom-up model with a high degree of technology detail spanning the entire energy system.

Each of the hundreds of technologies in the model is associated with data on capital and operating costs, efficiency, lifetime, availability (i.e. taking account of downtime for maintenance), and other relevant characteristics. Future technology costs and characteristics are included, so that the model database represents the expected improvements in new and existing energy technologies. Domestic resources (such as oil), and technologies such as wind power and solar are available in a series of tranches corresponding to a stepped supply curve, in which additional capacity becomes increasingly expensive per unit. Key relationships and constraints in the energy system, such as peak capacity margins in the power sector, are incorporated through constraints that are added to the model. This means that sufficient 'back-up' capacity is assumed to be installed to ensure that a system with a high level of variable renewable electricity is sufficiently reliable. The costs of such back-up systems are fully accounted for.

An additional key input is a set of forecasted energy service demands. The energy service demand forecasts are taken largely from UK government forecasts, such as those produced by the Department for Transport.

[125] Scottish Energy Study (2006). Volume 1: Energy in Scotland: Supply and demand, Scottish Executive, Scotland, 2006
[126] Anandarajah, G. and W. McDowall. 2012. What are the costs of Scotland's climate and renewable policies? Energy Policy 50(0): 773-783.
[127] https://www.ucl.ac.uk/energy-models/models/uk-markal/uk-markal-documentation

With these key inputs—the resource and technology database, including the various technical constraints, and the energy service demand forecasts—the model then calculates the least-cost way of meeting those demands based on the technologies and resources available in the model database, subject to constraints such as carbon targets. In technical terms, the model does this using linear programming, and it optimises the energy system by minimising the total discounted energy system cost across the modelled time horizon. The model will find cost optimal solutions (energy resources, technologies and its usages) to meet the energy services demands while meeting several technology, policy and operational constraints.

Conceptually, this is equivalent to an energy system that is governed by a single social planner, who has perfect foresight of future demands, technology costs, resource availabilities and import prices. This is clearly not a "realistic" view of how change occurs in the real world. The strength of the paradigm is not that it aims to accurately forecast real-world developments, but rather than it provides a conceptually clear way of developing and selecting scenarios that are the least-cost way of achieving particular policy objectives, given the assumptions used.

It is important to be clear about the meaning of 'costs' in the MARKAL modelling presented in this report. 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).

The core strengths of this paradigm are as follows. First, it enables the model to explore and represent sectoral interactions, between the end-use sectors and between the supply and demand sectors. For example, it enables examination of the way in which developments in the transport sector (such as uptake of electric vehicles) might influence the power sector (through changing demand for electricity), with corresponding impacts on other sectors (driving up electricity prices and hence making other energy vectors or demand savings relatively more attractive, for example). Second, the model enables insight into the relative costs and emissions impacts of different system options and policies, taking into account the sectoral interactions and dependencies.

There are also weaknesses and limitations of the framework. As discussed in the body of this report, the model is not suited to examining the micro-level detail within particular sectors, such as power station operational strategies, or consumer choices in particular segments of vehicle markets.

Similarly the model does not provide significant insights into the spatial distribution of energy supply and demand—it is a national-scale model, and is therefore unsuited to exploring issues associated with power network constraints, for example. Finally, the model does not include various macro-economic feedbacks, either those directly relating to the influence of changing energy prices on the long-term evolution of economic structure, or those associated with innovation and corresponding economic change.

A feature of a linear optimisation framework is model behaviour known as 'penny-switching'. This means that a given technology will take all of the available market share, even if it differs from an alternative technology by only a penny in cost. A related aspect of model behaviour is relatively rapid switches from one technology to another. Both of these aspects of the model can lead to unrealistic scenarios. Additional constraints are added to the model to limit these unrealistic outcomes.

Scenarios, models and uncertainties

MARKAL is not a forecasting model; it is a decision support tool. It does not provide forecasts of what is expected to happen, but rather provides a structure for learning about possible scenarios and the interactions that might be expected to be relevant. Through the process of modelling scenarios, examining and critiquing them, the model provides a way of generating insights about what is possible, and about what seems to be technically or economically implausible. It can be used—as it has been used here—to explore specific scenarios through a process involving iteration between the model and consultation with stakeholders and experts in specific technology fields.

The uncertainties associated with the input data—in terms of future resource prices, technology costs and energy service demands—are very great, as are the uncertainties relating to the important future drivers of energy system change. Past attempts to forecast the long-term future of energy systems show that such attempts almost invariably fail, and no model can be expected to provide a forecast. In light of such significant uncertainty about the future, the aim of scenario studies using energy system models like MARKAL is not to predict; the aim is rather to explore possible futures and attempt to draw insights about what would be required to meet particular goals, from a techno-economic perspective.

UK 2R MARKAL: Key assumptions and characteristics specific to the model

UK2R MARKAL was developed by disaggregating the resource allocations, demands and technology potentials in the pre-existing UK MARKAL model. The major data sources for this disaggregation were publications produced by the Scottish Government and various UK government bodies including DECC and the CCC. Further details on the specific data sources used, and the assumptions made in disaggregating particularly energy resources, can be found in Anandarajah and McDowall (2012)[128]. Following disaggregation, the model was then calibrated in its base year (2000) to data on resource supplies, energy consumption, electricity output, installed technology capacity and CO_2 emissions.

The two-region model treats Scotland and rest-of-the-UK has having separate energy systems linked by trade of energy carriers (electricity, fuels, etc.). This ensures that the model is able to track activities in each region (Scotland and rest-of-the-UK), and it enables the modelling of different policy targets and policies within each region. It is not 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 GB-wide markets operating for electricity and gas. 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. Care has thus been taken to ensure that the results presented here reflect the behaviour of a single, integrated energy system.

Legislated targets for Scotland are on the basis of greenhouse gases, whereas the UK 2R MARKAL model represents only energy-related CO_2 emissions. In the original 2R model, it was assumed that the targets directly apply to energy-related CO_2, and the emissions inventory and baseline were thus adjusted in the model using data from Thomas et al (2011)[129]. In this study, we have taken the overall targets for Scotland, and reduced them to account for those parts (such as land use, forestry, and international aviation) that do not relate to domestic energy demand.

Key input data and assumptions: final demand

The final demand forecasts used in this study are derived from UK-level demand forecasts (found in the UK MARKAL documentation), and it has been assumed that the Scottish share of final demand remains the same as that in the base year.

The base year (2000) for the single region UK MARKAL model was calibrated to data in the annual Digest of UK Energy Statistics produced by the Department for Energy and Climate Change. 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.

[128] Anandarajah, G. and W. McDowall. 2012. What are the costs of Scotland's climate and renewable policies? Energy Policy 50(0): 773-783.
[129] Thomas, J., Thistlethwaite, G., MacCarthy, J., Pearson, B., Murrells, T., Pang, Y., Passant, N., Webb, N., Conolly, C., Cardenas, L., Malcolm, H., Thomson, A., 2011. Greenhouse gas inventories for England, Scotland, Wales and Northern Ireland: 1990-2009, in: DEFRA (Ed.). AEA report for the National Air Emissions Inventory, London.

Transport sector energy consumption by fuel and mode for the Scotland (SCT) region is taken from BERR (2008)[130]. 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[131], which reports that 9% of UK households are in Scotland. Gas and electricity consumption data for Scotland and the UK (data from the Department for Energy and Climate Change's Energy Trends series of publications) 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. The energy service demand forecasts for the residential sector of the UK as a whole can be found in the UK MARKAL documentation. In these forecasts, growth is driven by assumed growth in the number of households, using forecasts from the UK government. As noted above, Scotland is assumed to account for 9% of these energy service demands.

Services sector data are taken from Scottish Energy Study (2006)[132] which reports Scotland's share of UK final consumption as 11.6%. The forecasts for the UK as a whole are derived from growth rates estimated by BRE, and can be found in the UK MARKAL documentation[133]. It is assumed that Scotland's share of UK service sector energy service demand (11.6%) remains constant across the modelling period. Agriculture sector energy consumption data are taken from DECC (2008)[134]. 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 21.

Table 21: 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%	22.6%
Other industry	79.1%	92.2%	54.0%	66.7%
Total	100%	100%	100%	100%

130 BERR (2008). Experimental regional and local authority transport fuel consumption statistics, BERR, London, 2008.
131 BRE (2008). Domestic Energy Fact File, Department for Energy and Climate Change, 2008.
132 Scottish Energy Study (2006). Volume 1: Energy in Scotland: Supply and demand, Scottish Executive, Scotland, 2006
133 UK MARKAL documentation
134 DECC, 2008. Estimates of non gas, non electricity and non road transport fuels at regional and local authority level, Publication URN 08/P2c

Key input data and assumptions: Installed power generation capacity

Scotland's installed power generation capacity in the base year was about 9.5GW. 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. 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)[135].

Key input data and assumptions: 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[136]. 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. 0-30km, 30-60, 60-90, 90-120 and >120 km offshore). These concentric bands have been further subdivided into different zones on a geographical basis as shown in Figure 16.

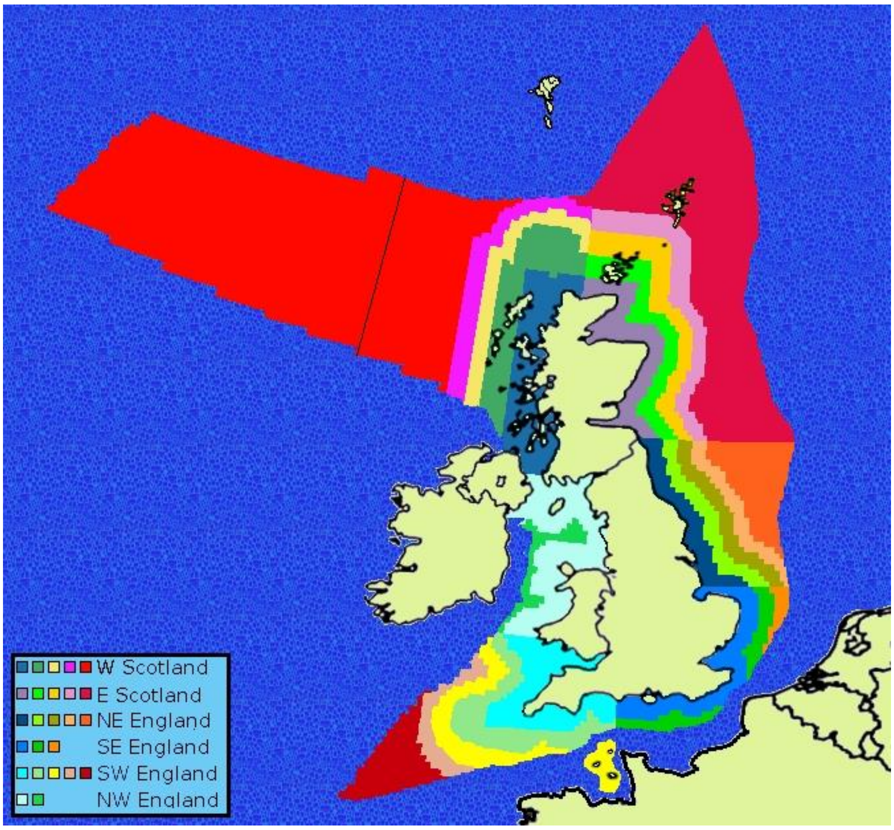


Figure 16: Offshore wind resource regions in UK2R MARKAL

[135] BERR (2009). Installed capacity of sites generating electricity from renewable sources (1): 2000 – 2007, Department for Business, Enterprise and Regulatory Reform (BERR), London.
[136] Dalvit, G. 2009. UK Offshore Wind Source. Internship report. UCL Energy Institute. London

Further assumptions on feasible water depths (the data assumes no regions deeper than 50m 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)[137] which reports that maximum UK onshore wind capacity is about 20GW of which 8.66 GW is available in Scotland.

Key input data and assumptions: Biomass resources

Biomass resource availability in Scotland is mainly taken from Scotland's Renewable Resource (SRR, 2001)[138]. Data for energy crops and forest residue is taken from Andersen et al. (2005)[139] 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 Figure 17.

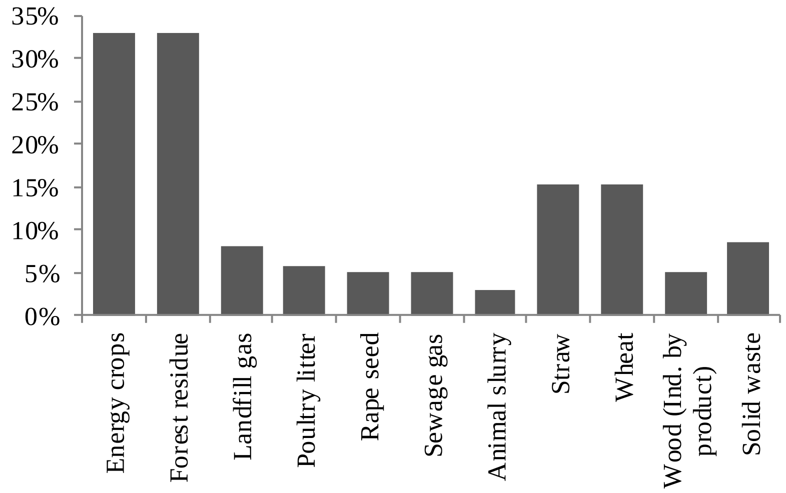


Figure 17: Scotland's assumed share of UK bioenergy resources

Scotland's energy crop and forest residue resources are relatively high because of Scotland's greater relative land area. Please note that, specific assumptions on domestic biomass resource availability and constraints on imported biomass were made under this project and are documented in the main body of the report.

[137] Enviros (2005), The Cost of Supplying Renewable Energy, DTI, London, 2005.
[138] SRR, 2001. Scottish Renewable Energy Resources-2001: Volume I The Analysis, Garrad Hassan and Partners Limited, Document No. 2850/GR/02
[139] Andersen, R. S., Towers, T, Smith, P. 2005. Assessing the Potential of Biomass Energy to Contribute to Scotland's Renewable Energy Needs, Biomass and Bioenergy 29, pp. 73-82

Annex 2: Underlying data

This annex includes the data tables in this report, as well as the underlying numbers for all charts generated through this project. Other charts are referenced to their original source.

General

Emissions trajectory for RPP2 policies versus required trajectory under Climate Change (Scotland) Act (tonnes of CO_2e per year)

YEAR	RPP2	Required
2013	47,941,000	47,976,000
2014	47,283,000	46,958,000
2015	46,736,000	45,928,000
2016	46,121,000	44,933,000
2017	45,415,000	43,946,000
2018	44,762,000	42,966,000
2019	44,182,000	41,976,000
2020	43,680,000	40,717,000
2021	40,177,000	39,495,000
2022	40,047,000	38,310,000
2023	39,857,000	37,161,000
2024	39,728,000	35,787,000
2025	39,222,000	34,117,000
2026	39,171,000	32,446,000
2027	38,646,000	30,777,000
2028	38,646,000	29,853,690
2029	38,646,000	28,958,079
2030	38,646,000	28,089,337

Emissions by sector for base year and for 2030 in RPP Optimistic and RPP Realistic scenarios (figures in millions of tonnes of CO_2e)

	2010	Optimistic	Realistic
Agriculture	0.8	0.5	0.5
Industry	11.5	5.7	5.3
Residential	13.2	3.4	3.5
Services	7.8	0.6	0.6
Transport	10.1	7.0	6.0
Other	2.6	2.7	2.7
Rural land use	2.9	5.6	5.9
International aviation	2.5	2.5	3.3
Total	51.4	28.1	27.8

Installed capacity by scenario, in GW

	2010	Optimistic	Realistic
Wind	2.39	13.81	14.93
Hydro	2.77	2.75	2.75
Gas	1.37	-	-
Storage	0.62	0.62	0.62
CCS	-	0.4	0.4
Other	0.32	0.2	0.2
Marine	-	0.1	0.1
Coal	3.4	-	-
Nuclear	2.44	-	-
Oil	0.67	-	-

Primary energy supply in Scotland in 2010 and in RPP Optimistic and RPP Realistic scenarios for 2030 (petajoules)

	2010	Core	Conservative
Renewable electricity	11.4	51.9	56.9
Biomass and waste	4.4	12.7	12.9
Gas	121.7	62.2	52.7
Oil	103.3	49.6	48.0
Coal	46.5	0.25	0.06
Nuclear	43.7	-	-

Technology costs

Updated assumptions for electricity generation

Generation type	Technology	Upfront costs (£/kW)	Fixed operating and maintenance costs (£/kW/year)	Variable operating and maintenance costs (£/GJ)
CCS	New GTCC[140] with capture in 2030	906	17	0.38
	New IGCC[141] with capture in 2030	2,281	92	0.38
Nuclear	Combined E-PWR and AP1000 (URN) – 2020	2,935	49	0.57
Wind	On shore T6 (6.5 m/s) >5MW	1,089	25	-
	Off shore New T2-Scotland East (assumed equivalent to offshore Round 2)	1,750	43	0.38
	Off shore New T4-Scotland East (assumed equivalent to offshore Round 3)	1,842	48	n/a – use existing figure
Hydro	Pumped Storage	2,353	17	1.13
	Small (1.25–20MW)	2,145	30	1.89
	Micro (<1.25MW)	3,064	71	-
Marine[142]	Wave energy technology T2	3,139	67	-
	Tidal stream	1,839	98	0.19
Geothermal	District heat low temp heat generation	3,228	24	1.89
PV	Commercial (building mounted)	681	15	-
	Residential (roof mounted, <4kW)	1,294	16	-

[140] Gas Turbine Combined Cycle
[141] Integrated Gasification Combined Cycle
[142] Figures for marine are for 2025 introduction – assumed not to be commercially deployed in significant volume before then

Comparison of cost estimates between 2016 and 2020 for electricity generation technologies

Generation type	Technology	CAPEX (£/kW)		Fixed O&M (£/kW/year)		Variable O&M (£/GJ)	
		Current	*2020*	Current	*2020*	Current	*2020*
Wind	On shore T6 (6.5 m/s) >5MW	1,089	1,021	25		0.95	
	Off shore New T2-Scotland East (assumed equivalent to offshore Round 2)	1,750	1,614	43	37	0.38	
	Off shore New T4-Scotland East (assumed equivalent to offshore Round 3)	1,842	1,706	48	39	-	
Hydro	Pumped Storage	2,353	2,489	17		1.13	1.51
	Small (1.25–20MW)	2,145	2,281	30		1.89	2.27
	Micro (<1.25MW)	Not given – assume no cost reduction					
PV	Commercial (building mounted)	681	613	15		-	
	Residential (roof mounted, <4kW)	1,294	1,089	16		-	

Cost reductions by 2030 for electricity generation technologies

Technology	Reduction in 2020	Reduction in 2025	Reduction in 2030
Onshore wind	2%	4%	5%
Offshore wind	15%	30%	30%
PV	8%	16%	22.5%
CCS demonstration	0%		
Nuclear	0%		
Marine	0%		

Current costs for heating, domestic installations

	Typical size (kW)	Capital cost (£)	Operating cost excluding fuel (£/year)	Seasonal efficiency	Load factor
Biomass boilers	8	5,880	230	85%	11%
Biomass district heating[143]	1,200	914,078	22,852	51%	14%
Solar Thermal	2.6	3,947	46	50%	8%
Ground Source Heat Pump	6	1,135	54	373%	14%
Air Source Heat Pump (Air to Air)	4	1,615	55	172%	11%
Air Source Heat Pump (Air to Water)	6	7,057	53	314%	13%
Liquid biofuels	20	3,586	188	93%	4%
Electric heating	4	738	0	90%	8%
Gas	20	3,025	188	94%	4%
Oil boiler	20	3,026	188	93%	4%

Assumed current vehicle purchase costs (£, current prices)

	Diesel	Petrol	Hybrid diesel	Hybrid petrol	Plug-in hybrid diesel	Plug-in hybrid petrol	Battery EV
Bus	187,948	-	203,547	-	374,726	-	319,642
Car	16,323	15,702	18,396	18,103	27,864	27,610	32,514
LGV	18,614	17,298	21,240	19,948	28,811	27,718	37,365
HGV	80,478	-	94,788	-	129,064	-	-

[143] Cost for boiler and heat network. The seasonal efficiency is lower than for individual boilers due to heat losses from the network. Over the summer when heat loads are low as the system is only supplying hot water, these losses can be relatively high compared to the heat delivered and lead to a lower system efficiency

Purchase costs of vehicles – assumed trends to 2030

Costs shown relative to cost in 2010, in real terms

Technology	2015	2020	2025	2030
Bus Battery EV	88%	76%	72%	68%
Bus Diesel ICE	104%	108%	110%	112%
Bus Hybrid Diesel ICE	101%	103%	103%	103%
Bus Hydrogen FC	79%	59%	52%	46%
Car Battery EV	84%	68%	62%	56%
Car Diesel ICE	105%	110%	111%	113%
Car Gasoline ICE	104%	108%	110%	112%
Car Hybrid diesel ICE	99%	98%	97%	96%
Car Hybrid gasoline ICE	97%	95%	94%	93%
Car Hydrogen FC	70%	40%	30%	21%
Car Plug-in hybrid diesel ICE	96%	91%	87%	83%
Car Plug-in hybrid gasoline ICE	95%	90%	86%	82%
HGV Diesel ICE	112%	124%	127%	130%
HGV Hybrid diesel ICE	103%	106%	107%	107%
HGV Gas-Fuel ICE	102%	104%	103%	103%
HGV Dual-Fuel diesel/gas ICE	102%	103%	103%	103%
HGV Hydrogen FC	71%	42%	33%	24%
LGV Battery EV	84%	68%	63%	57%
LGV Diesel ICE	105%	110%	112%	114%
LGV Gasoline ICE	104%	109%	111%	113%
LGV Hybrid diesel ICE	99%	99%	98%	97%
LGV Hybrid gasoline ICE	99%	97%	97%	96%
LGV Hydrogen FC	70%	40%	31%	21%
LGV Plug-in hybrid diesel ICE	97%	94%	91%	87%
LGV Plug-in hybrid gasoline ICE	97%	93%	90%	86%

Technology efficiencies

Heat pump efficiency trends assumed

	2010	2015	2020	2025	2030
ASHP ATA	172%	192%	217%	217%	217%
ASHP ATW	314%	334%	359%	359%	359%
GSHP	373%	393%	418%	418%	418%

Fuel efficiency of vehicles to 2030 (figures in km per MJ)

	2015	2020	2025	2030
Car Gasoline ICE	0.4242	0.4856	0.5400	0.5945
Car Hybrid diesel ICE	0.6217	0.6748	0.7232	0.7717
Car Hybrid gasoline ICE	0.5351	0.5953	0.6446	0.6940
Car Hydrogen FC	1.0021	1.0686	1.1357	1.2028
Car Plug-in hybrid diesel ICE	1.5253	1.6008	1.6731	1.7454
Car Plug-in hybrid gasoline ICE	1.5253	1.6008	1.6731	1.7454
HGV Diesel ICE	0.0945	0.1024	0.1156	0.1288
HGV Hybrid diesel ICE	0.0998	0.1075	0.1215	0.1356
HGV Gas-Fuel ICE	0.0822	0.0891	0.1005	0.1120
HGV Dual-Fuel diesel/gas ICE	0.0945	0.1024	0.1156	0.1288
HGV Hydrogen FC	0.1988	0.2153	0.2365	0.2576
LGV Battery EV	1.4586	1.5167	1.5641	1.6115
LGV Diesel ICE	0.3722	0.4010	0.4276	0.4543
LGV Gasoline ICE	0.3893	0.4281	0.4558	0.4835
LGV Hybrid diesel ICE	0.4363	0.4614	0.4840	0.5067
LGV Hybrid gasoline ICE	0.4989	0.5392	0.5654	0.5916
LGV Hydrogen FC	0.7540	0.7967	0.8353	0.8739
LGV Plug-in hybrid diesel ICE	1.4586	1.5167	1.5641	1.6115
LGV Plug-in hybrid gasoline ICE	1.4586	1.5167	1.5641	1.6115

Annex 3: Renewable Energy Percentage Calculations

The Renewable Energy Directive (2009/28/EC) sets out how the renewable energy percentage will be calculated for each EU Member State. In order to allow our results to be compared to those figures, and to the Scottish Government's figures, we have calculated the renewable energy percentage for Scotland on the same basis. In this annex, we describe how the calculation works.

The calculation is laid out in Article 5 of the Directive. We reproduce the relevant sections below:

Article 5 Calculation of the share of energy from renewable sources

1. The gross final consumption of energy from renewable sources in each Member State shall be calculated as the sum of:

(a) gross final consumption of electricity from renewable energy sources;

(b) gross final consumption of energy from renewable sources for heating and cooling; and (c) final consumption of energy from renewable sources in transport.

Gas, electricity and hydrogen from renewable energy sources shall be considered only once in point (a), (b), or (c) of the first subparagraph, for calculating the share of gross final consumption of energy from renewable sources. Subject to the second subparagraph of Article 17(1), biofuels and bioliquids that do not fulfil the sustainability criteria set out in Article 17(2) to (6) shall not be taken into account.

2. [not relevant – relates to force majeure]

3. For the purposes of paragraph 1(a), gross final consumption of electricity from renewable energy sources shall be calculated as the quantity of electricity produced in a Member State from renewable energy sources, excluding the production of electricity in pumped storage units from water that has previously been pumped uphill….

4. For the purposes of paragraph 1(b), the gross final consumption of energy from renewable sources for heating and cooling shall be calculated as the quantity of district heating and cooling produced in a Member State from renewable sources, plus the consumption of other energy from renewable sources in industry, households, services, agriculture, forestry and fisheries, for heating, cooling and processing purposes…

Aerothermal, geothermal and hydrothermal heat energy captured by heat pumps shall be taken into account for the purposes of paragraph 1(b) provided that the final energy output significantly exceeds the primary energy input required to drive the heat pumps.

5. [not relevant – energy content of fuels].

6. The share of energy from renewable sources shall be calculated as the gross final consumption of energy from renewable sources divided by the gross final consumption of energy from all energy sources, expressed as a percentage…

Paragraph 6 states that the renewable energy percentage is to be calculated as the ratio of the total renewable energy consumption in the country to the total energy consumption.

Paragraph 1 defines total renewable energy consumption as total renewable electricity consumption, plus total renewable heat consumption, plus total renewable transport consumption.

Paragraph 3 then notes that renewable electricity consumption, for these purposes, should be taken to be renewable energy *production* in the country[144].

[144] There is a later article that notes that the renewable electricity produced by "joint projects" between two countries should be shared between those countries for the purpose of determining renewable energy levels. There is a question about whether projects funded under the Renewables Obligation and CFD FITs would count towards this. We ignore this issue in our analysis, for consistency with the Scottish Government's calculations.

Paragraph 4 then notes that where heat pumps transfer heat into buildings from the external air, water or ground, this heat shall be taken into account provided that the heat pumps exceed a certain efficiency threshold (we assume an efficiency of 300%, which is well above the threshold).

We assume that total energy production, in the calculation in paragraph 1, is total renewable energy production plus total production from other sources. That is, where the renewable energy production figures have been adjusted as a result of paragraphs 3 and 4, the total energy production figure should be adjusted in the same way. For example, where additional heat has been added because of heat extracted from the air by heat pumps, that heat should be added to both total renewable energy production and total energy production. This is not completely clear from the Directive, but we assume that anything that counts towards renewable energy production must also count towards total energy production.

We illustrate how we have calculated the 44% and 48% figures below. We start with the total renewable electricity production, and then look at other (non-electric) sources of renewable heat and renewable transport, to avoid double counting. The figures are shown in Table 22.

Table 22: Renewable energy consumption in 2030

Energy (PJ)	RPP Optimistic	RPP Realistic
Renewable electricity production	188	206
Renewable heat (from air)	41	41
Biomass (heat and transport)	14	13
TOTAL RENEWABLE ENERGY	**242**	**260**

We then calculate total energy consumption. This starts from total energy consumption, and we then add any renewable electricity produced which is above 100% of demand, plus energy from the air provided by renewable heat. The figures are shown in Table 23.

Table 23: Total energy consumption in 2030

Energy (PJ)	RPP Optimistic	RPP Realistic
Energy consumption before adjustments	453	444
Electricity production above 100% of electricity consumption	55	55
Renewable heat (from air)	41	41
TOTAL ENERGY	**549**	**540**

We can then work out the renewable energy percentages in each scenario. These are:

- 242/549=44% in the “Optimistic” scenario
- 260/540=48% in the “Realistic” scenario

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