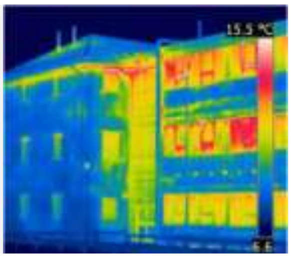
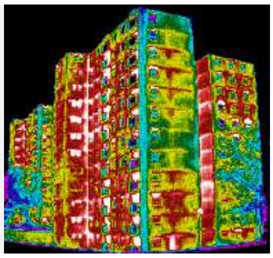
Pathways to 2050 – Detailed Analyses

MARKAL Model Review and Scenarios for DECC's 4th Carbon Budget Evidence Base

Final Report





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1 Introduction

This report presents the detailed analyses that underpin the findings of the Pathways to 2050 project as a whole. It is designed to be read as an adjunct to the summary report "Pathways to 2050 – Key Results", in which all context and broader project introductions are presented.

This report consists of 14 studies, each of which includes one or more model scenario runs. Each run is associated with a specified set of assumptions regarding one or more of the following metrics:

- demand levels,
- emissions reduction targets,
- emissions reduction trajectories,
- the availability of international tradeable permits
- the extent of the ability of consumers to respond to price changes
- the timing of abatement action
- the availability of a variety of technologies and resources, and
- the rate at which these technologies and resources can be adopted.

A fuller summary of the content of each run, along with a summary of cross-cutting results, may be found in the companion report "Pathways to 2050 – Key Results" section 1.

Presentation of economic metrics in this report

All costs associated with a specific year in the body of this report are presented in undiscounted real year 2010 UK pounds, except where explicitly stated. This means they are adjusted for inflation, but not for the green book real discount rate (3.5%).

All costs associated with the entire time horizon are presented in discounted year 2010 pounds, using the green book discount rate. The timeframe for which these metrics applies is 2010 to 2050.

2 Model Runs

2.1 Baseline Study: Business as usual

2.1.1 Description of Study

This study creates the baseline cases for all other phase 1 studies in the project. The philosophy adopted regarding the baseline is that all technologies are available to the model and that the DECC Carbon Plan targets are satisfied up to 2020. Beyond 2020 the model is free to choose the least cost pathway without any overarching constraint on system CO_2 emissions.

Five baseline runs have been defined to reflect different possibilities regarding the level of service demand experienced, and different possible levels of fossil fuel prices. These are:

1. Central Service Demand, Central Fossil Fuel Price – Run A, Code **DECC-0A**
2. High Service Demand, Central Fossil Fuel Price – Run B Code **DECC-0B**
3. Low Service Demand, Central Fossil Fuel Price – Run C, Code **DECC-0C**
4. Central Service Demand, Low Fossil Fuel Price – Run D, Code **DECC-0D**
5. Central Service Demand, High Fossil Fuel Price – Run E, Code **DECC-0E**

The set of studies presented here are the baseline runs for all other studies in the project. It should be noted that the first stage of the project updated the UK MARKAL database to version 3.26. The key changes made were increases to the majority of service demand levels over the time horizon, and a complete overhaul of the power generation sector. Due to the timescales of this project the database has not been re-calibrated to UK energy statistics data following the database update. This is expected to introduce a small error into the results of the order of <1% for the undiscounted system cost metric (i.e. a key model metric).

The discussion below outlines the changes in technologies, energy use, costs and emissions in the UK energy system.

2.1.2 Key Results

The total discounted system cost, and discounted consumer/producer surplus for these runs are shown in Table 1. As expected, a run with higher service demand levels increases system cost, and a lower service demand level decreases system cost. Note that the discounted system costs presented in this table are identical to those without demand response, which means the database has been calibrated for elastic demand correctly. Furthermore, it follows that change in consumer/producer surplus is zero for these runs, as they are the baseline against which this metric is measured for later runs.

Table 1: Key Result Metrics

	DECC-0A	DECC-OB	DECC-OC	DECC-OD	DECC-OE
Technical Energy System Cost (2010 £UK Billions)	5,940	6,258	5,600	5,602	6,195
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	0	0	0	0

The profile of (undiscounted) system cost over time is shown in Figure 1. By 2050, the high service demand case results in an increase in annual system costs of 12%, whilst the low service demand case decreases annual system costs by 11% relative to the central case.

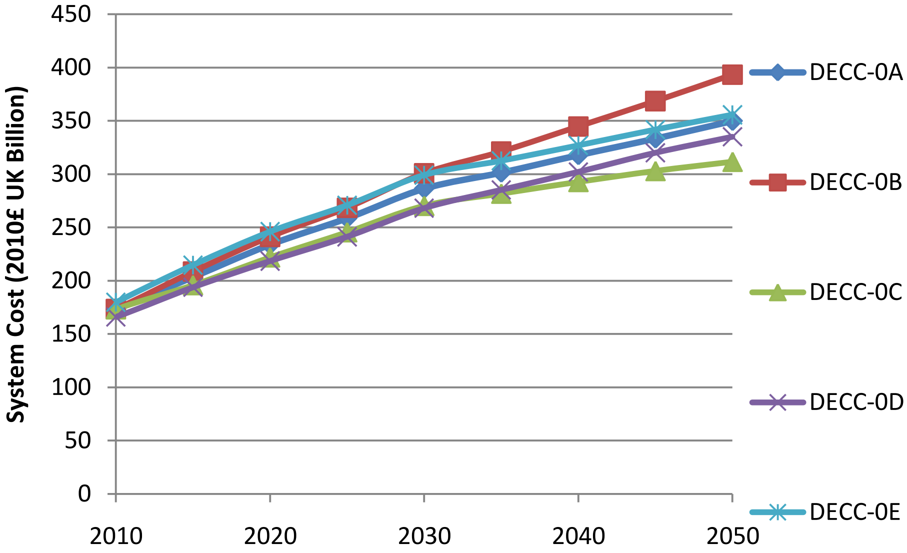


Figure 1: Undiscounted System Cost for Baseline Runs

Figure 2 plots the emissions trajectoiry for each of the runs. As expected, the emissions are largely proportional to the service demand. In 2050, the high demand run results in an increase of 7.7% in emissions, whilst the low demand run results in a 11.2% decrease (both relative to the central demand case). Aggregate emissions in the central demand and low fossil fuel prices run (DECC-0D) are lower than the low service demand run (DECC-0C). As is discussed in this briefing, this is due to a sizable shift from coal (and other fuels) to gas in this case, triggered by the lower gas price.

When compared with the CCC reference case published in Usher et al (2010) of 592Mt in 2050, the DECC-0A reference case emission levels are around 7% higher.

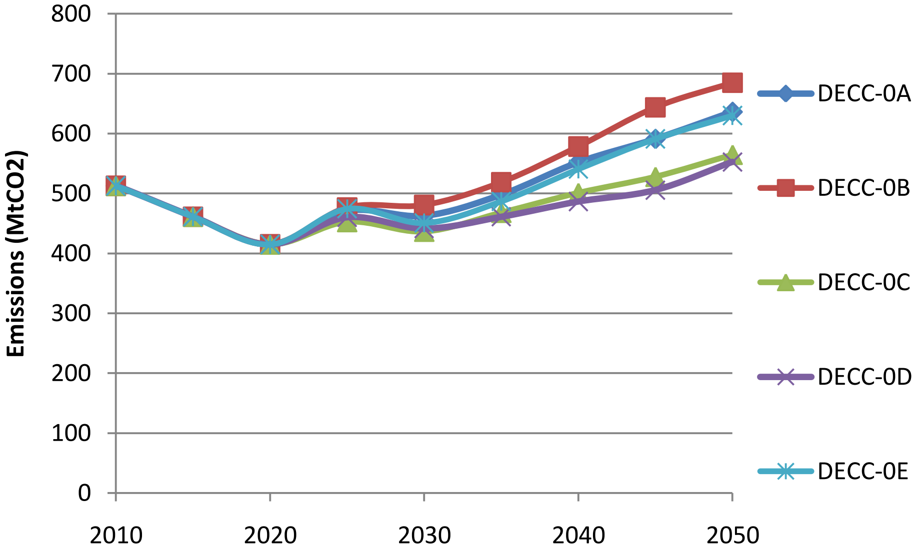


Figure 2: The Emissions Trajectory

The comparison between the emissions intensity from electricity generation is plotted in Figure 3. This shows a very small difference between the scenarios, except DECC-0D which has significantly lower emissions intensity than the other cases from 2020 onwards. In all cases except DECC-0D, grid emissions rates are well above what they are today by 2050.

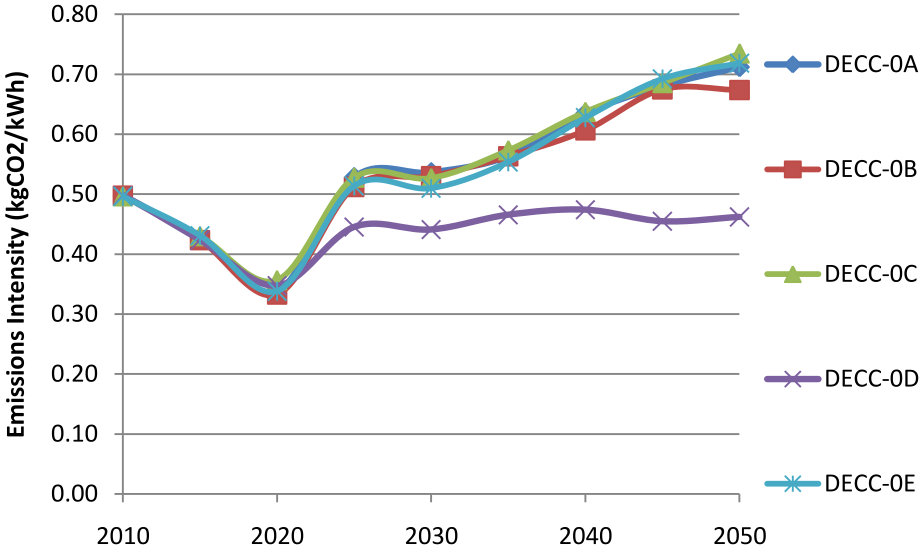


Figure 3: The Emissions Intensity of Grid Electricity

The figures associated with Figure 3 are presented in numerical form in Table 2.

Table 2: Figures for the Emissions Intensity of Grid Electricity (kgCO$_2$/kWh)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
DECC-0A	0.50	0.43	0.34	0.53	0.54	0.56	0.63	0.68	0.71
DECC-0B	0.50	0.42	0.33	0.51	0.53	0.56	0.61	0.67	0.67
DECC-0C	0.50	0.43	0.36	0.53	0.53	0.57	0.64	0.69	0.73
DECC-0D	0.50	0.42	0.35	0.45	0.44	0.47	0.47	0.45	0.46
DECC-0E	0.50	0.43	0.34	0.51	0.51	0.55	0.63	0.69	0.72

As suggested to above, the reason for the distinction of run DECC-0D surrounds the response of the model to fuel prices. Run DECC-0D is a low fossil fuel price scenario. In this run, the model chooses to install and operate more gas-fired generation by 2050, as demonstrated in Figure 4. This leads to the lower average CO_2 intensity of grid electricity observed in Figure 3 for run DECC-0D, because there has been a shift from coal to gas relative to the other runs presented. This result suggests that the balance between the cost-effectiveness of coal and gas-fired generation is quite fine in the baseline, and both fuels could remain important in the future.

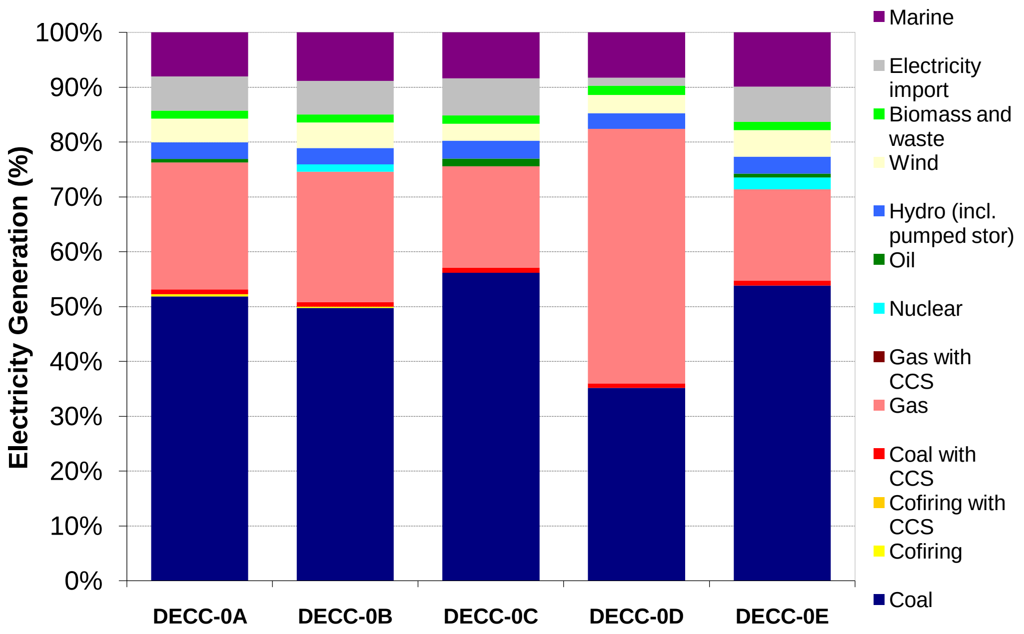


Figure 4: Percentage Shares of Power Generation by Fuel/Technology Type in 2050

Figure 5 presents the take-up of conservation measures in these baseline scenarios. All runs have equal take-up of conservation measures and this take up is equal to the upper bound. Clearly these measures are cost-effective, as the model chooses to adopt them to the maximum degree possible in all runs, even though there is no aggregate carbon dioxide emissions constraint.

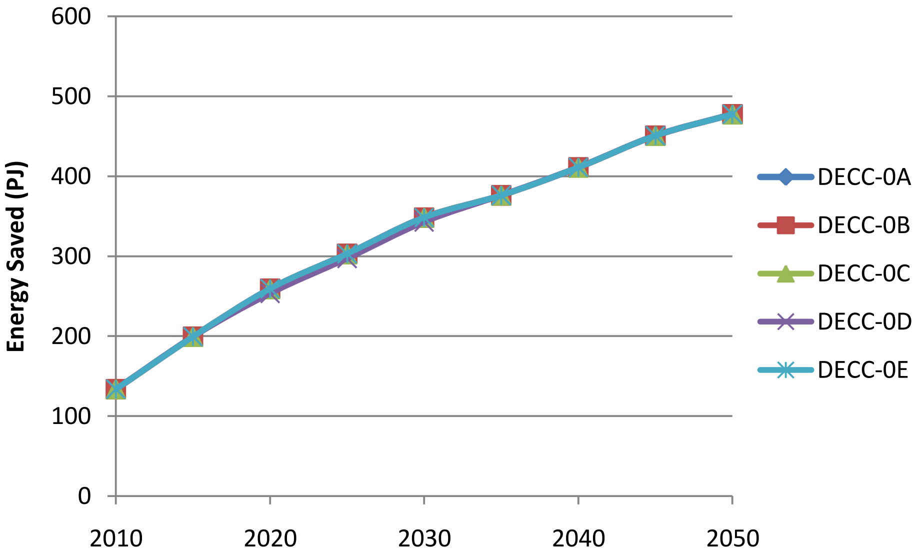


Figure 5: Use of Conservation Measures by Sector for Each Run

Finally, the reader should note that there is no demand response in these baseline runs (i.e. the level of service demand does not change in response to the price of serving that demand). This is because each baseline run presented here is calibrated for demand response. Where MARKAL ED has been calibrated correctly, this means that even when the elastic demand function is switched on, there will be no demand response in the baseline. In this series of studies, demand response only occurs in reaction to the price increases associated with imposition of carbon dioxide emissions constraints.

In general, as is seen in Figure 1 and Figure 2, and in the analysis below, the high and low service demand runs tend to be associated with the greatest variation in result metrics (i.e. the most extreme results observed are generally associated with the high and low service demand runs; DECC-0B and DECC-0C). The other case of specific interest is the low fossil fuel price run, as if often displays a different trend when compared with the other central demand runs. This difference revolves around the use of natural gas, most notably in power generation and heating, as it becomes price competitive with a range of other options.

2.1.3 Primary and Final Energy Statistics

Primary and final energy consumption trends in the studied runs are presented in Figure 6. As per the majority of result metrics, the high and low service demand runs (DECC-0C and DECC-0D) show the most extreme high/low energy consumptions.

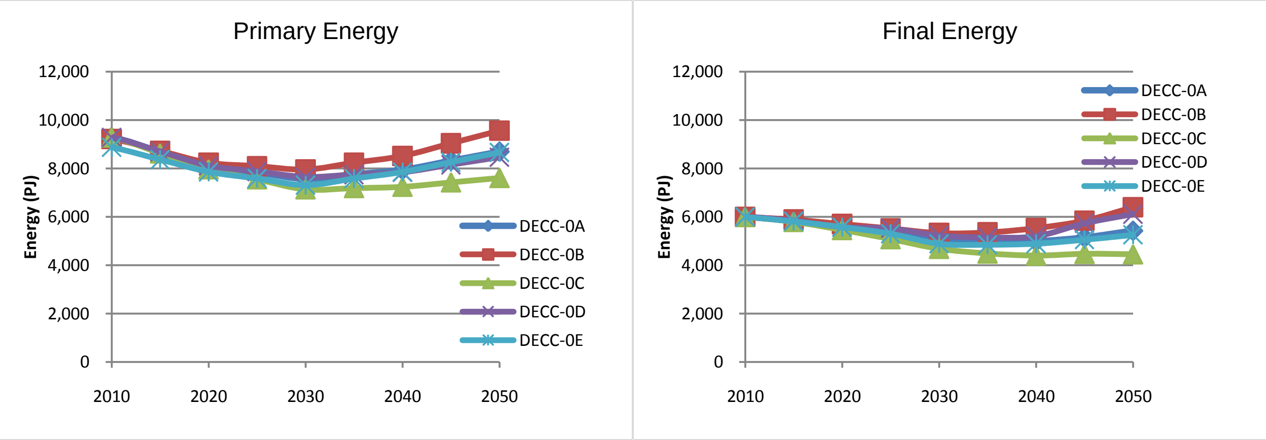


Figure 6: Primary and Final Energy Consumption over Time for Each Run

These aggregate trends can be split out by resource and/or energy carrier as per Figure 7, which contrasts the choices made in the central, high and low service demand cases. As can be seen in this figure, trends are very similar in all cases.

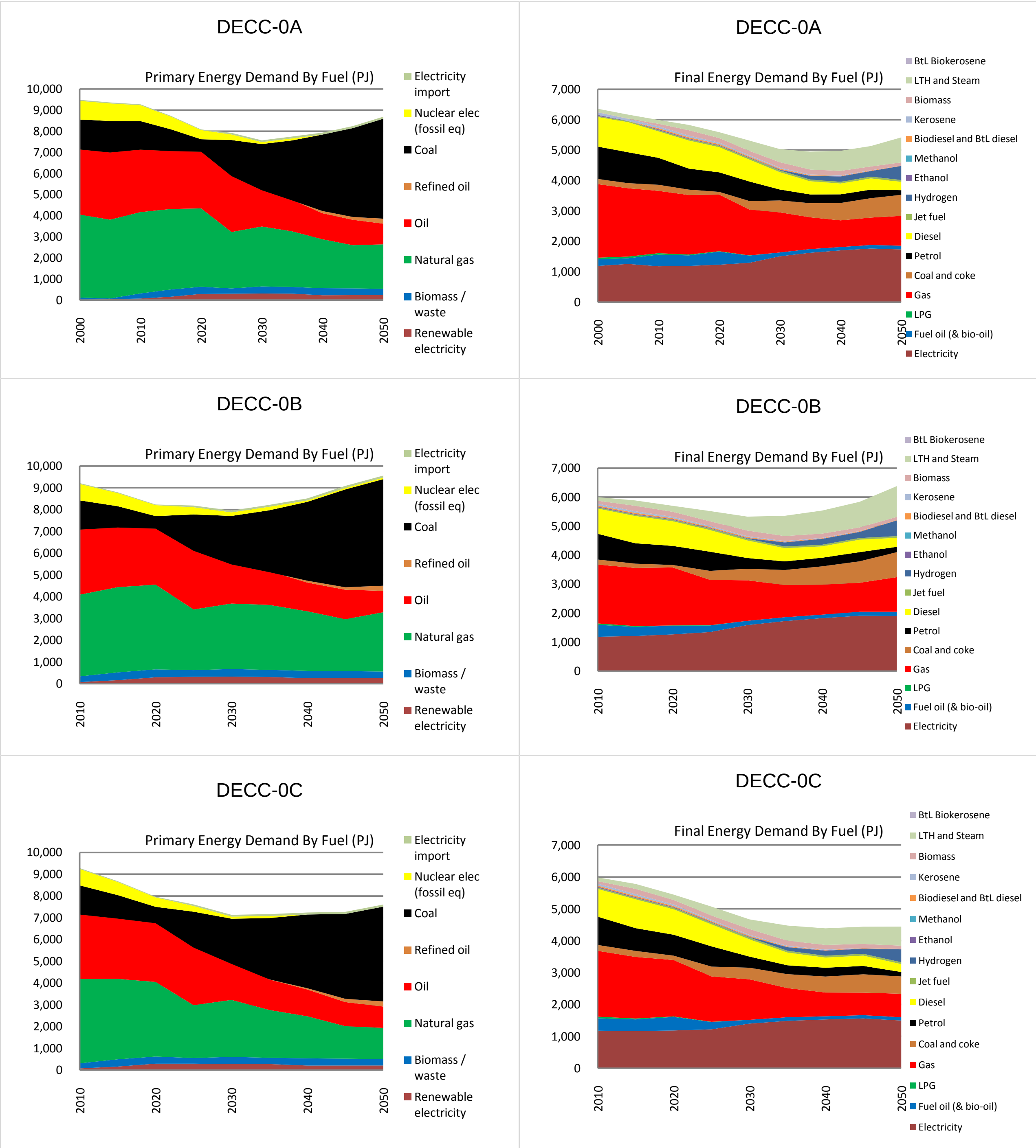


Figure 7: Primary and Final Energy Consumption Disaggregated by Energy Carrier

In primary energy consumption, the fuel type that is most responsive to changes in service demand and fossil fuel price (i.e. the parameters varied across these scenarios) is natural gas. In the low fossil fuel price scenario, primary consumption of natural gas increases by more than 80% in comparison to the central demand and central price run. In the high and low service demand runs, primary natural gas consumption increases/decreases by 30%, respectively. This change in consumption is far larger than for any other resource.

For final energy consumption, all energy carriers respond fairly consistently to high and low service demand levels. More marked variation in change in final consumption is apparent between non-central and the central/central scenario for the case of change in fossil fuel prices. In particular, natural gas final consumption is extremely responsive to low fossil fuel price, more than doubling consumption. As discussed below, this is driven by increased uptake of gas-fuelled technologies in almost all sectors, particularly for heating.

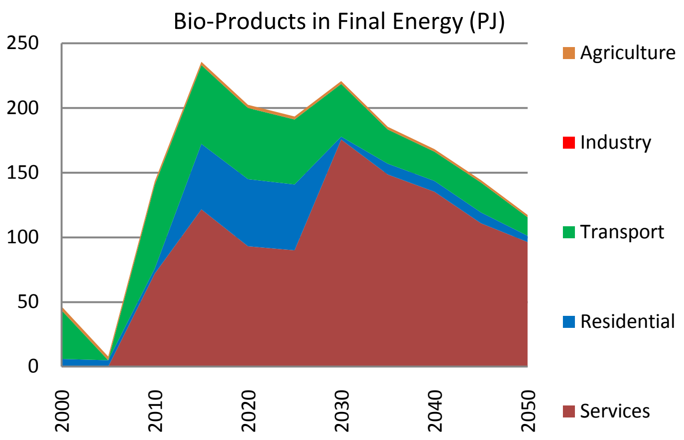


Figure 8: Sectoral Split of Bio-Products in Final Energy Consumption for Run DECC-0A

Figure 8 shows the sectoral split of consumption of bio-energy. As discussed below, wood is heavily utilised fuel for heating in the services sector. Transport has a relatively constant share of the bio-energy consumption, predominantly biodiesel use in cars and LGVs, and ethanol use in cars.

2.1.4 Power Generation and Installed Capacity

As per the majority of result metrics, the high and low service demand runs result in the highest and lowest aggregate generation and installed capacity. Installed capacity is also relatively small in the low fossil fuel price run.

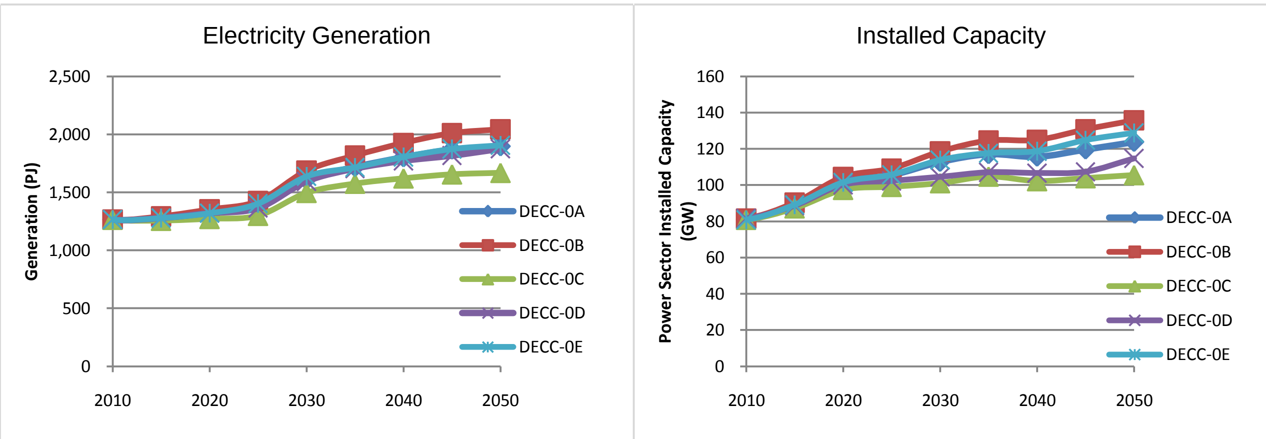


Figure 9: Aggregate Generation and Aggregate Installed Capacity over Time for Each Run

Figure 10 disaggregates the information in Figure 9 by energy carrier. Other than the aggregate level of generation and capacity discussed above, the key difference here is in the relative share of centralised coal and gas, and CHP from 2020 onwards. The high service demand run (DECC-0B) largely fills the additional output required with generation from CHP plants. The low fossil fuel price case (DECC-0D) shows the most extensive switch from coal to gas.

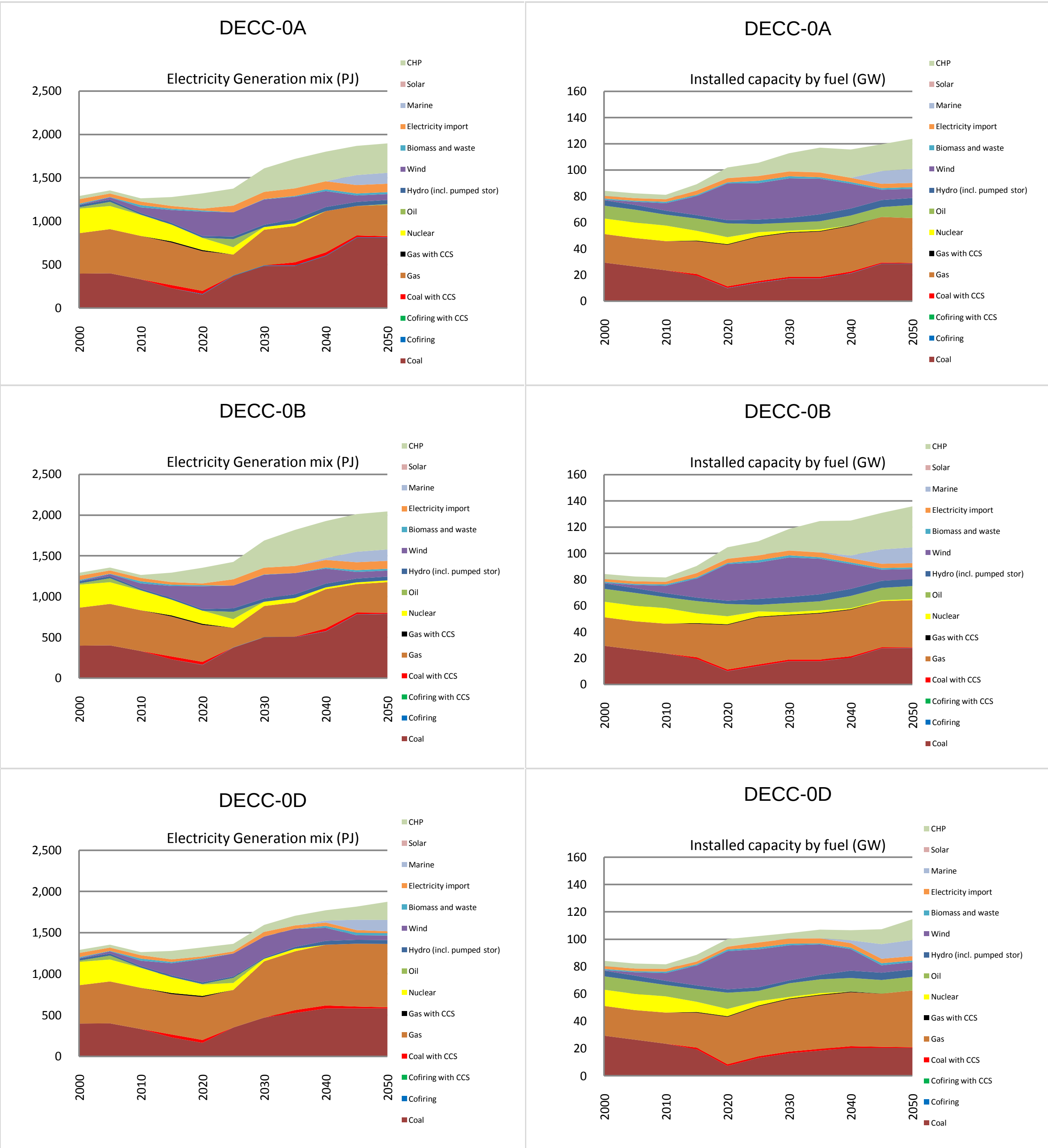


Figure 10: Generation and Installed Capacity by Fuel/Technology over Time for Selected Runs

In all subplots of Figure 10 display a "turning point" at approximately 2020. This is due to the carbon constraint in these baseline runs; aggregate CO_2 is constrained out to 2020 according to the government's carbon plan. From 2020 onwards, particularly coal-fired generation undergos a renaisance, which corresponding impact on the emissions intensity of electricity as per Figure 3.

2.1.5 End-use Sectors

Industrial Sector

Figure 11 shows the fuel mix in industry final consumption for run DECC-0A (central demand and central price). From 2020 onwards, consumption of coke oven gas increases significantly, whilst the contribution of all other energy carriers remains approximately constant. All four baseline scenarios investigated in the study show this pattern of activity. However, the characterisation of the industrial sector in MARKAL is relatively high level, so it would be unwise to draw detailed conclusions from this trend.

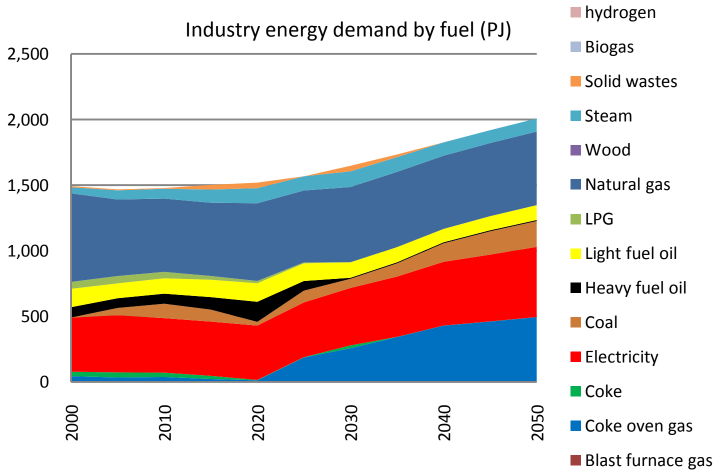


Figure 11: Industrial Energy Consumption for Run DECC-0A

Instead, these baseline results are more useful in terms of broad comparison with the results of the stabilisation runs, where aggregate shifts in energy carriers can be charted.

Residential Sector

Figure 12 pots the change in final energy consumption in the residential sector. In contrast to industry, this sector has consistently declining consumption (due to uptake of efficiency measures and increasing efficiency of end-use devices offsetting increased service demand levels) and substantial change in mix of energy carriers from 2020 onwards.

In the central/central run (DECC-0A – left subplot), natural gas based heating (i.e. condensing boilers) declines rapidly, and is replaced by a combination of heat pumps and district heating. The share of direct electric heating falls to its lower bound, and oil-based heating disappears entirely by 2050. This pattern is observed in all the runs in this study except DECC-0D (low fossil fuel price), where the modelled outcome is that natural gas is retained for longer as a heating fuel, and there is no introduction of district heating. Heat pumps still appear in the solution, but to a smaller degree than the other runs.

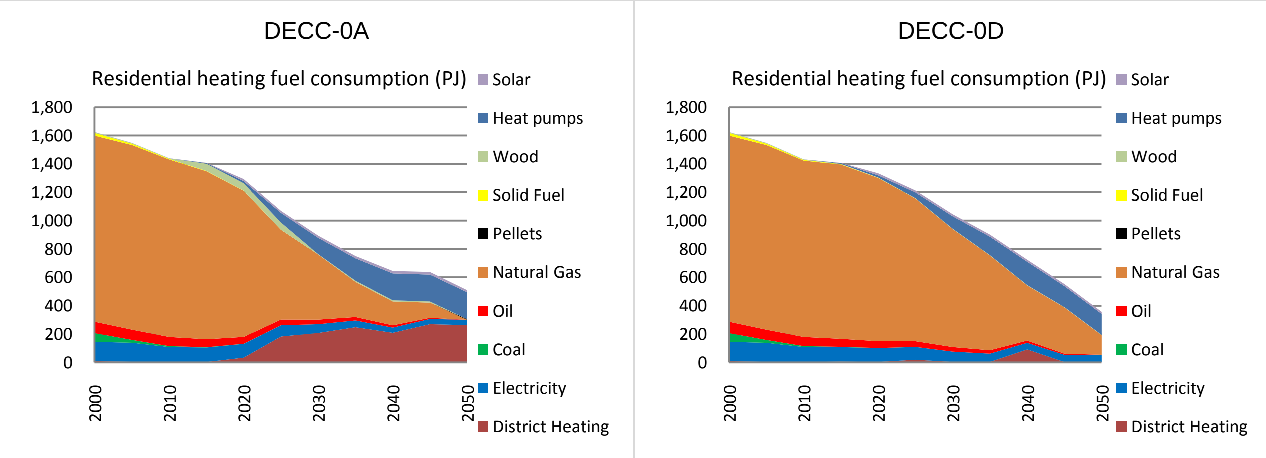


Figure 12: Residential Heating Fuel Consumption for Runs DECC-0A and DECC-0D

Services Sector

Figure 13 show the split of final energy consumption for the services sector. The pattern here is similar to that of the residential sector: In the central/central runs (DECC-0A) low temperature heat (LTH; which is otherwise known as district heating) begins to become dominant in heating from 2020 onwards, at the expense of natural gas. This pattern is consistent in all baseline scenarios except for DECC-0D, where the shift away from natural gas does not happen.

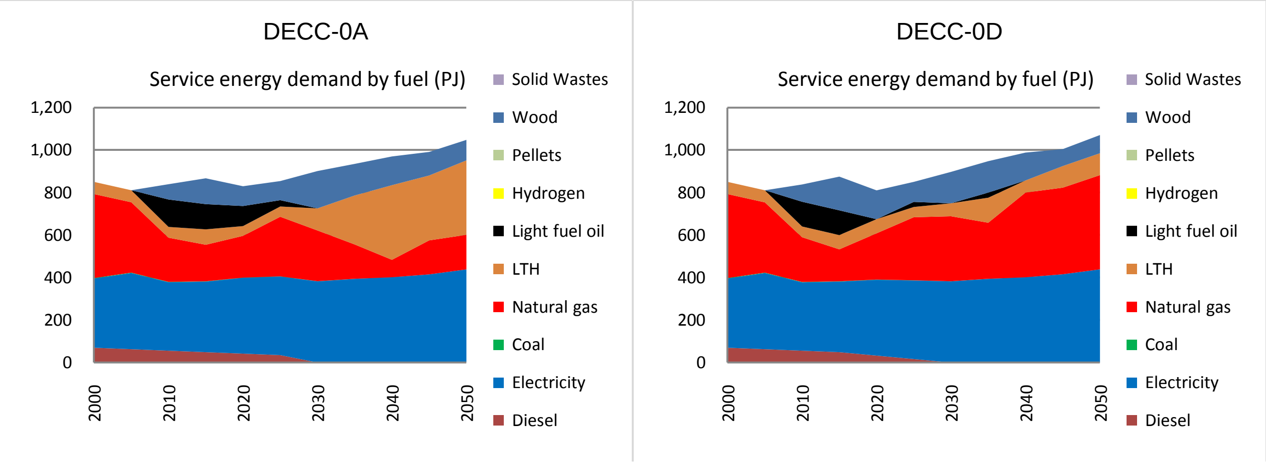


Figure 13: Service Sector Energy Consumption for Runs DECC-0A and DECC-0D

The drivers of the result here is the same as the residential (and many other) areas of the energy system. The increasingly high price of natural gas in the majority of scenarios motivates a shift to alternative forms of energy. Conversely, in the low fossil fuel price scenario (DECC-0D) the gas price remains low enough for it to be a competitive heating fuel.

Transport Sector

Figure 14 shows the final energy consumption in run DECC-0A. Although there is generally declining consumption, the fuel mix remains relatively constant until the mid-2020s. Use of petrol and diesel then decline steeply, giving way to electricity (primarily in hybrid diesel and battery electric cars) and hydrogen (initially in the bus and HGV fleets, and moving into cars and LGVs).

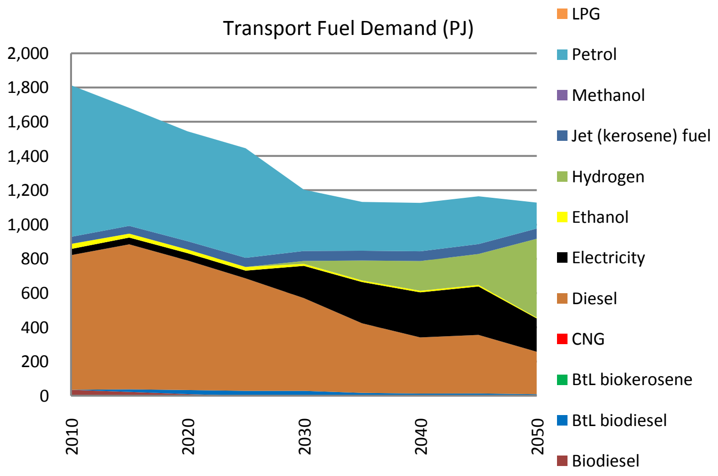


Figure 14: Transport Sector Energy Consumption for Run DECC-0A

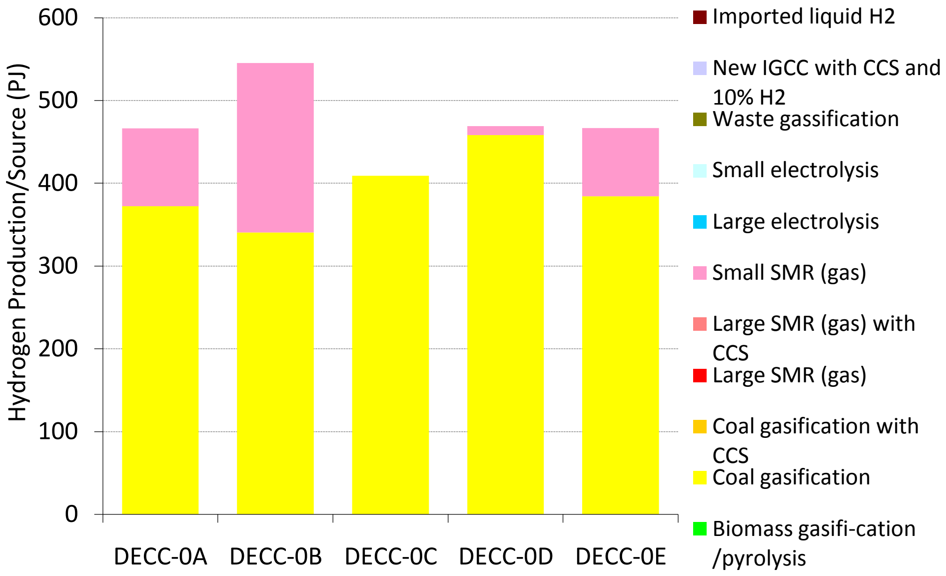


Figure 15: Comparison of Hydrogen Production Methods in 2050

The primary source of the hydrogen used in transport is coal gasification, producing approximately 450PJ of H_2 by 2050. Figure 15 displays the means of hydrogen production across the reviewed runs. Small SMR appears to generally be the marginal technology, but coal gasification dominates in all runs. Note that hydrogen is not necessarily solely used in transport, but in these runs this is by far the dominant use.

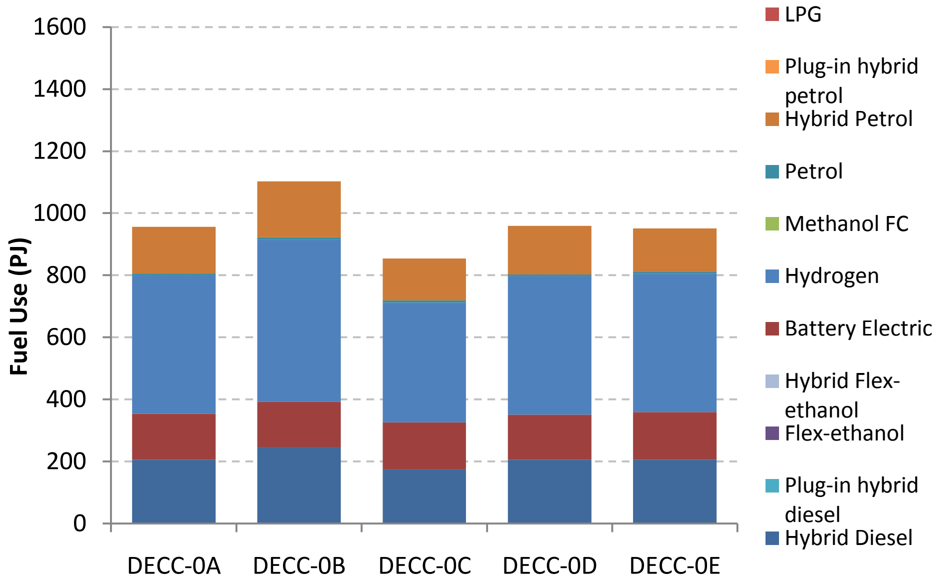


Figure 16: Transport Sector Fuel Use by Technologies in 2050 Comparison

The technology splits are shown in Figure 17 (in terms of billion-vehicle-kilometres served for each technology). For road transport, the typical progression is from conventional engines, through to hybrids, followed by hydrogen. This pattern is generally consistent across all runs investigated in this study, with approximate fuel splits in 2050 proportionally comparable (i.e. % share is comparable, whilst total demand level is proportional to service demand level) as per Figure 16.

Also in relation to Figure 17, it is clear that some technology types or fuel types enter the mix extremely rapidly. For example, hydrogen in buses, and hybrid diesel and then hydrogen in HGVs would require exclusive investment in these technologies to achieve such uptake rates. Constraints have been added later in this project (i.e. phase 2 modelling runs) to address these where they are perceived to be infeasible.

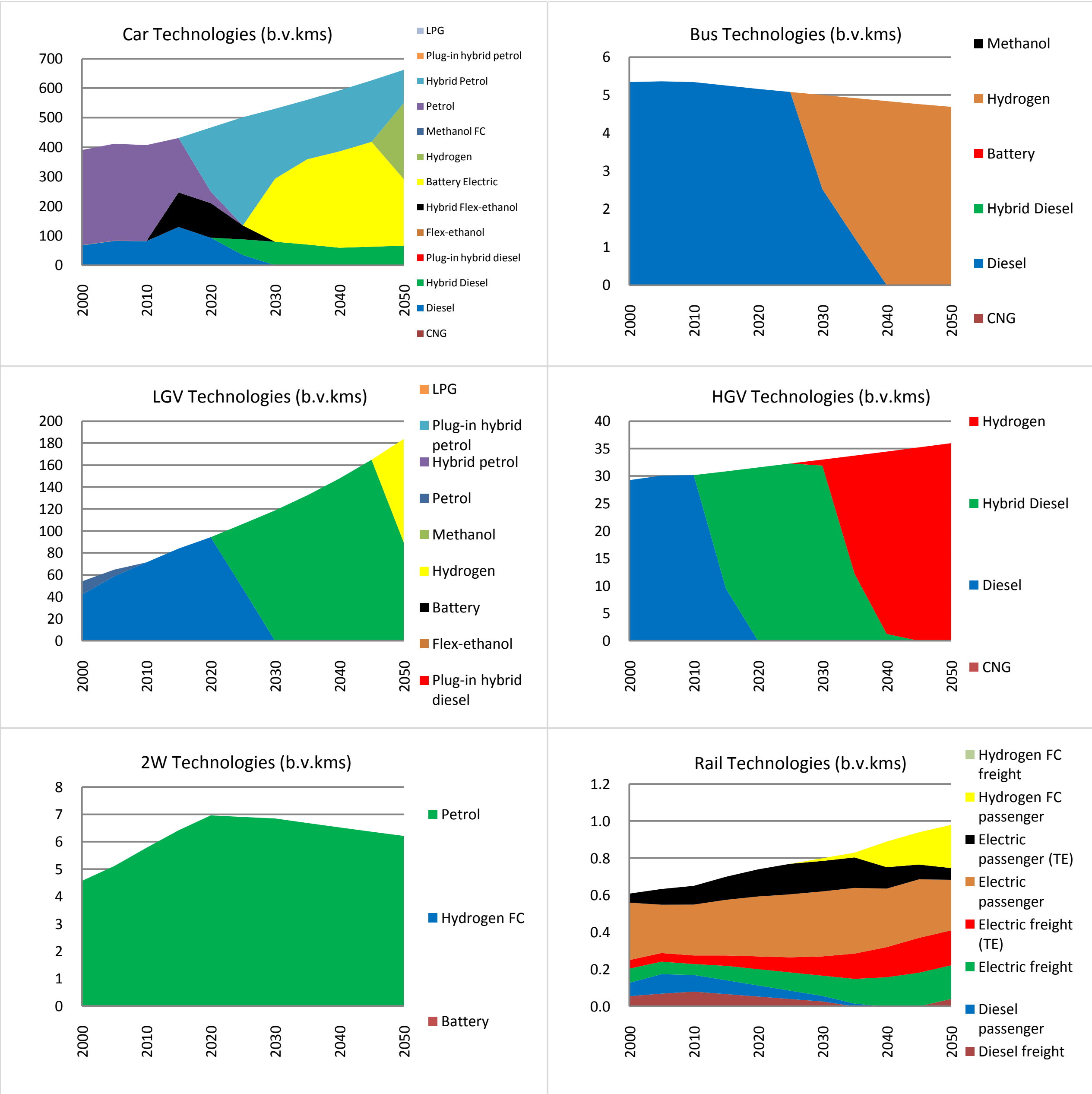


Figure 17: Transport Sector Technologies for Run DECC-0A

2.2 Study 1: 90% CO_2 Reduction by 2050

2.2.1 Description of Study

This study is intended to explore pathways to a 90% CO_2 emissions reduction[1] in the energy system by 2050, with on “abated” run for each baseline run described above. Five separate boundary conditions are considered for the study, relating to the level of energy service demand and the assumptions regarding key fossil fuel prices (for coal, gas, and oil). The five studies are arranged as follows:

1. Study 1 Run A – Central Service Demand and Central Fossil Fuel Prices, Code **DECC-1A** (Baseline DECC-0A)
2. Study 1 Run B – Central Service Demand and Low Fossil Fuel Prices, Code **DECC-1B** (Baseline DECC-0D)
3. Study 1 Run C – Central Service Demand and High Fossil Fuel Prices, Code **DECC 1C** (Baseline DECC-0E)
4. Study 1 Run D – High Service Demand and Central Fossil Fuel Prices, Code **DECC-1D** (Baseline DECC-0B)
5. Study 1 Run E – Low Service Demand and Central Fossil Fuel Prices, Code **DECC-1E** (Baseline DECC-0C)

The pathway for emissions reduction in this run is bounded (in addition to the baseline bounds to 2020) as per Figure 18.

Year	Emissions Target (MtCO2)
2025	299.8
2030	216.6
2035	156.5
2040	113.0
2045	81.7
2050	59.0

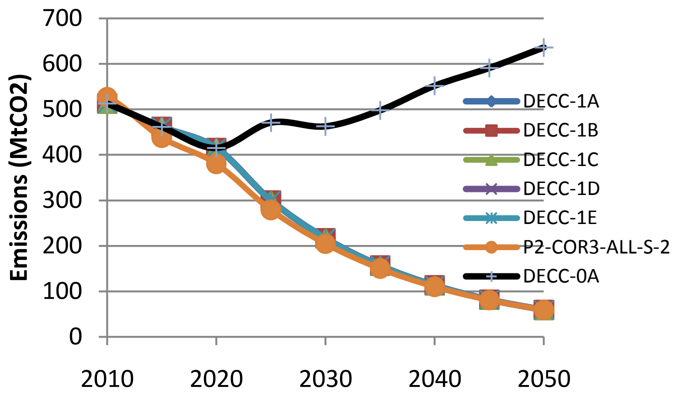


Figure 18: Target and Resultant Emissions Reduction over Time in the 5 Study 1 Runs

As is clear from Figure 18, which plots the CO_2 emissions observed in each run, these targets are achieved by the model in each time period (i.e. all runs are identical and meet the emissions reduction target). The P2-COR3-ALL-S-2 run from Usher *et al* (2010) and a selected baseline run (DECC-0A) are also included in Figure 18 for comparison.

The baseline scenarios for comparison with these runs differ according to the run. Here the underlying assumption is that service demands and prices vary in the baseline as well as the core runs. Therefore each run in this study has its own corresponding baseline run.

2.2.2 Key Results

All cost metrics reported here are in year 2010 UK pounds sterling. Discounted quantities are adjusted for time-preference (i.e. discounted to year 2010 at the Green book rate of 3.5%) and undiscounted quantities are presented in real 2010 UK pounds.

The total discounted system cost, and discounted change in consumer/producer surplus for these runs are presented in

[1] A 90% reduction target has been chosen because it would be expected that the energy sector decarbonises more than the rest of the economy in order to achieve the national legislated 80% reduction target.

Table 3. When considering results relative to run DECC-1A, which is considered the central estimate of demand and fossil fuel price, it is apparent that service demand levels have the larger impact than fossil fuel price on results. For example, the difference between the change in consumer/producer surplus between run DECC-1A and run DECC-1D (i.e. a move from central to high service demand levels) is approximately -£76 billion (i.e. a decrease in change in surplus relative to DECC-1A). In contrast, the difference between DECC-1A and DECC-1C which represents a move from central to high fossil fuel prices, but maintaining the same level of service demand, is £6 billion (i.e. an increase in change in surplus relative to DECC-1A).

Table 3: Key Result Metrics

	Study 1 Run A DECC-1A	Study 1 Run B DECC-1B	Study 1 Run C DECC-1C	Study 1 Run D DECC-1D	Study 1 Run E DECC-1E
Baseline Run	DECC-0A	DECC-0D	DECC-0E	DECC-0B	DECC-0C
Baseline Discounted Energy System Cost (2010 UK£ Billions)	5,940	5,602	6,195	6,258	5,600
Discounted Energy System Cost (2010 UK£ Billions)	6,014	5,702	6,264	6,369	5,655
Discounted Change in Consumer/Producer Surplus (2010 UK£ Billions)	-293	-322	-287	-369	-231

The undiscounted system costs are displayed in Figure 19. This charts the annualised cost of the system over time. In the worst-case scenario in run DECC-1D (high demand, central prices), costs peak at over £400 billion per year. In comparison, the most manageable scenario is DECC-1E (low demand, central prices), where annual total system cost peaks at just over £320 billion per year.

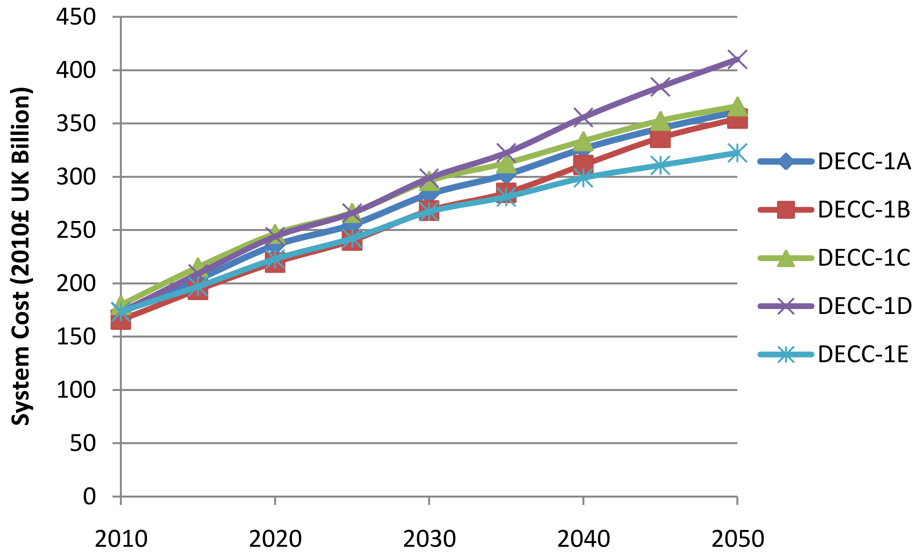


Figure 19: Undiscounted System Cost for Each Run

As shown in Figure 18, all mitigation scenarios follow the same emissions reduction trajectory, which was imposed upon the model as an upper bound in this study. Figure 20 plots the corresponding marginal price of CO_2 in each run. The marginal price of CO_2 is defined by the gradient of the MARKAL objective function at the CO_2 constraint of Figure 18. In all runs the marginal price of CO_2 is high in later periods, even approaching £800/tCO_2 in the high demand run. In the low demand run, it reaches just over £500/tCO_2 (note that these figures are in undiscounted real terms – 2010 prices) . Furthermore, the marginal price of CO_2 increases markedly in later periods from 2035. However, as stated in the Executive Summary and elsewhere, it is important to note these prices are significantly above the expected price of international tradable permits, and the applied MARKAL modelling did not consider the possibility that innovation may circumvent such prices materialising. As such, it is unlikely the UK economy would be exposed to these prices in practice. Equivalent runs published in Usher et al (2010) have significantly lower carbon prices towards the end of the time horizon. Likely causes of this difference are the higher prices of power generation and higher levels of service demand introduced, and discounting to a different base year (i.e. 2010 in this study, versus 2000 in the former).

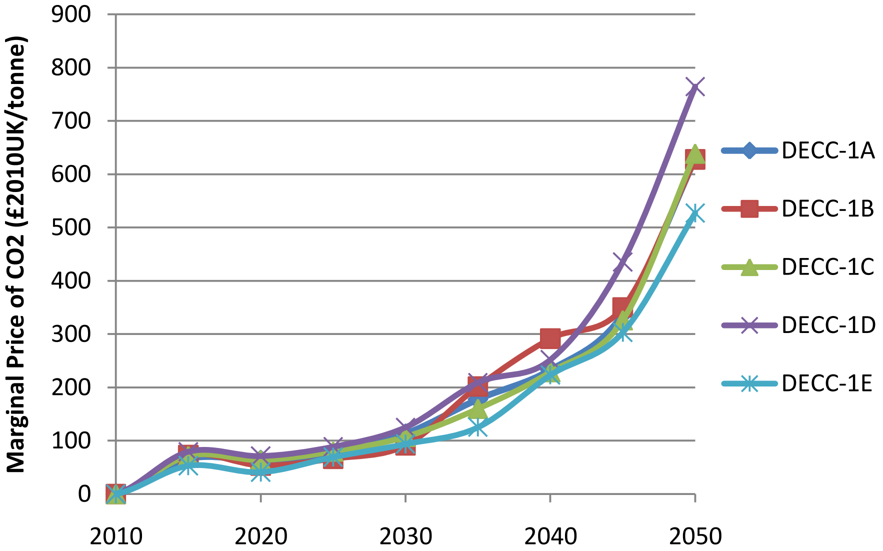


Figure 20: Marginal Cost of CO_2 for Each Run

Another important characteristic of all the runs investigated in this study is the consistency and timing of decarbonisation of electricity. As shown in Figure 21, all five runs follow approximately the same decarbonisation pathways for electricity. This figure also includes the emissions intensity pathway for the P2-COR3-ALL-S-2 run from User et al (2010). This shows more rapid decarbonisation of electricity in the 2020s than all runs in this study. For example, in 2030 the range of CO_2 intensities of electricity in the runs in this project was 0.7 to 0.1kgCO_2/kWh, whereas in Usher et al (2010) it was closer to 0.0kgCO2/kWh The model may favour more rapid decarbonisation in the runs based on the older database because that version incorporated lower capital and operating costs in the power sector. The new version, with higher power sector costs, is likely to favour decarbonisation in other sectors as these may have become relatively affordable. Nonetheless, despite the changes made to input parameters, rapid power sector decarbonisation is still apparent.

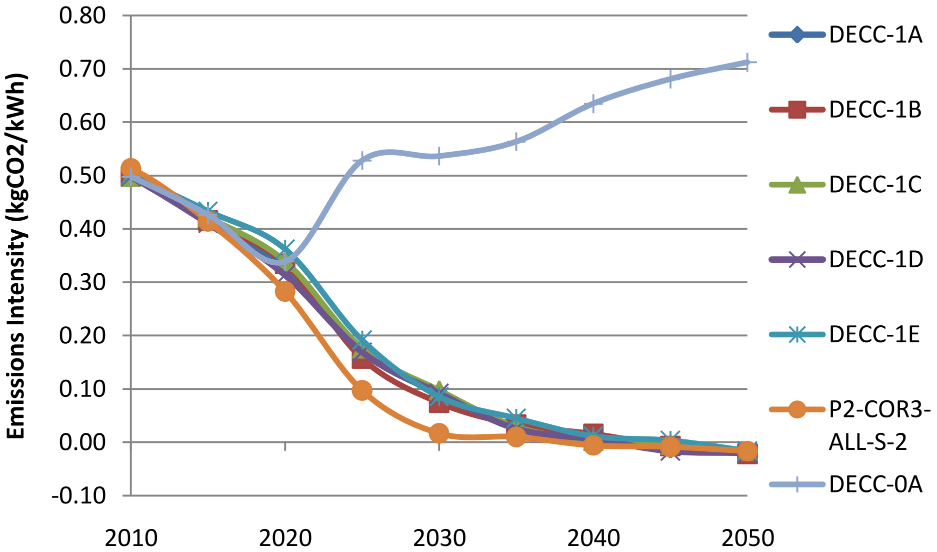


Figure 21: The Emissions Intensity of Grid Electricity

Table 4 presents the numerical figures of Figure 21, reinforcing the conclusion that all five stabilisation runs follow a remarkably similar trajectory of decreasing carbon intensity. The period of the 2020s is particularly important, with grid electricity CO_2 rates decreasing by approximately 80% in all cases. By 2045 the emissions intensity of electricity would be zero or less (a negative emissions rate for electricity in these runs relates to the use of biomass in co-firing power stations, coupled with carbon capture and storage). This is in contrast to a selected baseline run, where the CO_2 intensity may reach 0.7kgCO_2/kWh by 2050. However, when interpreting these results it should be noted that MARKAL installs but does not use significant gas-fired peaking capacity (i.e. to satisfy a peaking constraints in the model). The impact of this gas backup capcity is not captured in the CO_2 intensities reported here.

Table 4: Figures for the Emissions Intensity of Grid Electricity (kgCO_2/kWh)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
DECC-1A	0.50	0.42	0.33	0.17	0.09	0.03	0.01	-0.01	-0.02
DECC-1B	0.50	0.42	0.33	0.16	0.07	0.03	0.02	-0.01	-0.02
DECC-1C	0.50	0.42	0.34	0.18	0.10	0.03	0.00	0.00	-0.02
DECC-1D	0.50	0.41	0.31	0.17	0.09	0.03	0.01	-0.02	-0.02
DECC-1E	0.50	0.43	0.36	0.19	0.09	0.05	0.01	0.00	-0.02

Figure 22 presents the use of conservation measures in each of the five runs. This uptake is identical in all cases, and also identical to the respective baseline cases. Clearly some conservation measures, at the prices depicted in MARKAL v3-26-4, are no-regrets measures in the sense that they are cost-effective regardless of national carbon targets. However, it is also worth noting that the total level of uptake of conservation measures is constrained in this version of MARKAL. The model chooses to adopt these measures to the full extent possible according to these constraints. Therefore there are likely to be conservation measures characterised in the model that are not cost effective, and it would be wrong to conclude that all conservation measures in the model are adopted. The appropriate conclusion is that there are sufficient cost-effective conservation measures available to reduce final energy consumption up to the level defined in the constraints.

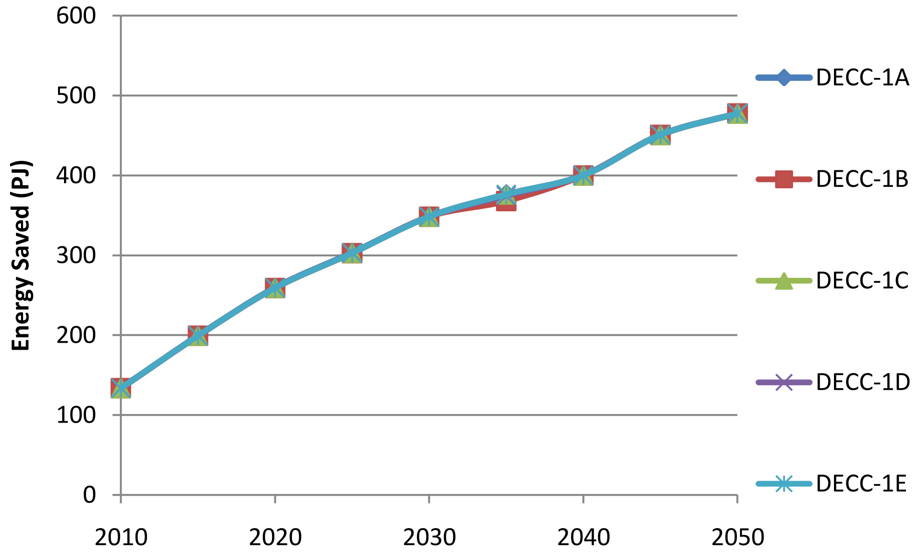


Figure 22: Use of Conservation Measures by Sector for Each Run

2.2.3 Primary and Final Energy Statistics

Primary energy consumption and final energy consumption are presented in Figure 23 and Figure 24, respectively. For Figure 23, the three central demand cases result in very similar aggregate primary energy consumption, despite the differences in fossil fuel prices. Conversely, the high and low service demand runs result in significantly higher/lower primary demand.

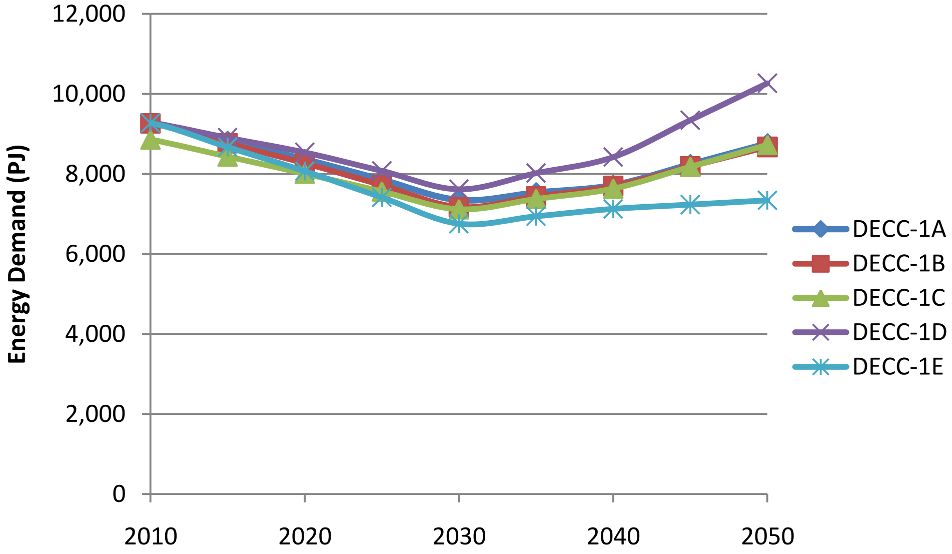


Figure 23: Primary Energy Demand over Time for Each Run

Final energy consumption shows similar distinction between the runs, with the high and low demand cases at the extremes. There is also greater distinction here between the three central service demand runs, particularly for the low price case.

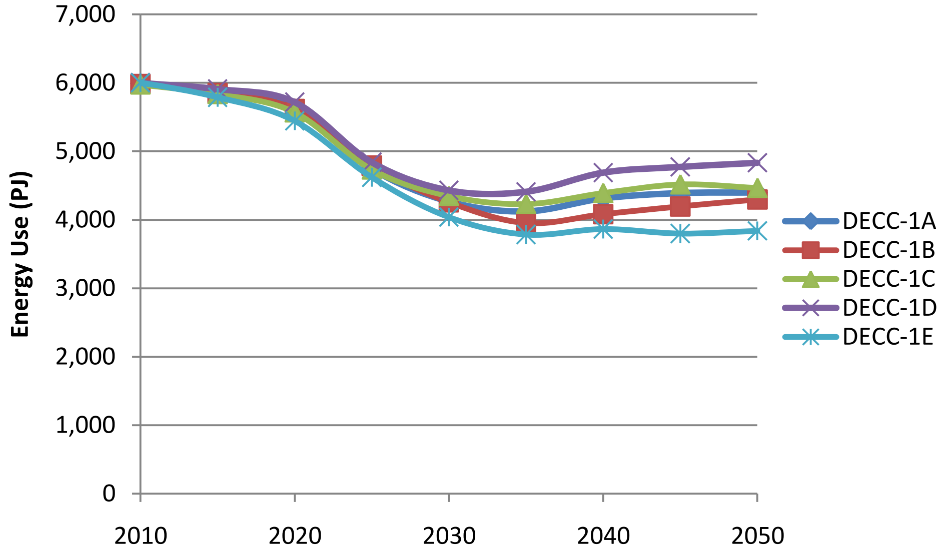


Figure 24: Final Energy Consumption over Time for Each Run

The results for primary and final energy consumption may also be compared in terms of the energy carriers. This is done for the central/central baseline versus the central/central stabilisation runs in Figure 25. For primary energy consumption, the most apparent differences between baseline and stabilisation runs relate to the introduction of nuclear power versus use of coal, and the utilisation of biomass instead of natural gas. This pattern of substitution is consistent across the runs, although exact proportions and timing of substitutions can be slightly different.

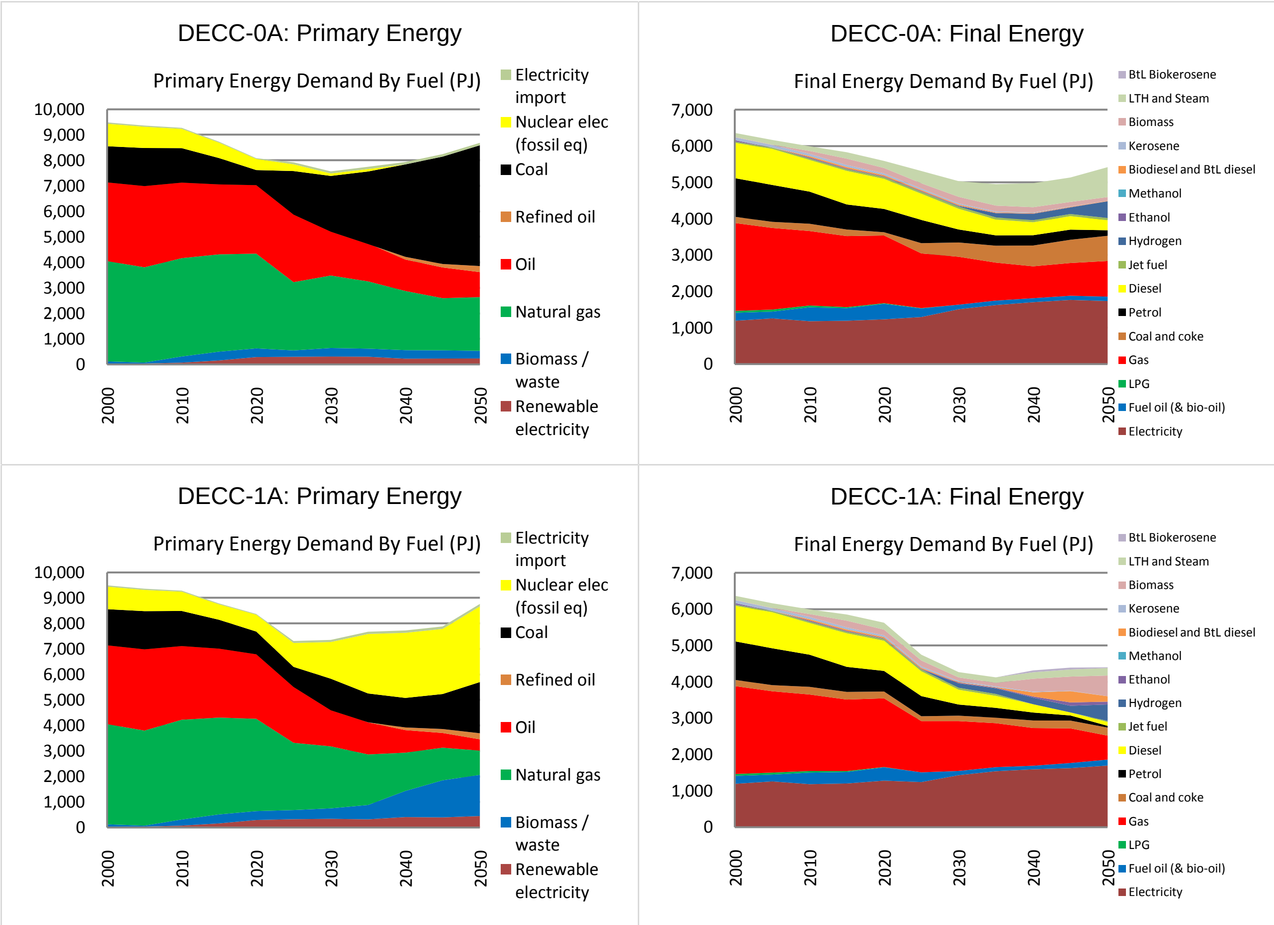


Figure 25: Primary and Final Energy Consumption Disaggregated by Energy Carrier

Final energy consumption profiles in Figure 25 are remarkably similar given the 90% reduction in CO_2 emissions in run DECC-1A. Perhaps the most important difference is that total final energy demand in run DECC-1A is almost 20% lower than in the corresponding baseline. Also, there are differences surrounding the use of low temperature heat (LTH) and steam in the baseline versus biomass in the stabilisation run, which also shows reduced use of coal, diesel and petrol.

Bio-energy in primary energy consumption is mainly imported; 1260PJ imported versus 350PJ sourced domestically by 2050. The primary import is solid biomass, at slightly more than 1000PJ in 2050. The upper bound on bio-energy import is hit in 2050 only.

Bio-products in final consumption are shown in Figure 26, disaggregated by end-use sector. By 2050, bio-products directly serve almost 20% of final energy demand.

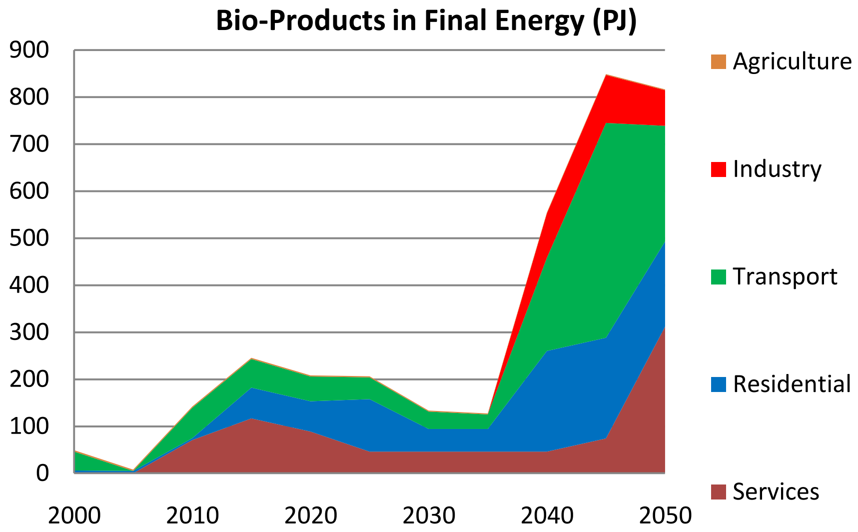


Figure 26: Bio-Products in Final Energy Consumption

Clearly bio-products are a favoured abatement measure later in the period, from 2040 onwards. This suggests they represent relatively high cost abatement, although further investigation would be required to make firm conclusions in this regard (e.g. constraints on uptake or various bio-energy resources or technologies may also be responsible for this trend). Industry bio-product use is limited to biomethane, transport use is primarily bio-diesel (both 1st and 2nd generation) with a good measure of ethanol, whilst services and residential are dominated by use of pellets and/or wood for heating.

2.2.4 Power Generation and Installed Capacity

Likewise with primary and final energy consumption, electricity generation and associated installed capacity are more sensitive to the level of service demand in the model than they are to the level of fossil fuel prices. This is displayed in Figure 27 and Figure 28. In the high demand (DECC-1D) run, generation in 2050 is more than 20% higher than in the central demand (and central price) DECC-1A run. Similarly, installed capacity is almost 20% higher, at 186GW in 2050 in the high demand run. In the corresponding central demand run, installed capacity in 2050 is 158GW.

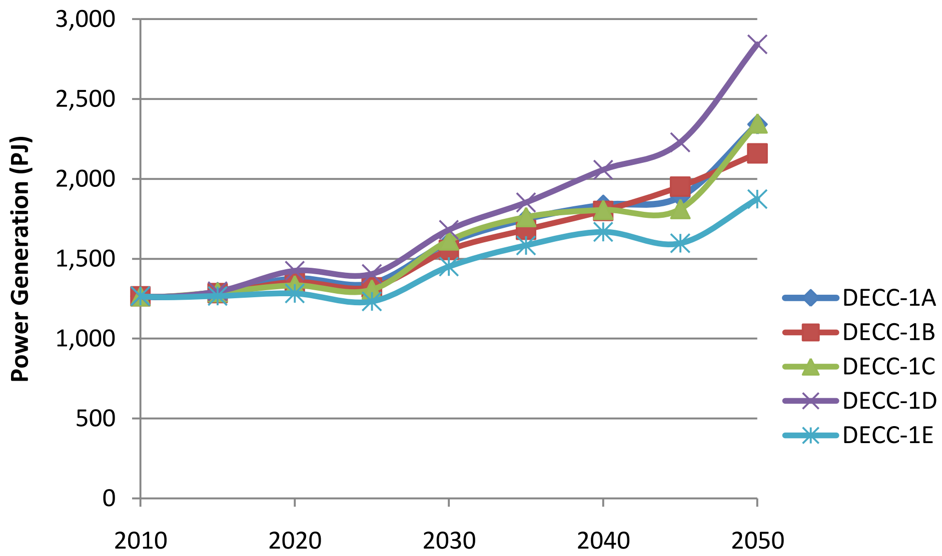


Figure 27: Aggregate Generation over Time for Each Run

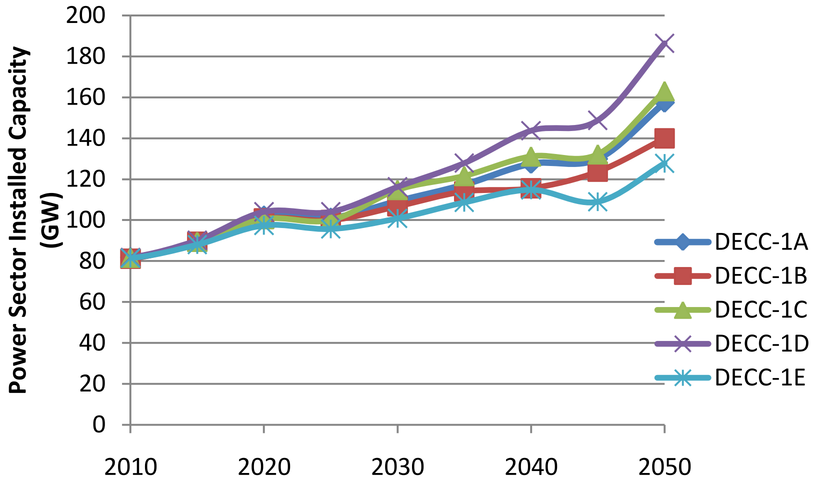


Figure 28: Aggregate Installed Capacity over Time for Each Run

The fuel/technology mix of these generation and installed capacity profiles, for the central demand central price baseline and stabilisation scenarios, is shown in Figure 29. The decarbonisation of electricity discussed in relation to Figure 21 is apparent in Figure 29. In scenario DECC-1A, unabated coal-fired power generation is phased out early in the 2020s, followed by the reduced use of installed gas-fired capacity later in the 2020s. The capacity gap is filled by the introduction of wind, nuclear and abated co-firing of biomass. Between 2020 and 2030, 12GW of abated co-firing power plants (i.e. with CCS), and 8GW of nuclear power plants are installed. Wind power is installed earlier as part of the government's carbon plan, with 28GW in place by 2020 (and note that this level of wind investment is also included in the baseline).

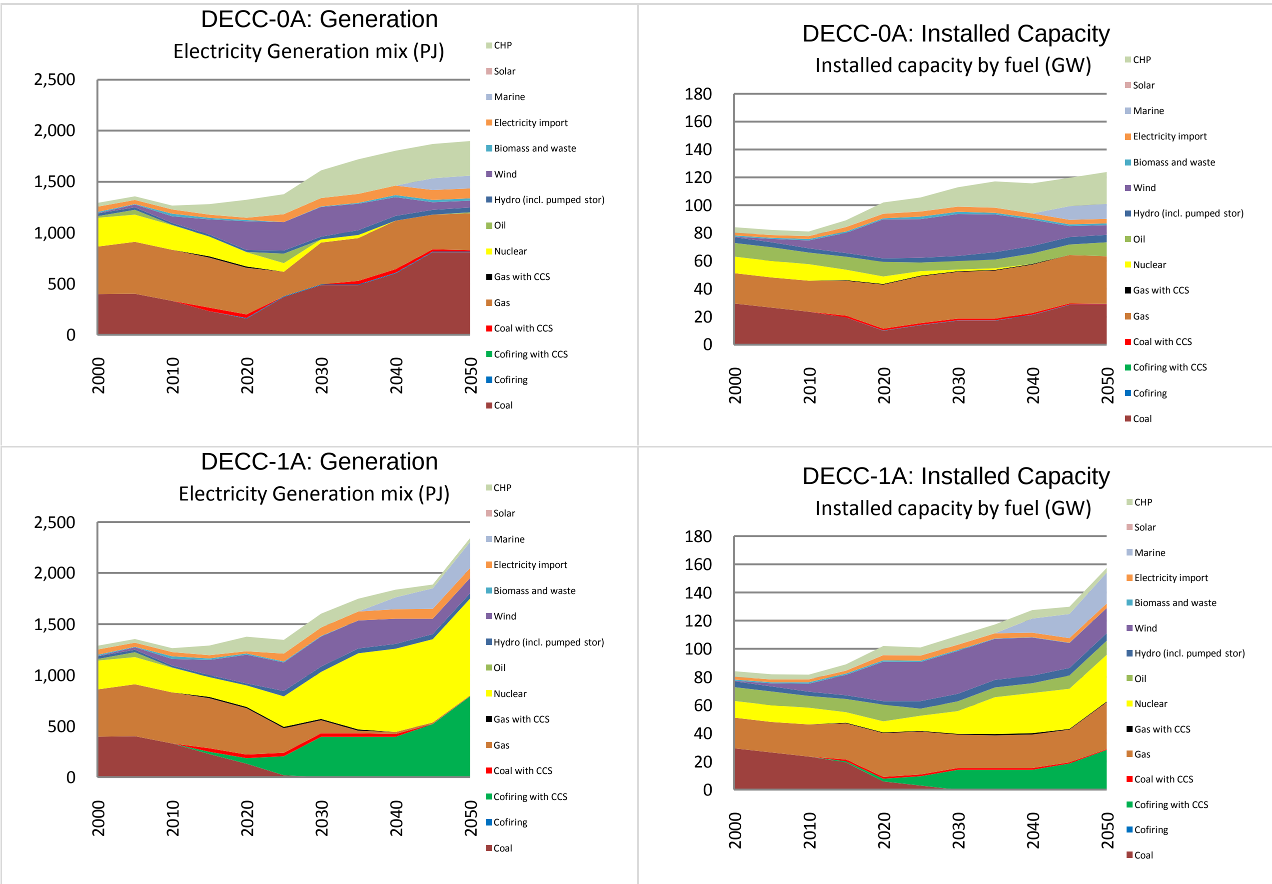


Figure 29: Generation over Time by Technology for DECC-0A/DECC-1A Runs

Gas-fired generation remains a large portion of installed capacity in both baseline and stabilisation scenarios. In the baseline, the system continues to rely on this generation to meet a large portion of electricity demand. In contrast, in the stabilisation scenario, the gas-fired generation is only used to meet peak demands. The gas-fired generation used in the stabilisation scenario benefits from retrofitting of carbon capture and storage technology.

Carbon capture and storage with power generation is an important technology from 2020 onwards, generating more than a third of all electricity. In essence, MARKAL uses this technology to achieve negative emissions rates for electricity by sequestering the CO_2 associated with the biomass share (25% of fuel input to these generators in 2050 is biomass).

2.2.5 End-Use Sectors

As shown in Figure 30, aggregate reductions in final energy consumption occur mainly for residential and transport sectors. Although this may be due to a combination of factors including elasticity of service demand and available end-use technologies, it will also to a large degree be due to the availability of abatement technologies in each sector. For example, as is discussed below, industry has the ability to abate via the installation of CCS, which reduces the need for it to find alternative end-use technologies.

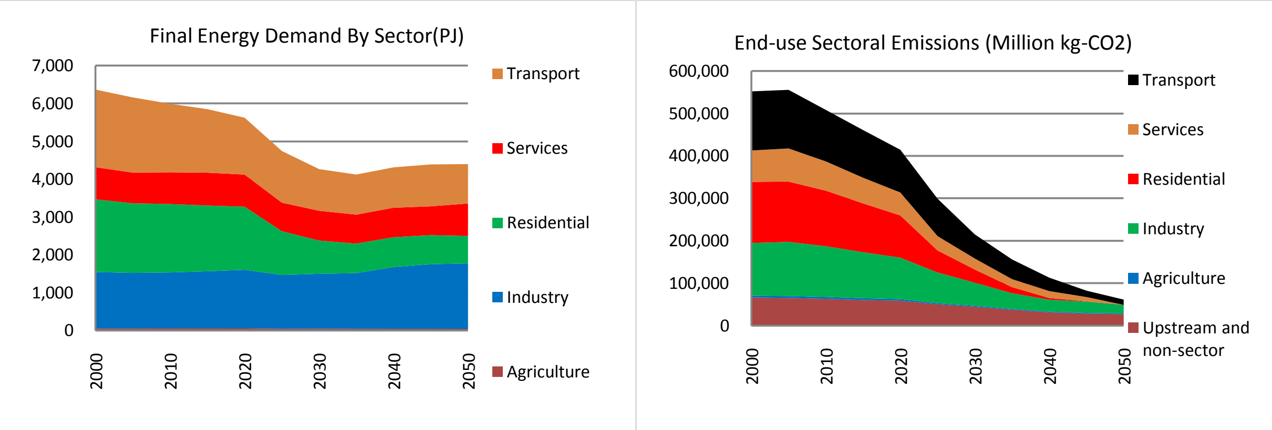


Figure 30: End-Use Sectoral Final Energy Consumption and Emissions Disaggregation for Run DECC-1A

End-use sectoral CO_2 emissions are also shown in Figure 30. This demonstrates the contrast between final energy consumption and CO_2 emissions, where industry and services show a clear decline in the right subplot whilst are relatively unchanged in the left.

The following sections consider each end-use sector in more detail, focusing on run DECC-1A. It should be noted that all scenarios in this study follow generally the same pattern, only with particular aspects amplified or reduced, and timing altered slightly.

Industrial Sector

The industrial sector experiences a high level of demand reduction, facilitated by MARKAL's elastic demand response characterisation. In Figure 31, which displays the calculated demand reduction in industry, the chemicals, iron and steel, and non-ferrous metals sectors all exhibit the maximum allowable demand reduction of 25% from the central estimate of service demand. Other industry and pulp and paper reach 15-20% demand reduction by 2050. This indicates that, as currently calibrated, the MARKAL model suggests that industry might scale back operation quite significantly given the energy price rises brought about by decarbonisation.

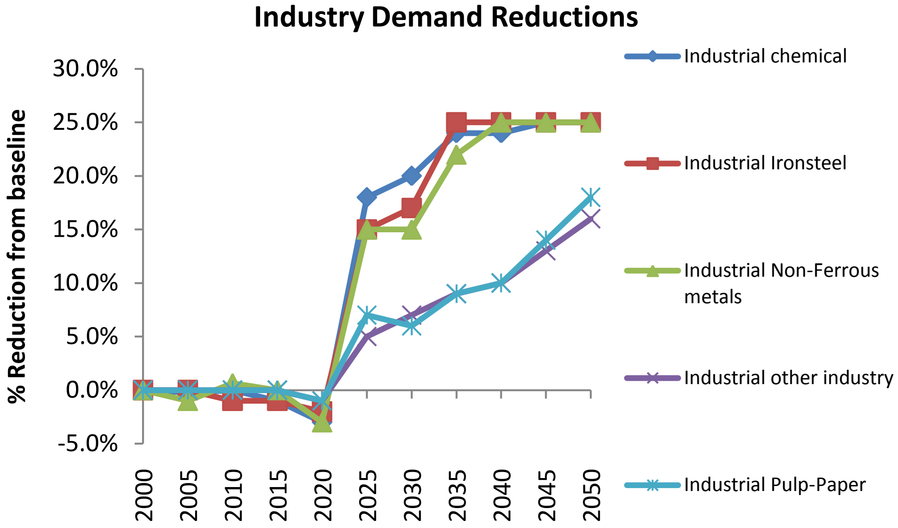


Figure 31: Industrial Service Demand Reductions for Run DECC-1A

The share of each energy carrier serving final energy consumption is shown in Figure 32. Only small changes are apparent here, with electircity and wood acieving a greater share late in the time horizon. Note however that the natural gas energy carrier here includes biomethane injected into the gas network. Of the natural gas consumed by industry in 2050, 16% is biomethane.

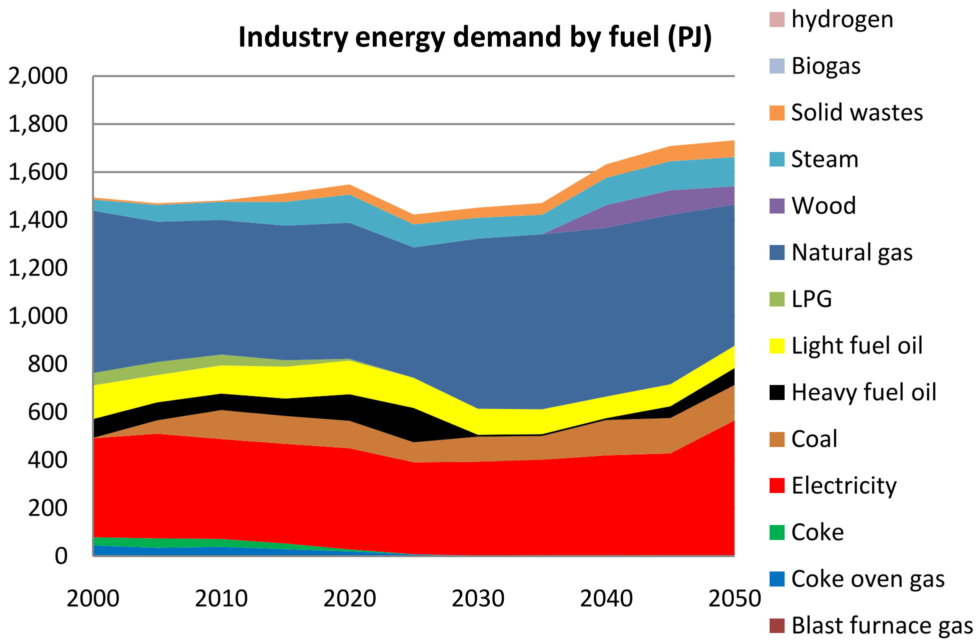


Figure 32: Industrial Final Energy Consumption Run DECC-1A

Industry also benefits from the ability to adopt CCS in the MARKAL model. By 2050, 48MtCO_2 per year is sequestered via this route (including "process" related CCS related to the production of hydrogen). Therefore, industry CO_2 emissions can be reduced to approximately 20MtCO_2 per year in 2050, primarily through the use of biomethane and attachment of CCS to large industry facilities.

Residential Sector

Unlike industry, the residential sector does not benefit from the ability to apply CCS to direct emissions. Therefore it must find other ways to meet the stringent 90% CO_2 reduction target in 2050. Firstly, it does this by demand reduction. Figure 33 shows this reduction across each of the service demand categories in the sector. The largest demand response is in space and water heating, which hovers around the 15% mark post 2025.

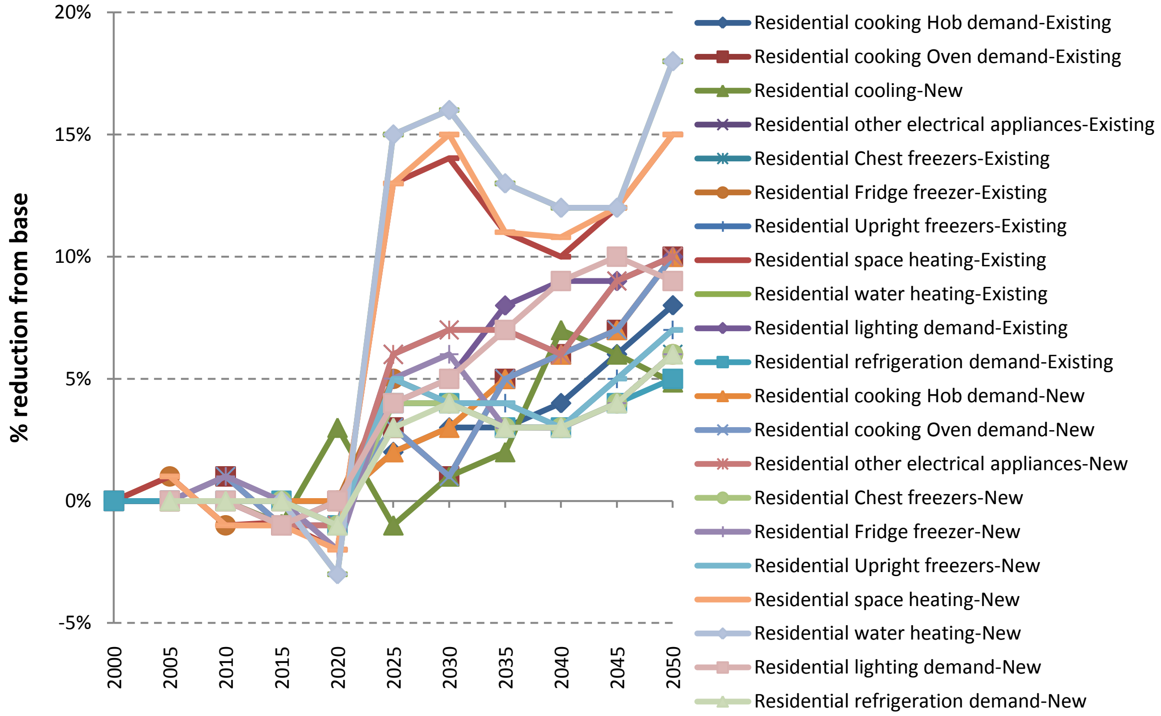


Figure 33: Residential Service Demand Reduction for Run DECC-1A

This reduction in demand is accompanied by a large reduction in final energy consumed in the sector. As per Figure 34, natural gas disappears from heating almost entirely from 2040 onwards. Electricity consumption increases, and pellets contribute significantly.

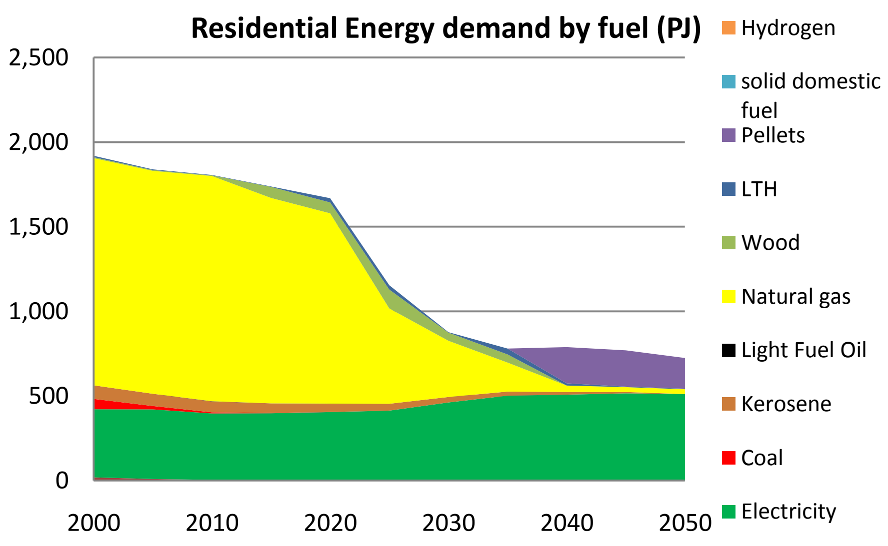


Figure 34: Residential Final Energy Consumption for Run DECC-1A

The driving force of this change can be seen by drilling down into residential heating as presented in Figure 35. Gas heating is removed from the mix by 2040, replaced by heat pumps and solar water heating. In 2040, biomass pellet based heating makes a significant appearance. Both heat pumps and solar thermal heating hit their upper bounds of activity between 2020 and 2030. For heat pumps, this a limit on the share of residential heating served of 52.6%. For solar thermal, activity (i.e. PJ output) is limited to 16.5PJ in 2020, which then rises to 76PJ in 2030 and remains a constant upper bound thereafter.

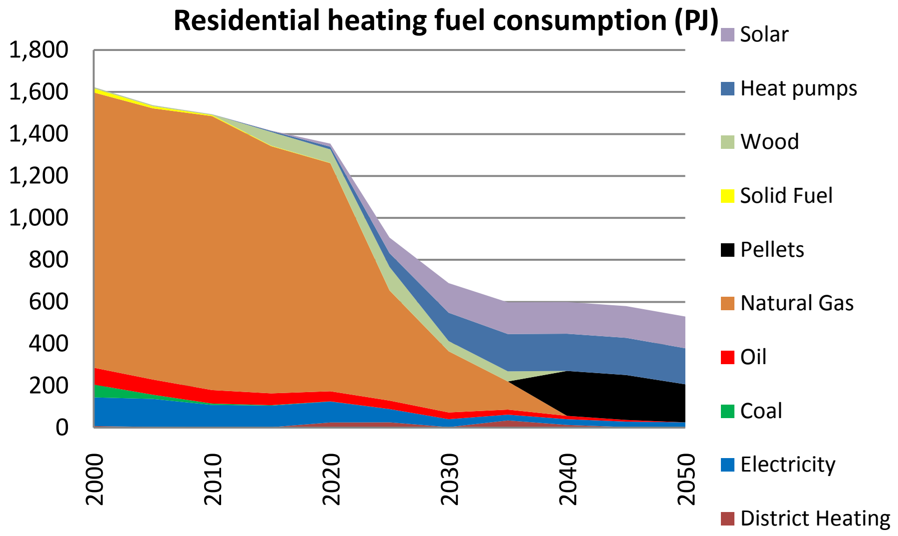


Figure 35: Residential Heating Final Energy Consumption for Run DECC-1A

However, the reader should note that Figure 35 is final energy *consumption* of the end-use device serving thermal demand, not production of thermal energy. Therefore heat pumps, which draw energy from the surrounding environment in addition to consuming electricity, serve a much larger portion of heating service demand than the other technologies. For an example of comparison on an output basis, see Figure 35.

Services Sector

The services sector also exhibits a significant demand response. Similarly to residential heating, the largest response is observed in space and water heating, which both reach the maximum 25% reduction in service demand by 2050.

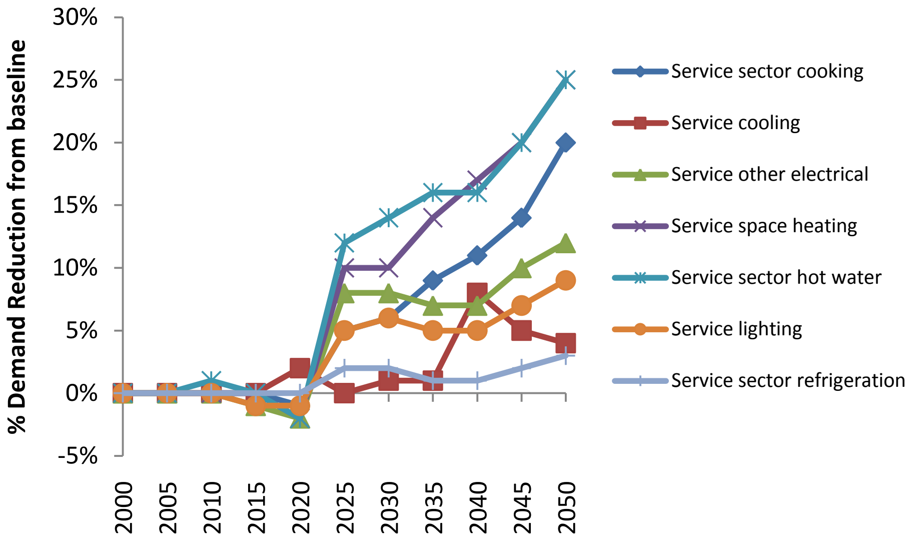


Figure 36: Service Sector Service Demand Reduction for Run DECC-1A

As discussed above in relation to Figure 30, and similarly with the industrial sector, the services sector does not achieve significant reduction in final energy consumption over the time period. However, some fuel switching is apparent, particularly towards the consumption of electricity, and rapid introduction of the use of pellets for heating from 2040 onwards. There is no significant change in the services sector over the 2020s.

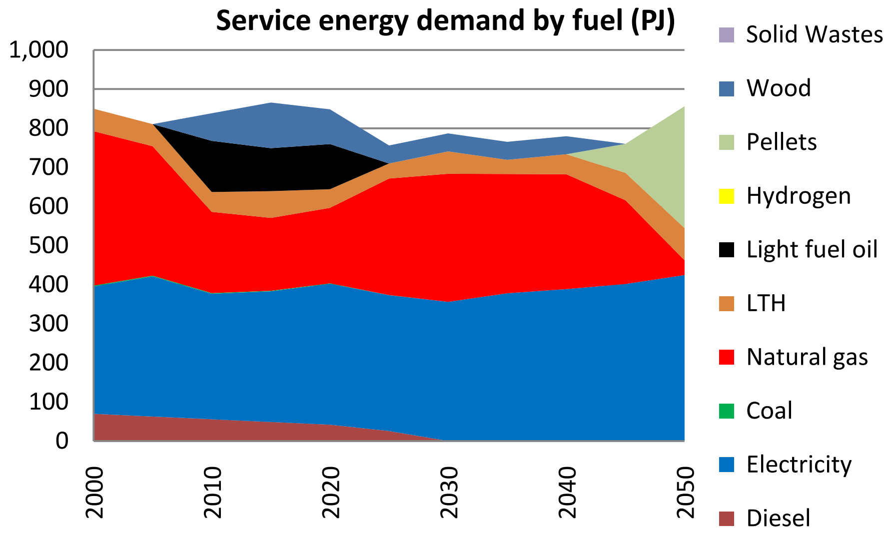


Figure 37: Service Sector Final Energy Consumption for a Selected Run

Therefore decarbonisation of the services sector is achieved by decarbonisation of grid electricity, and switching away from natural gas for heating towards heat pumps and biomass pellet boilers.

Transport Sector

Of all the end-use sectors, transport shows the least demand response in run DECC-1A. Response is observed at approximately 5% for most service demand categories.

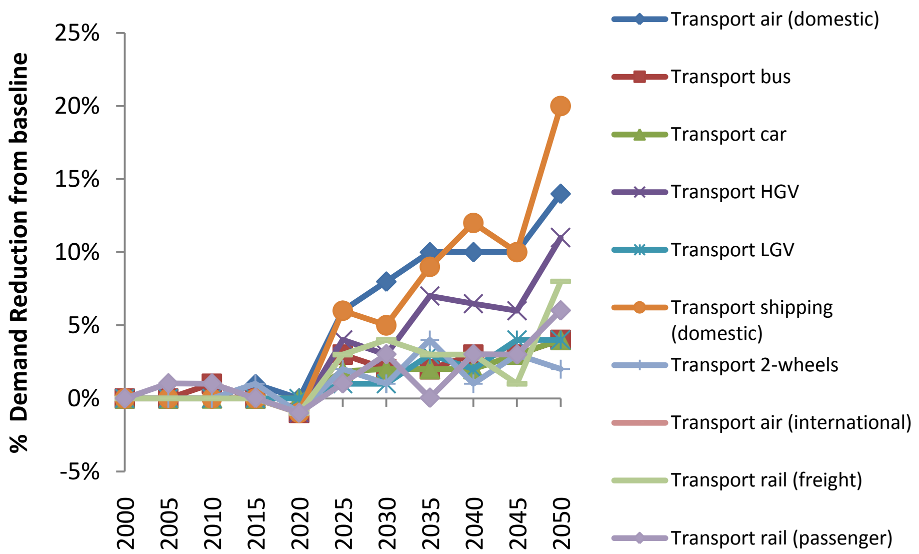


Figure 38: Transport Service Demand Reduction for Run DECC-1A

Transport demand also sees a steep decline in final energy consumption, as presented in Figure 39. Similarly to the residential sector, this is driven by a shift to the more efficient electric vehicles and plug-in hybrid electric vehicles.

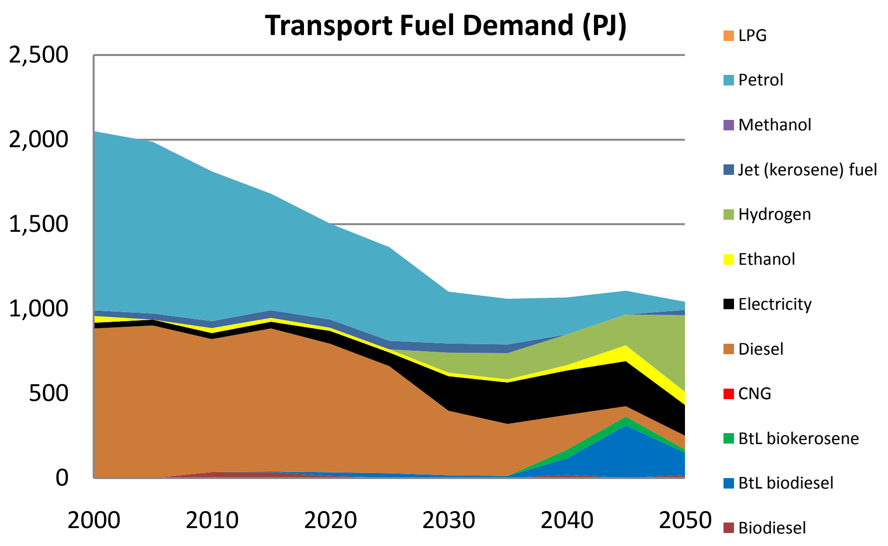


Figure 39: Transport Final Energy Consumption for Run DECC-1A

The mix of end-use technologies is extremely heterogeneous in 2050 in comparison to the situation at present. Notable contributors in terms of fuel consumption are projected to be biomass-to-liquids, electric, and hydrogen particularly later in the period. Conventionally fuelled vehicles are not expected to make a significant contribution by 2050 under this optimised pathway.

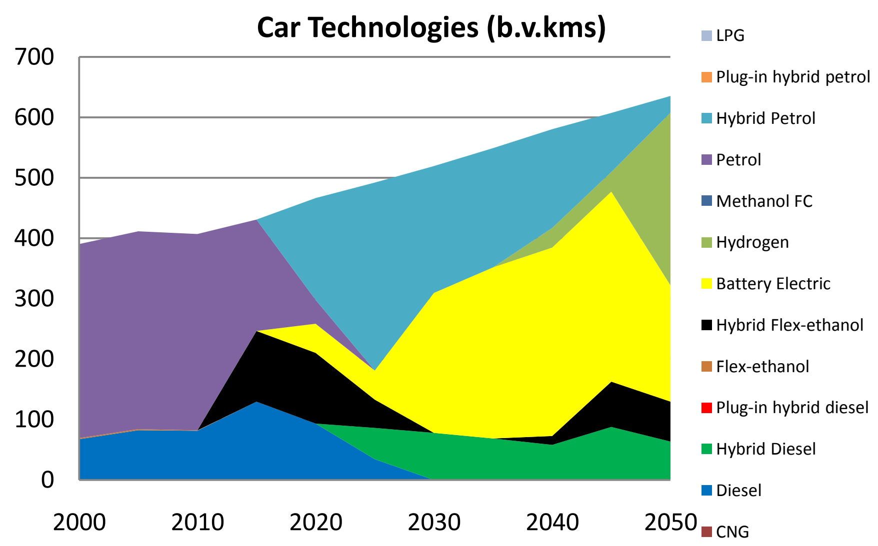


Figure 40: Car Technology Choices to 2050 for Run DECC-1A

The significant changes that could be experienced in the transport sector are exemplified in Figure 40, Beginning with conventional petrol and diesel technologies in 2010, hybrid, battery, and then hydrogen technologies each play an important role.

2.3 Study 2: 85% CO_2 Reduction by 2050

2.3.1 Description of Study

Following on from the study presented above, which considered energy system change to meet a 90% CO_2 emissions reduction target, this study examines a similar set of runs that strive to reach an 85% reduction target. As per study 1, the constraints to 2020 are formed from the Government Carbon Plan, and all technical abatement options remain unchanged in the model database.

Three studies are considered each with variations in the fossil fuel prices (coal, gas and oil). The three studies are arranged as follows:

1. Study 2 Run A – Central Service Demand and Central Fossil Fuel Prices. Code **DECC-2A**
2. Study 2 Run B – Central Service Demand and Low Fossil Fuel Prices. Code **DECC-2B**
3. Study 2 Run C Central Service Demand and High Fossil Fuel Prices. Code **DECC-2C**

The pathways for emissions reduction in this run is bounded (in the addition to the baseline bounds to 2020) by the figures in Table 5.

Table 5: Target Annual Emissions to 85% Reduction in 2050

Year	2025	2030	2035	2040	2045	2050
Emissions Target ($MtCO_2$)	321.1	248.4	192.2	148.7	115.0	89.0

The resulting CO_2 emissions from each run are shown in Figure 41. Each run of the model meets the targets set.

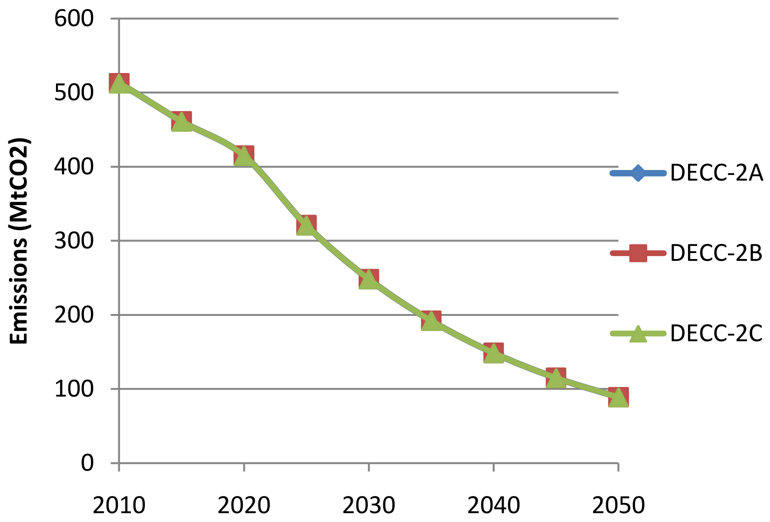


Figure 41: Emissions Reduction over Time in the 3 Study 2 Runs

The baseline scenarios for comparison with these runs differ according to the run. For this study the underlying assumption is that fossil fuel prices vary in the baseline as with the corresponding study run, but the service demand is consistent.

Throughout this study comparisons are made across the different fossil fuel prices of the three studies, as well as with the equivalent runs in Study 1, which were limited to a 90% reduction in CO_2 emissions by 2050. From this it was possible to estimate the marginal impact of the change from 85% to 90% emissions targets in terms of changes in choice of energy carriers and technologies.

2.3.2 Key Results

The total discounted system cost, and discounted consumer/producer surplus for these runs are presented in Table 6. DECC-2A uses the central estimate of demand and fossil fuel price. When comparing this with the lower price estimate (DECC-2B) and the higher price estimate (DECC-2C) it is clear that changes in the fossil fuel prices have a corresponding impact on the total discounted system cost. This behaviour is similar to that of Study 1. Table 6 also includes system costs when considering a 90% reduction in CO_2 emissions by 2050.

Firstly, we compare the case of 90% emissions reduction with that of 85%. The difference in total discounted technical energy system cost[2] between the central fossil fuel price runs with different levels of emissions reduction (i.e. DECC-2A and DECC-1A) is £23 billion. However, the 85% reduction run provides considerably improved impact on surplus, reducing the burden by £80 billion. The difference in total discounted technical energy system costs for the case of lower fossil fuel prices (DECC-2B and DECC-1B) is larger at £49 billion, and impact on discounted surplus is much the same at £85 billion. The difference between system costs for the case of the high fuel prices runs (DECC-2C and DECC-1C) is £23 billion, and difference in surplus is £70 billion. Therefore, the cost of moving from 85% to 90% target for the energy system has significant range, and averages just under £32 billion (in real year 2010 pounds). The average impact on surplus is a loss of £78 billion over the timeframe.

Table 6: Key Result Metrics

	Study 2 Run A DECC-2A	Study 2 Run B DECC-2B	Study 2 Run C DECC-2C
Baseline Run	DECC-0A	DECC-0D	DECC-0E
Baseline Discounted System Cost (Year 2000 £UK Billions)	5,940	5,602	6,195
Discounted Energy System Cost (Year 2010 £UK Billions) – 85% CO_2 emissions reduction	5,991	5,653	6,241
Discounted Energy System Cost (Year 2010 £UK Billions) – 90% CO_2 emissions reduction	6,014	5,702	6,264
Discounted Consumer/Producer Surplus (Year 2010 £UK Billions) – 85% CO_2 emissions reduction	-213	-237	-217
Discounted Consumer/Producer Surplus (Year 2010 £UK Billions) – 90% CO_2 emissions reduction	-293	-322	-287

The annual undiscounted costs of the system over time are displayed in Figure 42. The three profiles are rather similar, with year-on-year increase in system costs. As expected, high and low fossil fuel price runs show prices higher and lower, respectively, than the central price run.

[2] Note that technical energy system cost does not take into account any change in utility associated with demand response.

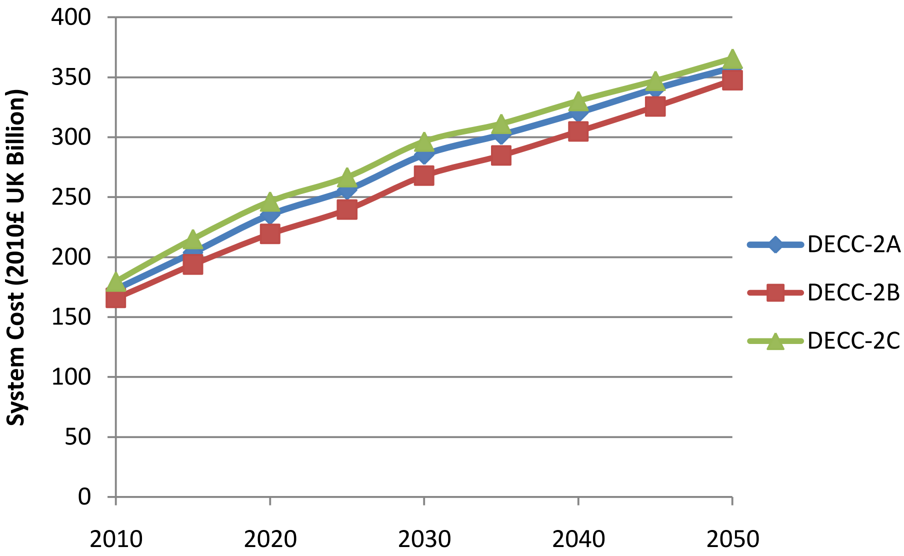


Figure 42: Undiscounted System Cost for Each Run

As with the 90% CO_2 emissions reduction scenarios, the three emissions reduction scenarios considered here follow the same emissions reduction trajectory. Figure 43 plots the corresponding marginal price of CO_2 in each run. In general the marginal CO_2 price in Study 2 runs is lower than that of Study 1 runs, as would be expected given the more relaxed carbon constraints. By 2050, the difference in the marginal cost of CO_2 between the corresponding scenarios has increased.

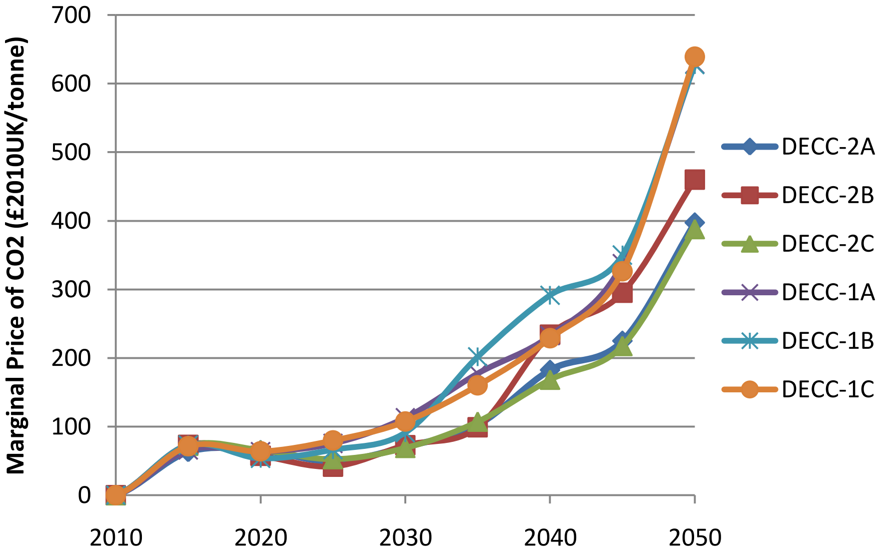


Figure 43: Marginal Cost of CO_2 for Each Run

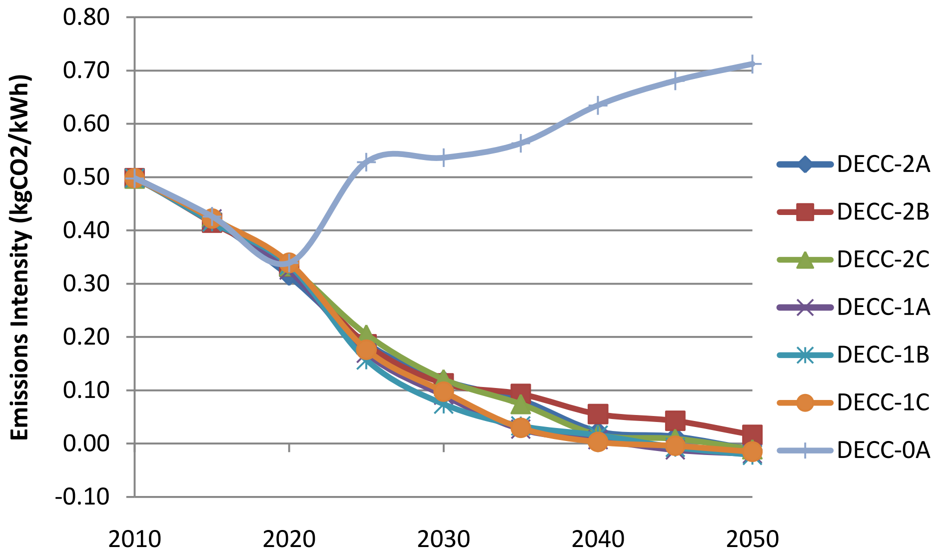


Figure 44: The Emissions Intensity of Grid Electricity

Figure 44 plots the carbon intensity of grid electricity in various runs. As can be seen, all the studies follow a similar pathway beyond 2020 in contrast with their corresponding baseline studies in which emissions intensity increase. Relative to the 90% emission reduction scenarios (study 1), emissions intensity is slightly higher in this study (0.11 - 0.12 $kgCO_2/kWh$). However, this difference in small and the general trend of rapid decarbonisation of grid electricity (which is particularly rapid in the 2020s) is still apparent.

Table 7 contains the numerical figures associated with Figure 44, along with those corresponding to the 90% emissions reduction scenarios. In the 90% reduction scenarios, electricity production becomes a sink for CO_2 from 2045, whereas this does not happen until slightly later in DECC-2A and DECC-2C until 2050. With DECC-2B, this does not happen at all in the time horizon.

Table 7: Emissions Intensity of Grid Electricity ($kgCO_2/kWh$)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
DECC-2A	0.50	0.42	0.31	0.19	0.12	0.08	0.02	0.01	-0.01
DECC-2B	0.50	0.41	0.33	0.19	0.11	0.09	0.06	0.04	0.02
DECC-2C	0.50	0.42	0.33	0.20	0.12	0.07	0.02	0.01	-0.01
DECC-1A	0.50	0.42	0.33	0.17	0.09	0.03	0.01	-0.01	-0.02
DECC-1B	0.50	0.42	0.33	0.16	0.07	0.03	0.02	-0.01	-0.02
DECC-1C	0.50	0.42	0.34	0.18	0.10	0.03	0.00	0.00	-0.02

Figure 45 represents the use of conservation measures in each of the runs. As with the reference study and study 1, the uptake is identical in all cases and almost identical to the corresponding reference cases. In all investigated runs conservation measures are adopted up to the limit allowed in the model.

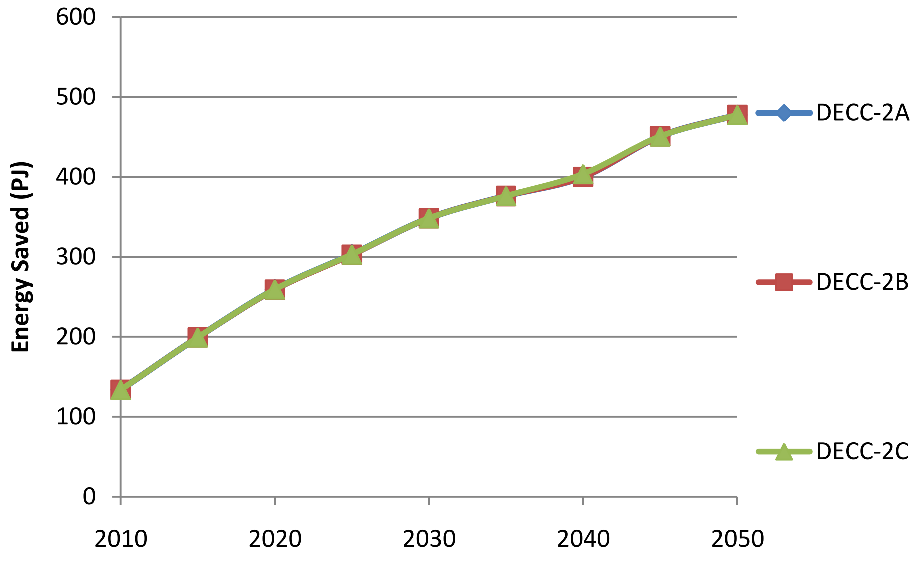


Figure 45: Use of Conservation Measures by Sector for Each Run

2.3.3 Primary and Final Energy Statistics

Primary energy consumption and final energy consumption are presented in Figure 46 and Figure 47, respectively. For Figure 46, the three different price scenarios result in very similar aggregate primary energy consumption. This is similar to the trend in the 90% reduction scenarios, although DECC-1A plotted here shows greater consumption beyond 2040. The central price 90% scenario DECC-1A results in a final energy demand of 8759 PJ, or 7% higher than the corresponding DECC-2A scenario. This suggests that less efficient (but lower carbon) conversion technology is employed in DECC-1A in order to meet the more stringent 90% emissions target.

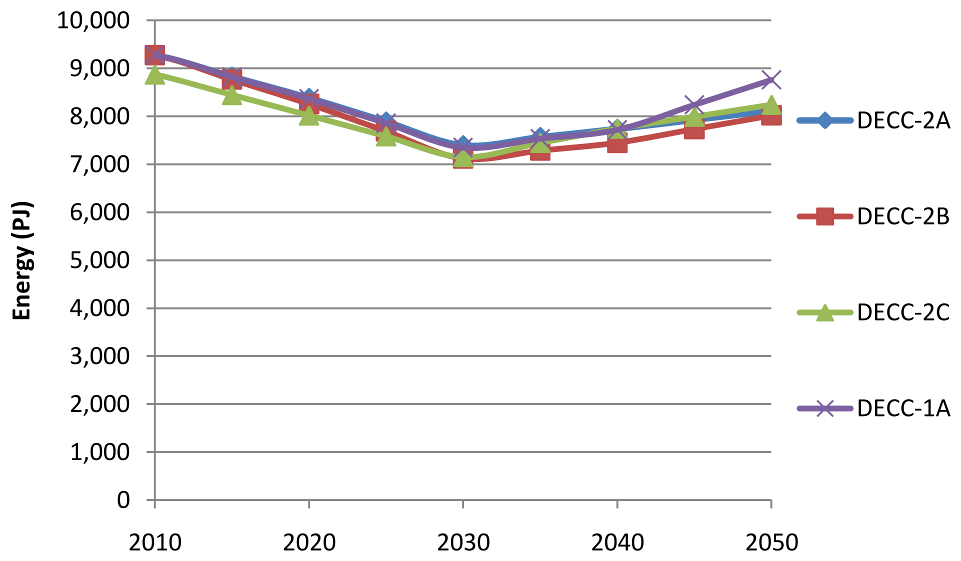


Figure 46: Primary Energy Demand over Time for Each Run

Final energy consumption also shows similar results between all the runs, across all the 85% CO_2 emissions reduction scenarios and the 90% CO_2 emissions reductions scenarios.

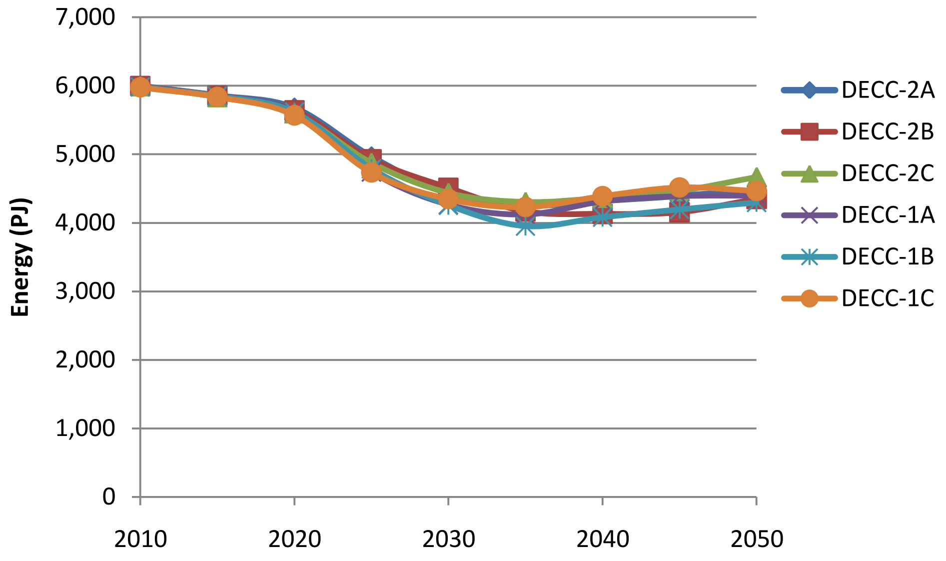


Figure 47: Final Energy Consumption over Time for Each Run

The results for primary and final energy consumption may also be compared in terms of the energy carriers. This is done for the central/central 85% CO_2 emissions reduction run (DECC-2A) versus the central/central 90% CO_2 emissions reduction run (DECC-1A) in Figure 48. The primary energy demand is higher in the 90% run at 8759 PJ, compared to 8116 PJ in the 85% run. Of this, fossil fuels account for 42% of the total energy and 45% respectively. Biomass plays the largest role in accounting for the reduction in reliance on fossil fuels between the runs.

The most significant difference in the final energy consumption profiles in Figure 48 is that of natural gas. The overall trend in final energy use is very similar as is the total consumption in 2050. In the 85% run, DECC-2A, gas accounts for 23% of total consumption. In DECC-1A, this is down to 15%, identifying natural gas as a marginal generation technology. This energy differential is balanced by an increase in electricity and biomass generation.

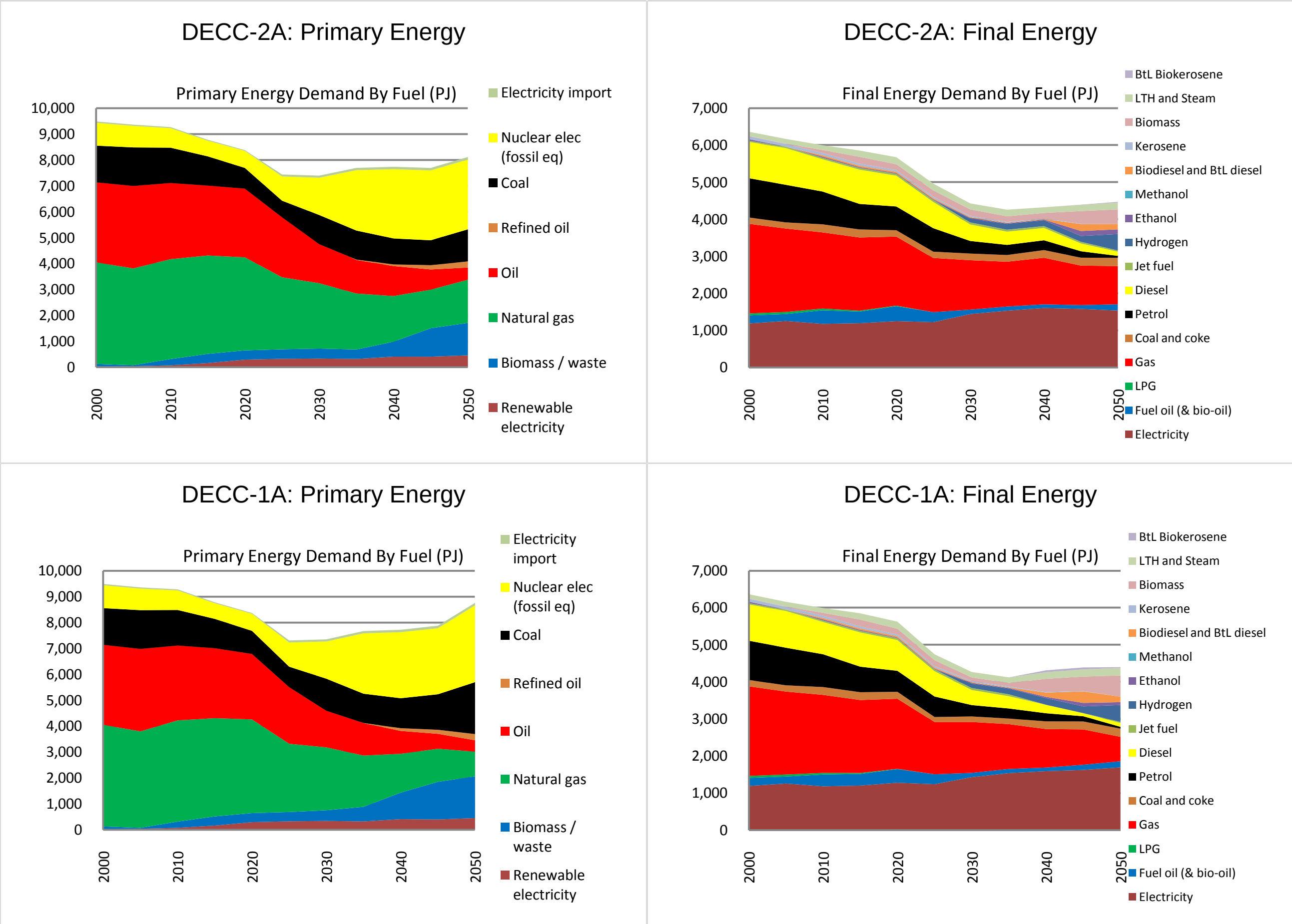


Figure 48: Energy Generation Mix and Final Energy demand for run DECC-2A and DECC-1A

2.3.4 Power Generation and Installed Capacity

There is little sensitivity to fossil fuel price fluctuations in electricity generation with all 3 of the study 2 scenarios closely following a similar trend. This can be seen in Figure 49.

The lower fuel prices of the DECC-2C run result in a higher capacity being installed than in the other runs of this study. This is shown in Figure 50. This difference is particularly evident beyond 2030. In the DECC-2C run, an earlier take up of marine renewables occurs in 2030, whilst in DECC-2A and DECC-2B, this does not happen until 2035. The marine uptake in DECC-2B is less significant, with the lower fossil fuel prices, which provides less of an incentive for the more expensive renewable options.

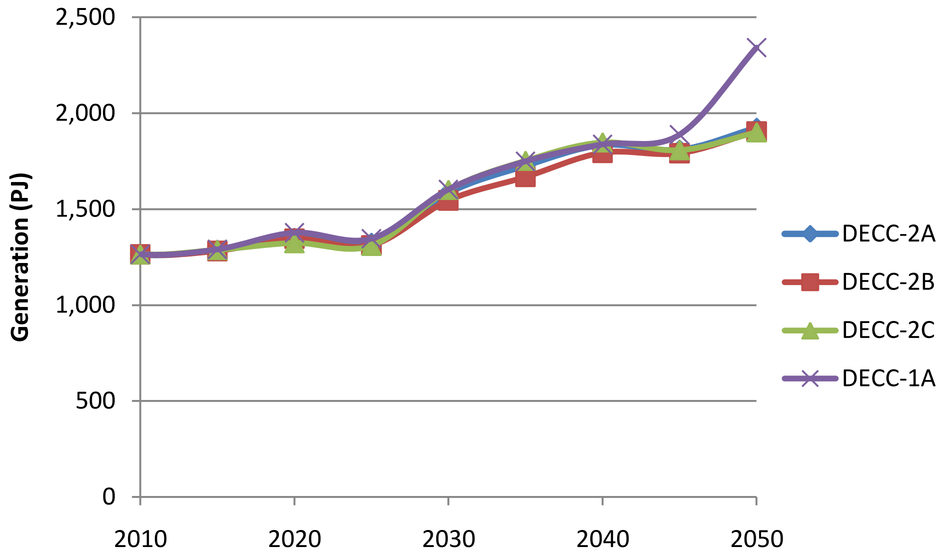


Figure 49: Aggregate Generation over Time for Each Run

The full fuel/technology mix for the central and high price stabilisation scenarios is shown in Figure 51. The central and lower price runs have a similar mix of technologies. However in the low priced run, natural gas fired generation with CCS is introduced in 2020, with 19.1GW installed by 2050, whereas this technology appears to a small degree in 2015 on the other 2 runs, but is phased out by 2040.

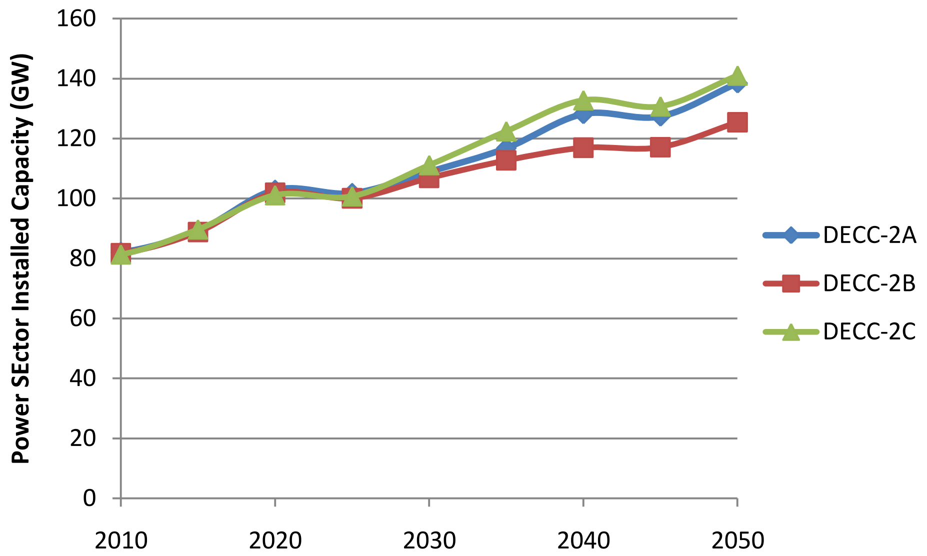


Figure 50: Aggregate Installed Capacity over Time for Each Run

Considering the different carbon reduction scenarios DECC- 2A and DECC-1A, there is a greater installed capacity in the 90% scenario of 157GW compared to 138GW. In both scenarios, unabated coal-fired power generation is phased out early in the 2020s. The increase in co-firing of biomass in carbon capture plants taking place in DECC-1A, is not apparent to such an extent in DECC-2A. By 2030, 11.4GW have been installed in DECC-2A and 14.1GW in DECC-1A. By 2050, this increases to 28.3GW in DECC-1A, but only rises to 16.4GW in DECC-2A, so the negative impact on electricity emissions intensity of biomass with CCS is not as prevalent.

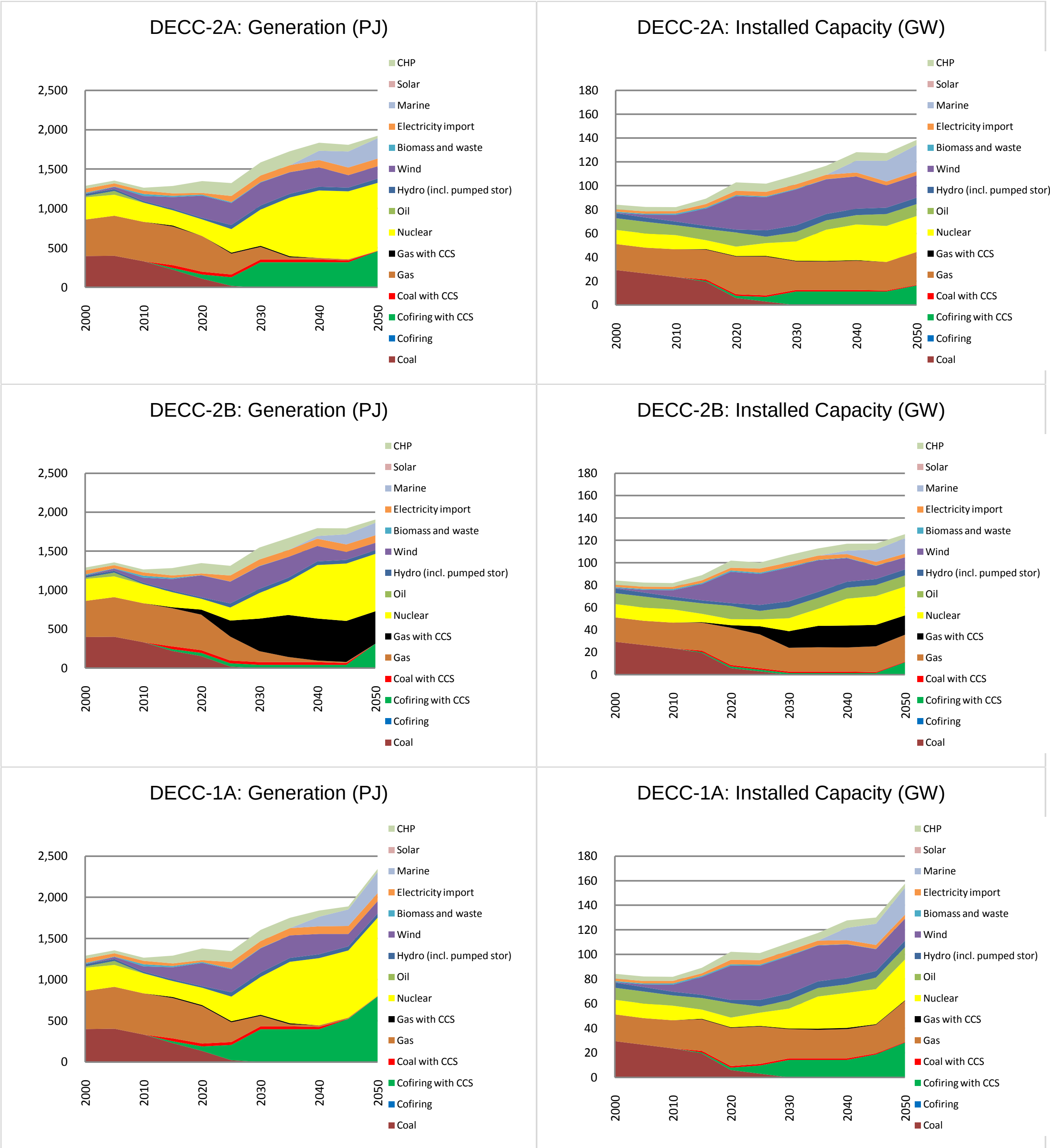


Figure 51: Generation over time by technology

2.3.5 End-Use Sectors

As is shown in Figure 52, aggregate reductions in final energy consumption follow a similar trend in both emissions reduction scenarios whereby reductions in emissions occurs mainly in the residential and transport sectors. Within the industry sector CO_2 emissions decline whilst energy consumption remains unchanged.

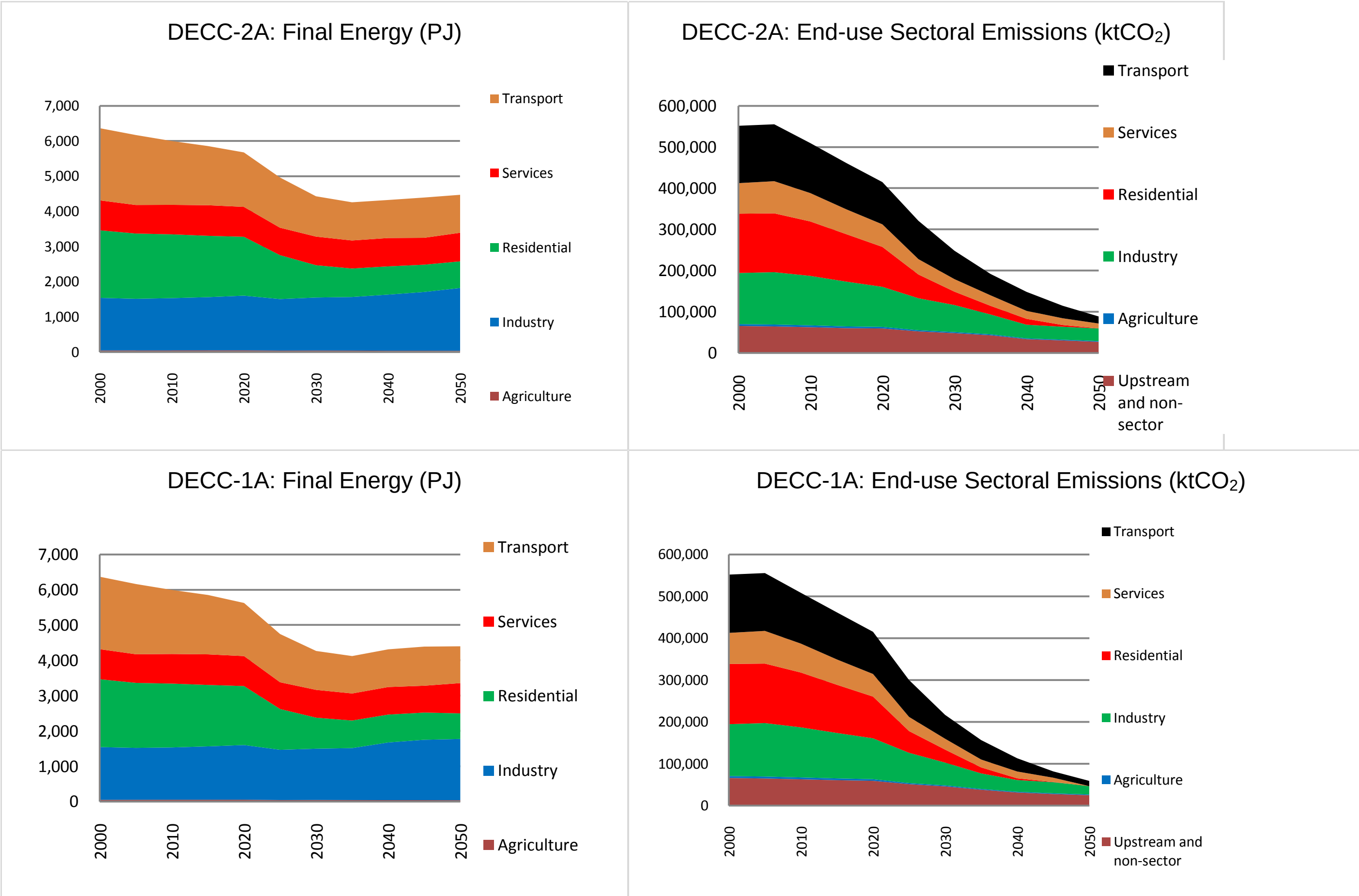
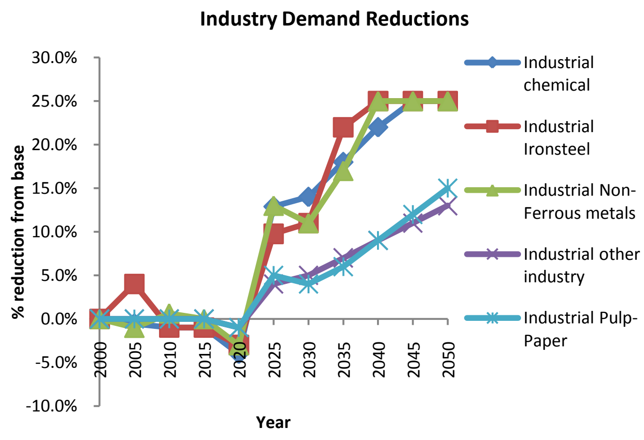


Figure 52: End-Use Sectoral Final Energy Consumption and Emissions Disaggregation for Run DECC-2A and DECC-1A

Industrial Sector

Figure 53 shows a comparison between the demand reductions from baseline within the industrial sector of the DECC-2A run in comparison to the DECC-1A run. Clearly the two runs are very similar in terms of demand response.

DECC-2A



DECC-1A

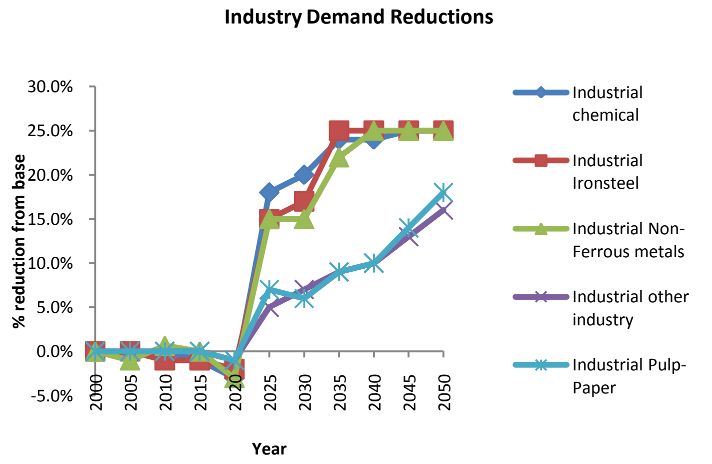


Figure 53: Industrial Energy Consumption for a Selected Run

A slightly smaller decrease in demand beyond 2020 is evident for the chemical, iron and steel sectors in the 85% emissions reduction scenario. However, by 2040, these sectors all exhibit the maximum allowable demand reduction of 25% from the central estimate of service demand, as is the case in the Study 1 90% emissions reduction runs.

Residential Sector

Also as per study 1, the residential sector demand reduction is dominated by reductions in water and space heating. This is a trend which is also evident in the 90% emissions reduction scenario. Table 8 shows the service demand from the residential sector in the 90% emissions reduction scenario subtracted from demand in the 85% scenario. When compared in this way, a decrease in demand in the residential sector is evident in the 90% emissions reduction scenario, relative to the 85% scenario.

Table 8: Residential Sector Difference in Demand between DECC-2A and DECC-1A

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Residential Sector (PJ)	5.1	3.8	2.9	92.9	40.9	28.4	13.1	4.7	31.9

The final energy demand by fuel in the two different study runs is shown in Figure 54. The total energy demand in both runs is similar. In 2020, the difference is 2.9 PJ rising to 92.9 PJ in 2025, but falling to 31.9 PJ in 2050. In the 90% reduction scenario, demand for natural gas falls off in 2025, and is replaced by electric heating (predominantly heat pumps) and biomass pellets. The same trend occurs in the 85% reduction scenario, but in that case wood and gas have a slightly bigger part to play in the path to 2040 before being replaced by pellets and electricity.

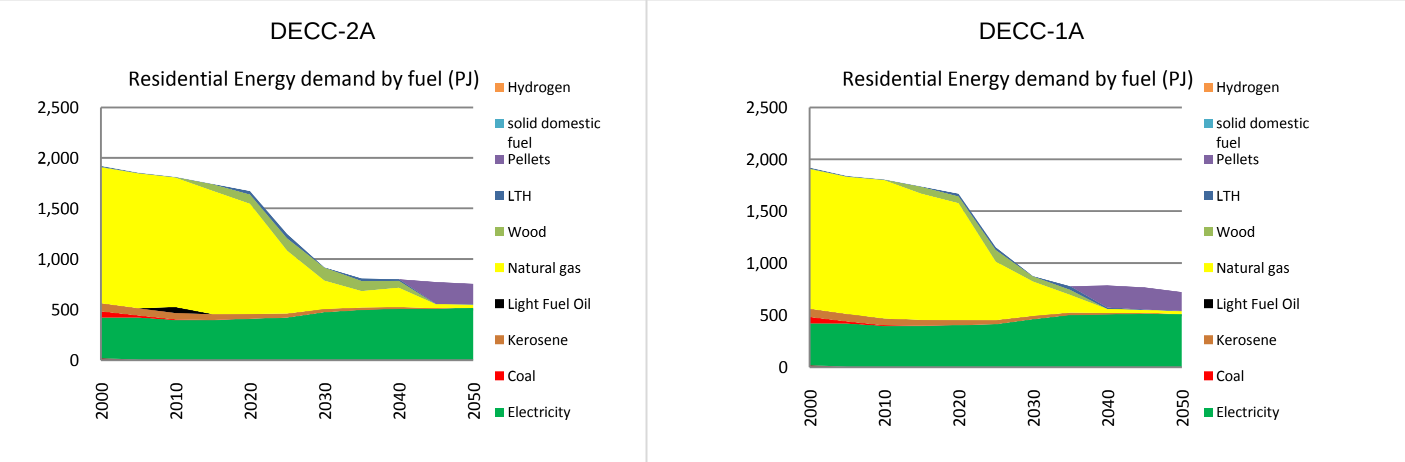


Figure 54: Comparison of Final Energy Demand by Fuel in the Residential Sector for studies DECC-2A and DECC-1A

Services Sector

Table 9 shows a smaller decrease in demand between the different emissions reduction scenarios than was evident in Table 8. However, by 2050 demand in the service sector in the 90% scenario is larger than in the 85% scenario.

Table 9: Services Sector Difference in Demand between DECC-2A and DECC-1A

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Services Sector (PJ)	-1.1	3.3	1.8	23.2	25.2	30.8	25.8	3.5	-44.5

Whereas in DECC-1A there is a drop in natural gas demand in the service sector, which is replaced by biomass pellets, this does not occur in the 85% reduction scenario. This is similar to the response seen in the residential sector; the less stringent emissions reduction target results in a delay in the uptake of pellets. Figure 55 shows the similarities between the model runs in both energy demand by fuel and heating by fuel, until 2040 and the uptake of biomass pellets, used for heating.

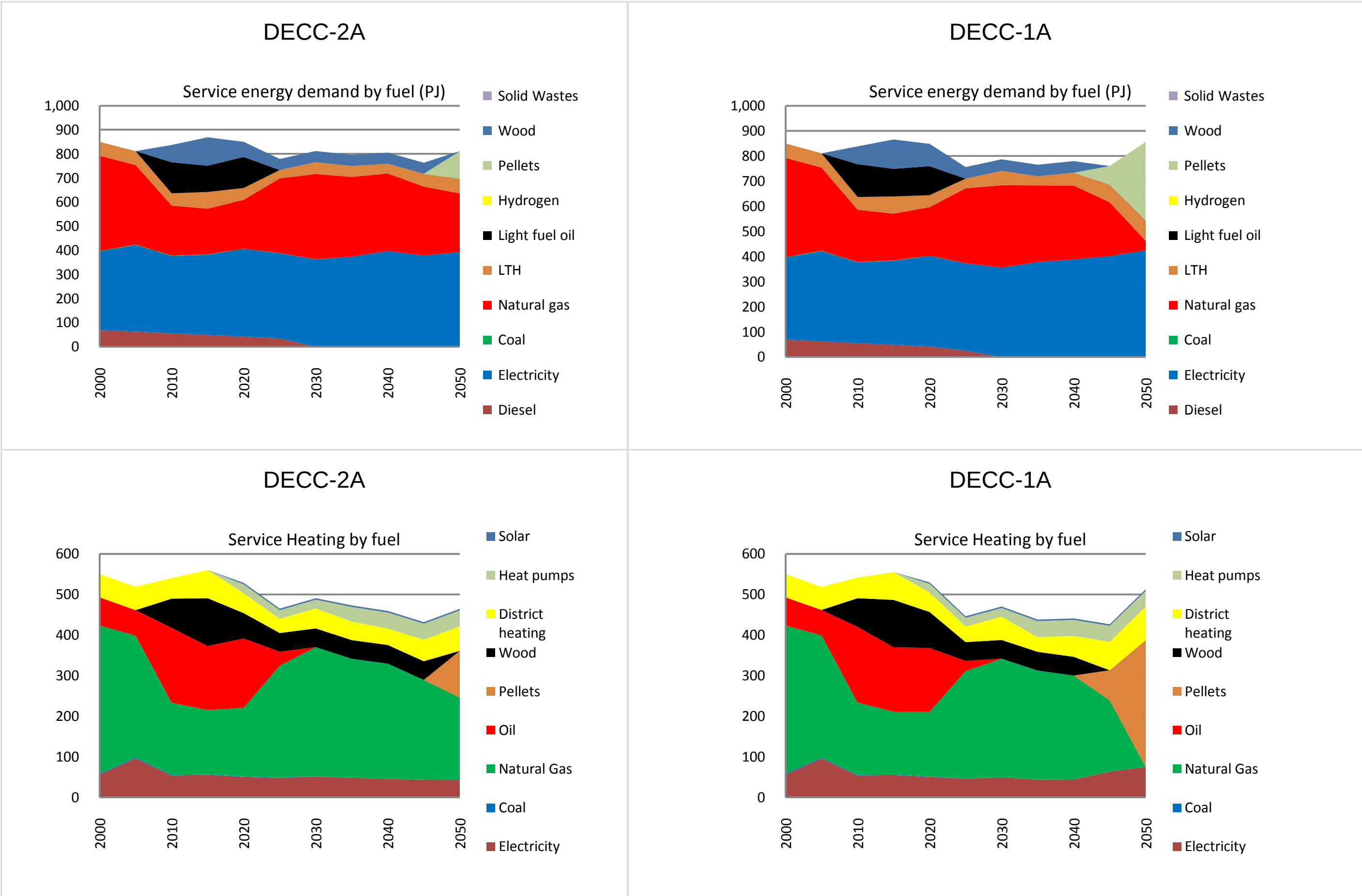


Figure 55: Service Sector Demand Reduction Comparison between DECC-2A and DECC-1A

Transport Sector

As shown in Figure 52 transport final energy consumption and CO_2 emissions reduce greatly to 2050. Figure 56 shows how this reduction is achieved. The most significant reduction coming from the domestic shipping sector, with domestic air and HGV transport this accounts for 39% of the total demand reduction.

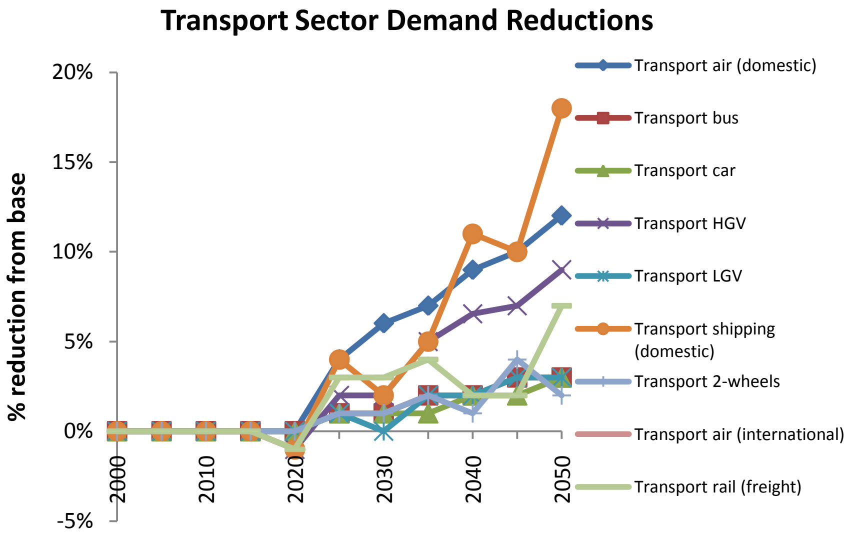


Figure 56: Transport Service Demand Reduction for Run DECC-2A

Table 10 shows the difference in demand between DECC-2A and DECC-1A for the residential sector, that is the demand from the residential sector in the 90% emissions reduction scenario subtracted from demand in the 85% scenario. A decrease in demand from the residential sector is evident in the 90% emissions reduction scenario.

Table 10: Transport Sector Difference in Demand between DECC-2A and DECC-1A

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Transport Sector (PJ)	0.5	0.5	43.7	62.4	44.0	25.6	13.0	37.5	36.7

Figure 57 presents the fuel demand for transport. Biomass to liquid diesel becomes more widely used at an earlier stage (2035) in the DECC-1A study, and its replacement of diesel is more rapid than in DECC-2A.

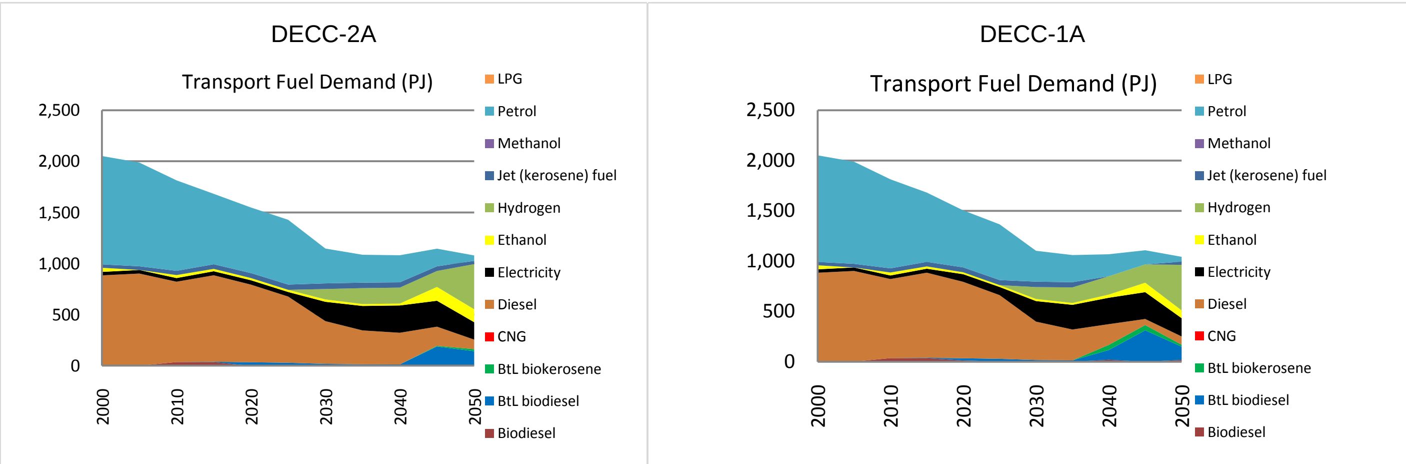


Figure 57: Transport Final Energy Consumption for Runs DECC-2A and DECC-1A

Across both the study runs, it is apparent that there is a greater variety of technologies in use in 2050, as shown in Figure 57. The total vehicle kilometres is similar across both scenarios (635.5 billion vehicle kilometres in DECC-1A, 642.1 b.v.kilometres in DECC-2A). In the 85% scenario the final mix of hybrid-flex ethanol accounts for 17% of travel kilometres, whereas in the 90% scenario it is only 10%. The stricter emissions limit does encourage an earlier uptake of new technologies, with the battery electric vehicles being introduced in 2020 in the DECC-1A scenario, but not until 2030 in DECC-2A. Hydrogen take up is also a decade earlier in 2040 the DECC-1A scenario, whereas not until 2050 in DECC-2A.

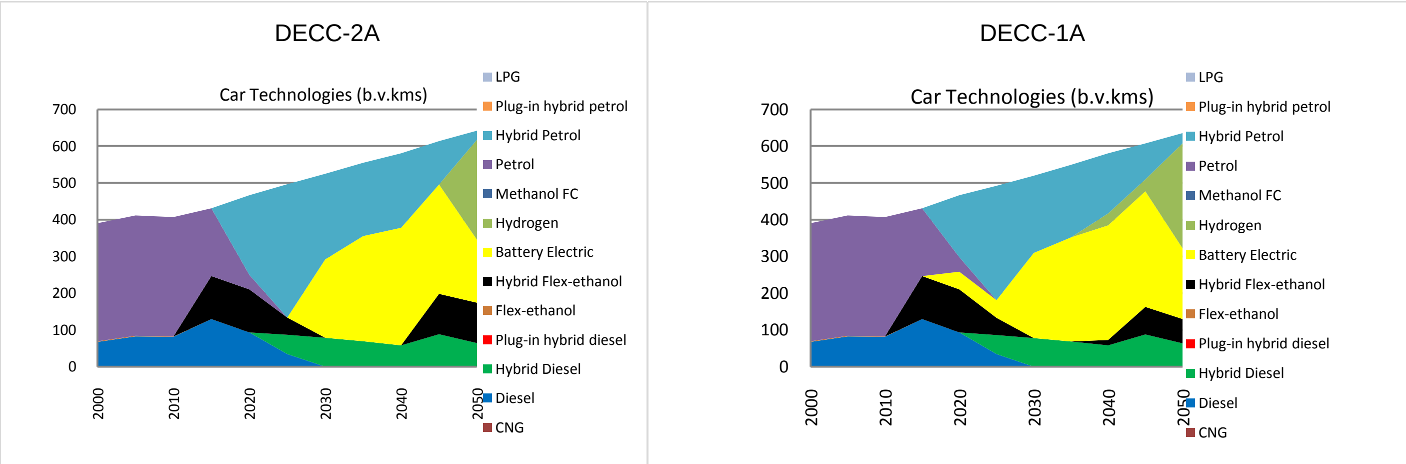


Figure 58: Car Technology Choices for Runs DECC-2A and DECC-1A

2.4 Study 3: Cumulative CO_2 Constraints

2.4.1 Description of Study

This study explores the pathways to cumulative CO_2 emissions reduction targets in the energy system by 2050. It is designed to explore the timing of abatement, where the model is allowed to choose when to abate to minimise the impact on welfare. The result of this freedom is that MARKAL chooses to smooth the marginal cost of abatement over the 2020 to 2050 timeframe. As such the discount rate applied in these runs is particularly important; in this case investments are subject to sector-specific discount rates, and then derived cash flows are discounted at the green book rate of 3.5%. Two different cumulative emissions targets are considered: 85% and 90%. There is no annual upper bound for emissions post 2020, but the total emissions over the whole period are less than the sum of emissions obtained under the annual target. In both cases, central level of energy service demand and central fossil fuel prices are considered. The two studies are arranged as follows:

1. Study 3 Run A – Central Service Demand and Central Fossil Fuel Prices. 90% cumulative reduction in emissions by 2050.
   Code **DECC-3A**
2. Study 3 Run B – Central Service Demand and Central Fossil Fuel Prices. 85% cumulative reduction in emissions by 2050.
   Code **DECC-3B**

The pathways for emissions reduction in the two runs are bound by the baseline bounds to 2020. In the later periods, there is no annual upper bound on emissions. Instead there is a single cumulative emissions target for each run as shown in Table 11. These targets are equal to the cumulative emissions in runs 1A and 2A, respectively.

Table 11: Target emissions for 85% and 90% cumulative emission targets

Run	Emissions Target ($MtCO_2$)
DECC-3A	17,115
DECC-3B	18,055

Figure 59 shows the resulting annual emissions for each of the runs. As seen from Figure 59, the cumulative targets are achieved by the model through choosing to abate earlier, but these are not significantly different to the concave equal annual percentage reduction trajectory imposed for other studies.

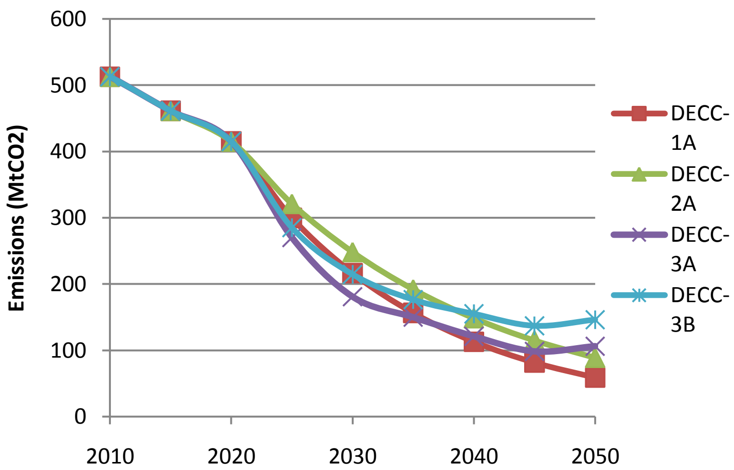


Figure 59: Emissions Reduction in the two Study 3 runs compared with runs DECC-1A and DECC-2A, representing 90% and 85% non-cumulative emission targets.

The baseline scenario for the two Study 3 runs is DECC-0A which corresponds to central demand/central fossil fuel prices. In this study comparisons are also made with the runs DECC-1A and DECC-2A corresponding to the 90% and 85% emission targets, where in those cases emissions are constrained to follow a particular upper bound to the final reduction. All these runs have the same service demand levels and fossil fuel prices.

2.4.2 Key Results

The total discounted system cost, and discounted consumer/producer surplus for these runs are presented in Table 12. Runs from studies 1 and 2 (DECC-1A and DECC-2A) are included for comparison. For the emission reduction target of 90% (studies DECC-3A and DECC-1A), the energy system costs are lower by £7 billion when the targets are cumulative (DECC-3A). Likewise, system cost is £18 billion lower for study DECC-3B than for study DECC-2A with cumulative emissions target. These changes are typical of cumulative targets, where the model is able to find cheaper technical abatement pathways when it is less constrained regarding the timing of abatement.

The price of moving from 85% to 90% target is similar whether the emission targets are cumulative or not: the difference in total discounted technical energy system costs in runs 3A and 3B is £34 billion compared to £23 billion difference between runs 1A and 2A.

Table 12: Key Result Metrics

	Study 3 Run A DECC-3A	Study 1 Run A DECC-1A	Study 3 Run B DECC-3B	Study 2 Run A DECC-2A
Baseline Run	DECC-0A	DECC-0A	DECC-0A	DECC-0A
Baseline Discounted System Cost (2010 £UK Billions)	5,940	5,940	5,940	5,940
Discounted Technical Energy System Cost (2010 £UK Billions)	6,007	6,014	5,973	5,991
Discounted Consumer/Producer Surplus (2010 £UK Billions)	-294	-293	-223	-213
Discounted Welfare Impact of Demand Reduction (2010 £UK Billions)	236	227	198	170

The figures for the welfare impact of demand reduction[3] show that change in social welfare due to greenhouse gas abatement is driven largely by changes in the quantity of energy services demanded. This means that consumers will demand less energy services as their prices increase, which has a subsequent impact on economic welfare. For example, as shown in Table 12, the total discounted impact on welfare is £236 billion for run 3A; this accounts for 80% of the total loss of welfare associated with the CO_2 target. Figure 60 shows yearly changes in area under demand curve (positive number meaning demand reduction, which implies a negative consumer welfare impact) for scenarios 3A and 3B. Note that for run 3A this reduction is more severe than for run 3B in the 2020s driven by the more stringent long term cumulative CO_2 target.

[3] A metric commonly used to measure consumer welfare is the "consumer surplus". The "welfare impact of demand reduction" presented here is a measure of how this consumer surplus changes as the price of energy (and thus the quantity of energy demanded) changes under greenhouse gas abatement. When the price of services increases (e.g. due to the cost of abatement), consumers often demand less of those services. This in turn reduces the amount of consumer surplus, and therefore reduces consumer welfare. Readers should refer to basic microeconomic theory for more information.

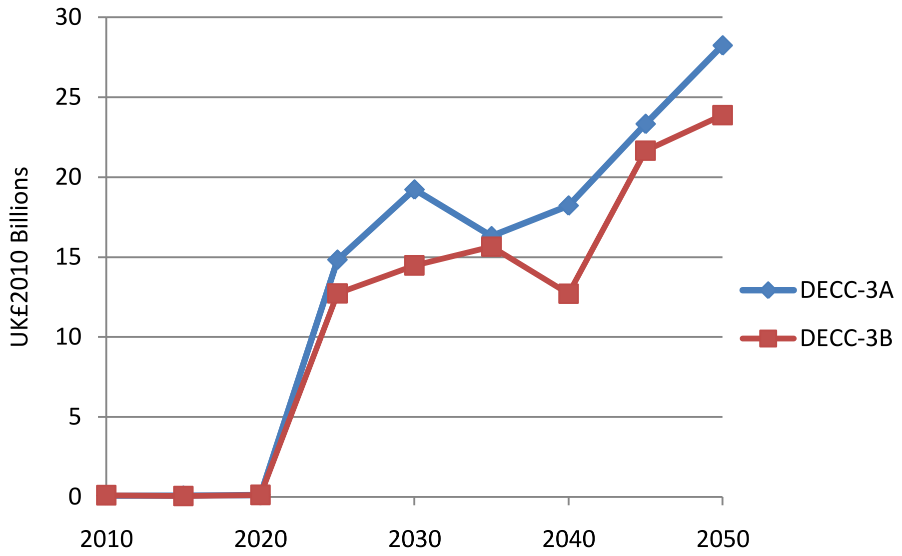
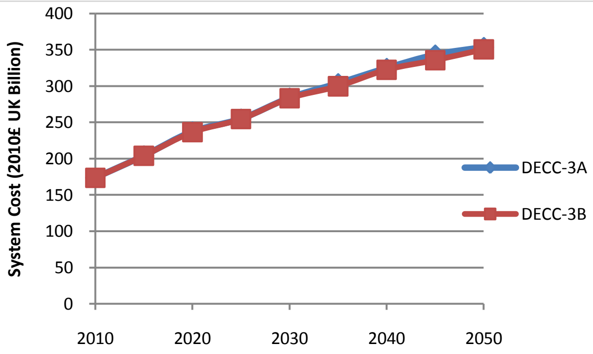


Figure 60: Undiscounted impact on consumer welfare of demand reduction for runs DECC-3A and DECC-3B. See footnote 3 for a description of this metric.

The undiscounted system costs are displayed in Figure 61, charting the annual costs of the energy system over time. The costs are similar for the runs, becoming slightly higher for scenario DECC-3A than in DECC-3B in the later periods (£353 and £351 Billion respectively). These figures are slightly lower than the costs under scenario DECC-1A and DECC-2A with equal annual emission reduction targets.



Scenario	Undiscounted peak system cost (2010£ UK billion)
DECC-1A	361
DECC-2A	358
DECC-3A	353
DECC-3B	351

Figure 61: Undiscounted System Cost for Each Run

The two runs in this study follow similar emissions reductions trajectories that suggest that it is preferable to abate in the earlier periods. The corresponding marginal price of CO_2 for each run is plotted in Figure 62. The marginal price of CO_2 increases steadily over the time horizon, however it does so relatively linearly and to a much lesser extent than in the scenarios with equal annual reduction targets. Demand and fuel prices being the same, for the emissions reduction target of 85%, the maximum marginal carbon price of £232/tCO_2 is reached in 2050 for the cumulative scenario compared to £397/tCO_2 for DECC-2A scenario with equal annual reduction targets. The difference is even more significant for the 90% CO_2 emission reduction target: £308/tCO_2 and £629/tCO_2 for the scenario with cumulative targets (DECC-3A) and the one with equal annual targets (DECC-1A), respectively.

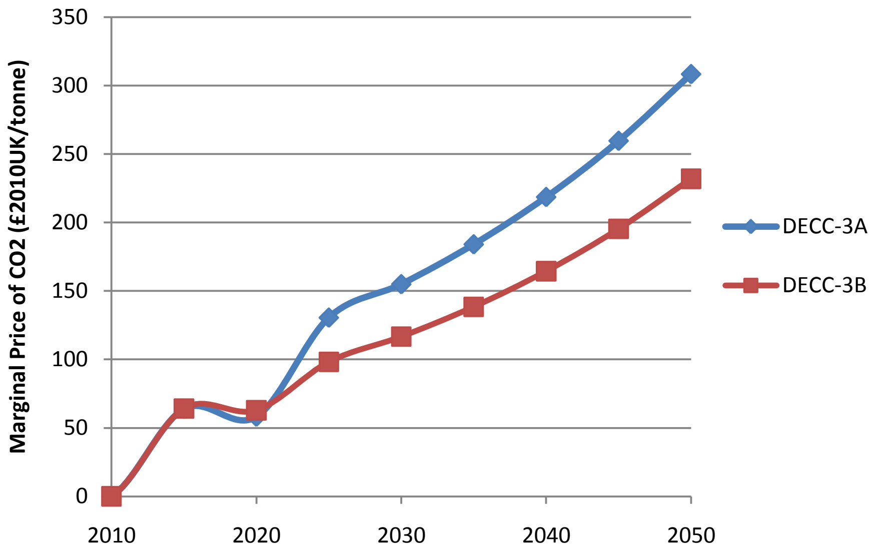


Figure 62: Marginal Cost of CO_2 for Each Run

In study 3 runs, the difference between marginal CO_2 price in scenarios with 85% and 90% targets increases slowly towards the end of the time horizon, compared with larger increase of this difference in the later periods for comparable Study 1 and Study 2 runs.

Figure 63 shows the carbon intensity of electricity in the two study 3 runs as well as scenarios 1A and 2A for comparison. It illustrates the sharper initial drop in carbon intensity in the 2020s that is particularly noticeable for the 3A run. This pattern is similar to the overall emissions trajectory pattern seen in Figure 59. So, when given the choice of decarbonisation pathway, even more radical decarbonisation of electricity is observed in the 2020s than the reference scenarios.

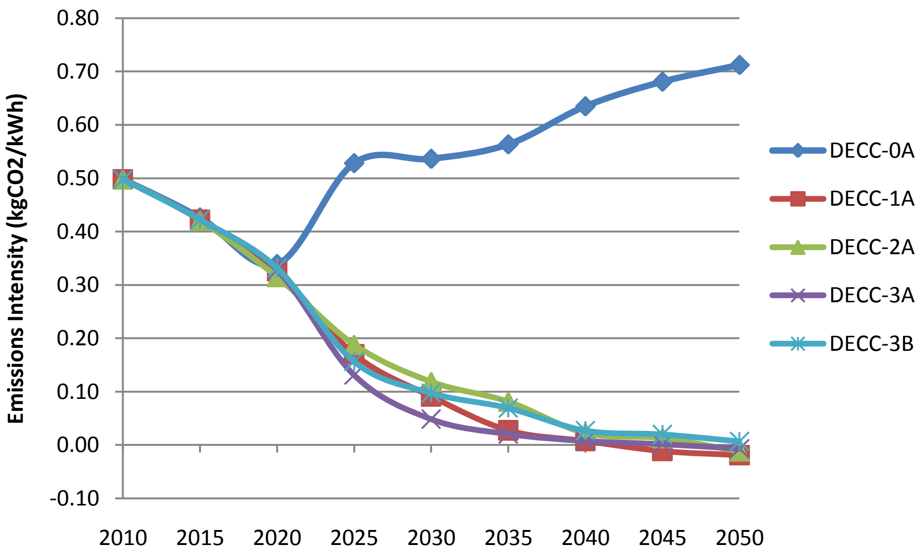


Figure 63: The Emissions Intensity of Grid Electricity

The numerical figures associated with the figure above are shown in

Table 13. Another difference between scenarios with cumulative versus equal annual emission reduction targets can be spotted from these numbers: The decarbonisation rate slows down in the later periods for the two runs in study 3. Therefore while electricity production becomes a sink for CO_2 in 2045 for scenario 1A it does so only in 2050 for scenario 3A (negative numbers in

Table 13). Similarly the emissions intensity falls below zero in 2050 for scenario 2A (85% emission reduction target) while it does not happen at all in the time horizon for scenario 3B.

Table 13: Figures for the Emissions Intensity of Grid Electricity (kgCO$_2$/kWh)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
DECC-0A	0.50	0.43	0.34	0.53	0.54	0.56	0.63	0.68	0.71
DECC-1A	0.50	0.42	0.33	0.17	0.09	0.03	0.01	-0.01	-0.02
DECC-2A	0.50	0.42	0.31	0.19	0.12	0.08	0.02	0.01	-0.01
DECC-3A	0.50	0.42	0.33	0.13	0.05	0.02	0.01	0.00	-0.01
DECC-3B	0.50	0.42	0.33	0.16	0.10	0.07	0.03	0.02	0.01

2.4.3 Primary and Final Energy Statistics

Primary energy and final energy consumption are presented in Figure 64 and Figure 65. The primary energy demand patterns for the two study 3 runs are quite similar for the length of the time horizon. In comparison with runs 1A and 2A, the study 3 runs with cumulative emission reduction targets show lower demand levels over most of the time horizon.

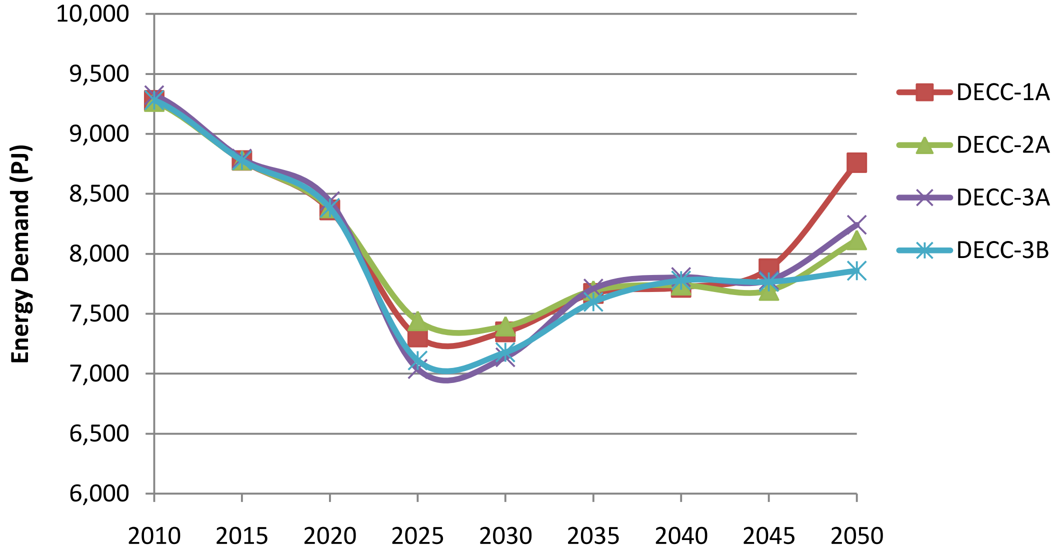


Figure 64: Primary Energy Demand over Time

For final energy consumption levels, the run corresponding to 85% emission reduction targets (DECC-3B) shows higher levels of demand in 2020s which even out in later time periods.

The drop in final energy use levels is less sharp for the runs 1A and 2A with equal annual emission reduction targets, but by the end of the time horizon it stabilises around similar levels, slightly higher for Study 3 runs.

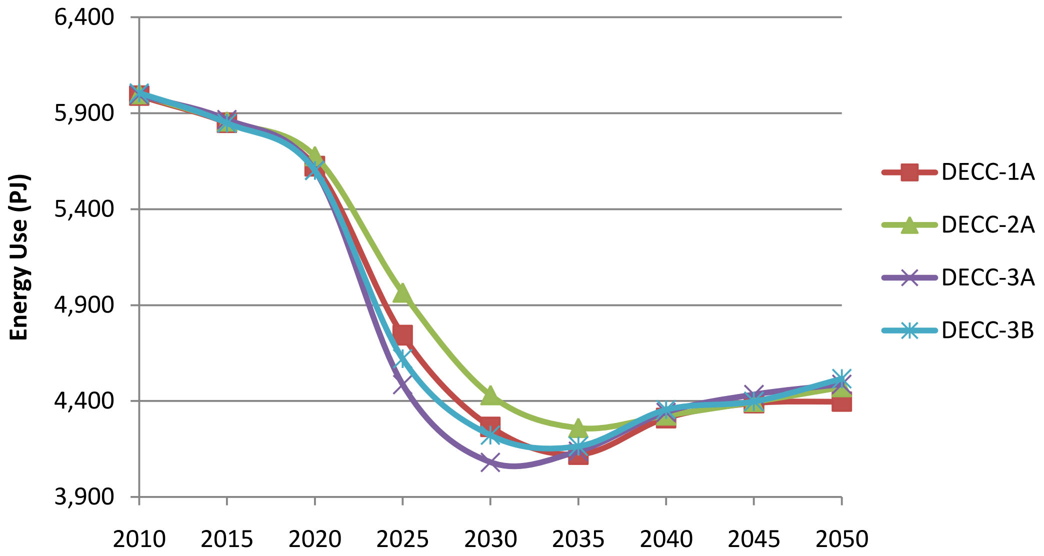


Figure 65: Final Energy Consumption over Time

The primary and final energy consumption can be compared in terms of energy carriers. Figure 66 shows results for run DECC-3A with cumulative emission reduction target of 90% versus run DECC-1A with the equal annual emission reductions of the same level.

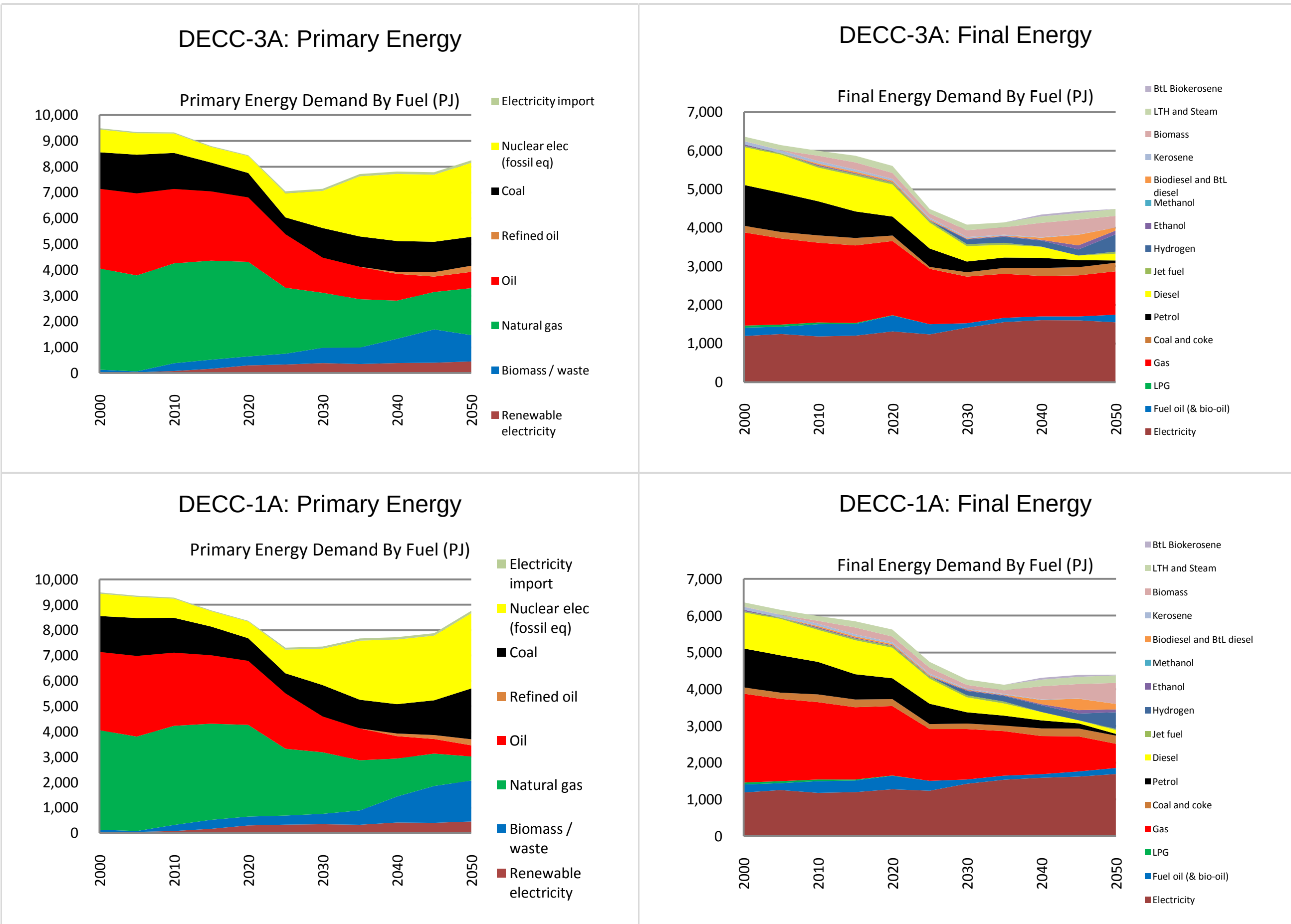


Figure 66: Primary and Final Energy Demand by Energy Carrier

For primary energy consumption in the 2050 the most significant difference is the use of natural gas, coal and biomass. The use of oil and gas is 30% in run DECC-3A compared to 16% in run DECC-1A. This difference can be accounted by the increased use of biomass and coal. Coal usage is 14% for run 3A compared to 23% for run 1A and biomass is 12% in run 3A versus 18% in run 1A. This result is similar for run 3B that has 85% cumulative emissions reduction target if compared with 2A, but the use of oil and gas is even higher in run 3B at 35% while biomass use is only 9%.

Final energy consumption shows similar trends. For the year 2050, the main difference is in the use of gas which is 25% for run 3A and only 15% for run 1A. This is compensated in scenario 1A by increased use of biomass, biodiesel and electricity generation (Figure 67).

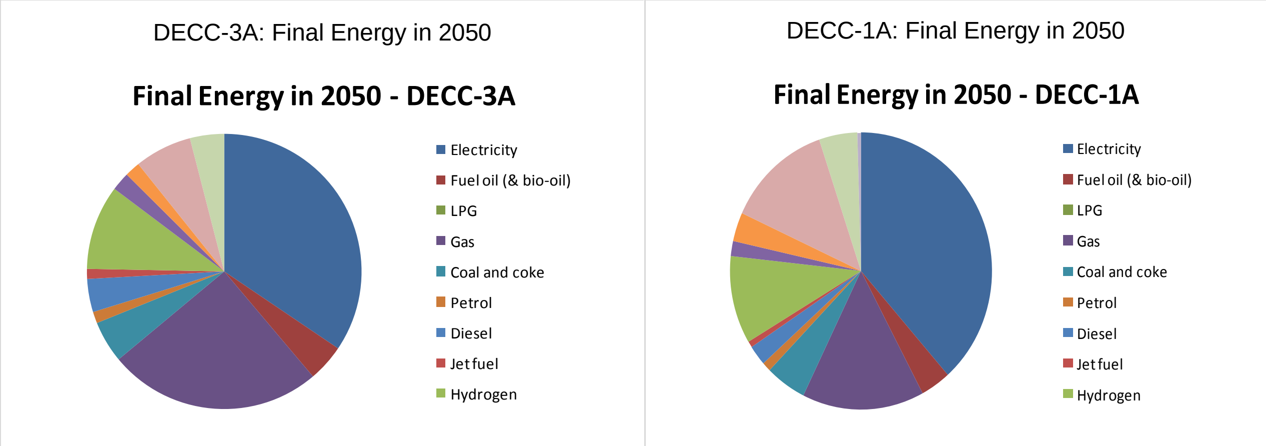


Figure 67: Final energy use by energy carrier in 2050

Bio-product use is an important abatement measure compared to the base scenario, but for study 3 runs it shows small increase peaking in 2045 before dropping again in the last period of the time horizon (Figure 68). Overall consuimption of biomass in 3B is much lower than in 3A.

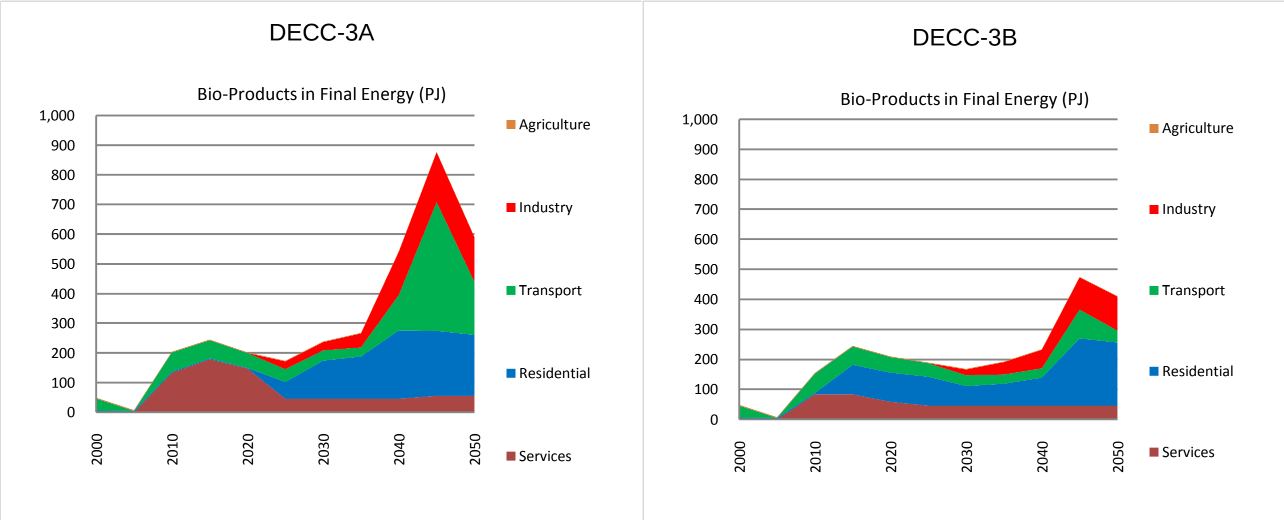


Figure 68: Bio-Products in Final Energy Consumption

Overall, it seems that by decarbonising earlier, the system does not have to achieve as low emission levels in any one period as those occurring at the end of the time horizon with equal annual emission reduction targets. This allows more flexibility in choosing less expensive energy carriers later in the time horizon which reduces the energy system costs.

2.4.4 Power Generation and Installed Capacity

Power generation capacity follows similar trends for the two runs in this study as well as the two comparison runs from previous studies that all have the same demand levels and fuel prices. This is shown in Figure 69 and Figure 70.

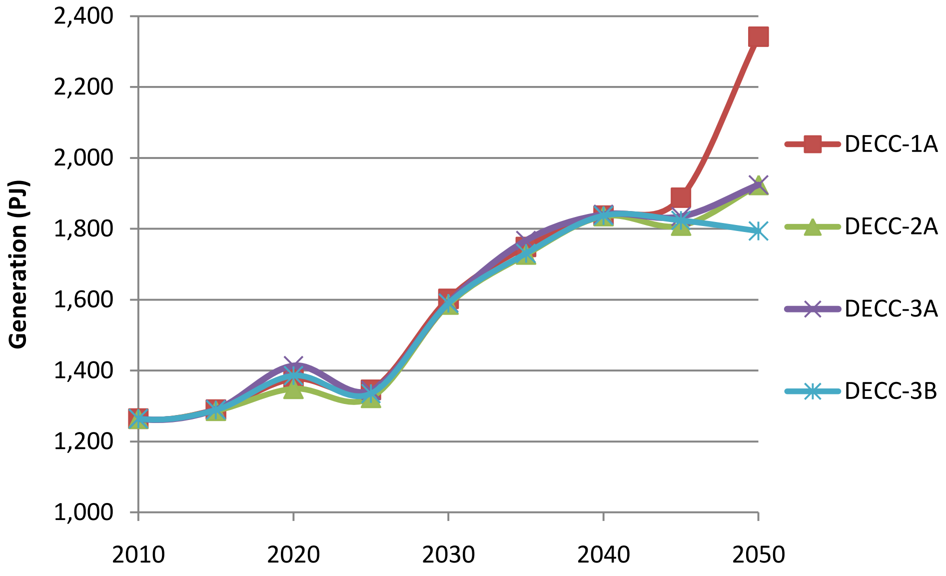


Figure 69: Aggregate Generation over Time for Each Run

Similarly, the patterns are alike for the installed capacity, with a separation at the very last period of the time horizon, where the capacity for run 1A increases to 158GW, making it 15% higher than the analogical cumulative targets run 3A.

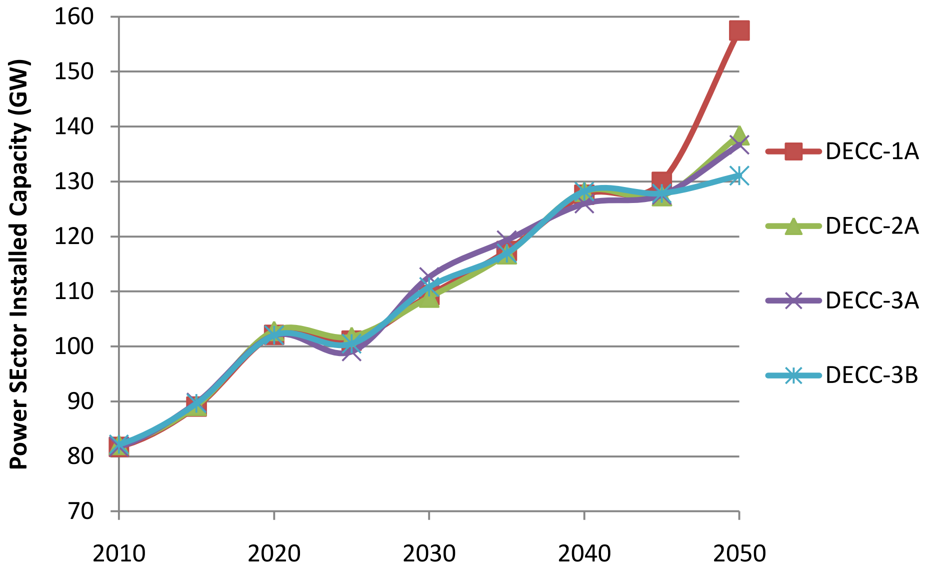


Figure 70: Aggregate Installed Capacity over Time for Each Run

Figure 71 shows the fuel/technology mix of these generation and capacity profiles for the runs with 90% emission reduction targets: cumulative (3A) and equal annual targets (1A). As in run DECC-1A, in run DECC-3A coal-fired power generation is phased out in the 2020s followed by the reduced use of gas-fired capacity. This gap is filled by increasing nuclear and wind power together with abated co-firing power plants. In addition to similar power capacity of these technologies installed between 2020 and 2030, marine technology is introduced and more wind power capacity installed. In this period almost 30GW new power generation capacity is installed, most of it renewable. Compared to scenario 1A also the phasing out of gas is more rapid in this period which explains subsequently lower emissions.

In later periods while for scenario DECC-1A the installed capacity continues to increase sharply, adding more renewable energy capacity, scenario DECC-3A capacity grows more slowly and less renewable capacity is installed in those periods.

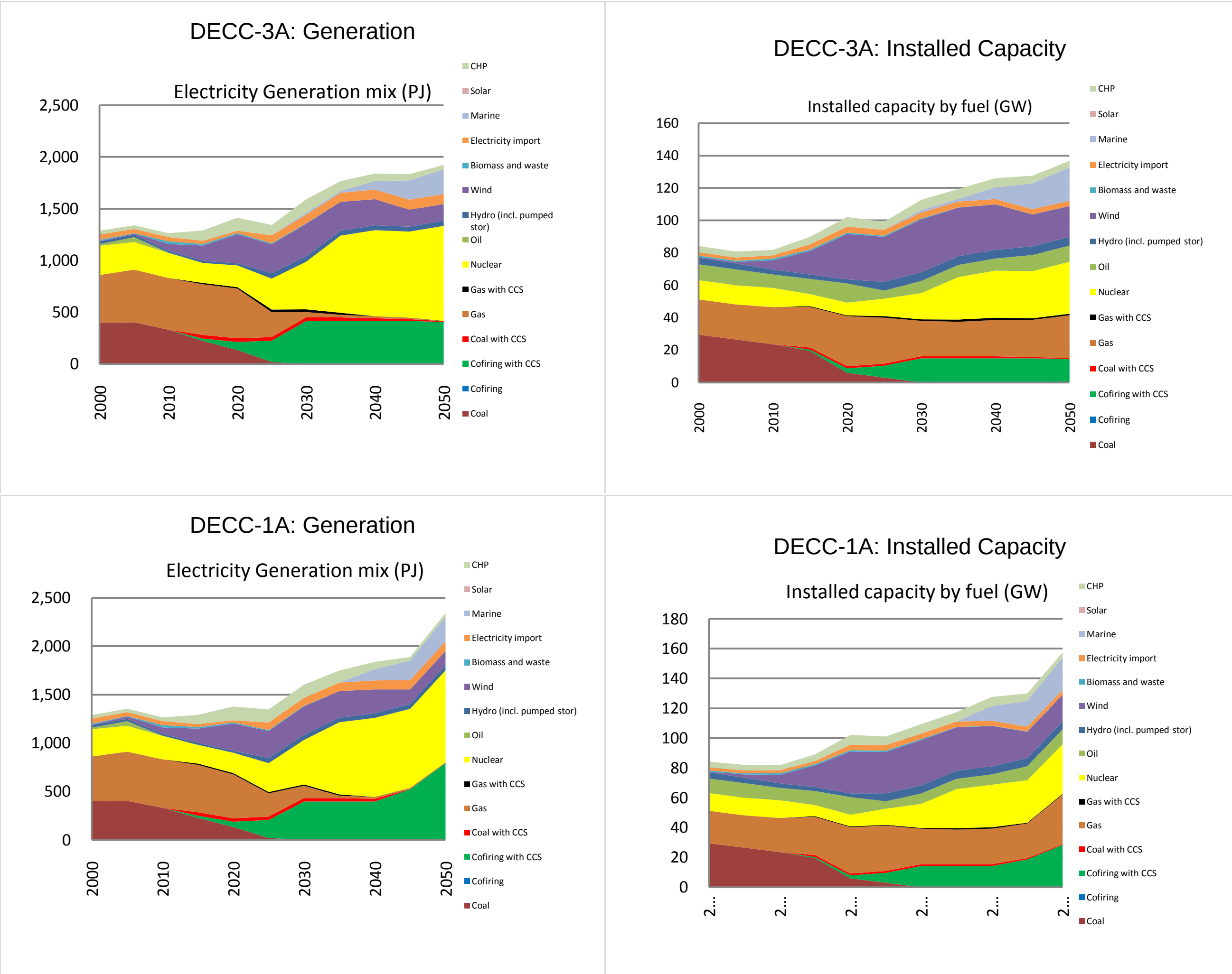


Figure 71: Generation over Time by Technology for DECC-3A/DECC-1A Runs

Similarly to DECC-1A scenario, for DECC-3A run, the installed gas-fired generation is used to meet peak demands and contributed little to actual electricity generation by 2050.

In terms of resulting power generation, in 2050 renewable energy technologies generate 23% of all electricity, 22% comes from CCS technologies and 48% from nuclear power. In the comparison run 1A, CCS technologies generate 34% of electricity.

The results are similar for run DECC-3B, but the proportion of electricity generated by renewable technologies is even higher as shown in Table 14.

Table 14: Generation by technology groups for study 3 runs and comparison runs

	DECC-3A	DECC-1A	DECC-3B	DECC-2A
Renewable technologies	23.4%	19.5%	25.8%	24.4%
Nuclear	47.7%	40.5%	48.2%	44.8%
CCS technologies	21.7%	33.9%	17.1%	24.1%

2.4.5 End-Use Sectors

Figure 72 shows the final energy demand and CO_2 emissions by sector for study 3 runs. For the whole of the time horizon the total energy demand figures are very similar between the two runs with 85% and 90% cumulative emission reduction targets and so is the distribution among sectors. The demand remains almost unchanged in service sector and even increases for industry, but falls for residential and transport sectors.

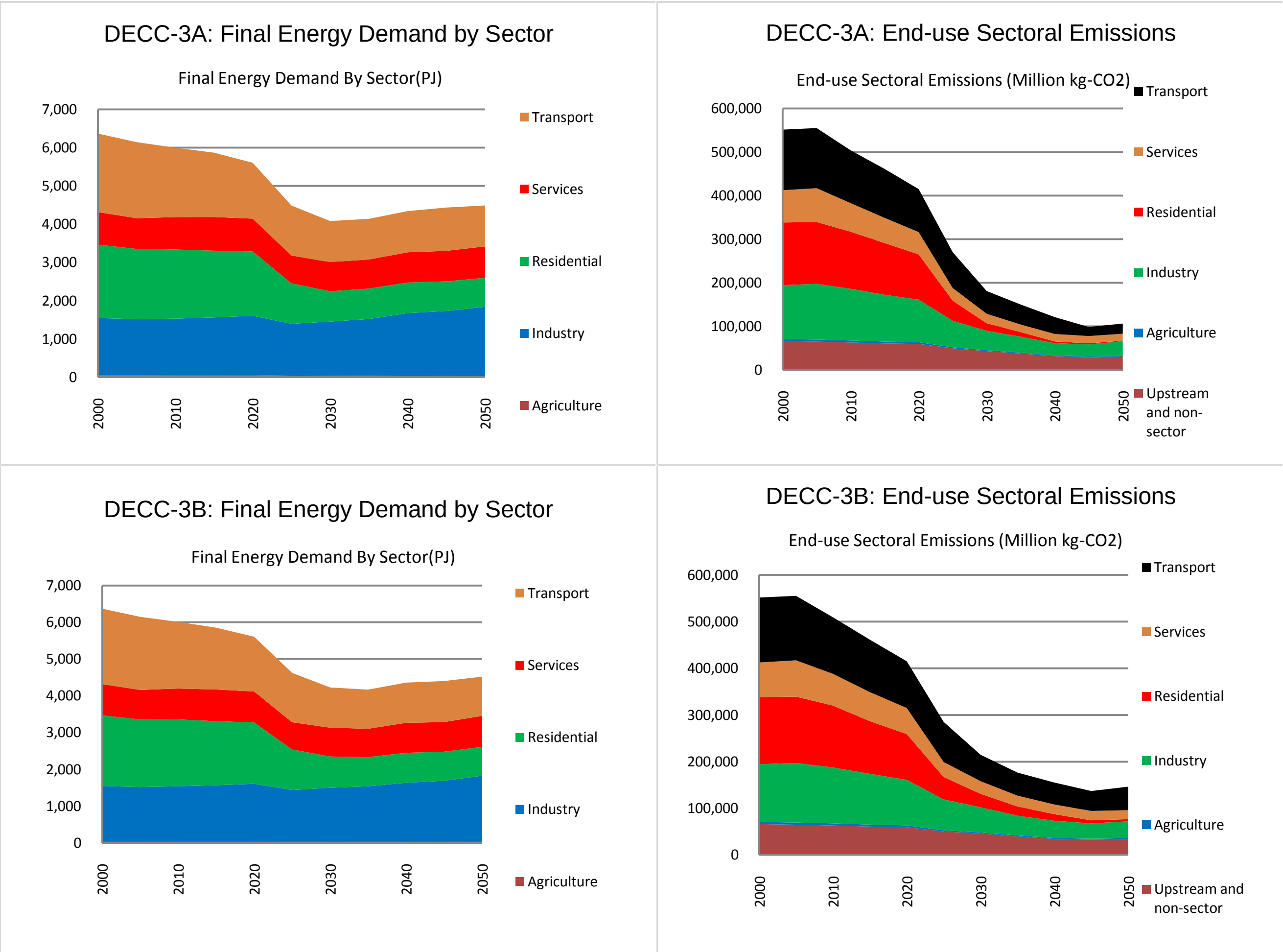


Figure 72: End-Use Sectoral Final Energy Consumption and Emissions Disaggregation for Runs DECC-3A and DECC-3B

For run 3A with 90% emission reduction target the decrease in demand is less than 1%. However, emissions are significantly smaller for run 3A in the later periods and is reduced across all sectors. This change is more significant for transport and residential sectors, but is also apparent for services and industry where the demand is unchanged or increasing.

The following sections consider each end-use sector in more detail, focusing on comparison of run DECC-3A with DECC-1A and in some cases discuss scenario DECC-3B comparison with DECC-2A. Note that for most issues addressed here the patterns and differences will be similar between scenario 1A and 3A to those between 2A and 3B.

Industrial Sector

Industrial sector demand reductions are shown in Figure 73. The demand reduction in the chemical industry, iron and steel and non-ferrous metals sectors all exhibit the maximum allowable demand reduction of 25% from the central estimate of service demand for both study 3 runs. This is similar result to that of DECC-1A and DECC-2A, although in study 3 these demand reductions occur earlier. This indicates that the MARKAL model suggests that industry might scale back operation earlier given the energy price rises brought about by earlier decarbonisation. In addition to that, pulp and paper industry and other industry demand reduction changes more slowly for study 3 runs and reaches just over 10% in comparison to 15-20% demand reduction by 2050 in the equal annual emissions reduction scenarios.

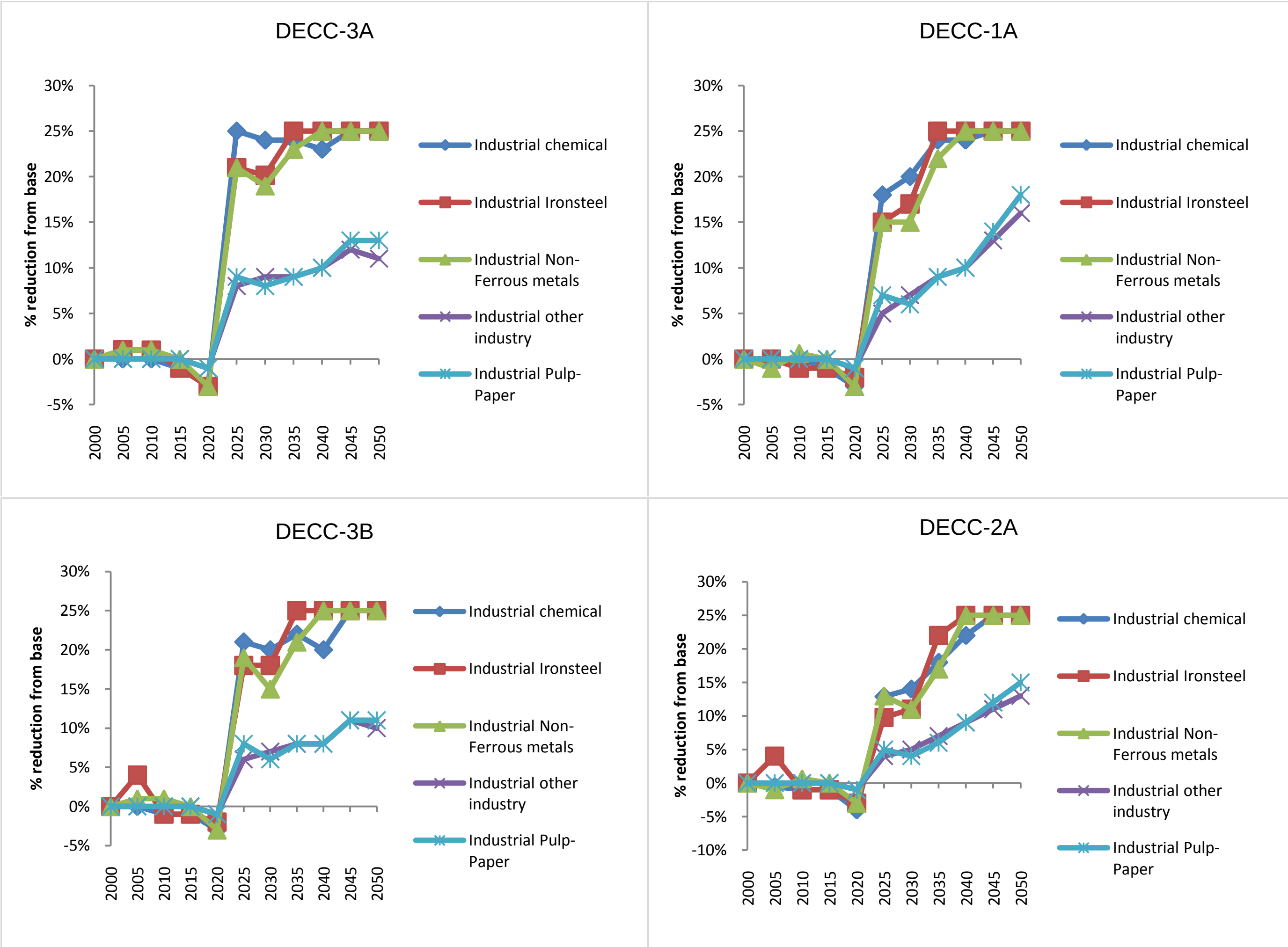


Figure 73: Industrial Demand Reductions for runs DECC-3A, DECC-3B, DECC-1A and DECC-2A

The share of each energy carrier serving final energy consumption for runs 3A and 1A is shown in Figure 74. The pattern of change is very similar for the two runs with the proportion of natural gas having a greater share for run 3A while electricity and wood usage is more prominent in run 1A late in the time horizon.

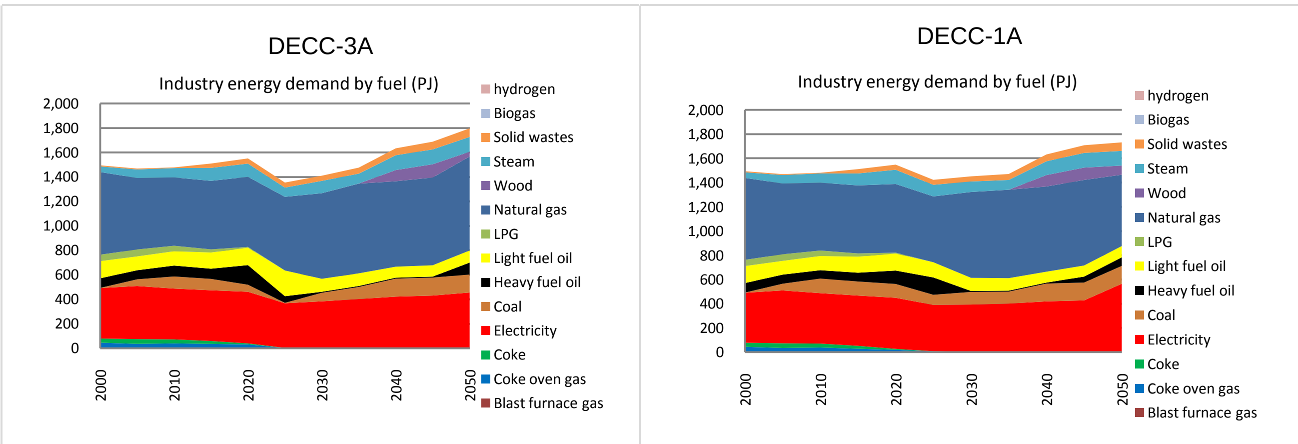


Figure 74: Industrial Final Energy Consumption for Runs DECC-3A and DECC-1A

Residential Sector

Residential sector demand reductions differ slightly between runs DECC-3A and DECC-1A. The main difference is that in the 2020s the demand response for the most affected demands, space and water heating, is 5-6% higher for run DECC-3A than for run DECC-1A. This indicates that stricter demand reduction is one of the ways to achieve higher emission reductions in the 2020s.

The overall reduction in final energy consumption observed is significant in both run DECC-3A and DECC-1A. The split by fuel for both runs is shown in Figure 75. The drop in energy consumption occurs earlier and quicker for DECC-3A run with cumulative emission reduction targets. The use of natural gas falls sharply over 2020s.

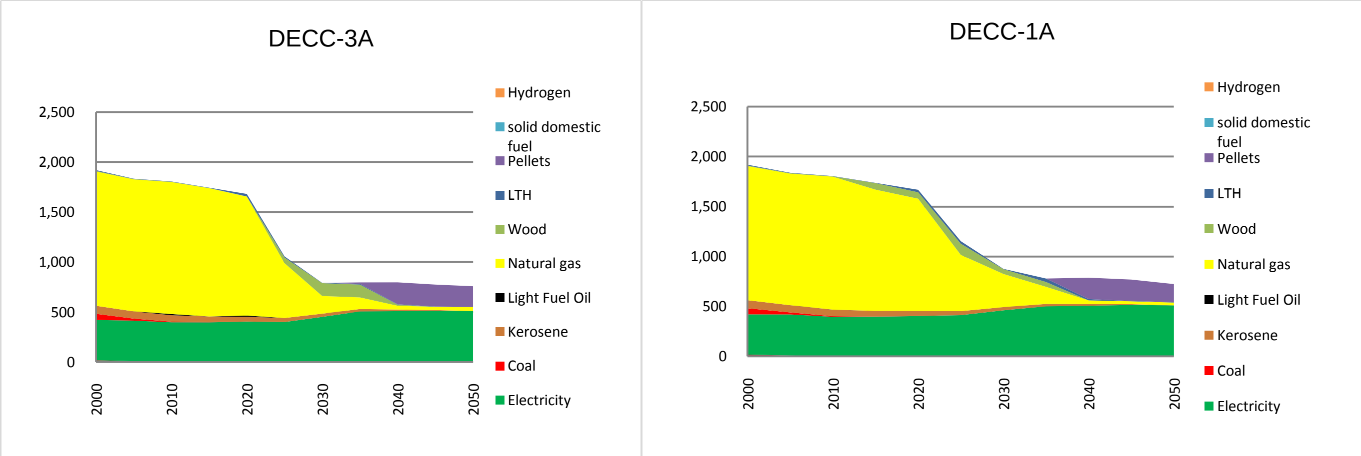


Figure 75: Residential Final Energy Consumption for Runs DECC-3A and DECC-1A

The results are similar for runs DECC-3B and DECC-2A.

Services Sector

The service sector demand reductions follow a similar pattern to the residential sector. For service sector hot water and space heating demands the reductions are highest in all considered scenarios. For scenarios with cumulative emission reduction targets, these two demands are reduced earlier than in respective equal annual emission target scenarios. Figure 76 shows that for DECC-3A run, the demand reduction for these two demands reaches around 15% in 2025 and then the rise is smoother. For DECC-1A run the reductions are slower but they reach the maximum reduction of 25% by 2050. Service sector cooking demand reduction is also less significant for run 3A.

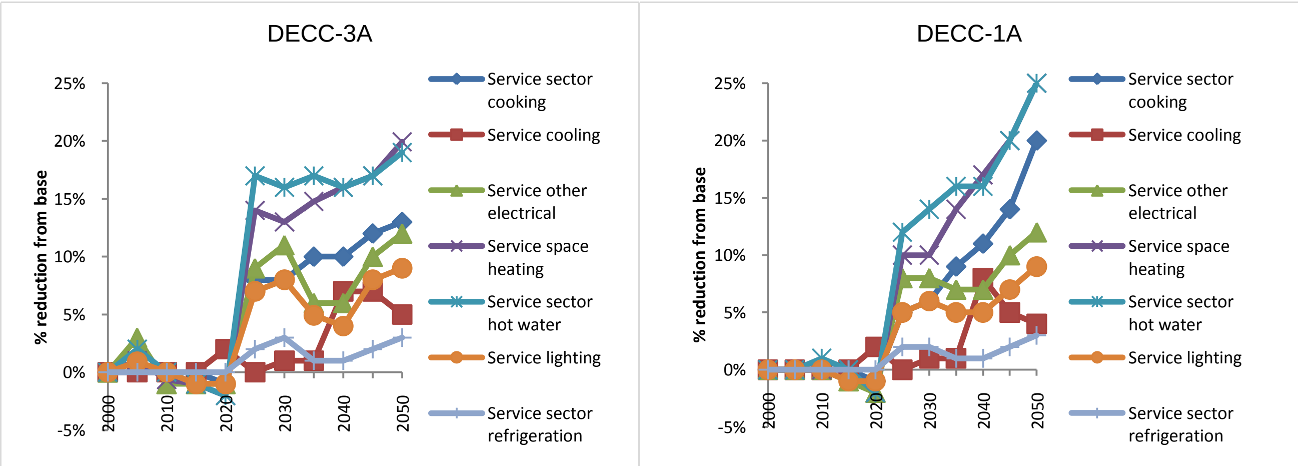


Figure 76: Service Sector Service Demand Reduction for Runs DECC-3A and DECC-1A

The final energy consumption levels do not change significantly for Study 3 runs. The fuel composition is similar to that of scenario DECC-1A in the first periods of the time horizon. In the later periods for run DECC-3A, natural gas remains one of the preferred fuels and the use of pellets is introduced but to a much smaller scale than for run DECC-1A.

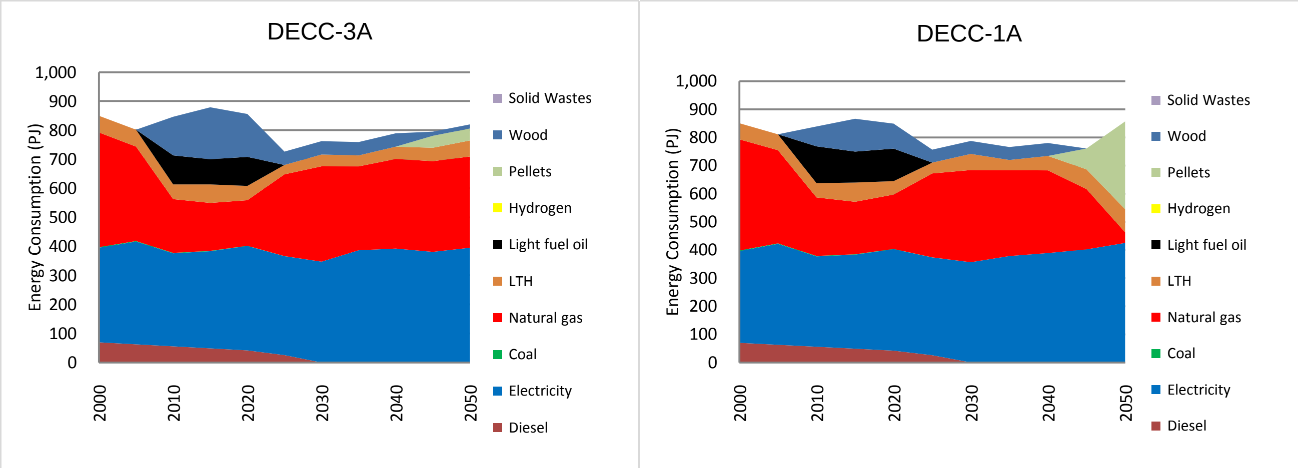


Figure 77: Service Sector Energy Consumption for Runs DECC-3A and DECC-1A

This kind of fuel mix in the later periods is enabled by the fact that service sector emissions do not drop as significantly for run DECC-3A as for run DECC-1A towards the end of the time horizon, as shown in Figure 78.

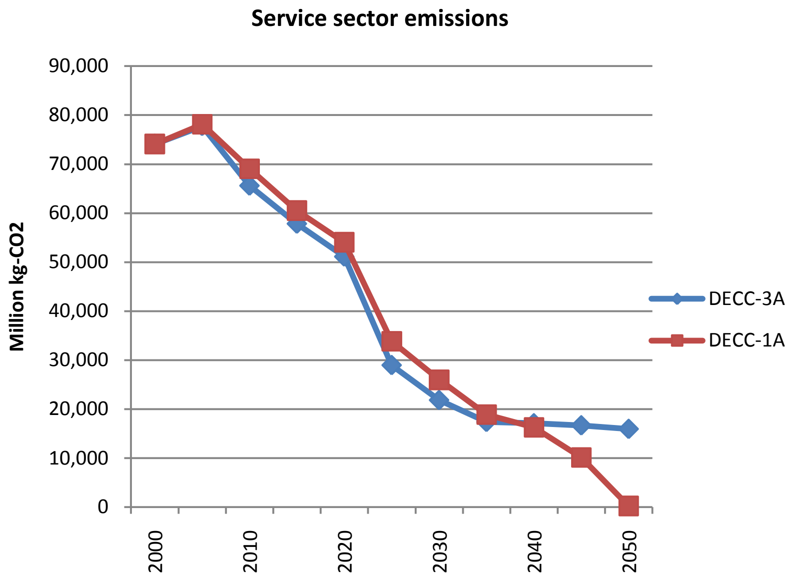


Figure 78: Service Sector Emissions DECC-3A and DECC-1A

Transport Sector

Most demand categories in the transport sector show quite low demand reduction rates. For shipping, HGV and domestic air transport the reductions are more substantial (Figure 79). For these categories, similarly to other sectors, the difference between transport sector demand reductions for scenarios DECC-3A and DECC-1A is that for run DECC-3A the reduction occurs in the 2020s. This helps achieve the high decarbonisation levels that are suggested by the model in that period.

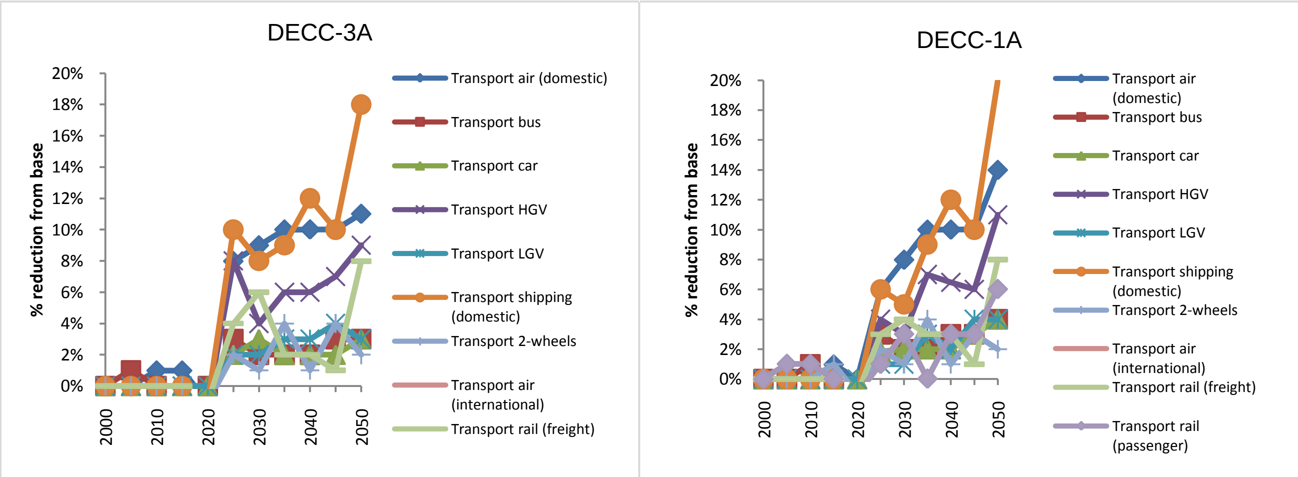


Figure 79: Transport Service Demand Reduction for Runs DECC-3A and DECC-1A

Transport fuel demand patterns are very similar for the cumulative and equal annual emission reductions targets as shown in Figure 80.

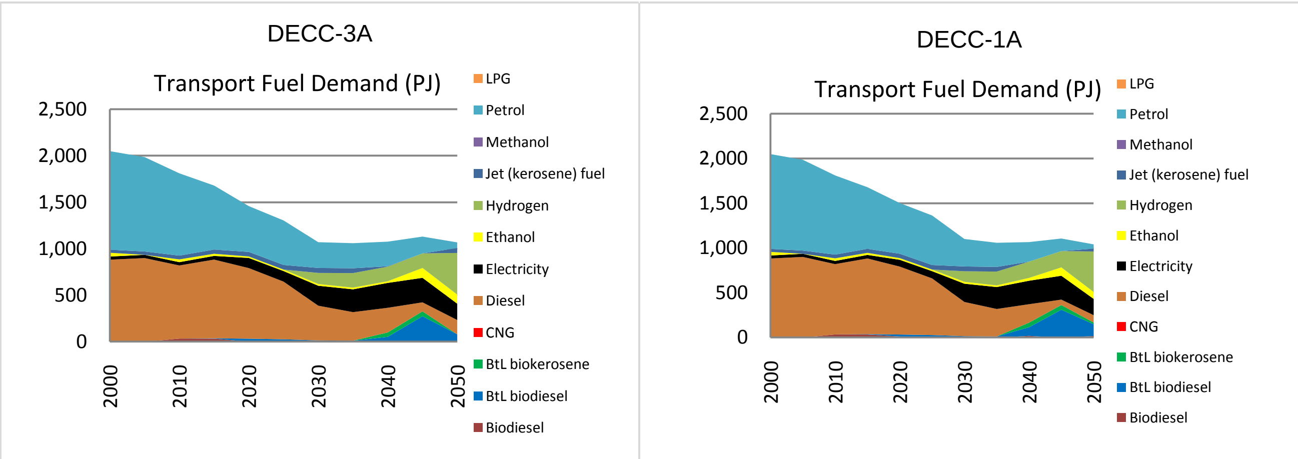


Figure 80: Transport Fuel Demand for Runs DECC-3A and DECC-1A

2.5 Study 3.2: Cumulative CO_2 Constraint Phase 2

2.5.1 Description of Study

This analysis is a variation on study 3A, which explored a 90% cumulative CO_2 emission reduction target by 2050, assuming central level of energy service demand and central fossil fuel prices. This study includes "added frictions" in phase 2 of the modelling, such as constraints on the uptake of certain measures: heat pumps, biomass and wood boilers, solar thermal in both residential and services sectors; industry CCS uptake rate has been limited and market shares of various transport technologies have been limited. Also, transport service demand has been adjusted downwards in the year 2000, and discount rates have been set to 3.5% across the model. Finally, demand response limits have been imposed in an attempt to limit response to 1% of service demand per year. This study consists of three runs:

1. Study 3 Run C – Central Service Demand and Central Fossil Fuel Prices. Cumulative emissions reduction target bounded by that observed in the results of run DECC-1A-IAB-2A (i.e. a 90% reduction in emissions by 2050) with additional constraints.
   Code **DECC-3C**
2. Study 3 Run D – Same as DECC-3C but the cumulative CO_2 emissions target has been increased by 10% for the period 2020 to 2050.
   Code **DECC-3D**

3. Study 3 Run E – Same as DECC-3C but the cumulative CO_2 emissions target has been reduced by 10% for the period 2020 to 2050.
   Code **DECC-3E**

The pathways for emissions reduction in the three runs are bound by the baseline trajectory to 2020. In the later periods, there is no annual upper bound on emissions. Instead there is a single cumulative emissions target for each run as shown in Table 15. This cumulative target applies over the entire time horizon. The level of the cumulative constraint is calculated to approximate an increase/decrease of 10% in cumulative emissions over the period from 2020 to 2050, for runs DECC-3D and DECC-3E, respectively. As such, the total cumulative target over the entire time horizon changes by slightly more than +/-3%, as shown in Table 15.

Table 15: Target cumulative emission targets

Run	Emissions Target (MtCO2)
DECC-3C	17,115
DECC-3D	17,686
DECC-3E	16,546

Figure 81 shows the resulting annual emissions for each of the runs. The baseline run for these scenarios is **DECC-0A-IAB-1A** and includes no carbon target except those in relation to the Government Carbon Plan. This baseline differs from run DECC-0A in that it includes the additional constraints described above, revised discount rates, and the modified bounds on elasticity of demand. The emissions reduction trajectory observed in run DECC-1A-IAB-2A is also plotted in Figure 81. This is to provide comparison with run DECC-3C. These two runs achieve identical cumulative emissions over the time horizon, but DECC-3C has more flexibility regarding when emissions reductions are achieved.

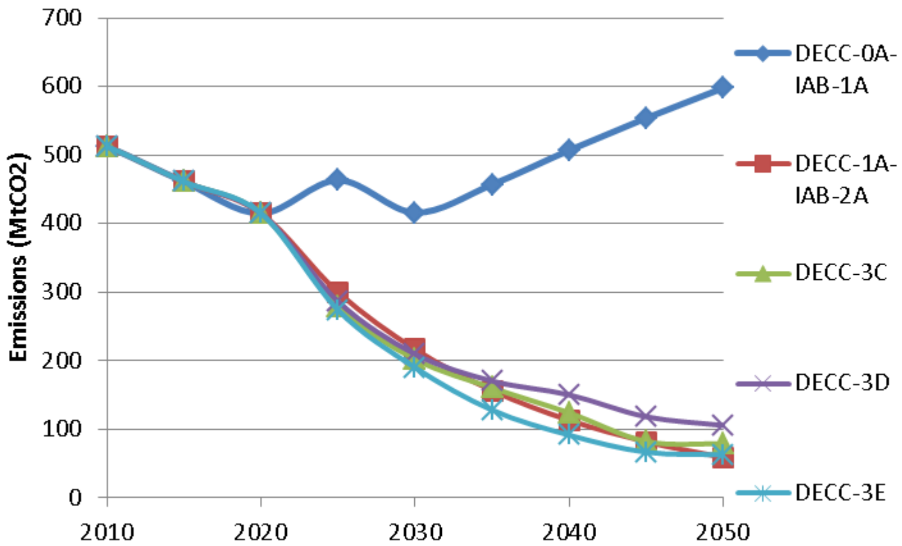


Figure 81: Resulting Annual Emissions for DECC-0A-IAB-1A, DECC-1A-IAB-2A, DECC-3C, DECC-3D and DECC-3E Runs

As seen from Figure 81, the cumulative emission target is achieved by the model through choosing to abate emissions earlier (i.e. the comparison between DECC-1A-IAB-2A and DECC-3C) in the 2020s, but also to arrive at a higher final annual national emissions in 2050. As one would expect, the energy system reduces emissions faster for the higher cumulative target, hence the more constrained run DECC-3E declines faster than the DECC-3C and DECC-3D runs.

2.5.2 Key Results

The change in discounted consumer/producer surplus for the runs in this study is presented in Table 16.

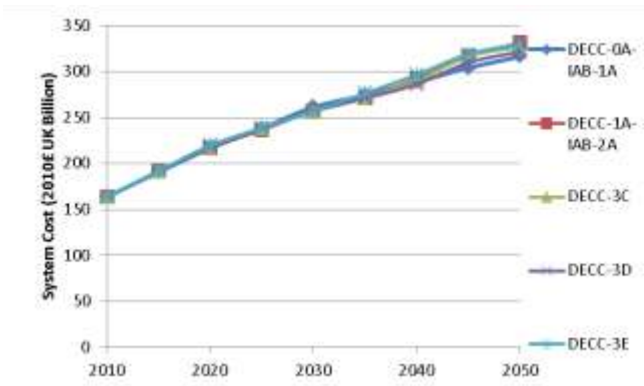
Table 16: Key Result Metrics

	Run DECC-0A-IAB-1A	Run DECC-1A-IAB-2A	Run DECC-3C	Run DECC-3D	Run DECC-3E
Baseline Run	-	DECC-0A-IAB-1A	DECC-0A-IAB-1A	DECC-0A-IAB-1A	DECC-0A-IAB-1A
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	-194	-198	-157	-251
Discounted Technical Energy System Cost (2010 £UK Billions)	5,448	5,474	5,472	5,447	5,511
Change in Discounted Technical Energy System Cost w.r.t. Baseline (2010 £UK Billions)	0	26	24	-1	63
Discounted Welfare Impact of Demand Reduction[3] (2010 £UK Billions)	0	175	182	164	198

For run DECC-3C the welfare loss is approximately 200 billion pounds (discounted UK£2010). This compares with a 194 billion loss of surplus in the equivalent equal-annual percentage emissions reduction run DECC-1A-IAB-2A. This basic result suggests that the equal annual percentage reduction trajectory is slightly less expensive than achieving the same cumulative emissions with flexibility about the timing of that reduction (i.e. run DECC-3C). This counter intuitive result is due to the fact that the MARKAL objective function includes taxes, and when this aspect is taken into account the cumulative run provides greater welfare than the equal annual reduction run, provided the specific levies included in the model (the climate change levy and fuel duties only) are considered to be genuine costs and not transfer payments. However, the technical energy system cost increase (relative to the baseline run) associated with the equal annual percentage reduction run (DECC-1A-IAB-2A) is greater than that associated with the corresponding cumulative run. So, in terms of technical energy system change, the equal annual percentage reduction approach is slightly more expensive. This is a more intuitive result. Therefore the change in surplus discussed above is not driven by technical energy system change, but rather is associated with demand response and levies. This is evident from Table 16 in that welfare impact of demand reduction (i.e. the aggregate discounted impact of demand response) is greater for the cumulative run as compared to the equal annual percentage reduction run.

When the cumulative target is varied +/-10% (i.e. runs DECC-3D and DECC-3E) the impact is most notable in changes in technical energy system cost, which increase/decrease markedly. For the most stringent emissions target – run DECC-3E – the change in technical energy system cost w.r.t. the baseline almost triples when compared with that of DECC-3C. Changes in demand response are much less significant, but this is to be expected as the potential for demand response is typically used to a large degree in all runs. This is because the cost of even small emissions reductions result in a large enough change in the costs of serving demand to stimulate a large share of the full potential for demand response.

The undiscounted annualised system costs are displayed in Figure 82, charting the annual cost of the energy system over time. The cost peak is slightly lower for DECC-3E compared with the equal annual percentage emissions reduction scenario.



Scenario	Undiscounted peak system cost (real 2010 prices, UK£ billion)
DECC-0A-IAB-1A	317
DECC-1A-IAB-2A	331
DECC-3C	327
DECC-3D	321
DECC-3E	330

Figure 82: Undiscounted System Cost for Each Run

The marginal price of CO_2 is plotted in Figure 83. Post-2020, the marginal price of CO_2 follows a different trajectory for each run. Although the emissions target was increased/reduced by the same amount correspondingly in scenarios DECC-3D and DECC-3E, Figure 83 shows that the system does not behave linearly in that the price difference is slightly greater between 3E and 3C when compared to the difference between 3D and 3C. Following a steep increment in price in 2020, the trajectory for run DECC-3E leads to a marginal price of £368/tonne of CO_2 by 2050 (compared to £250/tonne of CO_2 for run DECC-3D and £298/tonne of CO_2 for run DECC-3C). This increased price is due to the system running out of options for cheaper decarbonisation. However, the highest CO_2 price is still achieved in the equal annual percentage emissions reduction run DECC-1A-IAB-2A, which arrives at £417/tonne CO_2. All three cumulative emissions runs opt for higher prices of CO_2 in the 2020s than the equal annual percentage run. This reinforces the conclusion that when there is flexibility over when to abate, it is more cost-effective over the whole timeframe to do it early.

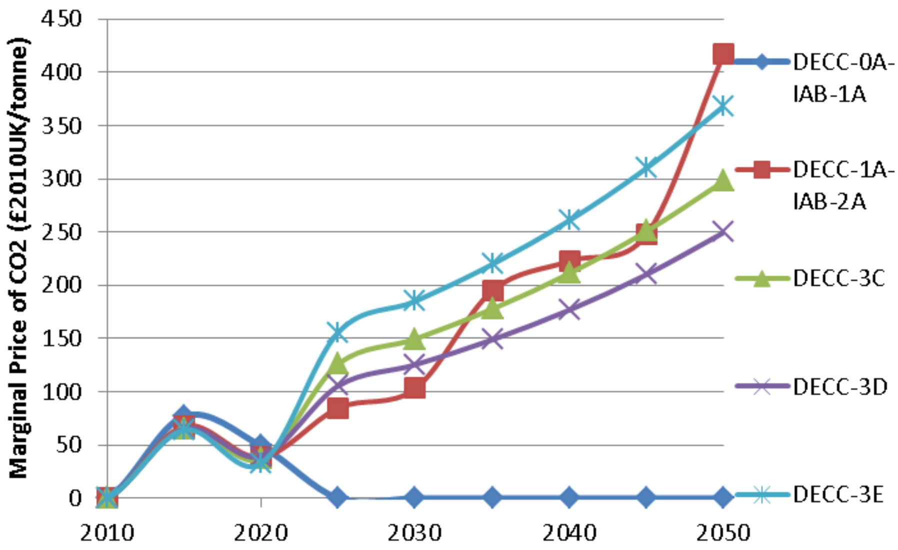


Figure 83: Marginal Cost of CO_2 for Each Run

As represented in Figure 84, the CO_2 emissions intensity of grid electricity shows approximately the same behaviour as the annual national emissions chart in Figure 84. Similarly, post-2020 decarbonisation of electricity is faster in the run with the highest emission target (DECC-3E). By 2045, the electricity system reaches its minimum CO_2 intensity (which is approximately zero), indicating that electricity production becomes CO_2 neutral. This also happens for the DECC-3C and DECC-3D runs, although slightly more slowly. As per the other runs in this project, electricity decarbonisation is a key factor in overall system decarbonisation. When given flexibility about the timing of that overall decarbonisation the model will choose to decarbonise electricity earlier.

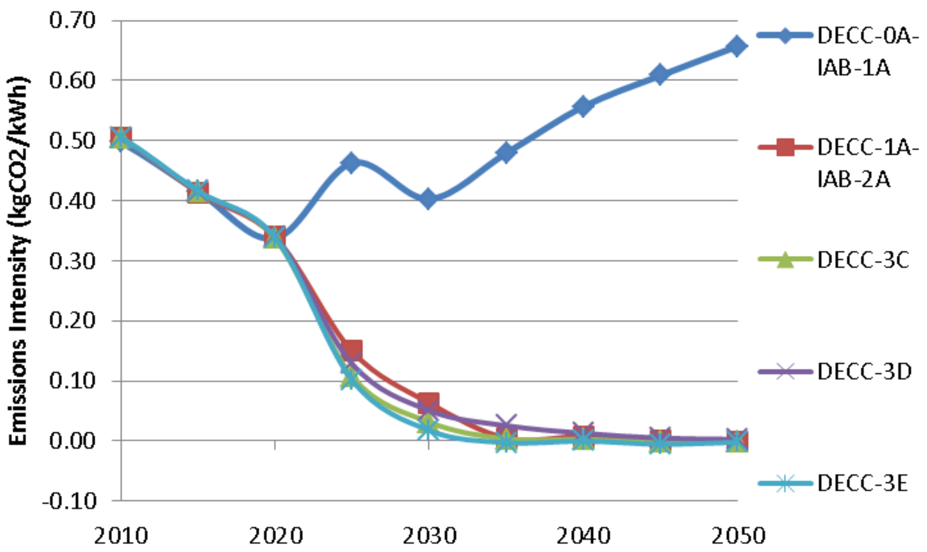


Figure 84: The Emissions Intensity of Grid Electricity

2.5.3 Primary and Final Energy Statistics

Primary energy and final energy consumption are presented in Figure 85. Primary energy consumption follows a concave trajectory, with a minimum point in the three runs around 2030. This point is just over 10% lower in runs DECC-3C, DECC-3D and DECC-3E in relation to their baseline. After this time period the trajectories have larger positive gradients than the baseline; by 2050 DECC-3C and DECC-3E runs show similar energy consumption values and run DECC-3D lags slightly behind. Final consumption follow similar trajectories in all three scenarios, with slightly lower values by 2050 for run DECC-3E than for runs DECC-3C and DECC-3D. By the same year, these final energy consumption values are considerably lower than their baseline by 18%, 17% and 16% respectively.

In the case of primary energy, by 2050 the three runs have energy use values less than 10% lower to their baseline. However, their final consumption is lower than the baseline run by more than 15%. Overall this suggests that the energy system becomes less efficient as it decarbonises. This may be explained by a large shift towards low carbon technologies, but these have relatively low conversion efficiency. It may also indicate greater electrification of the energy system, where losses in power generation (i.e. cooling, and transmission and distribution) become dominant.

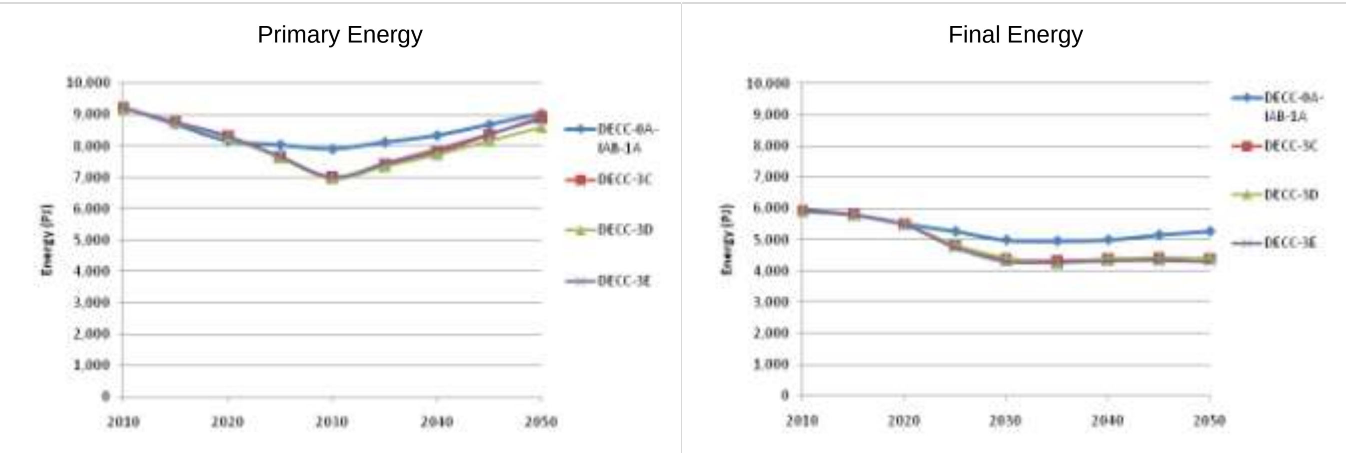


Figure 85: Aggregate Primary and Final Energy Consumption over Time

The underlying mix of energy carriers serving the demand is quite different for runs DECC-3C, DECC-3D, DECC-3E compared to their baseline, as shown in Figure 86. In the baseline run, coal serves over 50% of the primary energy use. In contrast, coal is reduced to less than 10% of the mix in DECC-3C, DECC-3D and DECC-3E runs. In these scenarios, the main contributor with over half of the total share is nuclear electricity.

Although the level of final energy consumption is similar between the three runs studied in this analysis, the combination of energy carriers serving the energy demand is slightly different in between them and in comparison with the baseline. Nuclear electricity is the main contributor to meeting primary demand in the three scenarios studied. The comparison of the final energy carriers composition between DECC-3C and DECC-3D shows an increase in the use of gas in the latter run. The observation that run DECC-3C and DECC-3E show higher primary energy levels than DECC-3D yet lower final energy values, suggests that the overall energy system is more efficient in scenario DECC-3D than in the former two.

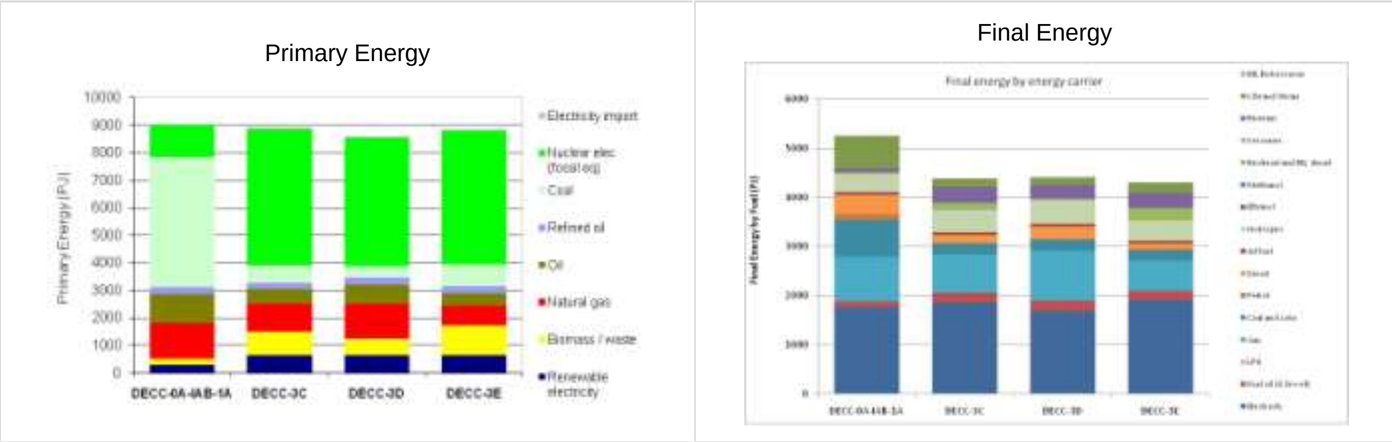


Figure 86: Primary and Final Energy Demand by Energy Carrier in 2050

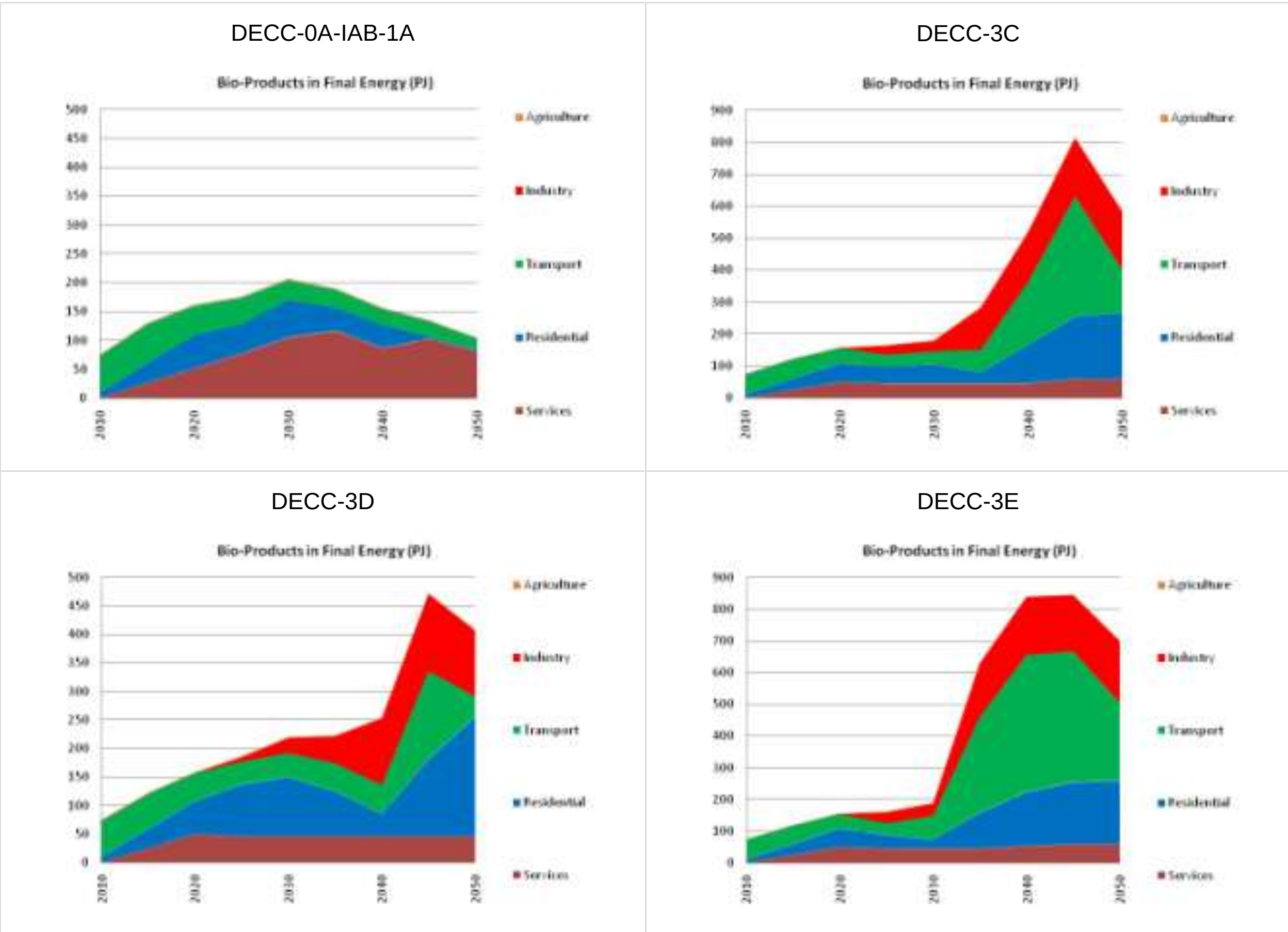


Figure 87: Bio-Products in Final Energy Consumption (note varying scales on the vertical axis)

Bio-products in final consumption are shown in Figure 87 for runs DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E, disaggregated by end-use sector. Note the varying scales of the vertical axes in this figure.

In the baseline, the use of bio-products increases from 2010 up to its maximum level of 207 PJ in 2030; then it declines to about half this quantity by 2050. In run DECC-3C the system experiences a sharp increase in the use of bio-products in 2035 up to its peak value of 816 PJ, followed by a steep decline in the last time period over 2045. In run DECC-3D, the use of bio-products increases in 2040 up to a maximum of 473 PJ by 2050, declining afterwards. Finally, in run DECC-3E bio-products are adopted earlier than in the previous runs, in 2030. The use of bio-products in this run reaches a peak value of over 840 PJ in 2040, followed by a steep decline in 2045.

2.5.4 Power Generation and Installed Capacity

The three scenarios under consideration and their baseline show a similar power generation trajectory up to 2030, as represented in Figure 88; after that, run DECC-3E shows an earlier increase to generate nearly 2590 PJ by 2050. Run DECC-3C produces nearly 2% less electricity by the same year, whilst run DECC-3D generates 9% less electricity.

The installed capacity graph in the right subplot (Figure 88) represents the power generation capacity of the energy system by year. As expected from the power generation graph on the left subplot, DECC-3C and DECC-3E runs have the largest installed capacity out of the three scenarios under consideration, with nearly 40% more generation capacity than the baseline by 2050; run DECC-3D has about 32% more capacity by the same year.

Figure 88 suggests that a 10% increase of the cumulative CO_2 emissions target from 2020 to 2050 has a larger effect on the power generation capacity of the system by the end of this period than a 10% reduction of the CO_2 emissions target.

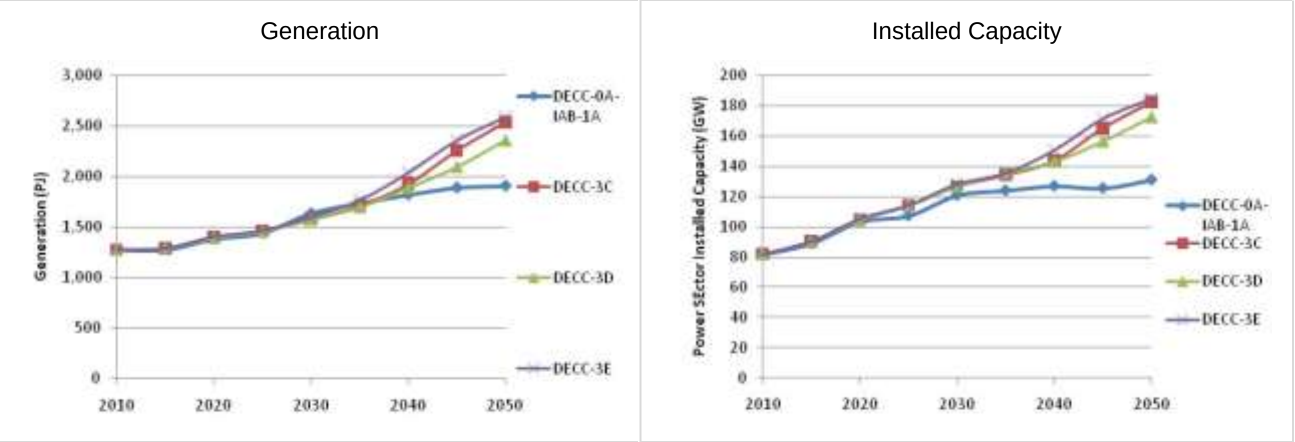


Figure 88: Aggregate Generation over Time for Each Run

As seen in Figure 89, the underlying mix of technologies used to generate power varies significantly between DECC-0A-IAB-1A and DECC-3C, DECC-3D and DECC-3E runs in 2050. In the baseline, coal and nuclear electricity are the main contributors to meeting the increase in primary demand. In the three runs analysed in this study, nuclear electricity grows considerably and coal disappears from the electricity generation mix. In run DECC-3C nuclear electricity is by far the largest contributor to meet demand (about 62%), while marine energy generates 15% of the total. In run DECC-3D nuclear electricity generates a similar proportion of the total electricity produced, with marine energy generating 16%. In run DECC-3E nuclear plants and marine energy remain the main contributors, although co-firing with CCS increases its production significantly.

In terms of installed electricity generation capacity, the main difference between the baseline and the three scenarios analysed is the expansion in the use of some resources and the disappearance of coal power plants from the installed capacity mix. Nuclear electricity and marine energy increase significantly; gas power plants remain an important contributor as well as wind turbines. In run DECC-3E in particular, co-firing with CCS plants takes 10% of the total installed capacity compared to a zero contribution in the baseline run.

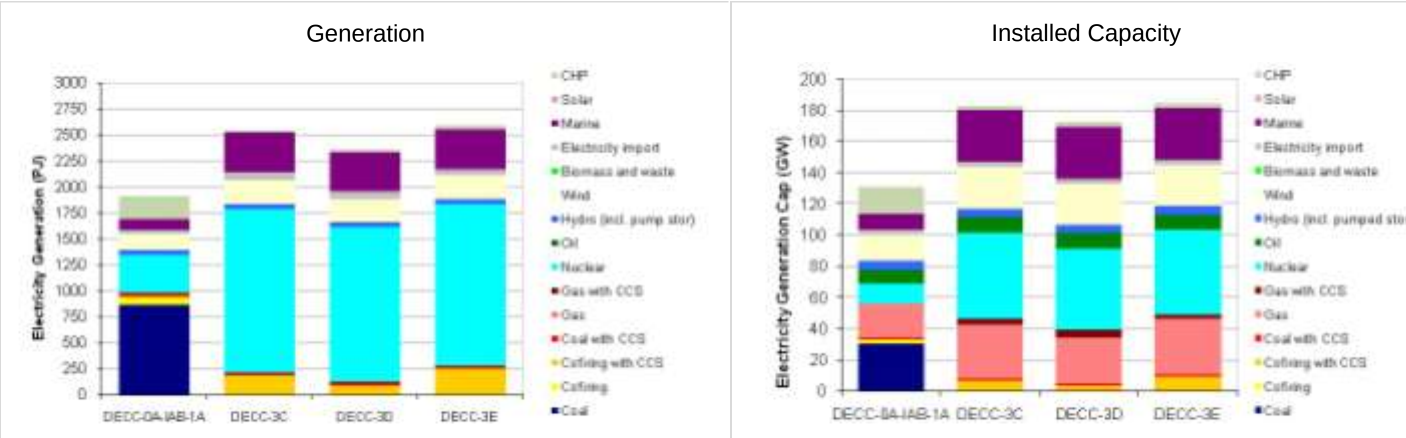


Figure 89: Generation by Technology for DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs in 2050

2.5.5 End-Use Sectors

Sectoral and end-use sectoral CO_2 emissions reductions are shown in Figure 90. Runs DECC-3C, DECC-3D and DECC-3E show a similar profile of emission reductions relative to the baseline (run DECC-0A-IAB-1A), although their CO_2 emissions reduction level varies as expected given the different cumulative emission reduction targets in DECC-3D and DECC-3E runs relative to run DECC-3C. CO_2 emission reductions occur mostly in the electricity generation and industry sectors. Aggregate reductions in final energy consumption occur mainly for industry, residential and transport sectors. Although this may be due to a combination of factors including elasticity of service demand and available end-use technologies, the availability of abatement technologies in each sector will also play an important role.

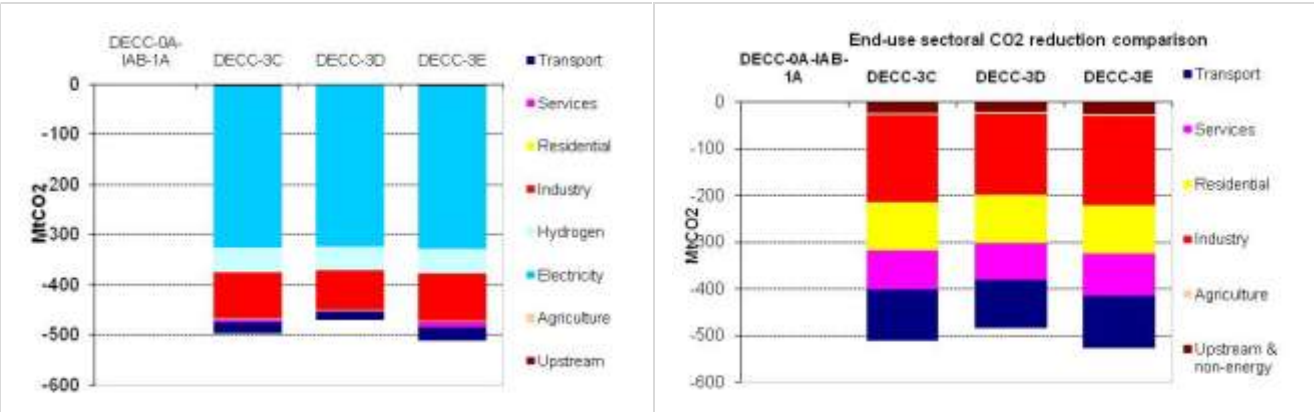


Figure 90: Sectoral and End-Use Sectoral CO_2 Emissions Reduction Disaggregation in 2050

The following sections consider each end-use sector in more detail, focusing on runs DECC-3C, DECC-3D and DECC-3E (compared to DECC-0A-IAB-1A).

Industrial Sector

Industrial sector demand reductions are shown in Figure 91. In DECC-3C, DECC-3D and DECC-3E runs, chemicals, iron and steel and non-ferrous metals sectors all exhibit the maximum allowable demand reduction of 25% from the central estimate of service demand by 2050. In run DECC-3E the pulp-paper industry and other industries show a slightly higher demand reduction to increased energy prices after 2025 than in scenarios DECC-3C and DECC-3D. Overall, the industrial sector experiences a high level of demand reduction in these scenarios, facilitated by MARKAL's elastic demand response characterisation. Similarly with other studies, it is clear that some industries might scale back operation quite significantly given the energy price rises brought about by decarbonisation.

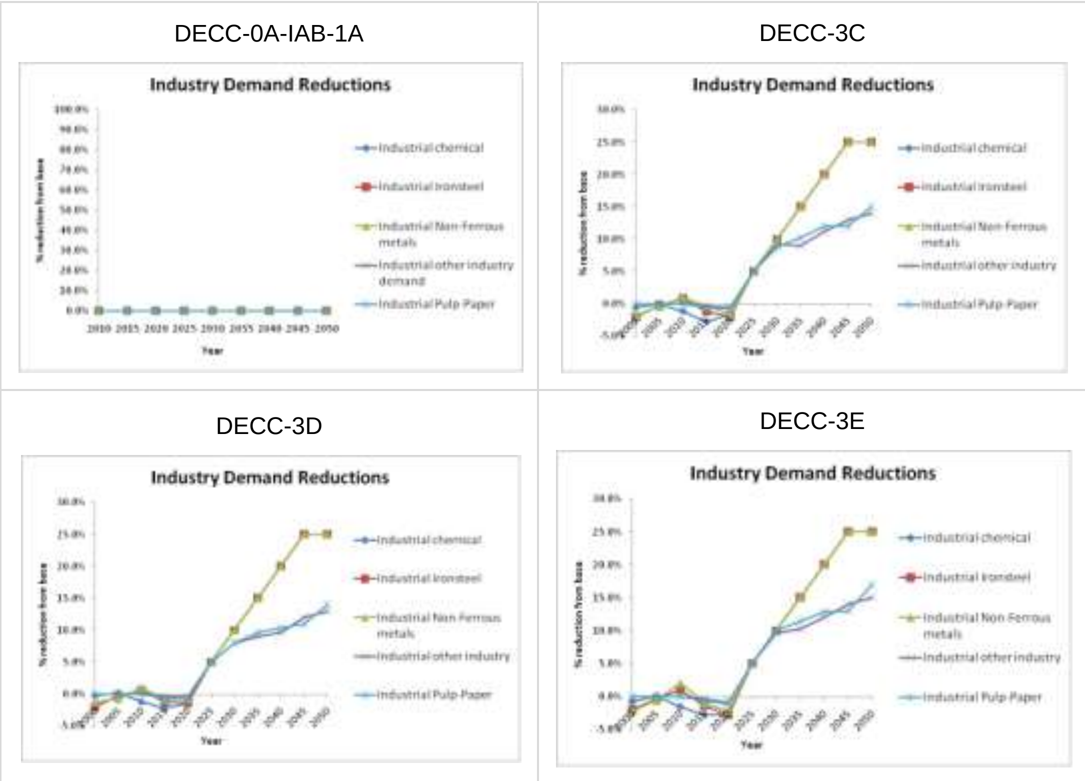


Figure 91: Industrial Demand Reductions for DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs

As shown in Figure 92, industry energy demand in run DECC-0A-IAB-1A experiences continuous growth, increasing from its 2010 level by 38% in 2050. In contrast, industrial demand in run DECC-3C increased only by 19% in the same year; in run DECC-3D demand grew by 20% and in run DECC-3E it increased by 18%.

Figure 92 also shows the share of each energy carrier serving final energy consumption. A clear difference between the baseline and the three runs under analysis is that coke oven gas almost disappear from the fuel mixes that supply industry demand in DECC-3C, DECC-3D and DECC-3E runs. In between these three scenarios, the main difference is in the use of natural gas and electricity, the two most important contributors to the profiles shown below.

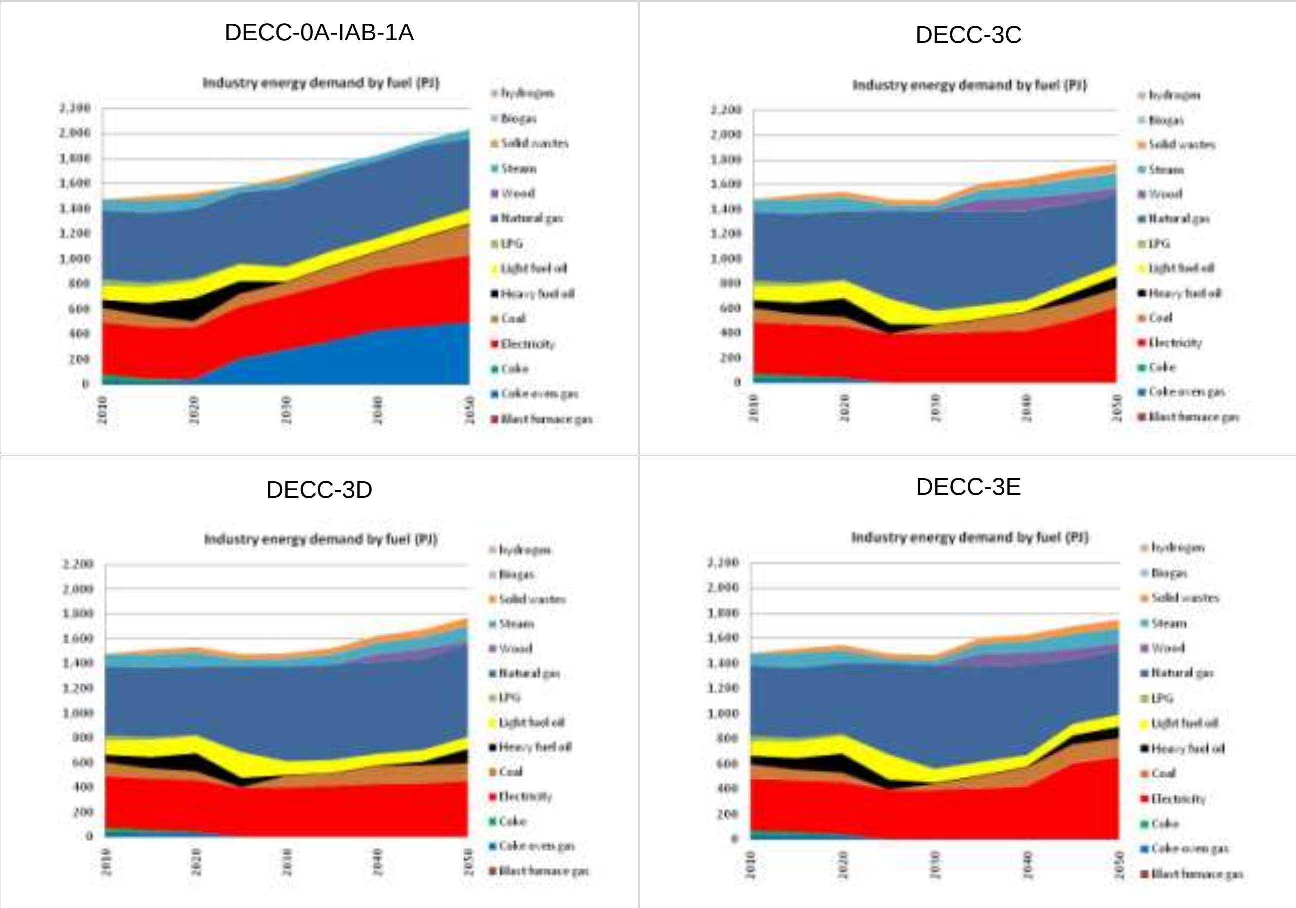


Figure 92: Industrial Final Energy Consumption for DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs

Residential Sector

In order to meet the CO_2 reduction targets in 2050, the model initially resorts to demand reduction. However, meeting these targets will depend largely on a number of factors such as the availability of abatement technologies and the implementation of government policies and directives, such as the eco-design of Energy Using Products (EuP). All the runs depicted in Figure 93 show different fuel mixes. In the baseline run the model uses mainly electricity (57%) and LTH (36%) to satisfy energy demand by 2050. In the three scenarios under consideration, demand is mostly supplied by electricity (68%) and pellets (27%); the main difference between scenarios is in the time of adoption of these fuel sources, with DECC-3D run resorting to pellets later in time in favour of natural gas.

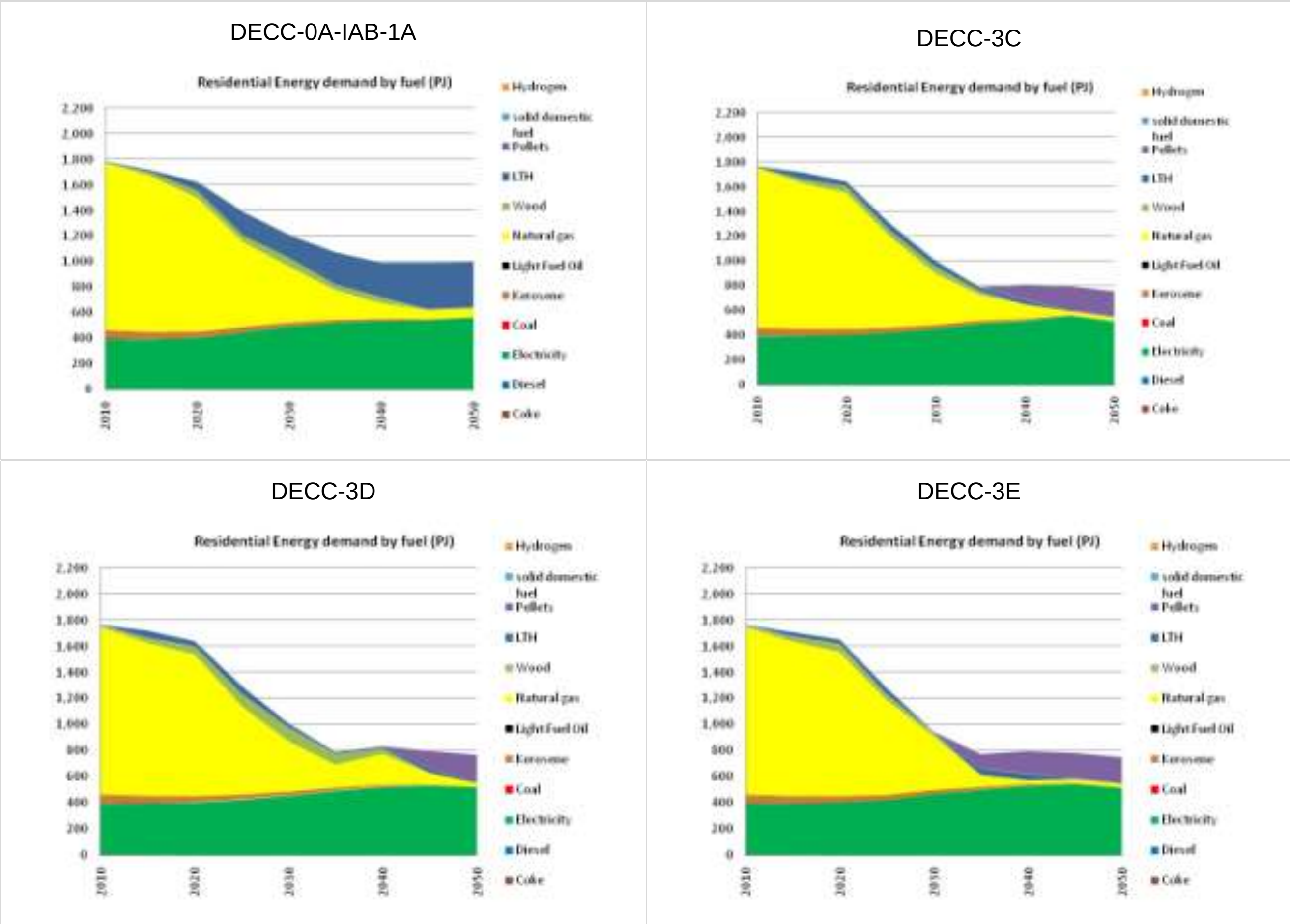


Figure 93: Residential Final Energy Consumption for DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs

Overall, Figure 94 shows that the drop in energy consumption for heating in DECC-3C, DECC-3D and DECC-3E runs occurs earlier and faster than in run DECC-0A-IAB-1A. In the baseline run district heating is the main fuel consumed for residential heating by 2050, the other significant contributor being heat pumps. In comparison, in run DECC-3C district heating almost disappears from the fuel mix, replaced mainly by solar water heating and pellets by 2050. In run DECC-3D, natural gas remains the main contributor over 2040, whilst in run DECC-3E pellets are adopted earlier than in the other scenarios and natural gas does not contribute to the mix after 2040. In all scenarios, the use of natural gas falls sharply over 2020.

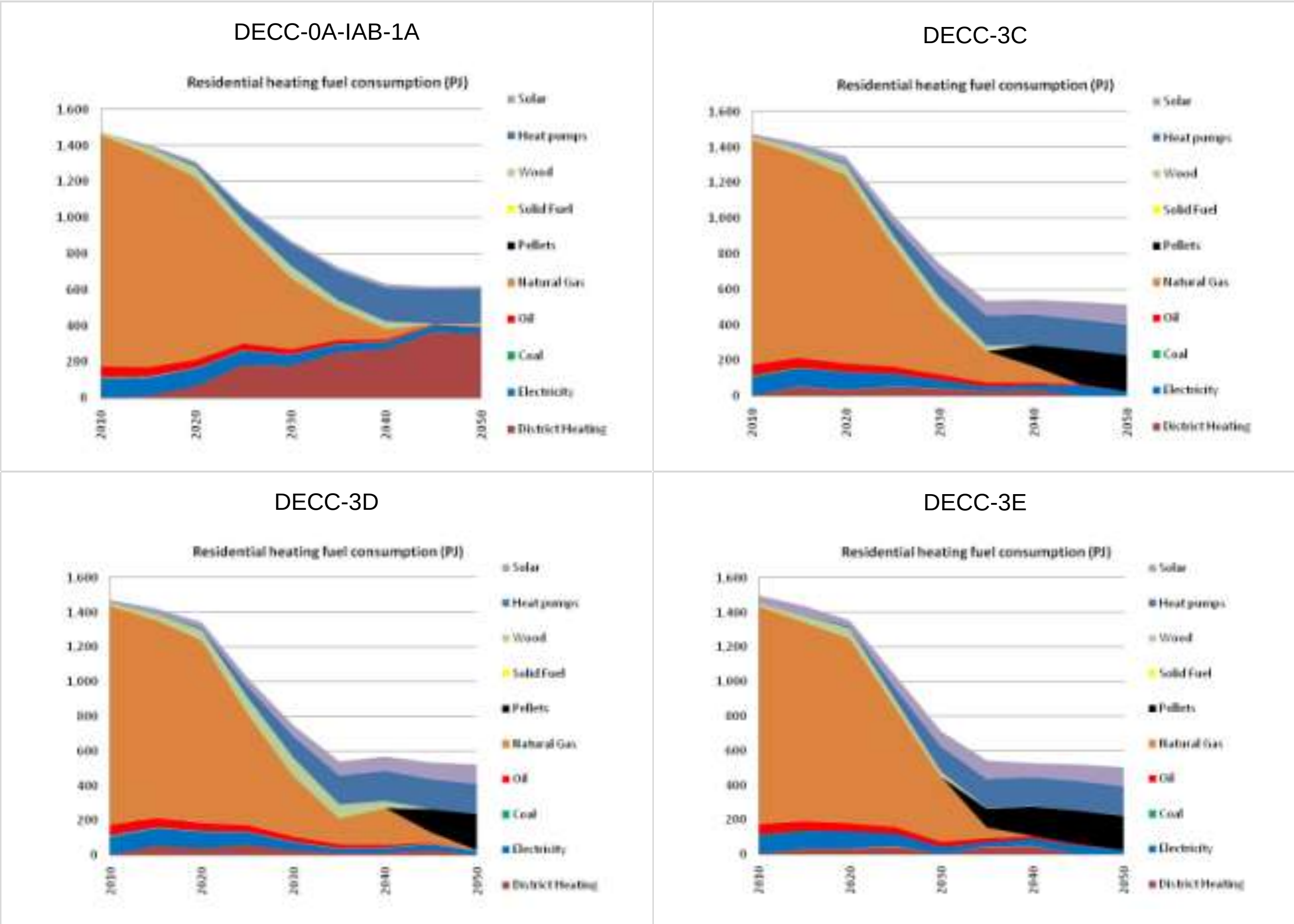


Figure 94: Residential Final Energy Consumption for Heating in DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs

However, the reader should note that Figure 94 is final energy consumption of the end-use device serving thermal demand. Therefore heat pumps, which draw energy from the surrounding environment in addition to consuming electricity, serve a much larger portion of heating service demand than the other technologies.

Services Sector

In general, as shown in Figure 95, the service energy demand by fuel has a similar profile for the runs represented up to 2020. In the baseline run, LTH increases its share in the fuel mix from 2025 onwards, fulfilling almost one quarter of the demand by 2050. In contrast, run DECC-3C reduces the use of LTH to only 6%, increasing electricity to 64% and introducing pellets to the mix in 2050. In run DECC-3D electricity and natural gas are also the main contributors, the difference being that pellets are not in the fuel mix and wood remains a part of it. In run DECC-3E, electricity fulfils nearly 70% of the total demand in the services sector by 2050.

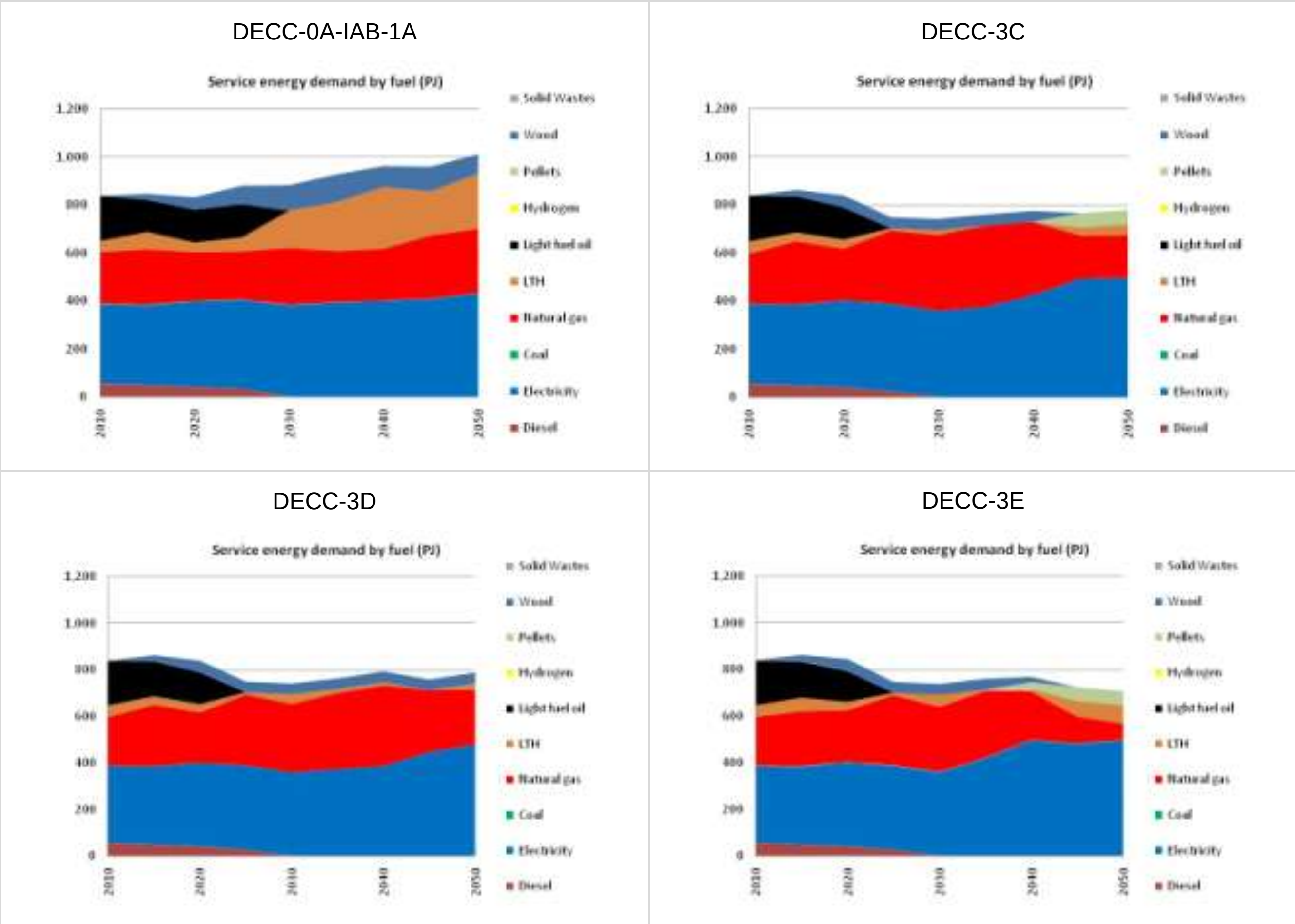


Figure 95: Service Sector Final Energy Consumption for DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs

As shown in Figure 96, the service sector final energy consumption for heating changes significantly both in fuel combinations and in overall consumption levels. In the baseline, district heating and natural gas are the main contributors to meeting demand by 2050. The total energy consumption for this run increases 15% by 2050 from its value in 2010. In run DECC-3C, the use of electricity increases sharply over 2035 to supply a third of the demand by 2050; in the period from 2010 to 2050, total energy consumption decreases by 20%. In run DECC-3D natural gas has a larger contribution to the fuel mix than in the other two scenarios, with about 44% of total demand by 2050; in this scenario the total energy consumption is reduced by 20% from its value in 2010. In run DECC-3E, electricity supplies 40% of the demand, reducing significantly the contribution of natural gas in the mix by 2045. Energy consumption in this sector drops sharply between 2020 and 2025, and then gradually for a 66% reduction in fuel consumed by 2050. In all scenarios, the use of light fuel oil disappears from the fuel mix by 2030.

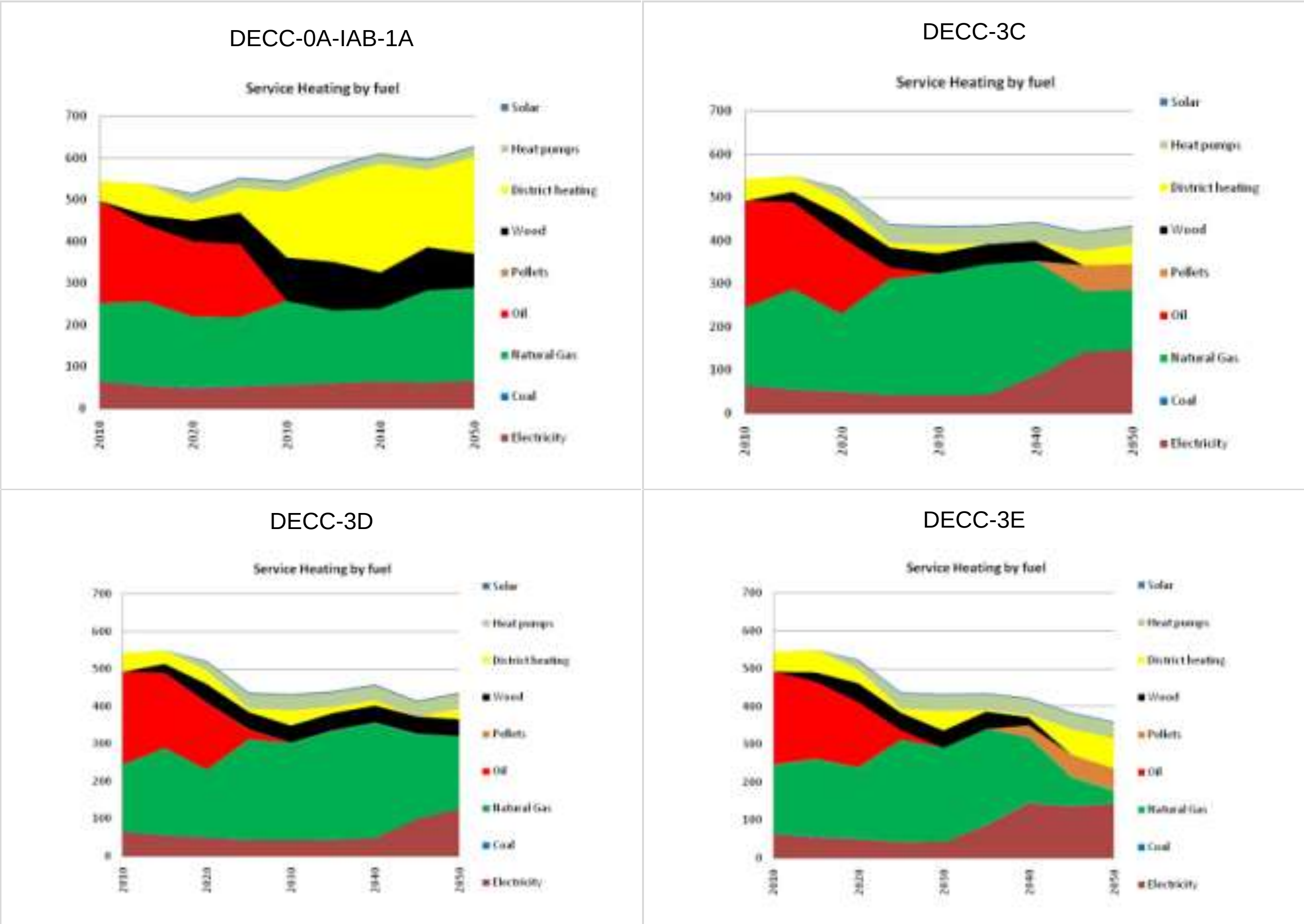


Figure 96: Service Sector Final Energy Consumption for Heating in DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs

Transport Sector

Overall, transport fuel demand shows a steep decline up to year 2030. Afterwards, as illustrated in Figure 97, fuel demand decreases slightly over time in an attempt to meet the CO_2 emission targets. This effort also involves a change in the fuel mix to more cost-effective options, factoring in the various constraints such as supply, technical limitations and emission targets. The main difference between the studied scenarios is in the adoption of BtL biodiesel in the last periods; post-2035 BtL biodiesel replaces some of the diesel used in the baseline's fuel mix in run DECC-3C. An earlier adoption of the same fuel occurs in run DECC-3E, with a sharp increase after 2030. In run DECC-3D, BtL biodiesel increases its contribution to a lesser extent, ten years later.

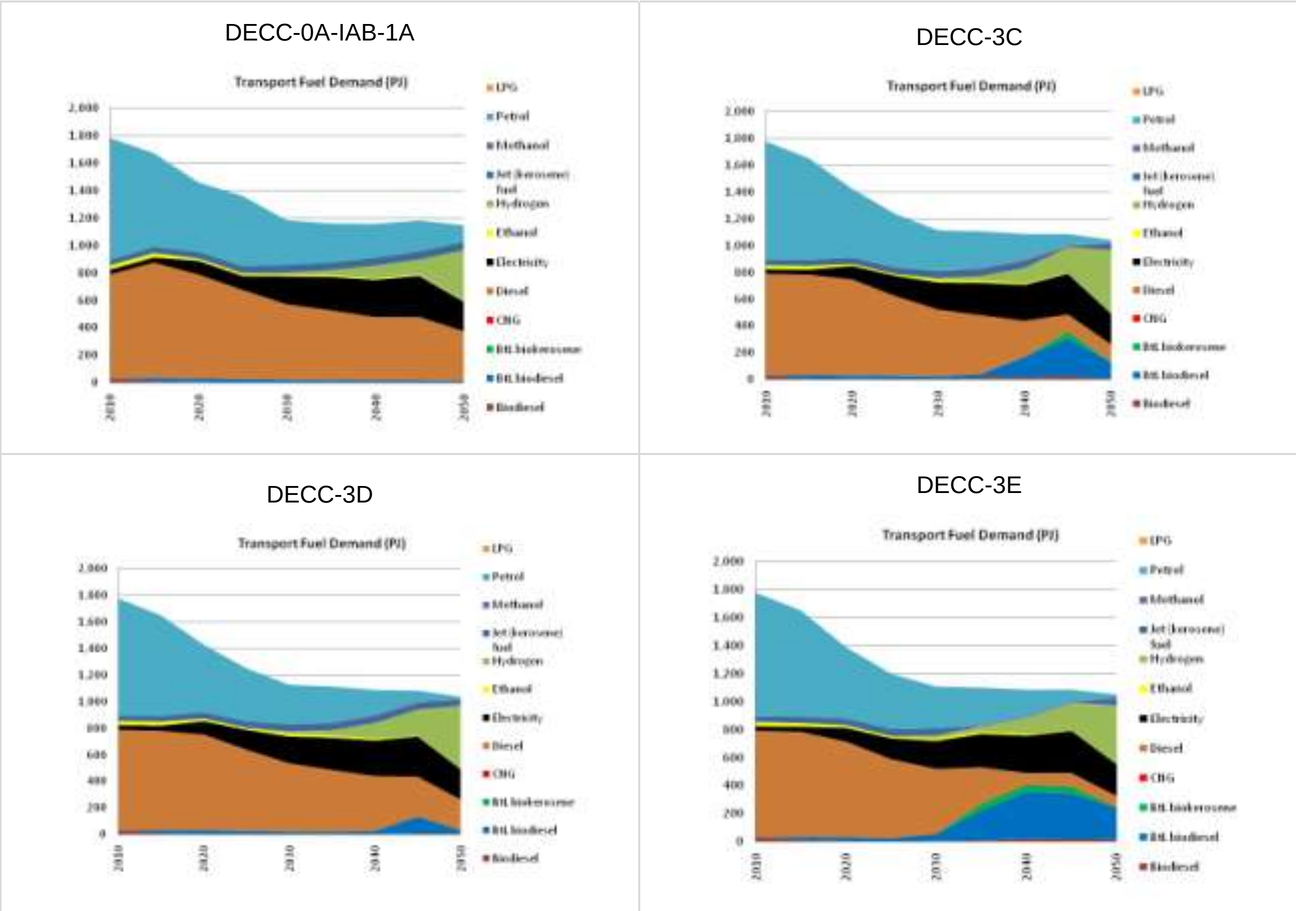


Figure 97: Transport Fuel Demand for DECC-0A-IAB-1A, DECC-3C, DECC-3D and DECC-3E Runs

2.6 Study 4: International Tradable CO_2 Emission Permits

2.6.1 Description of Study

Study 4 looks at a scenario where international tradable carbon permits are available to purchase from 2025 onwards at DECC's published traded carbon prices. It is identical to run DECC-1A except for the availability of these permits. There are three runs in this study:

1. Study 4 Run A – Central Service Demand. Central Fossil Fuel Prices. Central DECC carbon credit prices. Code **DECC-4A**
2. Study 4 Run B – Central Service Demand. Central Fossil Fuel Prices. High DECC carbon credit prices. Code **DECC-4B**
3. Study 4 Run C – Central Service Demand and Central Fossil Fuel Prices. Low DECC carbon credit prices. Code **DECC-4C**

Until 2025 the purchase of credits is not available. From 2025 onwards, the purchase of credits is unconstrained. The pathways for emissions reduction in this study is bounded (in the addition to the baseline bounds to 2020) by the figures in Figure 98.

Year	Emissions Target (MtCO2)
2025	299.8
2030	216.6
2035	156.5
2040	113.0
2045	81.7
2050	59.0

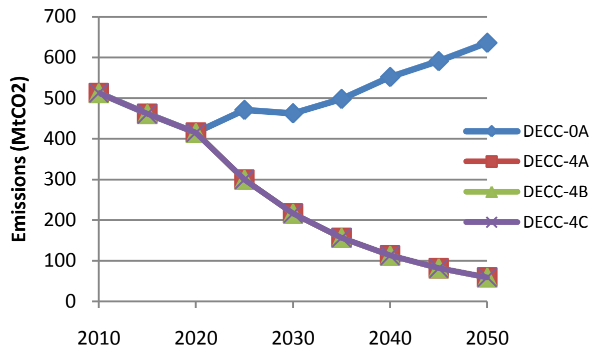


Figure 98: Target and Resultant Emissions Reduction over Time in the Study 4 runs

The baseline run for each of the runs in this study is taken as DECC-0A. Throughout this study comparisons are made across different carbon credit prices as well as with the DECC-1A run from Study 1, which was limited to a 90% reduction in CO2 emissions at a central service demand and central fossil fuel prices i.e. the only difference from the scenarios in this study is the introduction of carbon credits at different prices. From this it was possible to determine the marginal impact of different energy carriers and technologies.

2.6.2 Key Results

The total discounted system cost and discounted consumer/ producer surplus for these runs is shown in Table 17. The discounted system cost of the high price carbon credit run, DECC-4B, is £7 billion lower than the other lower carbon price runs. This is because the higher credit price brings about greater demand response, reducing the need for system investment.

Table 17: Key Result Metrics

	Baseline Run DECC-0A	Study 1 Run A DECC-1A	Study 4 Run A DECC-4A	Study 4 Run B DECC-4B	Study 4 Run C DECC-4C
Discounted Technical Energy System Cost (Year 2010 £UK billions)	5940	6014	6,042	6,035	6,042
Discounted Consumer/Producer Surplus comparison (Year 2010 £UK billions)	-	-293	-246	-286	-187

All the runs in Table 17 have an improved surplus when compared to the run with no CO_2 credits available (DECC-1A), so as expected there is a cost efficiency associated with the ability to buy credits. The increase in surplus of the carbon credit priced runs, DECC-4A, DECC-4B and DECC-4C when compared to the non carbon credit run DECC-1A are £47 billion, £7 billion and £106 billion, respectively. As expected, the low carbon credit cost results in the largest benefit in surplus. In essence, the unconstrained availability of carbon credits offers a more cost effective mechanism for reducing emissions. The MARKAL model is a cost optimising model and therefore pursues this cheaper option. So if the marginal cost of non-credit options (i.e. technical change or demand response) is higher than the carbon credit price, the credit will be purchased.

The undiscounted system costs are displayed in Figure 99. The system cost difference between the runs is small up to £4 billion per year.

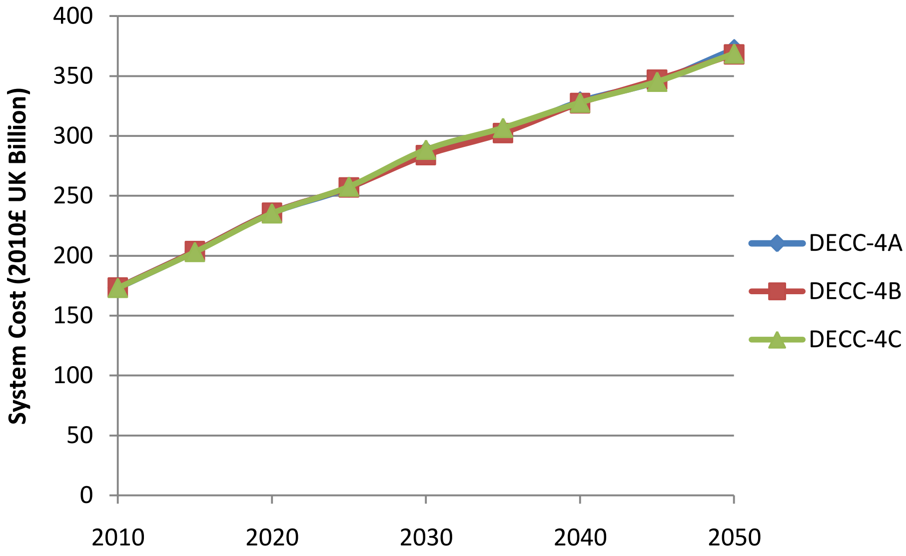


Figure 99: Undiscounted system cost for each run

Table 18 shows the carbon credit price for each of the 3 runs from 2025. Note that these prices are in real year 2000 UK pounds.

Table 18: Undiscounted Carbon Credit Price (UK£2000/tCO_2)

Year	2025	2020	2035	2040	2045	2050
DECC-4A	34.3	55.7	81.5	107.3	133.2	159
DECC-4B	49.9	83.5	122.2	161	199.7	238.5
DECC-4C	17.3	27.8	40.7	53.7	66.6	79.5

This should be correlated with the marginal cost of carbon, utilised by MARKAL as shown in Figure 100. The marginal cost of carbon equates to the carbon credit price for each of the runs. The carbon credits set a constraint on the marginal cost of carbon in MARKAL.

Table 19 shows the quantity of emissions offset by carbon credits across each of the runs beyond 2025.

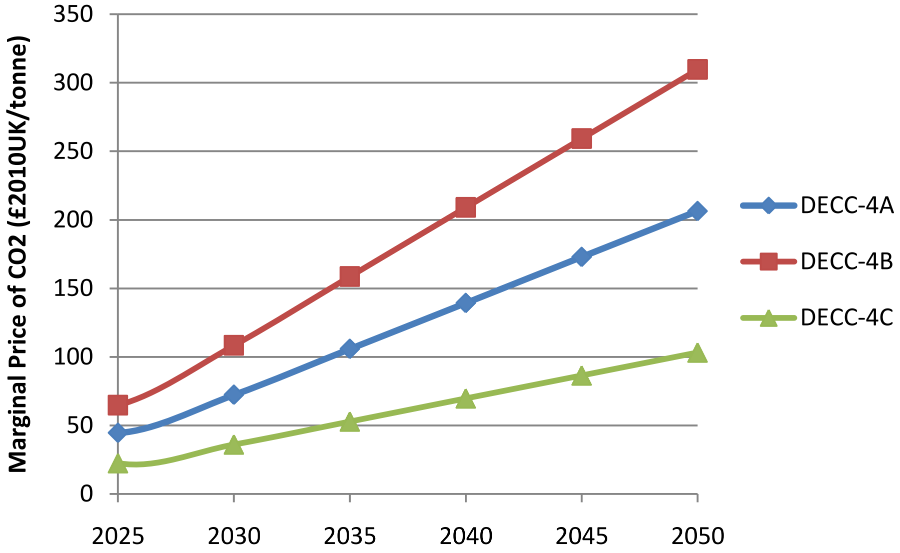


Figure 100: Marginal Cost of CO_2 for Each Run for 2025 onwards

Table 19: Total number of carbon credits utilised to meet the emissions target ($MtCO_2$)

Year	2025	2020	2035	2040	2045	2050
DECC-4A	31.2	29.1	31.0	58.9	77.3	104.9
DECC-4B	7.5	3.8	2.8	17.9	17.7	45.4
DECC-4C	61.1	63.5	82.4	114.0	139.7	171.8

Figure 101 shows the emissions intensity of grid electricity across each of the runs in this study. The runs all follow a similar trend to that of DECC-1A, implying that marginal cost of carbon is not solely dependent upon electricity generation sector. Reduction in emissions intensity is slightly less rapid in the 2020s as a result of the ability to purchase credits, and this is particularly clear in the DECC-4C (low credit price) scenario. In 2030 the range of emissions intensities in study 4 runs was 0.1 to 0.14 $kgCO_2/kWh$.

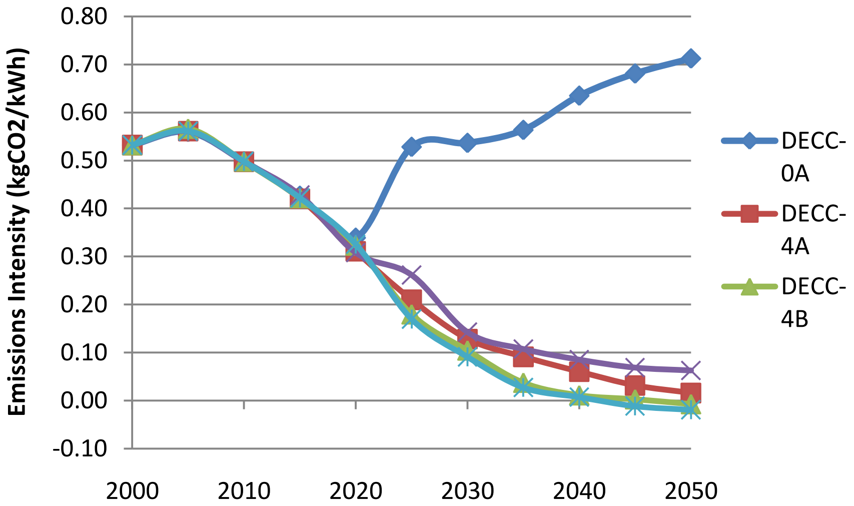


Figure 101: The Emissions Intensity of Grid Electricity and Hydrogen Production

2.6.3 Primary and Final Energy Statistics

Primary energy consumption and final energy consumption are presented in Figure 102 and Figure 103, respectively. For Figure 102, the three different runs in this study result in very similar aggregate primary energy consumption, despite the differences in carbon credit prices. This trend is very similar to the run without credits.

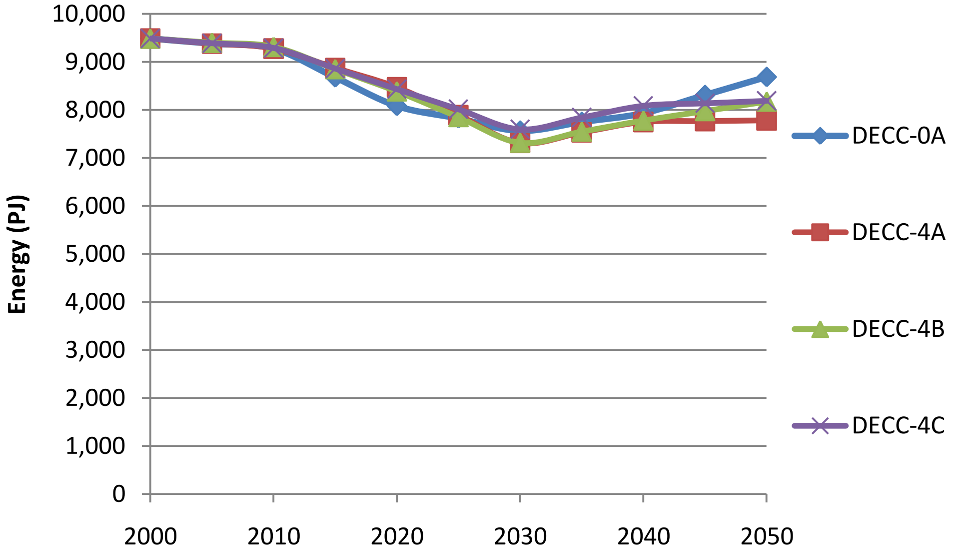


Figure 102: Primary Energy Demand over Time for Each Run

The final energy consumption has minor price sensitivity to carbon credit price with the lower price resulting in the higher demand and the higher price resulting in the lower demand. The higher priced credit run, DECC-4B, follows a very similar trend to that of the non credit run, DECC-1A. This is anticipated as DECC-4B results in the least number of credits being purchased, implying the smallest changes in the energy system as a result of the ability to buy credits.

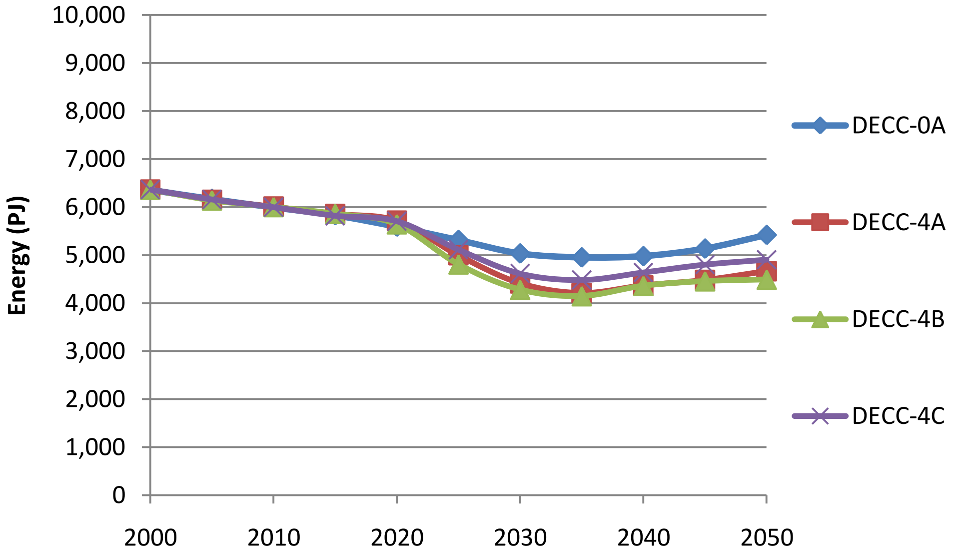


Figure 103: Final Energy Consumption over Time for Each Run

Figure 104 shows the primary energy consumption and final energy consumption of DECC-1A, DECC-4B and DECC-4A disaggregated by fuel type. DECC-4A and DECC-4C (not shown) follow a similar trend and mix of primary energy demands by fuel and final energy demands by fuel. The higher carbon credit prices of DECC-4B again result in response similar to that of DECC-1A, where a greater uptake of biomass is utilised, replacing natural gas. This increase in biomass demand in DECC-4C and DECC-1A increases the overall primary energy demand. This is particularly evident in 2050.

In the carbon credit runs, fossil fuels (oil, gas and coal) increase in primary energy demand with decreasing credit prices, with 58% of total fuel supplied in DECC-4C, 52% in DECC-4A and 46% in DECC-4B. The uptake of biomass increases to provide the difference. This is consistent with the trade-off between buying credits versus using more low carbon primary energy sources in the energy system.

In contrast to this observation, with coal there is a decrease in demand as the credit price increases from DECC-4C to DECC-4A, however demand increases again as the credit price increases in DECC-4B. As per Figure 108, this later increase is related to use of coal in electricity generation with CCS.

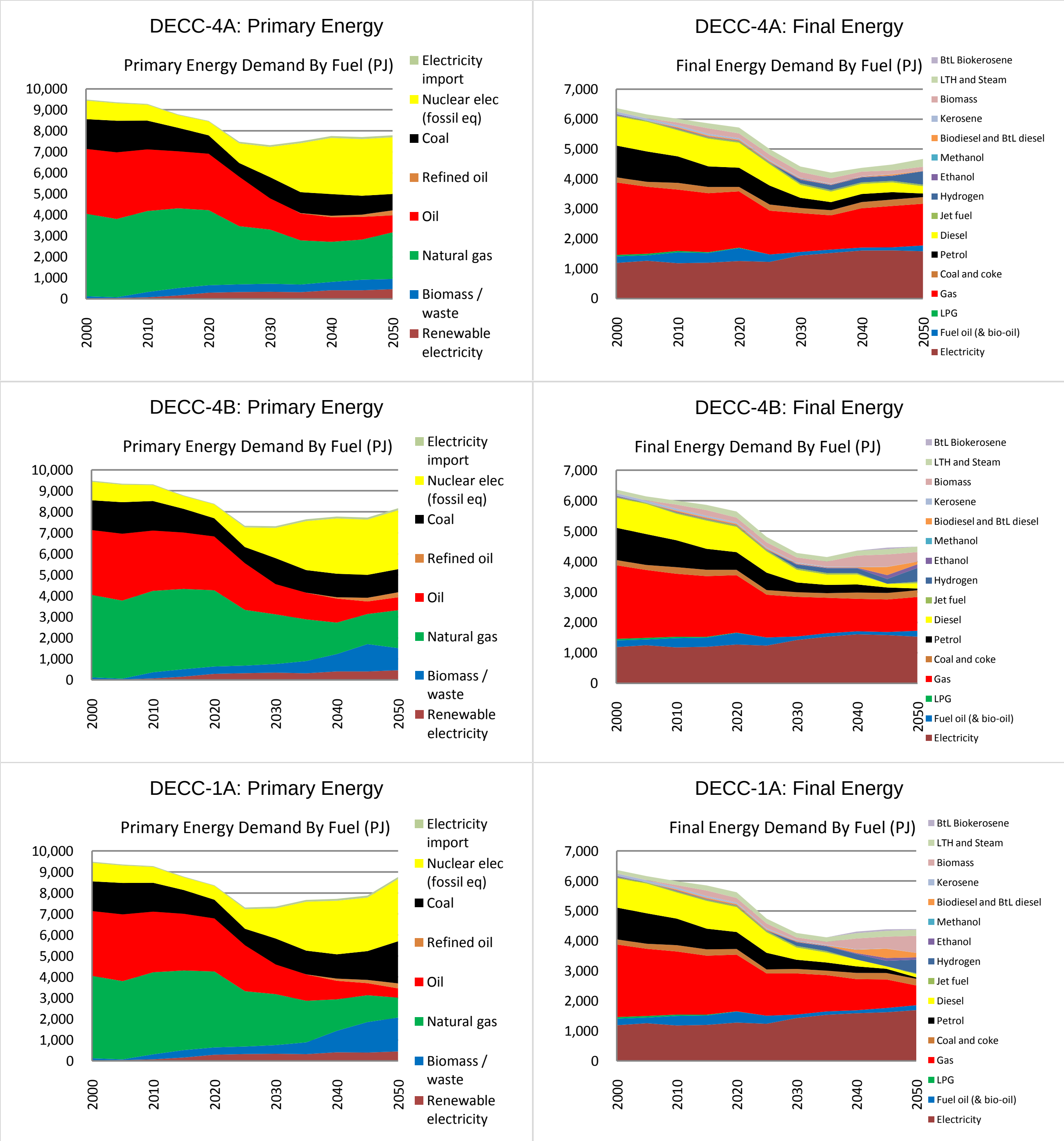


Figure 104: Primary Energy Demand and Final Energy Demand for run DECC-4A, DECC-4B and DECC-1A

The introduction of carbon credits leads to an increase in the final energy demand as the marginal cost of carbon decreases. The final energy demand figures are provided in Table 20. With no carbon credit DECC-1A, final energy demand in 4,397 PJ. With the highest priced carbon credit DECC-4B, this increases to 4,492 PJ. Final energy demand increases to 4,666 PJ in DECC-4A and is at its maximum in DECC-4C at 4,905 PJ.

Table 20: Final Energy Demand by Fuel for runs DECC-4A, DECC-4B, DECC-4C and DECC-1A

	2010	2015	2020	2025	2030	2035	2040	2045	2050
DECC-4C	5,998	5,820	5,707	5,115	4,616	4,482	4,638	4,802	4,905
DECC-4A	6,007	5,856	5,716	4,996	4,414	4,210	4,368	4,479	4,666
DECC-4B	6,003	5,862	5,644	4,809	4,281	4,148	4,361	4,458	4,492
DECC-1A	5,992	5,850	5,624	4,743	4,265	4,121	4,311	4,389	4,397

Figure 104 highlights another impact of the higher credit price of DECC-4B, similar to that in DECC-1A. The increased take up of final energy biodiesel and biomass to liquid fuels, which occurs in 2040. This is discussed further in the Transport sector section of this report. The disaggregated breakdown of bio-products in final energy demand is shown in Figure 105.

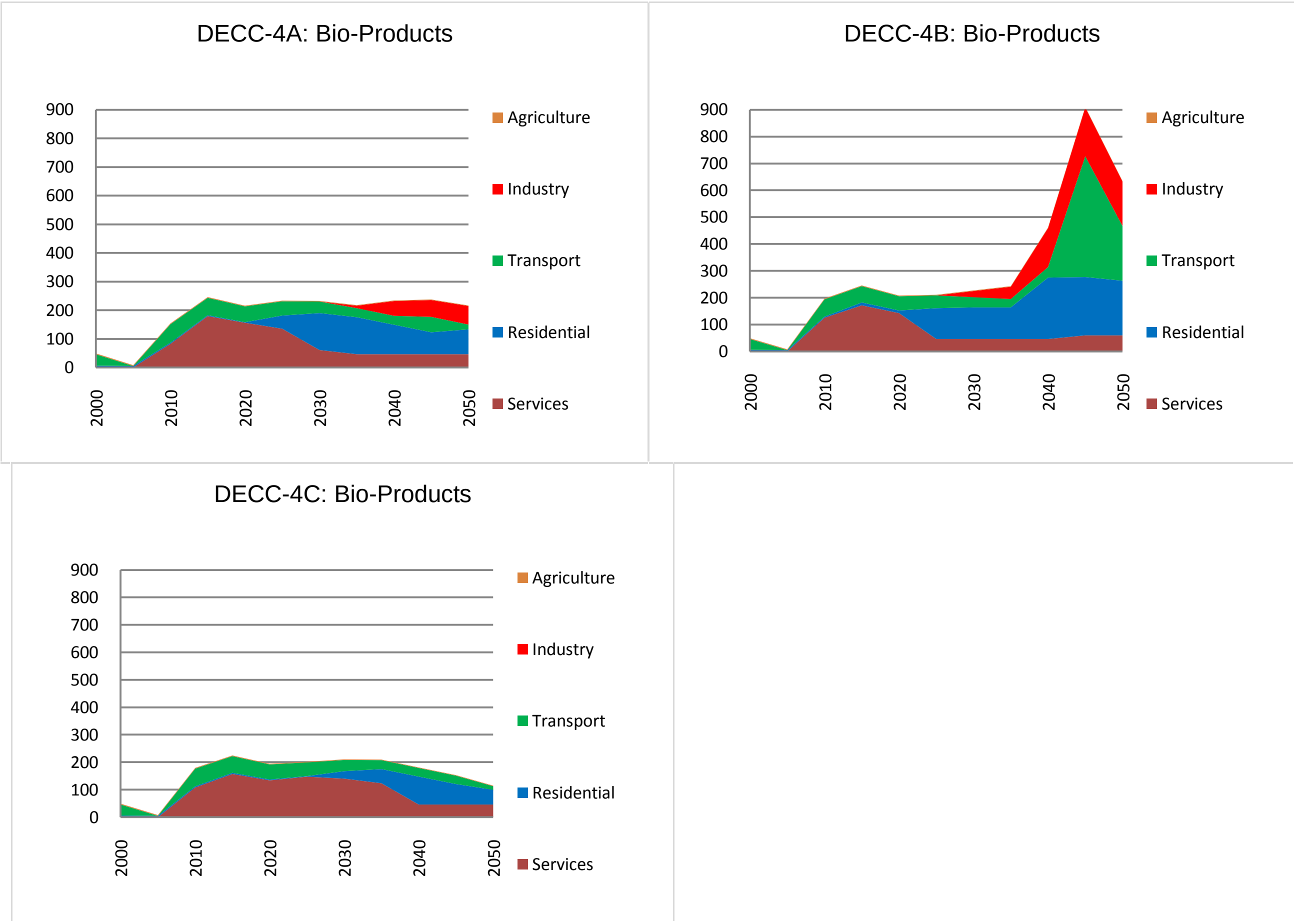


Figure 105: Bio-Products in Final Energy Consumption

The increase in carbon credit price from DECC-4C to DECC-4A results in an increase in the total bio-products meeting final energy demand. Once the marginal price of carbon is higher than this, as in DECC-4B, bio-product demand increases over threefold as it is used as biodiesel and biomass to liquid fuels in the industrial and transport sectors.

2.6.4 Power Generation and Installed Capacity

There is little difference in the total electricity generation between the 3 carbon credit runs until 2050. This is shown in Figure 106. By 2050, the least amount of energy is generated in lowest carbon credit price run, DECC-4C, whilst the most in generated in DECC-4B. Only 1.4 PJ more electricity is generated in DECC-4A, than in DECC-4C, but this is considerably less than the generation in DECC-1A. Generation in DECC-4A is 23% less than DECC-1A, and this is primarily due to the carbon credits allowing the system to avoid investment in expensive low carbon capacity and buy credits instead. A decrease in the marginal cost of carbon has resulted in an increase in the amount of energy generated.

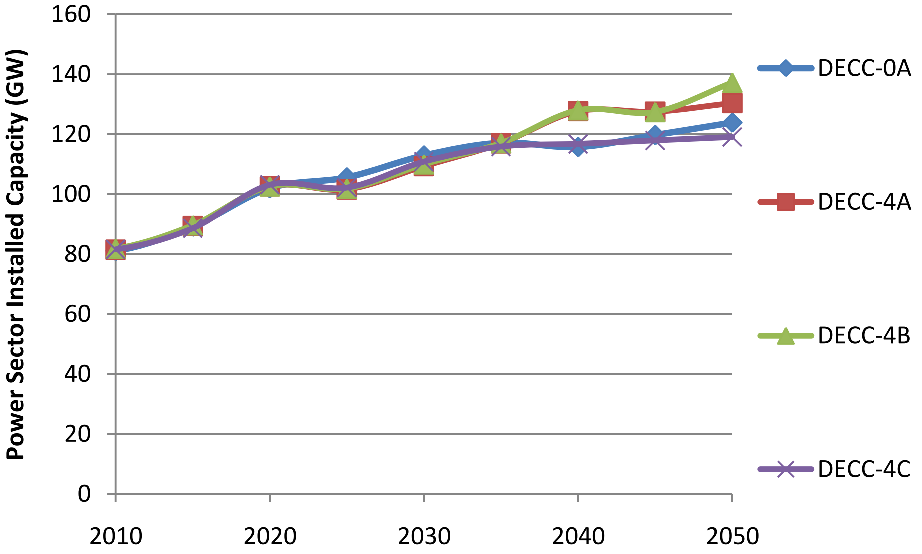


Figure 106: Aggregate Generation over Time for Each Run

DECC-4C has an installed capacity of 119 GW by 2050. DECC-4A has an installed capacity of 130GW and DECC-4B has an installed capacity of 137GW. The 9% increase in capacity from DECC-4C to DECC-4A has resulted in a minimal increase in electricity generation. Beyond 2035, the installed capacity of DECC-4C remains relatively stable. This suggests that extreme power sector decarbonisation (to below approximately 0.06kgCO_2/kWh) entails a cost of carbon between those used in DECC-4A and DECC-4C.

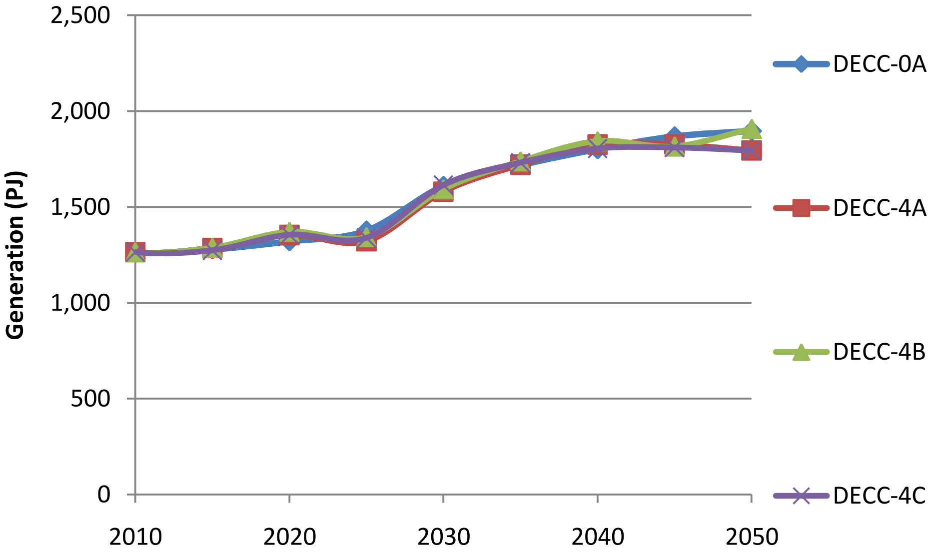


Figure 107: Aggregate Installed Capacity over Time for Each Run

The fuel/ technology mix of these generation and installed capacity profiles for these runs is shown in Figure 108. It highlights a number of differences between the different runs. The increase in generation that is apparent in DECC-1A at 2050 as a result of increased cofiring with CCS is not apparent in any of the carbon credit runs.

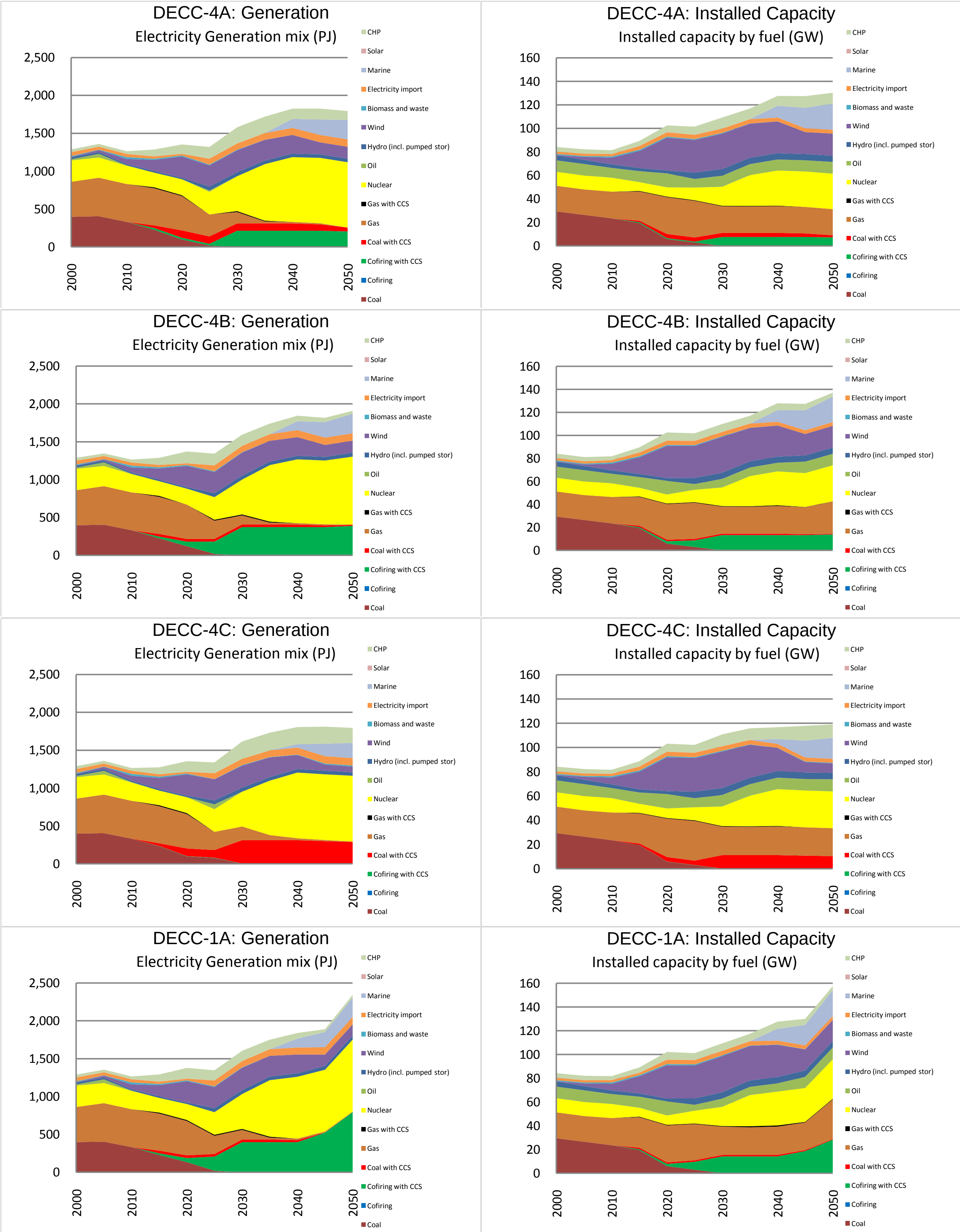


Figure 108: Generation over time by technology for DECC-4A, DECC-4B, DECC-4C and DECC-1A

Also cofiring with CCS is a marginal technology in these runs in general; it is taken up to a degree in runs DECC-4A and DECC-4B, but does not get adopted in DECC-4C. Therefore, this marginal technology relies on a higher cost of carbon than in DECC-4C, but less than those of DECC-4A. This technology is completely replaced in the low carbon credit price run by coal fired carbon capture and storage. From 2035, in the DECC-4A and DCC-4B runs, renewables (marine, wind and hydro) consistently have the same installed capacity which at 2050 is 46GW. In contrast, the DECC-4C run only has 30GW renewables installed in 2050. This suggests there is a carbon price above the carbon credit price of DECC-4C (but below DECC-4A) at which the installation of renewable generation reaches its maximum.

In the highest carbon credit price run, we see the lowest capacity of CHP installed at 3GW, albeit arguably at higher marginal carbon price than co-firing with CCS or renewables as discussed above. In the DECC-4A run this is 9GW, whilst in DECC-4C this is 12GW. This may indicate that the higher carbon prices lead to an alternative source of low carbon heat.

2.6.5 End-Use Sectors

As is shown in Figure 109, aggregate reductions in final energy consumption follow a similar trend in both the carbon credit run DECC-4A and the non credit run DECC-1A. Reductions in emissions occur mainly in the residential and transport sectors. In the DECC-4A run, within the industry sector CO_2 emissions decline whilst energy consumption increases slightly.

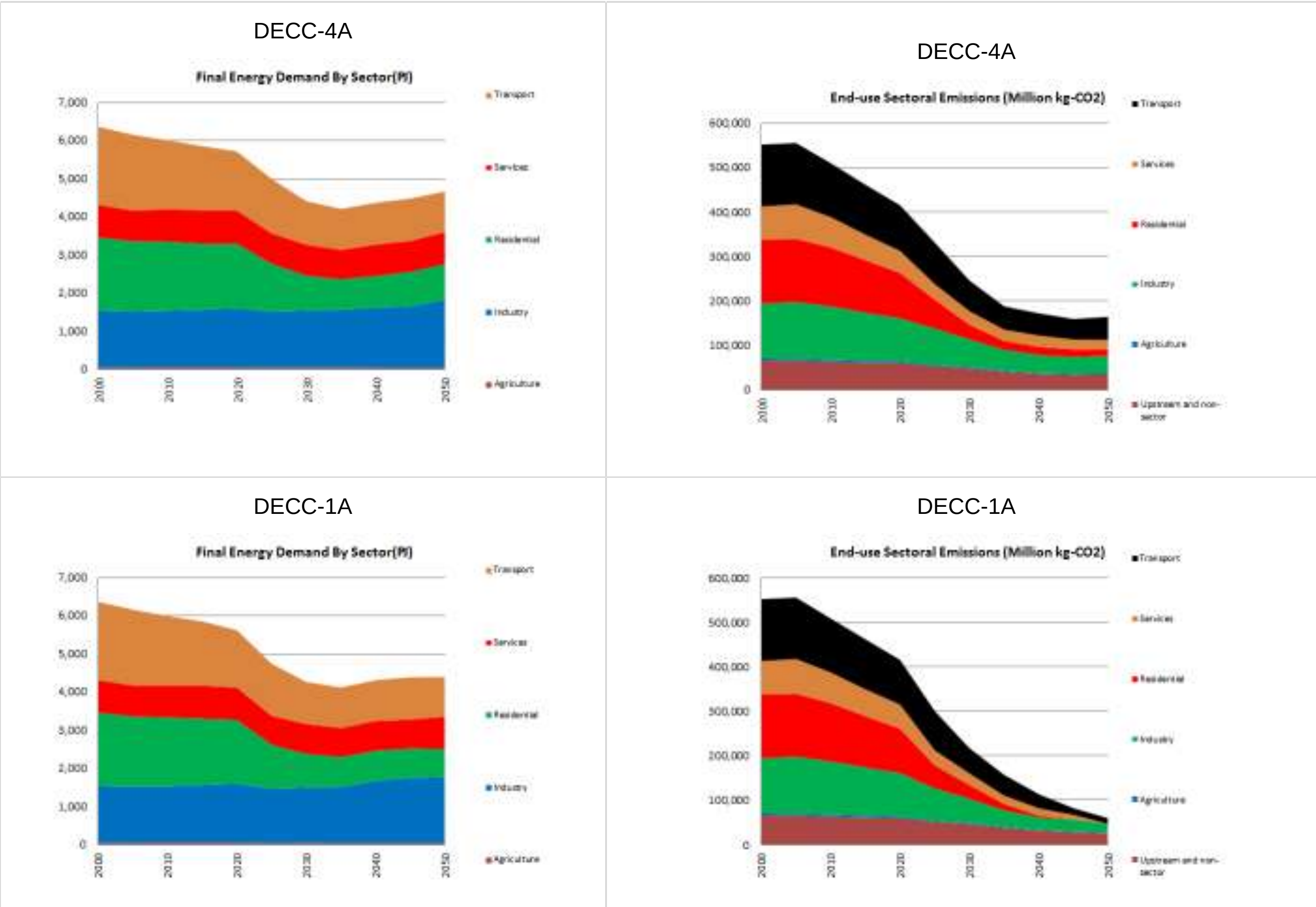


Figure 109: End-Use Sectoral Final Energy Consumption and Emissions Disaggregation for Run DECC-4A and DECC-1A

The main difference between these runs is the aggregate level of domestic emissions. In both runs, the overall emissions after credit are subtracted are constrained to the same level. Therefore, as is intuitive, the domestic emissions in DECC-4A are higher, with carbon credits purchased to ensure the national emissions constraint is upheld.

The following sections consider each end-use sector in more detail.

Industrial Sector

Figure 110 shows a comparison between the demand reduction from baseline within the industrial sector of the DECC-4A run and the DECC-1A run. Whilst the demand reduction is less in the carbon credit run, the three subsectors industrial iron & steel, chemical and non-ferrous metals have all still reached the maximum allowable demand reduction by 2035. However, whilst the limit of demand response is reached only slightly later, the ability to buy credits significantly reduces the rate at which demand reduction would be required, particularly in the 2020s.

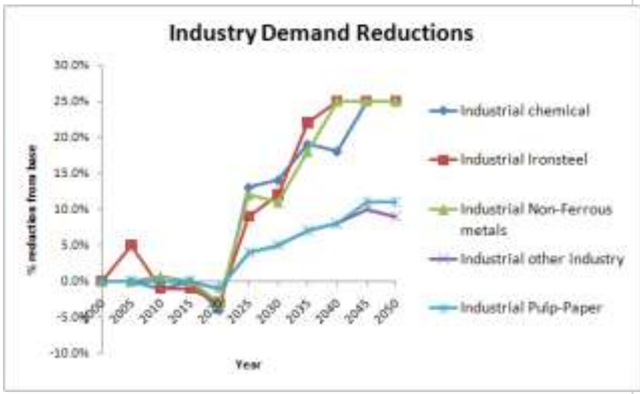
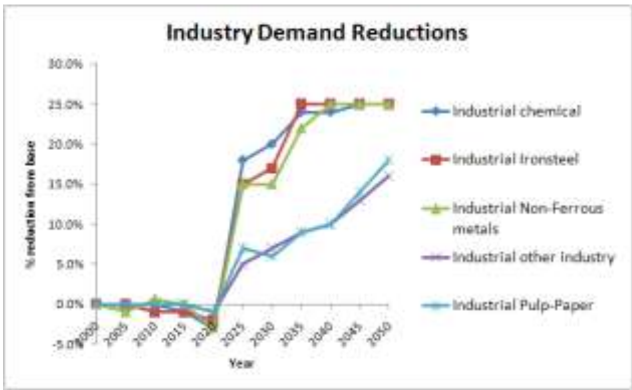
DECC-4A: Industrial Sector Demand Reduction	DECC-1A: Industrial Sector Demand Reduction
	

Figure 110: Industrial sector demand Reduction for runs DECC-4A and DECC-1A

Whilst there is a decrease in service demand w.r.t. baseline demand in the industry sector, there is an increase in the fuel demand across the timeline of the runs as shown in Figure 111.

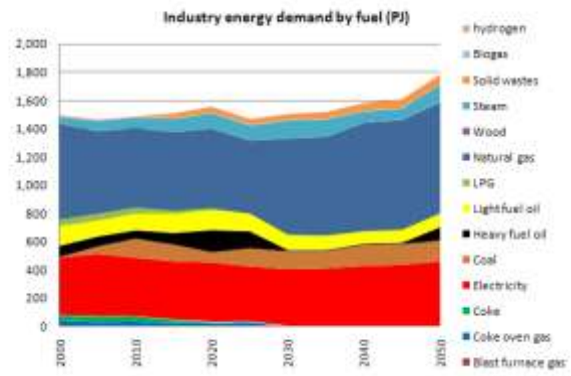
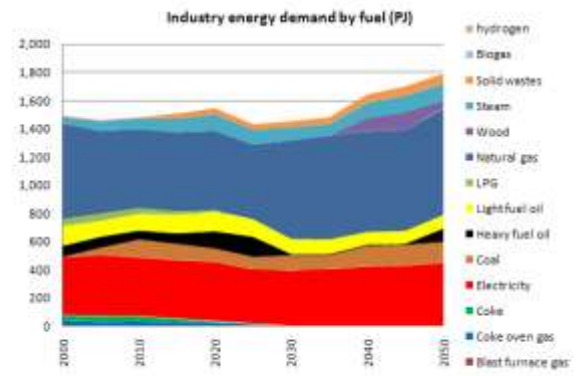
DECC-4A: Industry Energy Fuel Demand	DECC-4B: Industry Energy Fuel Demand
	

Figure 111: Industrial Energy Consumption for a runs DECC-4A and DECC-4B

The energy carrier meeting the fuel demands of the industry sector is consistent between the 2 lower priced carbon credit runs, DECC-4A and DECC-4C. Figure 111 shows that beyond 2035, the marginal energy carrier is wood, which is used as a replacement for natural gas in the higher priced carbon credit run DECC-1B.

High temperature heat is primarily used in the industrial sector. The primary energy carriers providing this high temperature heat are shown in Figure 112. Again the fuel mix of run DECC-4A and DECC-4B are very similar, with coal providing less and less of the energy mix and completely phased out by 2050, replaced by natural gas. This is not the case in the high carbon credit run of DECC-4C where coal makes a significant 7% contribution.

DECC-4A: High Temperature Heat	DECC-4C: High Temperature Heat

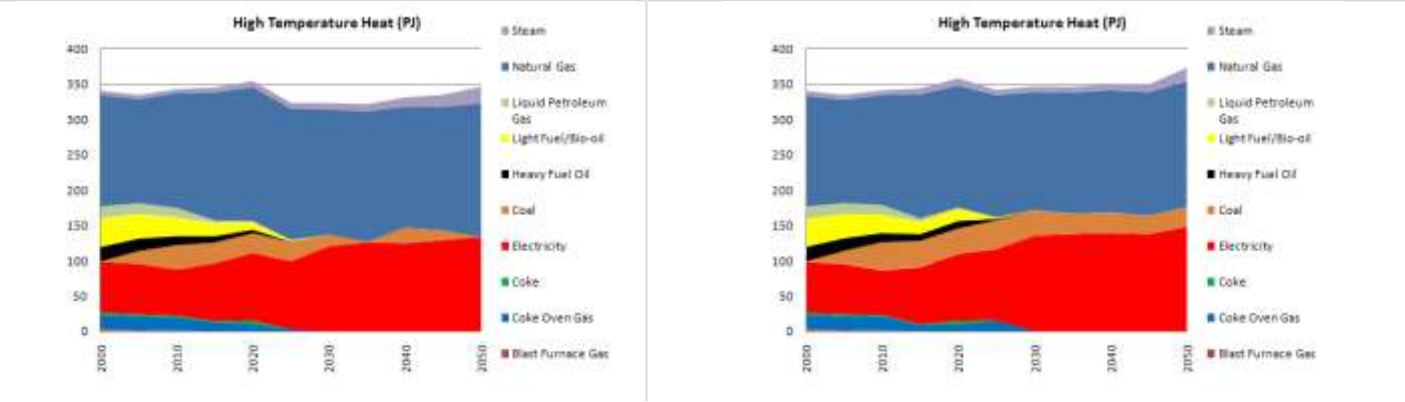


Figure 112: High Temperature Heat Fuel Mix in runs DECC-4A and DECC-4C

Residential Sector

As in Study 1, the Residential demand reduction is primarily dominated by reductions in the residential water and space heating. Table 8 shows the difference in demand between DECC-4A and DECC-1A for the residential sector. The demand in the carbon credit run is almost always higher than in DECC-1A.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Residential Demand	9.7	-6.1	16.9	98.8	31.7	15.1	34.8	137.1	205.5

Table 21: Residential Sector Difference in Demand between DECC-4A and DECC-1A

In the three carbon credit runs, the residential demand for electricity is consistent, as can be seen in the residential energy demand graphs in Figure 113. Where there is significant variation between the runs is with the energy that is used for heating. Between the lower credit prices DECC-4A and DECC-4C it is evident that there is a demand for wood and natural gas which is partially replaced by a demand for pellets in the high carbon credit run (DECC-4B). Therefore pellet-based boilers are a marginal technology in this area.

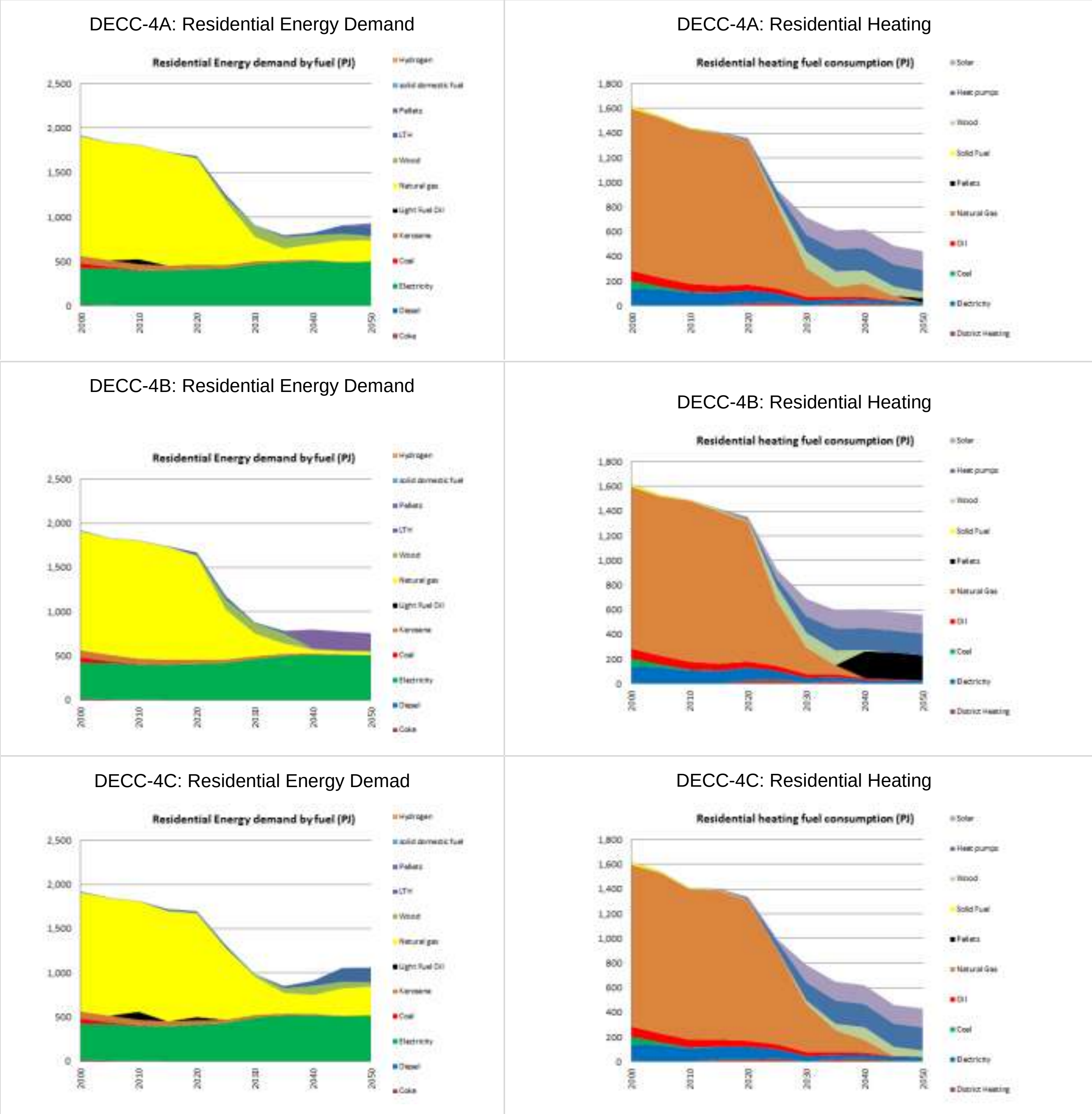


Figure 113: Comparison of Final Energy Demand and heating in the Residential Sector for carbon credit studies

In all runs there is a significant drop in the demand for natural gas. The replacement fuels that appear are solar, heat pumps (i.e. electricity), wood and pellets. With the introduction of pellets in DECC-4B, the residential heating demand remains over 25% higher than the other runs. A reduction in energy demand to meet carbon emissions targets is less necessary if pellets are the marginal fuel supply. Solar and heat pump fuel consumption is consistent across all carbon credit runs.

Services Sector

A significant reduction in demand is also evident in the service sector as shown in Figure 114. However, this demand reduction is not as large as in Study 1.

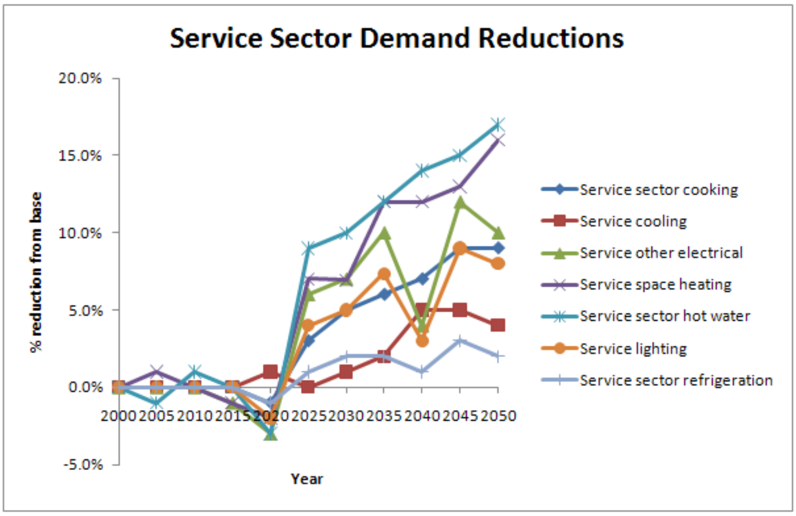


Figure 114: Service Sector Demand Reduction for Run DECC-4A

Demand in the DECC-4B run is lower than all other carbon credit runs and the non carbon credit run DECC-1A. From Figure 115, it is evident that when the carbon credits are unconstrained in 2025, in the lower carbon credit priced run DECC-4C, there is an increase in the demand for wood fuel, replacing the demand for natural gas. This is not as evident in the higher priced runs. The cost of wood places it at the margins of service sector energy demand. By 2050, the fuel mix in run DECC-4C is similar to the mid priced run. In the higher carbon credit priced run, a demand for pellets occurs from 2040. This is not evident in the other runs, but does feature in the study 1 run. This demand for pellets as a fuel completely replaces the demand for wood fuel.

As can be seen from the right hand side of Figure 115, wood fuels and pellets, where used, both supply heat in the service sector.

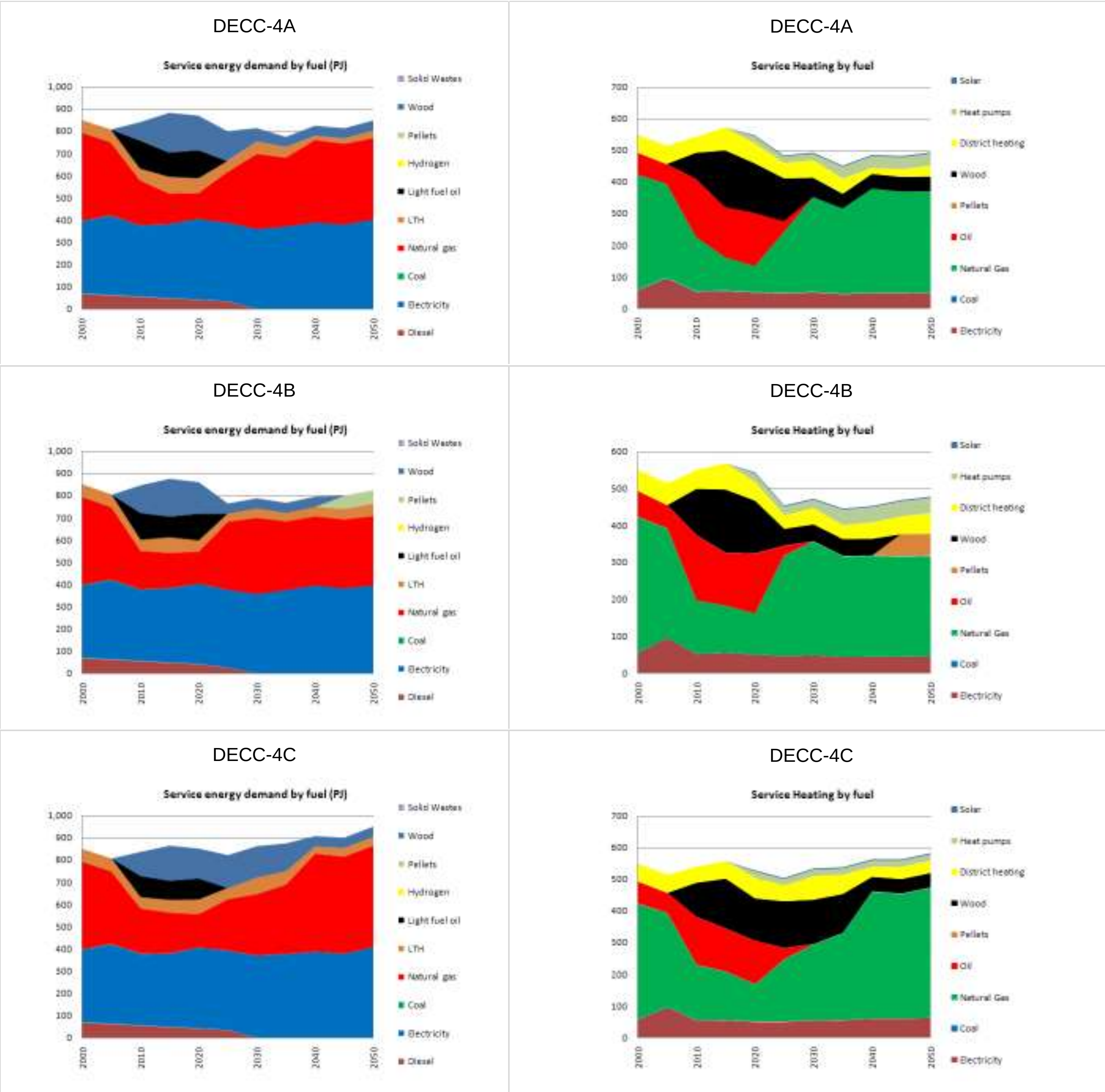


Figure 115: Service Sector Energy Demand and Heating Fuel Demand for carbon credit runs

Transport Sector

Vehicle kilometres travelled increases across almost all transport modes throughout the timescale of the study. The exceptions are buses and 2 wheel vehicles. There is however a decrease in the demand for transport in comparison to the baseline as is shown in Figure 116 for run DECC-4A. During this period there is a 62.7% drop in end use emissions.

The total fuel demand across each of the runs is consistent between each of the runs. The composition of this fuel demand does differ as can be seen in Figure 117. The higher marginal cost of DECC-4B, results in an increased uptake of the marginal fuel types biomass to liquid biodiesel and ethanol. This was seen in the total system final energy demand in Figure 104.

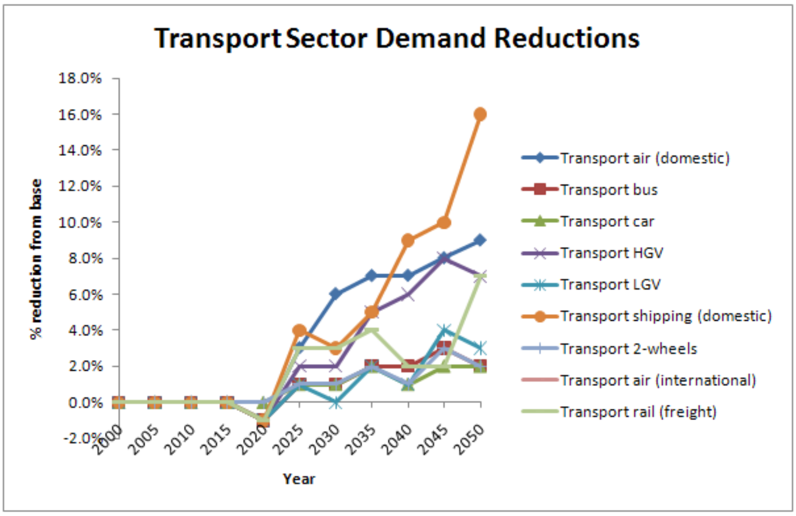


Figure 116: Transport Demand Reduction for Run DECC-4A

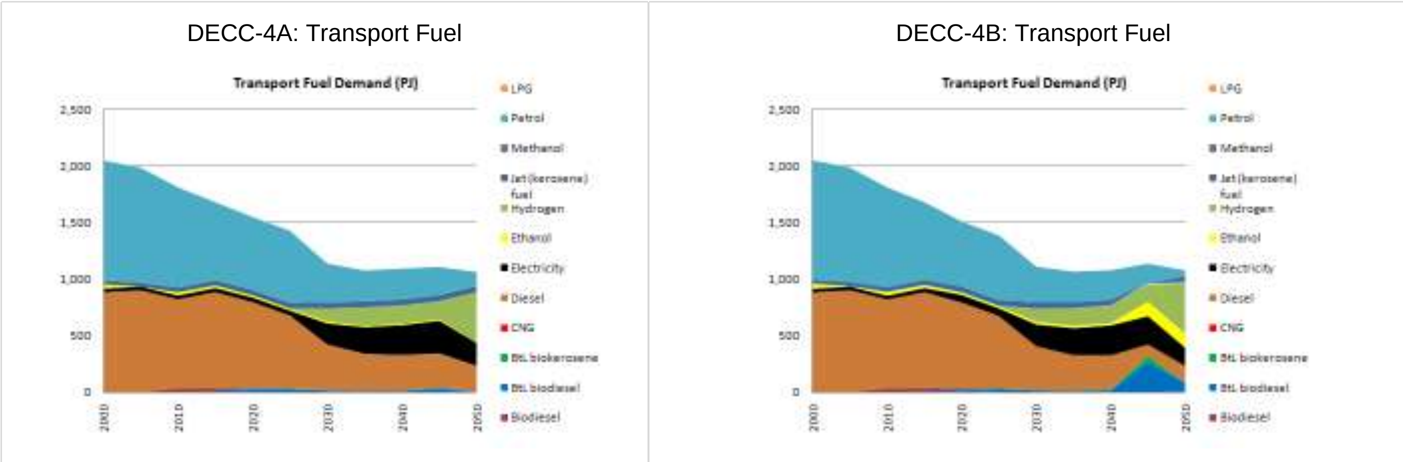


Figure 117: Transport Final Energy Consumption for Runs DECC-4A and DECC-4B

The technologies using these are shown in Figure 118 where the uptake in liquid to biodiesel is primarily used by Light Goods Vehicles and Cars.

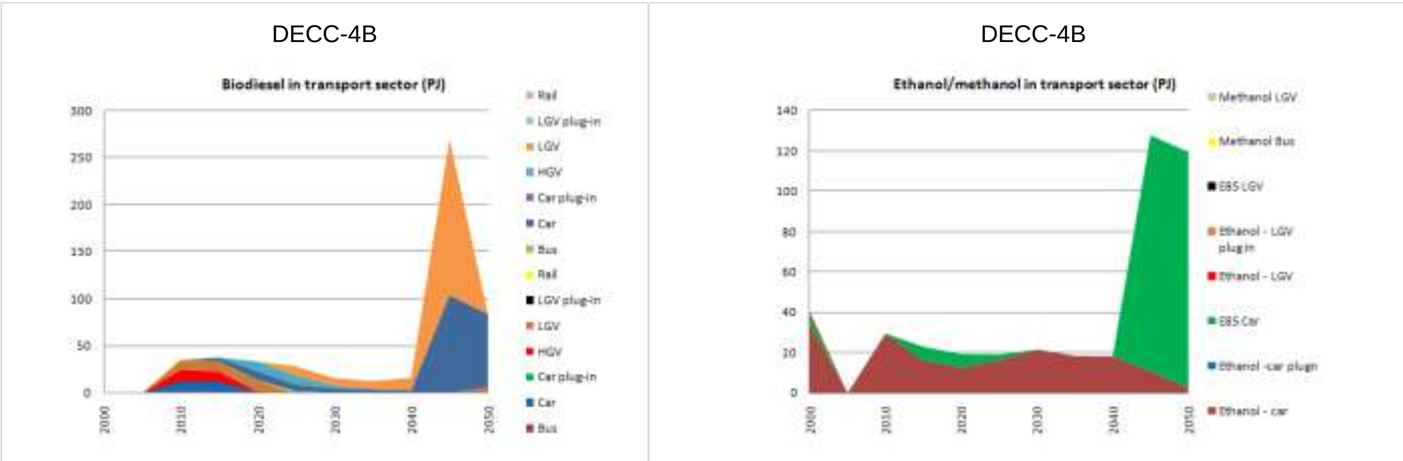


Figure 118: Transport Technologies Utilising Biodiesel or ethanol/ methanol in run DECC-4B

More than half of the energy demand in the transport sector is from car technologies. This has the most heterogeneous source of fuels. This is shown in Figure 119. Across all the carbon credit runs, the uptake of hybrid flex-ethanol technologies beyond 2040 that takes place in DECC-1A does not take place, hence the cost of this technology remains beyond the carbon credit cost.

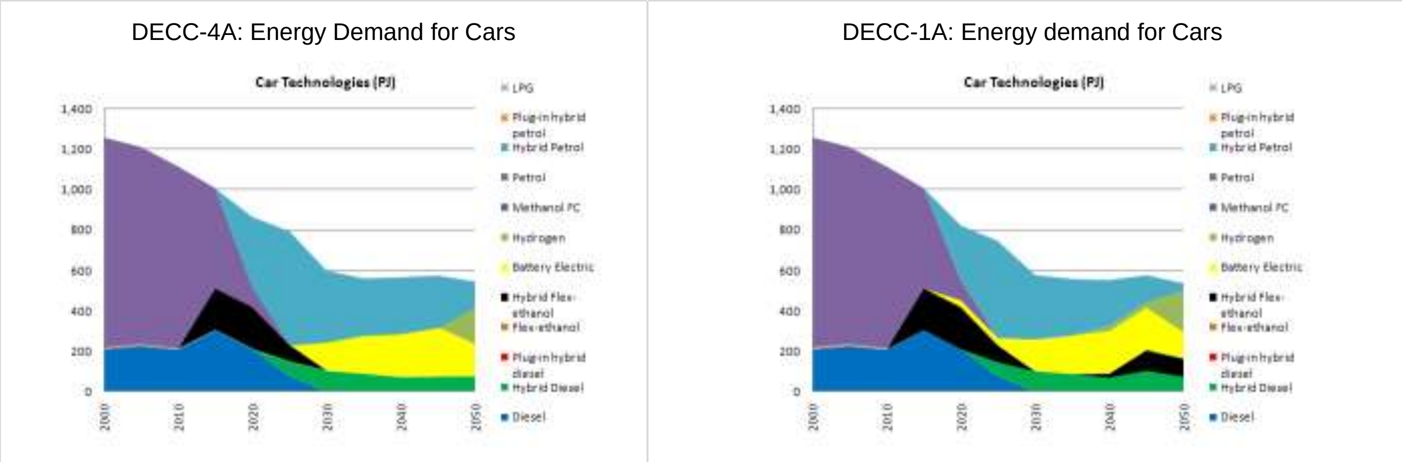


Figure 119: Energy demand from Car Technologies for runs DECC-4A and DECC-1A

2.7 Study 5: No Demand Response

2.7.1 Description of Study

This study explores the pathways to a 90% CO_2 emissions reduction in the energy system by 2050, but adds the additional dimension that the demand response feature of MARKAL ED has been switched off. This removes an important source of potential CO_2 reduction available to the model. As was seen in the central demand and central fossil fuel price run (DECC-1A), demand response is taken up heavily in the model results, all the way up to the upper bound in many cases. This study investigates the influence of removing this option and forcing the model to meet the full service demand. This study consists of a single study:

1. Study 5 Run A – Central Service Demand and Central Fossil Fuel Prices. 90% reduction in emissions by 2050. No demand response.
   Code **DECC-5A-EO**

The pathways for emissions reduction in the run are bound by the trajectories as per the report for study 1. In this study comparisons are made with the run DECC-1A, which is identical to this run except for the fact that demand response has been switched off.

2.7.2 Key Results

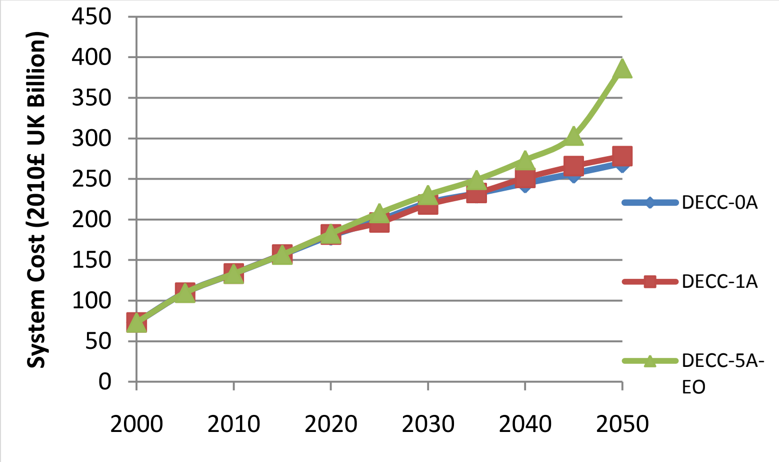
The change in discounted consumer/producer surplus for this run is presented in Table 22, with the corresponding result for the central price and central demand run from Study 1 included for comparison. For the emission reduction target of 90% (studies DECC-5A-EO and DECC-1A), the loss of surplus is £263 billion greater when there is no demand response possible. This is a very significant difference; it almost doubles the loss in surplus associated with the 90% target. Note however, as discussed further below, that the "backstop"[4] technology is adopted in small amounts in this run. This indicates that there is no technically feasible pathway to the emissions target under the current model structure, and therefore system cost and surplus metric should be treated with caution.

Table 22: Key Result Metrics

	Study 1 Run A DECC-1A	Study 5 Run A DECC-5A-EO
Baseline Run	DECC-0A	DECC-0A
Discounted Consumer/Producer Surplus (2010 £UK billions)	-293	-556

The undiscounted system costs are displayed in Figure 120, charting the annual cost of the energy system over time. The cost peak is almost 40% higher for DECC-5A-EO as opposed to either of the other runs. Costs increase radically in later years, particularly at 2050. As discussed below, this is due to the model reverting to its backstop technology.

[4] The backstop technology is a notional technology that reduces CO_2 emissions at a very high cost – indicating that there are no remaining technical options available to the model at this time.



Scenario	Undiscounted peak system cost (real 2010 prices, UK£ billion)
DECC-0A	350
DECC-1A	361
DECC-5A-EO	503

Figure 120: Undiscounted System Cost for Each Run

The marginal price of CO_2 is displayed in Figure 121. In comparison with the run with demand response switched on (DECC-1A), carbon prices are generally higher when they are switched off. By 2040, they are 66% higher, and from there the increase is extreme. This is due to the system running out of options for further decarbonisation. Finally, by 2050, the price reaches the backstop price; £5,000/tCO_2.

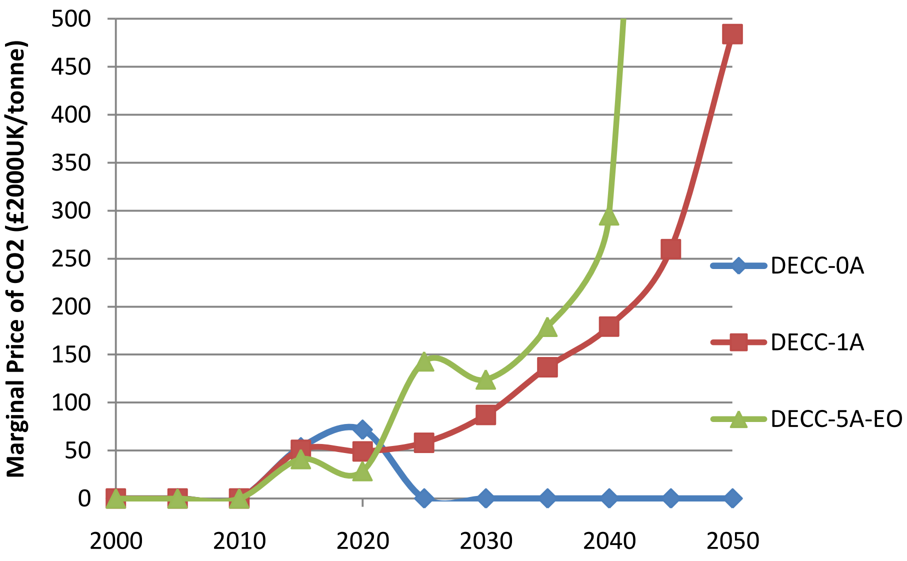


Figure 121: Marginal Cost of CO_2 for Each Run

As shown in Figure 122, the CO_2 emissions intensity of grid electricity follows approximately the same trajectory as per the run with demand elasticity. The most distinct difference here is that post-2020, decarbonisation of electricity is more rapid in the run without demand response. By 2030 to emission intensity is at 0.05 kgCO_2/kWh, and by 2040 the electricity system reaches its minimum CO_2 intensity (which is negative).

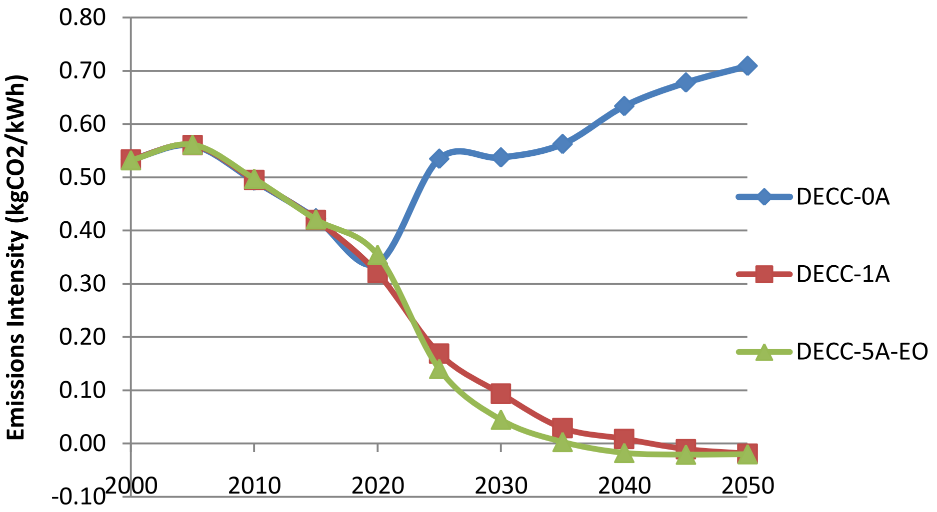


Figure 122: The Emissions Intensity of Grid Electricity

2.7.3 Primary and Final Energy Statistics

Primary energy and final energy consumption are presented in Figure 123. As expected, they are significantly higher in the run without demand response (DECC-5A-EO) when compared with the run that includes demand response (DECC-1A). In the case of primary energy, DECC-5A-EO reaches significantly higher values, 33% higher than either previous run. Final consumption is approximately equal to the baseline run. Overall this suggests that the energy system becomes much less efficient as it decarbonises where there is no scope for demand response. This may be explained by a large shift towards low carbon technologies, but these have relatively low conversion efficiency. It may also indicate greater electrification of the energy system, where losses in power generation (i.e. cooling, and transmission and distribution) become more influential.

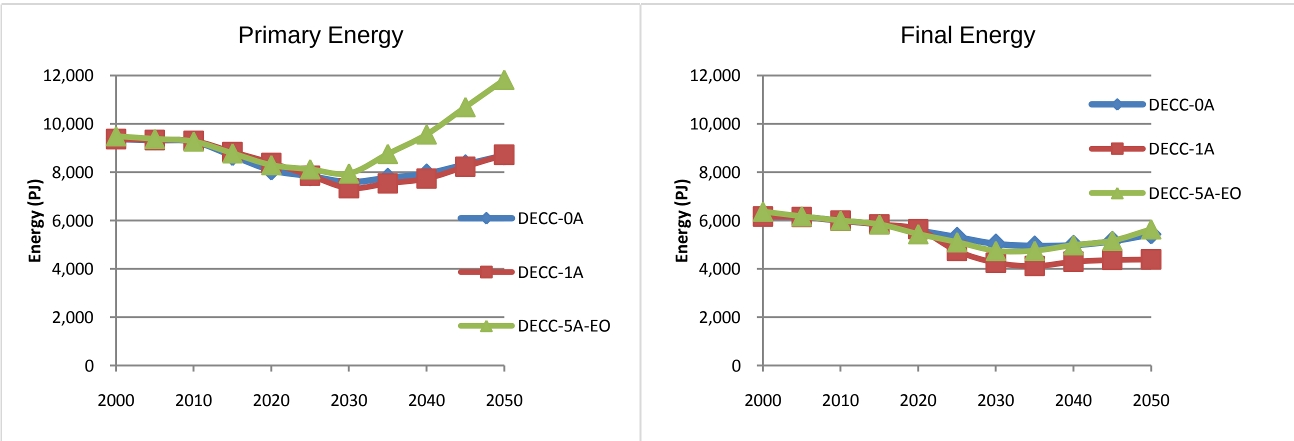


Figure 123: Aggregate Primary and Final Energy Consumption over Time

Despite the level of final energy consumption being approximately equal between the baseline scenario and the run in this study, the underlying mix of energy carriers serving that demand is quite different, as shown in Figure 124. Electricity serves a far greater portion of final consumption, and coal and coke have virtually disappeared. Hydrogen also plays a much greater role in DECC-5A-EO.

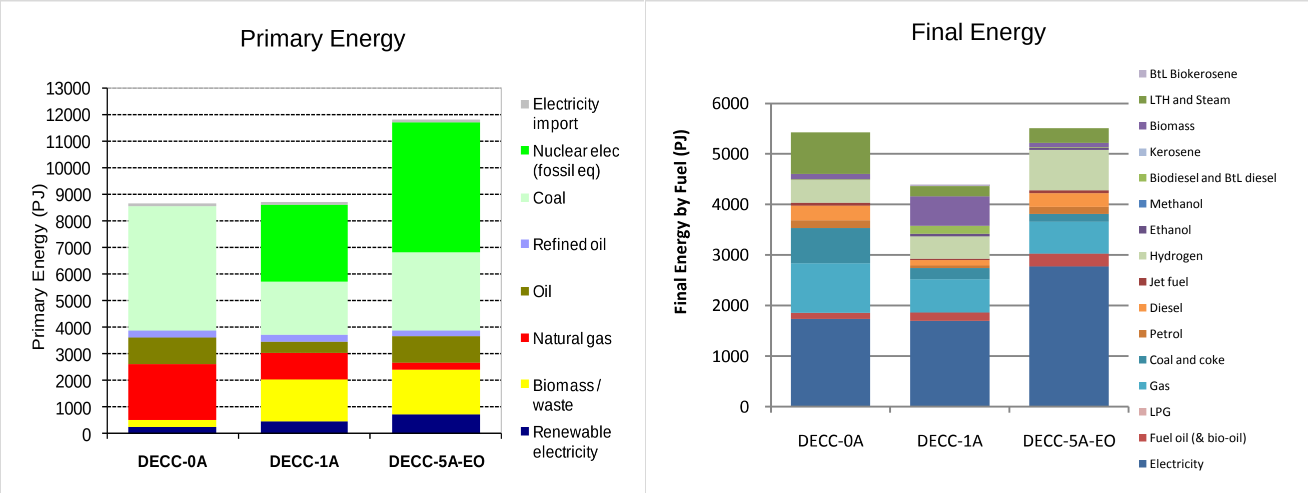


Figure 124: Primary and Final Energy Demand by Energy Carrier in 2050

A similarly contrasted view can be seen in relation to primary consumption in Figure 124. Nuclear electricity is the main contributor to meeting the increase in primary demand in the DECC-5A-EO run. Between DECC-1A and DECC-5A-EO, the distinction is less marked (other than the total level of consumption as discussed above). Use of each resource expands somewhat, although nuclear electricity and renewable electricity more-so than others.

Bio-products in final consumption are shown in Figure 125 for runs DECC-1A and DECC-5A-EO, disaggregated by end-use sector.

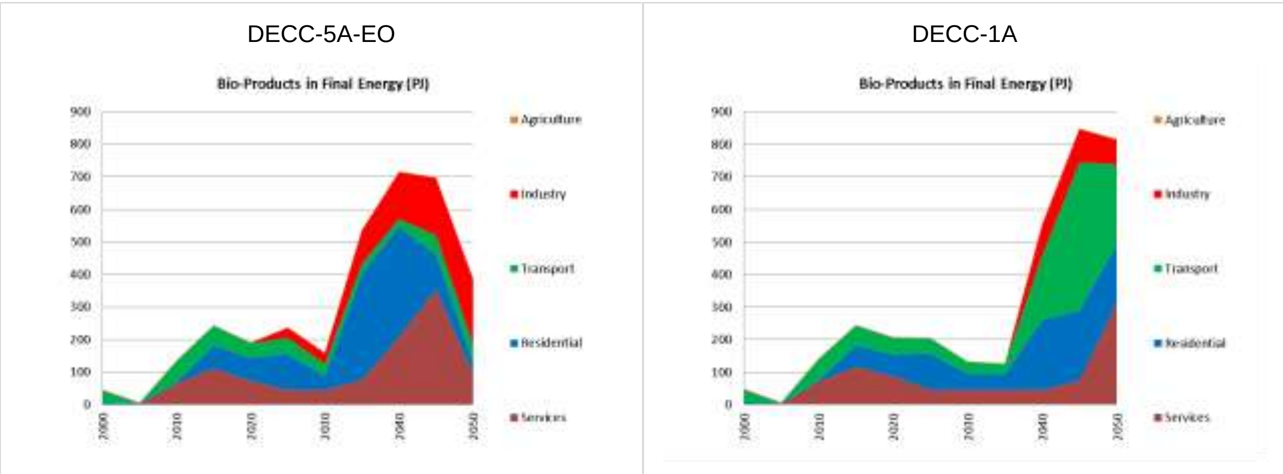


Figure 125: Bio-Products in Final Energy Consumption

In run DECC-1A, the use of bio-products increases enormously around 2035, as compared to 2030 in run DECC-5A-EO. In DECC-5A-EO bio-products are a favoured abatement measure from 2030 up to 2040; afterwards their share of the final energy consumption declines significantly. Post-2040 bio-products are displaced by electricity and hydrogen as the energy system runs out of options for further decarbonisation whilst facing a growth in energy demand, which leads to an increase in generation capacity from other energy carriers and the use of a backstop technology to comply with emission targets by 2050. By this year, bio-products directly serve almost 20% of final energy demand in DECC-1A; almost twice the level in final energy consumption shown in DECC-5A-EO by the same year.

2.7.4 Power Generation and Installed Capacity

The three scenarios represented in Figure 126 show a similar power generation trajectory up to 2020; after that, run DECC-5A-EO simulates an increase in generation motivated by larger energy demand levels than those in the two other runs. Around 2040 a marked increase in power generation can be observed in DECC-5A-EO (about 30% more than in run DECC-1A), leading to a difference of about 60% more power generated by 2050.

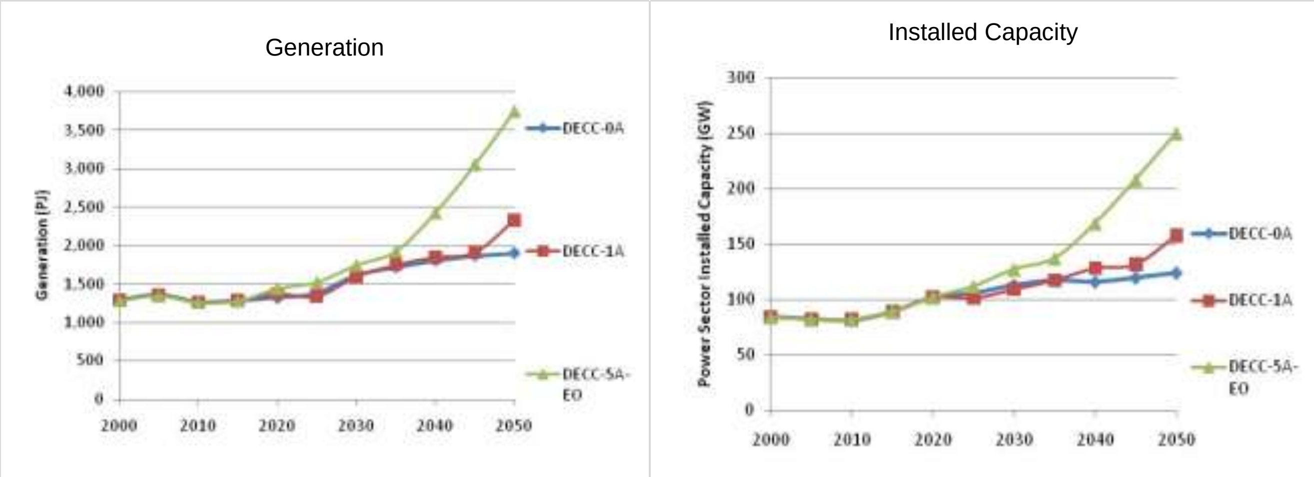


Figure 126: Aggregate Generation over Time for Each Run

The Installed Capacity graph in the right subplot (Figure 126) represents the power generation capacity of the energy system by year. As expected, the trajectories of the three runs have a similar behaviour as in the power generation graph. The installed capacity of the system by 2040 is over 30% more in scenario DECC-5A-EO than in DECC-1A, growing to almost 60% more by 2050.

As seen in Figure 127, the increased level of consumption in DECC-5A-EO leads to a significant expansion in the use of resources. As mentioned before, nuclear electricity is the main contributor to meeting the increase in primary demand, generating over 50% more than in DECC-1A. Although not as significant in terms of the amount of power generated, other technologies experience an important increase under scenario DECC-5A-EO. Marine energy increases by a third, hydropower generation is nearly two times larger and CHP generation is about four times the quantity generated in DECC-1A.

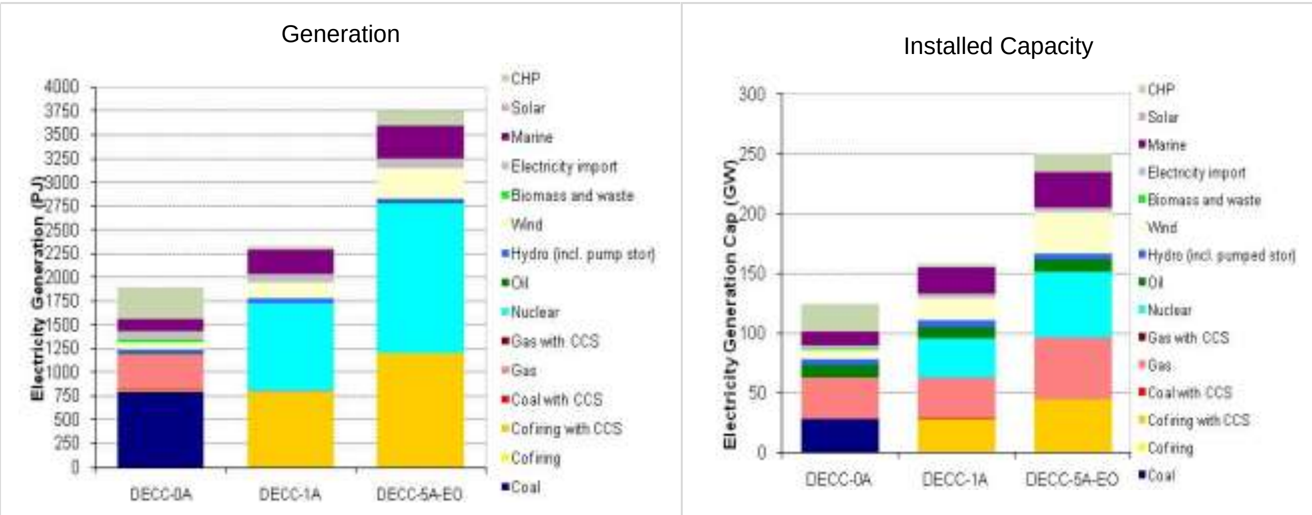


Figure 127: Generation by Technology for DECC-5A and DECC-1A Runs in 2050

2.7.5 End-Use Sectors

Sectoral and end-use sectoral CO_2 emissions are shown in Figure 128. Runs DECC-1A and DECC-5A-EO show a similar profile of emission reductions relative to the baseline (run DECC-0A), even though the final energy consumption by sector is higher in DECC-5A-EO from 2020 onwards (up to 30% more by 2050). This contrast between increasing final energy consumption and decreasing CO_2 emissions forces the system to adopt several expensive technologies before finally resorting to a backstop technology in the very last period, even though at a very high cost. Similarly to run DECC-1A, in DECC-5A-EO aggregate reductions in final energy consumption occur mainly for residential and transport sectors. Although this may be due to a combination of factors (excluding elasticity of service demand in this run), the availability of abatement technologies in each sector will play an important role.

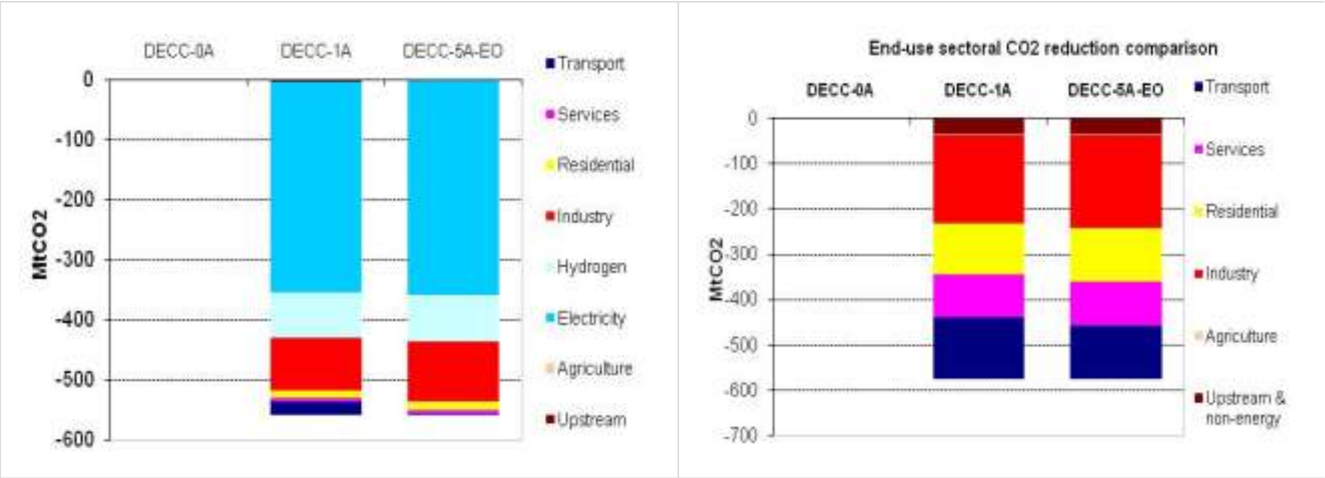


Figure 128: Sectoral and End-Use Sectoral CO_2 Emissions Reduction Disaggregation in 2050

The following sections consider each end-use sector in more detail, focusing on runs DECC-1A and DECC-5A-EO.

Industrial Sector

Figure 129 shows that the industrial sector experiences a high level of demand reduction in run DECC-1A, facilitated by MARKAL's elastic demand response characterisation. The modelled run suggests that industry might scale back operation quite significantly given the energy price rises brought about by decarbonisation; as seen in the right subplot, the chemicals, iron and steel and non-ferrous metals sectors all exhibit the maximum allowable demand reduction of 25% from the central estimate of service demand. Since scenario DECC-5A-EO has the demand response feature switched off, an important source of potential CO_2 reduction has been removed.

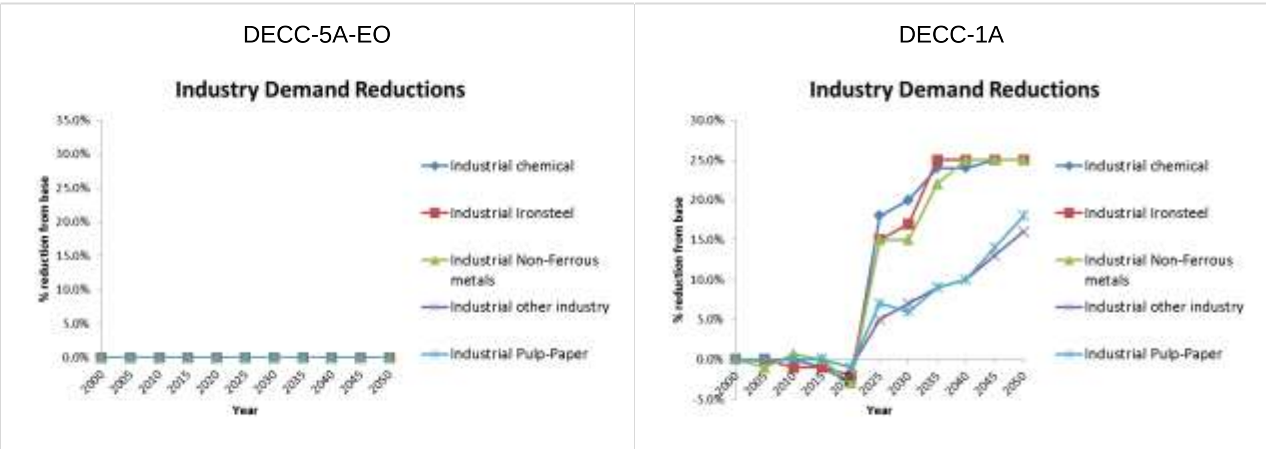


Figure 129: Industrial Demand Reductions for runs DECC-5A-EO and DECC-1A

Overall, industry energy demand in DECC-1A shows a slight decline prior to 2025 and a moderate increase from 2025 onwards. In contrast, industrial demand in DECC-5A-EO grow continuously post-2020 and more significantly from 2030 onwards. This can be seen in Figure 130, which also shows the share of each energy carrier serving final energy consumption. The total energy demand is over 20% higher in DECC-5A-EO than in DECC-1A, largely due to electricity achieving almost twice the share than in the latter run by 2050.

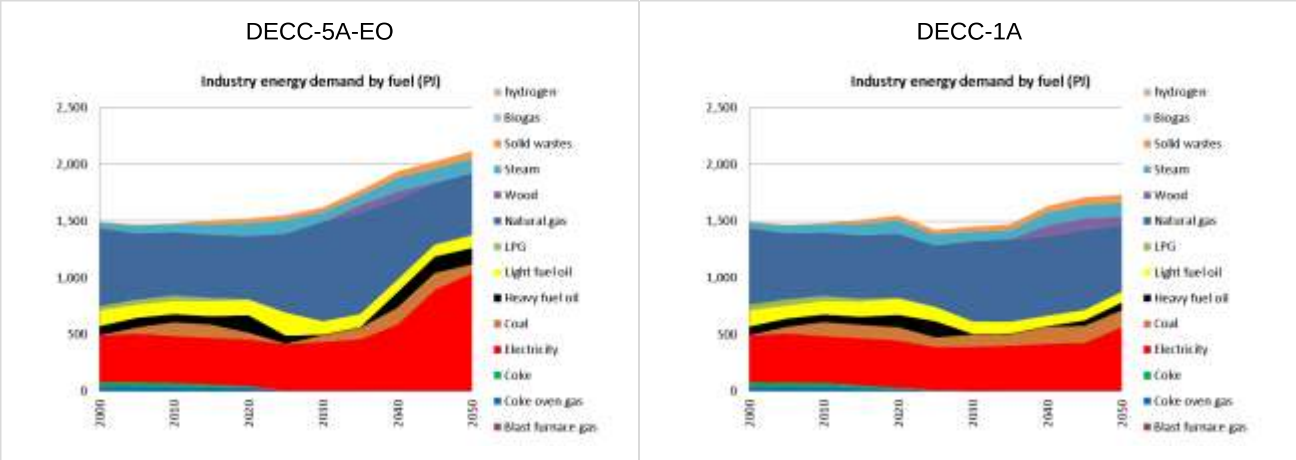


Figure 130: Industrial Final Energy Consumption for Runs DECC-5A-EO and DECC-1A

Residential Sector

In order to meet the 90% CO_2 reduction target in 2050, run DECC-5A-EO cannot rely on emission reductions resulting from demand response; it will depend largely on a number of factors such as the availability of abatement technologies and the implementation of government policies and directives such as the eco-design of Energy Using Products (EuP). Appliance and lighting products account for a large proportion of the energy consumption in the residential sector in early years, as reflected by the electricity share in Figure 13. However, electricity demand in later years is brought about by increased need for decarbonisation of heating, leading to the use of electric heat pumps and direct electric heating (e.g. night storage heating or direct resistive heating), as discussed below. The main difference between runs DECC-1A and DECC-5A-EO is the increase in electricity consumption in the latter scenario post-2035. This action allows the residential sector to decarbonise earlier in 2035 (as opposed to 2040 in DECC-1A), thus meeting targets without reverting to demand response.

Figure 131: Residential Final Energy Consumption for Runs DECC-5A-EO and DECC-1A

This increase in electricity consumption is explained to a large extent by the left subplot in Figure 131, where electricity significantly increases its share as residential heating fuel. In both runs natural gas heating is removed from the mix by 2040, being replaced by heat pumps, solar water heating and pellets. In run DECC-5A-EO pellets are removed from the mix by 2050. The removal of pellets here results in further decarbonisation because the emissions rate for grid electricity is negative, and it is therefore a sink for CO_2, as opposed to pellets which are “only” zero carbon.

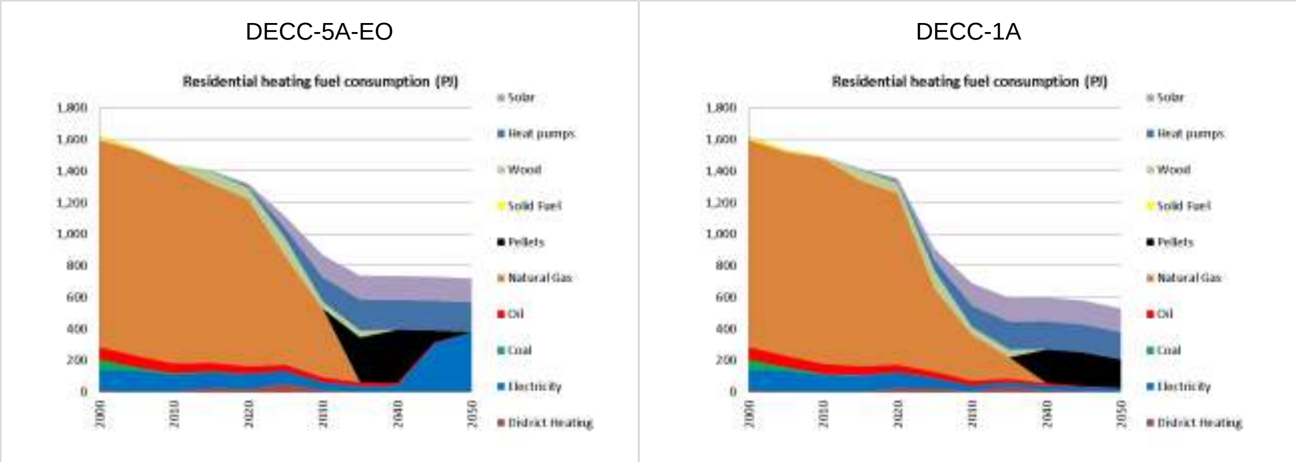


Figure 132: Residential Final Energy Consumption for Heating in Runs DECC-5A-EO and DECC-1A

Services Sector

The services sector exhibits a significant demand response in run DECC-1A; however, similarly to the residential sector, run DECC-5A-EO will rely on various factors such as the availability of abatement technologies and government regulations to meet the 90% CO_2 reduction target in 2050. Overall, as shown in Figure 133, the service sector energy demand by fuel has a similar profile for both runs up to 2030. However, the larger system demand for run DECC-5A-EO is met mainly through an increase in the share of electricity from 2035 onwards. By 2050 hydrogen has been introduced to the mix and pellets have been removed.

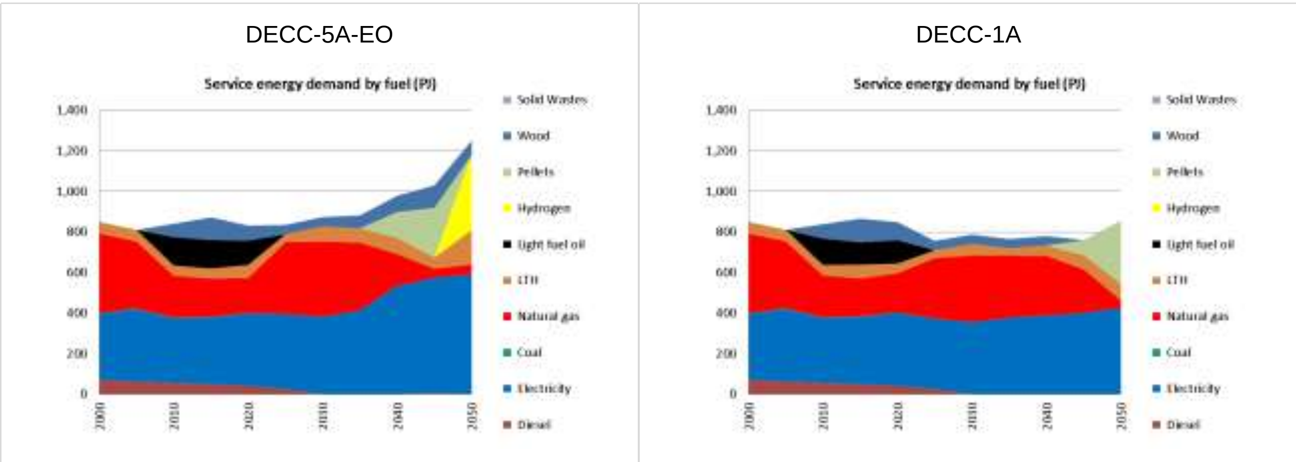


Figure 133: Service Sector Final Energy Consumption for Runs DECC-5A-EO and DECC-1A

As shown in Figure 134, the service sector final energy consumption for heating does not change significantly between both runs in the first periods of the time horizon. In the later periods for run DECC-5A-EO there is a peak in energy consumption (around 2045), mostly covered by a significant increase in the share of electricity. By 2050 both runs have significantly different mixes; in run DECC-5A-EO pellets have been removed from the mix, wood is still present (although in a small proportion) and electricity has more than doubled its share in the fuel mix.

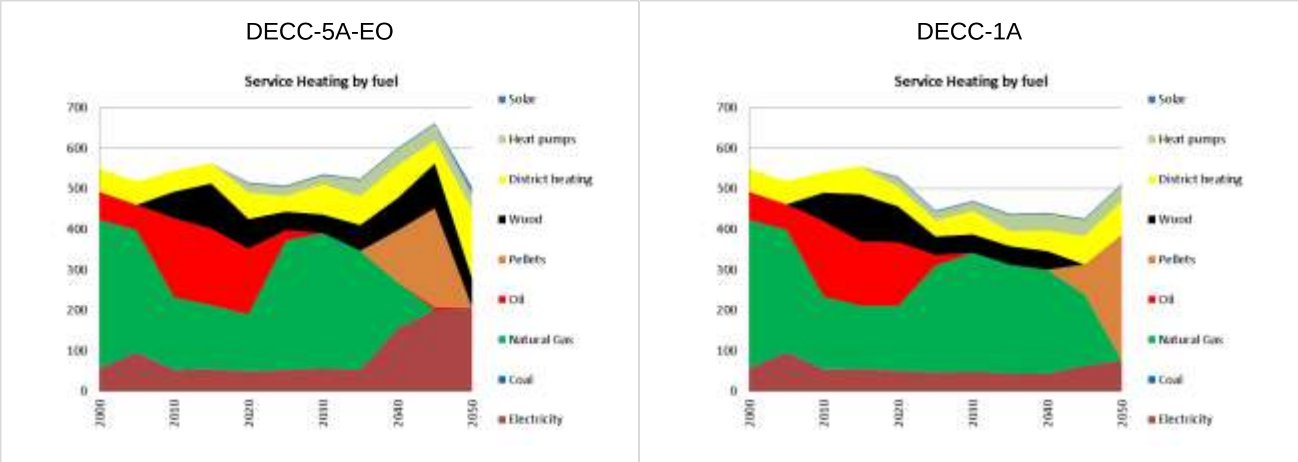


Figure 134: Service Sector Final Energy Consumption for Heating in Runs DECC-5A-EO and DECC-1A

Transport Sector

In comparison to the other end-use sectors, transport shows the least demand response in run DECC-1A. This response is limited to approximately 5% for most service demand categories; hence, the effect of switching off the demand response is not as evident as in the previous sectors.

As illustrated in Figure 135, transport fuel demand declines significantly over time in an attempt to meet a 90% reduction in CO_2 emission targets. This effort also involves a change in the fuel mix to more cost-effective options, factoring in the various constraints such as supply, technical limitations and emission targets. In both runs, petrol and diesel decrease their share in the fuel mix over time; however, in run DECC-5A-EO BtL biodiesel is removed from the mix by 2050, and replaced mostly with diesel. This suggests there are other places in the energy system where this bio-energy can be used, where it is more effective than in transport for run DECC-5A-EO. This is likely to be in electricity generation, where the system is able to create a sink via co-firing coal and biomass with CCS, as shown in Figure 127.

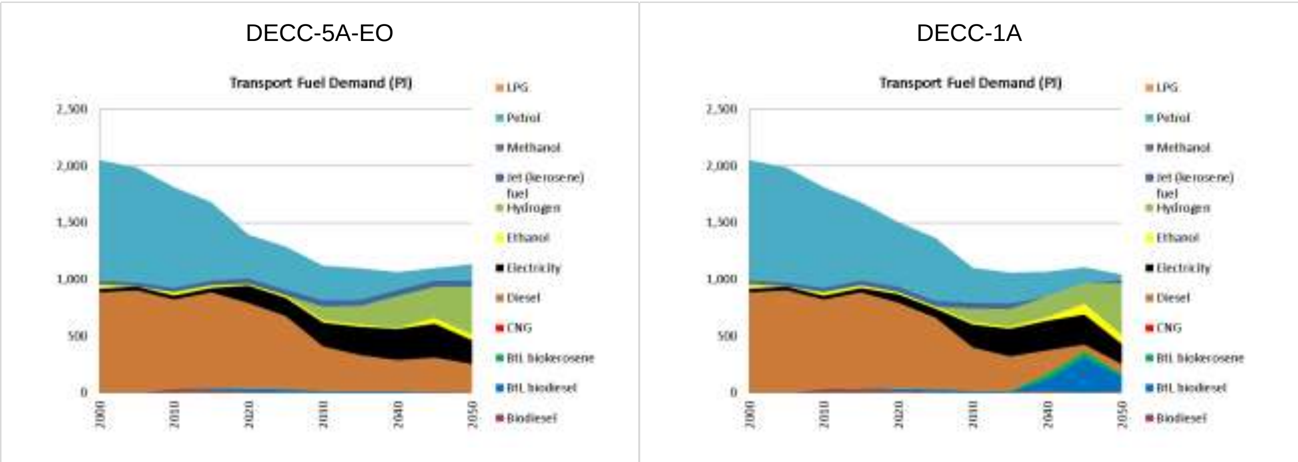


Figure 135: Transport Fuel Demand for Runs DECC-5A-EO and DECC-1A

2.8 Study 6: No Action in the 2020s?

2.8.1 Description of Study

The purpose of these studies is to evaluate the effect of the target of the 4th carbon budget. The comparison studies investigate the differences between scenarios where there is no target until 2030 with the one where those targets are set from 2020 onwards following a equal annual percentage reduction trajectory from 2020 to 2050.

For all the runs in this study, additional constraints of phase 2 of the modelling have been added to the database: uptake of certain measures, such as heat pumps, biomass boilers, solar thermal and wood boilers in the residential and service sectors; limited CCS uptake rate in the industry sector and limited market shares of various transport technologies. The discount rates have been set to 3.5% across the model, and demand response limits have been imposed – limiting response to 1% of service demand per year. Therefore a further comparison with the study DECC-1A explores how the introduction of these constraints changes the technology mix.

The runs in this study are arranged as follows:

1. IA Study B Run 1A – follows the baseline trajectory to 2030, and then achieves a 90% emissions reduction target by 2050 via equal annual percentage reductions from 2030 onwards.
   Code **DECC-1A-IAB-1A**
2. IA Study B Run 1A-C – follows the baseline trajectory to 2030, and has a cumulative emissions target equal to that observed in the results of DECC-1A-IAB-2A + 10%.
   Code **DECC-1A-IAB-1A-C**
3. IA Study B Run 2A – 90% emissions reduction target – equal annual percentage reduction from 2020 onwards. This run is equivalent to study 1 run DECC-1A with the additional constraints and different discount rate as described above.
   Code **DECC-1A-IAB-2A**

The baseline run for the above scenarios is **DECC-0A-IAB-1A** and includes no carbon target except those in relation to the Government Carbon Plan. It differs from run DECC-0A in that it includes additional constraints, revised discount rates, and modified bounds on elasticity of demand.

The pathways for emissions reduction in the first and second run (1A and 1A-C) is bound to follow the trajectory of baseline system until 2030, while the third run (2A) follows the baseline system only until 2020. In the later periods, runs 1A and 2A are bound by the targets shown in Table 23. There is no annual upper bound on emissions for run 1A-C from 2030 onwards, but a single cumulative emissions target equal to that observed in the results of run 2A, plus 10%. The relaxed constraint (i.e. the additional 10% emissions leeway) prevents the model adopting the backstop technology. The "backstop technology" is a notional (i.e. unspecified) technology that reduces CO_2 emissions at a very high cost. Therefore run 1A-C has been formulated to force those technologies actually defined in the model to provide emissions reduction. In addition to that, if this constraint is reduced further, the model would give quite unrealistic results, such as the unlikely increase of marginal CO_2 price to up to £100,000 per tonne (or whatever price limit is set by the backstop technology). The model would also indicate the need to decrease emissions sevenfold in the period between 2030 and 2035. Such a transition is very unlikely to be achievable in reality, and this result would be more indicative of the scale of the technical challenge and the corresponding low chances of success of such a decarbonisation strategy.

Table 23: Emissions Targets ($MtCO_2$)

Run/Year	2025	2030	2035	2040	2045	2050
DECC-0A-IAB-1A (unconstrained)	463.31	416.03	457.23	507.15	554.07	598.05
DECC-1A-IAB-1A	463.31	416.03	265.80	160.94	97.44	59.00
DECC-1A-IAB-1A-C	18,827 total cumulative emissions (Total in DECC-1A-IAB-2A + 10%)					
DECC-1A-IAB-2A	299.81	216.60	156.48	113.04	81.67	59.00

Figure 136 shows the resulting annual emissions for each of the runs.

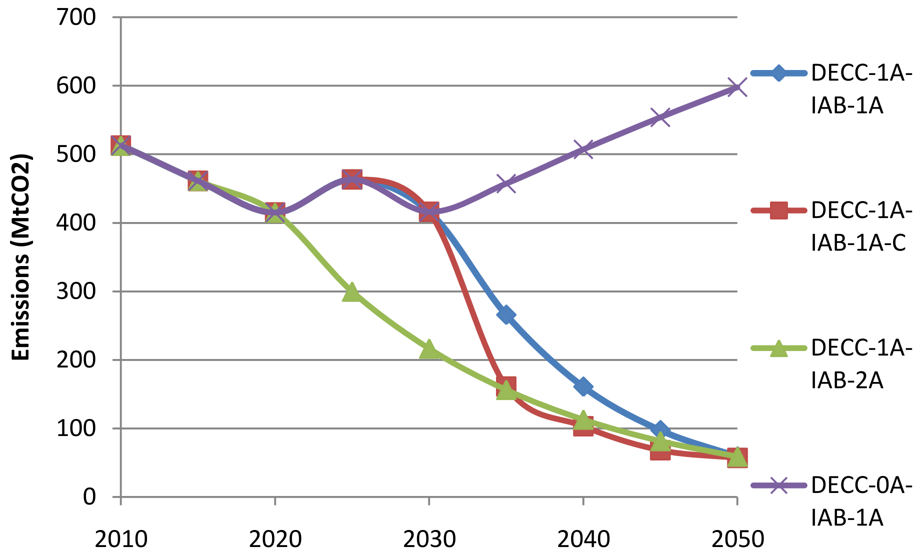


Figure 136: Emissions Reduction in all IA Study B runs

As seen from Figure 136, the run DECC-1A-IAB-1A of this study has quite a steep abatement curve compared to scenario DECC-1A-IAB-2A which starts earlier and therefore the decrease in emissions is more gradual. It is even more radical for the cumulative emissions run (DECC-1A-IAB-1A-C) which follows the baseline trajectory until 2030 but then has to suddenly meet very tight targets until 2050 to satisfy the cumulative constraint.

This study discusses the effects of earlier abatement in scenario DECC-1A-IAB-2A versus no target till 2030 policy of scenario DECC-1A-IAB-1A. It also compares the cumulative run with the untracked equal annual percentage run and the effect of the new constraints on technology uptake and demand reduction (comparison with study 1, run DECC-1A).

2.8.2 Key Results

The total discounted system cost, and discounted consumer/producer surplus for these runs are presented in Table 24. For each of these runs results need to be interpreted in the context that UK MARKAL does not endogenise technical learning (i.e. cannot benefit from early investment and learning around specific technologies), and may not capture the practicalities of real-world investment realistically. The user must input constraints on uptake rates and activity, and any under or over-estimation of these can substantially influence the resulting optimal trajectory of technology uptake and emissions reduction.

The energy system cost for scenario DECC-1A-IAB-2A is £26 billion[5] higher than baseline cost. It is a further £25 billion higher for scenario DECC-1A-IAB-1A where the decarbonisation process starts a decade later. However the energy system costs for the run with the cumulative emission target (DECC-1A-IAB-1A-C) are over £75 billion higher than for the untracked equal annual percentage run (DECC-1A-IAB-2A). This represents the cost of drastically reducing emissions in the latter half of the time horizon (2030 – 2050) as opposed to gradual reductions from 2020. Also note that the resulting total emissions are 10% higher for the cumulative run when compared to 2A (i.e. emissions are higher over the 2020s *and* over the timeframe as a whole).

The demand response is much higher for scenario DECC-1A-IAB-2A than for DECC-1A-IAB-1A, as can be seen from the figures showing total growth and reduction in surface under the demand curve. Subsequently the impact of demand response on consumer/producer surplus is greater for DECC-1A-IAB-2A run. This suggests that for the latter, the changes in system costs are affected more substantially by demand response. This result is a product of the fact that in run 2A abatement actions (and associated cost) start earlier. Therefore demand response acts over a longer period than run IAB-1A (which follows the baseline system trajectory for an additional ten years).

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[5] All figures are in UK 2010 pounds; the deflator is calculated using actual figures up to 2009 and forecasted market price change for 2010

Table 24: Key Result Metrics

	DECC-0A-IAB-1A (base)	DECC-1A-IAB-1A	DECC-1A-IAB-1A-C	DECC-1A-IAB-2A
Discounted Technical Energy System Cost (2010 £UK Billions)	5,448	5,499	5,550	5,474
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	-148	-213	-194
Discounted Welfare Impact of Demand Reduction[3] (2010 £UK Billions)	0	97	111	175
CO_2 saved over reference case (Mt)	-	7,667	8,635	10,346
Discounted change in surplus per tonne CO_2 saved (2010 £UK)	-	19.3	24.7	18.9

While the total consumer/producer surplus shows a bigger change in run DECC-1A-IAB-2A than in DECC-1A-IAB-1A, average surplus losses per tonne of CO_2 emissions saved over the entire time horizon are smaller for the earlier abating run DECC-1A-IAB-2A. The figures in Table 24 indicate that where total emission savings (from baseline) are taken into account, DECC-1A-IAB-2A surplus losses per tonne of CO_2 emissions avoided are £18.9 compared to £19.3 for run DECC-1A-IAB-1A. This indicates that early abatement results in lower surplus loss per tonne of CO_2 emissions saved.

However, the cumulative run DECC-1A-IAB-1A-C gives £18 billion greater loss of surplus than DECC-1A-IAB-2A, but the cost per tonne of CO_2 saved is about a third higher.

Figure 137 and Figure 138 shows yearly changes in area under demand curve (positive number meaning demand reduction, which has a negative impact on consumer welfare) and changes in consumer/producer surplus. Note how for scenario DECC-1A-IAB-2A the demand response starts earlier, before the other two scenarios leave the baseline. After 2030 for both runs that follow the baseline to 2030, the demand response jumps suddenly and catches up with the equal annual emissions run by the end of the time horizon.

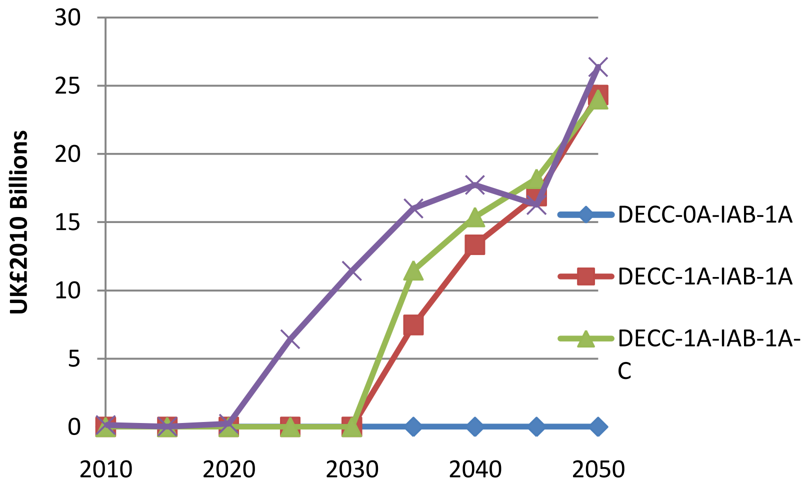


Figure 137: Undiscounted changes in area under demand curve for runs DECC-1A-IAB-1A, DECC-1A-IAB-1A-C, DECC-1A-IAB-2A (2010£UK Billion). See footnote 3 for a description of impact of changes in demand on consumer welfare.

Consumer/Producer surplus change also starts happening earlier for run DECC-1A-IAB-2A than for DECC-1A-IAB-1A (which follows the baseline until 2030). For the cumulative emissions run, the first period after 2030 costs most as the model attempts to reduce emissions extremely quickly and the surplus change is more than £25 billion pounds in a 5 year period. Later the changes become more gradual and are at similar level as for the other two runs in 2050.

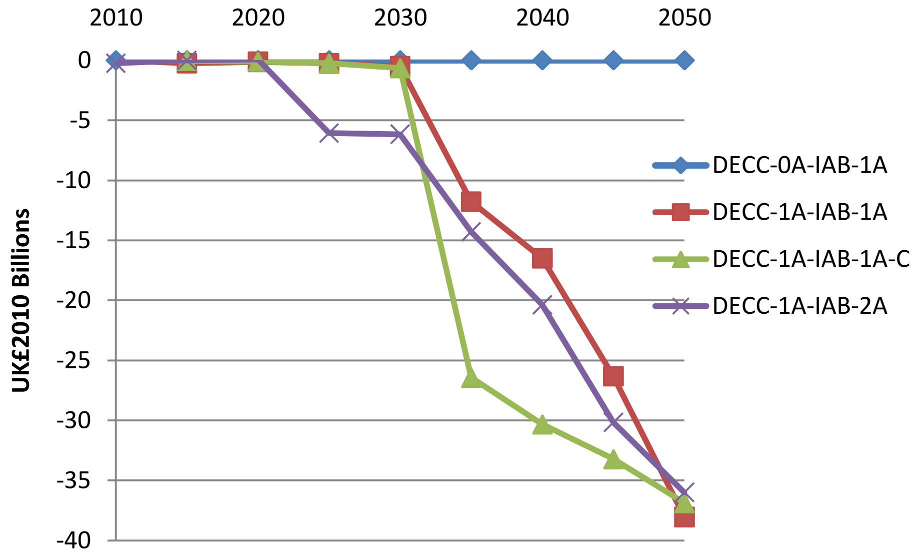


Figure 138: The undiscounted changes in consumer/producer surplus (£2010 UK billion)[6] with and without DECC-1A-IAB-1A-C run

The undiscounted annual average system costs are displayed in Figure 139, charting the annual costs of the energy system over time. The main difference, between runs DECC-1A-IAB-1A and DECC-1A-IAB-2A occurs between 2020 and 2030 (varies between £2-4 billion). This period accounts for most of the difference in the total energy system costs for these two runs, and again relates to the fact that IAB-1A must follow the baseline system to 2030. For the cumulative run the difference is larger, up to £12 billion especially during 2035 to 2040.

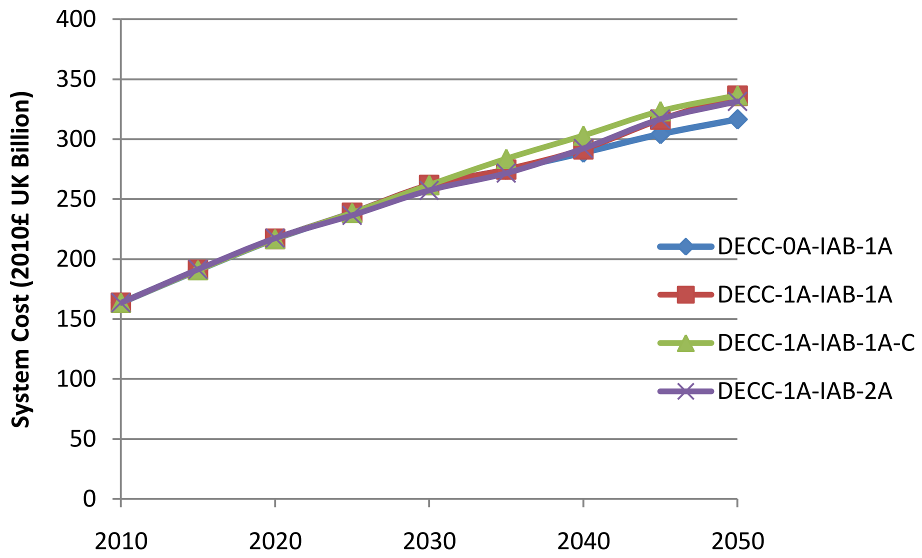


Figure 139: Undiscounted System Costs: DECC-1A-IAB-1A, DECC-1A-IAB-1A-C and DECC-1A-IAB-2A

As the DECC-1A-IAB-1A scenario is not starting abatement until 2030, in the 2020s the marginal carbon price is lower than for scenario DECC-1A-IAB-2A (Figure 62). By the end of the time horizon it catches

[6] Note that in the model results there is a small difference between the total discounted surplus parameter reported in Table 12 and the discounted sum of the undiscounted surplus changes. This means there may be a small (less than 1%) error in the numbers underlying this chart.

up and they are almost equal at £416.7 and £417.2 (2010UK£) per tonne respectively. For the cumulative run the marginal carbon price surges upwards when the target becomes binding in the 2030s, later this increase slows and in 2050 the marginal carbon price is slightly smaller than in DECC-1A-IAB-2A run at £398 (2010UK) per tonne of CO_2.

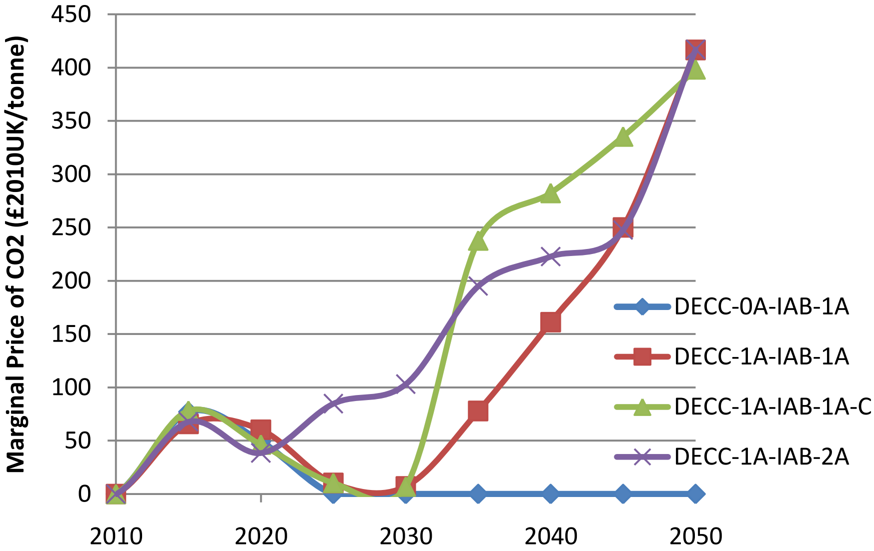


Figure 140: Marginal Cost of CO_2 for Each Run

Figure 141 shows the carbon intensity of electricity in all the IA study runs and a comparison between study 1 run DECC-1A and IA study run DECC-1A-IAB-2A. The trends are similar to those observed with emissions trajectory. For DECC-1A-IAB-2A the carbon intensity of the grid decreases gradually from 2020, while for DECC-1A-IAB-1A it drops more steeply after 2030. The cumulative run displays an even more abrupt fall in the first period after 2030 dropping almost to zero in this one period. Clearly decarbonisation of the electricity system is one of the foremost elements of any decarbonisation strategy.

In comparison with study 1 scenario DECC-1A, IA scenario with equivalent targets shows lower emissions intensity rates in 2020s and 2030s. This means that electricity decarbonises earlier in the IA study run than in study 1 run with equivalent targets. Therefore the additional constraints and frictions imposed on the model push decarbonisation onto the electricity system earlier.

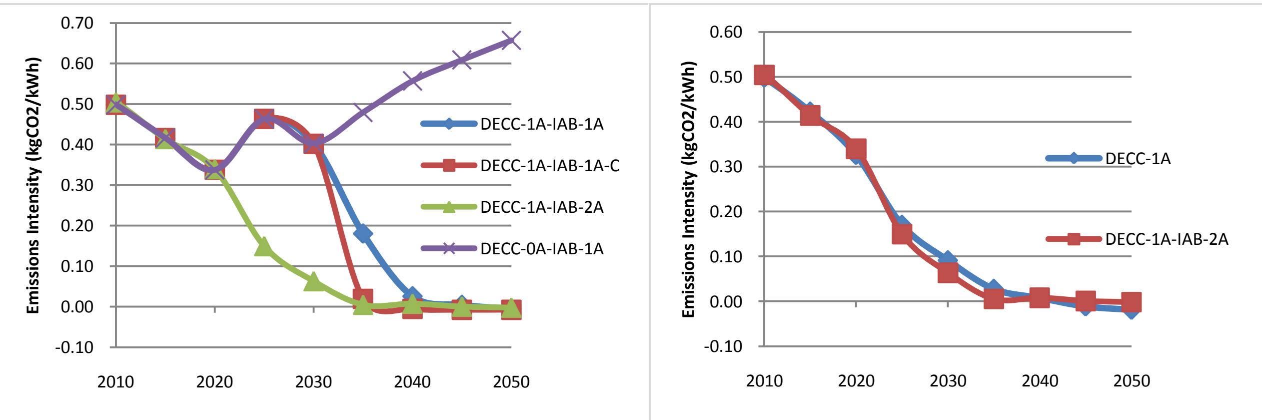


Figure 141: The Emissions Intensity of Grid Electricity

The numerical figures associated with the figure above are shown in Table 25. The numbers show that although for scenario DECC-1A-IAB-2A electricity decarbonises earlier than for scenario DECC-1A, electricity production does not become a sink for CO_2 until the end of the time horizon.

For cumulative scenario in IA study (DECC-1A-IAB-1A-C) electricity decarbonisation is especially intense in between 2030 and 2035, and electricity production becomes a sink by 2040. This is unlikely to be achievable in reality, but represents the actions necessary in a system faced with virtually unachievable targets.

Table 25: Figures for the Emissions Intensity of Grid Electricity (kgCO_2/kWh)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
DECC-0A-IAB-1A	0.50	0.42	0.34	0.46	0.40	0.48	0.56	0.61	0.66
DECC-1A-IAB-1A	0.50	0.42	0.34	0.46	0.40	0.18	0.03	0.00	-0.01
DECC-1A-IAB-1A-C	0.50	0.42	0.34	0.46	0.40	0.02	-0.01	-0.01	-0.01
DECC-1A-IAB-2A	0.50	0.41	0.34	0.15	0.06	0.01	0.01	0.00	0.00
DECC-1A	0.50	0.42	0.33	0.17	0.09	0.03	0.01	-0.01	-0.02

2.8.3 Primary and Final Energy Statistics

Primary energy and final energy consumption are presented in Figure 142 and Figure 143. The patterns are similar for equal annual percentage target runs, but the timing and scale vary. For run DECC-1A-IAB-1A the lowest demand level is higher and is reached a decade later than for DECC-1A-IAB-2A which starts to decarbonise earlier. For both cases the demand starts rising steadily after reaching the minimum level and gets to around the same level by the end of the time horizon.

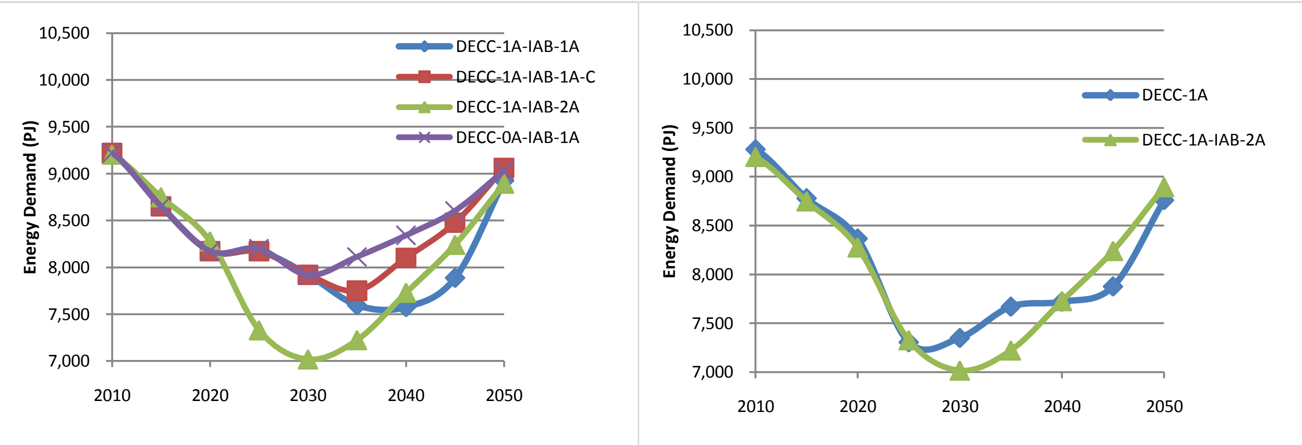


Figure 142: Primary Energy Demand over Time

The cumulative run shows even less change in primary energy demand, dropping to 7751PJ in 2035 compared to 7018PJ in 2030 for run DECC-1A-IAB-2A. This corresponds to a 10% difference. The demands are at similar levels at the end of the time horizon.

The final energy demand for runs DECC-1A-IAB-1A and DECC-2A-IAB-2A falls in the 2030s and 2020s respectively and converges to similar levels towards the end of the time horizon. The trend observed for the cumulative run is comparable to that of DECC-1A-IAB-1A.

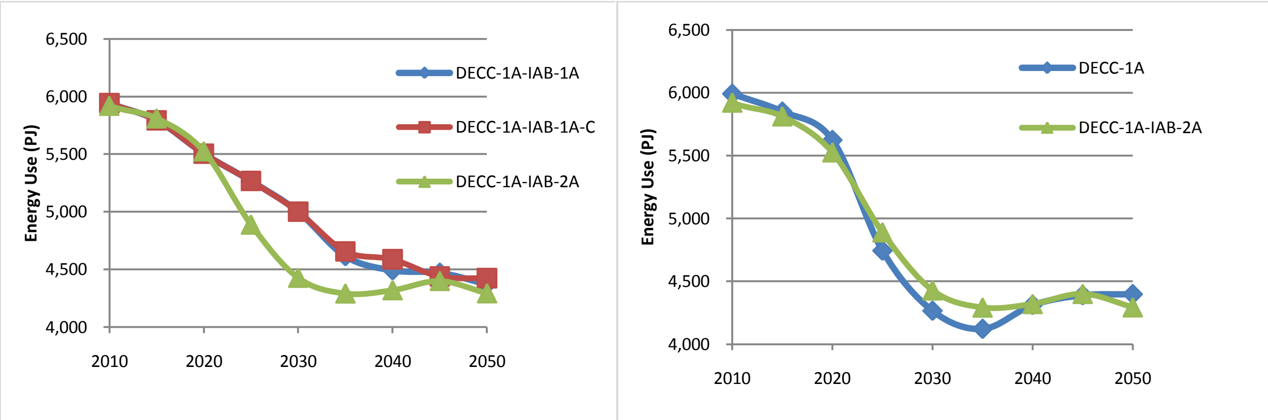


Figure 143: Final Energy Consumption over Time

In contrast with the primary energy demand patterns, the final energy consumption drops lower for run DECC-1A than for run DECC-1A-IAB-2A in the 2020s and 2030s indicating reduced transformation losses in the run DECC-1A-IAB-2A. This trend is reversed in the last two periods.

The primary and final energy consumption can be compared in terms of energy carriers as seen in Figure 144. The figure shows the composition of primary and final energy for runs DECC-1A-IAB-1A and DECC-1A-IAB-2A. In the primary energy the use of coal is decreasing in the 2020s for the latter run, being displaced by nuclear energy, while for the run that follows the baseline until 2030 the coal use increases in that period. Towards the end of the time horizon the patterns of change are quite similar for the two runs resulting in virtually the same energy carrier composition in 2050.

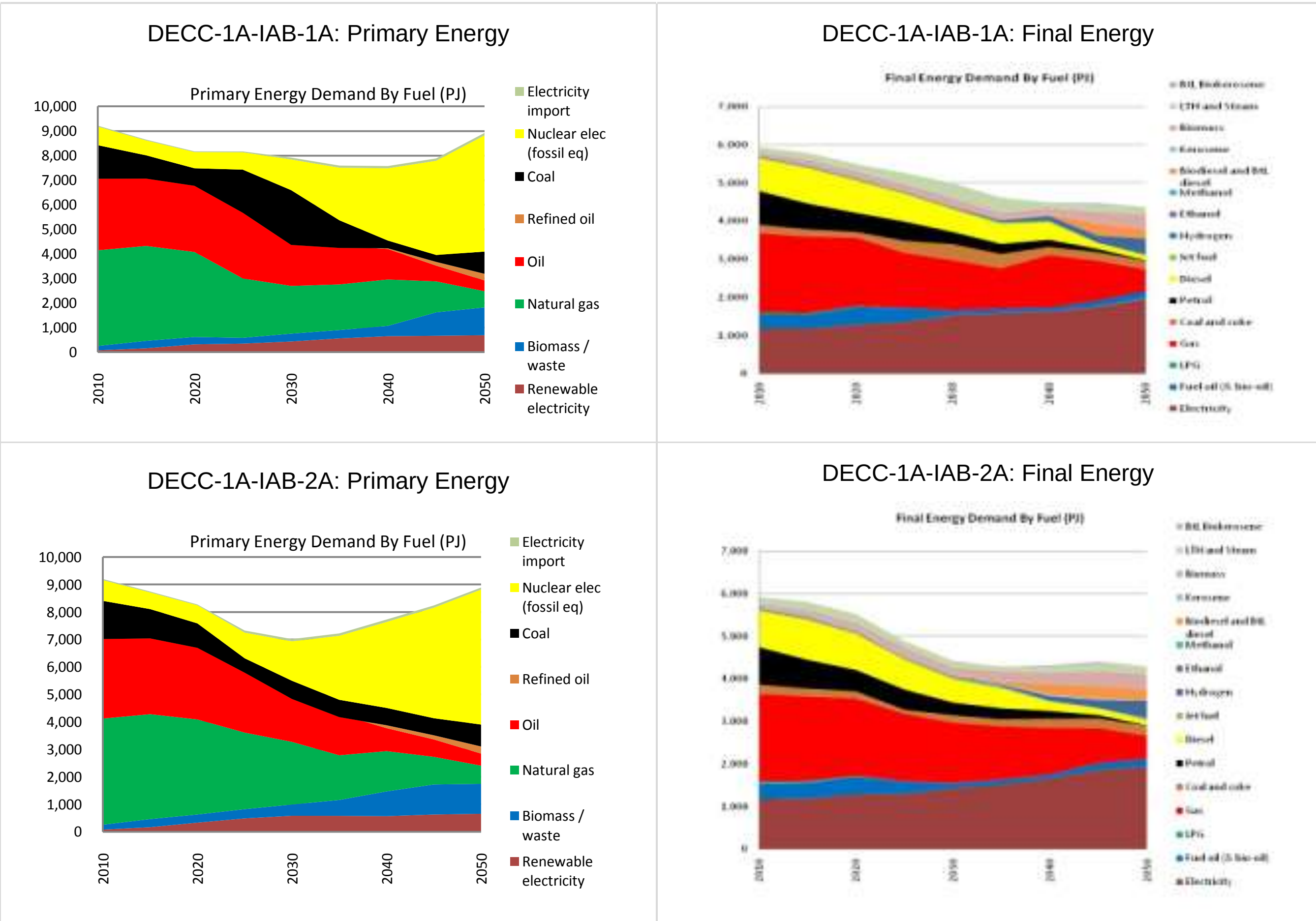


Figure 144: Primary and Final Energy Demand by Energy Carrier runs DECC-1A-IAB-1A and DECC-1A-IAB-2A

The same is true for final energy consumption. Although scenario DECC-1A-IAB-2A experiences earlier changes, the final make-up of energy use is almost identical in 2050, dominated by electricity.

For the cumulative run, the pattern of change follows the same path as DECC-1A-IAB-1A run until 2030, later it is very similar to that of run DECC-1A-IAB-2A (Figure 145). In the final period, primary energy contains a bit more coal and less nuclear for the cumulative run.

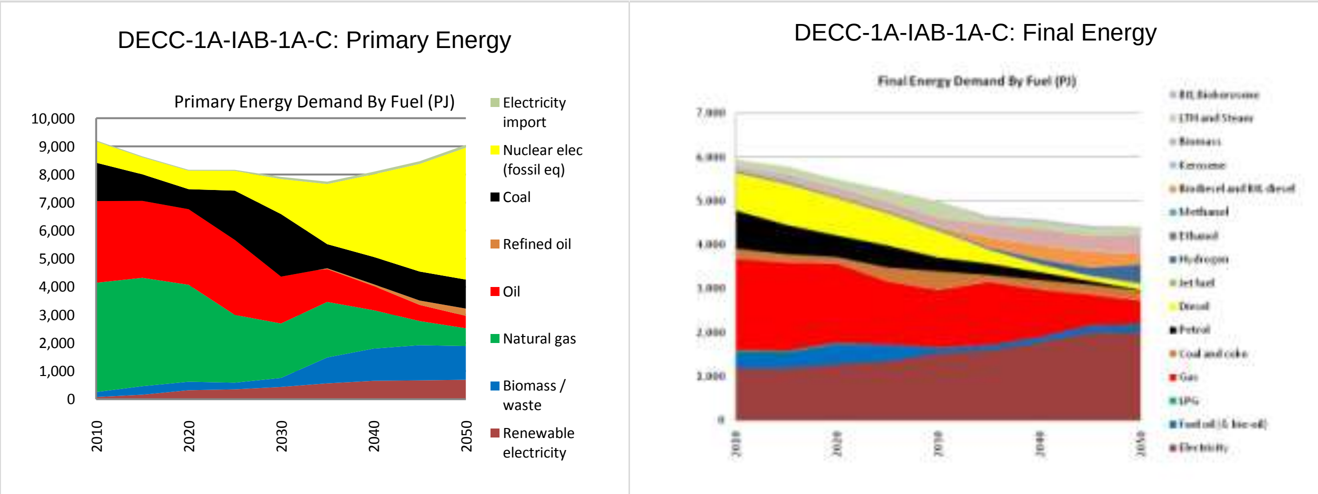


Figure 145: Primary and Final Energy Demand by Energy Carrier, run DECC-1A-IAB-1A-C

Figure 146 illustrates the primary and final energy composition by energy carrier for runs DECC-1A and DECC-1A-IAB-2A. The pattern of change in the primary energy is similar for oil and gas as the use of these fuels decreases to similar proportions over time. Similarly, biomass and renewable electricity is introduced in the mix, although to a greater level in scenario DECC-1A. The main difference is the extent of nuclear power in the primary energy. It increases steadily replacing most of the coal in DECC-1A-IAB-2A scenario while it is used less in run DECC-1A. By 2050, 55% of total primary energy is nuclear and 9% comes from coal in run DECC-1A-IAB-2A while it is 34% and 23% respectively in scenario DECC-1A.

Final energy composition in general follows similar trend, but by the end of the time horizon, in run DECC-1A-IAB-2A electricity has a larger proportion (45% compared to 39% in DECC-1A), while biomass and natural gas have higher proportions in the final energy for run DECC-1A.

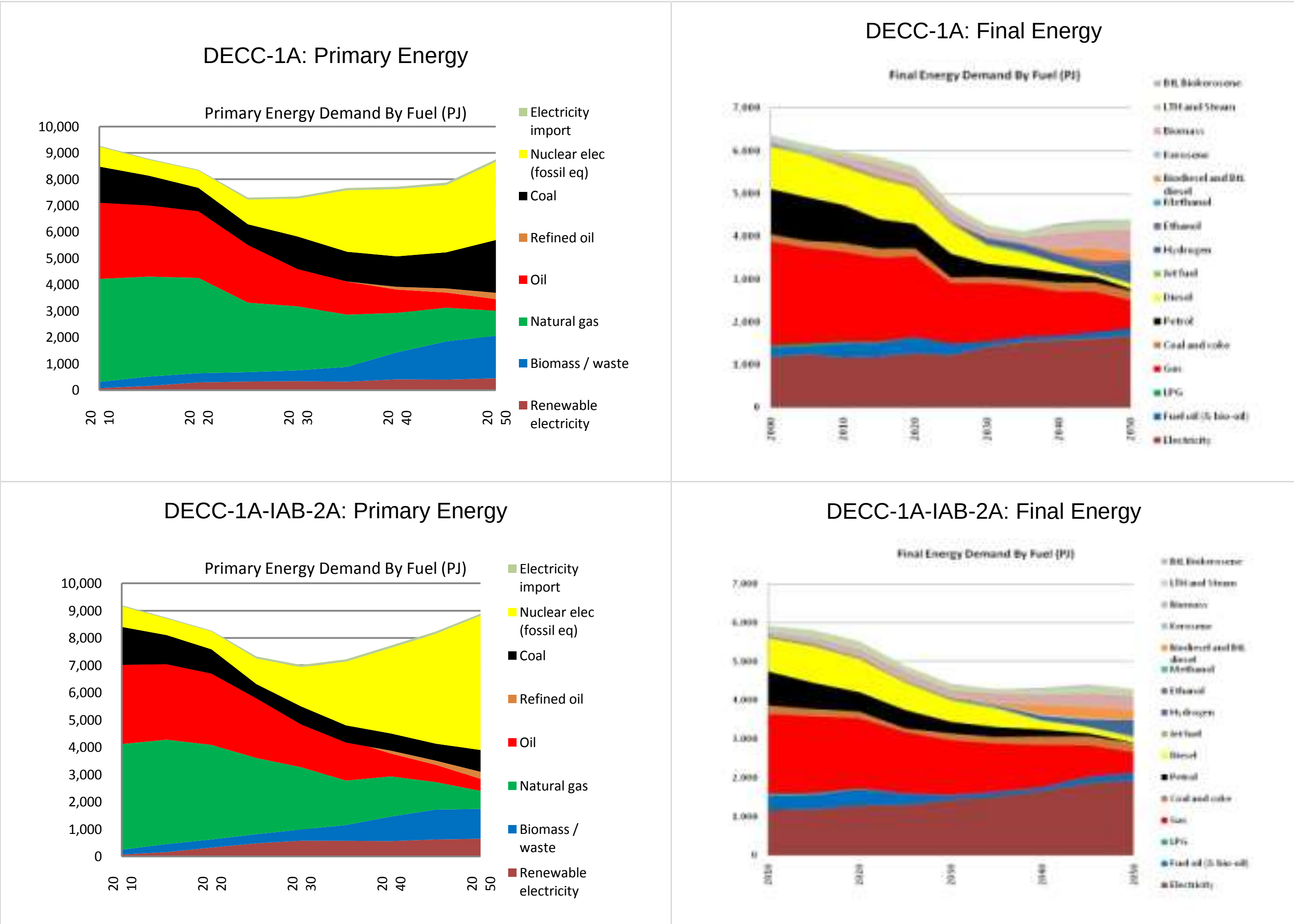


Figure 146: Primary and Final Energy Demand by Energy Carrier, runs DECC-1A-IAB-2A and DECC-1A

Bio-product use is an important abatement measure in the IA study runs although a bit less so for run DECC-1A-IAB-1A. The extent of such product use experiences a rapid increase at different points for different runs (Figure 147). The increase in use of bioproducts happens a decade later in run DECC-1A-IAB-1A than in DECC-1A-IAB-2A scenario. For the latter run, bioproducts gain greater importance in the industry sector.

The cumulative run shows even earlier and greater increases in bio-product use.

Compared to study 1, bio-products show an earlier increase in use for scenario DECC-1A-IAB-2A. This is mainly happening in the industry sector where the differences are largest between the two scenarios. In the last period, service sector demand for bio-products increases fourfold for study DECC-1A resulting in service sector bio-products taking almost 40% of all bio-product energy. It remains at a much lower 14% for DECC-1A-IAB-2A scenario. This is a result of the new constraints added relating to the use of bio-energy (wood and pellets) in the residential and services sectors.

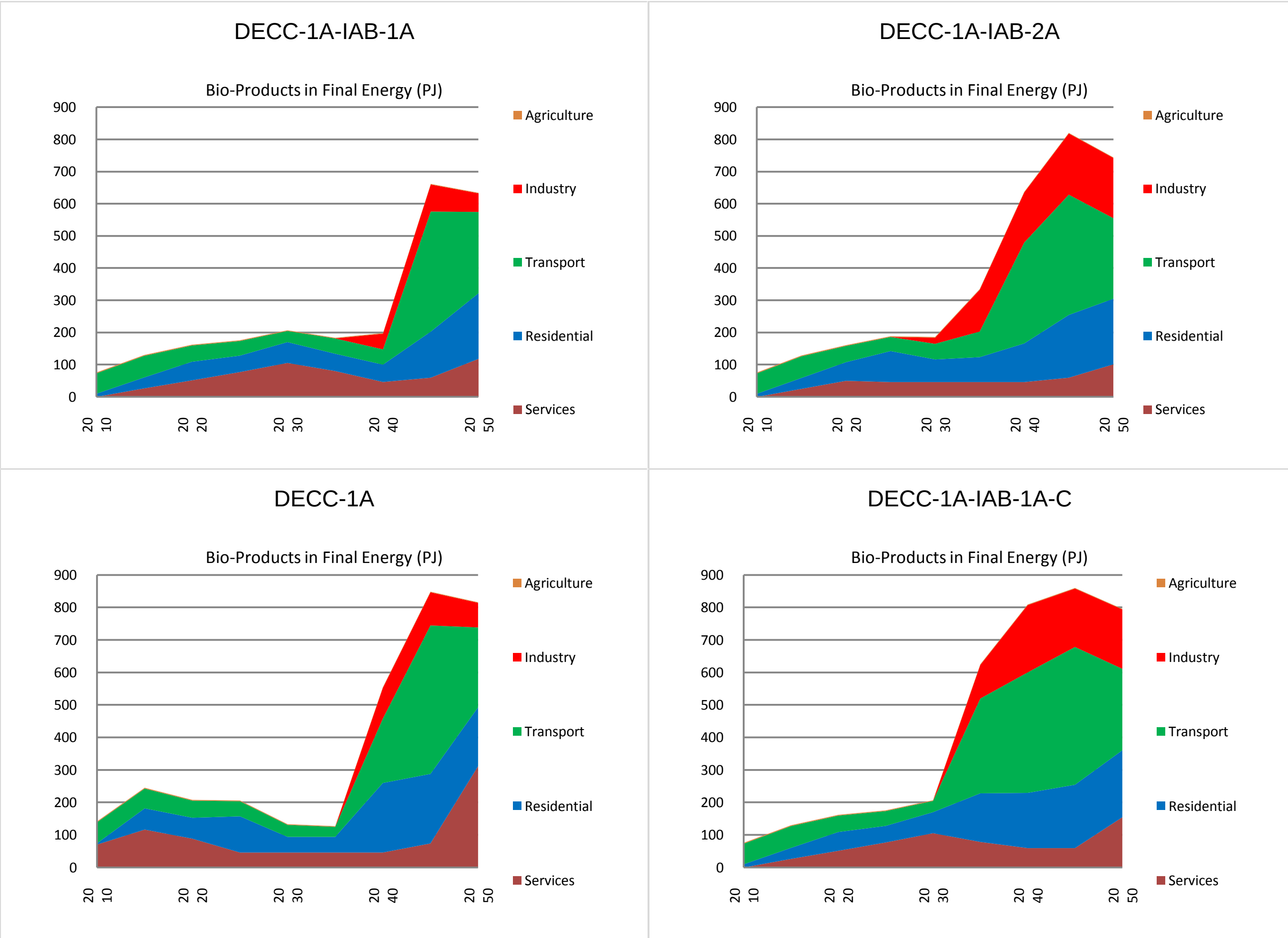


Figure 147: Bio-Products in Final Energy Consumption (note varying scales of vertical axes)

2.8.4 Power Generation and Installed Capacity

Power generation capacity follows similar trends for the two equal annual percentage target runs in this study. It increases somewhat more steeply in the later periods for run DECC-1A-IAB-2A. Power generation for cumulative run DECC-1A-IAB-1A-C grows more rapidly after 2030 as the system is trying to decarbonise quickly. This is shown in Figure 148. The right hand side of the figure shows comparison between scenarios DECC-1A and DECC-1A-IAB-2A. These two scenarios follow a similar trend to 2040; afterwards generation capacity increases more rapidly for run DECC-1A-IAB-2A.

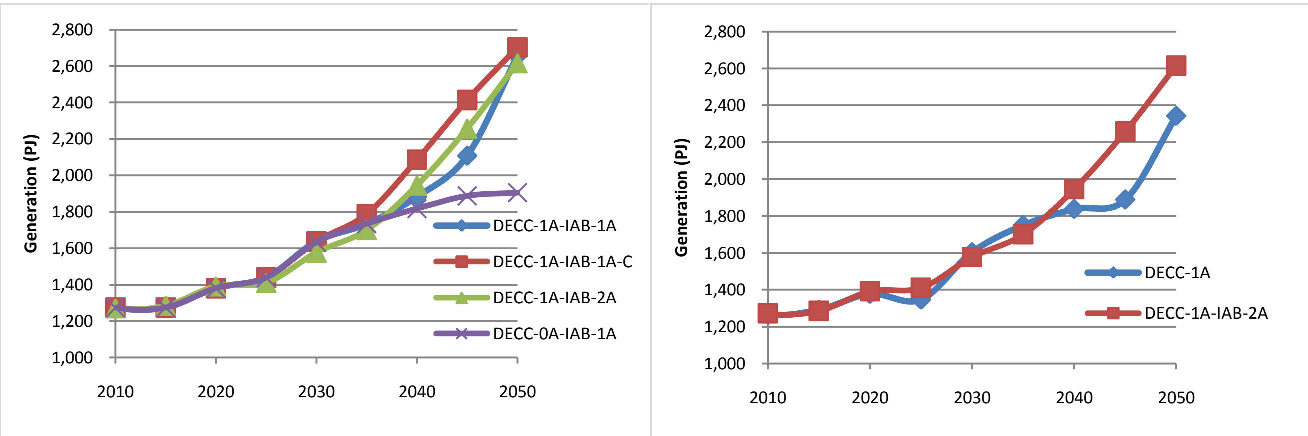


Figure 148: Aggregate Generation over Time for Each Run

Similarly, the patterns are alike for the installed capacity for runs DECC-1A-IAB-1A and DECC-1A-IAB-2A (Figure 149) with the cumulative run showing a greater increases from 2030 onwards. Installed capacity in study 1 run DECC-1A increases steadily but is lower than DECC-1A-IAB-2A capacity in each period. In 2050 the capacity reaches 157GW in run DECC-1A compared to 186GW in DECC-1A-IAB-2A.

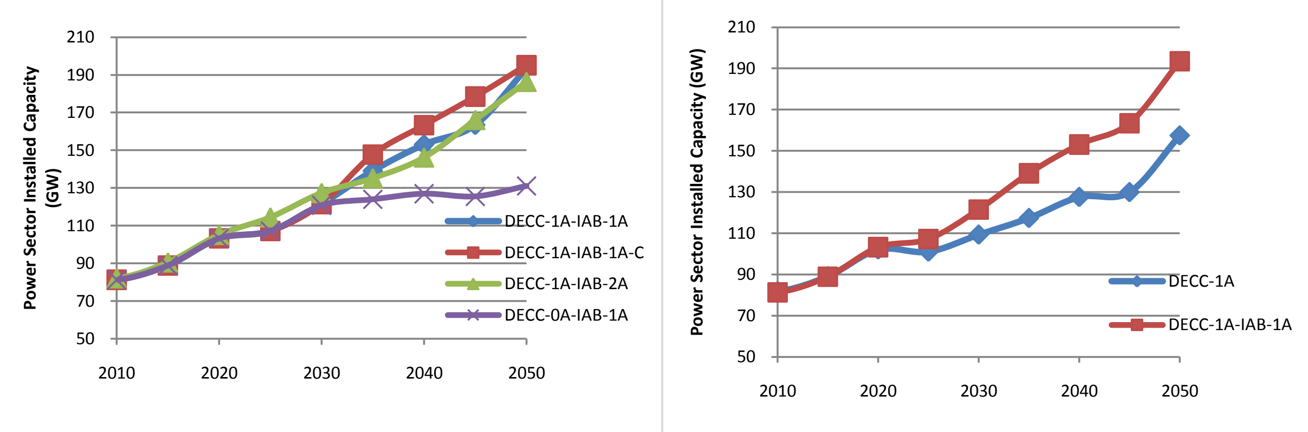


Figure 149: Aggregate Installed Capacity over Time for Each Run

Figure 150 shows the fuel/technology mix of these generation and capacity profiles for the runs DECC-1A-IAB-1A and DECC-1A-IAB-2A. In terms of installed capacity, the latter scenario shows an early introduction of cofiring with CCS which quickly removes coal from the profile. It retains more oil and gas facilities than DECC-1A-IAB-1A run while installing similar amounts of renewable and nuclear power. In the generation mix, both scenarios use fossil fuels mostly to satisfy peak demands and they are removed from the electricity generation mix by the end of the time horizon. It happens sooner for run DECC-1A-IAB-2A which abates earlier.

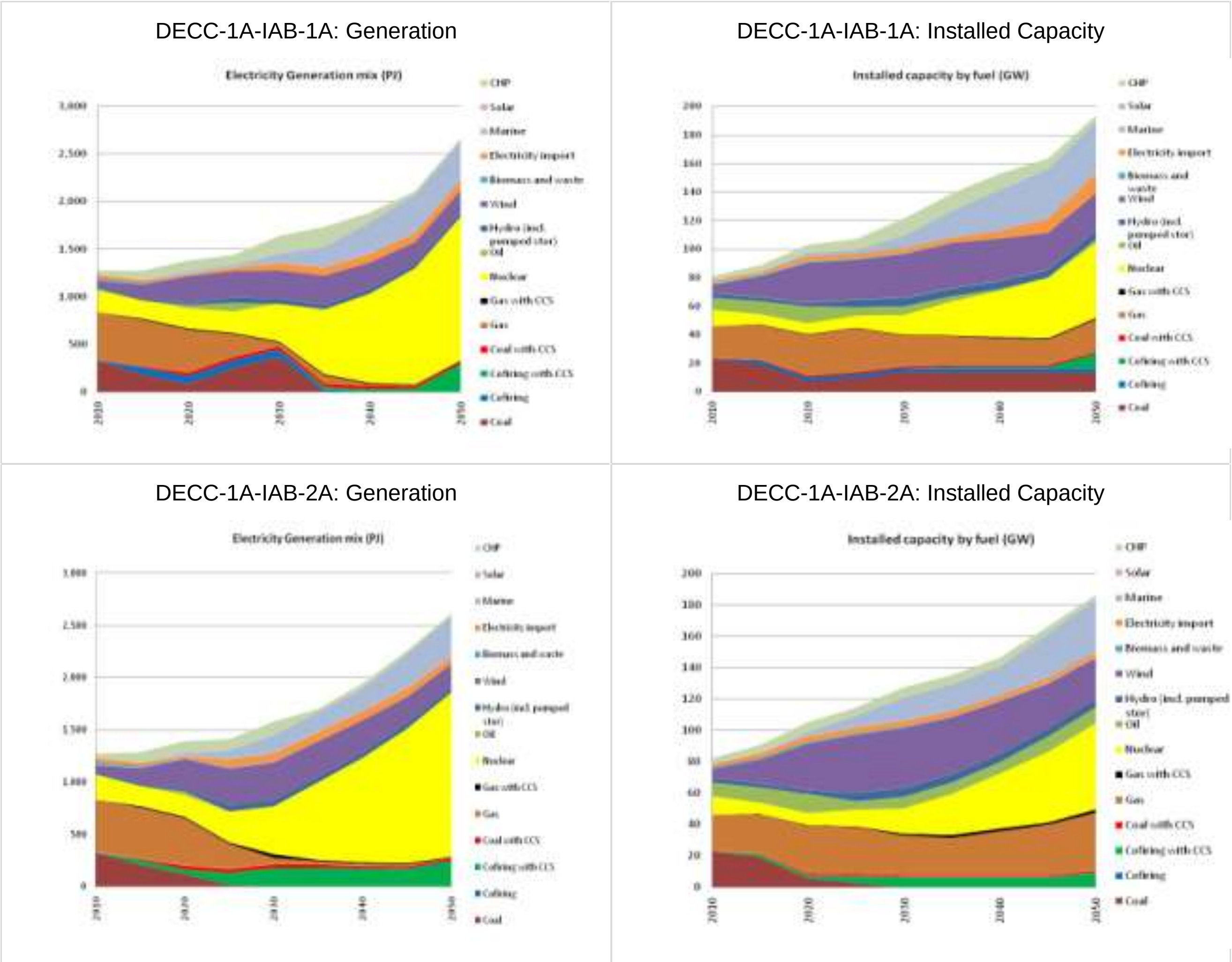


Figure 150: Generation over Time by Technology for runs DECC-1A-IAB-1A and DECC-1A-IAB-2A

The cumulative run DECC-1A-IAB-1A-C shows similar trends to the equal annual percentage run DECC-1A-IAB-1A (both of which follow the baseline system to 2030) in terms of capacity and power generation. A notable exception is that cofiring with CCS is introduced earlier.

The Study 1 run differs from the equivalent IA study B run in several ways here (Figure 151). First, lower cofiring with CCS uptake is observed in the impact assessment study. Instead, marine technology is introduced earlier and much more nuclear power is installed.

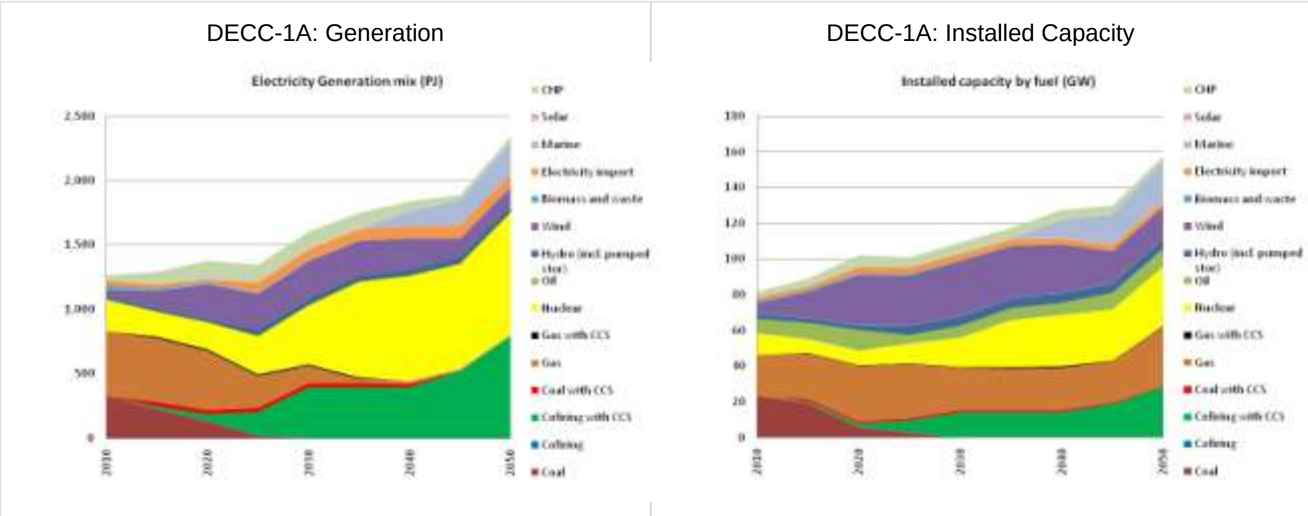


Figure 151: Generation over Time by Technology for run DECC-1A

Table 26 shows the proportion of electricity generated by different technology groups in 2050 for all the runs discussed. It can be observed that early abatement option leads to more nuclear energy use by the end of the time horizon, while using less CCS than the other two runs. Study 1 run DECC-1A shows quite different proportions compared to the equivalent scenario in IA study. The system only generates 40.5% of electricity using nuclear power with run DECC-1A compared to over 60% in the IA scenario and 19.5% comes from renewable sources compared to 25.1% in DECC-1A-IAB-2A.

Table 26: Generation in 2050 by technology groups for IA runs and comparison scenario DECC-1A

	DECC-1A-IAB-1A	DECC-1A-IAB-1A-C	DECC-1A-IAB-2A	DECC-1A
Renewable technologies	26.1%	25.7%	25.1%	19.5%
Nuclear	56.9%	55.6%	60.1%	40.5%
CCS technologies	12.4%	14.2%	10.8%	33.9%

2.8.5 End-Use Sectors

Figure 152 shows the final energy demand and CO_2 emissions by sector for runs DECC-1A-IAB-1A and DECC-1A-IAB-2A.

For both runs the consumption declines very little in service sector and even increases for industry, but falls for residential and transport sectors. Naturally the changes start happening earlier for DECC-1A-IAB-2A run as it starts abating earlier. The cumulative run displays a very similar pattern to DECC-1A-IAB-1A, as they both follow the baseline till 2030, except the energy consumption decreases a bit less for the cumulative run.

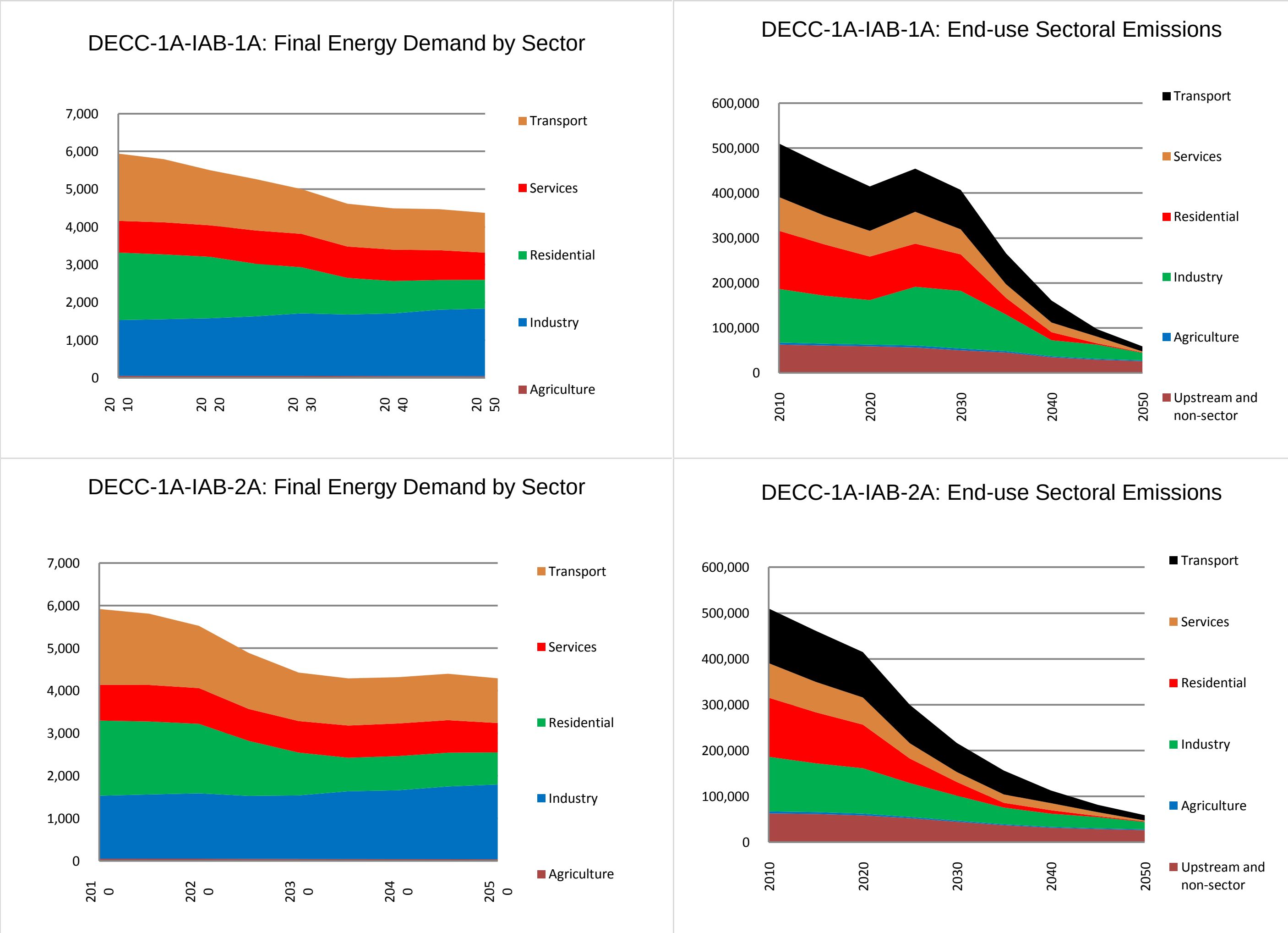


Figure 152: End-Use Sectoral Final Energy Consumption and Emissions Disaggregation for runs DECC-1A-IAB-1A and DECC-1A-IAB-2A

The emissions for both runs in the figure above drop to the same levels by 2050. The sectoral distribution of the final emissions is very similar for both runs, although DECC-1A-IAB-1A is forced to achieve this in a shorter period of time. The cumulative run has even smaller emissions in the final period of the time horizon, and the sectors that are squeezed most are residential and services. They also account for an even smaller proportion of emissions than is the case for the other two runs (3% of total emissions). The actual emissions of the residential sector are almost twice as low for the cumulative run than for the DECC-1A-IAB-2A.

The emissions disaggregation by sector for year 2050 for runs DECC-1A and DECC-1A-IAB-2A is shown in Figure 153. The total emissions in that year for both scenarios are the same. However, the additional constraints and altered discount rates introduced in the impact assessment study change the distribution of the emissions among sectors somewhat. Industry accounts for 34% of total emissions in the study 1 run DECC-1A while it is 27% in the equivalent impact assessment study run. On the other hand compared to the IA study run, services and residential account for an even smaller part of total emissions in study 1 run DECC-1A. In fact, residential sector becomes a sink for CO_2 by 2050 in scenario DECC-1A and services account for 0.4% of total emissions.

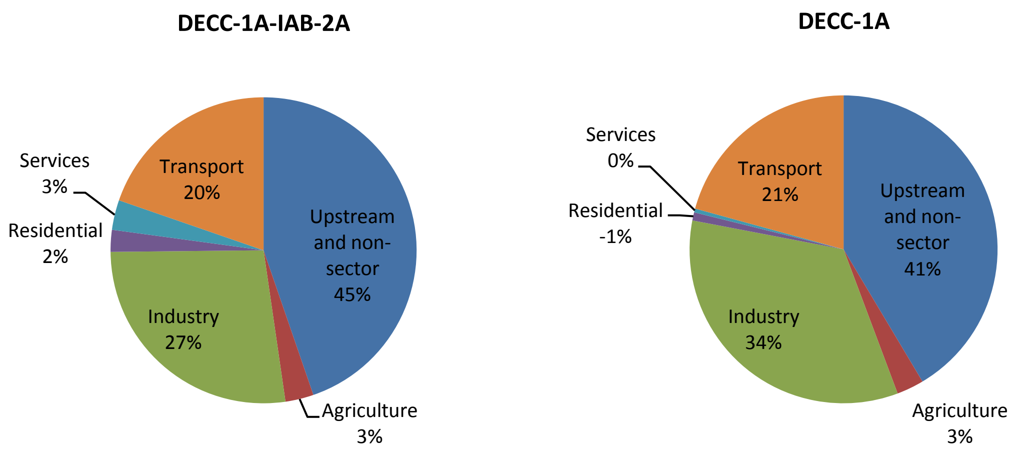


Figure 153: End-Use Sectoral Emissions Disaggregation for runs DECC-1A and DECC-1A-IAB-2A in 2050

The following sections consider each end-use sector in more detail, seeing how decarbonisation was achieved in those sectors.

Industrial Sector

Industrial sector demand reductions (from base) are shown in Figure 154. For the Impact Assessment study, the demand response is limited to 1% per year. For DECC-1A-IAB-1A that does not begin abatement until 2030, all industry demand responses go up to the maximum allowed limit in the first year of abatement. Industrial iron and steel, chemical and non-ferrous metal industry follow this trend till the end of the time horizon (reaching the maximum allowed 20% reduction) while the others reduce slightly less in later periods. On the other hand, scenario DECC-1A-IAB-2A leaves the baseline in the 2020s and the demand response starts immediately in all industries. However, after one period only industrial iron and steel, chemical and non-ferrous metal industries follow the trend until they reach the maximum allowed reduction (25%). The reductions in other industries are smaller.

The trend in the cumulative run is similar to that of scenario DECC-1A-IAB-1A.

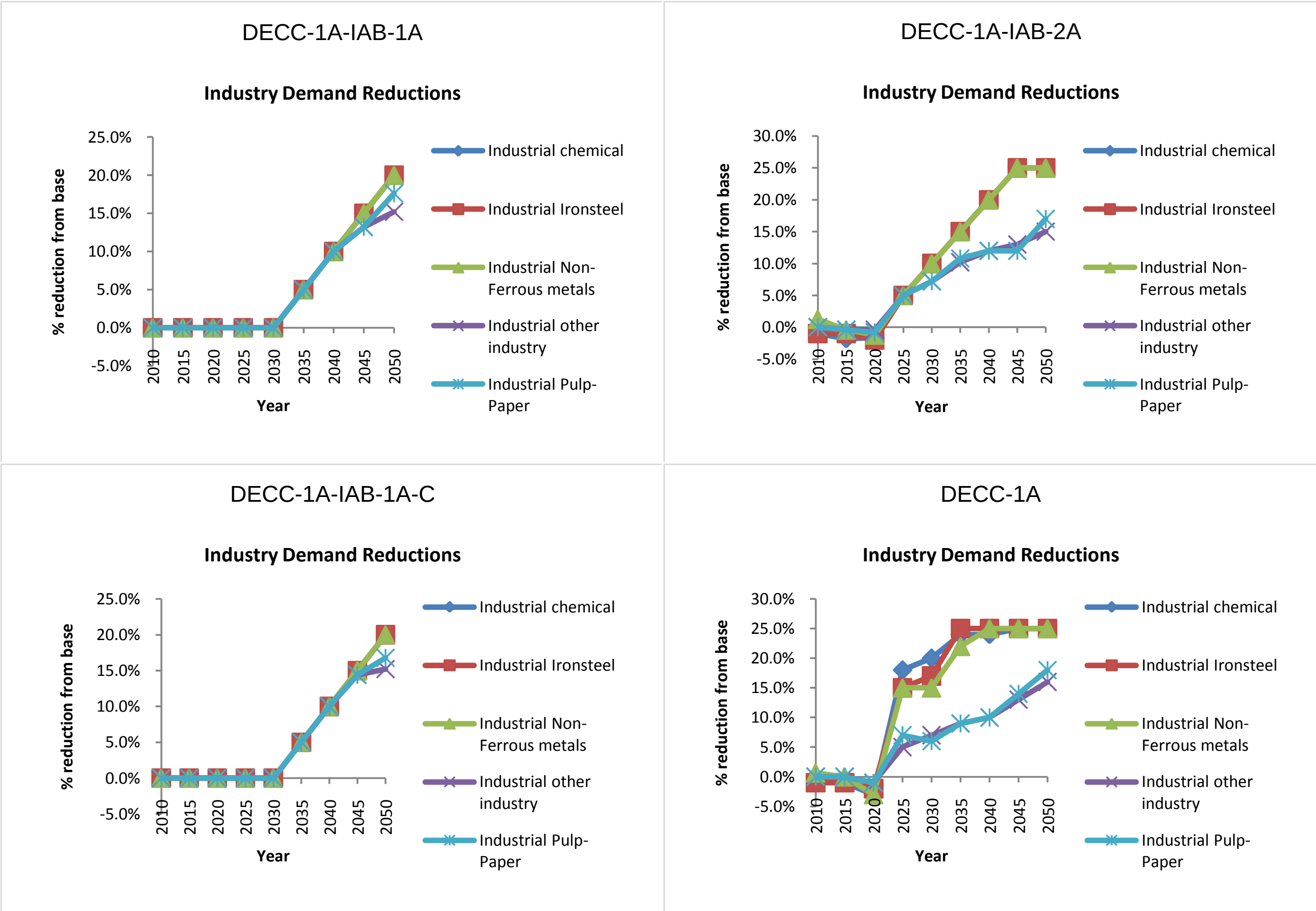


Figure 154: Industrial Demand Reductions for all runs in IA Study B and DECC-1A

In contrast with the IA runs, for the scenario DECC-1A demand response rises sharply in the 2020s and then flattens out for industrial iron-steel, chemical and non-ferrous metal industries while the other industries have smaller demand response. This is a result of the additional demand response constraints in the impact assessment study.

The share of each energy carrier serving final energy consumption for all of the above runs is shown in Figure 155. The later abating run with equal annual percentage reductions is forced to increase coke oven gas use in the 2020s while the early abatement run takes it out of the mix almost entirely in that period. The oven gas remains in the mixture for the run DECC-1A-IAB-1A until 2040, when it is replaced by natural gas and later electricity. In the early abatement run DECC-1A-IAB-2A the natural gas use increases earlier, in the 2020s before giving way to electricity. In short, the patterns of change are similar but the timings are different. The effect is similar in the cumulative run after it leaves the baseline, but the changes are more rapid than for DECC-1A-IAB-1A.

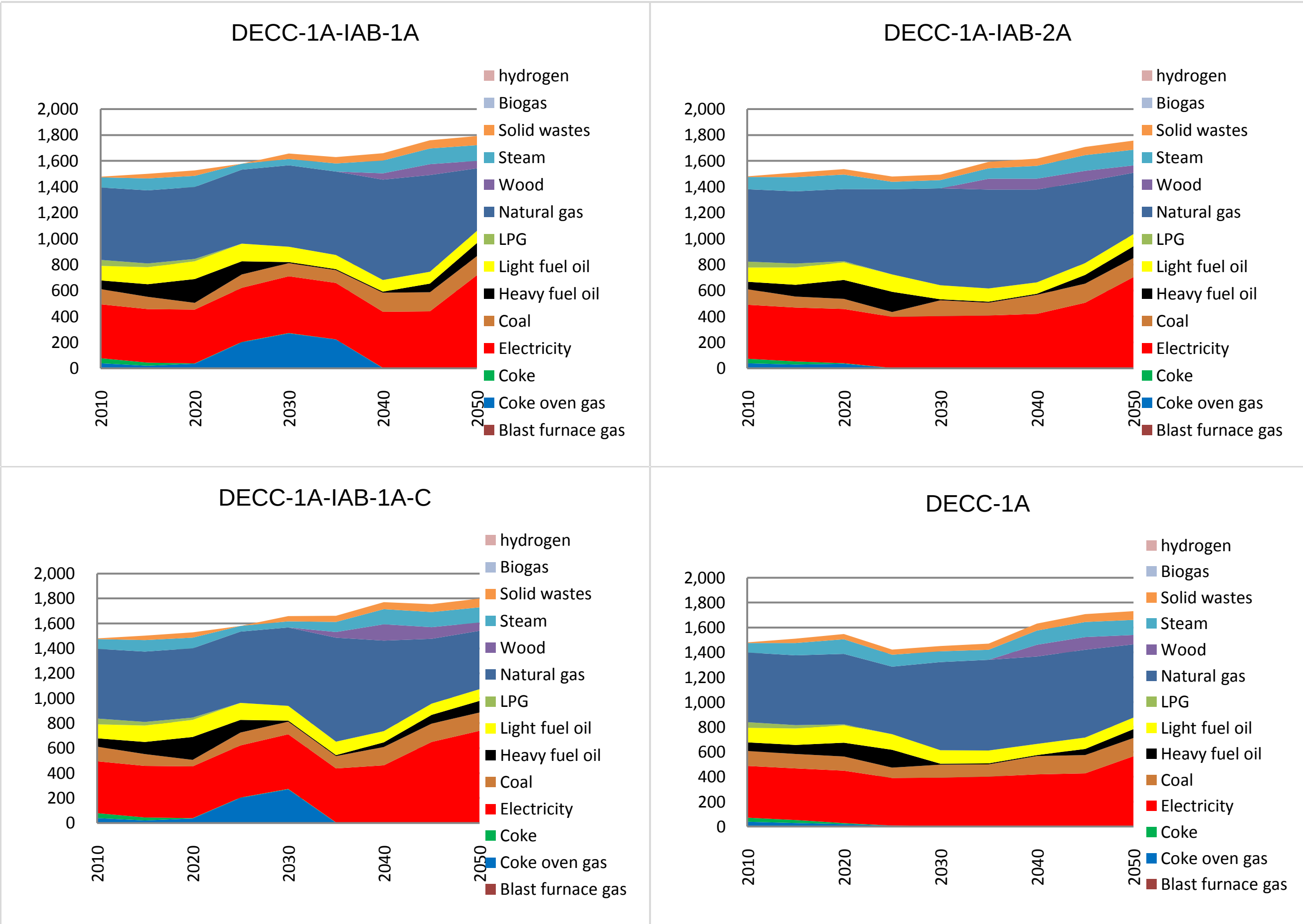


Figure 155: Industrial Final Energy Consumption

Final period industry sector emissions are smaller for DECC-1A-IAB-2A than for DECC-1A. As seen in later sections the trend is opposite for residential and service sectors. This means that the additional constraints in the IA study run make it cheaper overall to reduce industry sector emissions more than for DECC-1A scenario.

Residential Sector

Residential sector demand reductions for all the IA study runs are significant. Similarly as for the industry sector, the demand response can be observed from 2020s for the early abating run (DECC-1A-IAB-2A). It is most important for water and space heating demand which reduces by the maximum allowable amount until it reaches 15% then the response slows down. For the late abating run as well as the cumulative run, the demand reduction for water and space heating is also equal to maximum allowance until it reaches 15%. For the cumulative run, the trend for these is very similar to the non-cumulative late abating scenario.

The demand response is higher in DECC-1A than in DECC-1A-IAB-2A and for water heating technologies the reduction is 15% in the first period the abatement starts and similar effect can be observed for space heating. For other technologies the demand reductions are not as high and vary between 5-10% in 2050. This is similar for DECC-1A-IAB-2A scenario.

The split by fuel for runs DECC-1A-IAB-2A and DECC-1A is shown in Figure 156. The reduction in total energy consumption and the split by fuel is remarkably similar for these two runs. This indicates that the difference in residential sector emissions level in 2050 between these two runs is largely due to the differences in demand responses described above.

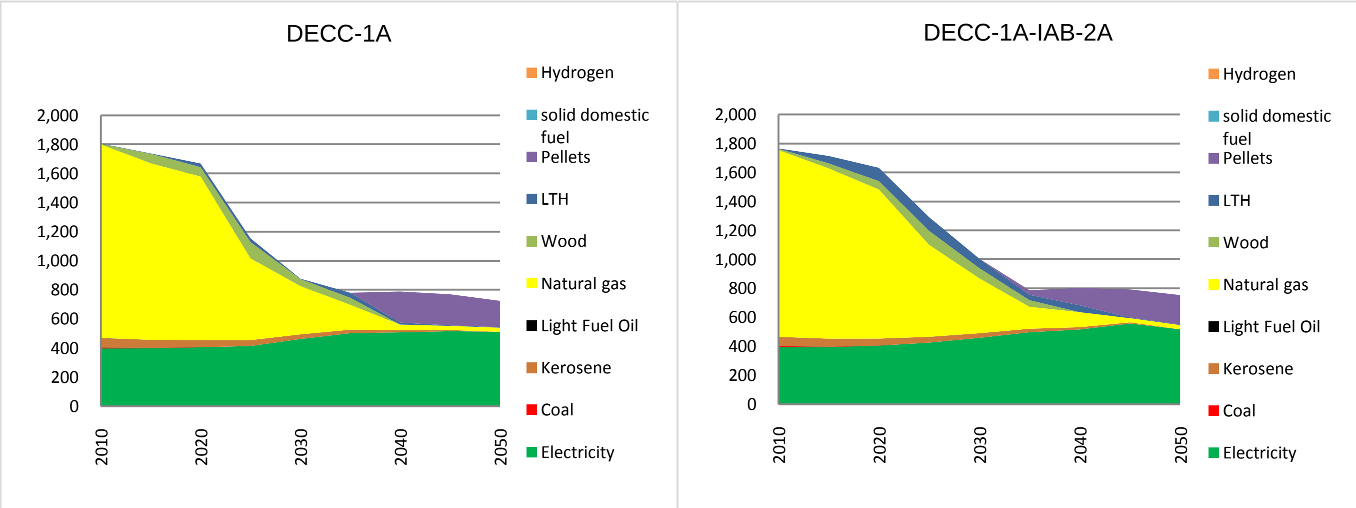


Figure 156: Residential Final Energy Consumption for Runs DECC-1A-IAB-2A and DECC-1A

Services Sector

The service sector demand reductions follow a similar pattern to the other sectors. For service sector hot water and space heating demands the reductions are highest in all considered scenarios. For the early abating scenario, these demands are decreasing by the maximum permitted amount from 2020s until it reaches 25% for hot water and 23% for space heating in the 2050. For the late abating scenarios, this process starts later and the demand reductions reach 20% by the end of the time horizon. This is obviously works as an advantage for the early abating scenario.

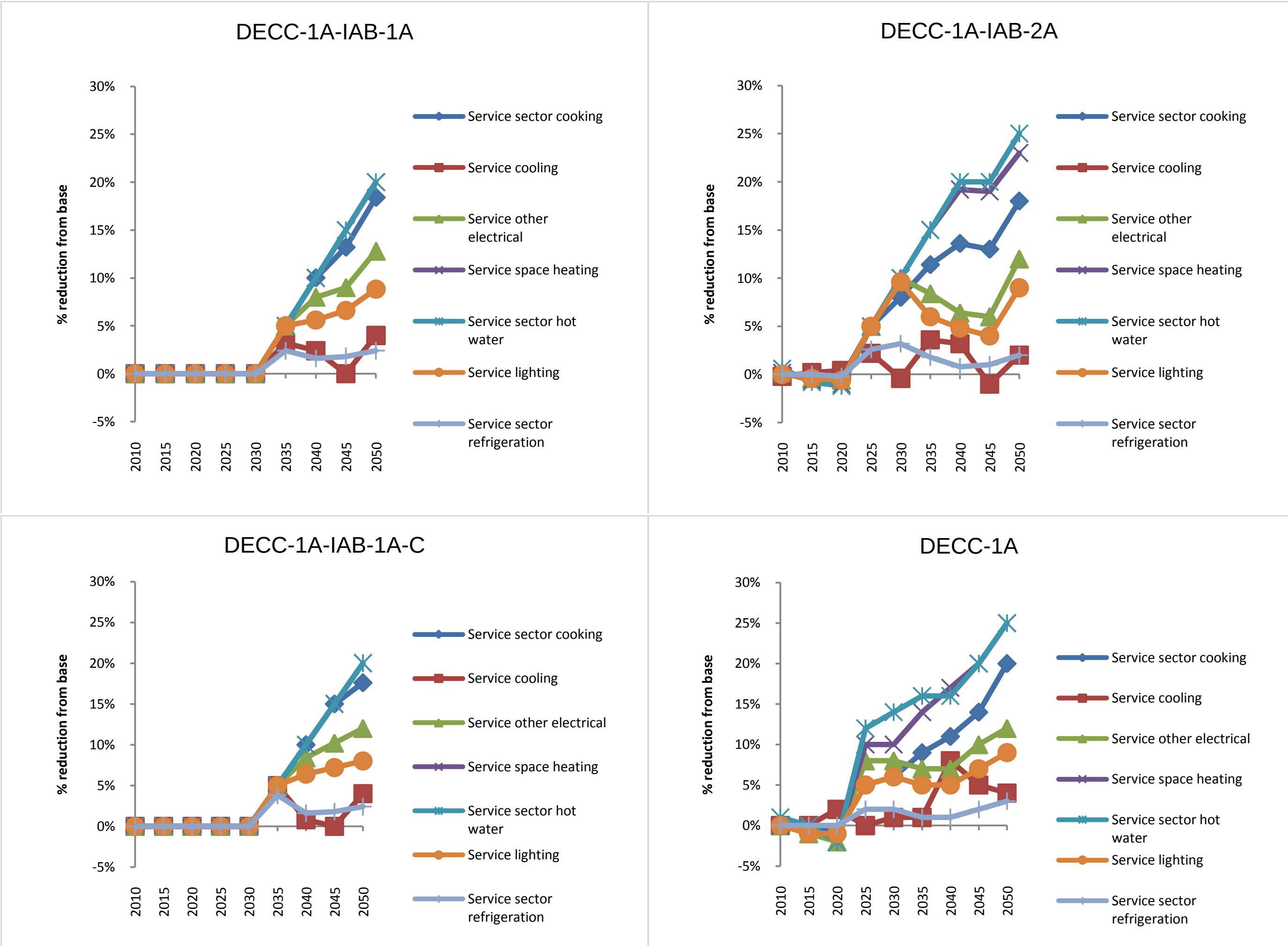


Figure 157: Service Sector Service Demand Reduction

The final energy consumption levels do not change significantly for either of the runs in this study. For scenarios DECC-1A-IAB-1A and DECC-1A-IAB-2A, the energy consumption composition by energy carrier is very similar in 2050 (Figure 158). However, the pathways to arrive there differ with more changes in natural gas and LTH use for DECC-1A-IAB-1A compared to the early abating run. For the cumulative run the model shows introduction of pellets earlier and to a larger extent than for the early abating run DECC-1A-IAB-2A. This is one of the factors that allow service sector emissions to become 50% lower in 2050 for the cumulative run.

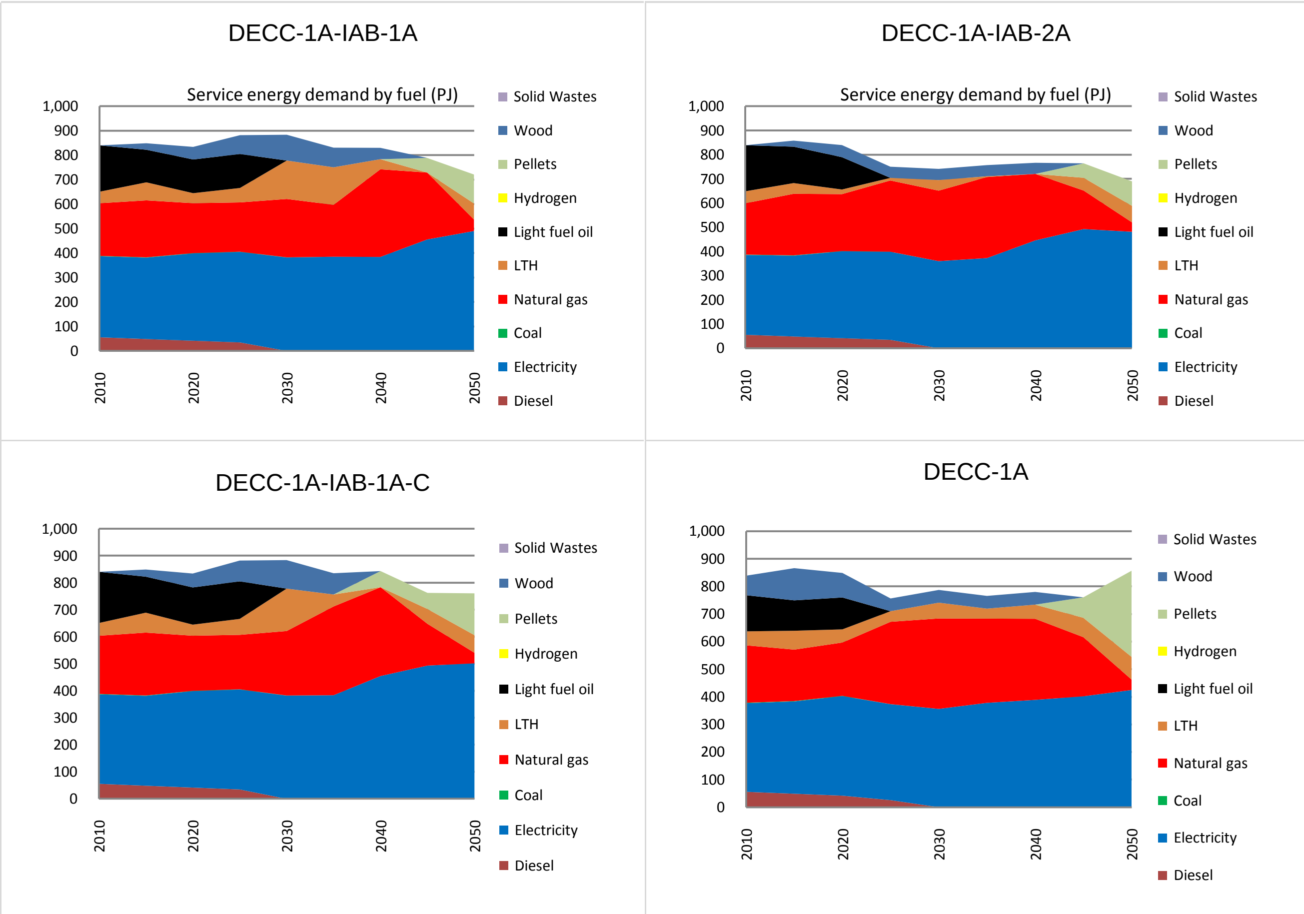


Figure 158: Service Sector Energy Consumption by fuel

DECC-1A scenario demonstrates almost 8 times lower emissions for service sector in 2050 than its equivalent scenario in the impact assessment study. While the demand reductions are a bit higher for DECC-1A, Figure 158 also shows a much more significant use of pellets in the final period. This change is attributable to the additional constraints added to the database for this study.

Both for service and residential sectors, additional constraints in the IA study (regarding technology uptake levels) lead to less significant emission reductions in these sectors by the end of the time horizon.

Transport Sector

Most demand categories in the transport sector show quite low demand reduction rates. For shipping, HGV and domestic air transport the reductions are more substantial (Figure 159). For these categories, similarly to other sectors, for the early abating scenario initial response happens a decade earlier than in the other two IA study scenarios.

DECC-1A shows higher demand reductions compared to DECC-1A-IAB-2A scenario for shipping, but lower for HGV and domestic air transport.

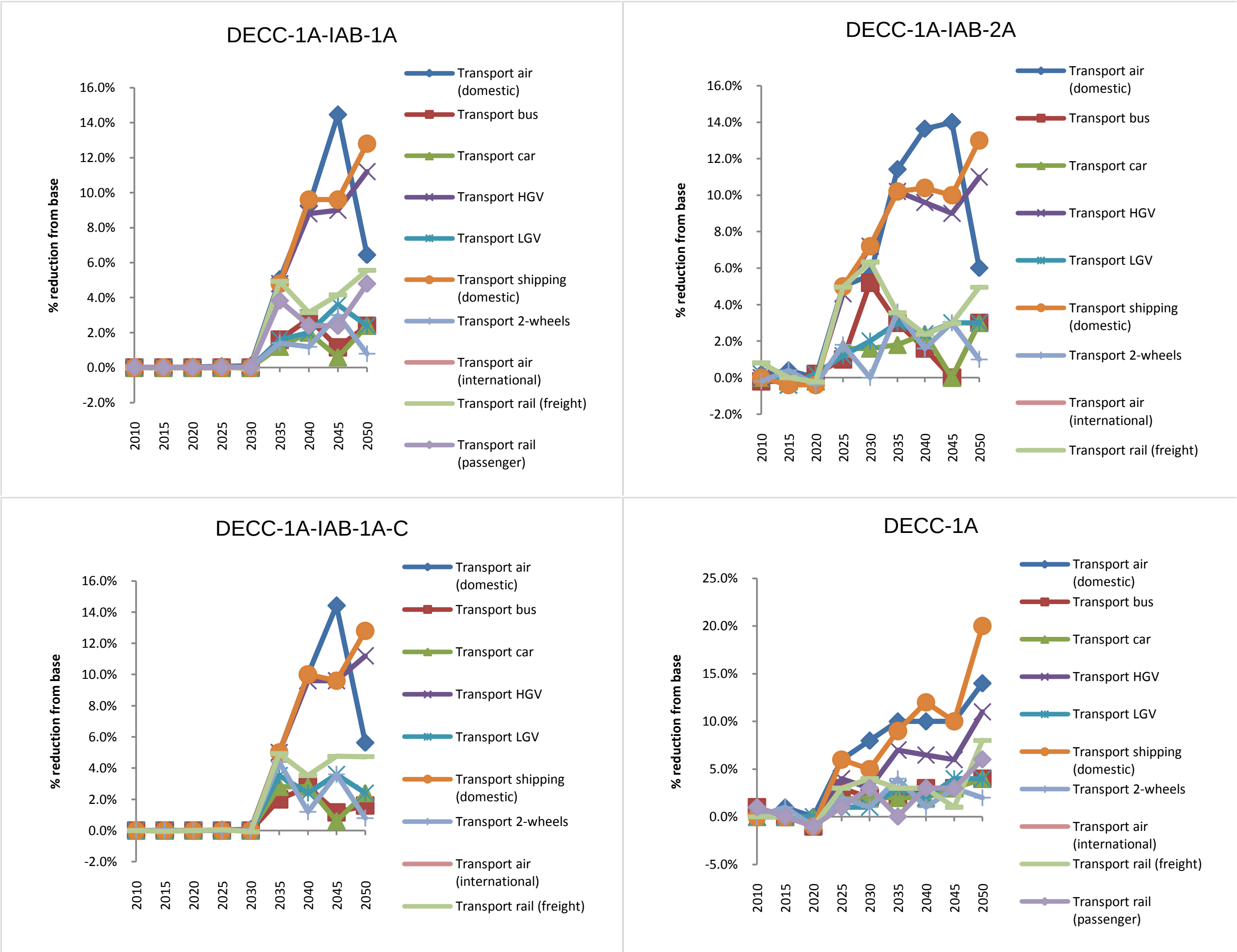


Figure 159: Transport Service Demand Reduction

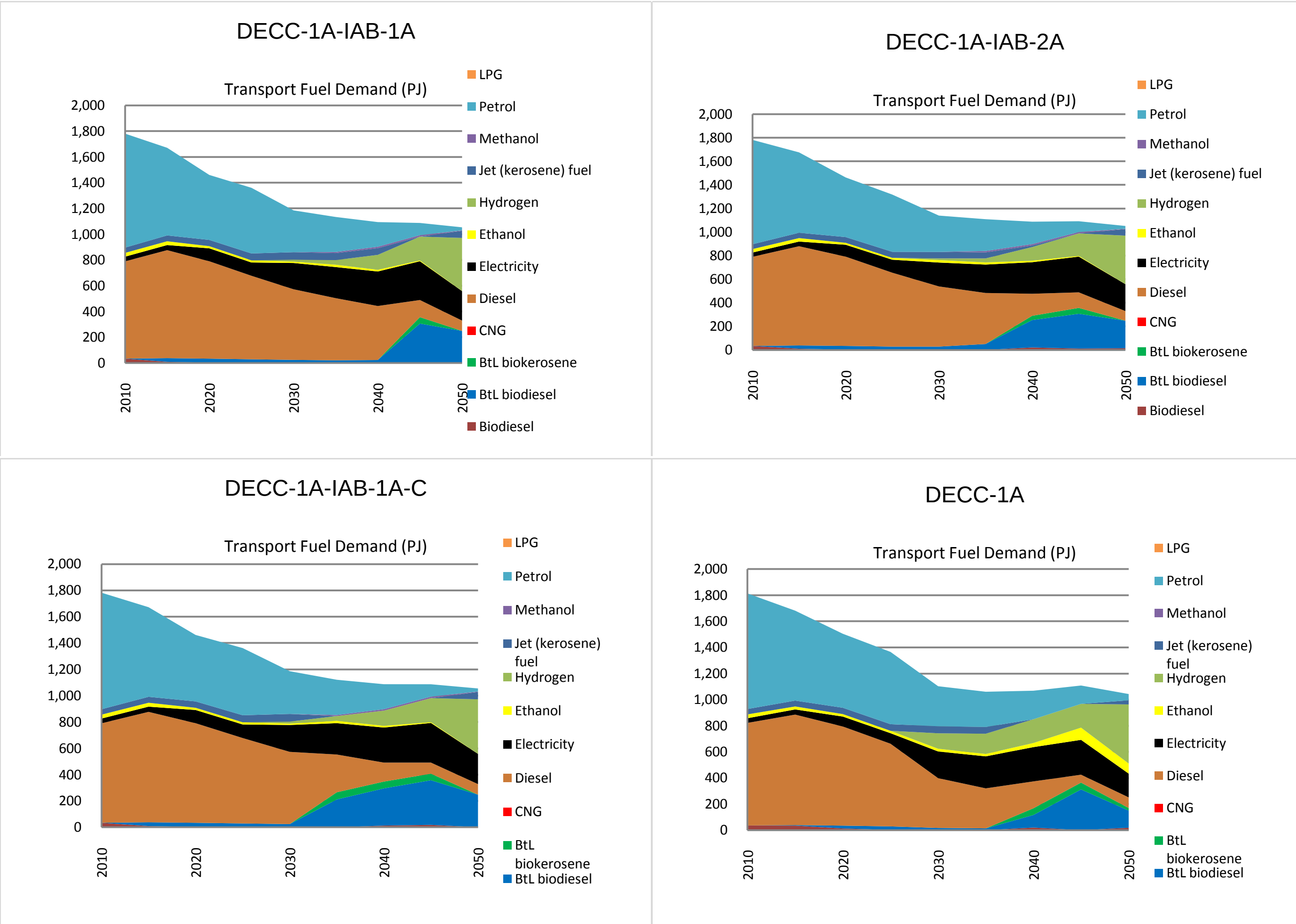


Figure 160: Transport Fuel Demand

Transport fuel demand patterns are quite similar for DECC-1A-IAB-1A and DECC-1A-IAB-2A as shown in Figure 160. For the latter BtL biokerosene and BtL biodiesel are introduced earlier. However, the cumulative run shows even earlier introduction of these energy carriers than DECC-1A-IAB-2A run as it tries to decarbonise quickly.

The main difference from the DECC-1A run is that the uptake of hydrogen happens more slowly for the impact assessment study run although it reaches the same levels by 2050. There is also more uptake of ethanol in DECC-1A and due to the presence of these technologies, the uptake of BtL biokerosene and BtL biodiesel is slower.

The impact assessment study has additional constraints that limit the market shares of various transport technologies and in particular the rapid uptake of hydrogen observed in DECC-1A. The result of these new constraints can be seen in Figure 161 which shows the choice of HGV and bus technologies. Note how for DECC-1A Hydrogen is the only fuel in 2050 while its introduction is more gradual in the equivalent impact assessment run. For buses, methanol and battery vehicles are used as well as an increasing proportion of hydrogen-fuelled buses.

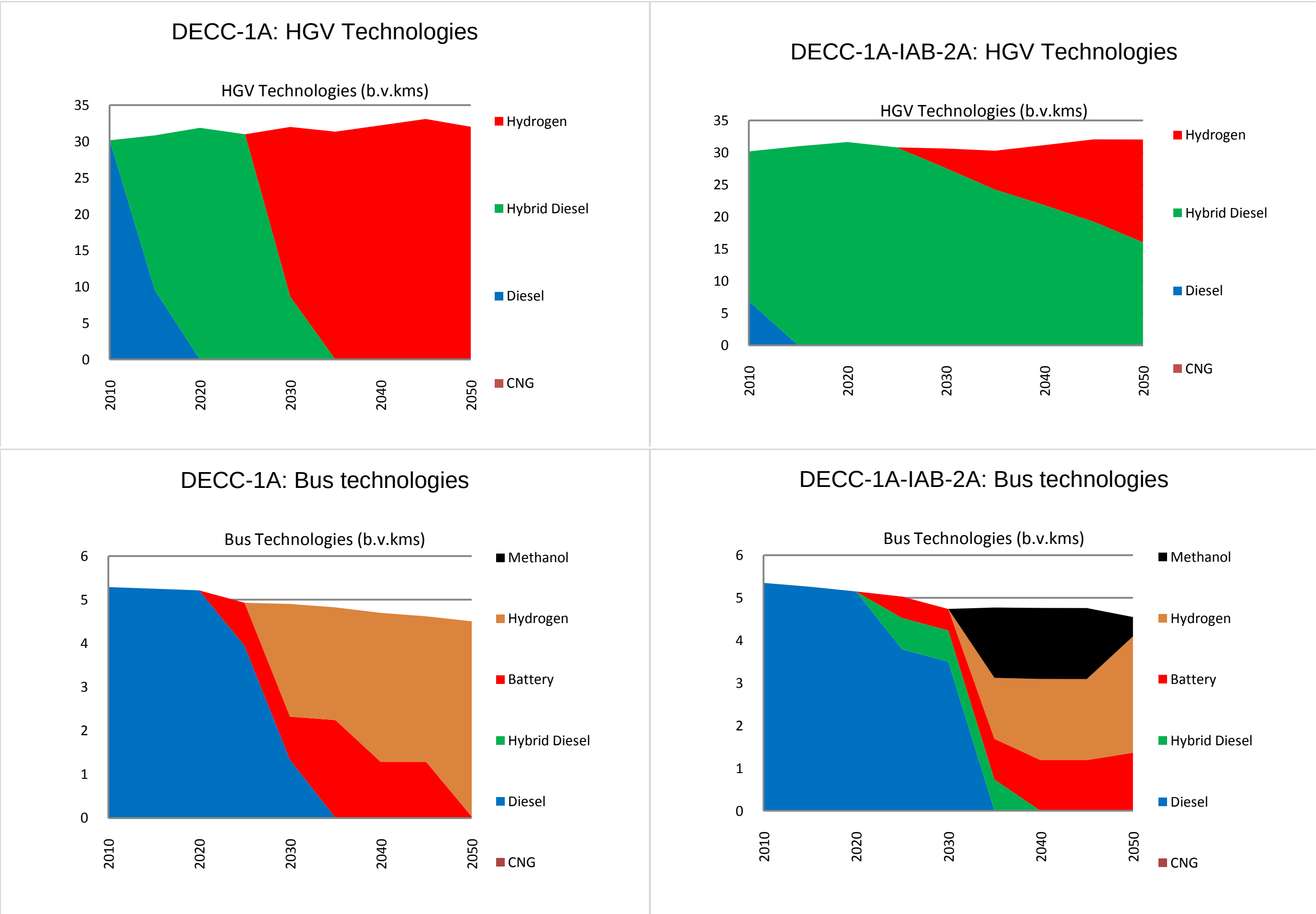


Figure 161: Bus and HGV Technology Choices to 2050 for Run DECC-1A and DECC-1A-IAB-2A

2.9 Study 7A: No CCS Available

2.9.1 Description of Study

The study explores the pathway to a 90% CO_2 emissions reduction in the energy system by 2050 where CCS is not an option. CCS is not available in the power generation sector, in any process or within the industry sector. This removes a key technology option for sequestering emissions from the energy system, and this study will identifies which technologies are implemented as an alternative to CCS and at what cost.

There is one run in this study:

1. Study 7 Run A. Emissions reduction in this run is bounded with equal annual emissions reduction to 2050, but no CCS technologies are available. DECC-1A-IAB-2A is the equivalent run to DECC-7A with the same carbon constraints, in which CCS technologies are available.

   Code: DECC-7A

The baseline case for run DECC-7A is DECC-0A-NOCCS. This is an equivalent run with no emissions constraints, except those in the Government Carbon Plan.

2.9.2 Key Results

Table 27 shows the discounted energy system costs, demand response and the discounted consumer/producer surplus for the case runs analysed in this study. There is a small difference in total discounted system cost with the DECC-7A costs lower by £2 billion than the DECC-1A-IAB-2A costs.

The demand response, however, is considerably higher for scenario DECC-7A, than for DECC-1A-IAB-2A, as evident by the £69 billion higher impact on welfare of demand reduction. The consumer/ producer surplus is therefore greater for DECC-7A. This demand response has little impact on the total system cost. In essence the lack of CCS has forced the model to choose demand response as a means to CO_2 reduction.

Table 27: Key Result Metrics

	DECC-0A-NOCCS (base)	DECC-7A	DECC-1A-IAB-2A
Discounted Technical Energy System Cost (2010 £UK Billions)	5,446	5,472	5,474
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	-268	-194
Discounted Impact on Welfare of Demand Reduction[3] (2010 £UK Billions)	0	244	175

The undiscounted annual average system costs are shown in Table 28. The difference between DECC-7A and DECC-1A-IAB-2A fluctuates over time. In 2030, the difference is £3.5 billion, dropping to less than £1 billion by 2040, but rising to £3.7 billion by 2050.

Table 28: Average annualised undiscounted system costs (2010£ UK Billion)

Run/Year	2025	2030	2035	2040	2045	2050
DECC-0A-NOCCS	238.33	261.32	274.21	288.61	304.03	316.36
DECC-7A	236.21	254.06	272.24	292.74	314.72	335.01
DECC-1A-IAB-2A	236.44	257.62	271.55	292.01	316.58	331.28

Figure 162 shows the marginal price of CO_2 across the timeline of the study. There is a significant increase in the marginal cost of CO_2 beyond 2035 in run DECC-7A. The price of CO_2 reaches almost

£200/t by 2030 in DECC-7A, but takes 5 years longer in case DECC-1A-IAB-2A. Beyond 2035, there is a significant divergence in price reaching £345/tCO_2 difference by 2050.

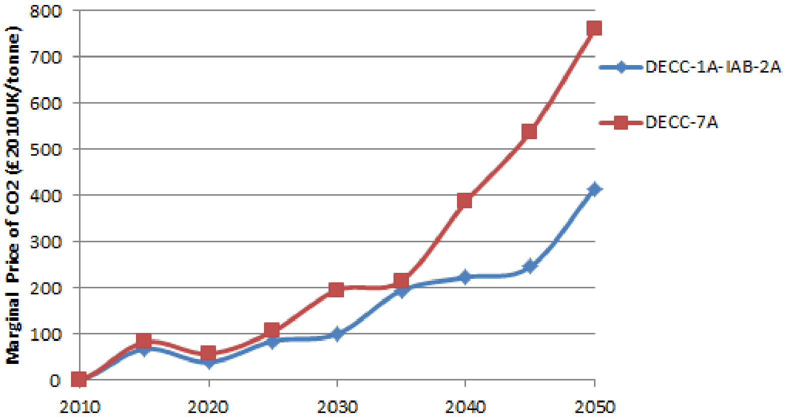


Figure 162: Marginal Price of CO_2

2.9.3 Primary and Final Energy Statistics

The primary energy demand throughout the case studies is shown in Figure 163. There is a 7% reduction in total energy demand in DECC-7A, than there is in DECC-1A-IAB-2A.

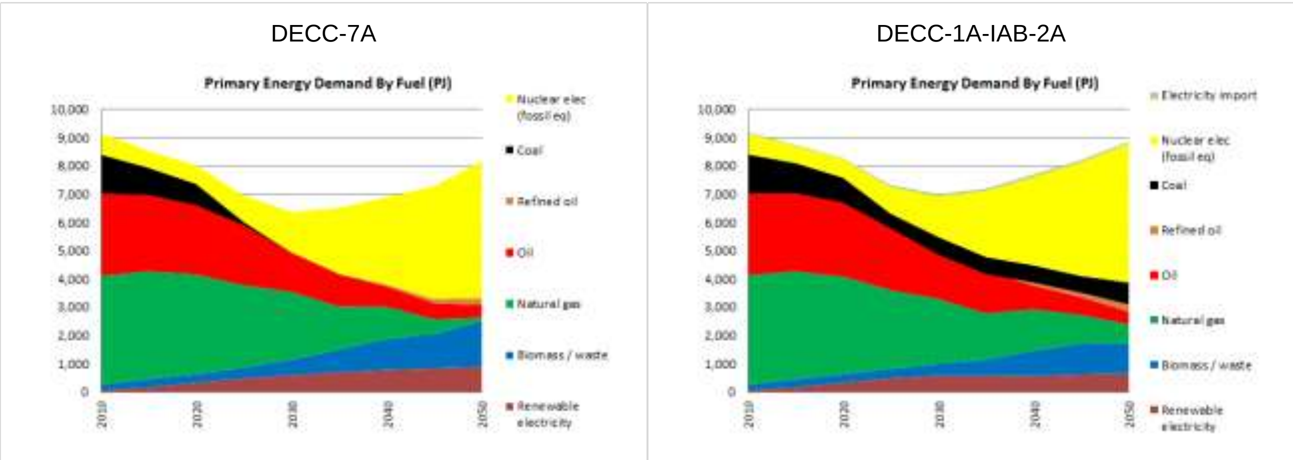


Figure 163: Primary energy demand over time

There is no longer any demand from energy produced by coal beyond 2030 in the DECC-7A scenario. There is also a significant drop in natural gas use. This is replaced by a 37% increase in the amount of renewables demanded to 898PJ of the 8261PJ total. There is also an increase in biomass from 1084PJ to 1612PJ.

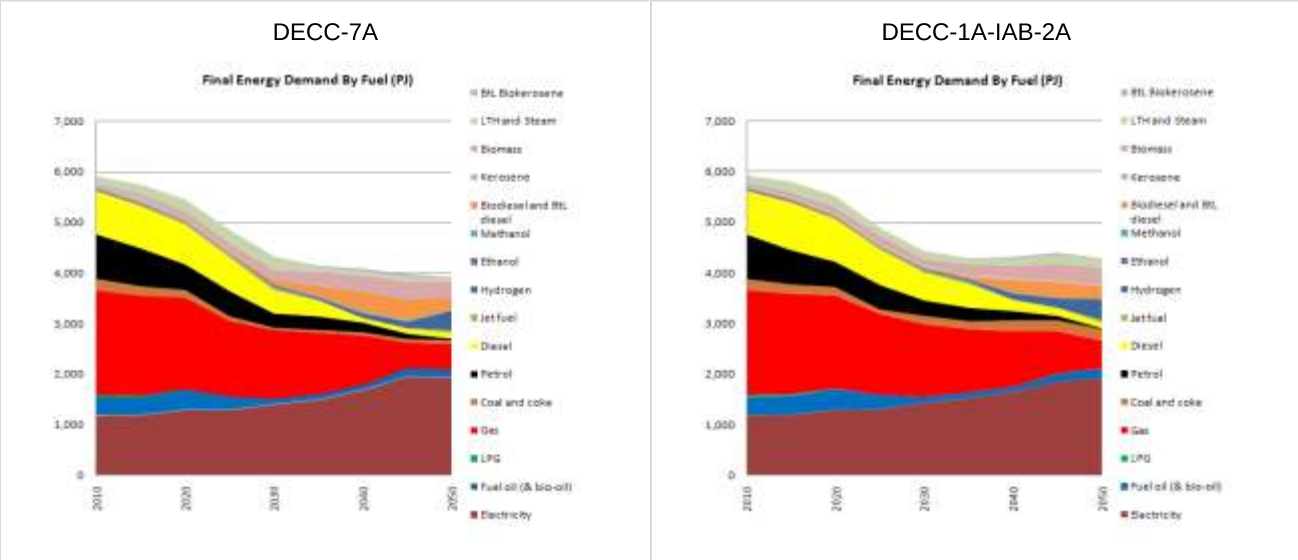


Figure 164: Final Energy Demand by Fuel over time

The difference in final energy demand by fuel type is apparent in Figure 164. The drop in demand results from a drop in demand of Coal and Coke along with Low Temperature Heat and Steam.

The quantity of bio-products in final energy demand by sector is shown in Figure 165. There is a significant increase in the total bio-products when CCS is not an available technology. Bio-products are utilised to abate the emissions which otherwise would have been sequestered. By 2050, this final energy demand is 33% greater than the case with the CCS option. The primary source of the increase in bio-products occurs in the industry sector. This is mainly from an increase in biomethane after 2020, with a small contribution from bio-oil. In the services sector there is more than double the amount of bio-products in final energy in 2040 and 2045 in DECC-7A than in DECC-1A-IAB-2A, in the form of wood and pellets.

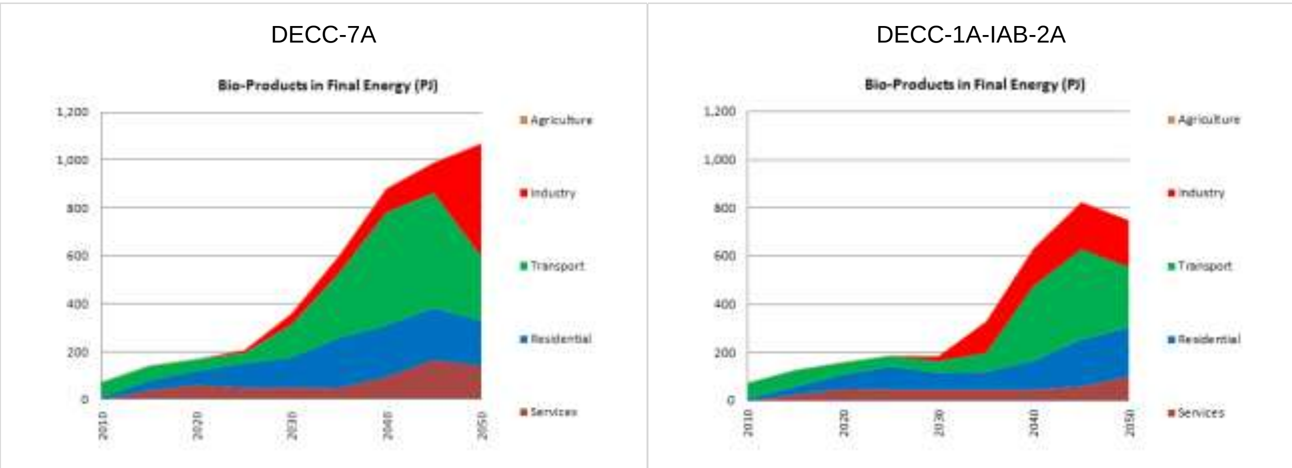


Figure 165: Bio-Products in Final Energy Demand disaggregated by sector.

2.9.4 Power Generation and Installed Capacity

Figure 166 shows the total installed capacity and the total electricity generated by the system. Until 2030, there is a similar installed capacity at which point there is a divergence. As can be seen from Figure 163 this coincides with the drop in coal as a primary fuel. The total installed capacity in DECC-7A is higher than that in DECC-1A-IAB-2A. The right side graph of Figure 166 shows that the generation is consistent. Hence the overall efficiency of generation system decreases when CCS is not included.

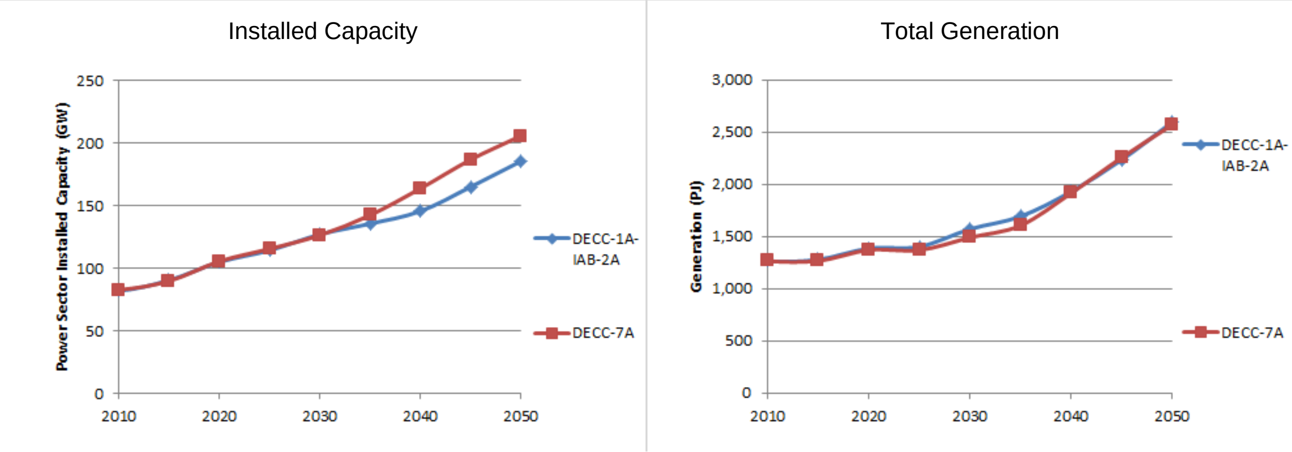


Figure 166: Total Installed Capacity (GW) and Generation (PJ) from the energy system out to 2050

In both cases the emissions intensity of electricity generation reaches zero by 2035, as can be seen from Figure 167. As CCS is no longer included as an option, then generation mix is different and is shown in Figure 169.

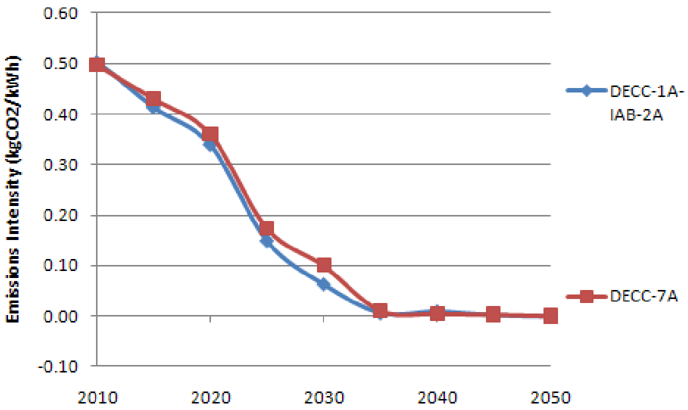


Figure 167: Emissions intensity of electricity generation out to 2050

The installed capacity of the two different cases in shown in Figure 168. The greater installed capacity of renewables is apparent with 35GW of wind installed by 2050 in DECC-7A (of a total 206GW), but only 26.4GW in the non CCS case (of a total 185GW). For marine renewables, this is 45GW in DECC-7A compared to 33GW. In 2025 there is twice as much CHP installed in DECC-7A, compared to DECC-1A-IAB-2A, peaking at 10.9GW in 2035.

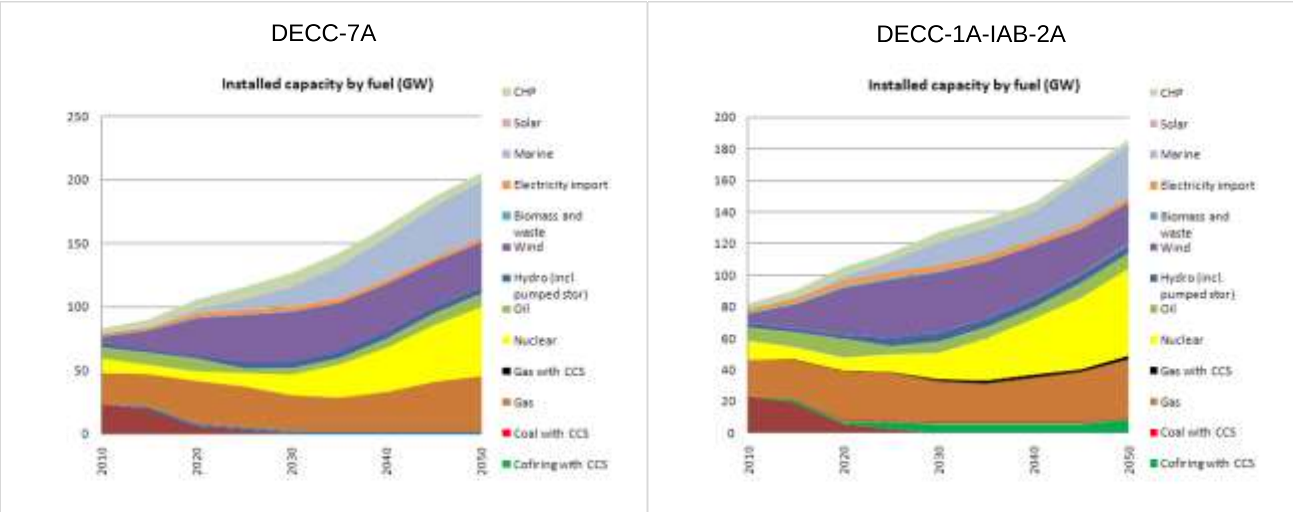


Figure 168: Installed electricity generation capacity over time

The total electricity generation out to 2050 in each of the cases is shown in Figure 169. There is a similar amount of electricity generated in both cases. In DECC-7A, there is a significant increase in generation from CHP over the period 2020 to 2030 in comparison to DECC-1A-IAB-2A. In 2025 and 2030, double the amount of electricity is generated from CHP. In both cases CHP generation reduces significantly in 2035, much greater than the drop in installed capacity. Installed capacity of this marginal technology is no longer utilised.

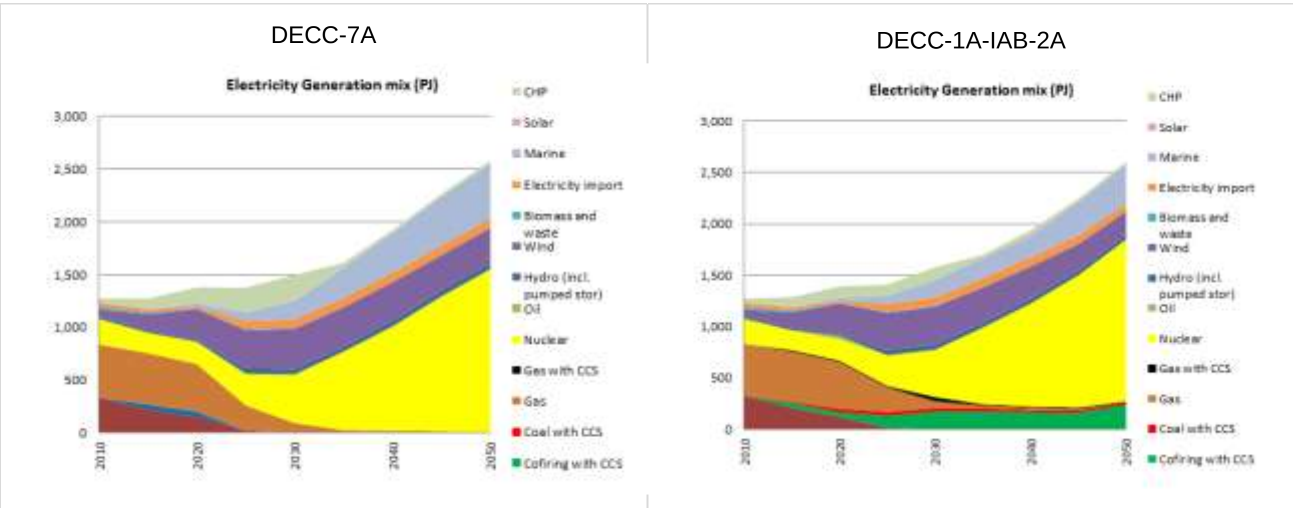


Figure 169: Electricity generation mix out to 2050

There is a much greater amount of electricity produced by renewable wind and marine generation. The increase in wind is 47% by 2050, when CCS is not an option and with marine this is 36%. In DECC-7A, over 2015 and 2020, there is a small amount of generation (3% of total in each year) by cofiring which does not take place in DECC-1A-IAB-2A.

2.9.5 End-Use Sector Emissions

The end-use emissions disaggregated by sector are shown in Figure 170. Whilst the total emissions reductions are constrained and so the same in both cases, there is a large drop in industry sector emissions in DECC-7A, counterbalanced by an increase in upstream and non-sector emissions.

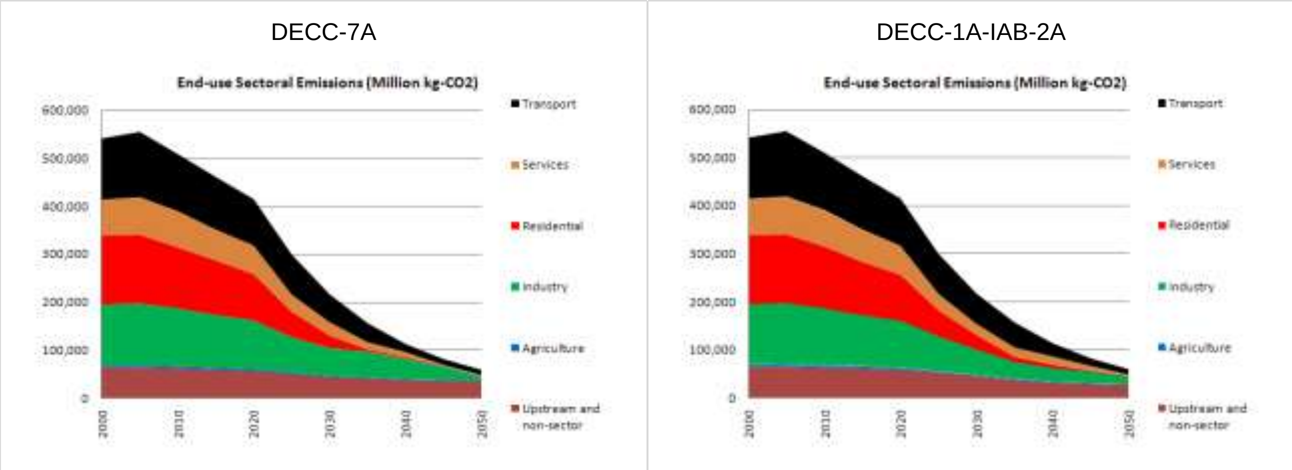


Figure 170: End use sectoral emissions to 2050

The industrial chemical, iron and steel and non-ferrous metal subsectors all see a reduction in demand from one time cycle to the next beyond 2020 at the maximum allowable within MARKAL's elastic demand constraint.

There is a large drop in coal and steam energy demand in DECC-7A when compared to DECC-1A-IAB-2A, which is counteracted by an increase in demand for electricity. This is shown in Figure 171. This starts after 2030 at which point in DECC-1A-IAB-2A, there is a demand for energy from wood, however this is not apparent in DECC-7A.

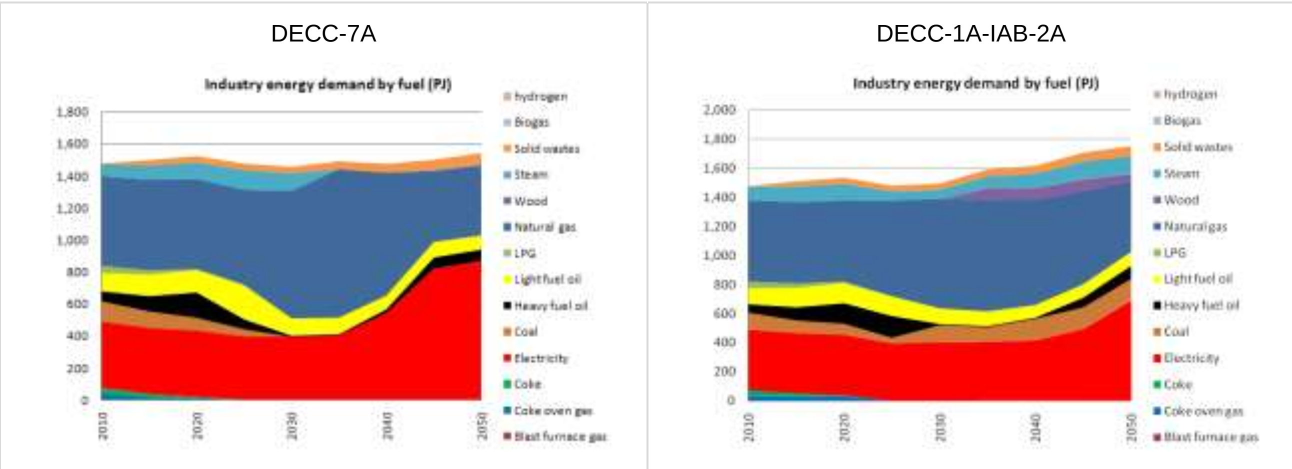


Figure 171: Industrial Sector Energy Demand by Fuel

2.10 Study 7B: Additional Low Carbon Electricity

2.10.1 Description of Study

The study explores the pathway to a 90% CO_2 emissions reduction in the energy system by 2050 where more imported low carbon electricity is available. This could also be interpreted as a scenario where there is more low cost low carbon electricity available, and it does not strictly need to be sourced from imports.

There is one run in this study:

1. **Study 7 Run B**. Emissions reduction in this run is bounded with equal annual emissions reduction to 2050, but extra electricity import options are available. The additional options consist of three tranches of 125PJ/year each from 2025 onwards, at a cost of £7, £10, and £14 year 2000 UK millions per PJ. The additional imported electricity is available in the 4^{th} carbon budget period (i.e. 2025 in MARKAL). DECC-1A-IAB-2A is the equivalent run to DECC-7B with the same carbon constraints.

   Code: **DECC-7B**

The baseline case for run DECC-7B is DECC-0A-AFELC. This is an equivalent run with no emissions constraints, except those in the Government Carbon Plan.

2.10.2 Key Results

Table 29 shows the discounted energy system costs, demand response and the discounted consumer/producer surplus for the case runs analysed in this study. The total discounted system cost in DECC-7B is £14 billion lower than the DECC-1A-IAB-2A costs.

The demand response is also lower for scenario DECC-7B than for DECC-1A-IAB-2A, as evident by the £14 billion lower reduction in surface under demand curve. The consumer/ producer surplus loss is therefore smaller for DECC-7B. This means that the demand response has less impact on the total system cost than in the comparison run. This means that technology change plays a bigger part as a means to CO_2 reduction in run DECC-7B.

Table 29: Key Result Metrics

	DECC-0A-AFELC (base)	DECC-7B	DECC-1A-IAB-2A
Discounted Technical Energy System Cost (2010 £UK Billions)	5,436	5,460	5,474
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	-178	-194
Discounted Impact on Welfare of Demand Reduction[3] (2010 £UK Billions)	0	161	175

The undiscounted annual average system costs are shown in Table 30. The difference between DECC-7B and DECC-1A-IAB-2A fluctuates over time. With the exception of 2025, for most of the time horizon, the costs are lower in DECC-7B. The difference increases steadily to £3.6 billion in 2045, dropping to £1.1 billion by 2050.

Table 30: Average annualised undiscounted system costs (2010 prices, UK£ Billion)

Run/Year	2025	2030	2035	2040	2045	2050
DECC-0A-AFELC	237.96	260.84	273.52	287.93	303.01	315.81
DECC-7B	237.10	257.56	270.09	290.18	312.97	330.17
DECC-1A-IAB-2A	236.44	257.62	271.55	292.01	316.58	331.28

Figure 172 shows the marginal price of CO_2 across the timeline of the study. The marginal cost of CO_2 increases more slowly in 2020s and in period 2030 in run DECC-7B. In 2035 there is a sudden jump in marginal cost as DECC-7B catches up with DECC-1A-IAB-2A. The figures remain similar till the last period when DECC-7B overtakes DECC-1A-IAB-2A and the costs reach £445/tCO_2 and £415/tCO_2 respectively.

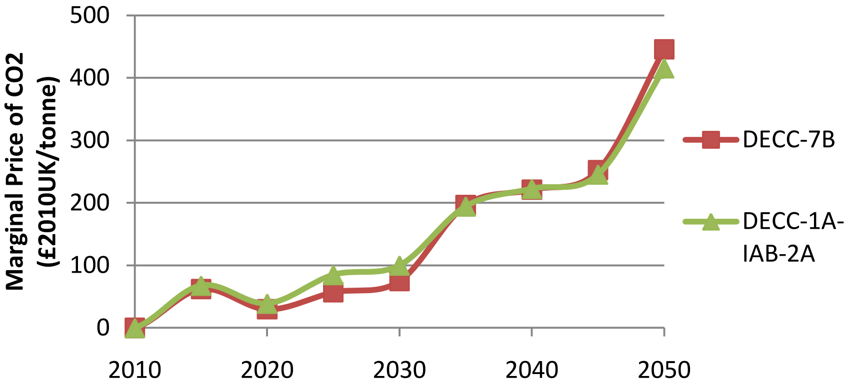


Figure 172: Marginal Price of CO_2

2.10.3 Primary and Final Energy Statistics

The primary energy demand throughout the case studies is shown in Figure 173. Total primary energy demand is lower in DECC-7B than in DECC-1A-IAB-2A over the entire time horizon (by 2-7%). Unsurprisingly, imported electricity plays a much more important part in the former scenario. This can be observed over most of the time horizon. In 2050, imported electricity constitutes 4% of all primary energy demand compared to 1% in DECC-1A-IAB-2A. This displaces part of coal demand which comprises 6% of the total primary energy demand in DECC-7B and 9% in DECC-1A-IAB-2A.

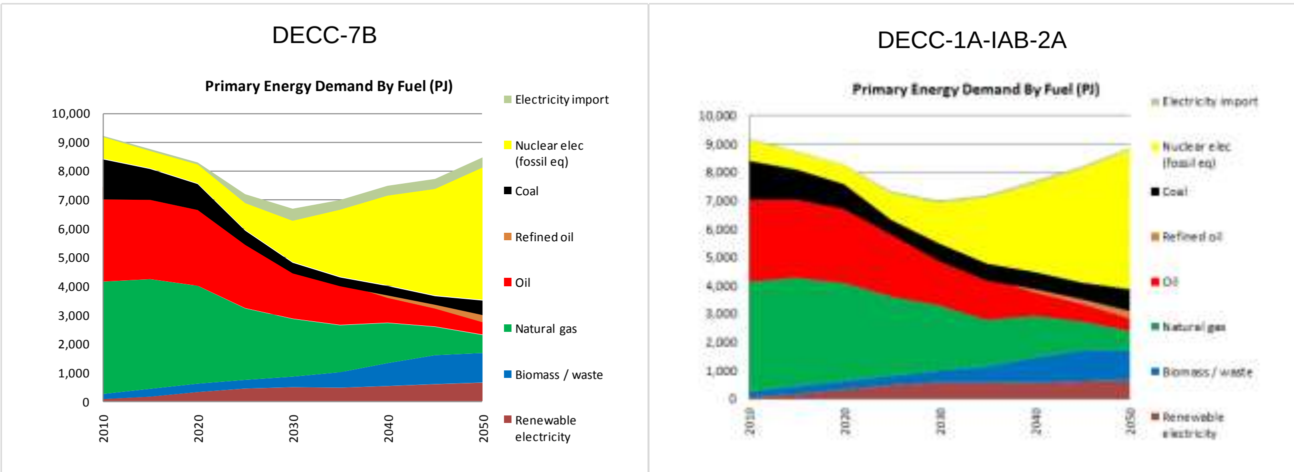


Figure 173: Primary energy demand over time

In absolute terms, imported electricity use in DECC-7B is four times that in scenario DECC-1A-IAB-2A between 2025 and 2050 (total demand between 2025-2050 being 2112PJ and 495PJ in DECC-7B and DECC-1A-IAB-2A respectively).

The difference in final energy demand by fuel type is apparent in Figure 174. Final energy demand is slightly higher in run DECC-7B over most of the time horizon. In run DECC-7B the fuel mix contains more electricity, more coal and less petrol, gas, LTH and steam (the largest difference is 1%).

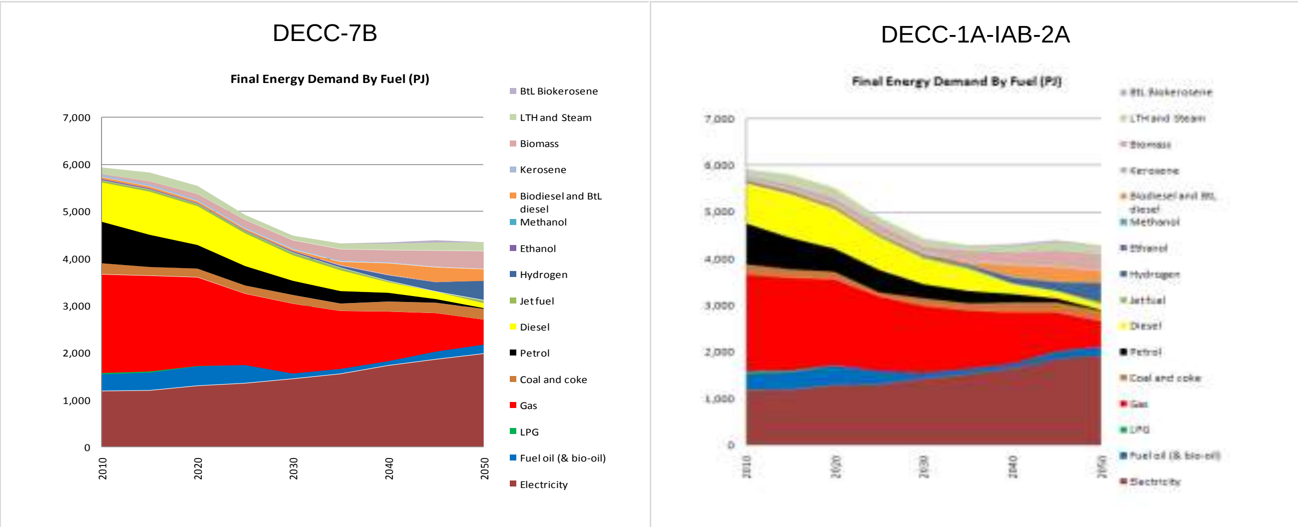


Figure 174: Final Energy Demand by Fuel over time

The quantity of bio-products in final energy demand is very similar for run DECC-7B to than of DECC-1A-IAB-2A. The distribution by sector is shown in Figure 175. The main difference is later uptake of bio-products in the industry sector observed in run DECC-7B.

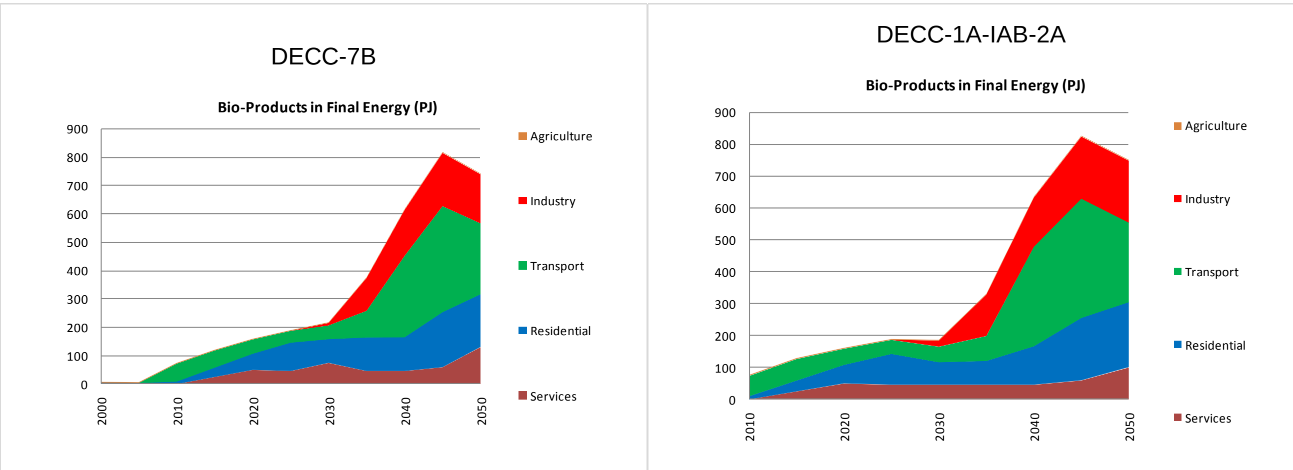


Figure 175: Bio-Products in Final Energy Demand disaggregated by sector.

2.10.4 Power Generation and Installed Capacity

Figure 176 shows the total installed capacity and the total electricity generated by the system. Installed capacity is lower in the 2030s in run DECC-7B after which the levels are similar until it overtakes the comparison run in 2050. The generation is rather consistent being slightly higher in run DECC-7B overall. In the 2030s these results indicate higher energy system efficiency for run DECC-7B, although this may be biased by the fact that any conversion losses associated with imported electricity are outside the accounting boundary of the model.

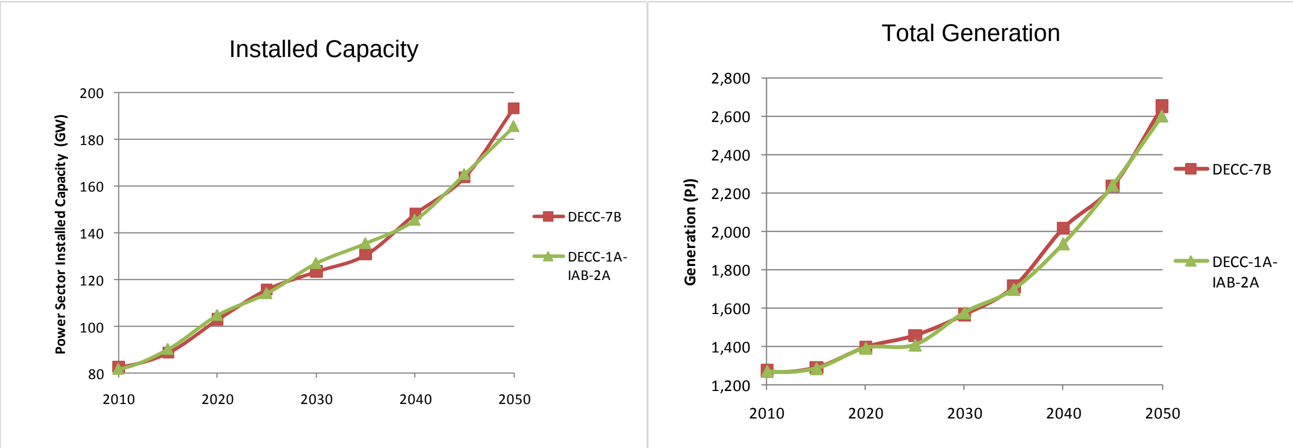


Figure 176: Total Installed Capacity (GW) and Generation (PJ) from the energy system

In both cases the emissions intensity of electricity generation becomes a sink by the end of the time horizon, as can be seen from Figure 177. It drops quicker for the imported electricity run DECC-7B, because the imported electricity has zero emissions associated with it for national accounting purposes.

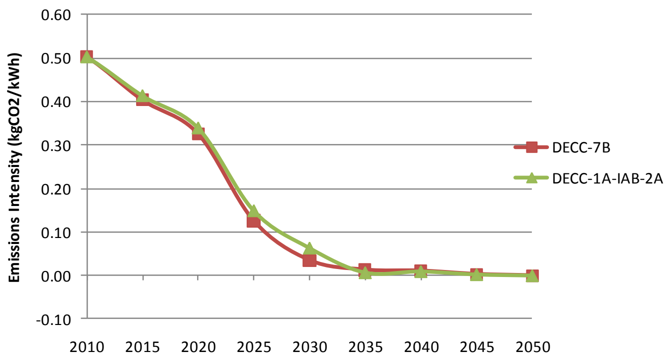


Figure 177: Emissions intensity of electricity generation out to 2050

The installed capacity mixture by fuel of the two different cases is shown in Figure 178.

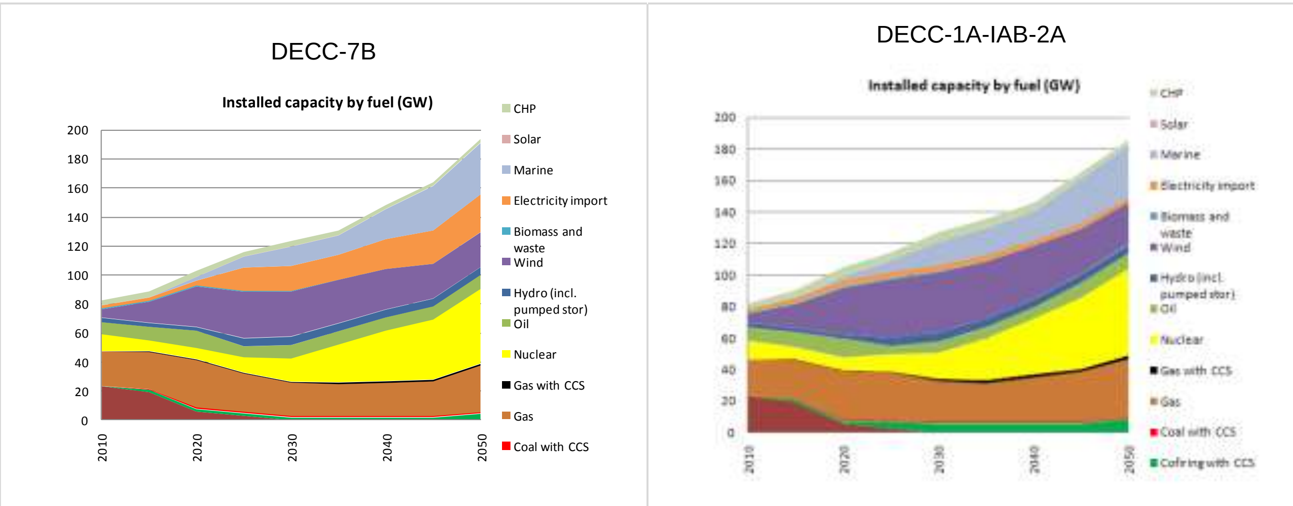


Figure 178: Installed Electricity Generation Capacity

The most obvious difference is a much greater proportion of imported electricity in run DECC-7B. Its use is steadily increasing in this run, and reaches 7 times the installed capacity of scenario DECC-1A-IAB-2A in the last period. In turn, other fuels get a smaller proportion of installed capacity, most notably gas, wind, cofiring with CCS and in later periods, nuclear power.

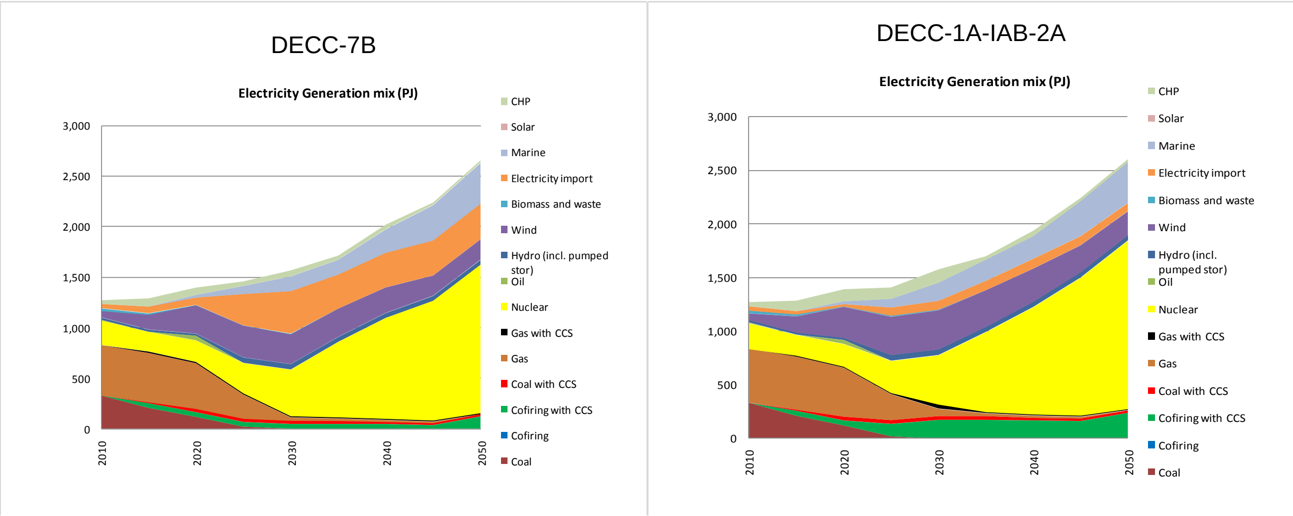


Figure 179: Electricity Generation Mix

Similar patterns can be observed in the total electricity generation mix as shown in Figure 179. In DECC-7B, there is a significant increase in generation from imported electricity from 2025 onwards in comparison to DECC-1A-IAB-2A. The effect of this is the more rapid reduction of gas usage in the generation mix, less take up of cofiring with CCS, wind and nuclear power in the later periods.

2.10.5 End-Use Sectors and Electricity Storage

The end-use emissions disaggregated by sector are shown in Figure 180. The total emissions reductions are the same in both cases and the differences in the sectors are small. The proportion of emissions from service and transport sectors is smaller in DECC-7B run, counterbalanced by an increase in industry sector emissions.

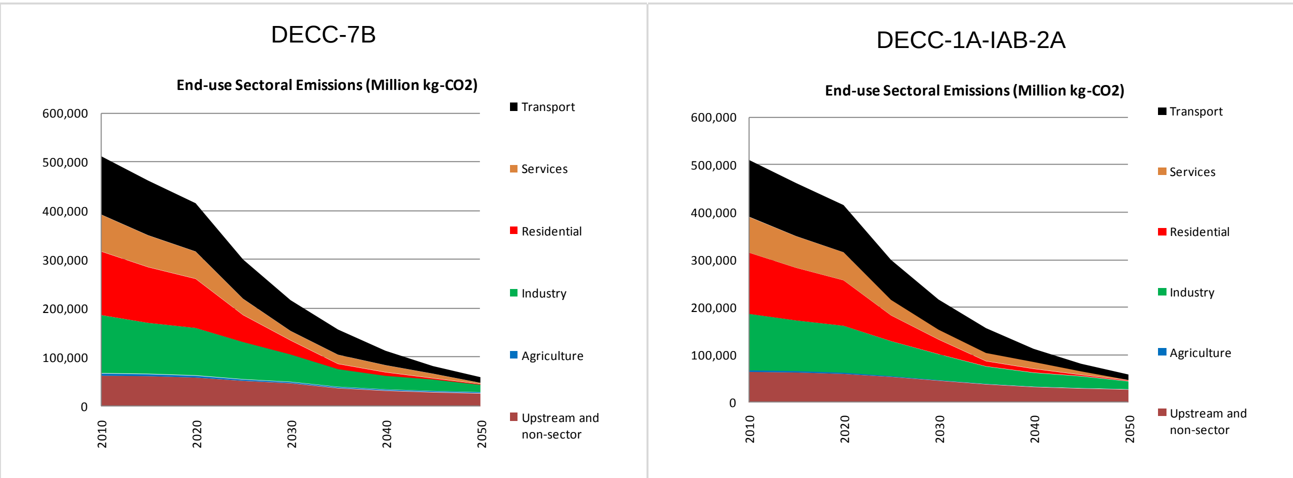


Figure 180: End use sectoral emissions to 2050

Demand reductions from the baseline in DECC-7B are smaller overall than in DECC-1A-IAB-2A. In particular, in the residential sector lighting demands, upright freezer (both existing and new) and cooling demand reductions are 5% smaller in DECC-7B run than in the comparison run over the period between 2020 and 2050. In service sector largest difference is in the cooling demand. This means that the same emission reductions are achieved with less demand reductions in all sectors, most significantly so in the residential sector.

Another apparent effect of the change in constraints is in the electricity storage as shown in Figure 181. The total electricity storage increases steadily in scenario DECC-7B and gets almost twice as high than in the DECC-1A-IAB-2A by 2045. Most of this change can be attributed to transport electric storage, but night heat storage is also significant.

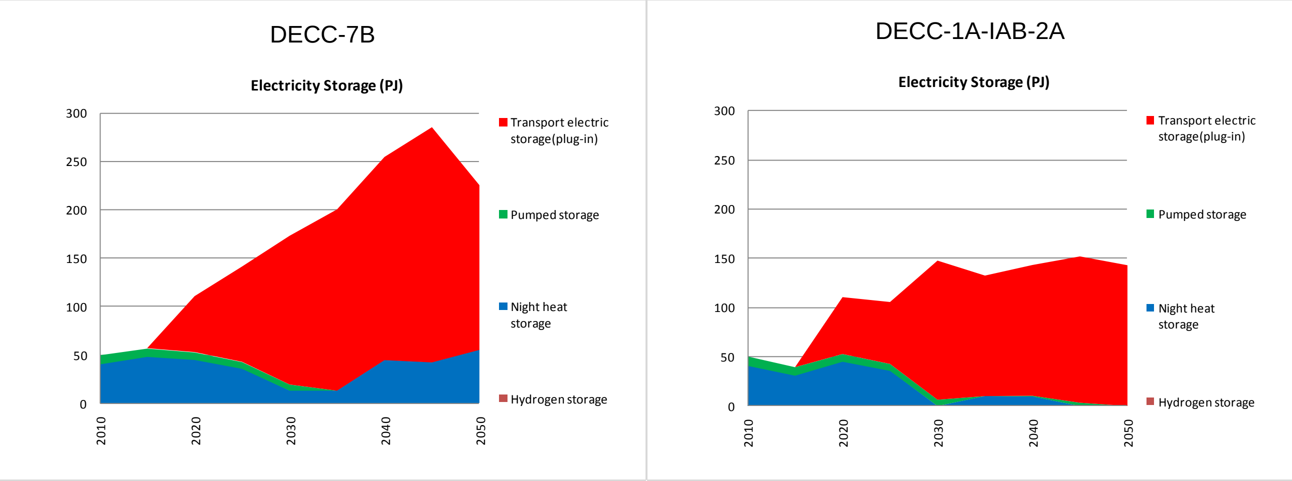


Figure 181: Electricity Storage in runs DECC-7B and DECC-1A-IAB-2A

2.11 Study 7C: High Cost Heating Technologies

2.11.1 Description of Study

The purpose of this study is to assess how changes in the capital cost of heating end-use technologies influences decarbonisation of the system as a whole. This study was motivated by the fact that costs for these technologies the database are low. For example, in version 3-26-5 of the UK MARKAL model, total residential space and water heating demand is 827PJ in the year 2000. This translates roughly to 13.3MWh (4.809×10^{-5}PJ/a) per house per year. The cost of boilers was £9.513 million per PJ/a capacity (i.e. enough capacity to serve one PJ spread out over an entire year). The implied cost of each boiler is therefore approximately £460, substantially below the current turnkey cost. Furthermore, updates to heat pump prices in the present project reduced their cost from £74M/PJ/a to £21.45M/PJ/a. The new implied price of a heat pump installation is therefore just above £1,000, and well below currently observed installation prices ranging from £5,000 to £15,000 where internal retrofit and (where applicable) ground works are included. Therefore this set of runs explores the impact of significant increases in the prices of space and water heating in general.

There are three runs in this study:

1. Study 7 Run C. Taking the reference case of run DECC-1A-IAB-2A, this run doubles the cost of all *end-use* technologies serving space and water heating demand in the residential and services sectors. Note that the capital cost of district heating technologies (which are not end-use system in MARKAL) remain unchanged. All other assumptions in run DECC-1A-IAB-2A remain unchanged.
   Code **DECC-7C.** Baseline for this run is DECC-0A-HEAT1.
2. Study 7 Run C High. As per run DECC-7C, but the capital cost of end-use heating technologies is doubled again (i.e. 4 times that of DECC-1A-IAB-2A).
   Code **DECC-7C-H.** Baseline for this run is DECC-0A-HEAT2.
3. Study 7 Run C Very very high. As per run DECC-7C-H, but the capital cost of end-use heating technologies is doubled again (i.e. 8 times that of DECC-1A-IAB-2A).
   Code **DECC-7C-VH.** Baseline for this run is DECC-0A-HEAT3.

This report will discuss the effects that these changes have on the decarbonisation pathway chosen. This is in the context of the fact that the overall trajectory for CO_2 emissions reduction in all scenarios is identical: they follow the baseline system until 2020 and in the later periods are bound by the targets shown in Table 31.

Table 31: Emissions Targets ($MtCO_2$)

Run/Year	2025	2030	2035	2040	2045	2050
DECC-0A (unconstrained)	463.46	416.31	457.74	507.45	554.19	598.24
All Constrained Runs	299.81	216.60	156.48	113.04	81.67	59.00

2.11.2 Key Results

Key result metrics are presented in Table 32. As expected, all runs where the cost of end-use technologies has been increased cause increases in technical energy system cost in their respective baseline and in the decarbonised run. The increasing capital costs also result in a greater loss on consumer/producer surplus, and a greater demand response. In general, the change in demand response is slightly more important in terms of impact on welfare than change in the cost of the technical aspects of the energy system, although this distinction is marginal.

Table 32: Key Result Metrics (2010£ UK Billion)

	DECC-7C	DECC-7C-H	DECC-7C-VH	DECC-1A-IAB-2A
Baseline System Technical Energy System Cost (2010 £UK Billions)	5,478	5,519	5,576	5,448
Discounted Technical Energy System Cost (2010 £UK Billions)	5,509	5,558	5,639	5,474
Change in Technical Energy System Cost from Baseline (2010 £UK Billions)	31	39	63	26
Discounted Consumer/Producer Surplus (2010 £UK Billions)	-206	-227	-283	-194
Discounted Impact on Welfare of Demand Reduction[3] (2010 £UK Billions)	181	194	226	175

Table 33 presents the annualised undiscounted (i.e. all values are in real 2010 UK pounds) technical system cost over time. Over the 4th carbon budget period from 2023 to 2027, the higher capital cost of heating technologies does have an impact; the difference between the highest and lowest cost implies an increase in system cost £8 billion pounds. From 2035 onwards this gap increases in approximately £12 to £13 billion pounds per year.

Table 33: Average annualised undiscounted system costs (2010£ UK Billion)

Run/Year	2025	2030	2035	2040	2045	2050
DECC-0A-IAB-1A	238	262	274	289	304	317
DECC-1A-IAB-2A	236	258	272	292	317	331
DECC-7C	238	259	274	295	320	334
DECC-7C-H	241	262	279	298	322	337
DECC-7C-VH	244	266	285	304	323	344

Figure 182 below charts the increasing cost of mitigation, represented by undiscounted year 2010 pounds per tonne of CO_2 saved. For the 4th carbon budget period (i.e. year 2025 in MARKAL) a quadrupling of the capital cost of heating technologies does not impact upon mitigation cost. However, once the capital cost multiple is increased to 8 in run DECC-7C-VH, a significant impact is observed, where the implied CO_2 price almost doubles. By 2045, all runs show the same CO_2 price again.

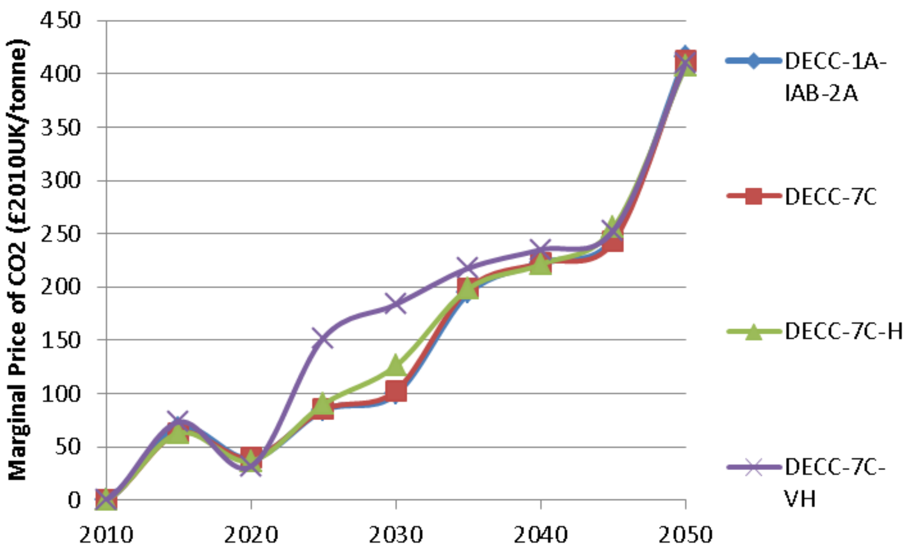


Figure 182: Marginal Cost of CO_2 for Each Run

Figure 183 presents the comparison of runs in terms of the decarbonisation trajectory of grid electricity. These results are largely identical across the runs; grid electricity is always decarbonised rapidly, especially in the 4th carbon budget period. Only the final very high capital cost run shows some difference in the 2030s, where decarbonisation is slightly slower.

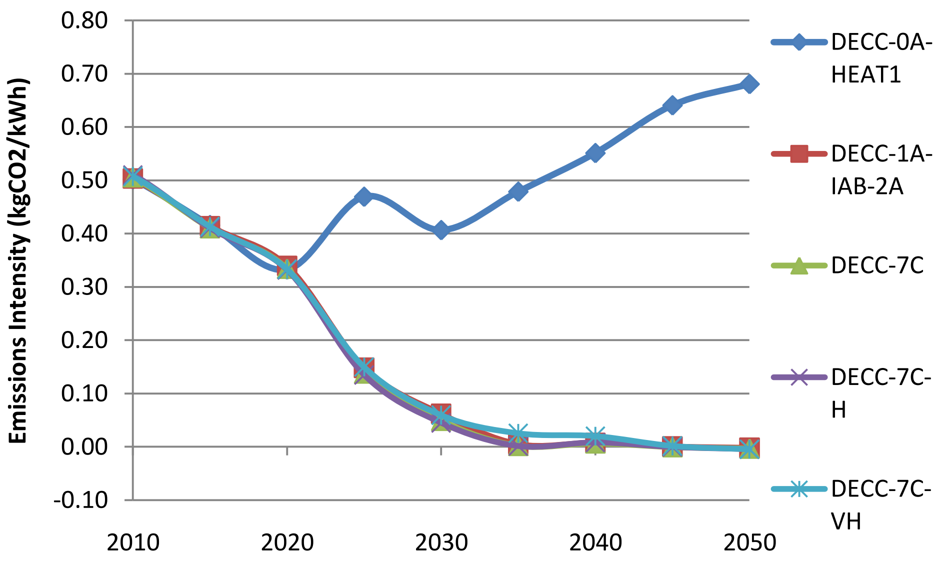


Figure 183: The CO_2 Emissions Intensity of Grid Electricity

2.11.3 Primary and Final Energy Statistics

Figure 184 compares primary and final energy consumption over time. Primary consumption is mostly identical across the time horizon, with a small departure from 2045 onwards, where runs with higher capital cost of heating technologies tend to produce higher demand for primary energy. However, final energy consumption shows the opposite trend; consumption in the high capital cost runs in higher earlier in the period, notably in the 4th carbon budget window. Later in the period from 2040 onwards, final energy consumption is similar across the abated runs. As per all of the abatement runs in this project, the energy system generally becomes less efficient as it decarbonises. It takes more primary energy to produce one unit of final energy. This is likely to be associated with increased electrification of the energy system and associated conversion and T&D losses.

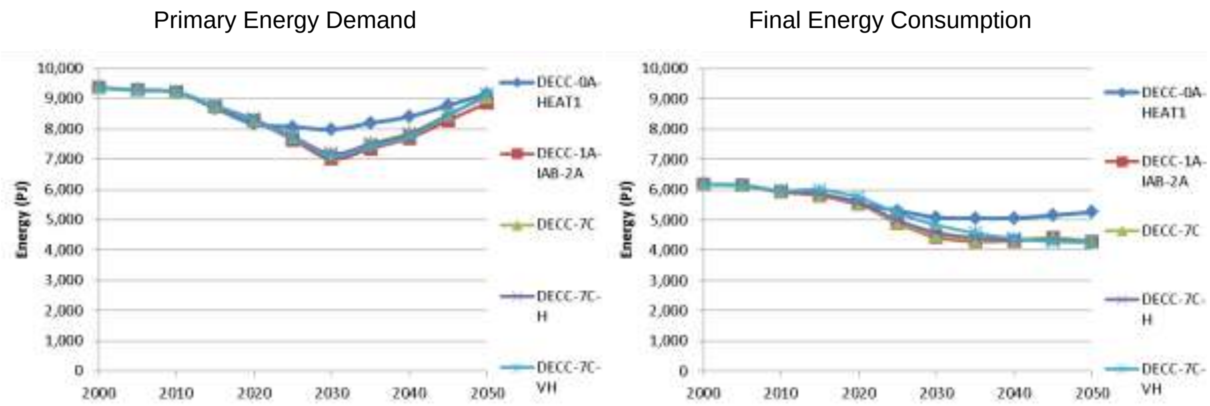


Figure 184: Primary Energy Demand and Final Energy Consumption over time

Fuel shares for primary and final energy consumption in 2050 are shown in Figure 185. For primary energy demand, key differences lie in an increasing share of coal and decreasing share of biomass/waste as the capital cost of heating technologies increases. This is indicative of a shift away from biomass as a heating fuel towards electricity, where that electricity generation is based on coal with carbon capture and storage. This hypothesis is borne out by the final energy consumption chart, which shows increasing electricity use with increasing capital cost of heating, and decreasing direct use of biomass.

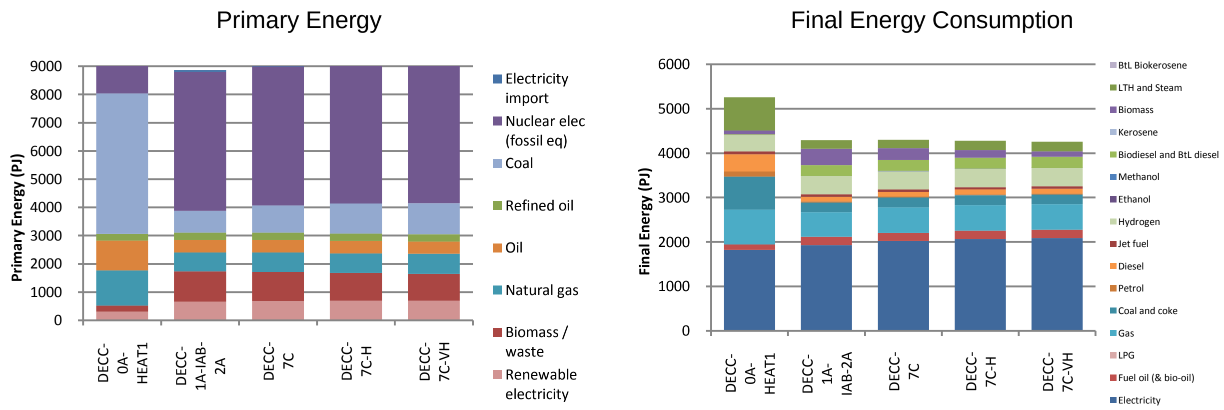


Figure 185: Primary and Final Energy Demand by Energy Carrier in 2050

Further investigation of the nature of change in bio-energy in final consumption is carried out via analysis of Figure 186 below. The decreasing trend in consumption is evident, with similar profiles across runs but decreasing peak consumption (from almost 800PJ per year in DECC-1A-IAB-2A, down to approximately 600 PJ per year in DECC-7C-VH). A key change across these runs is the reducing component in the residential sector. With each increase in capital cost this share declines, and is eventually completely eliminated in run DECC-7C-VH. Interestingly, in the 4th carbon budget period, the share of biomass in services increases under increasing capital cost of end-use heating technologies. This relates to the use of wood boilers over this period, which is in turn driven by the fact that these technologies are much cheaper than their residential sector counterparts.

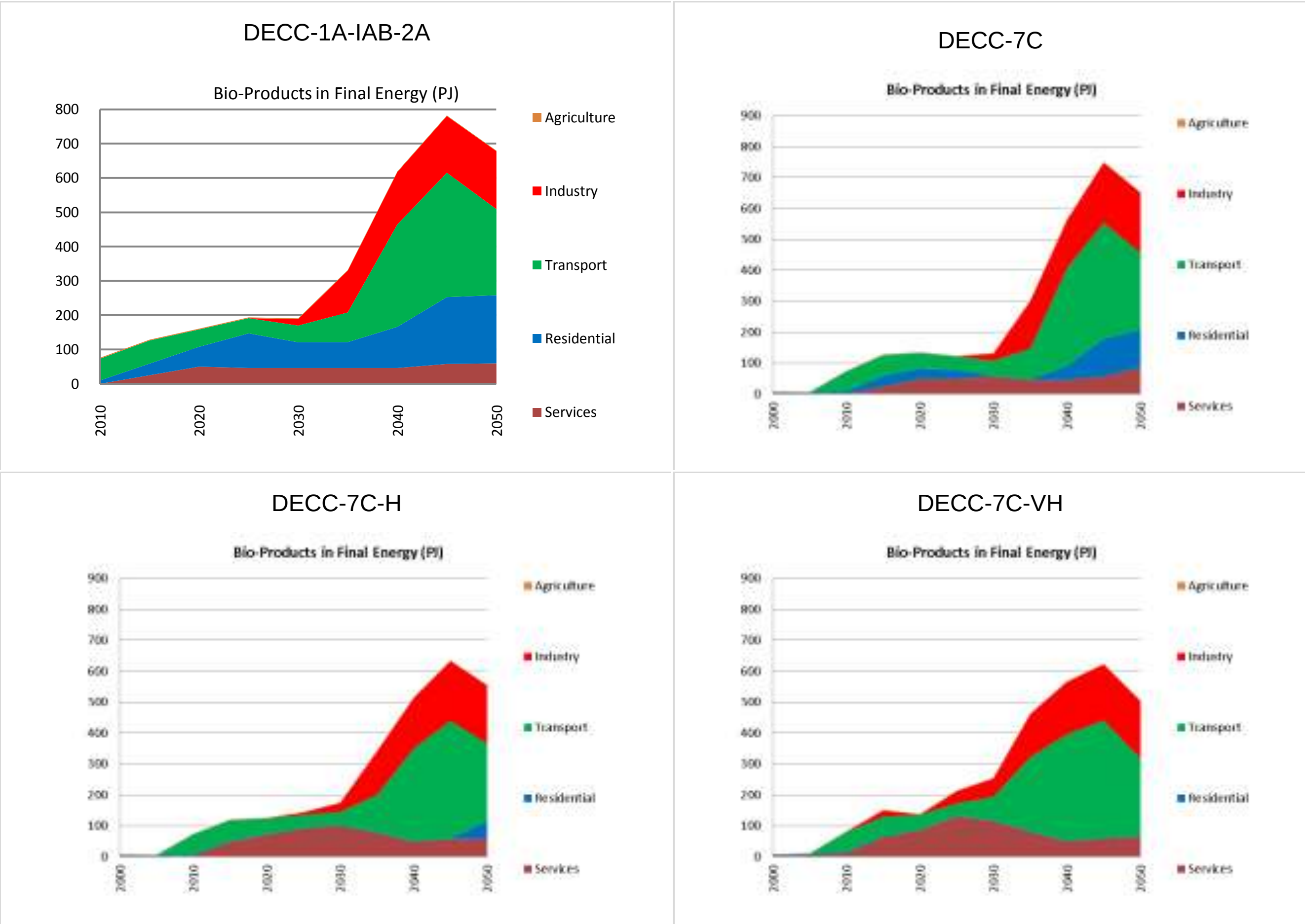


Figure 186: Bio-Products in Final Energy Consumption

2.11.4 Power Generation and Installed Capacity

Figure 187 presents the installed capacity and generation for the runs. In general these follow a consistent trend with increasing capital cost of end-use heating technologies being associated with increasing demand for electricity. This in turn creates a requirement for more generation capacity. This is consistent with the observations in the previous section; increasing capital cost of these end use technologies tends to favour those that run on electricity.

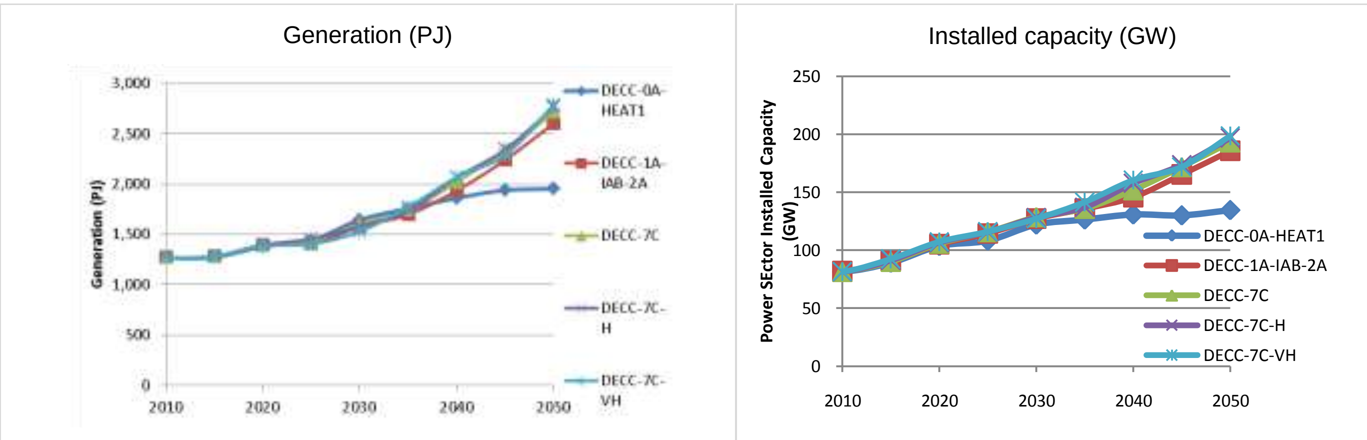


Figure 187: Installed Capacity and Electricity Generation over Time

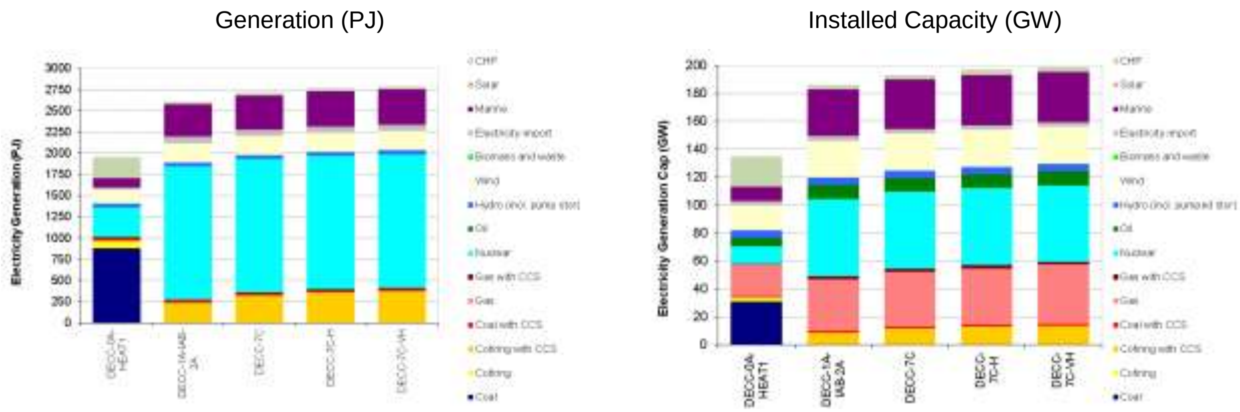


Figure 188: Generation (PJ) and Generation Capacity (GW) by Technology in 2050

The split (in terms of technology-type in 2050) of this generation and generating capacity is shown in Figure 188. The increase in capacity exists mainly in gas-fuelled and co-firing with CCS technologies. However, the increasing share of gas is not actually used by the system (it exists to back up the increasing share of wind power). Nuclear power is by far the dominant producer in terms of energy delivered in all runs.

2.11.5 End-Use Sectors

The split of sectoral CO_2 emissions and end-use sectoral emissions is shown in Figure 189. There is no significant change in the shares of these emissions across the end-use emissions of the abated scenarios. However, if the split upstream is considered, slight contrasts are apparent. The runs with higher capital cost of end-use heating technologies tend to decarbonise the electricity system more, combined with a slight increase in emissions from industry.

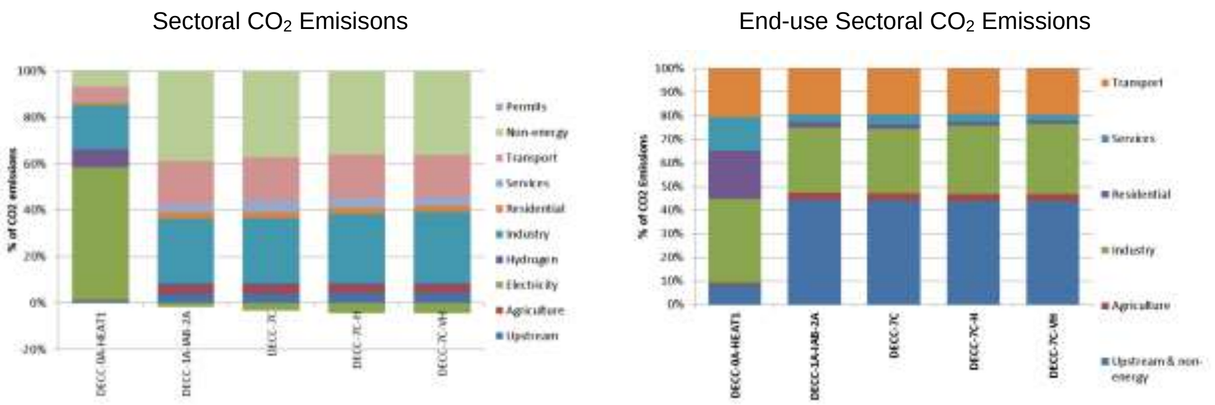


Figure 189: Sectoral and End-use Sectoral CO_2 Emissions Shares in 2050

The following sections consider the residential and services end-use sectors in more detail. These sectors have been chosen for further analysis because they contain the technologies for which capital cost sensitivity is being investigated.

Residential Sector

The distinguishing characteristic of these runs is that the cost of end-use heating technologies has increased. Therefore it is of interest to observe how this influences which technologies serve heating demand. Figure 190 shows useful thermal energy delivered, contribution of conservation measures, and demand not served due to demand response. Key points to note are:

- Conservation measures are used to their full extent in all scenarios. That is to say they are adopted up to the constraint imposed in the MARKAL database.
- Demand response increases with increasing capital cost of the end-use technologies.

- Heat pumps generally enter the mix later under the high capital cost scenarios, but this introduction is still rapid and they quickly become the dominant heating technology.
- Biomass pellet based heating features in the reference run (DECC-1A-IAB-2A), but gradually disappears, replaced by direct electric heating and demand response.
- Solar thermal is also squeezed out of the solution as capital costs rise.
- The rise of direct electric heating late in the period is likely to be driven by the fact that is it a very low cost technology. The relative impact of doubling/quadrupling/octupling capital costs is therefore smaller for this technology where electricity costs remaining constant.

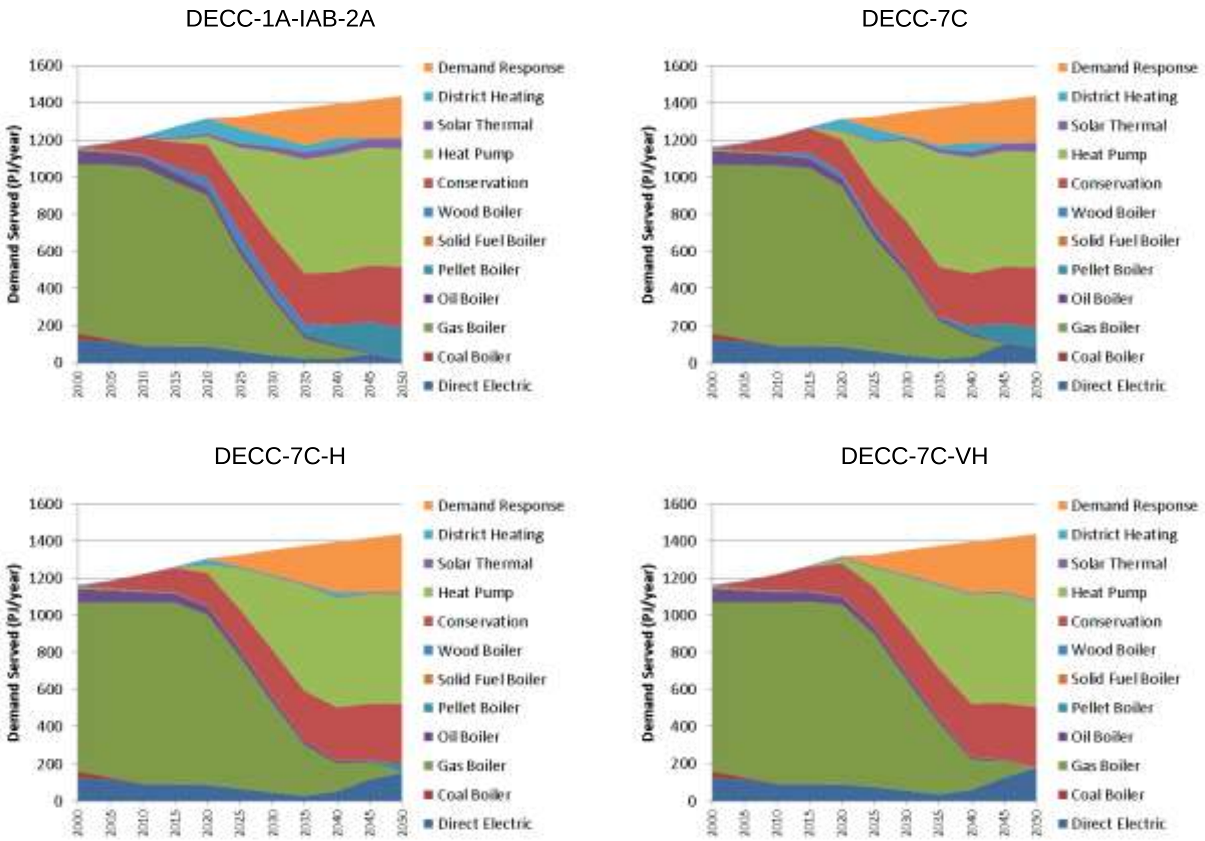


Figure 190: Technologies Serving Residential Heat Demand (Space and Water Heating)

In general it is clear the pellet based heating is a marginal technology. It can be replaced by direct electric heating. Even heat pumps are replaced by direct electric heating in extreme scenarios. Further investigation of this phenomenon would be required to pin down likely capital cost difference between these technologies to make firmer conclusions.

Services Sector

A similar analysis of service sector heating is carried out by reference to Figure 191. Key contrasts here relate to the longevity of gas use, and trade-off between heat pumps and district heating. As noted at the beginning of this briefing, the capital cost of district heating technology has not been altered across these runs, as it is not considered to be an end-use technology in MARKAL.

In general, the increasing costs of end-use heating technologies results in more rapid decline of the use of gas in heating. The use of heat pumps also declines with increasing capital cost. Their contribution is substituted largely by district heating and by earlier use of conservation measures. The projected uptake of district heating is very rapid, beginning now (i.e. approx 2010) and proceeding to become the primary supply of heat in the 4th carbon budget period.

Direct electric heating is also used to an increasing degree in high capital cost scenarios, and it is introduced earlier in the highest capital cost run (DECC-7C-VH). This is not driven by other technologies hitting their constraints, but rather is based on the fact that these technologies become increasing attractive from the levelised energy cost perspective.

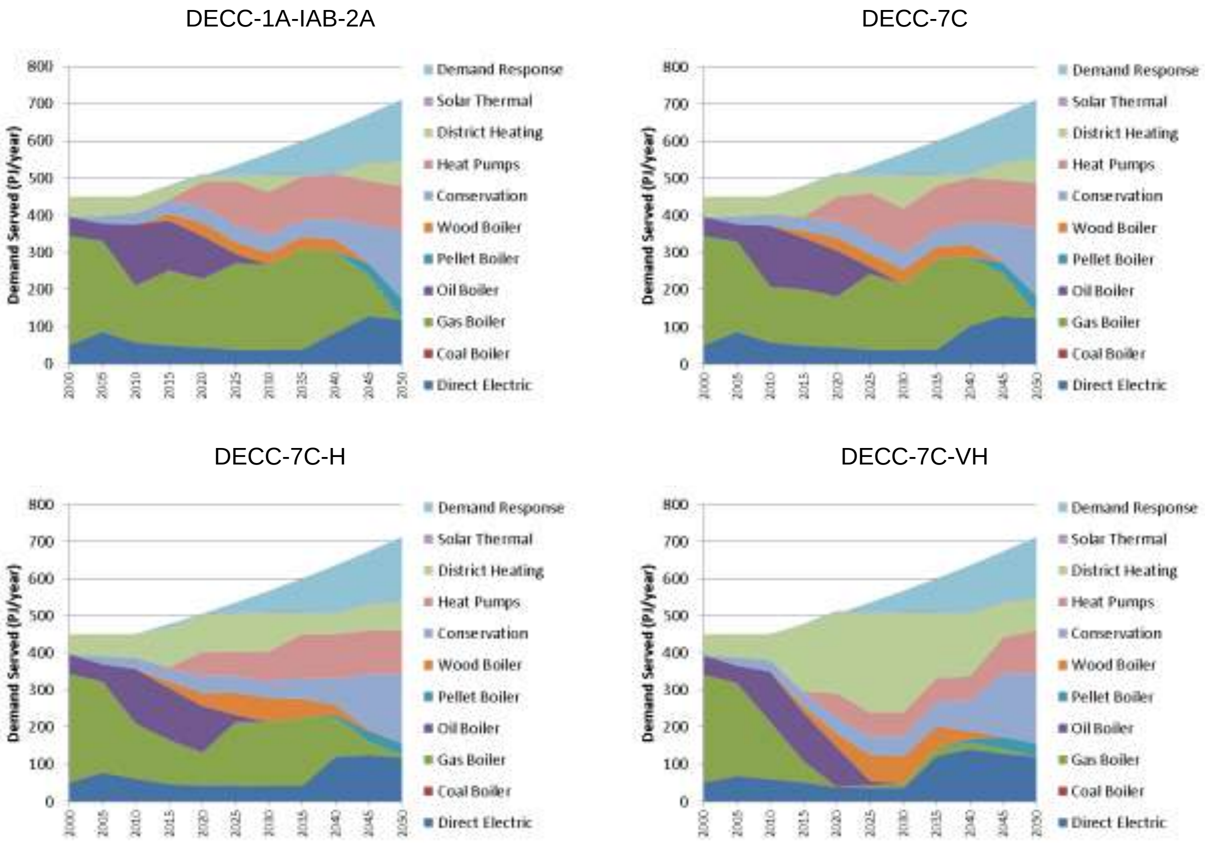


Figure 191: Technologies Serving Service Sector Heat Demand (Space and Water Heating)

2.12 Study 7D: A More Constrained Power Sector

2.12.1 Description of Study

The study explores the pathway to a 90% CO_2 emissions reduction in the energy system by 2050 where the deployment of power sector has additional constraints, particularly over the 4th carbon budget period.

There is one run in this study:

1. **Study 7 Run D**. Emissions reduction in this run is bounded with equal annual emissions reduction to 2050, but extra power sector constraints are present. This includes: 1) reduced maximum rate of nuclear build, 2) no CCS availability until after 2027 except for the government demonstration plants, 3) reduced renewable electricity build. DECC-1A-IAB-2A is the equivalent run to DECC-7D with the same carbon constraints, but without the additional power sector constraints.

   Code: **DECC-7D**

The baseline case for run DECC-7D is DECC-0A-POW. This is an equivalent run with no emissions constraints, except those in the Government Carbon Plan.

2.12.2 Key Results

Table 34 shows the discounted energy system costs, demand response and the discounted consumer/producer surplus for the case runs analysed in this study. The total discounted system cost in the DECC-7D is £6 billion higher than in the scenario DECC-1A-IAB-2A.

The demand response (i.e. impact on welfare of demand reduction) shown in scenario DECC-7D is higher than in DECC-1A-IAB-2A, as evident by the £24 billion higher reduction in impact on welfare. The consumer/ producer surplus loss is greater (£20 billion) for DECC-7D. This means that in run DECC-7D the demand response has more impact on the total system cost than in the comparison run and that demand reduction plays a bigger part as a means to CO_2 reduction.

Table 34: Key Result Metrics

	DECC-0A-POW (base)	DECC-7D	DECC-1A-IAB-2A
Discounted Technical Energy System Cost (2010 £UK Billions)	5,461	5,480	5,474
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	-214	-194
Discounted Impact on Welfare of Demand Reduction[3] (2010 £UK Billions)	0	199	175

The undiscounted annual average system costs are shown in Table 35. The difference between costs in DECC-7D and DECC-1A-IAB-2A fluctuates over time. The costs are lower in DECC-7D in 2025-2035, higher in 2040 and 2045 and drop lower again in 2050.

Table 35: Average annualised undiscounted system costs (2010£ UK Billion)

Run/Year	2025	2030	2035	2040	2045	2050
DECC-0A-POW	238.63	261.38	273.86	288.45	304.33	316.42
DECC-7D	234.91	255.11	271.20	292.64	317.11	331.03
DECC-1A-IAB-2A	236.44	257.62	271.55	292.01	316.58	331.28

Figure 192 shows the marginal price of CO_2 across the timeline of the study. The marginal cost of CO_2 increases sharply in 2025 for run DECC-7D to reach £220 per tonne. It drops again in the next period and is similar to that in run DECC-1A-IAB-2A for the rest of the time horizon. It is likely that the drop in 2030 is due to the CCS technologies becoming available after the 4th Carbon budget period.

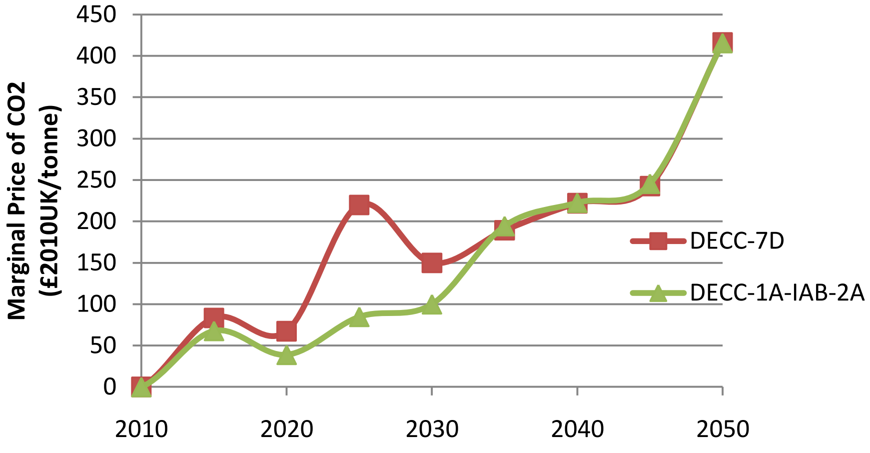


Figure 192: Marginal Price of CO_2

2.12.3 Primary and Final Energy Statistics

The primary and final energy demand timelines are shown in Figure 193. Both primary and final energy demands are slightly lower in run DECC-7D, the difference being particularly noticeable in the 2020s.

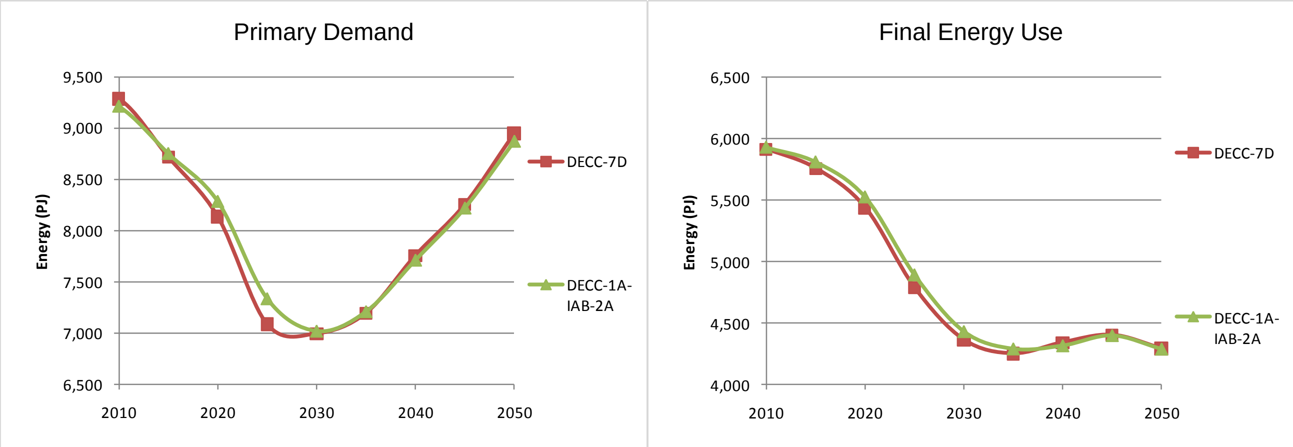


Figure 193: Primary and Final Energy Demand for runs DECC-7D and DECC-1A-IAB-2A

The primary energy demand fuel composition for both runs is shown in Figure 194. As the additional constraints would stipulate, the renewable and nuclear energy demands are lower in run DECC-7D than in DECC-1A-IAB-2A. The difference is smaller towards the end of the time horizon and is most significant in periods 2020 and 2025. There is also a drop in coal use in 2025, as seen in Figure 194. In part this reduction is compensated by an increase of bio-energy demand and natural gas proportion in the fuel mix. The total primary energy demand is also smaller overall in DECC-7D as seen in Figure 193.

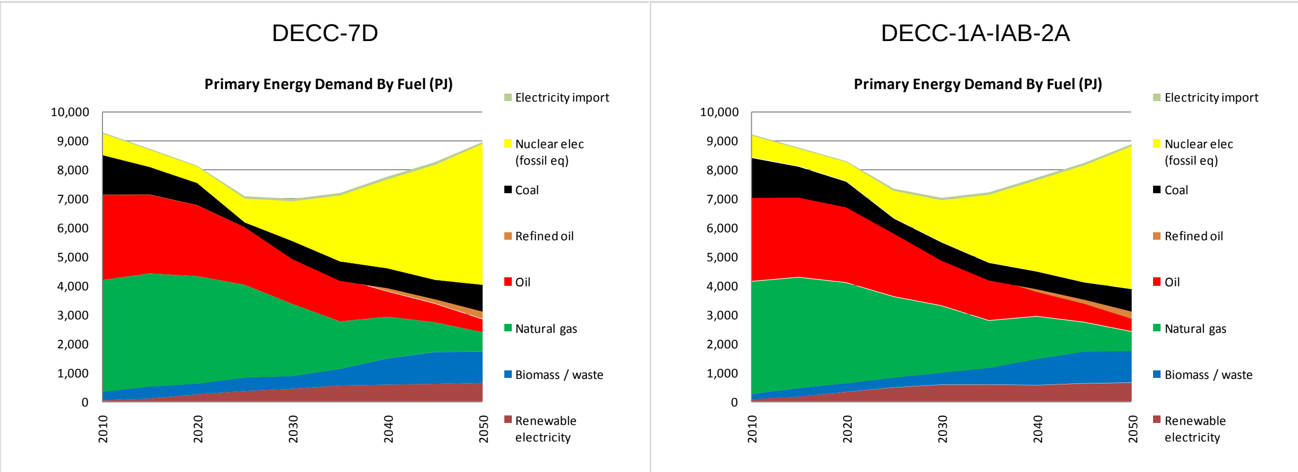


Figure 194: Primary Energy Demand by Fuel over time

In final energy mixture, the most noticeable change is the higher use of LTH and steam in run DECC-7D than in the comparison scenario that compensates for lower levels of diesel, coal and coke and gas.

The quantity of bio-products in final energy demand for run DECC-7D shows a sharper increase than in DECC-1A-IAB-2A in the earlier periods (Figure 195). In 2025 bio-product use is 71PJ or 38% lower for the latter scenario. The differences are highest in residential and transport sectors. In the rest of the time horizon, bio-product component in final energy demand is less significant for DECC-7D than in the comparison run.

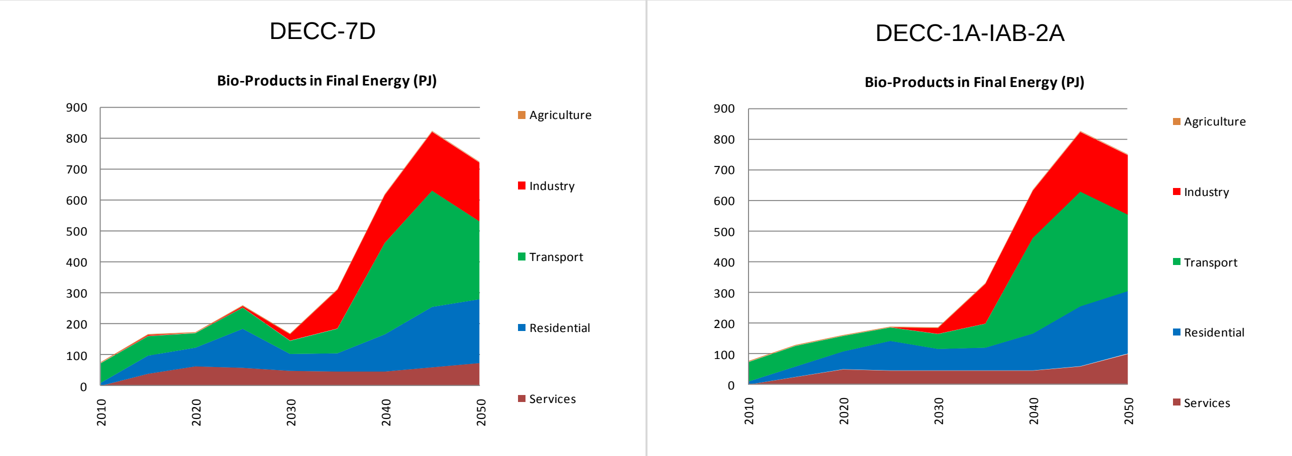


Figure 195: Bio-Products in Final Energy Demand disaggregated by sector.

2.12.4 Power Generation and Installed Capacity

Figure 196 shows the total installed capacity and the total electricity generated by the system. Installed capacity is lower up to 2035 in run DECC-7D after which the levels are similar to those in scenario DECC-1A-IAB-2A. The generation levels are similar throughout.

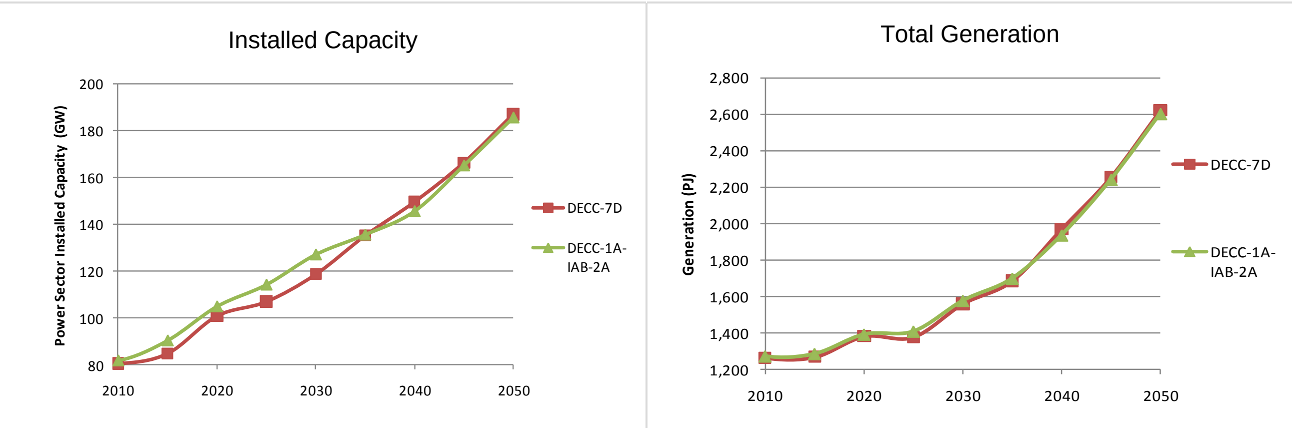


Figure 196: Total Installed Capacity (GW) and Generation (PJ) from the energy system

In both cases the emissions intensity of electricity generation becomes a sink by the end of the time horizon, as can be seen from Figure 197. However, up to 2035, the emissions intensity is consistently higher for DECC-7D. In 2030, the emissions rate in run 7D is 0.1 kgCO_2/kWh.

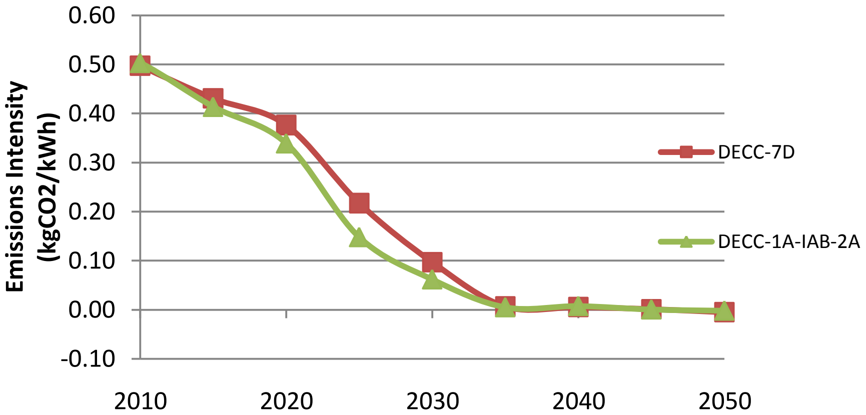


Figure 197: Emissions Intensity of Electricity Generation until 2050

The installed capacity mixture by fuel of the two different cases is shown in Figure 198. In the scenario DECC-7D, the most notable effect of new constraints is the increase of CHP and biomass compared to run DECC-1A-IAB-2A. This is due to the smaller use of nuclear, wind (and other renewable) and cofiring with CCS until 2030. Wind and nuclear use remains lower until the end of the time horizon in comparison with run DECC-1A-IAB-2A.

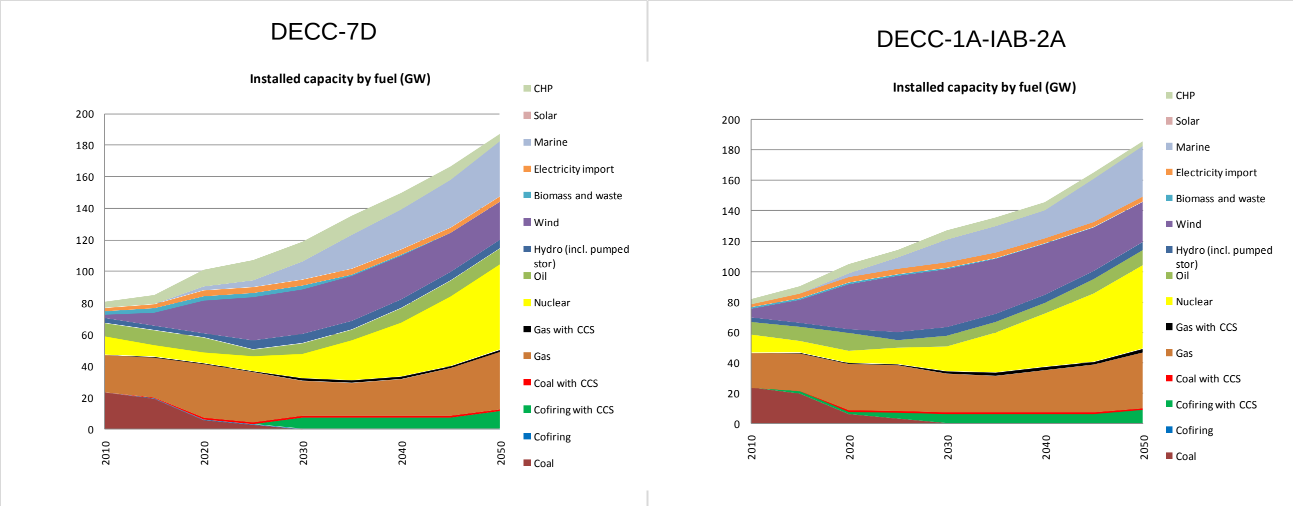


Figure 198: Installed Electricity Generation Capacity

Similar patterns can be observed in the total electricity generation mix as shown in Figure 199.

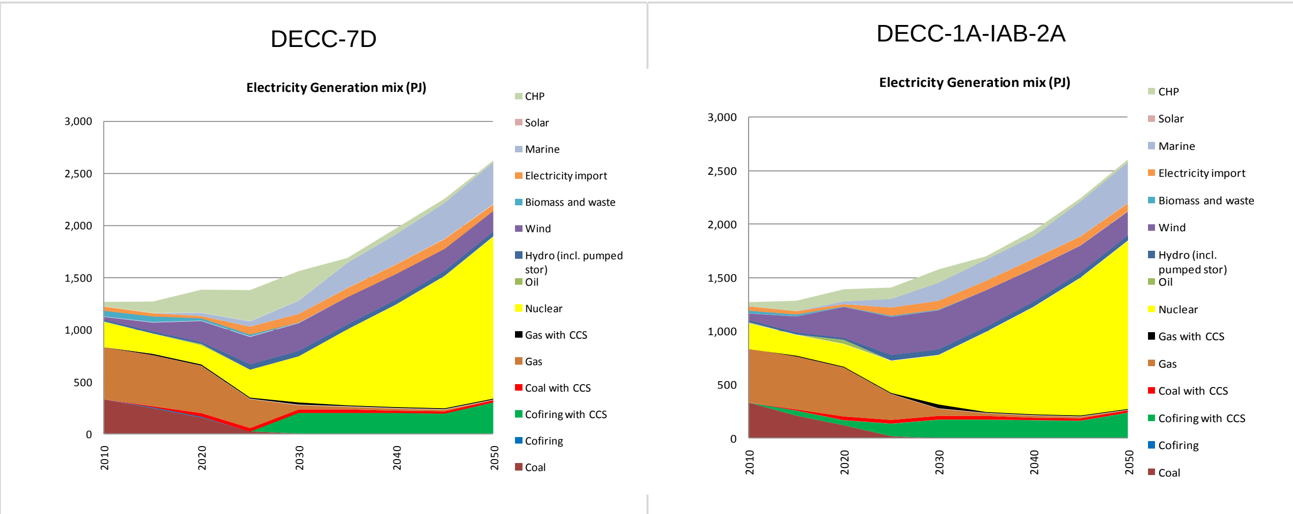


Figure 199: Electricity Generation Mix

Up to 2030s, the proportion of CHP and biomass is higher in DECC-7D than in the comparison run. This compensates for significantly lower wind energy contribution (in total 600PJ less generated from wind over the entire time horizon in DECC-7D than in DECC-1A-IAB-7D), as well as nuclear (almost 150PJ less over the entire time horizon). Marine and cofiring with CCS also contribute significantly less until 2030s.

2.12.5 End-Use Sectors

The end-use emissions disaggregated by sector are shown in Figure 200. The total emissions reductions are the same in both cases. The proportion of emissions from service and industry sectors is higher in DECC-7D run, counterbalanced by lower residential and transport sector emissions.

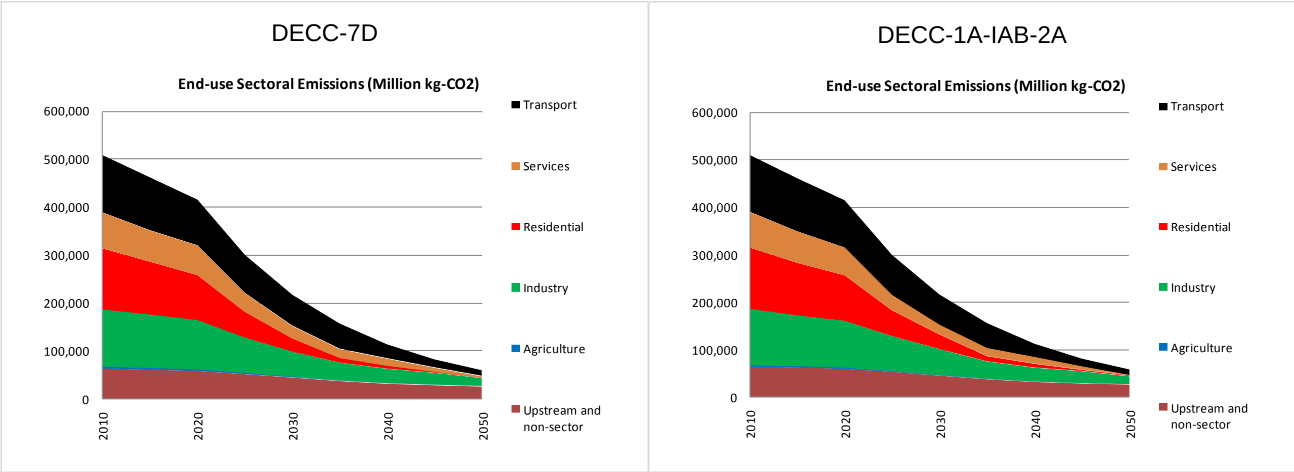


Figure 200: End-Use Sectoral Emissions to 2050

As expected from the figures in Table 34, the demand reductions from the baseline in DECC-7D are higher overall than in DECC-1A-IAB-2A. This is true for most demands in all sectors, most notably so for transport sector bus and domestic air travel demands. This explains some of the lower CO_2 emissions in transport sector.

For the residential sector, change in fuel mix in the energy demand is shown in Figure 201. While the total energy demand in this sector is lower, the fuel mix also indicates a move from natural gas to LTH systems which shows in residential heating demand through a switch to district heating.

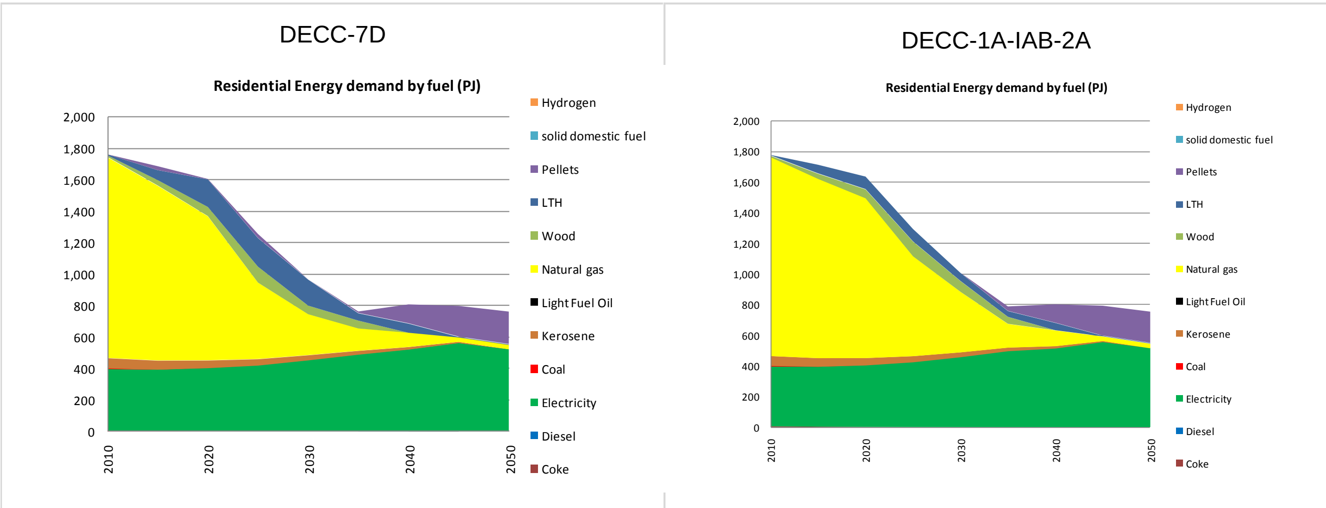


Figure 201: Residential Energy Demand by Fuel in runs DECC-7D and DECC-1A-IAB-2A

2.13 Studies 7E and 7F: Constrained Nuclear Power

2.13.1 Description of Study

Studies 7E and 7F explores the pathway to a 90% CO_2 emissions reduction in the energy system by 2050, where the new nuclear build is restricted. The runs are identical to the phase 2 core run DECC-1A-IAB-2A, except for the additional constraints on nuclear power.

There are two runs in this study:

1. **Study 7 Run E**. Emissions reduction in this run is bounded with equal annual emissions reduction to 2050 (DECC-1A-IAB-2A is the equivalent run). However, the maximum nuclear power investment per period is halved.
   Code: **DECC-7E**
2. **Study 7 Run F**. The same as above, but no new nuclear power investment is allowed.
   Code: **DECC-7F.**

The baseline cases for runs DECC-7E and DECC-7F are DECC-0A-LOWNUCS and DECC-0A-NONUCS respectively. These are the equivalent runs with no emissions constraints, except those in the Government Carbon Plan. This study focuses on the changes to the power sector.

2.13.2 Key Results

Table 36 shows the discounted energy system costs, demand response and the discounted change in consumer/producer surplus for the runs analysed in this study. The total discounted system cost in DECC-7E is £11 billion higher than in the scenario DECC-1A-IAB-2A and a further £29 billion higher for the DECC-7F run.

The demand response is highest for no-nuclear-investment run DECC-7F. The reduction in surface under demand curve in this run is £40 billion higher than in DECC-1A-IAB-2A, and the change in consumer/ producer surplus is also greater (£66 billion).

Restricted nuclear investment run DECC-7E shows figures in between the other two, indicating that demand response has less impact on the total system cost in the restricted run than in the no-nuclear scenario and changes in demand are less significant as a means to CO_2 reduction. This is expected, as the restrictions on nuclear power force the system to choose more expensive alternative abatement technologies, thus raising the marginal price of serving demand, which in turn increases demand response.

	DECC-0A-LOWNUCS	DECC-7E	DECC-0A-NONUCS	DECC-7F	DECC-1A-IAB-2A
Discounted Technical Energy System Cost (2010 £UK Billions)	5,450	5,485	5,459	5,514	5,474
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	-217	0	-260	-194
Discounted Welfare Impact of Demand Reduction[3] (2010 £UK Billions)	0	189	0	215	175

Table 36: Key Result Metrics

The annual undiscounted reductions in area under the demand curve (i.e. the impact on undiscounted welfare of demand reductions observed) and undiscounted changes in consumer/producer surplus are shown in Figure 202. The no-nuclear run shows higher demand reductions and surplus losses over the entire time horizon.

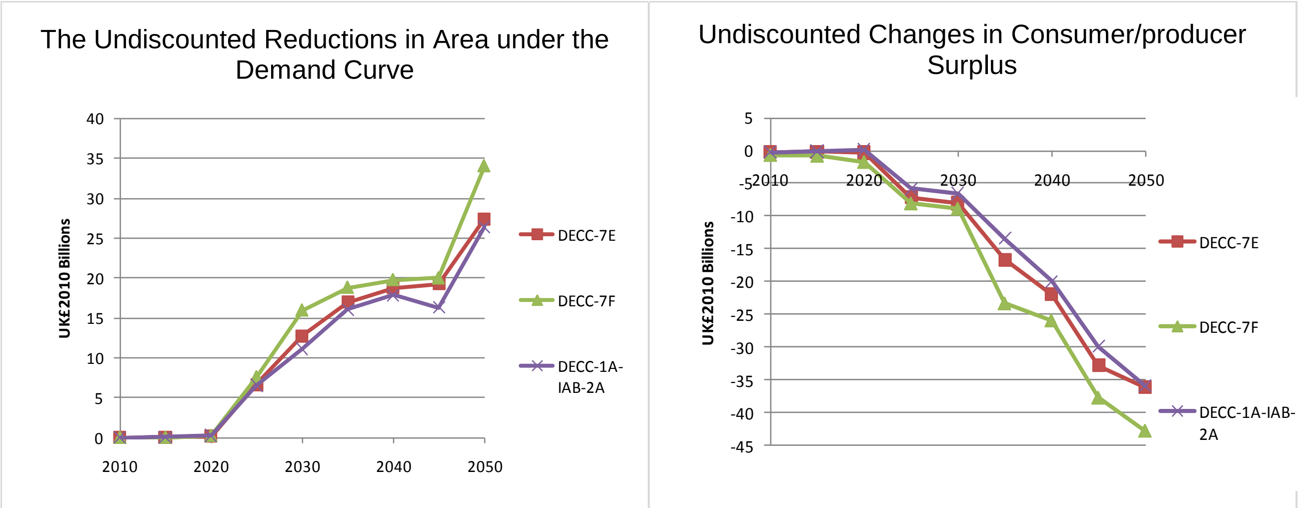


Figure 202: Undiscounted Reduction in Area Under the Demand Curve and Undiscounted Change in Consumer/Producer Surplus for runs DECC-7E, DECC-7F and DECC-1A-IAB-2A. See footnote 3 for a description of the impact on consumer welfare of demand reduction.

Figure 200 shows the marginal price of CO_2 across the timeline of the study. The difference in this metric between runs fluctuates slightly, but for most of the time horizon the marginal cost of CO_2 is higher in scenario DECC-7F than in the other two runs. The difference between marginal costs in DECC-7E and DECC-1A-IAB-2A is small in comparison and the cost is invariably larger in DECC-7E up to the last period. In 2050, marginal cost is highest for DECC-7F (no nuclear investment) run at £481 per tonne and lowest for restricted nuclear investment run DECC-7E at £349 per tonne of CO_2.

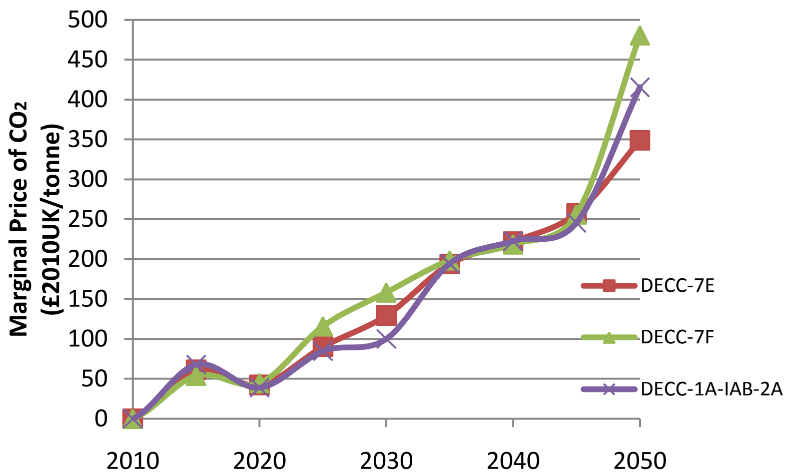


Figure 203: Marginal Price of CO_2

2.13.3 Primary and Final Energy Statistics

The primary and final energy demands are shown in Figure 204. Primary energy demand experiences a dip and a subsequent increase in all three runs although at different times. The demand drops significantly lower in no-nuclear-investment run than in the comparison run DECC-1A-IAB-2A (6500PJ in versus around 7000PJ). In the restricted investment run, the lowest point is similar to that in DECC-1A-IAB-2A, but the demand rises back up later and remains lower for the rest of the time horizon. In general this indicates that whatever is replacing nuclear power is also more efficient in terms of primary consumption.

For the final energy demand, the patterns are alike for the three runs, run DECC-7F showing the lowest energy use consistently throughout the time horizon.

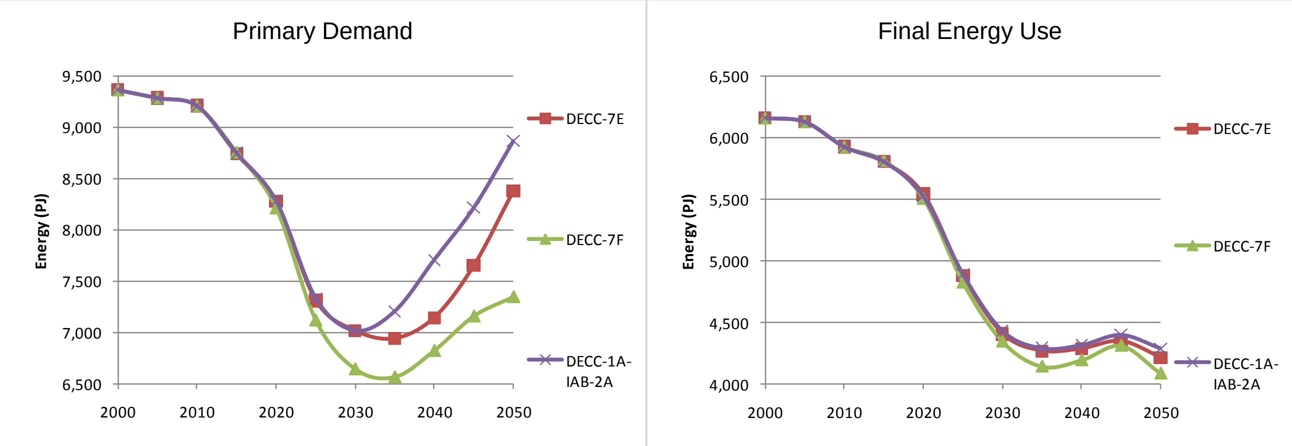


Figure 204: Primary and Final Energy Demand for runs DECC-7E, DECC-7F and DECC-1A-IAB-2A

The primary energy demand fuel composition for all three runs is shown in Figure 205. As required by the additional nuclear power constraints, the nuclear power demand after 2020 does not increase as much in DECC-7E scenario as it does in DECC-1A-IAB-2A. It disappears completely from the fuel mix in DECC-7F by 2040 (i.e. the last of the existing plants are gradually decommissioned by then).

In DECC-7E nuclear power demand is substituted mainly by coal and also biomass, coal having 26% of all demand by 2050 compared to 9% in the core phase 2 run. Similarly, the share of biomass reaches 17% in 2050 compared to 12% in DECC-1A-IAB-2A. Similarly, in DECC-7F, coal is the main fuel to replace nuclear, attaining a massive 40% of all demand. Biomass, natural gas and renewable electricity are other fuels that grow in importance both in absolute values and in their proportion in the fuel mix.

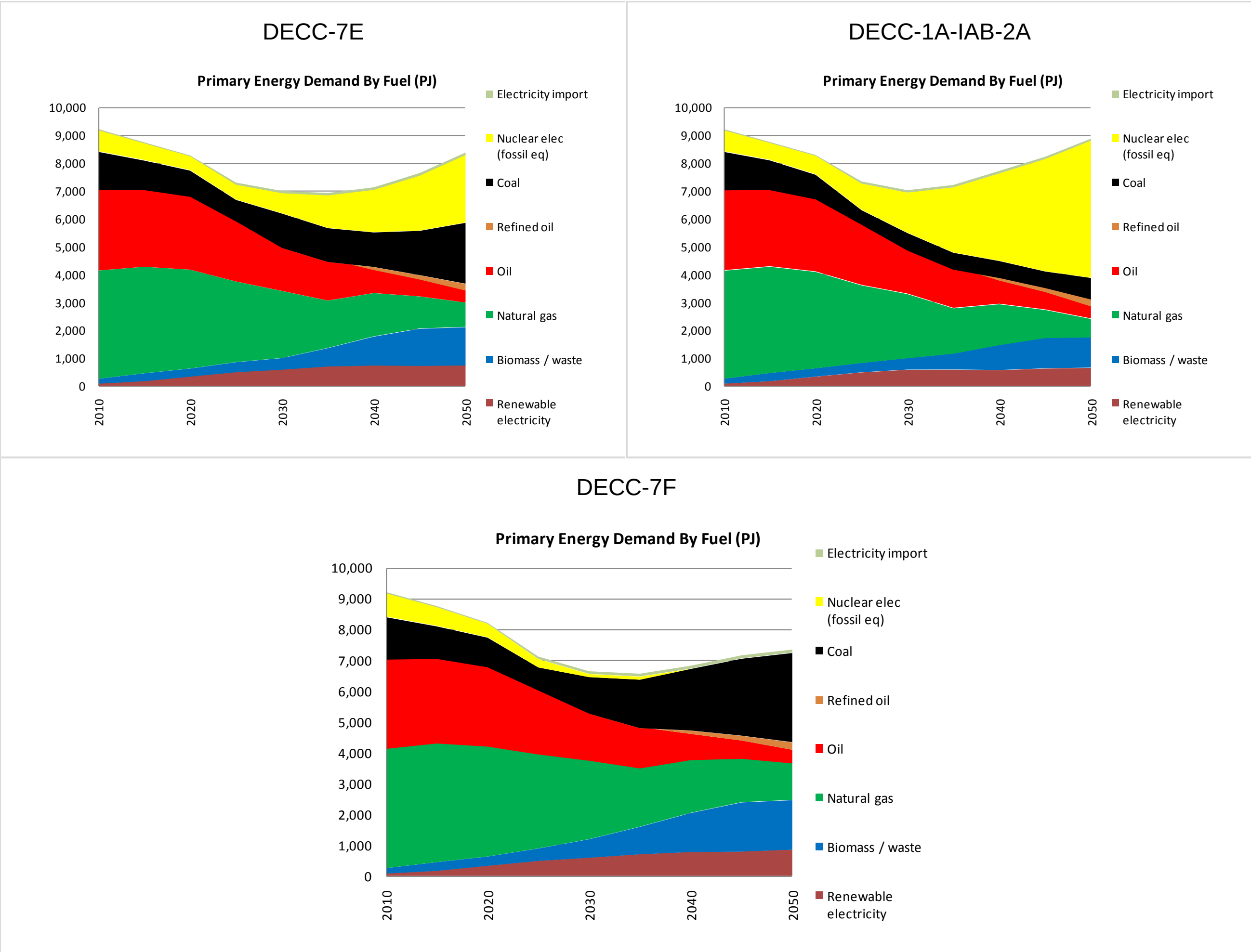


Figure 205: Primary Energy Demand by Fuel over time

In final energy mixture, the biggest change is lower levels of electricity in restricted runs than in the comparison run (more so in the no-nuclear scenario). On the other hand, gas use increases as the level of nuclear investment allowed drops.

The quantity of bio-products in final energy demand for all runs is similar. The higher biomass demand in the primary energy mix for runs DECC-7E and DECC-7F can be explained by the fact that most of that difference can be attributed to energy crop demand which is later used for electricity production and biomass gasification.

2.13.4 Power Generation and Installed Capacity

Figure 206 shows the total installed capacity and the total electricity generated by the system. Installed capacity is lowest for the comparison scenario DECC-1A-IAB-2A for all periods except the last. Installed capacity is only slightly higher for DECC-7F (no-nuclear) than DECC-7E (restricted-nuclear). For the generation levels the ordering is opposite which indicates that in run DECC-7F the energy system efficiency is lowest. It is highest in DECC-1A-IAB-2A.

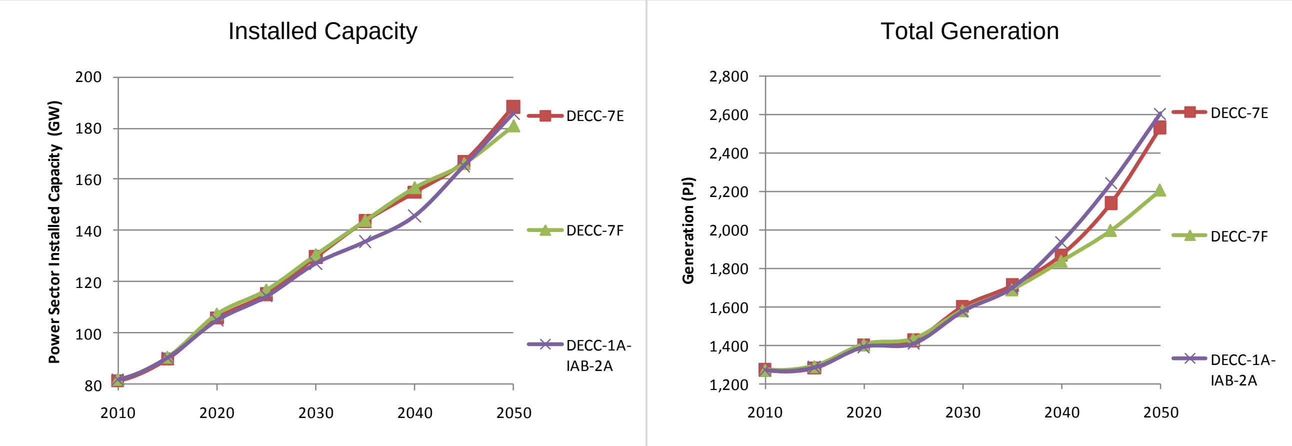


Figure 206: Total Installed Capacity (GW) and Generation (PJ) from the energy system

In all three cases the emissions intensity of electricity generation becomes a sink by the end of the time horizon.

The installed capacity mixture by fuel of the three different cases is shown in Figure 207. The installed capacity of nuclear generation is increasing much more slowly for DECC-7E (reduced investment scenario) than in the comparison run DECC-1A-IAB-2A and in 2050 reaches the maximum of 27GW compared to 55GW in the core phase 2 run. In run DECC-7F (no new nuclear plants build), as expected, the installed capacity falls to 0 as the last plants are decommissioned after 2035. To make up for this change there is more rapid increase in installed cofiring with CCS capacity in DECC-7F and DECC-7E runs (42 and 30GW respectively by 2050), as well as wind (31 and 36GW respectively in 2050) and marine technologies (36 and 41GW installed in 2050). Although smaller in scale, CHP installed capacity also doubles in DECC-7F compared to DECC-7E.

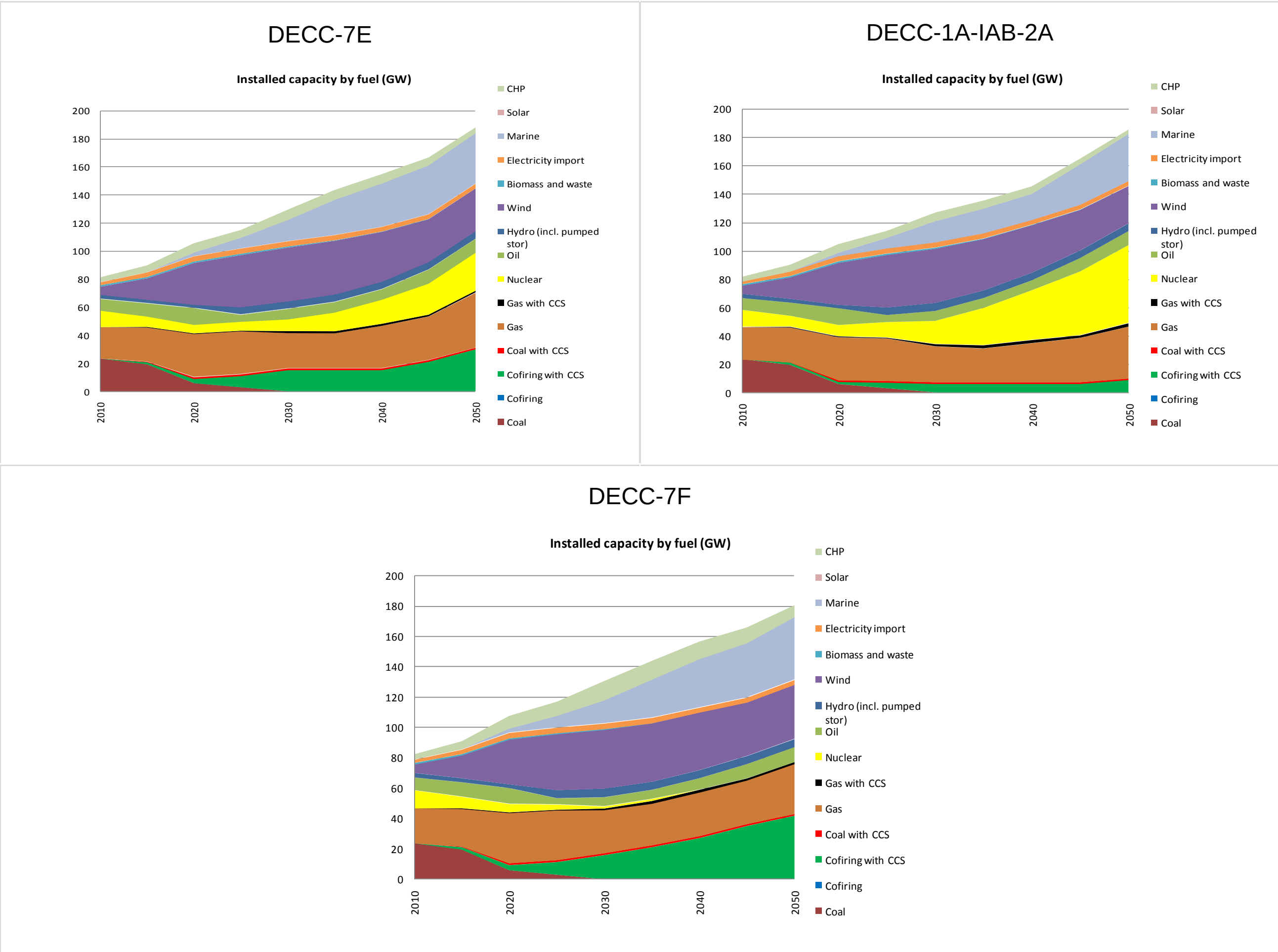


Figure 207: Installed Electricity Generation Capacity

Similar patterns can be observed in the total electricity generation mix (Figure 208).

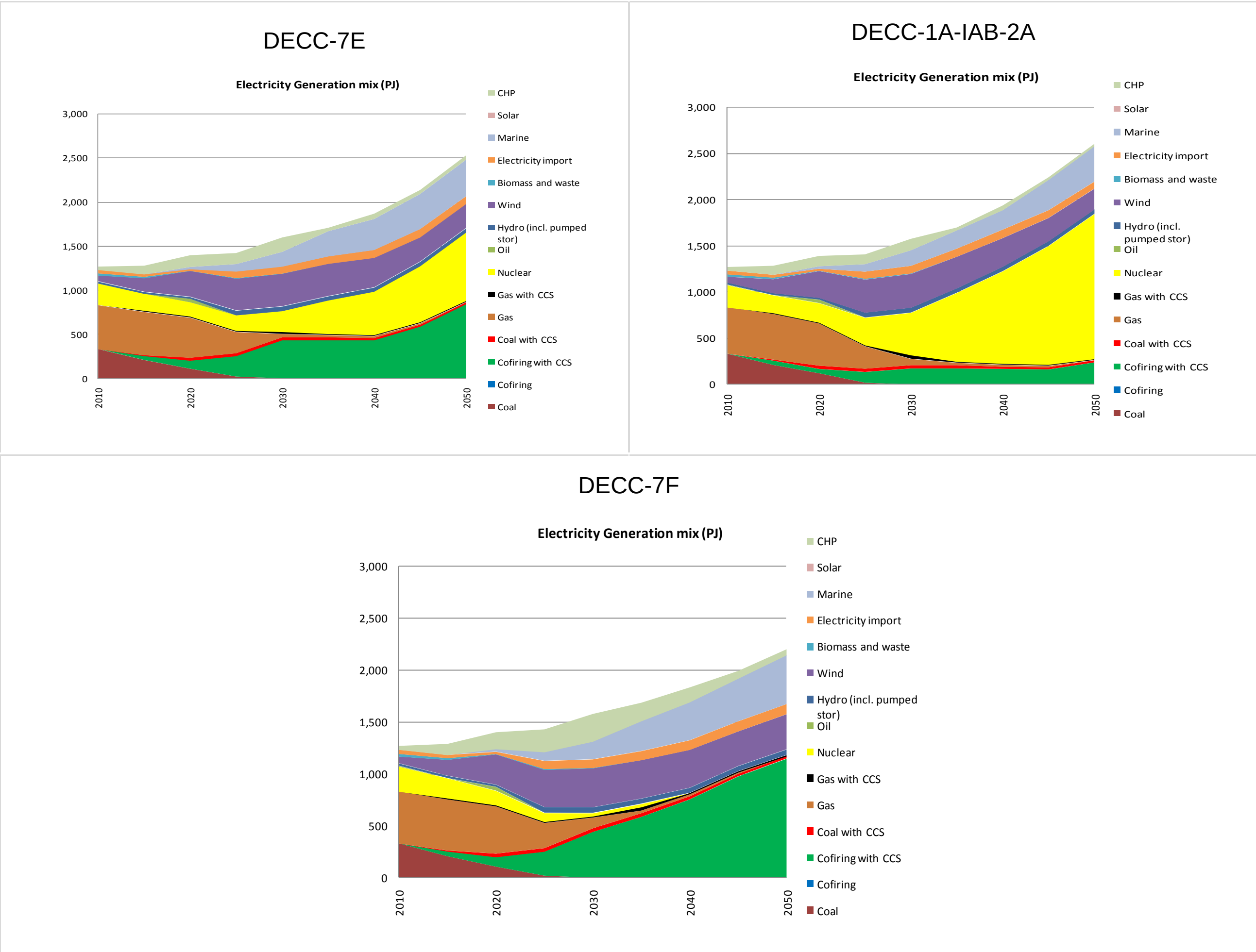


Figure 208: Electricity Generation Mix

The extreme decrease in generation of nuclear fuelled electricity is made up for with a steep rise in use of cofiring with CCS which generates 33% of all electricity in run DECC-7E by 2050, and 52% in run DECC-7F. Marine, wind and CHP generated electricity also increases (Figure 209).

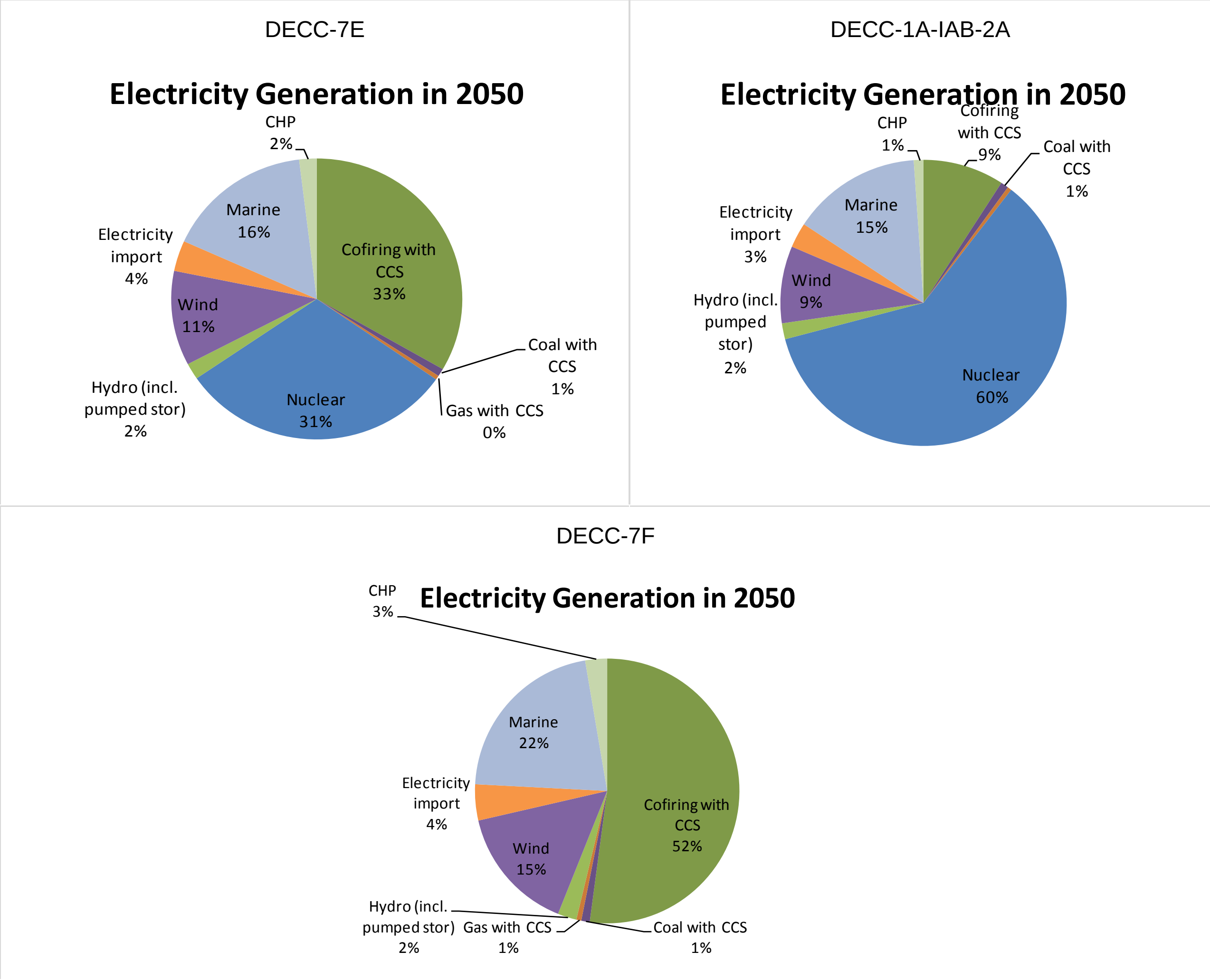


Figure 209: Fuel Proportions in Electricity Generation in 2050

2.13.5 End-Use Sectors

The end-use emissions by sector do not change significantly. The most notable difference is that in no-nuclear run, and to a certain extent, reduced nuclear investment run, industry sector emissions are higher at the expense of residential and service sectors towards the end of the time horizon.

As expected from the figures in Table 36, the demand reductions from the baseline in DECC-7F are higher overall than in DECC-7E which in turn has higher reductions than in DECC-1A-IAB-2A. This is true for most demands in all sectors. In residential sector largest differences are in lighting and other electrical appliances demands (both new and existing). In service sector, it is also lighting and other electrical demands that experience highest reductions for scenarios DECC-7E and DECC-7F. For transport, demands most affected are freight rail and domestic air transport.

For the residential sector, change in fuel mix in the energy demand is shown in Figure 216. The difference in this sector is that for no nuclear and restricted nuclear investment runs, LTH replaces a part of electricity demand. In a no nuclear investment run also less natural gas is consumed from 2035 onwards, partially substituted by wood, but mainly owing to the lower total energy demand in the sector.

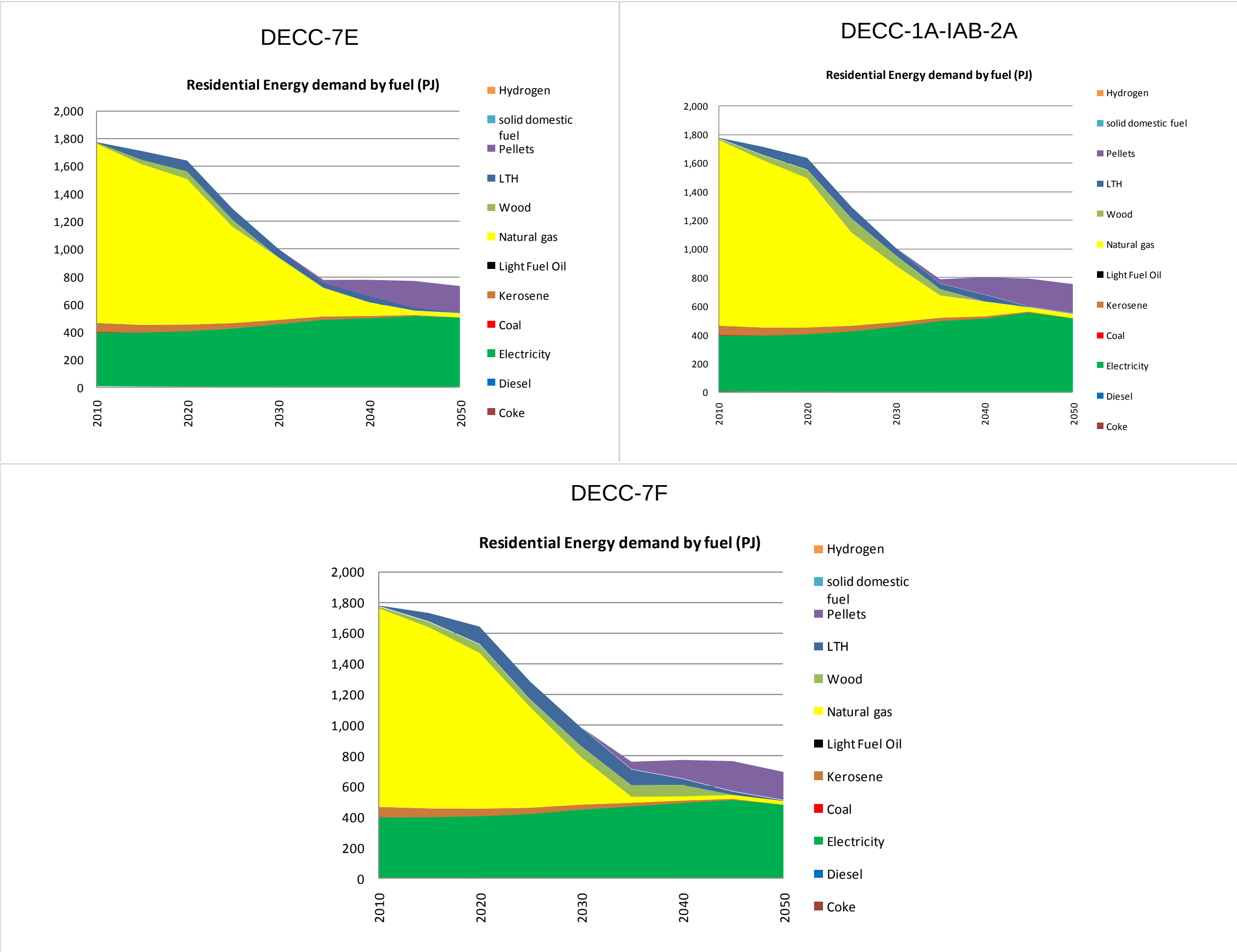


Figure 210: Residential Energy Demand by Fuel in runs DECC-7E, DECC-7F and DECC-1A-IAB-2A

In residential heating these changes manifest in no nuclear investment run using more pellets and wood instead of gas from 2035 onwards and in increased use of district heating. Similarly, in service sector, for later periods electricity demand is replaced by natural gas in run DECC-7F and to a smaller extent in DECC-7E. This is true both for overall sector and specific heating demand.

This is also true for industry sector, where light fuel oil in addition to natural gas takes a larger share of the fuel mix in the restricted nuclear runs than in the comparison run, replacing part of electricity demand in the second half of the time horizon. The trend is particularly clear in high temperature heat demand where the difference between electricity use in runs DECC-7F and DECC-1A-IAB-2A reaches 25% in 2050 (15% between runs DECC-7E and DECC-1A-IAB-2A).

In all sectors, a very important factor allows achieving the emission targets: lower overall energy demand in scenarios DECC-7E and DECC-7F, brought about by demand response and switching to more efficient conversion and end-use technologies.

2.14 Study 8: Variation of the Bio-energy Resource

2.14.1 Description of Study

The purpose of Study 8 is to assess how changes to bio-energy primary resource costs and resource constraints (including imports) influence the timing and nature of bio-energy uptake.

There are two runs in this study:

1. Study 8 Run A. It has a 90% emissions reduction target – equal annual percentage reduction from 2020 onwards. This run is equivalent to Impact Assessment study B scenario 2A (**DECC-1A-IAB-2A**)

with the changes in bio-energy constraints as follows: For domestically obtained resources, the changes include decreased rape seed oil prices over the entire time horizon in the new study, as well as decreased bound on the use of straw, poultry litter, forestry residues and additional agricultural wastes. For international resources (imports) the different bio-product constraints are separated into 3 steps. The cost constraints increase slightly for some products towards the end of the time horizon
Code **DECC-8A.**

2. Study 8 Run B represents high biomass sensitivity. As above, this run is equivalent to **DECC-1A-IAB-2A**, but in this case constraints are imposed such as to make bio-energy more expensive and less available.

The baseline run for the DECC-8A scenario is **DECC-0A-BIO** and includes no carbon target except those in relation to the Government Carbon Plan. The baseline for DECC-8B run is DECC-0A-BIO-H. They are equivalent to the impact assessment study baseline run **DECC-0A-IAB-1A**, except for the changes in bio-energy constraints.

This section will discuss the effects that these changes have on the uptake of bio-energy by comparing runs DECC-8A and DECC-8B and also comparing them with the equivalent core phase 2 run - DECC-1A-IAB-2A.

2.14.2 Key Results

The total discounted system cost, and discounted consumer/producer surplus for this study scenario and its comparison run are presented in Table 37. The changes are quite small with the current study runs DECC-8A and DECC-8B showing costs lower by about £2 billion than the comparison run DECC-1A-IAB-2A.

The demand response is slightly higher for scenario DECC-8A than for DECC-1A-IAB-2A, as the reduction in surface under demand curve (i.e. the measure of the impact on welfare of demand reduction brought about by high prices) is £2 billion higher. For DECC-8B this difference is a further £19 billion higher than for DECC-8A. Subsequently the impact of demand response on consumer/producer surplus is £15 billion greater for DECC-8B than in the comparison study (only £1 billion difference is observed between DECC-8A run and the comparison study). This suggests that the observed changes in system costs are influenced by demand response and significantly more so in the high biomass sensitivity run DECC-8B.

Table 37: Key Result Metrics

	DECC-0A-BIO (base)	DECC-0A-BIO-H	DECC-8A	DECC-8B	DECC-1A-IAB-2A
Discounted Technical Energy System Cost (2010 £UK Billions)	5,448	5,451	5,472	5,472	5,474
Discounted Consumer/Producer Surplus (2010 £UK Billions)	0	0	-195	-209	-194
Discounted Impact on Welfare of Demand Response[3] (2010 £UK Billions)	0	0	177	196	175

The undiscounted annual average system costs are displayed in Table 37, showing the differences between DECC-8A and DECC-1A-IAB-2A over time. The differences are small and the costs are higher for DECC-1A-IAB-2A for most of the time horizon.

Table 38: Average annualised undiscounted system costs (2010£ UK Billion)

Run/Year	2025	2030	2035	2040	2045	2050
DECC-0A-BIO	238.53	261.53	274.38	288.76	304.24	316.53
DECC-8A	236.78	257.39	271.38	291.61	316.60	331.27
DECC-8B	237.67	257.91	270.52	289.68	314.63	331.67
DECC-1A-IAB-2A	236.44	257.62	271.55	292.01	316.58	331.28

The effect of the changes in bio-product constraints in scenarios DECC-8A and DECC-8B on marginal carbon price is shown in Figure 211. From 2035 onwards the price rises more rapidly for run DECC-8A than for the comparison run DECC-1A-IAB-2A and reaches £442.5 (2010UK) per tonne of CO_2 by 2050s compared to £416 in the comparison run. However, the marginal carbon price for run DECC-8B rises even more sharply. It is 8-16% higher than in run DECC-8A and 15-20% higher than in the comparison run, the difference being highest in the 2030s.

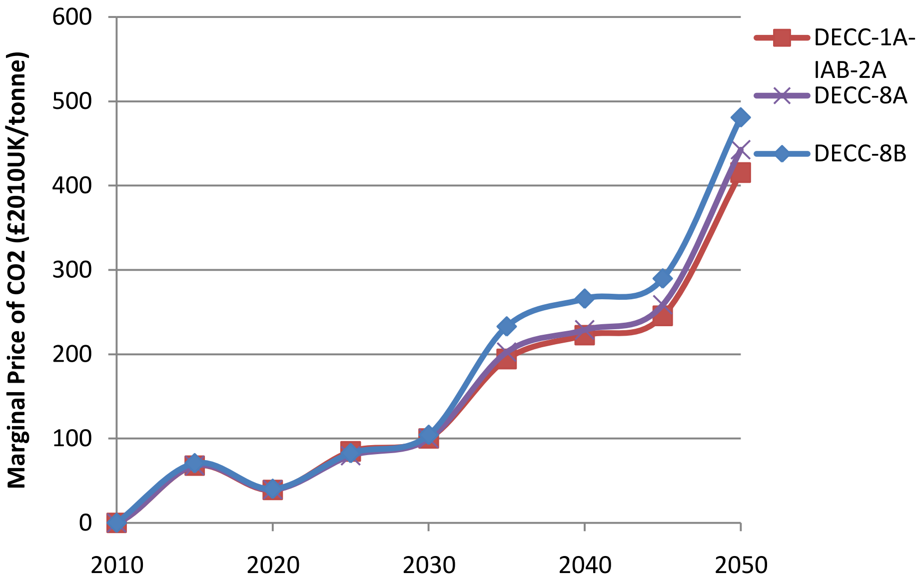


Figure 211: Marginal Cost of CO_2 for Each Run

The emissions intensity of grid electricity is not affected much by the changes in constraints and the figures are almost identical to those in the comparison run. For both study 8 scenarios as well as the comparison run the emissions intensity is less than 0.01kg CO_2 per kWh from 2035 onwards.

2.14.3 Primary and Final Energy Statistics

Primary energy and final energy consumption are presented in Figure 212 and Figure 213. The pattern is very similar with DECC-8A showing a bit lower primary energy demand for most of the time horizon than the comparison run. The most notable difference occurs in 2035 at almost 50PJ (which is still less than 1%). This indicates a slightly later increase in demand for DECC-8A, as in the 2040s and 2050s it catches up. Run DECC-8B shows even smaller numbers for primary energy demand for most of the second half of the time horizon, but in the last period it rises and exceeds the demand in the comparison run by 173PJ.

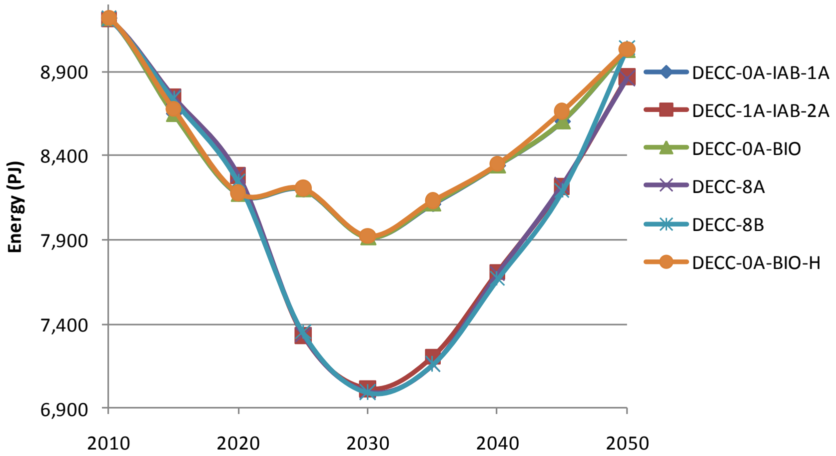


Figure 212: Primary Energy Demand over Time

The patterns for final energy demand for runs DECC-8A, DECC-8B and DECC-1A-IAB-2A are similar as well. From 2030 onwards the demand is slightly (up to around 1%) higher for DECC-1A-IAB-2A than DECC-8A. Scenario DECC-8B shows the lowest final energy consumptions levels, lower than DECC-8A by up to 2%. Contrary to primary energy demand, the difference here is growing steadily until the end of the time horizon.

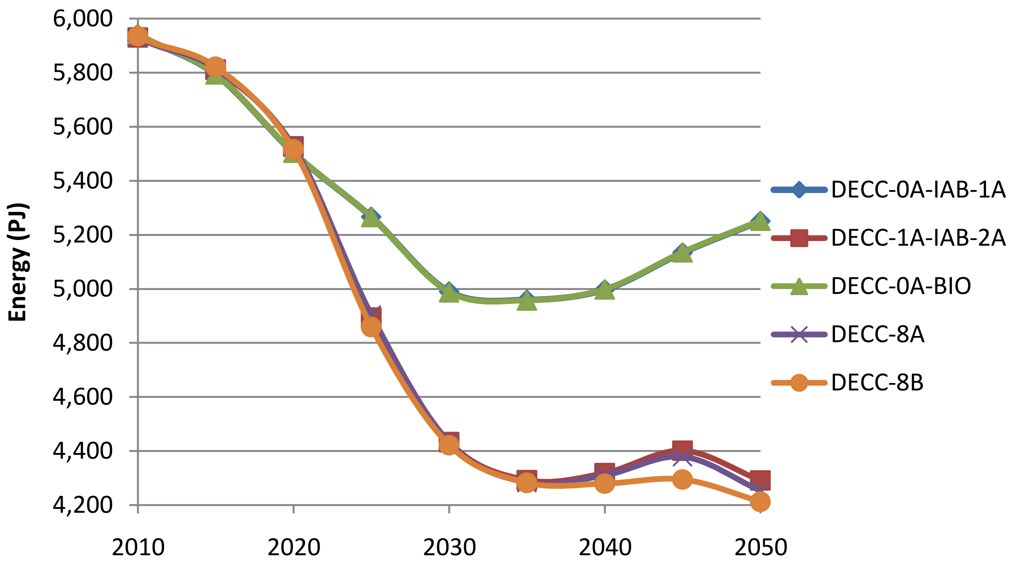


Figure 213: Final Energy Consumption over Time

Comparing the primary and final energy consumption in terms of energy carriers shows that the patterns and even proportions of different energy carriers are very similar (Figure 214). For primary energy, as noted above, the largest difference between DECC-8A and the comparison runs is notable in 2035. Most of this effect can be accounted for by a smaller amount of coal usage in scenario DECC-8A. This is also true for later years where more energy is supplied from renewable and biomass.

On the other hand, DECC-8B run with high biomass sensitivity shows different fuel compositions over the entire time horizon. Most notably, biomass and waste fuel demand is consistently lower for this run than for either DECC-8A or the comparison run. Instead coal and natural gas usage is higher over most of the time horizon for high biomass sensitivity run. In the last period (2050), coal demand is 30% higher in run DECC-8B than in DECC-8A and biomass lower by 13%. Subsequently coal is proportionally more important in the fuel composition.

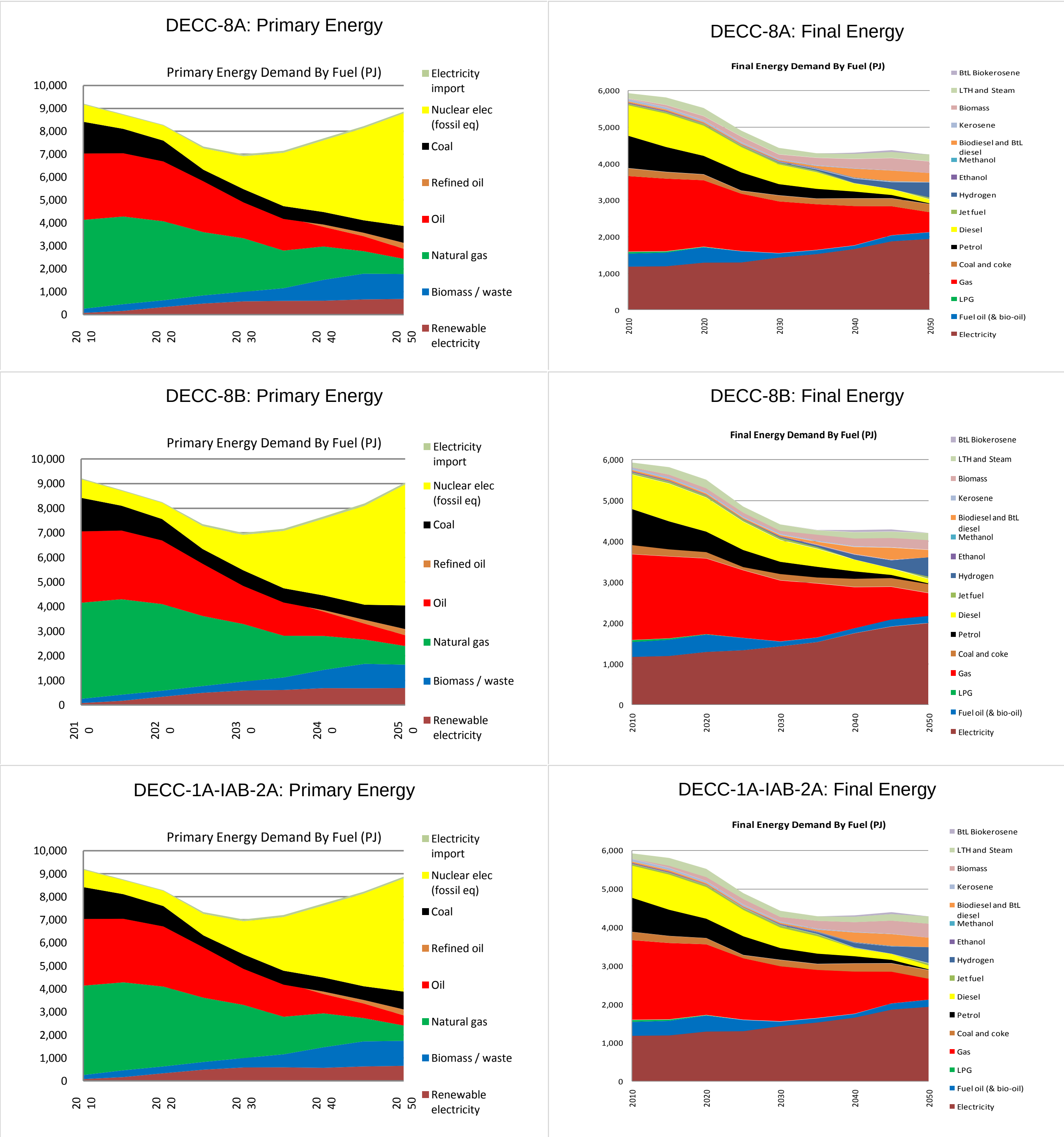


Figure 214: Primary and Final Energy Demand by Energy Carrier runs DECC-1A-IAB-1A and DECC-1A-IAB-2A

For the final energy, the most significant difference in demand between the runs can be attributed to changes in biomass demand as seen in Figure 215. The chart indicates that biomass demand is consistently higher for the comparison run DECC-1A-IAB-2A than for run DECC-8A. In the high biomass sensitivity run, the usage of biomass is significantly lower than either of the other runs. It is 25% - 40% lower than in run DECC-8A.

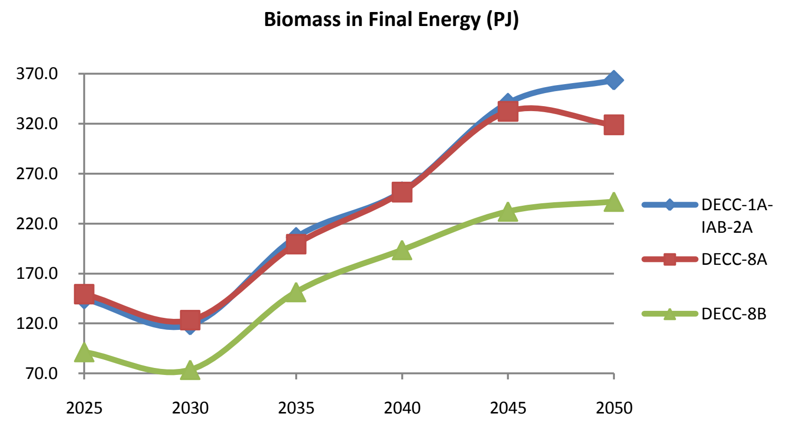


Figure 215: Biomass in Final Energy Demand runs DECC-8A, DECC-8B and DECC-1A-IAB-2A

The final energy from all bio-products is shown in Figure 216. It can be seen that from 2040 onwards the total energy from bio-products is smaller for run DECC-8A than for DECC-1A-IAB-2A and the difference gets larger every period reaching a disparity of 70PJ (or 10%) in 2050. For DECC-8B, the final energy obtained from bio-products is smaller than for the other two runs for the entire time horizon and this difference increases in absolute terms in later periods. The maximum difference between DECC-8A and DECC-8B is 150PJ and is reached in 2050.

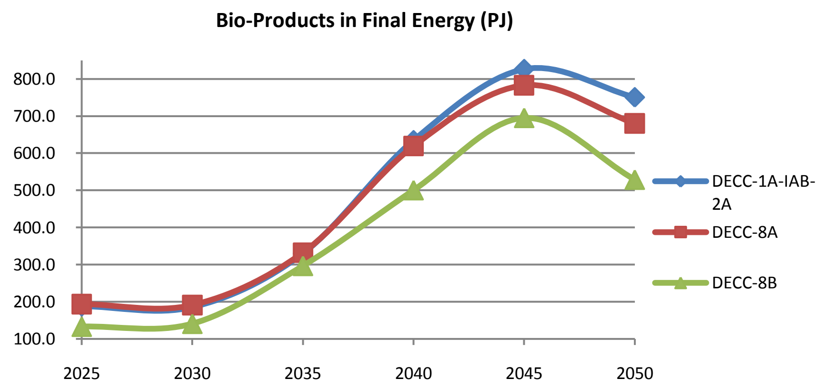


Figure 216: Bio-products in Final Energy Demand runs DECC-8A, DECC-8B and DECC-1A-IAB-2A

As shown in Figure 217, most of the difference between DECC-8A and the comparison run can be attributed to the services sector, particularly in the last period. The difference is also significant in the industry sector where it is apparent from 2035 onwards.

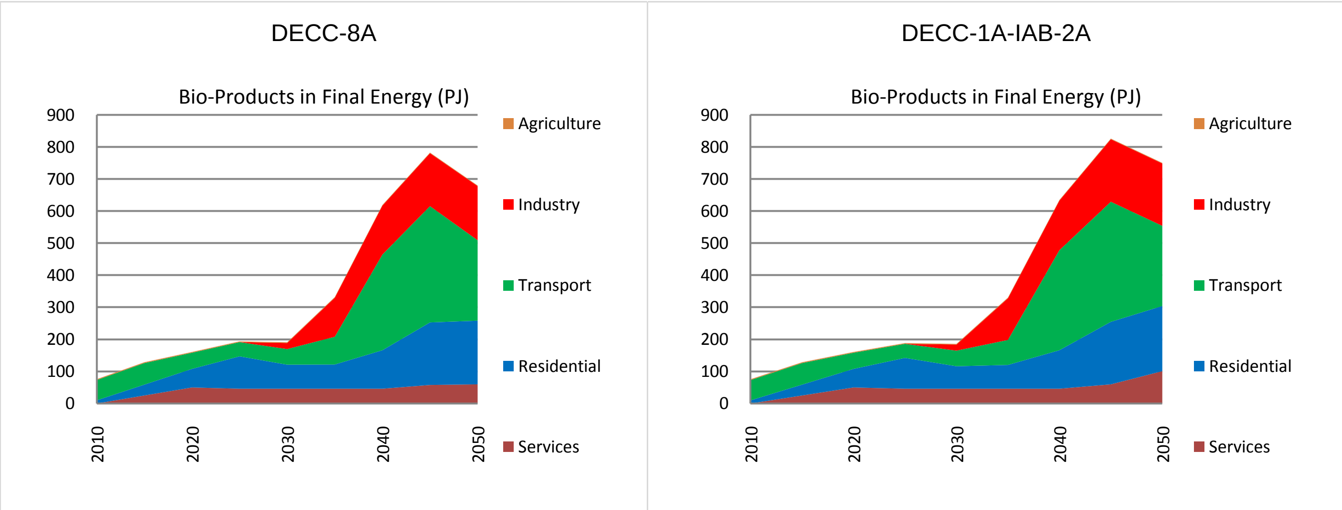


Figure 217: Bio-Products in Final Energy Consumption: runs DECC-8A and DECC-1A-IAB-2A

The effects of the constraints of the high sensitivity run are shown in Figure 186. The largest difference is apparent in the residential sector through the entire time horizon. Transport sector is affected as well, particularly in later periods.

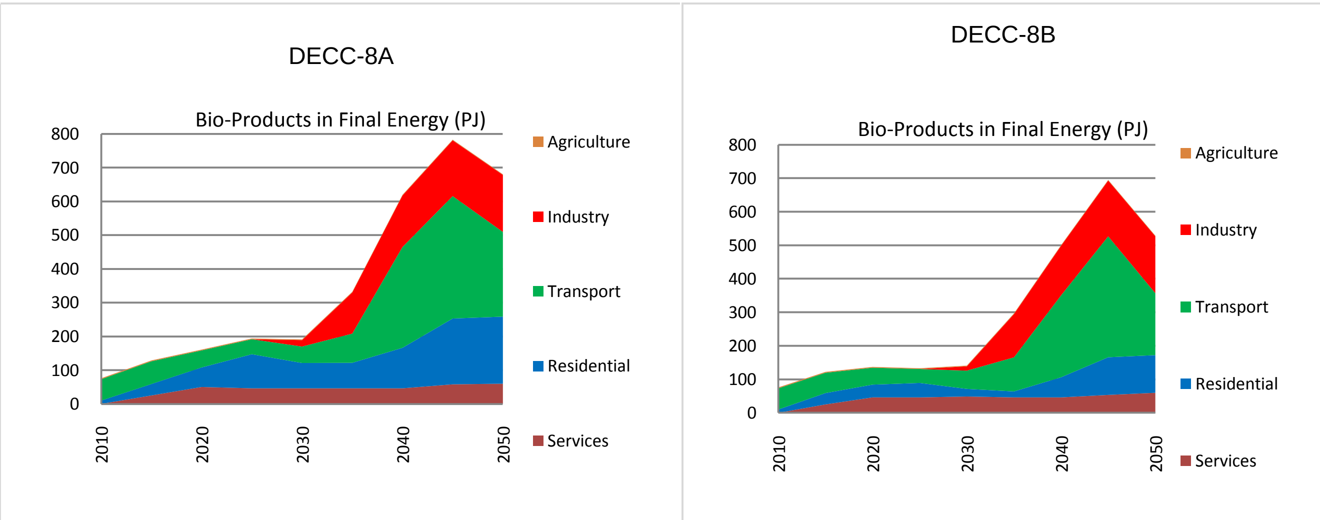


Figure 218: Bio-Products in Final Energy Consumption: runs DECC-8A and DECC-8B

2.14.4 Power Generation and Installed Capacity

The electricity generated in DECC-1A-IAB-2A and DECC-8A runs follows a very similar trajectory throughout the time period considered as shown in the left subplot in Figure 8. The power generated under these scenarios is about 37% higher in comparison to their baselines by 2050. The Installed Capacity graph in the right subplot of Figure 219 represents the power generation capacity of the energy system by year. As expected, the trajectories of the three runs have similar behaviour to the power generation graph. However, run DECC-8A shows slightly more capacity than run DECC-1A-IAB-2A from 2035 onwards, mainly due to an increased capacity in marine energy generation.

For the DECC-8B run, both installed capacity and generation are higher than the other two runs from 2035 onwards.

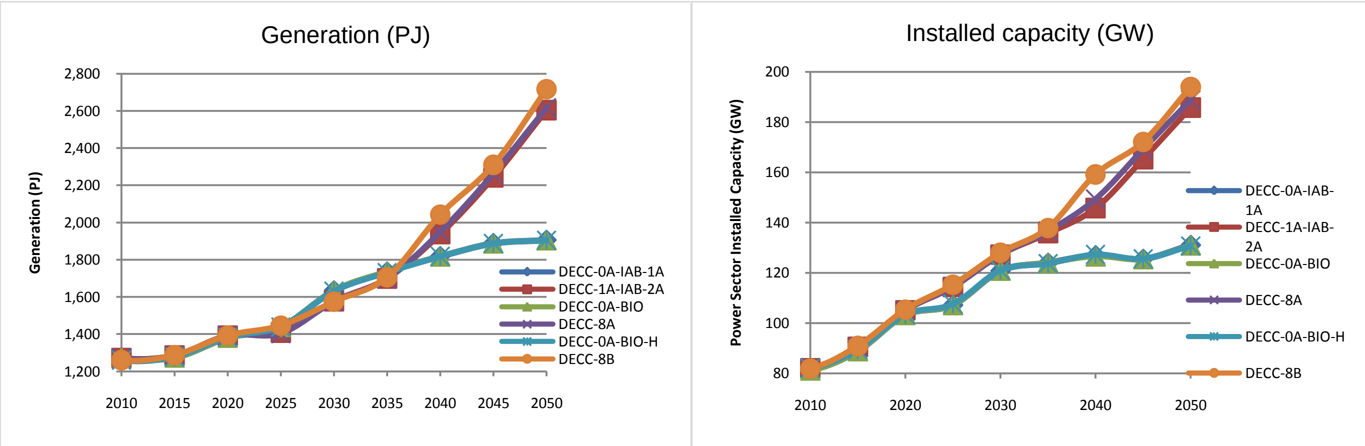


Figure 219: Installed Capacity and Electricity Generation over Time for Each Run

As seen in Figure 220, the capacity to generate marine energy experiences an increase of about 3 GW in run DECC-8A.

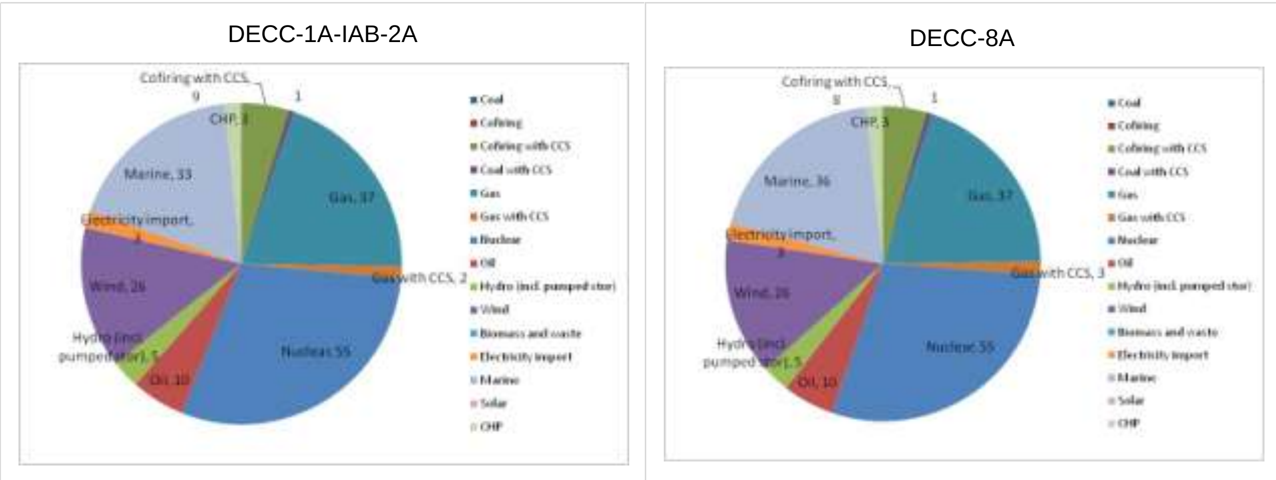


Figure 220: Generation Capacity (GW) by Technology for DECC-1A-IAB-2A and DECC-8A Runs in 2050

For run DECC-8B, the additional increase in generation capacity can be attributed to gas and cofiring with CCS in the final period (2050) as seen in Figure 221.

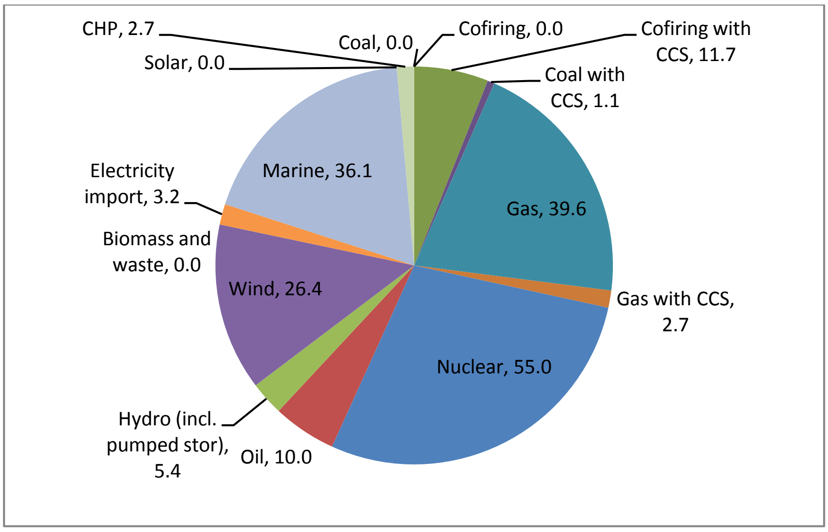


Figure 221: Generation Capacity (GW) by Technology in 2050, run DECC-8B

2.14.5 End-Use Sectors

Sectoral and end-use sectoral CO_2 emissions reductions are shown in Figure 222, where reductions are for year 2050 relative to the baseline. Runs DECC-1A-IAB-2A and DECC-8A show a very similar profile of emission reductions relative to the impact assessment study baseline run DECC-0A-IAB-1A, with only small variations (less than 2 $MtCO_2$) by sector as illustrated in the upper subplots in Figure 10.

The lower subplots in Figure 222 show that small differences between DECC-1A-IAB-2A and DECC-8A runs in aggregate reductions in final energy consumption occur mainly for services and industry end-use sectors.

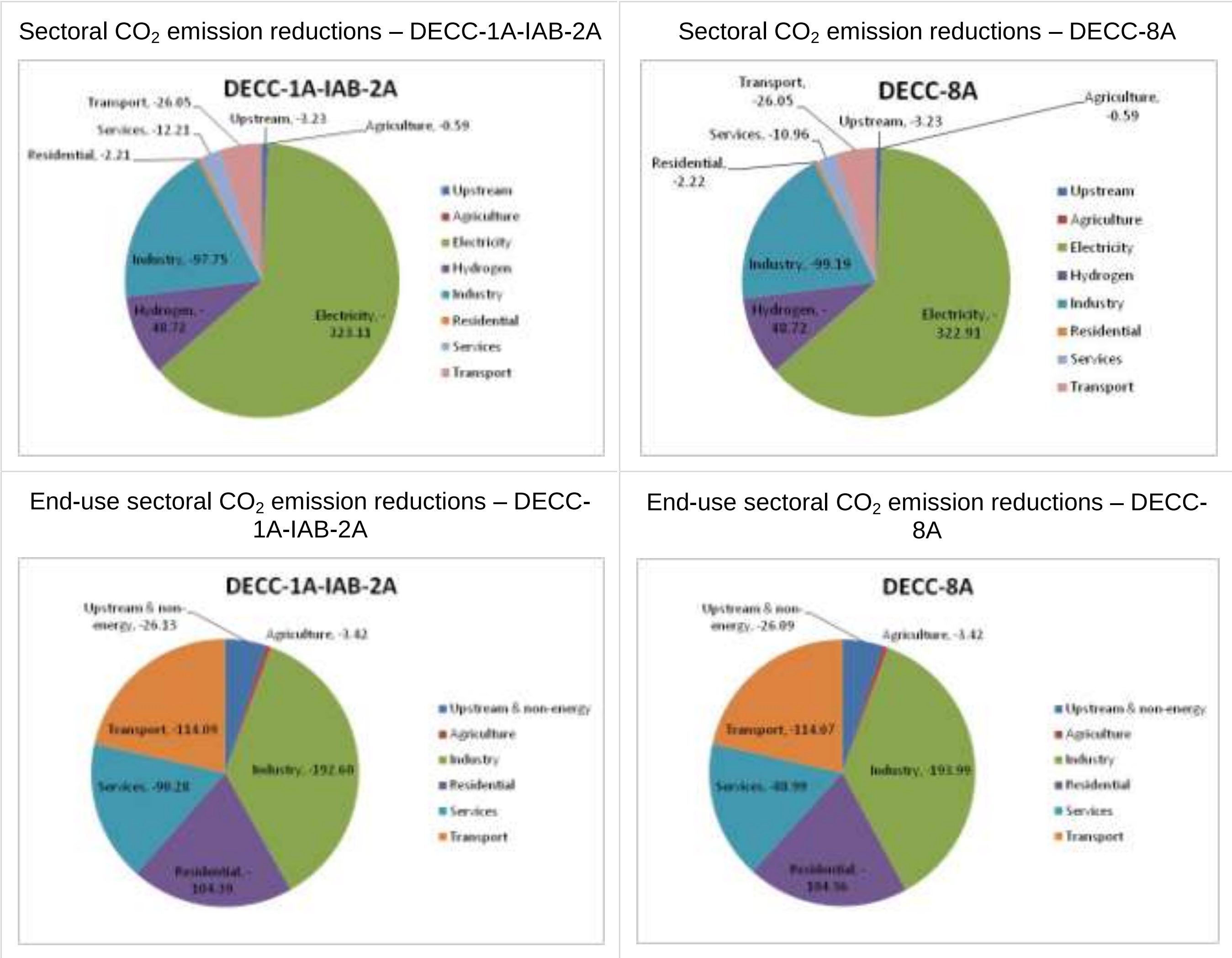


Figure 222: Sectoral and End-Use Sectoral CO_2 Emissions Reduction Disaggregation in 2050 (values in $MtCO_2$)

The total emissions reduction is the same in run DECC-8B as in the other runs, and the division among sectors is only slightly different, as shown in Figure 223.

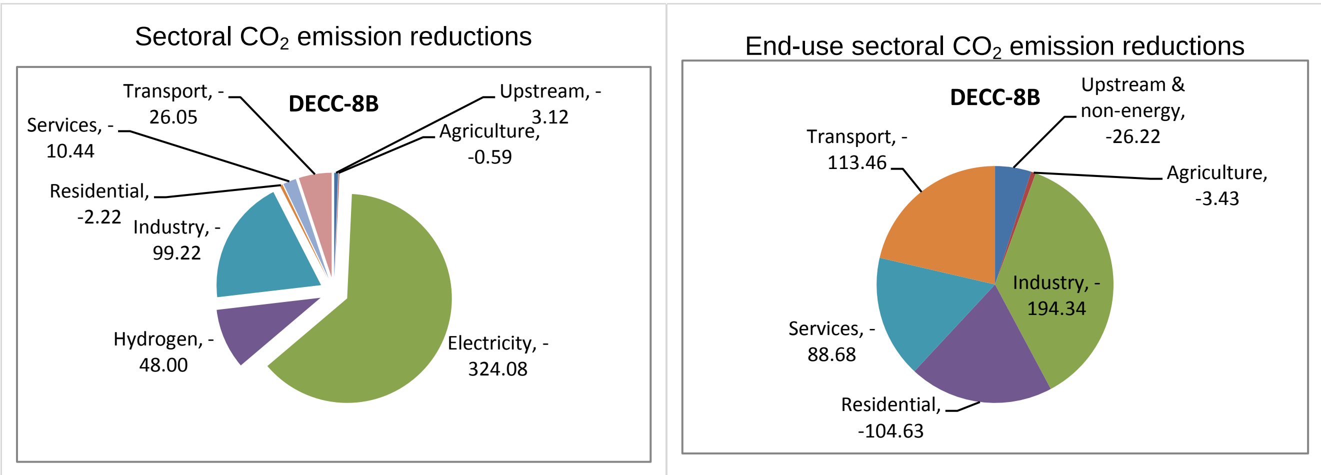


Figure 223: Sectoral and End-Use Sectoral CO_2 Emissions Reduction Disaggregation in 2050 (values in $MtCO_2$)

The following sections consider each end-use sector in more detail.

Industrial Sector

As shown in Figure 224, the only difference between the two scenarios under consideration occurs in the pulp-paper industry, where demand reduction is about 1% higher in 2050 for run DECC-8A in comparison to run DECC-1A-IAB-2A and another 1-2% higher for scenario DECC-8B.

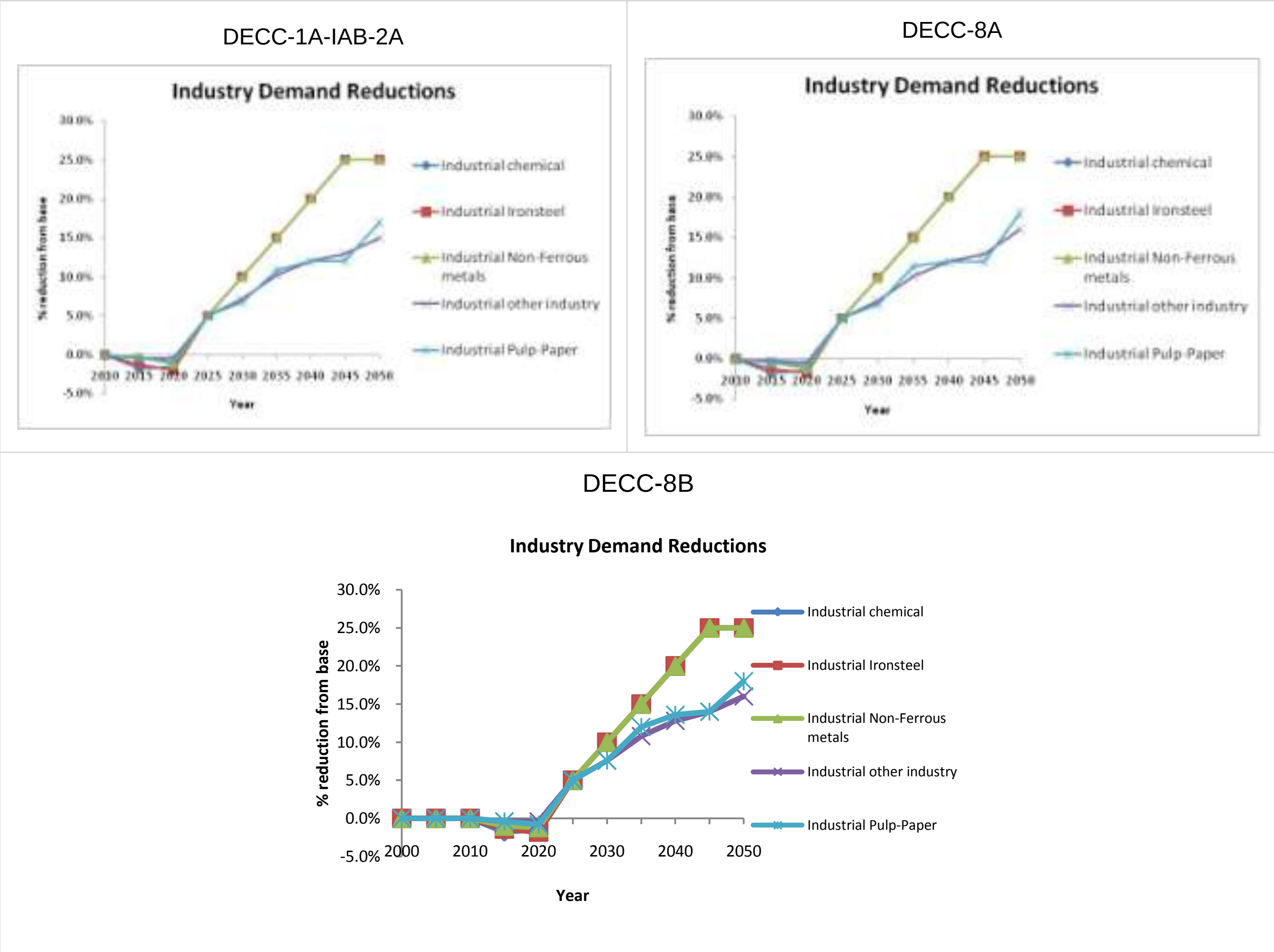


Figure 224: Industrial Demand Reductions for runs DECC-1A-IAB-2A and DECC-8A

By 2050, there are only minor differences in industrial energy demand in the electricity and natural gas sectors, as shown in Figure 225.

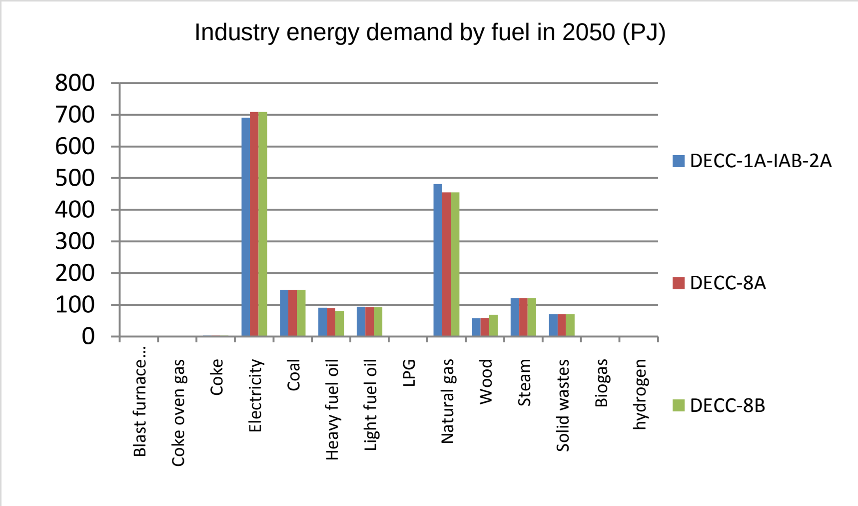


Figure 225: Industrial Final Energy Consumption for Runs DECC-1A-IAB-2A, DECC-8A and DECC-8B

Residential Sector

As shown in Figure 226, the difference between DECC-1A-IAB-2A and DECC-8A runs is negligible over the time period considered. In the run DECC-8B however, the demand for pellets and wood is lower than for the other two runs. For pellets, the demand comes one period later and is only about half that of run DECC-8A in the later part of the time horizon. For wood, its part in the fuel mix is more rapidly reduced than in scenario DECC-8A.

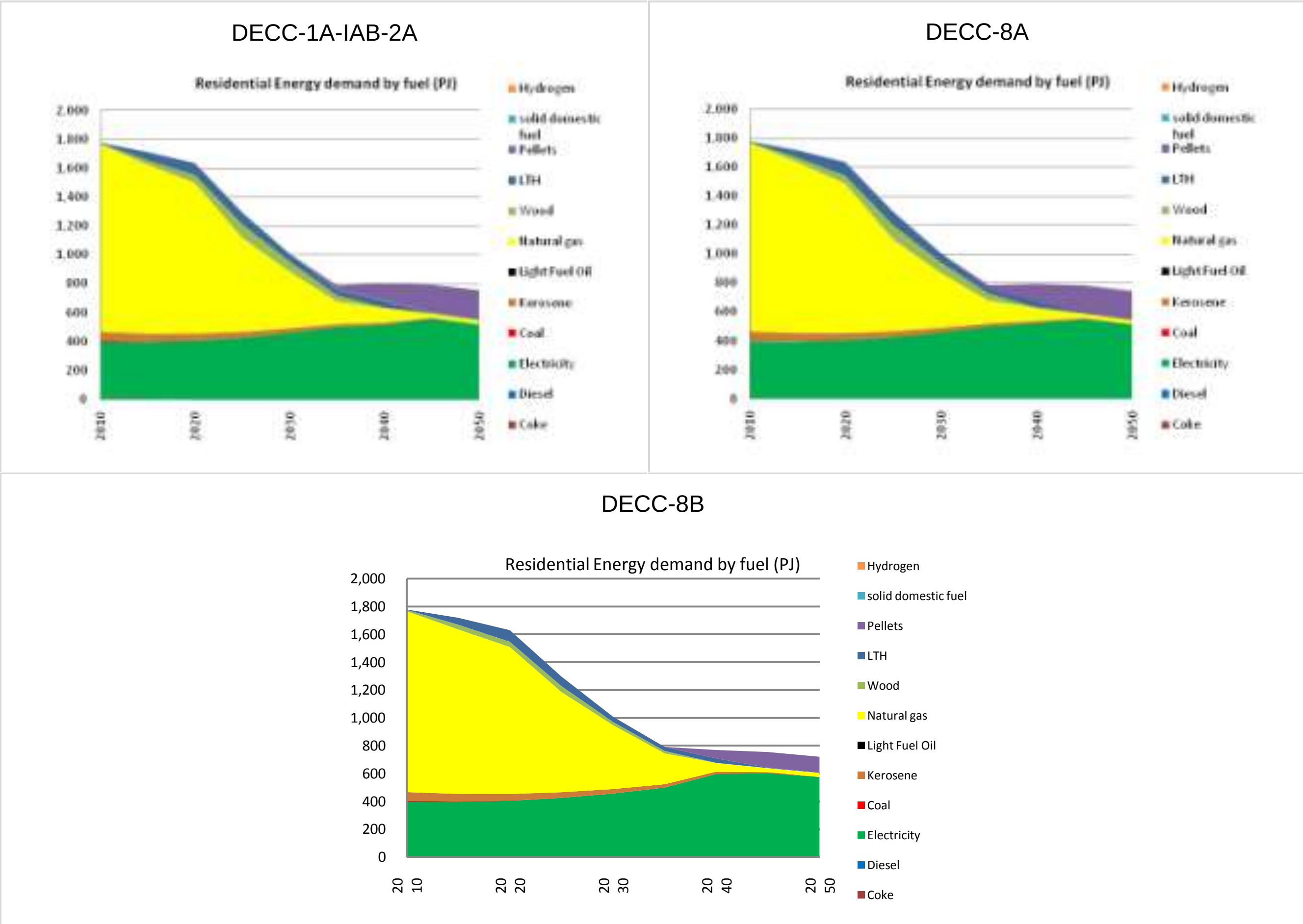
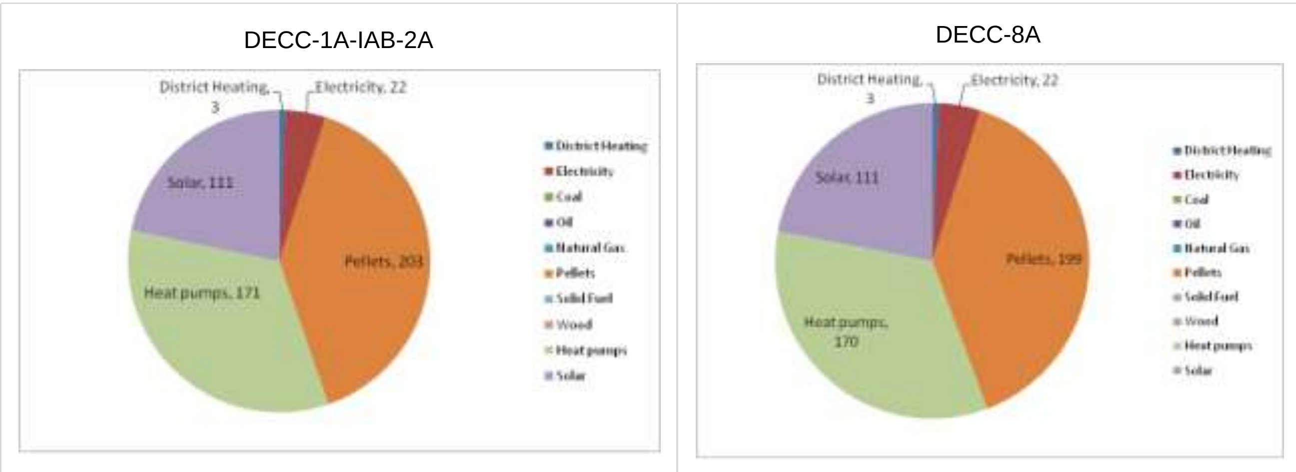


Figure 226: Residential Final Energy Consumption for Runs DECC-1A-IAB-2A and DECC-8A

By 2050, the residential energy demand for heating in scenarios DECC-1A-IAB-2A and DECC-8A is also very similar, as illustrated in Figure 227. Unsurprisingly due to the additional bio-energy constraints, DECC-8B displays a smaller proportion of pellets and increased use of electricity for heating.



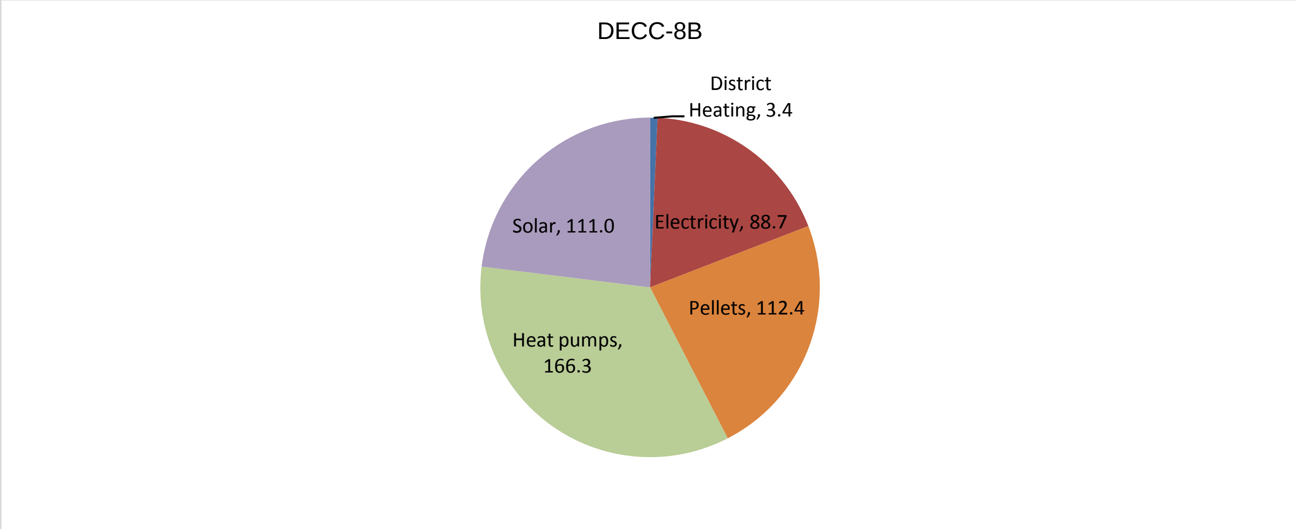


Figure 227: Residential Final Energy Consumption (PJ) for Heating in 2050

The reader should note that Figure 227 shows final energy consumption of the end-use device serving thermal demand. Therefore heat pumps, which draw energy from the surrounding environment in addition to consuming electricity, serve a much larger portion of heating service demand than the other technologies.

Services Sector

Overall, as shown in Figure 228, the service energy demand by fuel has a similar profile for runs DECC-1A-IAB-2A and DECC-8A up to 2050 (DECC-8B figure is very similar to that of DECC-8A).

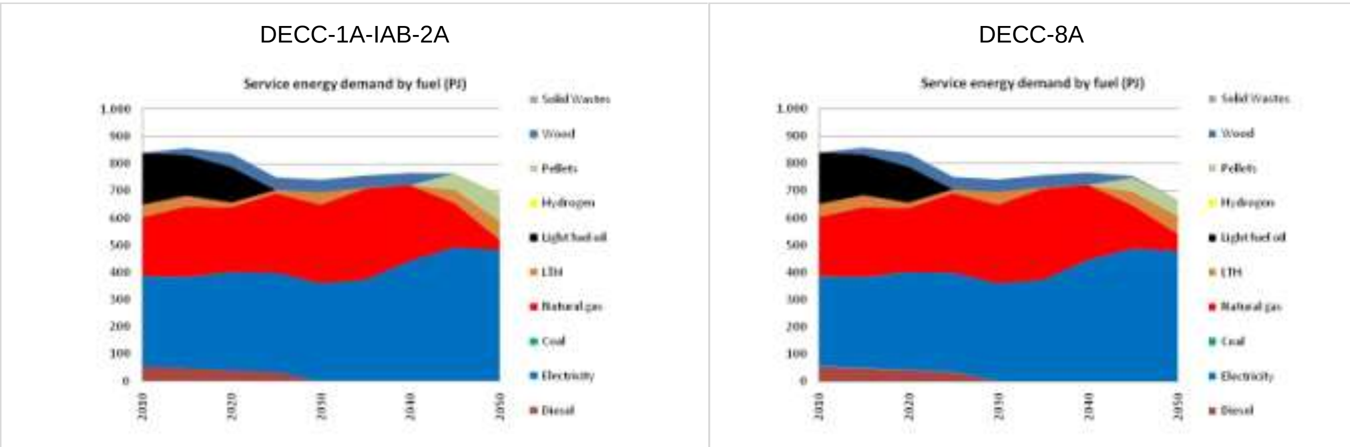


Figure 228: Service Sector Final Energy Consumption for Runs DECC-1A-IAB-2A and DECC-8A

By this year, the services sector exhibits a slight difference in the fuel mix as represented in Figure 229; the energy consumed by pellets is nearly 60% smaller and natural gas increases by almost 60% in run DECC-8A in relation to run DECC-1A-IAB-2A. DECC-8B displays an even higher use of natural gas and a lower level of LTH. Pellet use is similar to DECC-8A.

Figure 229: Service Sector Final Energy Consumption (PJ) in 2050

As shown in Figure 230, the services sector final energy consumption for heating does not change significantly between the runs (DECC-8B figure is very similar to that of DECC-8A).

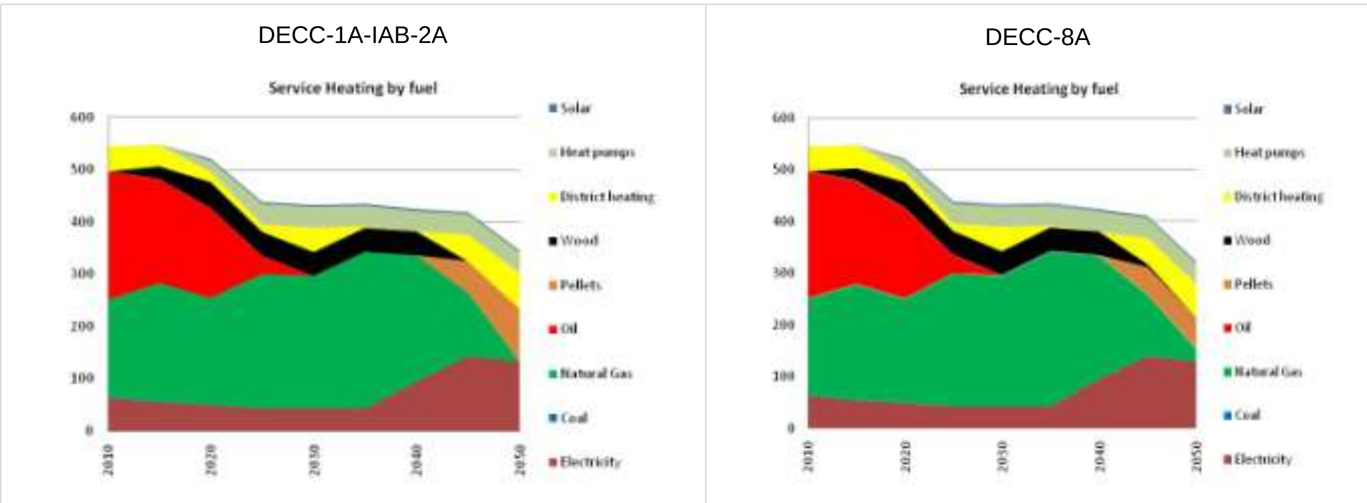


Figure 230: Service Sector Final Energy Consumption for Heating in Runs DECC-1A-IAB-2A and DECC-8A

It is only in the last periods where a change in the fuel mix for service heating can be observed (Figure 231), as natural gas appears in the mix and pellets decrease the contribution in runs DECC-8A and DECC-8B. High biomass sensitivity scenario DECC-8B also shows a drop in the contribution of district heating and a further increase in the proportion of natural gas in the final fuel mix compared to central biomass sensitivity run DECC-8A.

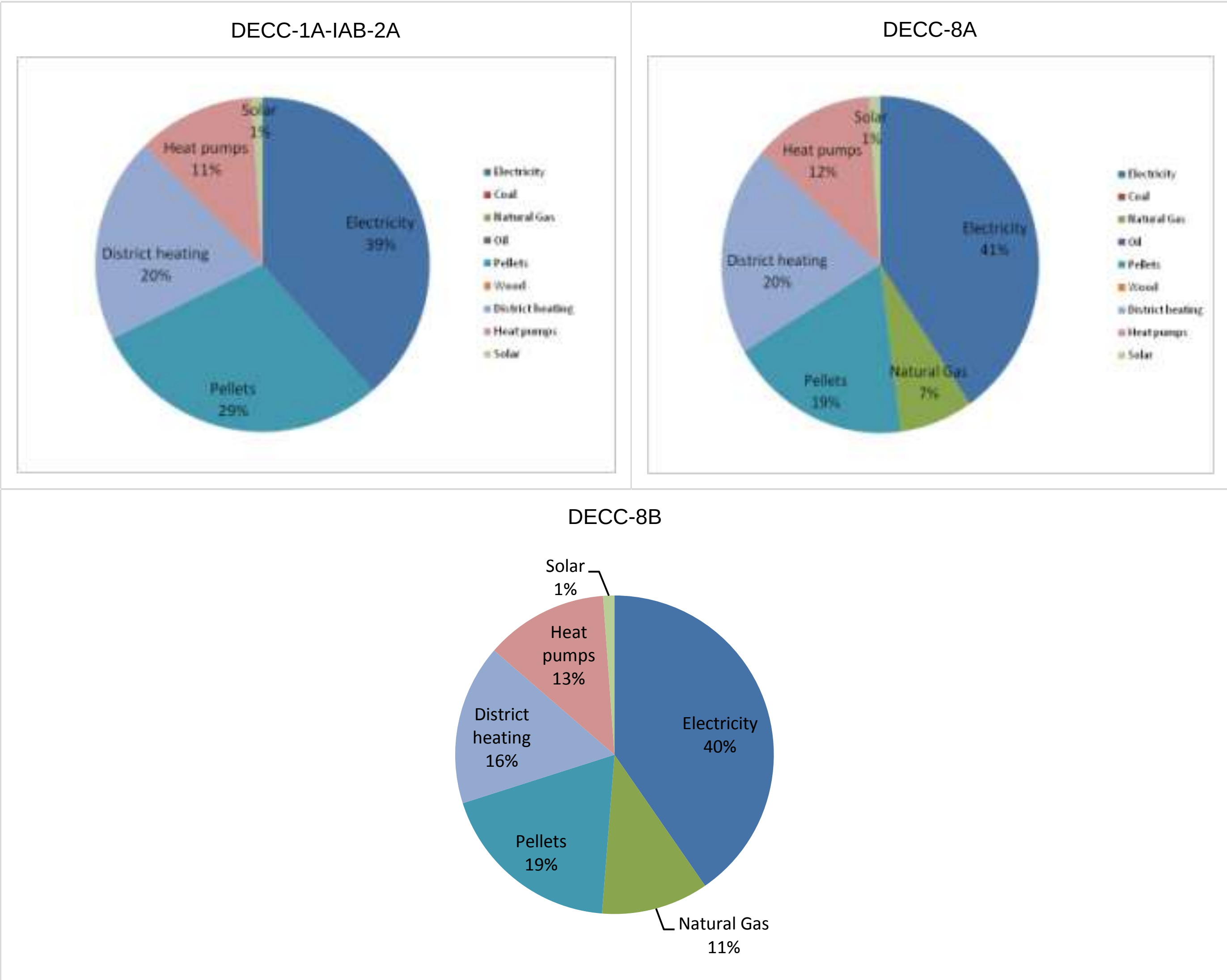


Figure 231: Service Sector Final Energy Consumption for Heating in 2050

Transport Sector

Although the overall profile of transport fuel demand is very similar in both scenarios, there are differences in the distribution of the biodiesel consumed amongst transport sectors over time. Figure 232 shows that in the last periods there is a larger consumption of biodiesel by LGVs in run DECC-1A-IAB-2A, whilst run DECC-8A apportions more biodiesel to HGVs and cars. In run DECC-8B, a sharp drop in biodiesel use in 2050 is observed and the very little of it is used for HGVs.

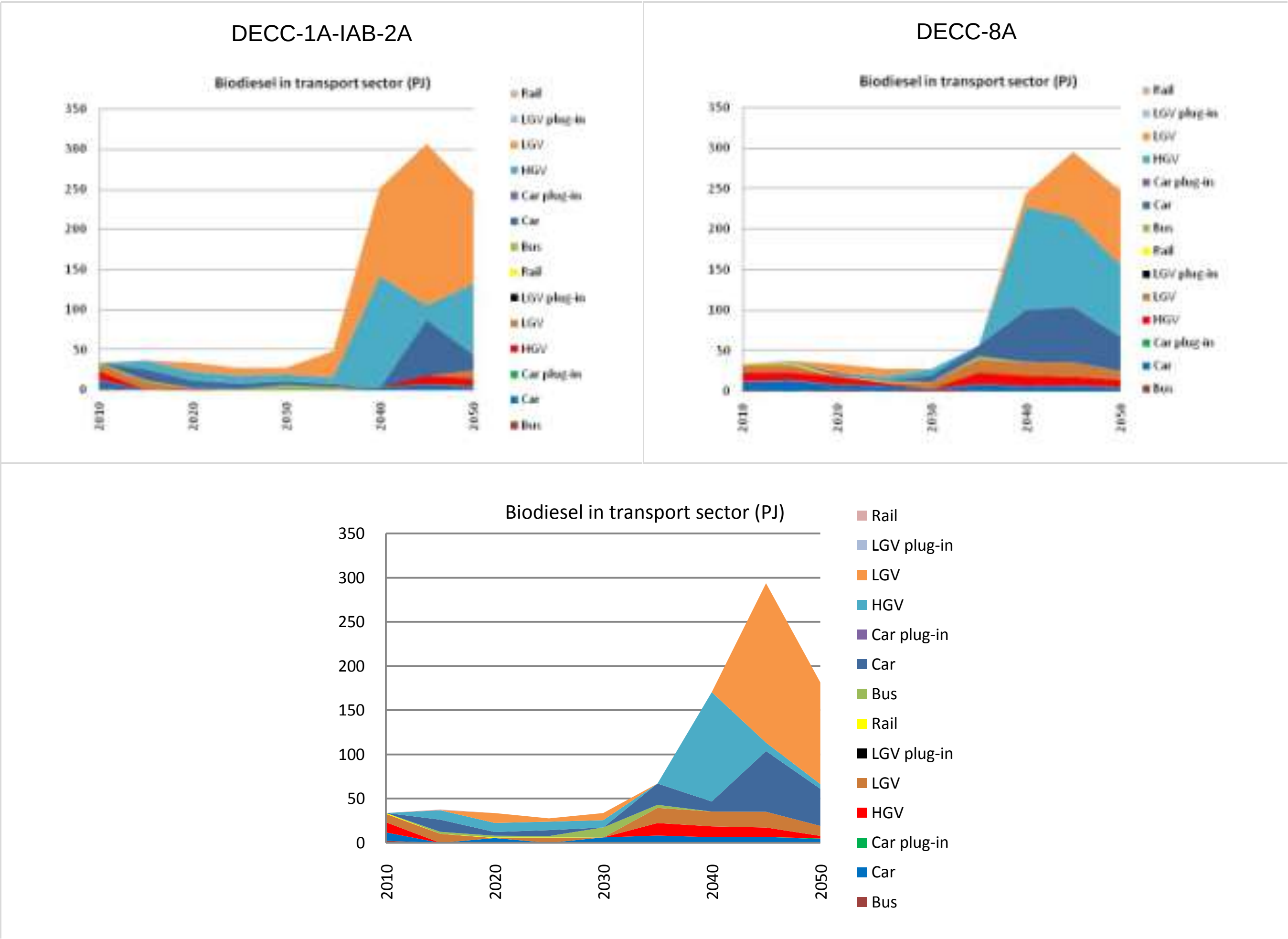


Figure 232: Biodiesel in Transport

3 Acronyms and Abbreviations

BEV:	Battery Electric Vehicle
CO_2:	Carbon Dioxide
CCC:	Committee on Climate Change
CCGT:	Combined Cycle Gas Turbine
CCS:	Carbon Capture and Storage
CNG:	Compressed Natural Gas
DECC:	Department of Energy and Climate Change
DfT:	Department for Transport
HGV:	Heavy Good Vehicle
LGV:	Light Goods Vehicle
MARKAL:	MARKet ALlocation model
O&M:	Operation and Maintenance
PHEV:	Plug-in Hybrid Electric Vehicle
PWR:	Pressurised Water Reactor
RES:	Reference Energy System
T&D:	Transmission and Distribution

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