Assessment of the appropriate uses of bioenergy feedstocks in the UK energy market

Final Report for the UK Department of Energy and Climate Change, and the Committee on Climate Change

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Contents

Executive summary

Bioenergy can play a key role in helping to meet the UK's renewable energy and greenhouse gas (GHG) emission targets and via a range of conversion routes has the potential to be used in virtually every part of the energy system. However, bioenergy resources (domestic and imported) are finite, and likely to be further limited due to sustainability issues. It is therefore important to gain a good understanding of how this scarce set of resources may be most appropriately deployed.

As part of this project we have developed a least cost optimisation model of the UK energy system to better understand the dynamic effects of using bioenergy in different pathways over the period to 2050. This also takes into account the potential for competing non-energy uses of biomass feedstocks, bioenergy lifecycle emissions, and competing conventional and low carbon technology options (but purposefully excludes current policy incentive schemes). The objective of the optimisation is to minimise the total discounted energy system costs (capital, operating, resource/fuel, etc) over the time horizon, subject to meeting key constraints. These include GHG and Renewable Energy Directive (RED)[1] targets, and the need to ensure that all energy service demands (for example, heating and transport) are met. Data has been compiled from the most recent available public sources, in particular from DECC, CCC, and DfT studies.

The analysis has examined six main scenarios including a core lower bioresource scenario and higher bioresource scenario[2]. It also examined bioenergy use with no Carbon Capture and Storage (CCS) options available, with no hydrogen production options, and under high oil price assumptions. Finally it looked at a scenario where the optimisation was undertaken myopically (ie period by period, without foresight across the full modelling horizon) to explore the risk associated with potential technology lock-in.

[1] Both the main target and transport sub-target, and using the RED accounting rules which are represented directly in the optimisation.

[2] Available resources across these scenarios represent approximately 6-11% of total primary energy demands in 2050 (estimated via a stylised case where bioenergy is allowed to supply 100% of total energy services), given the underlying scenario assumptions and potential conversion efficiencies.

The modelling is necessarily a stylised analysis of the energy system and key uncertainties remain in the input data, particularly over the longer-term. However, its main purpose is to identify key areas of commonality for bioenergy use (or non-use) which persist under different scenario assumptions, as well as to provide a more holistic view of appropriate use when the full energy system is considered on a consistent basis. It has highlighted the critical role that bioenergy plays in meeting the UK's targets, even with limited availability and from the scenario results a broad *hierarchy of appropriate uses* can be distilled:

- Non-energy uses for wood in construction as well as targeted uses in industry - particularly for process heat - appear desirable even without the availability of industry CCS in these scenarios. There are also a range of smaller scale uses which are generally more localised (eg waste products in Anaerobic Digestion (AD) to local heat sources) that are generally desirable[3]
- If CCS proves feasible it has the potential to generate 'negative emissions' when used with bioenergy and is highly desirable from the perspective of the overall energy system. Where it is used in the system becomes a question of the relative economics of different CCS options. These are still highly uncertain, but bioenergy could then be targeted towards hydrogen production (which can then be used in transport or power), large scale power/heat and liquid biofuels for aviation/shipping. The use of CCS in the production of liquid road transport fuels is potentially less desirable given the wider range of abatement options such as electric vehicles or fuel cell vehicles (using hydrogen produced from bioenergy + CCS routes).
- In a world without CCS, the use of liquid biofuels for higher value applications in aviation and shipping (along with non-energy uses and industry heat) is desirable; but in general, liquid biofuels for road transport and large-scale biomass for power (both without CCS) are less desirable in the long term to 2050 if biomass resources are scarce.

[3] Geographic factors were not modelled explicitly but are reflected in some technology costs (eg district heating in dense versus sparsely populated areas).

Key acronyms

- 1G – 1st generation biofuels
- AD – Anaerobic Digestion
- ASHP (ATW / ATA) – Air Source Heat Pump (Air to Water / Air to Air)
- AUB – Appropriate Use of Bioenergy (Model)
- BEV – Battery Electric Vehicle
- BTG – Biomethane to Grid
- BTL – Biomass to Liquid
- CAPEX – Capital Expenditure
- CBM – Compressed Biomethane
- CCC – Committee on Climate Change
- CCGT – Combined Cycle Gas Turbine
- CCS – Carbon Capture and Storage
- CNG – Compressed Natural Gas
- DDGS – Dried Distillers Grains with Solubles
- DECC – Department of Energy and Climate Change
- EFW – Energy from Waste
- FAME – Fatty Acid Methyl Ester
- FC-PHEV – Fuel Cell Plug-in Hybrid Electric Vehicle
- FCV – Fuel Cell Vehicle
- FOM – Fixed Operating and Maintenance
- FT – Fischer Tropsch
- GHG – Greenhouse Gas
- GSHP – Ground Source Heat Pump
- H_2 - Hydrogen
- HGV – Heavy Goods Vehicle
- HRJ - Hydrotreated Renewable Jet(fuel)
- HVO – Hydrogenated Vegetable Oil
- ICE – Internal Combustion Engine
- IGCC – Integrated Gasification Combined Cycle
- PHEV – Plug-in Hybrid Electric Vehicle
- PPO – Pure Plant Oil
- RED – Renewable Energy Directive
- RHI – Renewable Heat Incentive
- RO – Renewables Obligation
- SMR – Steam Methane Reforming
- SNG – Synthetic Natural Gas
- UPO – Unrefined Palm Oil
- vkm – Vehicle Kilometre
- VOM – Variable Operating and Maintenance

Glossary of key terms

- *Adjusted levelised cost* – extension of a standard levelised cost calculation to include the cost of GHG emissions and the 'value' to the system of meeting the RED targets and producing energy service demands
- *Backstop emission credit* – artificial product used as a last resort in the AUB model when other options are not sufficient to meet the GHG target
- *Bioenergy* – overarching term for all biomass-related energy feedstocks, resources, energy carriers, etc
- *Biofuels* – generic term used to refer to liquid transport fuels
- *Biogas* – gaseous form of bioenergy
- *Bioliquid* – liquid form of bioenergy
- *Biomethane* – gaseous form of bioenergy upgraded from biogas to comparable quality standard to natural gas
- *Constraint* – restriction on the optimisation model limiting its choice of decision variables (eg the maximum build rate of a new technology)
- *Decision Variable* – factors that AUB model can vary as part of finding an optimal least cost solution (eg new build or operation of technologies)
- *Energy carriers* – products only produced by technologies in the AUB model such as electricity or hydrogen
- *Feed and fodder crops* – covers various oil, starch and sugar crops
- *Forestry and forestry residues* – covers stemwood, sawmill co-products, short rotation forestry and various other forestry residues
- *Heat segmentation* – characteristic representation of the different types of heat demand disaggregated by sector, location, age of building, etc
- *Lifecycle emissions* – GHG emissions associated with the cultivation, transport and processing of bioenergy
- *Myopic foresight*- mode of operation of the AUB model, which optimises each time period sequentially without knowledge of future data
- *Negative emission* – generated by the application of CCS to bioenergy to avoid the re-release of carbon (absorbed during growth of the bioenergy) to the atmosphere
- *Non-energy use* – use of bioenergy outside of the energy system, such as wood in construction
- *Objective function* – the 'goal' for the model optimisation, which for the AUB model is the total cost of the energy system, to be minimised as part of finding an optimal solution
- *Optimisation* – mathematical problem aimed at finding a maximum or minimum value from a set of possible alternatives
- *Pathways* – conceptual representation of the flow of energy products from initial resource, through potential intermediate technologies to delivery of the final energy service demand
- *Perfect foresight* – mode of operation of the AUB model which finds an optimal solution across all time periods simultaneously
- *Products* – covers all energy and other flow in the AUB model including (bio)resources (eg energy crops), energy carriers (eg biomethane) and service demands (eg heat and transport vkm)
- *Shadow price* – change in objective function resulting from an incremental change in the right hand side of a binding constraint in the optimisation model, for example, the marginal cost of meeting the GHG emission target
- *Spare heat utilisation* – representation in AUB model of heat production used in district heat networks
- *Technologies* – covers all conversion (eg chipping or biofuel) and application technologies (those which produce service demand products)
- *Wastes* – covers food and other biodegradable waste, landfill gas, sewage sludge and livestock manures

1 Introduction

1.1 Overview of project

Bioenergy can play a key role in helping to meet the UK's renewable energy and greenhouse gas (GHG) emission targets and, via a range of conversion routes, can be used in virtually every part of the energy system. However, bioenergy resources (both in the UK and imports) are likely to be constrained, there are concerns about the level of resource which is truly sustainable, and there are also a range of non-energy uses for biomass feedstocks which must also be considered. It is therefore important to gain a good understanding of how best to use this scarce set of resources given the myriad of competing alternatives.

The Department of Energy and Climate Change (DECC) and the Committee on Climate Change (CCC) commissioned Redpoint Energy, with support from Ecofys UK, to assist with the *Assessment of appropriate uses of bio-energy feedstocks in the UK energy market Reference No: TRN 83/11/2010.*

The project has three main objectives:

1) to develop a framework to identify a hierarchy of 'appropriate uses' of bioenergy to 2050
2) to use the framework to provide input to the CCC's Bioenergy Review and DECC's bioenergy strategy, using the most recent available data (the project itself is not focused on new data gathering), and
3) to provide models that can be used in-house by DECC and the CCC to undertake further analysis as new input data becomes available.

The project has developed two modelling tools:

- a least cost energy system optimisation model, *which is the main focus of the project and of this report,* and
- a simple 'static hierarchy' Excel model.

Acknowledgments
A key part of this project has been to develop a model and the internal capability within DECC and the CCC so that it can continue to be used in future. As part of this process we have received extensive support and input on data, analysis and model testing from a number of individuals, and in particular we would like to thank David Joffe and Nina Meddings from the CCC, and Ewa Kmietowicz and Alexis Raichoudhury from DECC.

1.2 Overview of static hierarchy model

The static hierarchy model was developed at the beginning of the project to help structure the bioenergy pathways and as an aid to data compilation. It allows the user to specify a series of:

- Bioresources (eg UK energy crops or imported products),
- Intermediate conversion technologies (eg chipping or biodiesel production), and
- End-use applications (covering heating, transport and electricity).

The user can then specify the combinations of inputs/outputs to each of the conversion technologies and end-use applications, along with a corresponding counterfactual or alternative (ie non-bioenergy) end-use application.

Alongside this, the user enters a set of techno-economic data, such as the cost and lifecycle emissions associated with bioresources, and the capital and operating costs, efficiencies, lifetimes, etc, associated with the various technologies.

The model then calculates all valid combinations of bioenergy pathways from the initial bioresource through to final use based on the input/output combinations (several thousand given the current dataset). It then pulls in the corresponding techno-economic data to calculate standard levelised costs and emissions savings for each pathway, in 10-yearly intervals to 2050.

Finally the model uses the information for each pathway to calculate a number of pre-defined metrics such as £/tCO_2 saving or £/normalised unit contribution to the Renewable Energy Directive target, to rank the pathways against each other.

2 Overview of optimisation model

2.1 Introduction

Whilst the hierarchy model, mentioned above, provides a useful static ranking of pathways, it does not provide information on the absolute use of bioresources or installed capacity of technologies, or account for the dynamic effect of building up and operating a stock of technologies over time (in competition with non-bioenergy alternatives). We have therefore developed an energy system model to better answer the question of the 'Appropriate Use of Bioenergy' (or the AUB model).

The core of the model is a basic least cost energy system optimisation framework, similar in a number of respects to the MARKAL/TIMES framework or the Energy Technology Institute's ESME model. AUB decides to build and operate a stock of technologies over time (covering all sectors, intermediate conversion, heating, transport and electricity) to ensure that all energy service demands and other constraints are met. Other constraints include the GHG emissions and RED targets, resource availability limits, energy balances, and build rate constraints.

To assess appropriate uses the optimisation is driven by the aim of *minimising the total discounted energy system costs* (capital, operating, resource/fuel, etc) over the modelled time horizon, currently 5-year periods to 2050. AUB is resolved with annual granularity, but with a simplified representation of peak, mid-merit and baseload electricity requirements.

All dedicated bioenergy options (eg biofuel production plants or biomass boilers) as well as possible fuel switching options (eg a gas boiler or CCGT plant which could also use biomethane) are represented as explicit technology options, with multiple possible modes of operation. All other competing low carbon options (eg nuclear, other renewable electricity) are also represented as explicit technologies.

Conceptually, the model is focused on optimising a complex set of technology and energy choices, across the entire energy system, from a *societal resource cost* perspective. It is also designed to aid scenario analysis, particularly over the medium and long term, rather than trying to establish near term projections.

This is fundamentally different from other modelling approaches such as macro-economic/econometric or agent based models, which explore *price* based impacts more closely and the impact, for example, on investor behaviour in the near term.

As a result AUB has a relatively abstract representation of existing policy. It is focused on meeting both the absolute GHG and RED targets[4] in an optimal manner and not the likely impact of incentive policies or subsidies such as the Renewable Heat Incentive (RHI) or Renewables Obligation (RO) on deployment of bioenergy[5]. It also does not reflect the EU Emissions Trading Scheme; in reality the purchase of EUAs is a further abatement option that may be open to some sectors.

Technical Platform

AUB has been developed using AIMMS[6], a commercial optimisation development platform. This couples high performance and flexibility in future model development with transparency, as it is possible to inspect the model formulation directly to avoid the problem of a 'black box'.

We have also developed a user-friendly front-end (AIMMS has similar functionality to building forms in MS Access) so that data input, model configuration and analysis of results can all be undertaken without a detailed understanding of the underlying model.

Finally, we have also included a link to MS Excel so that a full dataset can be automatically imported from a single workbook and model results can be exported to an Excel file, for wider circulation.

[4] Including the full range of RED accounting rules explicitly within the optimisation.

[5] Although it could, for example, be used to gain a high-level understanding of how such support schemes could distort deployment relative to an 'optimal' solution.

[6] http://www.aimms.com/features/overview

2.2 Key features

AUB allows for a very detailed representation of bioenergy pathways and lifecycle GHG emissions as illustrated in the figure below.

These compete dynamically, via the optimisation framework, with all other specified alternatives, across all possible sectors and across all time periods simultaneously. End-use efficiency of the bioenergy pathways is implicit in the optimisation.

Figure 1 Illustration of bioenergy pathways

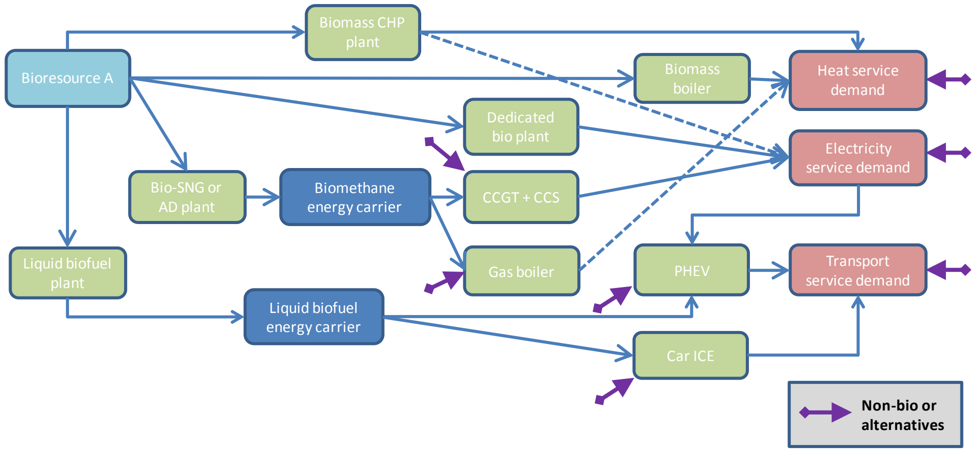

Figure 1 shows schematically some examples of pathways in the model. Other routes not shown include:

- Bioresource to H_2 (hydrogen) (+CCS) to vehicles or power,
- Biomethane to CNG (compressed natural gas vehicles);
- Biomethane to SMR (steam methane reforming) to bioH_2 to FCVs (fuel cell vehicles) or H_2 turbines;
- Bioresource to bioliquid to heat or electricity applications.

The current dataset is described in more detail in section 3, but currently contains around 50 unique bioresources[7] / bioenergy carriers[8] and around 50 unique bioenergy technologies. Over 2000 technologies exist in total with the conventional and low carbon alternatives, different typical sizes for some technologies[9], and different end-user segments (we have maintained the full 242 end-user heat segments used in CCC/DECC's low carbon heat work). Given multiple possible combinations of inputs and outputs to a technology (eg multiple feedstocks and electricity / heat from an AD CHP plant) there are thousands of possible bioenergy pathways in any time period, which the optimisation then automatically resolves as part of a least cost solution.

AUB also has a number of key functionality options:

- **Level of foresight:** the model can either optimise all time periods simultaneously (perfect foresight) or period-by-period carrying forward the stock of technologies it has built in preceding periods (myopic foresight)
- **Linear or 'Lumpy' investment:** the model can either be run as a pure LP (Linear Program) or as a MIP (Mixed Integer Programme) for new technology build – the latter allows only whole numbers of typical sizes of plant to be built to explore the effect of 'lumpy investment'[10]
- **Technology lock-in**: particular technology options can be forced into the model (eg CCS in the medium term) to explore the impact of infrastructure lock-in[10]
- **Non-energy issues:** the value of non-energy uses of bioenergy as well as co-products can also be considered as part of the optimisation

[7] Those where the user makes an exogenous assumption about cost and availability

[8] Those which can only be generated as an output from technologies in the model (eg biomethane)

[9] Only relevant in the Lumpy Investment mode

[10] This functionality was not used in the scenarios undertaken for this report

2.3 Key decision variables and constraints

This section describes the key decision variables (factors the model can vary as part of finding a least cost solution) and constraints (restrictions on the freedom to change these variables) in AUB.

Key decision variables

- Annual use of bioresources or other products such as gas or coal
- Non-energy uses of bioresources
- New build of technologies in a particular time period
- Activity of each technology in a time period, by build year vintage (which will have different costs and technical parameters) by mode of operation. A mode represents a unique combination of input(s) and output(s) products

Key constraints

- (Core) Satisfy energy balances – ie the supply of products (either use of a resource or production of outputs from a technology) must be at least equal to the consumption of products (or demand for energy services).
- (Core) Annual use of products (eg bioresources, fossil products) must be less than or equal to the maximum annual availability.
- (Core) Technology activity must be less than or equal to the maximum
- (Optional) GHG emissions per year must be less than or equal to a specified target. The user also has the option to include non-UK bioenergy lifecycle emissions within the specified target (see section 3.3). (The target can be replaced with a price of carbon which is then factored into least cost optimisation.)
- (Optional) Contribution of RED and transport output must be greater than or equal to specified targets. The outputs from different technology types are 'normalised' to reflect the specific RED accounting rules (eg whether the contribution is on an input or output basis, and specific rules for CHP)[11]
- (Optional) Utilisation of certain plant must be at least equal to a specified minimum load factor
- (Optional) Level of bioenergy contribution to energy service demands must be greater than a specified minimum (defined as a percentage for one or a group of energy service demands, eg all road transport)[12]
- (Optional) Inputs to certain plant must be maintained at least at the level of the first year of operation for a specified duration, to reflect supply contract lock-in. This constraint aims to approximate the lock-in of particular bioresource inputs to a technology over a specified time span. For example, this could reflect a long term supply contract to provide wastes to an AD plant, preventing these bioresources suddenly being diverted to other uses part way through the contract life (even if from an energy system perspective it may be considered a least-cost solution to do so). Consequently the model has a choice about whether to build and operate the AD plant, but if it does it must maintain the level of inputs over the specified contract length[12].

There are also a number of technology build constraints, which can be applied either to an individual technology or a group of user-specified technologies (ie AUB still has the freedom to vary its use of technologies within the group but only up to the overall constraint limit):

- Maximum (or forced minimum) build quantity that can exist in any time period
- Maximum absolute build rate per year in GW or number of vehicles
- Maximum build rate proportion – an expansion based on a % of installed capacity in the previous period, to better reflect expansion of the supply chain as a market expands.

[11] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF

[12] This functionality was not used in the scenarios undertaken for this report

3 Overview of current dataset

3.1 Introduction

The project was focused on the development of an analytical framework within which the most appropriate use of bioenergy could be analysed, as opposed to new data gathering. Whilst the core dataset reflects the best currently available data, uncertainties still remain. *A key objective of this project was therefore to produce a modelling framework that DECC/CCC can continue to use as new data becomes available.*

The 'core' dataset has been compiled based on the latest available studies from DECC, CCC, DfT and Defra (as well as a small number of academic and other sources). It has also received substantial input from both CCC and DECC directly as part of the project, and a high-level review of the bioenergy technology data was undertaken by E4Tech on behalf of the CCC and DECC.

The following sections outline the main data sources for each part of the model.

3.2 Data sources: global data and product data

Global data

Global data covers the overarching factors needed in all scenarios and includes the GHG emission target pathway, RED target and energy service demands, which the model must meet.

Table 1 Global data

Data	Source(s)
GHG pathway	– DECC / CCC - reflecting 80% reduction by 2050 on 1990 levels, including a share of international aviation/shipping emissions[13] and adjusting for non-CO2 GHGs, industrial process emissions and estimated industry CCS abatement (which is not included in this version of the model), and a linear reduction trajectory after the existing carbon budget periods
Energy service demands	From CCC / DECC (consistent with the CCC's Extended Ambition scenario to 2020 and Medium Abatement scenario to 2030 (from their December 2008 and December 2010 advice on the first four carbon budgets), and the Spread Effort pathway from the March 2011 version of DECC's 2050 calculator) – 'Base' (non-substitutable) electricity demand (eg for appliances, and net of additional demand generated by choices in the model for heat pumps, electric vehicles etc) split by baseload, peak and mid-merit. – Vehicle km by transport type – Heat by end-use segment End-use demands include the impact of demand-side efficiency measures consistent with the above CCC scenario

Product data

Product data covers the energy and other flows within the model which require exogenous assumptions from the user on their availability and/or cost. Energy carriers are also products, but are generated within the model by technologies.

Table 2 Product data

Data	Source(s)
Bioresource availability and costs	– AEA et al (2011) UK and Global Bioenergy resource report for DECC – E4Tech (2009) Biomass supply curves for the UK for DECC – E4Tech (2010) Biomass prices for Heat and Electricity for DECC – E4Tech (2009) Biofuels in aviation report for CCC – E4Tech (2011) TINA bioenergy analysis for Carbon Trust – FAPRI 2010 U.S. and World Agricultural Outlook – Nix (2011) Farm Management Pocketbook – NNFCC (2010) Evaluation of bioliquid feedstocks and heat, electricity and CHP technologies – CCC (2011) Bioenergy Review
Non-energy uses – availability and value	– Poyry (2011) "Alternative uses of biomass in decarbonising industry" for CCC
Fossil fuel prices	– Central DECC UEP (October 2011) prices
Co-Product Values	– DDGS (Dried Distillers Grains with Solubles) price from DfT AGLINK model central scenario

[13] These are included in the model although they are not currently included in the UK's 2050 greenhouse gas emission reduction targets. Also, non-UK bioenergy lifecycle emissions are included within the target, even though they do not fall within the current accounting framework. Therefore the results should **no**t be interpreted as a plan for meeting those targets, but rather how biomass could be most appropriately deployed to 2050 in a carbon-constrained world. The Climate Change Act 2008 requires the Government to lay regulation to the extent and circumstances in which emissions from international aviation and shipping should be brought within the target, or explain to Parliament why we have not done do so, by December 2012.

3.3 Data sources: bioenergy lifecycle emissions

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Bioenergy resources, carriers and conversion technologies have lifecycle greenhouse gas emissions based on the following components:

- Cultivation emissions and pre-processing transport (with an allocation to resource / co-products)
- Bioenergy conversion/processing emissions (excluding fossil fuel and electricity which are added directly as inputs to the relevant technologies, enabling emissions to be calculated endogenously[14])
- Bioenergy carrier transport inside UK
- International land transport / distribution (where relevant)
- International shipping (where relevant)

Lifecycle emissions do not include those associated with (direct or indirect) land use change given current uncertainties and is an area for further work. However, the bioenergy resource availability scenarios are fairly conservative (eg limited scope for bioenergy on land required for food) to minimise the impact of these and other sustainability issues.

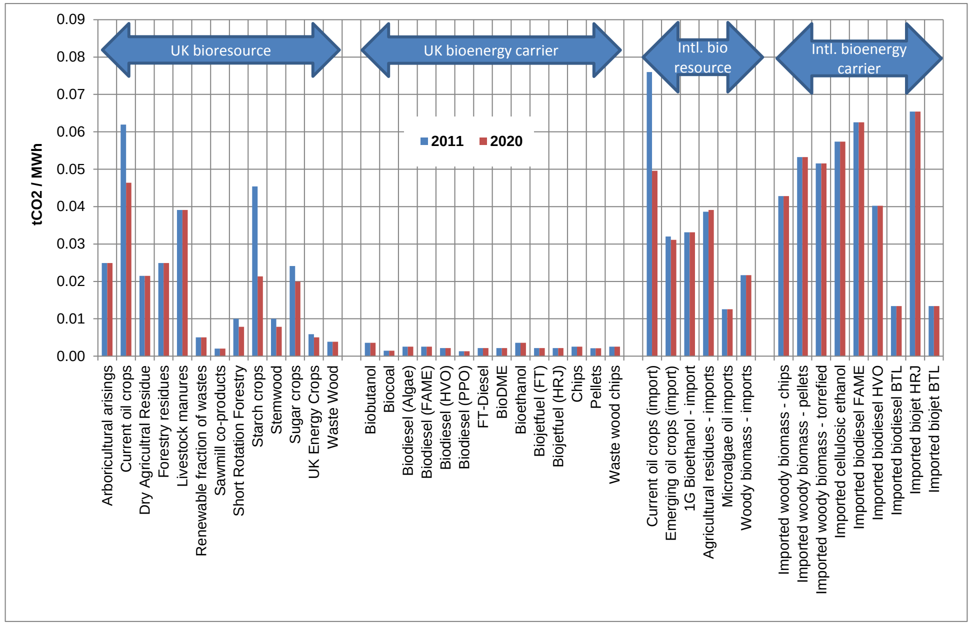
Table 3 Bioenergy lifecycle data

Data	Source(s)
Bioenergy lifecycle data	– RED Defaults / EU http://biograce.net/ project – Renewable Fuels Agency Carbon Calculator – DECC Carbon Calculator – Ecofys' own calculations

[14] This is important for electricity as the emissions factor is effectively being calculated endogenously in the model depending on the choice of fossil, bioenergy and alternative electricity supply options, and the scale of electricity demand, which is affected by the level and operation of eg heat pumps or PHEVs and EVs.

Total per unit lifecycle emissions for bioresources (UK and imports) and bioenergy carriers (UK and imports) are shown below. Values are held constant beyond 2020.

Figure 2 Overview of bioenergy lifecycle emission input values



It should be noted that the bioenergy carrier emissions only reflect production process and transport/distribution-related emissions and are *additional* to the bioresource emissions. Hence the total to produce a particular bioenergy carrier is dependent on the conversion efficiency of the producing technology for a specific bioresource input.

3.4 Data sources: technologies

Technology data covers the following key parameters:

- Lifetime, typical plant size, maximum availability (ie load factor), CO_2 capture rate (where relevant)
- Costs, CAPEX / FOM (fixed operating and maintenance) / VOM (variable operating and maintenance)
- Efficiency by 'mode' (combination of inputs/outputs)
- Existing stock of technologies
- Constraints data where necessary (eg maximum build quantities)

Table 4 Technology data

Data	Source(s)
Chipping / pelletising	– E4Tech estimates
Bioenergy conversion (including CCS)	– AEA (2010) options for decarbonising industry for CCC – Ecofys internal estimates – Element Energy (2010) application of CCS to UK industry and natural gas power generation for CCC – Poyry (2011) Levelised cost for biofuels model for DfT – SKM Enviros (2010) Analysis of characteristics and growth assumptions regarding Anaerobic Digestion for DECC – Uslu et al (2008) Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 33 (2008) pp 1206-1223

Table 5 Technology data continued

Data	Source(s)
Heat	– Element Energy / NERA (2011) Achieving deployment of renewable heat for CCC – CCC heat curve based on various NERA / AEA / Element Energy renewable heat studies for CCC and DECC as described above – NERA (2010) Analysis of low carbon heat to 2030 for DECC
Electricity / CHP (including CCS)	– ARUP (2011) Review of the generation costs and deployment potential of renewable electricity technologies in the UK for DECC – Mott Macdonald (2010) UK Electricity Generation Costs Update June for DECC – Mott MacDonald (2011) Biomass conversion of coal plant for CCC – NNFCC (2010) Evaluation of bioliquid feedstocks and heat, electricity and CHP technologies – PB Power update (2011) Electricity generation cost model: Power update for DECC – Redpoint Energy analysis for DECC
Transport	– CCC transport cost curve eg based on AEA (2009) Review of cost assumptions and technology uptake scenarios
Hydrogen production (including CCS)	– CCC (including US H_2A project) – Element Energy (2010) application of CCS to UK industry for CCC

3.5 Pathways overview

The following sections provide an overview of components of the current pathways (bioenergy and other) represented in the model.

Pathway setup

The specification of input / output products going to each technology creates the feasible set of pathways in the model. Each mode of operation of a technology represents a unique combination of input / output products. Many-to-many relationships as well as multiple conversion steps are possible.

For example, in terms of the bioenergy pathways:

- One or more bioresources can go directly to bioenergy applications (which produce the final service demands – electricity, heat, vehicle-km)
- One or more bioresources can go to a bio-conversion technology to produce one or more bioenergy carriers (eg biodiesel) which can be used in one or more bioapplications (power, heat, transport)
- A bioresource could go to a conversion technology, produce a carrier which is then used (wholly or partially) as an input to another conversion technology (eg biomethane to SMR instead of gas, to produce $BioH_2$)

Due to the very detailed segmentation of heat demand (see section 3.7) there are thousands of unique modes of technology operation in the current model. The number of unique bioenergy pathways (running from initial resource to final end-use) is even higher given the possibility of multiple conversion steps and the use of multiple bioenergy products from different routes going to the same application (for example, biodiesel and biomethane-generated electricity going to a PHEV).

Service demands

Service demands are the key products that the model must supply and are specified as exogenous inputs. In the case of electricity this reflects a base non-substitutable component of electricity demand (for example appliance use), but which can be added to as part of AUB's endogenous decisions, for example, from the use of heat pumps or electric vehicles.

Table 6 Products – service demands

Service demands	
– Electricity end use (Baseload) – Electricity end use (Midmerit - seasonal) – Electricity end use (Midmerit - diurnal) – Electricity end use (Peak) – End-user heat (see section 3.8)	– Vehicle-km artic small HGV – Vehicle-km artic large HGV – Vehicle-km rigid small HGV – Vehicle-km rigid large HGV – Vehicle-km aviation – Vehicle-TWh maritime fuel demand – Vehicle-km bus – Vehicle-km car – Vehicle-km van

Annual and within year/day model resolution

Whilst AUB resolves its energy balances on an annual level a simple form of indirect within year adjustment is applied to the different electricity segments, to reflect the requirements for additional generation capacity which can meet peak versus mid-merit versus baseload demands.

3.6 Bioenergy pathways - products

REDPOINT

Table 7 Products - resources

Bio (and other) resources	
– 1G Bioethanol - import – Agricultural residues - imports – Arboricultural arisings – Current oil crops – Current oil crops (import) – Dry Agricultural Residue – Emerging oil crops (import) – Food Waste – Forestry residues – Landfill gas – Livestock manures – Microalgae oil imports – Renewable fraction of wastes – Sawmill co-products – Sewage sludge – Short Rotation Forestry – Starch crops – Stemwood – Sugar crops – Tall Oil - imports – Tallow – UK Energy Crops – UK macroalgae – Used Cooking Oil – Waste Wood – Woody biomass - imports	– Coal - wholesale – Diesel – Oil - wholesale – Gas - wholesale – Jet fuel – Petrol – Fuel oil – Wind energy – Hydro energy – Tidal energy – Wave energy – Geothermal energy – Nuclear energy – Solar energy

Table 8 Products – carriers

Bio (and other) energy carriers	
– Bio fuel oil – Bio oil (pyrolysis) – Biobutanol – Biocoal – * Biodiesel (Algae) – Biodiesel (FAME) – Biodiesel (HVO) – Biodiesel (PPO) – Biodiesel (UPO) – Biodiesel BTL – BioDME – Bioethanol – BioH_2 – Biojetfuel (FT) – Biojetfuel (HRJ) – * Biojetfuel (JRCH) – Biojetfuel (Pyrolysis Oil) – Biomethane (biofuel - compression) – Biomethane (grid injection) – * Biomethanol – Chips – Imported biodiesel BTL – Imported biodiesel FAME – Imported biodiesel HVO – Imported biojet BTL – Imported biojet HRJ – Imported cellulosic ethanol – Imported woody biomass - chips – Imported woody biomass – pellets – Imported woody biomass – raw – Imported woody biomass - torrefied	– Pellets – Waste wood chips – Hydrogen – CNG – Electricity generation (Baseload) – Electricity generation (Midmerit - seasonal) – Electricity generation (Midmerit - diurnal) – Electricity generation (Peak) *Non Energy Uses* – Feedstock for glue lam beam for steel – Feedstock for glue lam beam for concrete – Feedstock for planed sawnwood *Co-products* – DDGS *Other* Coal, gas, oil and biomethane also have intermediate carriers which reflect additional costs to supply these to different end-user types (domestic, commercial, industrial and power)

Note: * *Not included in scenarios due to data availability/uncertainty but still considered a potential option*

3.7 Bioenergy pathways - technologies

Table 9 Technologies - conversion

Bioenergy and other conversion technologies	
– * Algae plant – (SV) – Biobutanol plant – (SV +CCS) – Biodiesel (HVO) plant – (SV +CCS) – Biodiesel (FAME) plant – (SV +CCS) – BioDME plant – (SV +CCS) – Cellulosic biobutanol plant – (SV +CCS) – Cellulosic plant – (SV +CCS) – Ethanol plant – (SV +CCS) – FT-Diesel plant – (SV +CCS) – Pure plant oil biodiesel plant – *Thermo/Biochemical Ethanol plant – (SV +CCS) – Biojetfuel FT plant – (SV +CCS) – Biojetfuel HRJ plant – (SV +CCS) – * Pyrolysis (Biojetfuel (JRCH)) plant – Pyrolysis oil plant – (SV +CCS) – Pyrolysis upgrading plant – diesel – Pyrolysis upgrading plant - jet – Pyrolysis upgrading plant - shipping – AD BTG – (SV) – Bio-SNG – (SV +*CCS) – Biomethane to CBM	– $BioH_2$ gasification (+CCS) – Distributed SMR (2 tpd) – Electrolyser (2 tpd) – SMR (+CCS) – Chipping – Pelletising – Torrefaction plant – Waste wood chipping – Electricity grid – Natural gas to CNG A number of 'dummy' importing technologies are also included (using the same techno-economic data for the UK variants) to allow the model to decide the form of the imported products (subject to the overarching availability restrictions on imported bioresources). – Importing biodiesel BTL – Importing biodiesel FAME – Importing biodiesel HVO – Importing biojet BTL – Importing biojet HRJ – Importing cellulosic ethanol – Importing woody biomass - chips – Importing woody biomass - pellets – Importing woody biomass - torrefied

Note: (SV) indicates a number of different typical Size Variants (important when examining 'lumpy' investment) of the technology. (+CCS) indicates an additional CCS variant for larger plants. * *Not included in scenarios due to data availability/uncertainty but still considered a potential option*

Table 10 Technologies – end-use application

Bioenergy and other applications	
– AD BTG / CHP / Heat / Electricity- (SV) – (Biomethane) CCGT - (+CCS) – (Biomethane) CHP - (SV +*CCS) – (Biomethane) OCGT – (Bio-syngas) CHP (+*CCS) – (Bio-syngas) Medium GT based CHP (50MWe) - (+*CCS) – * Fuel cell CHP – ACT – (SV) – Biodiesel engine – Biomass IGCC - (+CCS) – Biomass power only - (SV) – Co-firing standard / enhanced) Coal Plant - (+CCS) – EfW – CHP / electricity – Existing coal - Biomass retrofit – Flexible fuel CHP - (+*CCS) – Gas CHP / heat for CCS – Geothermal – H_2 Turbine – Hydro - (SV) – Landfill gas – Nuclear – Offshore / onshore wind - (SV) – Sewage gas – Solar – Solid CHP / heat for CCS – Tidal - (SV) – Wave	– ASHP ATA / ATW Storage- (SV) – Bioliquid boiler / CHP / electricity - (SV) – Biomass boiler / CHP / DH- (SV) – Biomethane boiler - (SV) – Conventional oil/coal boiler - (SV) – GSHP / GSHP storage- (SV) – Solar Thermal - (SV) – Waste Heat Utilisation - (SV) – BEV car / van- (SV) – Bus - (SV) – CNG bus – CNG HGV - (SV) – Diesel / petrol car - (SV) – Diesel van - (SV) – FC-PHEV car/ van - (SV) – FCV bus / car / HGV / van – (SV) – HGV - (SV) – PHEV car / van- (SV) – Dummy Conventional Plane – Dummy Maritime BioTechnology *(These technologies just reflect fossil to bioenergy fuel switching, efficiency improvements are implicit in the end-use service demands)*

3.8 Heat segmentation

In its previous analysis of low carbon heat options the CCC has developed a detailed segmentation of heating by end-user type (242 segments). This is maintained in AUB for both energy service demands and heat technologies, to allow this analysis to be consistent in terms of input data. The segmentation applies to the following technologies, albeit with certain suitability restrictions (eg district heating cannot be used to provide high temperature process heat for industry):

- Biomass boilers and biomass district heating
- (Biomethane) gas boilers and bioliquid boilers
- Solar thermal and all heat pump technologies
- Conventional (ie coal and oil) boilers

Table 11 heat segmentation

Segment	Sub-types
Sector	– Domestic – **D** / Commercial / Public – **C** / Industrial – **I**
Key counterfactual fuel type	– Electricity – **E** / Gas – **G** / Non net bound - **N**
Building / Heat type	– Flat - **FLA** – Detached - **DET** – Other House (semi-, terraced) - **OTH** – Large private – **LPR** / Small private - **SPR** – Large public – **LPU** / Small public - **SPU** – Large, space – **LSP** / Small, space - **SSP** – Large, high-temperature process - **LHT** – Small, high-temperature process - **SHT** – Large, low-temperature process - **LLT** – Small, low-temperature process - **SLT**
Location	– Rural – **R** / Suburban – **S** / Urban – **U** / All - **A**
Other	– Post-1990 – **POS** / Pre-1990 – **PRE** / New build - **NBD** – SWI - **SWI** – All - **ALL**

'Spare' heat utilisation

For biomass district heating the costs of the individual technology variants reflect both the cost of generating the heat as well as supplying it to the final end-consumer (eg costs of the heat network). For other technologies which produce heat as a co- or byproduct (eg CHP, bio-SNG plants) this is not the case and costs only reflect the generation of heat.

Dummy 'spare' heat utilisation technologies have been created (to reflect the network/supply costs). These act as an intermediate step which can use the heat output from the above technologies as an input and then produce the energy service output for a particular segment (eg heat commercial large / small, heat domestic).

Both spare heat outputs and the spare heat utilisation technologies are further differentiated based on whether the heat is going to a 'sparse' or 'dense' network due to the difference in network costs.

The model does not have to utilise all the spare heat it produces. The decision to do this will be a function of the costs of the generation options, spare heat utilisation technology and competing alternatives. However, spare heat can only contribute to meeting the relevant energy service demand via the utilisation technologies.

3.9 Imports

AUB has been set up so that there is both a set of directly importable resources (such as agricultural residues, 1G bioethanol or oil crops – imported in a semi-refined state[15]) and a larger pool of woody biomass which can either be imported directly or converted overseas and imported as a refined or semi-refined product[16].

'Dummy' overseas conversion technologies allow AUB to choose what form it wants the imported bioenergy to take. The costs of the conversion plants mirror the UK equivalents, but there are additional costs and lifecycle emissions associated with transport to the UK.

There are currently no CCS options included for the 'dummy' overseas conversion options. The combination of bioenergy and CCS is only possible via import of a resource or semi-refined product for further conversion (or end-use) in a UK plant.

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[15] Ie the oil crops are not imported directly and fully processed in the UK but the semi-refined oil can be used in subsequent UK process such as the production of biodiesel.

[16] This covers various forms of biodiesel and biojetfuel, cellulosic ethanol and chips, pellets and torrefied biomass.

3.10 Key areas of uncertainty

It is important to emphasise that our approach is focused on understanding differences in (data intensive) scenarios in a consistent manner. The goal is therefore not to project specific technology outcomes, but to understand key areas of *commonality* across the scenarios – ie the relative importance of bioenergy under different input assumptions. It should also be noted that we are not modelling the impact of policy incentive support in any scenarios (for example, the Renewables Obligation (RO) or Renewable Heat Incentive (RHI)). The goal is to try to understand the most appropriate uses of bioenergy to meet the emissions and renewable energy targets, and through identifying important trade-offs and risks, as well as key innovative technologies and pathways, help inform policy decisions

Data

Whilst the dataset has been subject to review as part of this project there are still key areas of uncertainty, some of which have been explored through sensitivity analysis. These include:

- The potential value and emission savings for non-energy uses of biomass feedstocks (only uses in construction were included for this project)
- The potential of industrial CCS options (not included explicitly as technologies, but accounted for through an adjustment to the GHG emissions target (see section 4.1))
- Availability of imported bioenergy resources
- Costs and feasibility of smaller scale CCS options for CHP/heating or larger-scale gasification options for biomethane
- Longer-term technology costs and build rate assumptions for novel technologies (eg advanced biofuels, CCS more generally)
- Estimates of distribution costs for new energy carriers such as hydrogen
- Estimates of the cost/role of heat networks
- Land use change emissions[17]

Explicit pathways

The energy pathways in the model have been set up so that it is possible to track energy carriers such as biomethane, H_2 or biodiesel through to a specific end-use (eg power generation or a particular vehicle type). This is helpful to better understand the implications of the end-use efficiency of bioenergy and factors such as the availability of CCS on appropriate uses. However, the infrastructure for the distribution of carriers (eg biomethane injected into the local gas distribution network) means that in practice it may not always be possible to direct the flow of bioenergy to an explicit end-use.

Optimisation modelling

Optimisation models can sometimes lead to sizeable switches in results due to small changes in costs. This is mitigated by, for example, the use of build rate constraints (to try to account for technical restrictions on the rate of new infrastructure deployment) and minimum load factors (eg to try to mimic the likely minimum level of utilisation that a private investor would require to generate a return on their investment), which reduce the speed of transitions.

Identifying ‘switching’ can still enable a better understanding of the key tipping points, where small changes in costs (e.g. relative costs over time) may lead to different bioenergy pathways. For example, the point at which H_2 (produced potentially via bioenergy + CCS) is preferred over electric vehicles for passenger road transport.

It is also important to note options which are not modelled explicitly in the current scenarios. In particular, retrofitting is only applied to conversion of the existing coal stock to dedicated biomass. Other forms of retrofitting such as CCS or converting bioliquid plants to produce a different range of fuel types would add further flexibility to the energy system and extend the life of existing infrastructure.

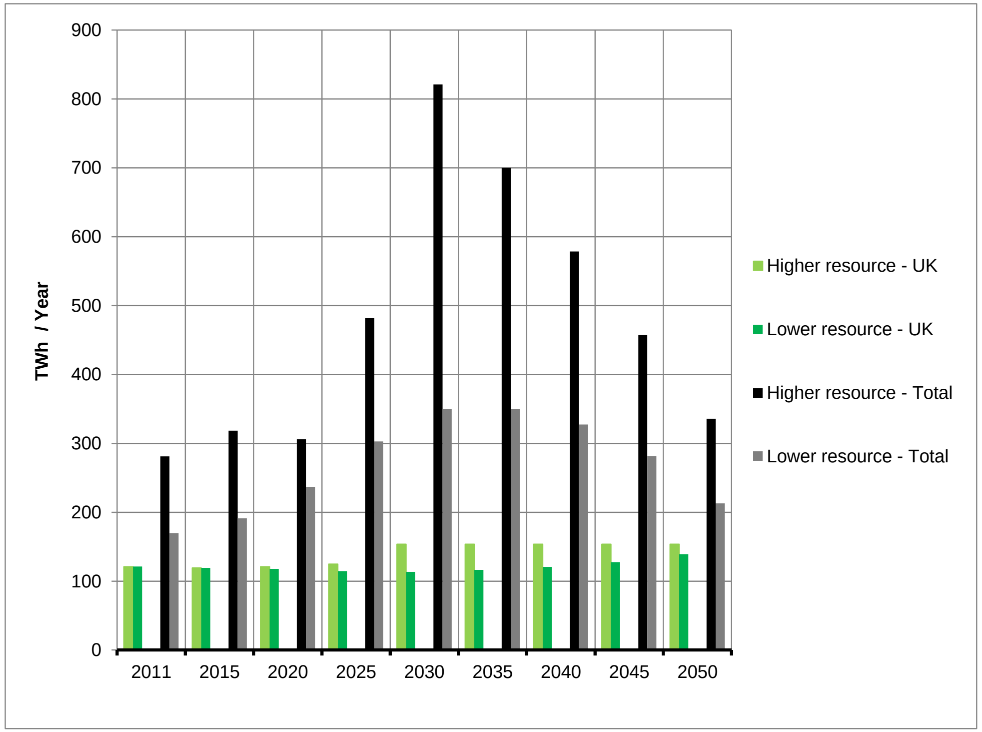
[17] These are not currently included in the lifecycle emissions in the model

4 Scenarios

4.1 Core scenarios

Two core scenarios and a number of sensitivities have been undertaken. The only difference between the core scenarios is the level of bioenergy available as summarised in Figure 3. A more detailed breakdown is shown in section 7.

Figure 3 Summary of bioenergy availability in core scenarios



Note: UK refers to domestic resource only, and hence the difference between this and the total reflects the availability of imports.

The **core** scenarios are otherwise comprised of the same elements:

- An emissions target path reflecting the current carbon budgets and a linear path to the 2050 target thereafter. The pathway is shown by the net emissions in the chart in section 5.1. Allowed CO_2 emissions in 2050 are 63 $MtCO_2e$/year, which reflects the full UK 2050 target of 160 $MtCO_2e$/year, including a hypothetical UK share of international aviation and shipping emissions[13], minus 55 Mt for non-CO_2 GHGs (assuming a 70% reduction vs 1990 levels). Further adjustments of 42 $MtCO_2$ have been made to account for the current absence in the model of process and non-energy emissions and abatement from industrial CCS. Non-UK bioenergy lifecycle emissions are included within the target to understand the likely impact on the energy system, even though they do not technically fall within the current accounting framework.
- The overall RED target for 2020 of 15% in final energy and the transport sub-target of 10%. Intermediate Renewable Transport Fuel Obligation (RTFO) targets are also included.
- The base demands for electricity (ie excluding additional electricity demand generated by choices within the model for EVs, heat pumps, etc), heat and transport are consistent with the CCC's Extended Ambition scenario to 2020 and Medium Abatement scenario to 2030 (from their December 2008 and December 2010 advice on the first four carbon budgets), and the Spread Effort pathway from the March 2011 version of DECC's 2050 calculator
- Fossil fuel prices are taken from DECC's central scenario from the October 2011 Updated Energy Projections (UEP).
- A global social discount rate of 3.5% has been applied[18].
- The core scenarios were run with perfect foresight and in LP (linear program) mode.

[18] Various technology specific discount rates (to reflect the cost of capital as a resource cost) are also applied in the model.

4.2 Constraints and sensitivities

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In addition to various maximum build quantity and build rate technology constraints, a number of additional constraints have been applied, based on input from DECC and the CCC:

- A 1:1 ratio of new build petrol / diesel cars has been fixed for different types of petrol/diesel cars and different types of PHEV diesel / petrol cars
- Constraints[19] on the *minimum* levels of:
  - New offshore wind (output corresponding to ~10GW by 2020 plus 1GW per year to 2030 – held constant thereafter)
  - Wave and tidal corresponding to the Arup (2011)[20] minimum trajectory to 2020, CCC 40% Renewables Review scenario for 2030 and held constant thereafter
  - Other renewables at 2010 levels to 2050
- Minimum load factors (to reduce sudden transitions in new technology build) of
  - 50% for a range of new build biofuel production technologies (built to 2025)
  - Minimum load factors equivalent to ~95% of maximum utilisation for new road vehicles

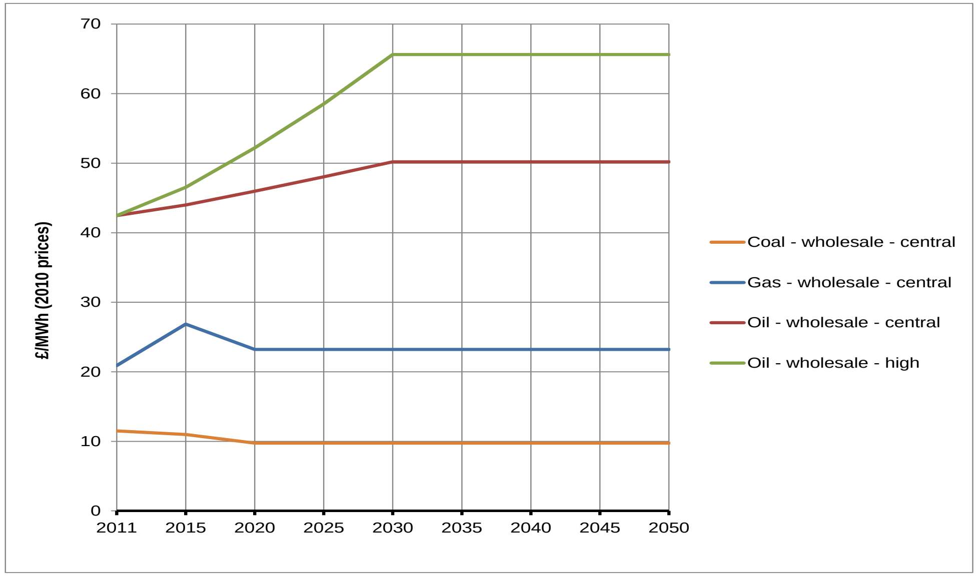
Sensitivities

The following sensitivities have also been examined. These reflect the core scenarios with the exception of the following differences:

- Core higher resource scenario with no CCS technologies (together with a downward adjustment to the emission target to reflect a lack of emissions reduction from industrial CCS).
- Core lower resource scenario with no H_2 technologies.
- Core higher resource scenario with high oil commodity costs (from DECC high scenario June 2010 UEP) for all oil related products, and central scenario prices otherwise.
- Core lower resource scenario run in myopic foresight mode.

Figure 4 summarises the core and high oil price scenario commodity costs.

Figure 4 Summary of commodity costs



[19] For power these were based on the lower end of the ranges in the DECC Renewables Roadmap and included to ensure some diversity in the generation mix.

[20] Arup (2011) Review of the generation costs and deployment potential of renewable electricity technologies in the UK report for DECC

4.3 Structure of results

Structure of results
The subsequent results sections are structured as follows:

- Section 5 provides some key contextual results for the overall energy system, to help better understand the role of bioenergy within each scenario.
- Section 6 provides an overview of how bioenergy is being used across the entire energy system on a primary energy basis, and also in terms of its normalised contribution to the 2020 RED target, based on the RED accounting rules.
- Section 7 provides a more detailed breakdown of overall bioenergy use.
- Section 8 provides further information on the role of bioenergy in each end-use sector (electricity, heat and transport) within the context of the competing alternatives.
- Annex A (section 10) provides a more detailed breakdown of use of bioenergy by technology type.
- Annex B (section 11) provides a more detailed breakdown of intermediate bioenergy carrier production and imports.

Adjusted levelised technology costs
The model's objective is to minimise the total discounted energy system costs[21] over the entire period (in perfect foresight mode), subject to meeting its overarching constraints. However, in understanding why the model is choosing particular technologies over available alternatives a conventional levelised cost of energy (or output for vehicles) analysis can be misleading.

This is due in part to the potential for changing utilisation and load factors over the lifetime of the plant, which can significantly raise the actual levelised cost of energy compared to a static assumption of a default, high load factor. Further, the implied cost of carbon changes significantly over the pathway as the emission constraint tightens, strongly influencing the cost of using particular technologies at the overall system level.

Finally, as the model has to meet its energy service demands and RED targets there is an implied *value* to the system from technologies which help produce these. This is also important in understanding the choice of technologies which can produce multiple products, such as peak and baseload electricity, with peak being more valuable (as inferred from a higher shadow price for this product in the model).

To better understand AUB's relative choices, an adjusted levelised cost can be calculated for each vintage of plant over its lifetime based on actual output, and including conventional costs (annualised CAPEX, FOM, VOM, fuel or product) and the cost of carbon using the model's shadow price. It also approximates the benefit of the outputs produced and the value to the system in terms of contribution to meeting the RED targets, based on shadow prices from the model.

References to these calculations are made in the following sections (and an example is shown in Annex A). The convention used is that the more negative the value the more cost effective is the technology to the overall system. It is important to note however that technology choices are affected by build constraints (see section 5.3) and hence more costly options will be employed when these constraints limit the use of lower cost options.

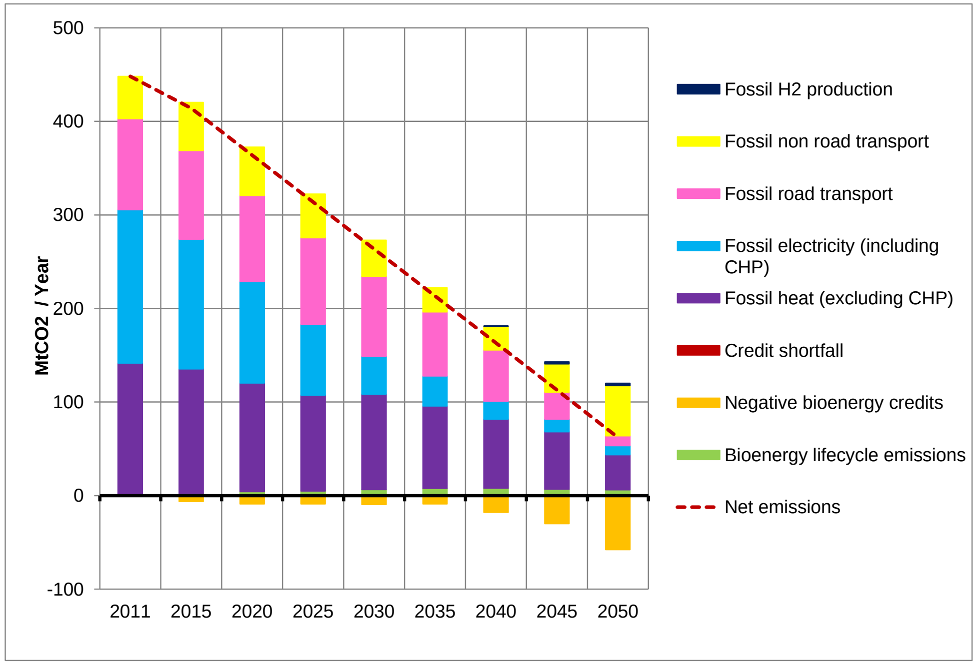
[21] Note that these are social costs and hence exclude distributional costs such as taxes and subsidies.

5 Results: general energy system context

5.1 GHG emissions summary

It is important to note that the scenarios are generally very tight in terms of the ability to meet the specified 2050 emission target, particularly given the inclusion of non-UK bioenergy lifecycle emissions in the emissions target.

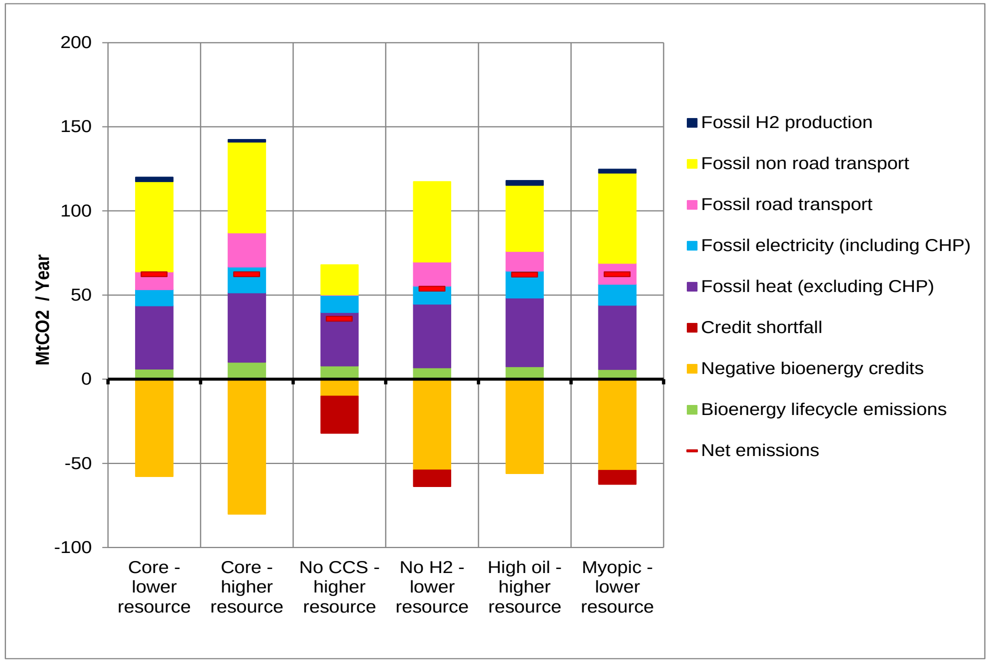
Figure 5 GHG emissions (Core - lower resource scenario)



The shadow (or marginal) price of carbon is over £500/tCO_2 in all scenarios by 2050 (see section 5.2) even in cases where an artificial 'backstop' is *not* needed[22]. In all the perfect foresight runs the end-point has a very strong influence on the overall energy system solution. In particular, there is a strong preference to combine CCS with bioenergy at various points throughout the energy system to generate negative emissions.

The emissions pathway under the core higher resource scenario is similar to that in the core lower resource scenario, but with higher overall bioenergy availability there is more scope for producing negative emissions.

Figure 6 GHG 2050 emissions summary (All scenarios)



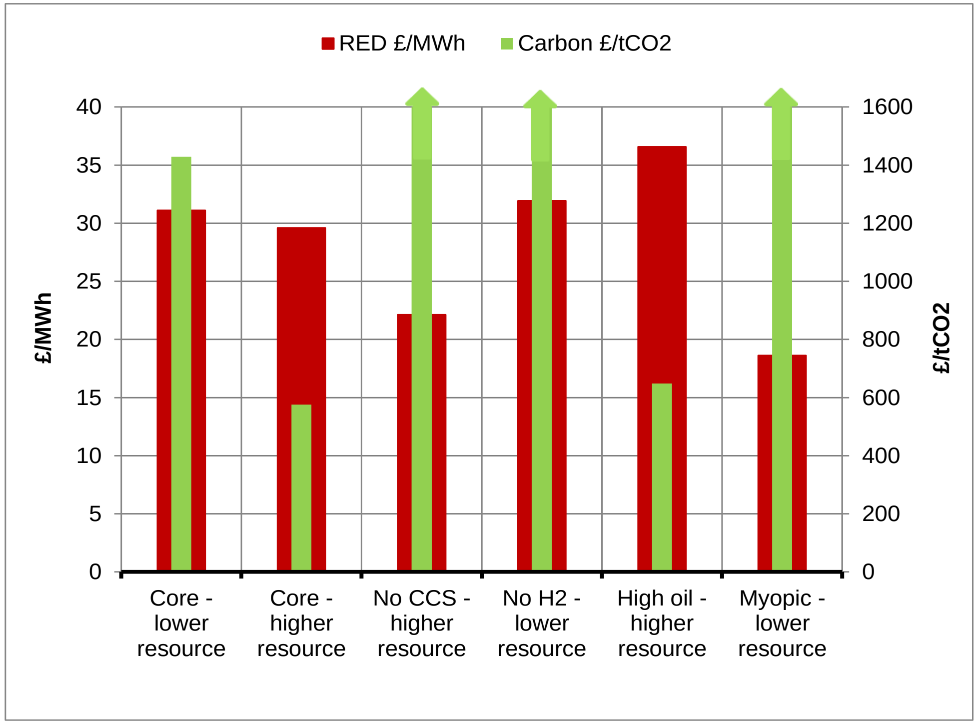
Without access to CCS or H_2 technologies it is not possible to meet the emissions target without resort to the 'backstop' emissions credit. However, this must also be seen within the context of scenario build constraints (see section 5.3) and bioenergy availability (see section 7). Similarly, in the myopic scenario, the severity of the tightening emission target does not become clear until the later periods, at which point the system cannot adapt quickly enough (eg due to build rate constraints) and must also use the backstop option.

[22] This is effectively equivalent to an emissions credit and is the most expensive last resort option.

5.2 Shadow Prices

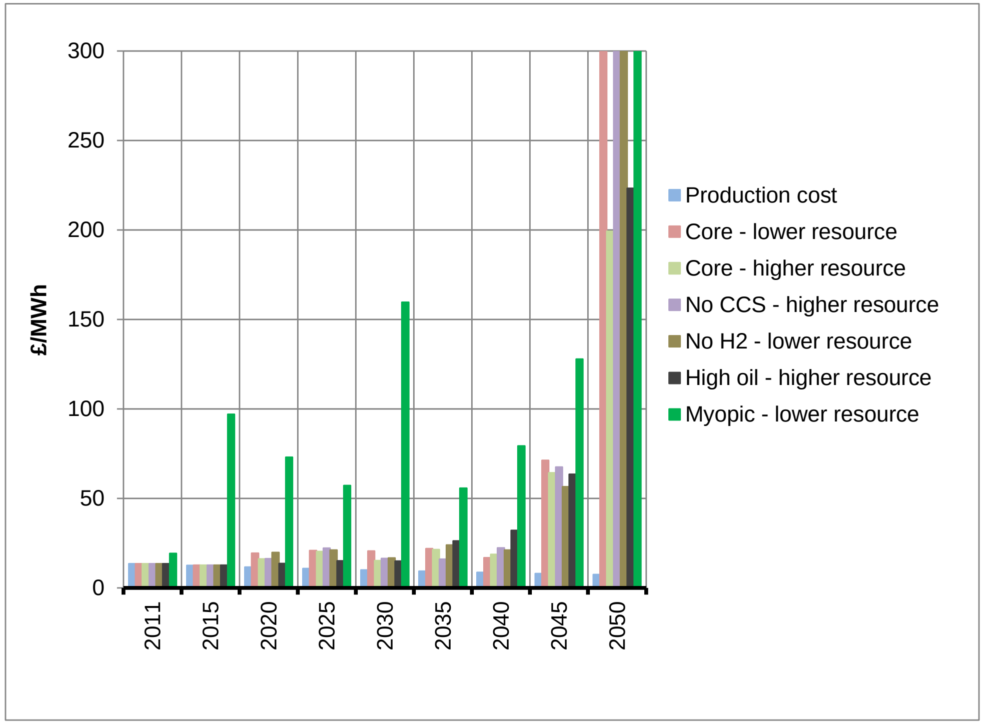
Shadow prices represent the marginal cost to the energy system of meeting a constraint (such as the RED target) when the constraint is binding. By 2050, the emissions target is sufficiently tight in all scenarios to generate Shadow Prices (SPs) of over £500/tCO_2 (in runs with a shortfall to the emissions target, the SP is effectively unlimited). The SP is lower with more bioresource available. The RED SP represents the incremental cost of meeting the target above and beyond all other costs (ie meeting energy service demands and the emission target). It is lower under the myopic scenario in 2020 as AUB makes decisions which appear cheaper in the first two individual periods (2011/15), but which do not position the system to meet its targets most cost-effectively in 2020. As the overall system is more expensive the incremental cost of meeting the RED alone is then lower.

Figure 7 RED (2020) and CO2 (2050) shadow prices (All scenarios)



The effect of the tight carbon constraint is further illustrated by Figure 8, showing the SPs versus production cost for UK energy crops (in this case the SP represents the effective overall 'value' to the energy system of one additional unit of energy crop). The SP rapidly exceeds the production cost, and dramatically so in the final period, primarily due to the value of energy crops in reducing emissions. In other words, the marginal cost of reducing emissions in the system (due to the need to use more expensive alternative abatement options) increases rapidly and this then becomes the key driver of the overall shadow price for the energy crops. Clearly, such high shadow prices would in reality indicate a strong willingness to pay to secure more bioenergy resource, whereas in each scenario they are subject to an absolute constraint on availability.

Figure 8 UK Energy crops shadow prices vs production costs (All scenarios)



5.3 Overview of key technology build constraints

There are a number of key build constraints that impact on the scenario results in the near and medium term. These comprise both individual and group constraints for maximum build quantities and build rates.

Near term build constraints

To 2020 a number of constraints on the maximum installed capacity of groups of similar technologies are binding (as outlined in Table 12), which reduce the freedom to meet the RED target. Most of the AD technologies are also being constrained by build rate constraints in the periods up to 2020.

Table 12 Key binding maximum group build quantity constraints in 2020

	Core - Lower resource	Core - Higher resource	No CCS - Higher resource	No H2 - Lower resource	High oil - Higher resource	Myopic - Lower resource
Waste Heat Group	100%	100%	100%	100%	100%	100%
2G biofuel capacity	100%	100%	100%	100%	100%	100%
Residential ASHP	100%	100%	100%	100%	100%	100%
Residential GSHP	68%	63%	56%	70%	64%	100%
Non-domestic ASHP	45%	33%	31%	45%	47%	100%
Non-domestic GSHP	100%	100%	100%	100%	100%	100%
Industry ASHP	100%	100%	100%	100%	100%	100%
Industry GSHP	100%	100%	100%	100%	100%	100%
Biomass boiler - Non-domes	100%	100%	100%	100%	100%	100%
Biomass boiler - Domestic	100%	100%	100%	100%	100%	100%
Biomass boiler - Industry	100%	100%	100%	100%	100%	100%
Biomass DH - Domestic	7%	7%	7%	7%	7%	100%
Advanced biodiesel import	100%	100%	100%	100%	100%	100%
AD CHP	100%	97%	96%	96%	97%	100%
AD heat	100%	50%	57%	100%	57%	50%
AD electricity	50%	50%	100%	50%	50%	50%

Note: *The table shows the percentage of technology capacity compared to build quantity constraint limit – ie 100% = the build constraint has been reached*

Longer term constraints

New nuclear build is currently capped at 39 GW to 2050 and this is reached in all scenarios. Individual technology quantity constraints (reflecting suitability) are also reached for heat pumps in a small number of heating segments.

Key binding build rate constraints are a group rate for all CCS technologies, and wind. For wind these bind in the last few periods of the no-CCS and myopic scenarios, with the offshore wind build rate equivalent to around 4-5GW/year from 2030 onwards.

The CCS build rate constraint rises from 0.6 GW/year in 2020 to 2 GW/year in 2035 and 3 GW/year from 2040 onwards. This constraint is binding in all scenarios[23] with the exception of the no-H_2 scenario.

In the current dataset there is a strong preference to combine CCS with H_2 production (primarily via bio-gasification to generate negative emissions) for both power generation and transport, but without this interaction the build rate limit is not reached. There is also a group H_2 production build constraint, but this is not reached, even in the no-CCS scenario, highlighting the interaction between the two technologies.

It should be noted that a number of other potential pathways for bioenergy+CCS were not included in the current scenarios, such as biomethane to grid + CCS, due to data uncertainties. Including these could then have an impact on the amount of bioenergy used in CCS-based H_2 production. More generally, it is important to note uncertainties around CCS feasibility and costs which could affect where CCS is deployed in practice.

[23] Ignoring the no-CCS scenario

5.4 System costs

The model's objective is to minimise the total discounted energy system costs over the period to 2050. It is, however, important to note that these costs only cover those explicitly modelled and therefore exclude others such as the cost of energy efficiency measures or industrial CCS.

Figure 9 provides an illustrative overview of the difference in the total present value (PV) of the energy system costs (at a 3.5% discount rate) from 2011 to 2050, against a scenario which is the same as the 'core lower resource scenario' but without an emissions constraint.

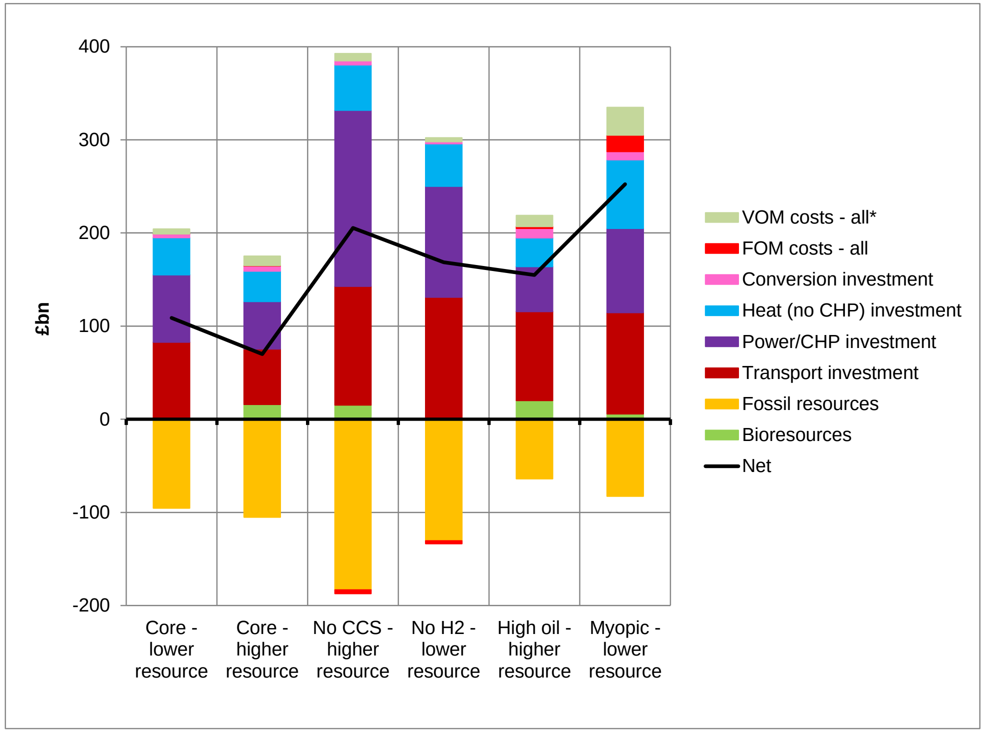
The total costs under the core lower and higher resource scenarios are around 2-3% higher, respectively, compared to the unconstrained case. These broadly trade off lower fossil fuel costs against higher technology investment costs across transport, power and heat.

A comparison of the six main scenarios illustrates that whilst availability of bioenergy does play a role in terms of overall costs, with these being lower under the higher resource scenario, it is the availability of CCS / H_2 technology options and the interaction with bioenergy that is the more important factor.

The no-CCS and no-H_2 scenarios have significantly higher overall costs, particularly in power generation. Note that in these scenarios the model cannot meet the emissions target without resorting to the backstop option, the implied cost of which is not included in these graphs. Therefore meeting the target through options such as additional nuclear (which is already used to the maximum allowed in the scenario) would lead to higher overall costs for these scenarios than are actually shown.

As expected, the myopic scenario is considerably more costly than the equivalent core resource scenario and in reality costs could be even higher due to more abrupt transitions in infrastructure, which are not explicitly modelled. This emphasises the importance of cost effective options which help maintain flexibility in the system such as retrofitting or low carbon energy carriers such as H_2 and biomethane, which can be applied to multiple end-uses.

Figure 9 Δ PV of total system costs from 2011-2050 (to comparable but unconstrained GHG emission scenario)



Note: Technology costs covered include capital, fixed and variable operating costs for all technologies listed in section 3.7. Note that VOM costs include electricity network costs. Also note that for overseas bioenergy conversion technologies (eg Imported biodiesel BTL) their costs have been set to the same as the UK equivalent technology. Hence the infrastructure component of the import cost is the same as domestic production, but overall cost will vary due to differences in eg transport costs/lifecycle emissions.

6 Results: summary of bioenergy by end-use

6.1 Bioenergy to end-use on primary energy basis (1)

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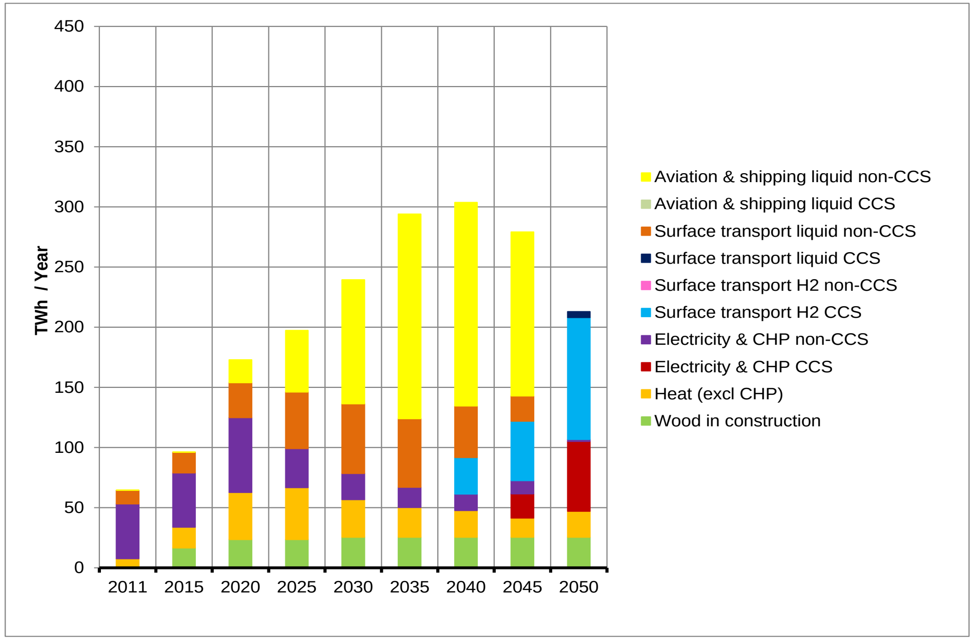
The following charts provide an overview of the end-uses of bioenergy across the energy system on a primary energy basis. Note that CCS means application either at the point of end-use or in production of the intermediate carrier (eg bioliquid). *It is also important to reiterate areas of general uncertainty discussed in section 3.10.*

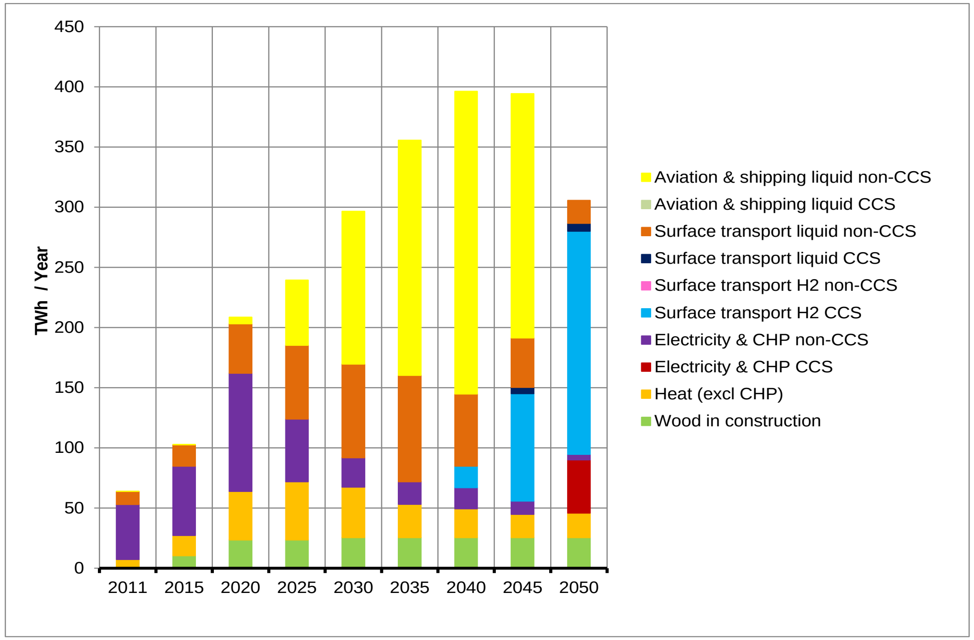
In both the core lower and higher bioresource scenarios the results show a number of key trends in bioenergy use, including early and ongoing non-energy use in construction (this is constrained in 2011). The modelling also shows a limited and somewhat transitional role for non-CCS liquid transport biofuels (extended slightly with higher bioresource availability) and non-CCS electricity. In transport, the use of liquid biofuels is driven initially by the need to meet the RED targets and lack of alternative abatement options, but these are eventually superseded by ultra-low emission vehicles (e.g. bioH_2 and electric vehicles).

Figure 10 Primary bioenergy use (Core lower resource scenario)



The model also finds a significant role for aviation and shipping non-CCS bioliquids, but these disappear in the last period as the tightening emission target diverts bioenergy towards CCS uses to produce negative emissions focused on H_2 for transport/power (it is important to note the *caveats* around the speed of such transitions and uncertainty around CCS feasibility/costs which may affect where it is deployed). There is also a small but consistent role in heat. In the near term this is predominantly for industry and the domestic sector, with the former transitioning out, before returning in later periods to be the dominant heat use. There is a shift from lower temperature/space heat to higher value high temperature heat (with fewer alternatives) as the GHG constraint tightens. With greater bioresources the results show more: near term use of bioenergy in non-CCS electricity, medium-term use in non-surface transport and late-stage use H_2 production, as well as some continued use for road transport (including CCS).

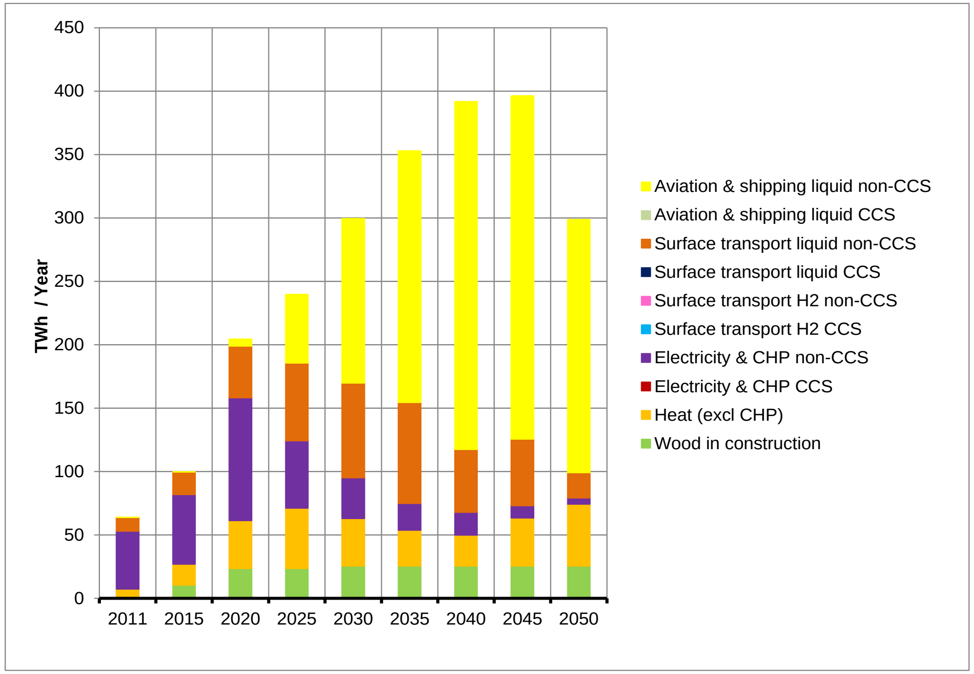
Figure 11 Primary bioenergy use (Core higher resource scenario)



6.2 Bioenergy to end-use on primary energy basis (2)

Without the availability of CCS technologies the model selects a near term pattern for bioenergy use similar to the equivalent core resource scenario. Over the longer term there is greater and continued use of non-CCS liquid biofuels all the way to 2050. There is also greater use in industrial heating, focused predominantly on process heat.

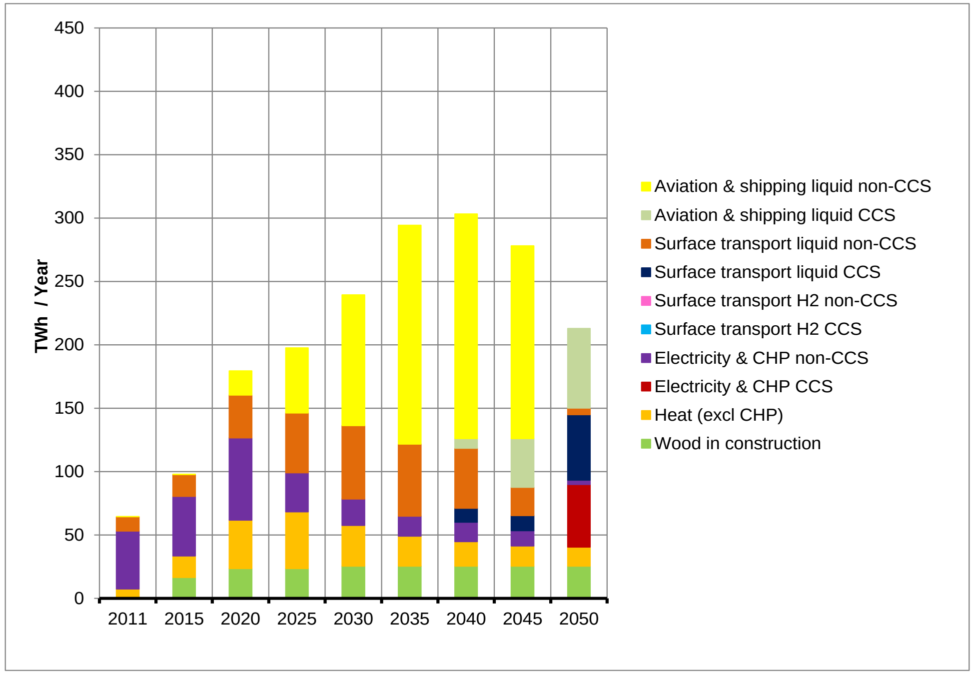
Figure 12 Primary bioenergy use (No CCS - higher resource scenario)



Without CCS to generate negative emissions, the model uses bioenergy to displace fossil fuels in sectors with limited alternatives (only fuel switching is modelled explicitly for maritime and aviation with efficiency improvements implicit in the energy service demands).

Without H_2 technologies a similar situation applies. However, in this scenario, the key late-stage bioenergy pathway – of CCS H_2 production to use in transport and electricity – is unavailable. The near term pathway is similar to the equivalent core resource scenario, but at the point of the original transition to H_2, bioenergy is now shifted towards transport liquid biofuels via CCS production.

Figure 13 Primary bioenergy use (No H_2 - lower resource scenario)



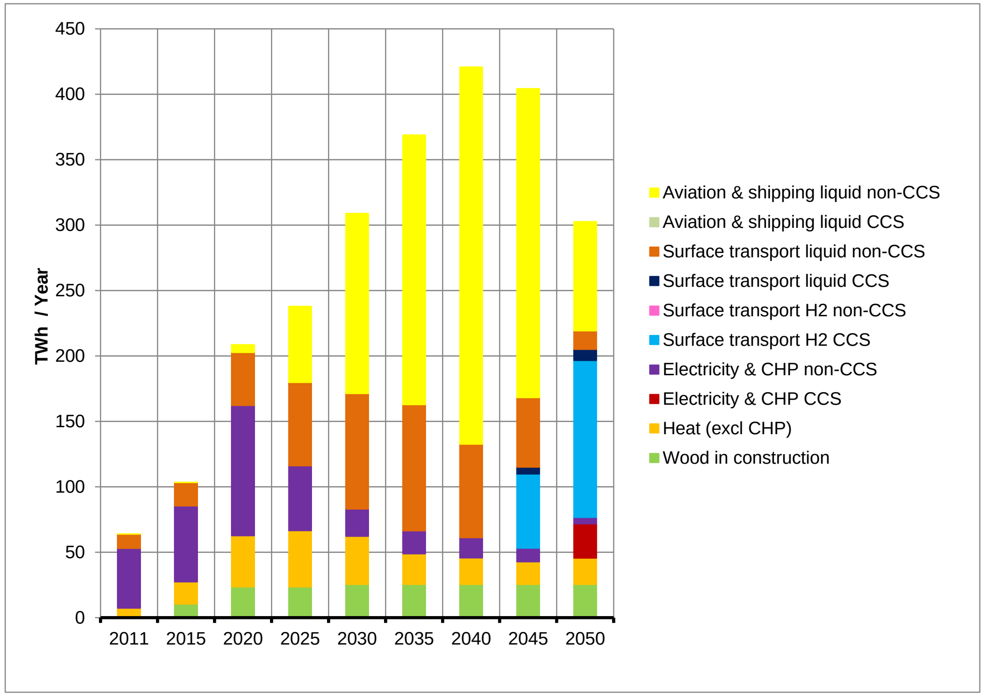
There is also a shift to the use of bioenergy in electricity with CCS in 2050 (from new enhanced co-firing of coal + CCS plant – see section 10.2). Whilst this is the most cost-effective option from the overall system perspective, it must be seen within the context of needing to resort to the expensive backstop "emission credit" option to meet the target. If further deployment of renewables or nuclear (beyond the assumed constraints in the model) was possible, this option would be unlikely to be pursued.

6.3 Bioenergy to end-use on primary energy basis (3)

Under higher oil prices, the key difference to the equivalent core resource scenario is slightly higher medium term use of non-CCS liquid transport biofuels, given the higher cost of conventional alternatives.

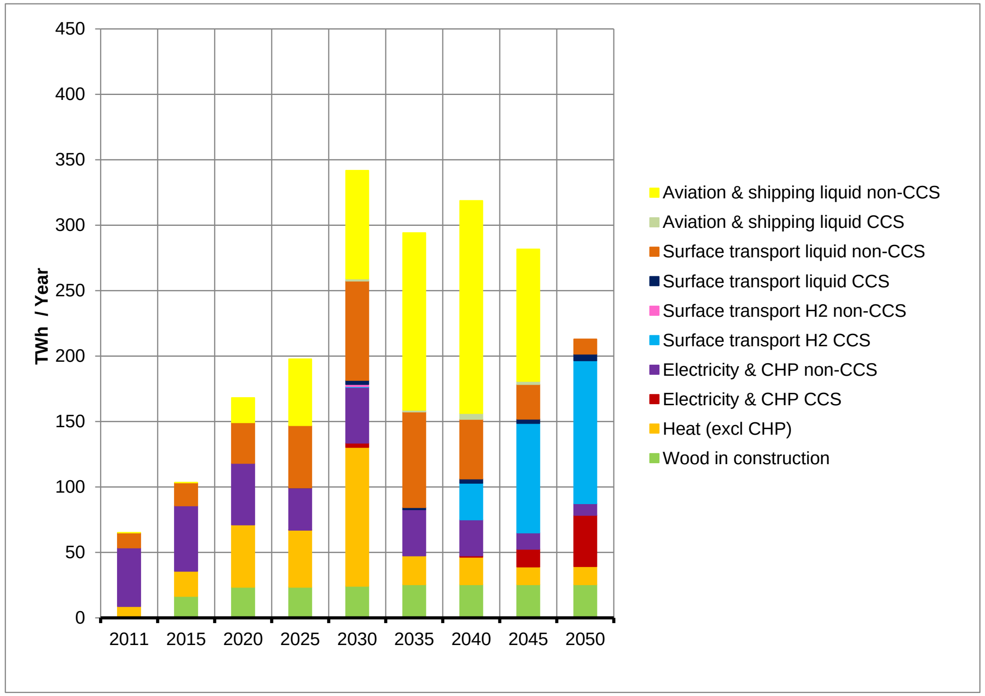
Over the longer term the focus shifts to greater and continued use of non-CCS liquid biofuels at the expense of some surface transport H_2 (+ CCS). The higher cost of alternatives means it becomes more valuable to the energy system to continue to substitute for, at least some, portion of these fuels with bioenergy, when there is greater overall bioresource availability.

Figure 14 Primary bioenergy use (High oil - higher resource scenario)



Without perfect foresight, there are many similarities with the start and end points of the equivalent core resource scenario, given the importance of the RED and GHG targets in driving the system solution[24], for example, late period use in CCS H_2 production. However, the myopia leads to nearer term choices which have consequences for infrastructure lock-in and sunk costs. Heat use is pursued more in the near to medium term, before the model moves back to pathways seen in the core scenarios. This has consequences, such as not then being in a position to use the retrofit of existing coal as a more cost-effective option to meet the RED.

Figure 15 Primary bioenergy use (Myopic – lower resource scenario)



[24] The myopic mode sees a target in each period (eg specified as a maximum emissions pathway over time) but it does not understand the full impact of future period targets until it reaches them.

6.4 Contribution to RED target in 2020

The various RED accounting rules[11] for the contribution of renewables to the RED targets are included explicitly in the optimisation.

As the model is constrained to meet the RED transport sub-target, bioenergy use in transport is relatively consistent across the scenarios. The only alternative to bioenergy is the use of renewable electricity in road or rail, which only makes a modest contribution by 2020. The model predicts that significant amounts of advanced biofuels will be deployed to reach the target in 2020 cost effectively. The maximum build limit is applied across all of the scenarios in this year and it is highly uncertain if this is achievable with unproven technologies.

Similarly, the use for heat is fairly consistent across the scenarios with the exception of the myopic scenario. Without foresight this scenario sees non-industrial heat as a more cost-effective option in the near-term than other uses of bioenergy, even if this not the case over the entire pathway.

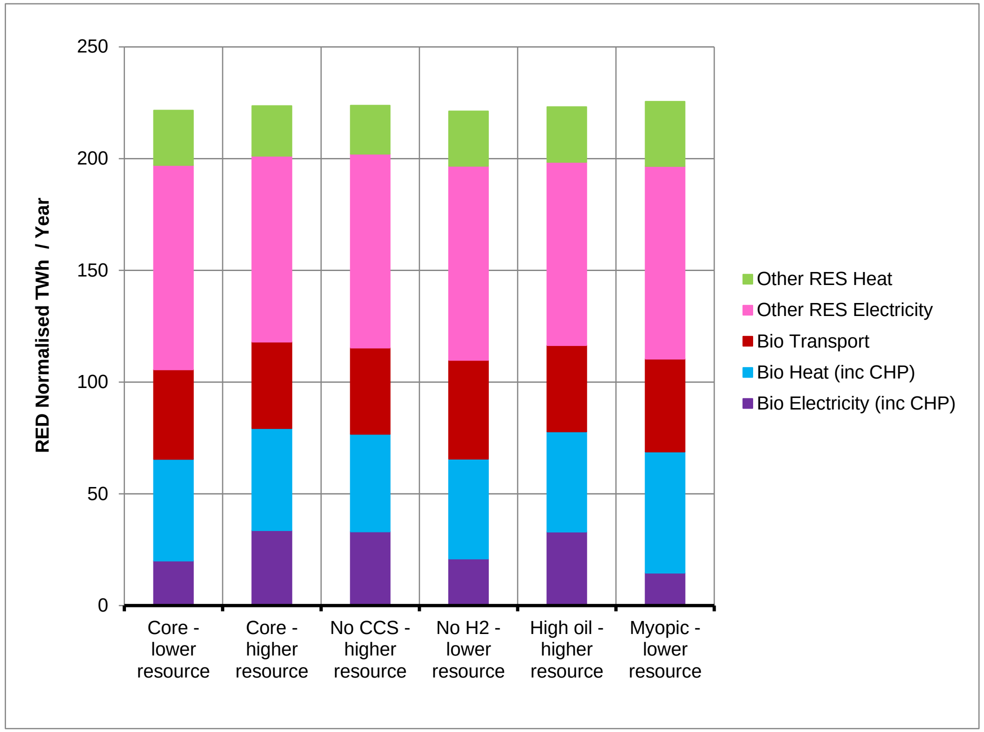
Bioenergy in electricity use varies more considerably across the scenarios. In all cases (see sections 10.1 to 10.3 for further details) there is a core component of electricity production from wastes (landfill and sewage gas and energy from waste). There is also some co-firing, direct AD electricity production and either biomethane in CHP or direct use of bioenergy via syngas CHP.

The key variant is bioenergy from retrofitting of biomass in coal plant. All scenarios (excluding myopic) show a degree of retrofitting, with significant generation in the higher resource-based resource scenarios where overall availability is higher (accounting for half of all contribution to electricity from bioenergy). Retrofitted capacity is in the order of 0.5-2.5 GW (net output basis) across the scenarios. In the myopic scenario the additional investment in renewable heating (bio-based and other) in earlier periods means that it is no longer necessary to apply retrofitting in 2020, and doing so would only lead to higher overall system costs.

Overall, bioenergy could account for around 50% of the RED target under these scenarios. However, it is important to note the significant uncertainty in the near term around factors such as advanced biofuels and the existing build rate constraint in the scenarios on deployment of this capability.

The results also serve to illustrate the potential cost optimal role of bioenergy in 2020 and so do not reflect a near term projection which, for example, accounts for the current incentive schemes and the impact on investor behaviour, which will be critical in determining actual deployment.

Figure 16 Normalised contribution to RED in 2020 (All scenarios)

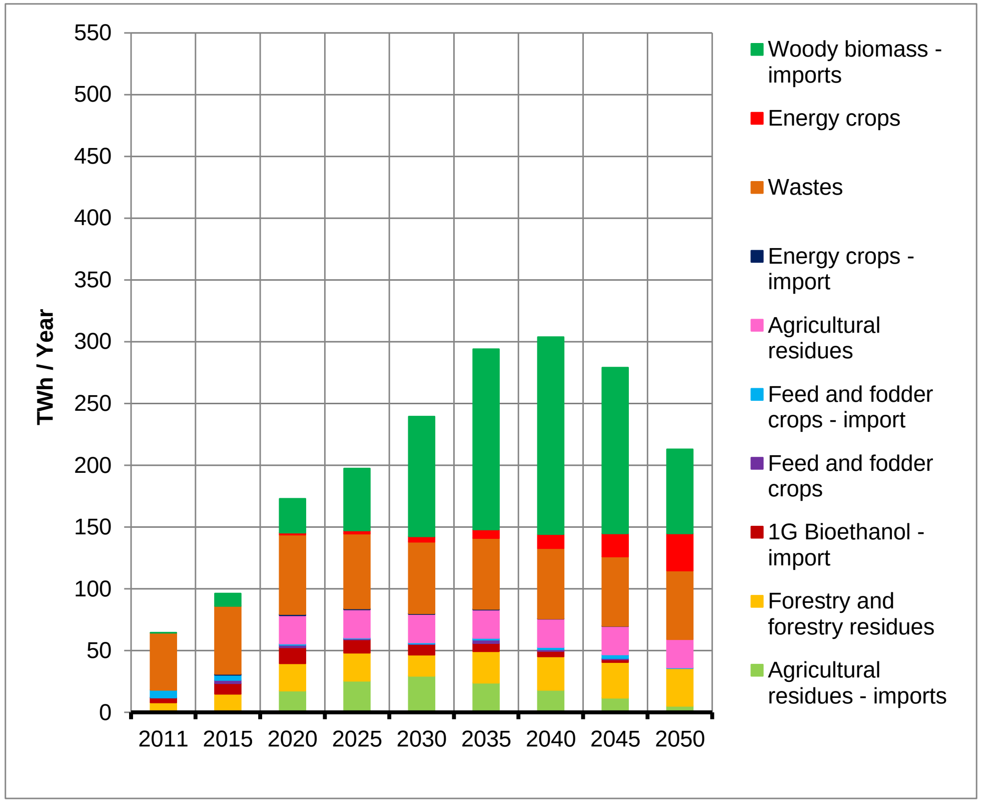


7 Results: detailed bioenergy use

7.1 Bioresource used / unused (1)

The assumed decline in the overall level of imported resource accessible to the UK (see Figure 3) from the mid-2030s onwards leads to effectively all available bioenergy resources (domestic and imports) being used by 2050 in the lower resource scenario.

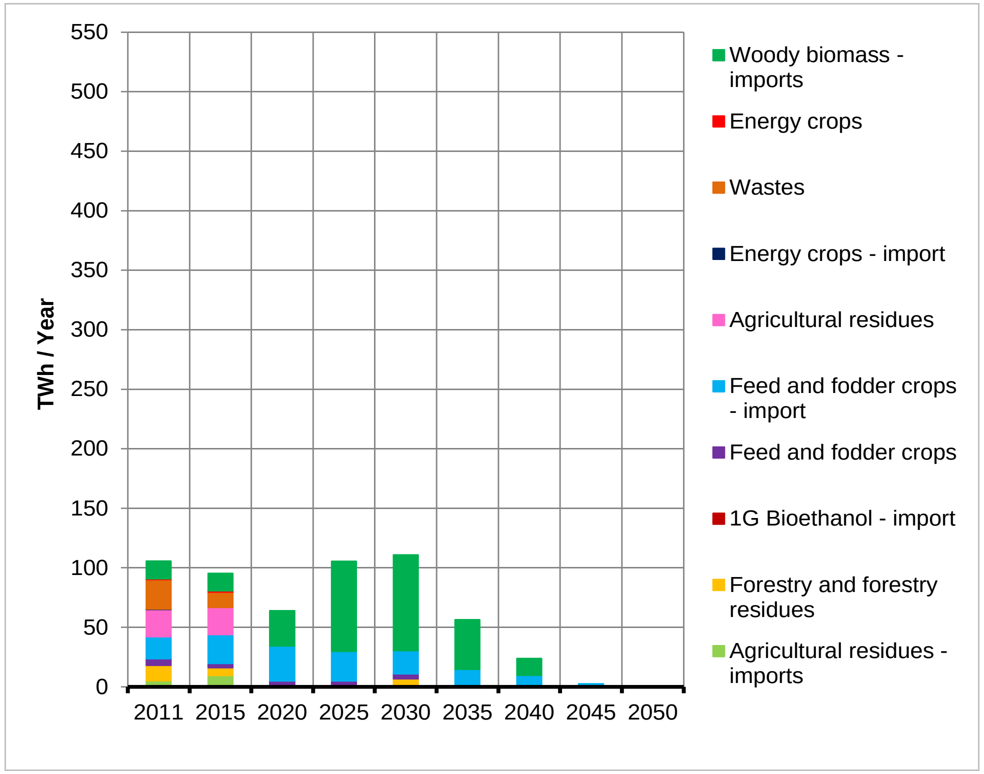
Figure 17 Bioresource used (Core - lower resource scenario)



The no-H_2 scenario (with lower resources) shows very similar results for both bioresources used and unused so it is not shown in subsequent graphs. It is also similar in the myopic scenario apart from a jump in woody biomass imports in 2030, as part of the temporary transition to increased use in heating.

UK resources (with the exception of some feed and fodder starch/sugar crops[25]) are effectively fully utilised from 2020 onwards and the results show a substantial jump in overall bioenergy use in 2020 to meet the RED target.

Figure 18 Bioresource unused (Core - lower resource scenario)



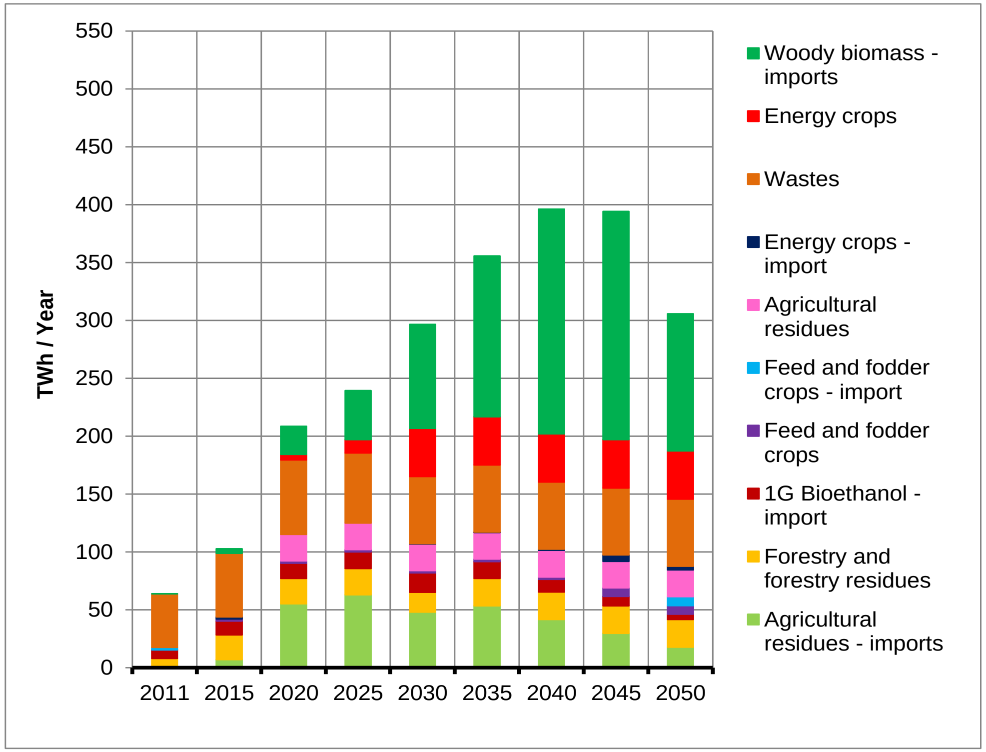
The main underused resources throughout the mid-part of the period are imports, given the generally high cost of transport compared to the domestic UK equivalents.

[25] Nb domestic bioethanol production is included in feed and fodder crops

7.2 Bioresource used / unused (2)

With higher overall availability of bioresources under the core higher resource scenario a similar pattern of resource use is seen in the near to medium term, including the jump (albeit higher in absolute terms) in 2020 to meet the RED.

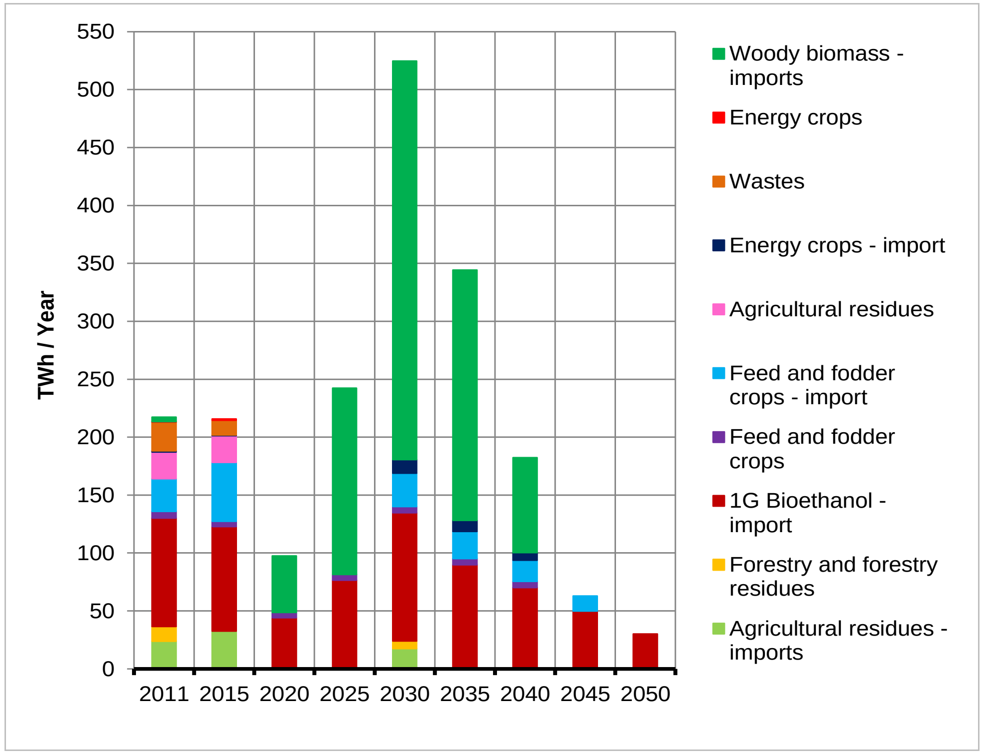
Figure 19 Bioresource used (Core - higher resource scenario)



The no-CCS scenario (with higher resource availability) shows very similar results for both bioresources used and unused, so this is not shown in subsequent graphs.

Whilst assumed overall import availability declines towards 2050, there is a spike in availability of imports in the medium term compared to the lower resource scenarios, which the model chooses not to use at this point (given the overall level of the emissions constraint and availability of alternative, cheaper abatement options and options used to meet the RED). However, as the emission constraint continues to tighten to 2050, all bioresources are fully utilised with the exception of 1G bioethanol imports (availability by 2050 is zero under the lower resource scenario), due primarily to limitations on the stock of remaining petrol vehicles in which it can be used. Further results are available in section 11.

Figure 20 Bioresource unused (Core - higher resource scenario)

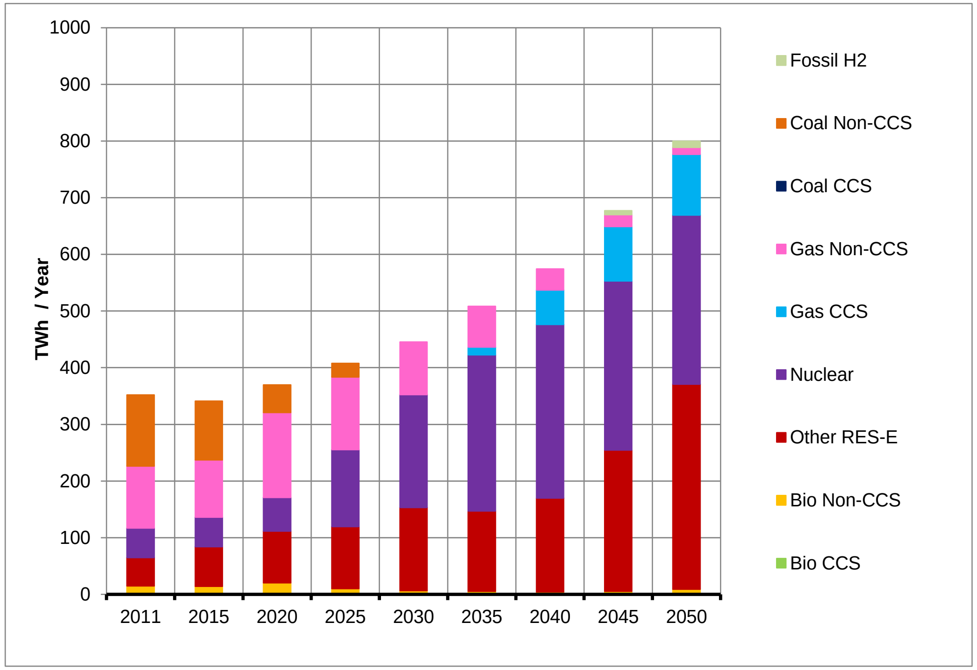


8 Results: role of bioenergy by sector

8.1 Electricity generation summary

A key feature of the modelling results in all scenarios is the rise in electrification of heating and transport; electricity demand effectively doubles from 2011 levels to 2050. After the near term contribution of bio-electricity to the RED, the model chooses only a minor long-term role, driven to a large extent by the availability of low carbon alternatives in this sector. The pattern over time in Figure 21 is similar across the other scenarios and hence it is the wider electricity system changes that are more pronounced, as summarised for 2050 in Figure 22 (further results are available in section 10).

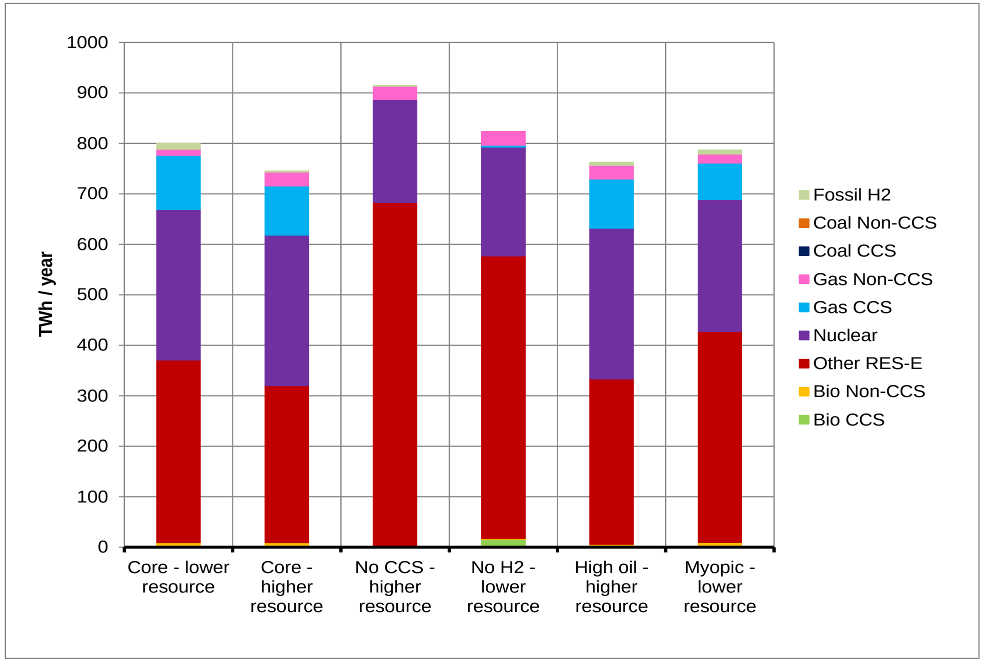
Figure 21 Electricity generation (Core - lower resource scenario)



The role for bio-electricity (as shown in sections 10.1 to 10.3) is comprised in the near term of declining production from landfill gas and a transitional role in co-firing and retrofitting of the existing coal stock. There is also a near-medium term role for small scale dedicated plant (eg AD or sewage gas) as well as CHP use either from direct biomass sources or indirectly via biomethane from AD.

By 2050, the role of bioenergy has generally been confined to H_2 turbines (with the H_2 produced via CCS routes[26]) producing more valuable - from the overall system perspective - peak electricity. The exceptions are the no CCS scenario, where a very small amount of bioenergy in electricity is confined to biomethane in CCGT for peak electricity, and the no-H_2 scenario where the difficulty in meeting the 2050 target leads to the introduction of coal + CCS running solely on torrefied biomass (biocoal) to generate negative emissions (and shown under bio CCS rather than coal CCS). However, in both scenarios the model struggles to meet the target and so is using all available abatement options, regardless of cost (subject to overarching build and other constraints on alternatives such as nuclear).

Figure 22 Electricity generation 2050 (All scenarios)



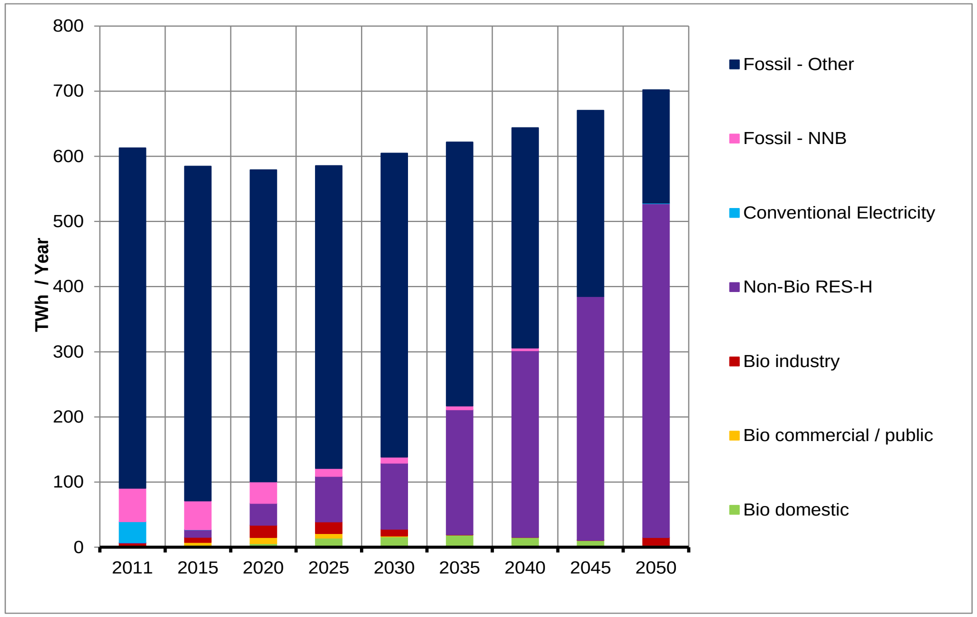
[26] Note $BioH_2$ with CCS in power generation is effectively pre-combustion (biomass) CCS.

8.2 Heat output summary

The results for bioenergy in heating also show a transitional near to medium term role in the domestic and non-domestic building sectors. Over the longer-term its use is restricted due to a lack of CCS options with which it can be combined. Industrial use in 2050 is focused primarily on higher temperature process heating, which is a cost-effective option for emissions reduction, given a more limited set of alternative abatement options (see sections 10.4 to 10.7 for a breakdown by technology). In the nearer term the main driver is the direct use of woody biomass for low temperature industrial process heat to help meet the RED.

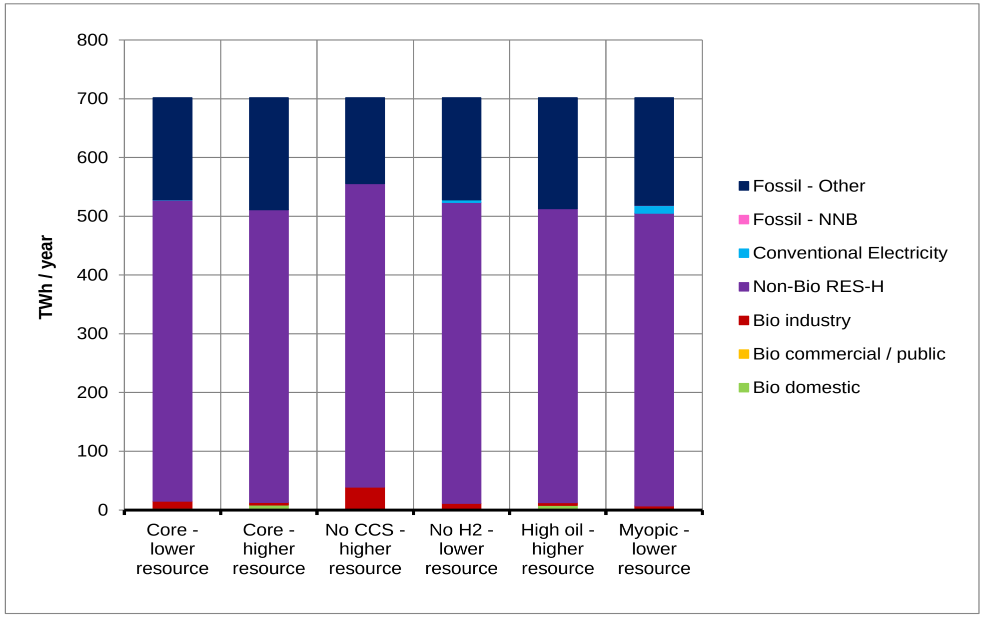
Smaller scale CCS options may become available in future, but these have been excluded in the scenarios (eg for CHP or gasification to produce biomethane which could then indirectly be used for heating) due to data uncertainty.

Figure 23 Heat output (Core - lower resource scenario)



Under the core higher resource scenario, some use in the domestic sector is maintained to 2050. This is primarily via district heating networks (although this is an area of particular data uncertainty), with the waste heat provided from AD plants as this uses bioresources with limited CCS pathway options (the AD use is split evenly between heat and grid biomethane injection – see section 9.4). In practice the heat could be used for a range of locally available demands and not just for households.

Figure 24 Heat output 2050 (All scenarios)

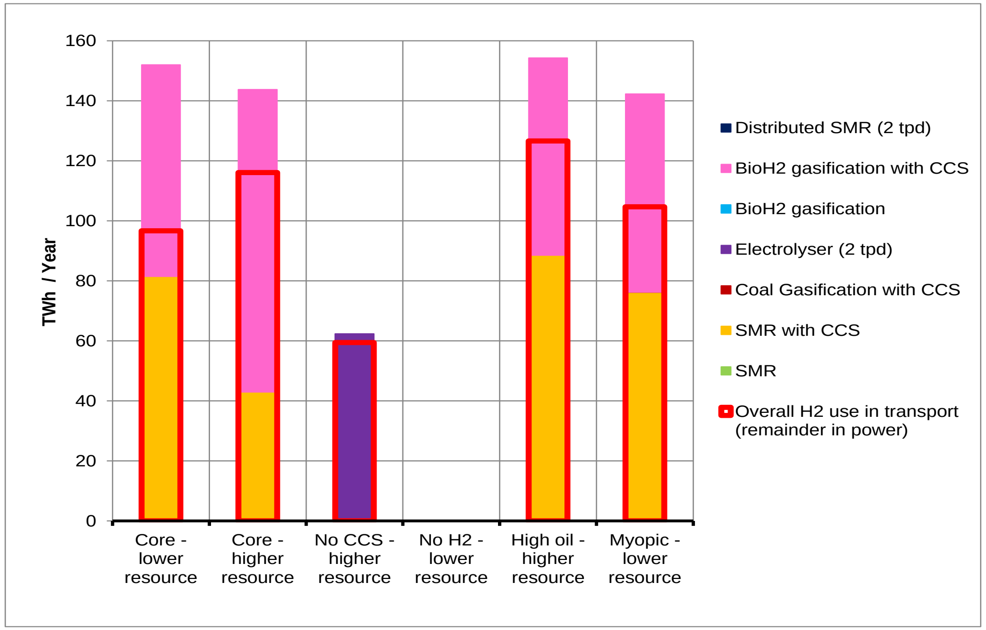


Without CCS options, the model diverts significantly more bioenergy to heating by 2050, and in this case is focused exclusively on industrial use, compared to the higher core resource scenario. To the extent that medium and smaller scale CCS options are likely to be focused in industry, this would reinforce the preference for use of bioenergy in process heat, compared to space heating, particularly given the potential for heat pumps which form the majority of non-bio renewable heat by 2050. Further results are available in section 10.

8.3 Hydrogen (H_2)

H_2 plays a key late stage role in most of the scenarios, primarily for transport (along with use in H_2 turbine plant for electricity production) and highlights the extensive use of bioenergy with CCS in H_2 production in the core scenarios; more so with higher bioenergy resource availability. The majority of H_2 production is from gasification of bioresources with CCS to generate negative emissions as well as SMR.

Figure 25 H_2 production (All scenarios 2050)



Under the high oil price case more H_2 is produced in the model overall, with greater use in transport due to the fossil fuel price. But more H_2 is produced from SMR with CCS and less from bioenergy as the model diverts this (primarily in terms of imported bioenergy) to liquid transport fuel production, which is now more cost-effective overall. Under the no CCS case some H_2 is still produced, but without the ability to produce low or negative emissions in production there is a limited switch to electrolysis.

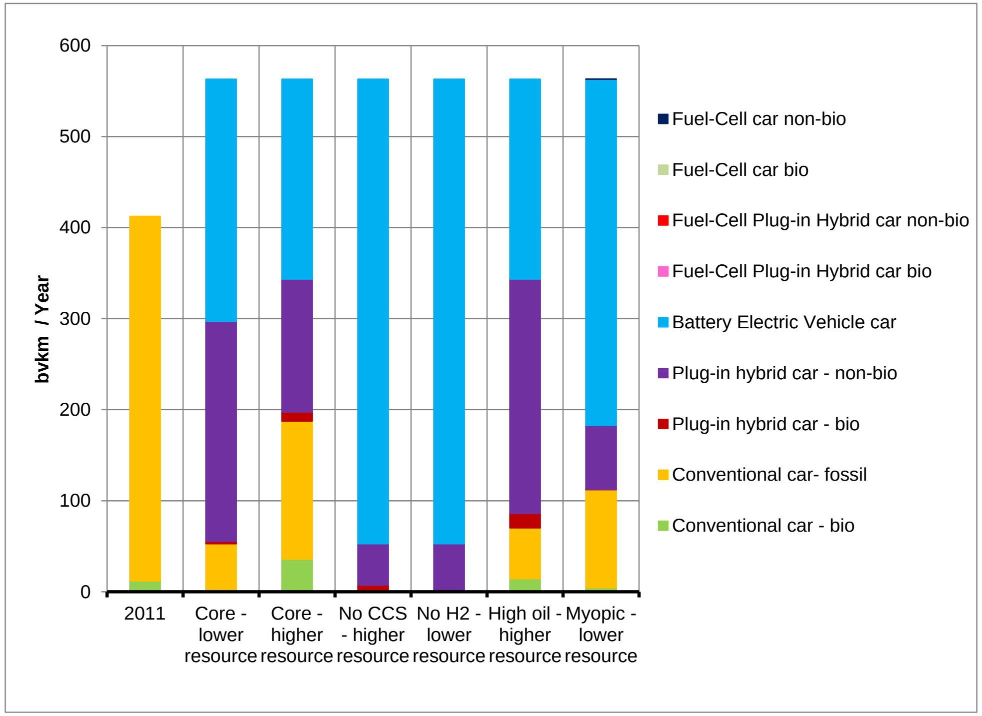
However, it is important to note the uncertainties around large-scale production and use of H_2. For example, as illustrated in section 6.2, without H_2 as an option more bioenergy is shifted towards liquid biofuel production with CCS.

8.4 Transport efficiency

Transport energy service demands (ie vehicle km), particularly for passenger car transport, are assumed to grow between now and 2050. However, the end-use efficiencies of different vehicle types (eg electrical versus ICE) are substantially different, and hence it is important to understand the shift in delivery of service demands by technology and fuel type, before examining the split of energy inputs to transport.

This is shown for car vehicle-kms in Figure 26, which highlights a significant expansion of electric vehicles, which (along with general improvements in new vehicle efficiency) is a key determinant in the overall drop in final energy consumption in the transport sector shown in section 8.5.

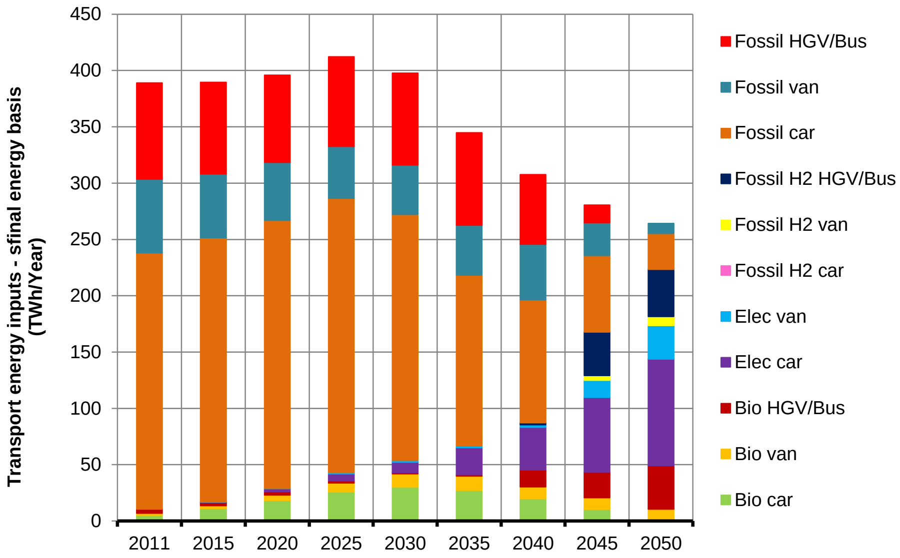
Figure 26 Output of cars by type (2011 and all scenarios 2050)



8.5 Road transport input summary

Under the core lower resource scenario the use of bioenergy in transport shows two main phases. Over the near to medium term the model chooses an increasing amount of liquid biofuel for use in road transport. This is driven primarily by the need to meet the 2020 RED targets. Bioliquid use does continue to rise after 2020 as the carbon constraint is still relatively loose, bioresource availability is increasing (before declining again from the late 2030s onwards) and more cost-effective abatement alternatives in transport (such as electric and H_2 vehicles) do not tend to become available until the middle of the period onwards.

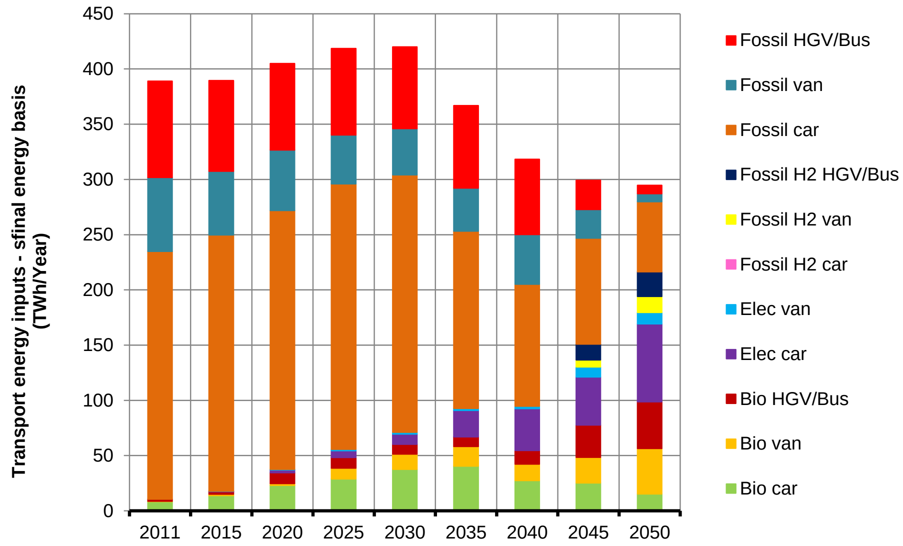
Figure 27 Road transport input (Core - lower resource scenario)



Note Charts include bioH_2 in the 'bio' totals.

As the emissions constraint tightens, there is a transition away from liquid biofuels towards bioH_2 in heavy vehicles (with production taking advantage of CCS via gasification and producing negative emissions). Without widespread H_2 use (ie in the no-CCS scenario) model still uses bioliquid in more niche transport segments, such as HGVs, where electrification is not suitable.

Figure 28 Road transport input (Core - higher resource scenario)



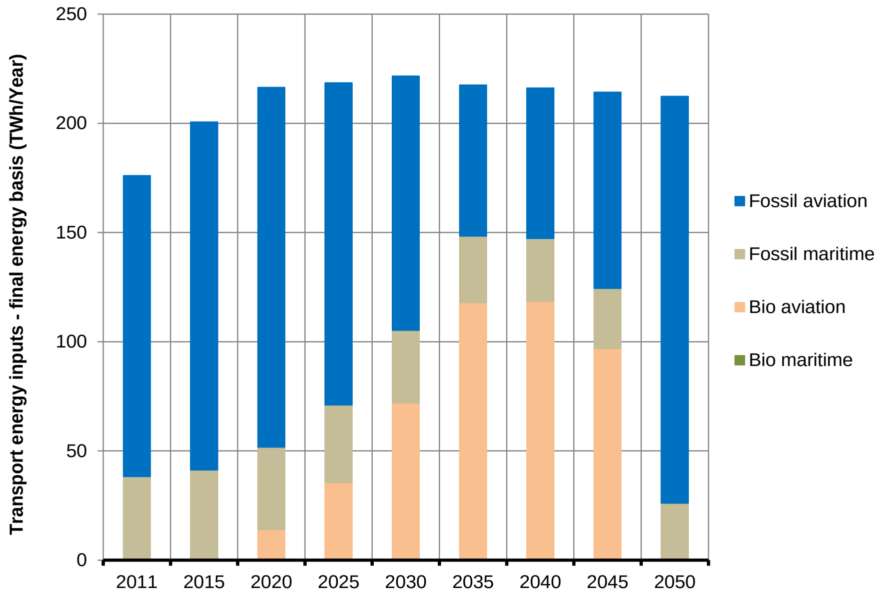
The core higher resource scenario shows a similar pattern of bioenergy use but, with higher overall resource availability, by 2050 there is around twice as much bioH_2. There is also more overall bioliquid fuel use in road transport including use in light vehicles in 2050, but the overall pattern is still an increase to the 2030s and gradual decline to the end of the period. Higher bioenergy use in road transport under the higher resource scenario comes primarily at the expense of electricity use in light vehicles. Further results are available in section 10.

8.6 Aviation and maritime transport input summary

The only explicit abatement options for aviation and maritime in the model are fuel switching to liquid biofuels away from fossil fuels, due to the uncertainty around alternative abatement options (with efficiency improvements implicit in the energy service demands). *Hence the distinction between maritime/aviation is very small and the results should be interpreted more in terms of the balance of fossil versus bioenergy in non-road transport as a whole.*

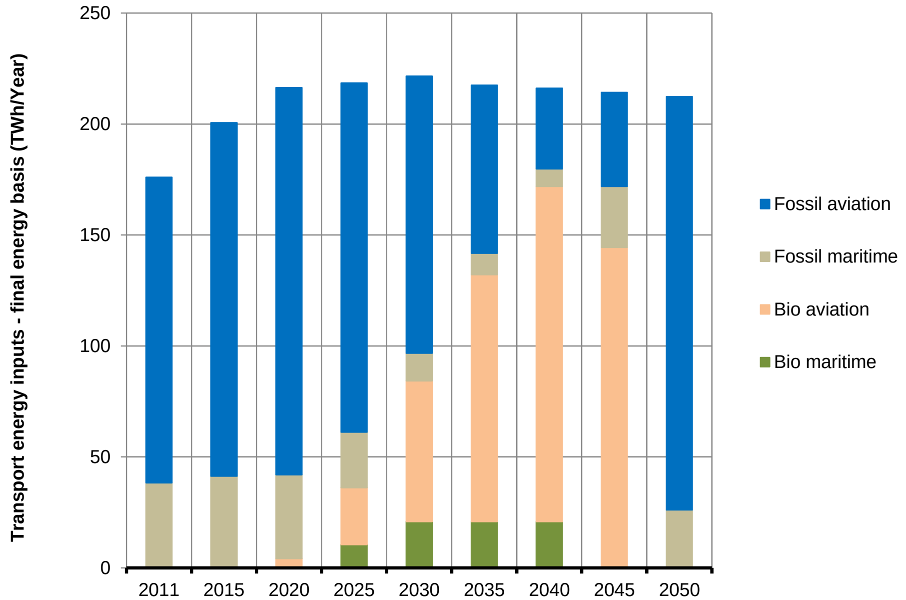
Under the core lower resource scenario the results show a key intermediate role for bioenergy in aviation. This is split between domestic production (see section 11.1) and imported biojetfuel (see section 11.4). In the final period the tightening emission constraint leads to the elimination of biojetfuel as bioenergy resources are transferred to pathways with CCS options (as noted in section 6.1, it is important to note the *caveats* around the speed of such transitions and uncertainty around CCS feasibility/costs which may affect where it is deployed). Although CCS options are available for biojetfuel production they are not deemed as cost effective in the core scenario.

Figure 29 Non-road transport input (Core - lower resource scenario)



The core higher resource scenario again follows a similar pattern, with bioenergy providing a valuable intermediate option in sectors with limited alternative abatement options. However, with higher overall resource availability there is now also a transitional role for domestically produced bio oil for maritime uses.

Figure 30 Non-road transport input (Core - higher resource scenario)

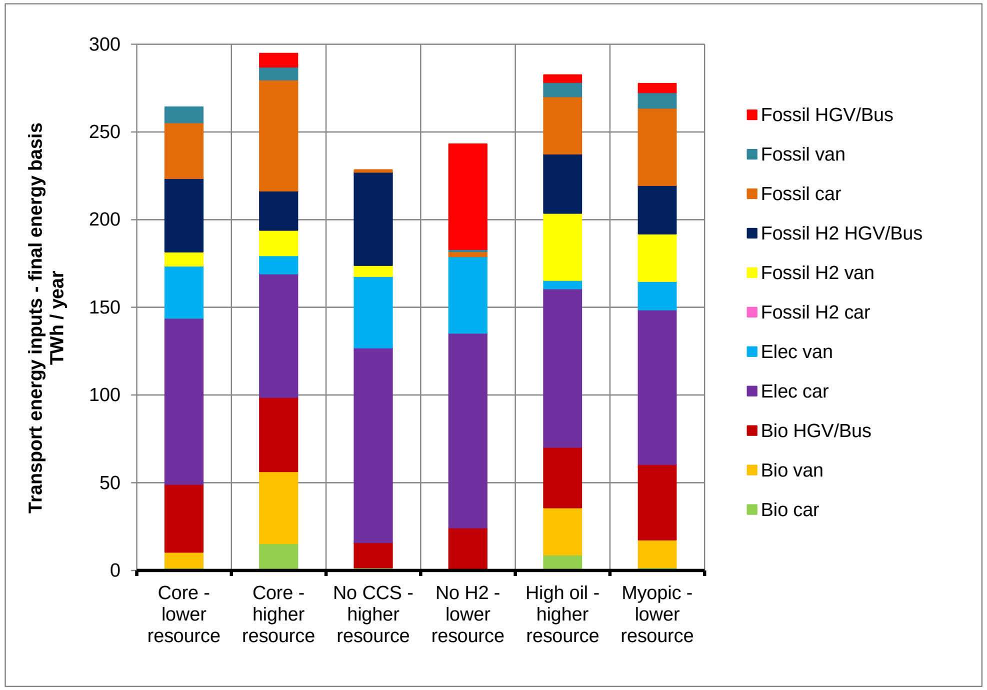


8.7 Transport input summary for 2050

Without the option of CCS the model is forced to deploy more electricity and fossil hydrogen in road transport to try to meet the emissions target in 2050, hitting its build rate limits for dedicated BEVs in the last three periods.

Under the no H_2 scenario transport becomes harder still to decarbonise as it also disallows electrolysis routes to H_2 which are still being used in the no CCS scenario.

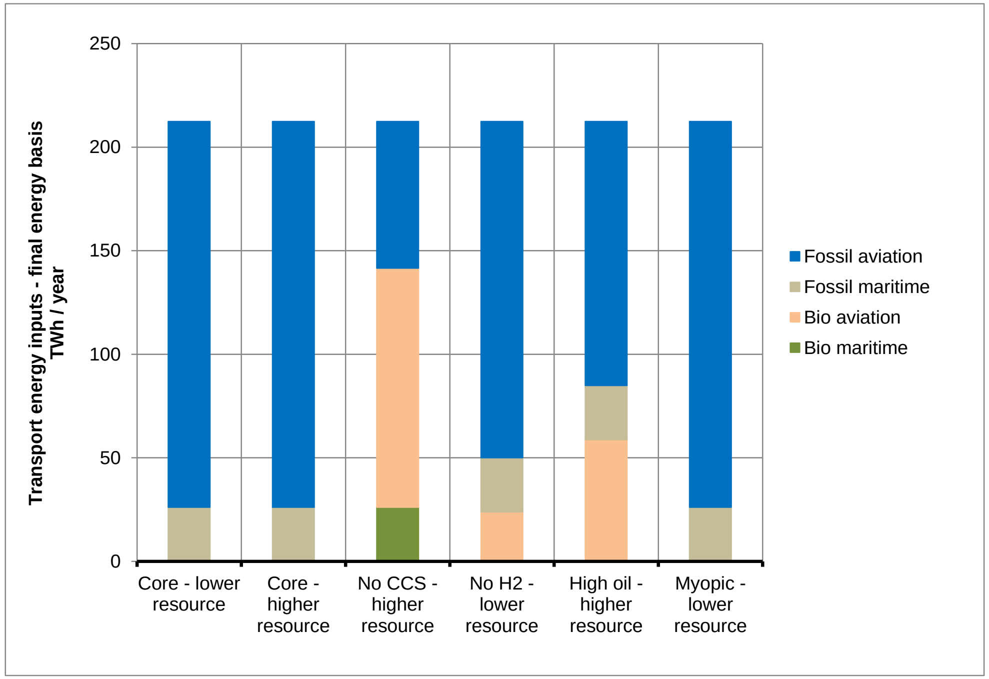
Figure 31 Road transport input (All scenarios 2050)



Under the no CCS scenario (as shown in Figure 32) a significant amount of biofuel is still being used in aviation and maritime by 2050 (this is a mix of imported biojetfuel and domestic production). Without negative emissions from use of bioenergy in CCS, bioenergy use in the model is concentrated on this and other sectors with limited/no alternatives.

Under the high oil scenario the main shift is an increase in electricity for road transport, at the expense of fossil fuels and bioH_2, rather than an increase in bioenergy use, which instead shifts to use in aviation and maritime.

Figure 32 Non-road transport input (All scenarios 2050)



9 Summary and conclusions

9.1 High-level implications for bioenergy use

The main aims of this project have been two-fold: to create a modelling framework that can help to assess the most appropriate uses of bioenergy and to apply this to the best data currently available.

Given the general uncertainties in data, particularly over future costs for more novel technologies, the purpose of the analysis is not to generate specific projections or blueprints for the energy system, but to identify key groups of technology options which are robust to uncertainties and should be developed with a view to meeting the UK's long term emission targets. A key part of this revolves around retaining flexibility in the energy system so that potential lock-in to inappropriate types of infrastructure is minimised, as highlighted by the increased energy system costs and more sudden technology transitions under the, arguably more realistic, situation of myopic (rather than perfect) foresight.

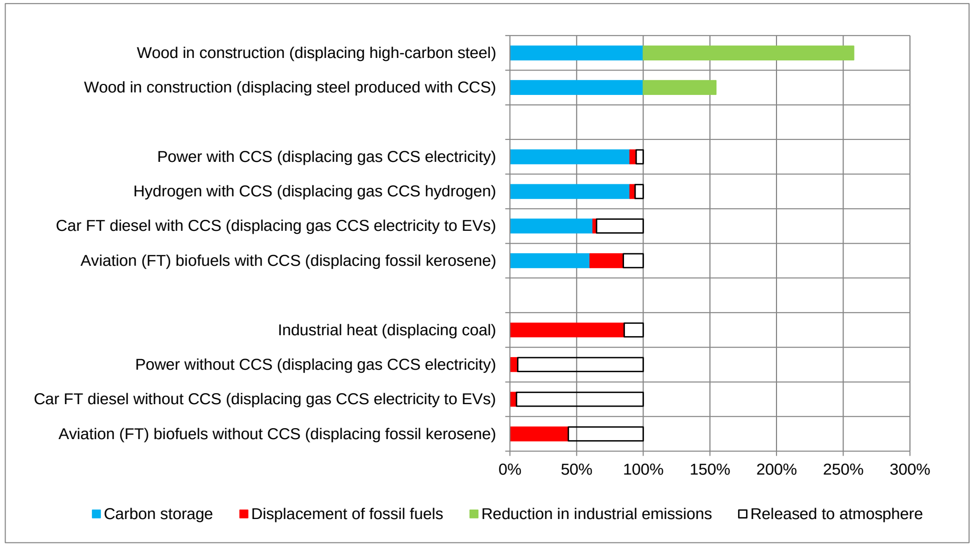
The modelling results indicate that bioenergy will play a critical role in meeting the UK's long-term emission targets and also provide an important contribution to the nearer term RED targets. But, there are clear limitations on the available (sustainable) bioenergy resource.

As a simple illustration, the resource required for bioenergy to meet fully the UK's primary energy demands by 2050 in these scenarios would be in the order of 3000-3500 TWh/year (given different conversion efficiencies across the pathways). Under the scenarios used in this analysis, the UK's indigenous resource is only around 4-5% of this total, with imports increasing this to between 6% and 11%. The availability and cost of imports will be a critical long-term factor.

The modelling also illustrates the challenge in meeting the emissions target by 2050 and the importance of using bioenergy in ways which maximise the benefits of carbon sequestration and/or the displacement of fossil fuels where there are limited alternatives. The scenario analysis shows key options to be the use of bioenergy with CCS (throughout the energy system and as a key enabler of large-scale H_2 production), wood in construction, and bioenergy for industrial process heat. Benefits are illustrated in Figure 33.

This suggests that a key value of CCS may not be to enable continued use of fossil fuels, but to generate negative emission reductions, which help reduce the overall costs of meeting the UK's targets by creating greater headroom for emissions in other sectors of the energy system which are difficult or more expensive to abate.

Figure 33 Illustrative carbon reduction benefits from using a unit of bioenergy in different applications



Notes: CCC calculations; based on solid biomass and do not include cultivation or transportation emissions. CO_2 capture rate for CCS applications assumed to be 90% in electricity and H_2 generation and 80% in biofuel production.

When thinking about appropriate uses of bioenergy, it is critical therefore to consider the implications in worlds both with and without CCS.

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9.2 Appropriate long-term uses

Regardless of CCS availability
Use of biomass feedstocks for wood in construction occurs throughout all of the scenarios, up to its specified maximum potential. Its use avoids emissions from high-carbon products such as steel and cement and acts as a long-term store of carbon (both of which are represented in the model as a negative emissions credit associated with its use), providing additional emission benefits compared to (non-CCS) combustion uses of bioenergy (noting that its ability to act as a long term store of carbon, as opposed to a near term temporary store is critical)[27].

Targeted use of bioenergy in industrial heat seems to be a key no-regret option as it appears in the near-term (driven primarily by the RED) and towards the end of the period (driven by the GHG target) regardless of whether CCS is available. Its use is focused primarily on process heat. This reflects the high value of bioenergy in industrial use given the limited alternatives for decarbonisation. Although not modelled explicitly, the combination of smaller scale CCS with bioenergy for industrial heat also has the potential for generating negative emissions and would likely lead to greater use in industry.

With CCS
The analysis suggests a key longer term role for the use of bioenergy with CCS to generate negative emissions which provide 'headroom' for sectors which are hard to abate (e.g. non-surface transport). In the current scenario results, use of bioenergy with CCS to produce H_2 is favoured, which, in addition to negative emissions, provides a flexible energy carrier that is used both for reducing emissions in transport as well as power generation (in particular providing peak electricity via H_2 turbines).

However, it is important not to be too prescriptive at this stage on the best use of bioenergy with CCS, given that the technology is yet to be demonstrated at the commercial scale and the relative economics of different CCS options are highly uncertain. For example, in the scenario with no H_2, CCS is instead applied to aviation and shipping biofuel production and bioenergy power generation. Whilst we have included a range of possible CCS options in the above scenarios there are number of others which may also be possible and warrant further investigation, including gasification with CCS for biomethane given the significant flexibility that this energy carrier can also provide and smaller scale CCS for heating / CHP applications. In addition, the build rate constraint on CCS is binding in all scenarios and is forcing additional prioritisation of CCS use.

Without CCS
In a world without CCS, use in industrial heat becomes of even more value than in a world with CCS, where it is still a desirable use. In addition, a continued and expanded use in higher value non-surface transport uses (particularly aviation) appears desirable, given the more limited set of alternatives for reducing emissions, compared to road transport where electric and hydrogen vehicles can provide a key alternative. There is also a potentially close link with a significant scale-up of H_2 production and availability of CCS, as without the latter the model cannot significantly reduce emissions of fossil-produced H_2 or generate negative emissions via bioH_2 production with CCS. In the no-CCS scenario the model shifts some production of H_2 to electrolysis routes, but is then faced with indirect constraints on emissions from the electricity sector.

Non-bioenergy alternatives
Given the likely limitations on availability of bioenergy and competing low-carbon alternatives, there are a number of key alternative technologies which are unlikely to be significantly displaced by bioenergy. These include nuclear and wind in power generation, electric heating in buildings and electric/H_2 transport vehicles. In addition, the tightness of the emissions target in 2050 (which the model is unable to meet without resort to an artificial backstop in some scenarios) highlights the importance of delivering the efficiency improvements implicit within the energy demands in the model.

[27] A range of other possibilities for non-energy use was considered by CCC as part of their bioenergy review but these were not included in the appropriate use modelling due to either high costs or limited abatement potential (see Poyry (2011) *Alternative uses of biomass in decarbonising industry report for CCC*).

9.3 Implications for near to medium terms uses

REDPOINT

The broad conclusions from the modelling suggest a pathway to 2050 that in the long-term contains limited use of bioenergy resources in non-CCS power generation and non-CCS liquid biofuels in surface transport, particularly if bioenergy resources are scarce.

The majority of the bioenergy in non-CCS road transport and power occurs in the near to medium term (eg peaking in the 2020s/2030s) before gradually phasing out. There is also a strong role for non-road transport (aviation and maritime) use in the medium term, but the extent to which this continues depends on either the availability of CCS or the oil price, which when rising tends to push bioenergy towards the higher value non-surface uses (while use in road transport is actually slightly lower).

To a large extent the near term choices are being driven by the need to meet the 2020 RED target, and the fact that the shadow price for this is positive in all scenarios indicates there is a distorting effect compared to an optimal pathway focused on meeting the emissions target alone[28].

Road transport biofuels
The RED transport sub-target also leads to deployment of a number of domestic liquid biofuel production plants (although the exact deployment in the modelling is a function of the cost of imports in 2020 which are highly uncertain). Once constructed, these continue to be used as their capital costs have been sunk, but with a gradually declining load factor over their lifespan.

Bioliquid use does continue to rise after 2020 as bioresource availability increases (before declining again from the late 2030s onwards) and more cost-effective abatement alternatives in transport (such as electric and H_2 vehicles) do not tend to become available until the middle of the period onwards.

Given the uncertainty over the long-term use of these types of technologies it will be important that any investment with a payback period over 15-20 years has the potential to retrofit CCS and/or be sufficiently flexible to cost-effectively shift production to non-surface transport fuels. Neither of these options were modelled explicitly in these scenarios but could be included in future analysis.

Power generation
Given the long-term focus on use of bioenergy with CCS, new dedicated biomass electricity generation without CCS is another option with a potentially limited, transitional use – unless there is the potential for cost-effective retrofit at a later stage (which again, was not explicitly modelled but could be added in future).

The modelling results do highlight that a potentially cost-effective way to help meet the RED, whilst avoiding the problem of infrastructure lock-in, is to retrofit some of the existing coal stock to dedicated biomass – in the order of 0.5-2.5 GW (net output basis) of capacity in the scenarios examined[29].

[28] If the most cost-effective way to meet the emission target required sufficient renewables capacity to be deployed anyway, which automatically satisfied the RED target, the constraint would no longer be binding and the shadow price would be zero.

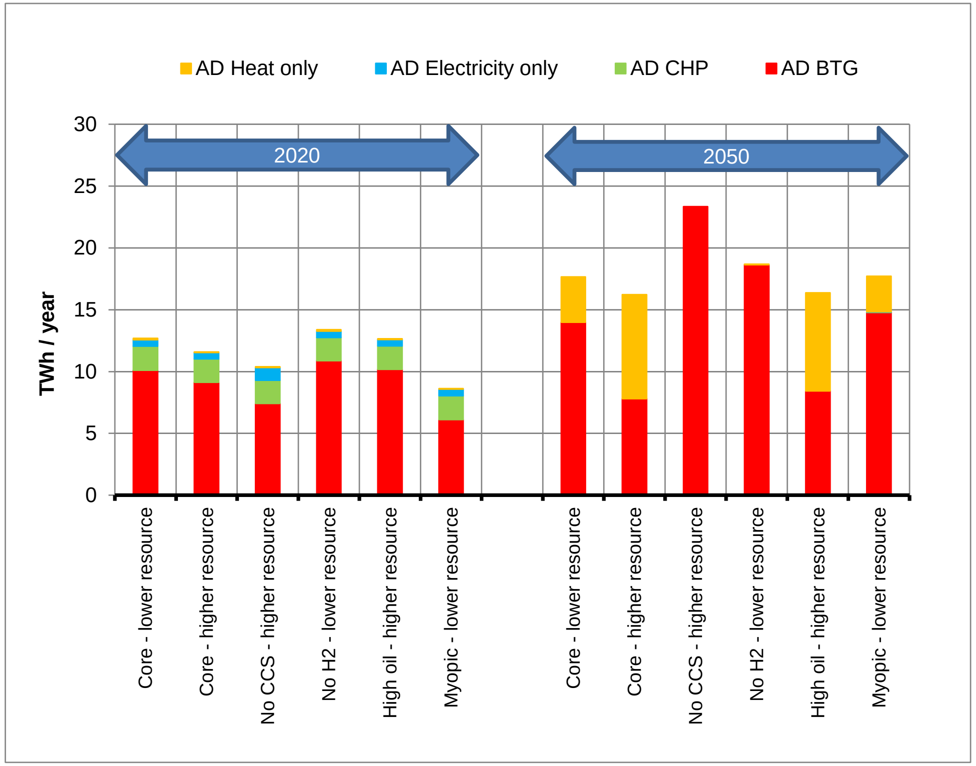
[29] With the exception of the myopic scenario, where greater near term investment in renewable heat and road transport biofuels mean retrofitting is not a cost-effective option in 2020 due to greater existing supply of renewable energy.

9.4 Implications for biogas and heat in buildings

AD and biogas

Biogas can be produced through AD plants or other gasification technologies making use of a range of feedstocks and waste streams. In the period up to 2020 most AD plants are hitting their imposed build rate limits and beyond this they provide a key, albeit smaller scale, option to 2050 for effectively using the available biowaste streams across all scenarios.

Figure 34 AD plant output in 2020 and 2050 (All scenarios)



The use of AD plants is shown in Figure 34 and highlights a focus on biomethane to grid injection (primarily for high temperature industrial heat in later periods) with some heat production (either CHP or dedicated heat) for suitable local heat.

Larger scale deployment of biomethane is not seen in the scenarios examined, but this may be a function of the lack of CCS on gasification production routes to biomethane (this was excluded due to data uncertainty).

Whether substantially higher production is seen with CCS in place will again depend on the relative economics of CCS options across the system, but in the current scenarios it only appears to have limited use when the point of capture is applied at the generation end of the pathway (eg CCGT + CCS). However, like H_2, biomethane can provide a flexible carrier that can be used across power, heating and to a lesser extent transport.

Heat in buildings

The modelling suggests a relatively limited role for direct use of bioenergy in the general provision of heat for buildings, due to the availability of key low carbon options such as heat pumps. There is still potential for a range of smaller scale niche applications, particularly in non-net bound buildings, or via use of local resources such as dedicated heat (or CHP) AD where there is a suitable nearby heat load.

The potential for greater indirect use of bioenergy for heating is again coupled to the availability and relative economics of CCS. For example, use of CCS in gasification to produce biomethane would allow it to be used in conventional gas boilers for heating, however, only where it is not possible or unnecessary (eg due to a surplus) to direct this to industrial process uses.

Similarly, if the economics of CCS were favourable to medium scale CHP and district heating boilers (CCS options for these technologies were not included due to data uncertainty) this could be coupled with use via heat networks.

9.5 Conclusions (1)

Given the myriad of possible uses for bioenergy and competing alternatives, the modelling has helped to provide a more holistic understanding of the most appropriate ways to use bioenergy within the UK energy system to 2050, whilst meeting both the UK's emissions and renewable targets. The optimisation modelling is necessarily a stylised analysis and key uncertainties remain in the input data, particularly over the longer-term. However, the purpose of the modelling is to identify key areas of commonality for bioenergy use (or non-use) which persist under significantly different scenario assumptions. It has highlighted the critical role that bioenergy plays, even with limited availability. From the results a broad *hierarchy of appropriate uses* can be distilled:

- Non-energy uses for wood in construction (and potentially others) as well as targeted use in industry (particularly for higher value process heat) appear highly desirable
  - There are also a range of smaller scale uses (eg waste products in AD for local heat loads) that are desirable. Most of the AD heat is supplying small scale district heating networks and is therefore subject to the caveat of suitable local heat loads - although the overall supply of local AD heat is very small as a proportion of total heat demand
- If CCS proves feasible it has the potential to generate negative emissions when coupled with bioenergy use and bioenergy carrier production, and is highly desirable from the perspective of the overall energy system
  - Where it is used in the system becomes a question of the relative economics of different CCS options, but could be targeted towards H_2 production (which can then be used in transport or power), large scale power/heat and liquid biofuels for aviation/shipping
  - Use of CCS in the production of liquid road transport fuels is less desirable in the longer term, given the wider range of abatement options such as EVs, or FCVs using H_2 produced from bioenergy + CCS
  - Use of CCS in the large-scale production of biomethane from gasification routes or on medium scale CHP/heating has not been included in the analysis, but could also play a potential role and compete with the existing power, H_2 and liquid biofuel bioenergy + CCS routes
- Without CCS, the use of liquid biofuels for higher value applications in aviation and shipping (along with non-energy uses and industry heat) is desirable
  - In general, the long-term use of liquid biofuels for road transport and large-scale biomass for power (both without CCS) to 2050 are less desirable if bioenergy resources are scarce

9.6 Conclusions (2)

Implications for policy

The results have a number of implications for policy, most urgently identifying the need to demonstrate CCS at commercial scale, but also to understand the feasibility and costs of using this with bioenergy in different parts of the energy system.

It also highlights the need to support a range of bioenergy options, particularly pathways which provide long-term flexibility, such as biofuel plants which can transition from producing road transport to aviation/maritime fuels, or technologies which produce bio-H_2 and biomethane energy carriers.

Next, there is a need to ensure that existing and future policy incentives, many of which are targeted at individual sectors[30], combine in a way that actually incentivises bioenergy towards the broad hierarchy of appropriate uses. There is also need to develop supporting policy to adequately capture uses of bioenergy with CCS and non-energy uses within a holistic framework for biomass feedstocks.

Finally, although the analysis has been undertaken for the UK, similar issues apply at a larger scale, particularly given the reliance on global availability of sustainable bioenergy. There is a case for the EU to look more closely at how bioenergy production and appropriate use is coordinated across Member States, building on the flexibility mechanisms within the current RED and potentially within the context of new renewable energy targets post-2020.

Areas for further work

The analysis has focused on using the most comprehensive set of data currently available in a consistent framework to distil a broad set of conclusions for the most appropriate uses of bioenergy across the energy system (and outside it).

It is, however, harder at this stage to draw more specific conclusions around individual bioenergy technology options and conversion pathways (eg bioH_2 versus biomethane) due to data uncertainty. This is particularly true with respect to the general evolution of long-term technology costs and the costs of using bioenergy with CCS in a range of different places across the energy system, both of which are important areas for further study.

Further analysis could be undertaken using the existing model and dataset, by undertaking a wider range of sensitivities on factors such as bioenergy availability and technology costs, to better understand the tipping points (eg costs / performance thresholds) at which key technologies start to play an important role. The additional functionality around lumpy investment and proportional build rate constraints (which were not used in these scenarios) could be helpful, for example, in exploring the implications of supply chain constraints.

Finally, a number of potential model enhancements that could improve the analysis include:

- Additional detail in the representation of parts of the energy system (eg within year representation of the profile of electricity and heat to understand seasonal swings and the impact on peak energy demands)
- More formal techniques for tackling uncertainty such as *probabilistic* simulation (repeated solutions with inputs sampled from a distribution rather than point values) and *stochastic* simulation (solving across a range of possible states of the world where key input data values such as fuel prices or technology costs become increasingly uncertain). The latter in particular represents a useful way to help understand what an '*optimised hedging pathway*' might look like for bioenergy

[30] Such as the Renewables Obligation for electricity, Renewable Heat Incentive, and Renewable Transport Fuel Obligation

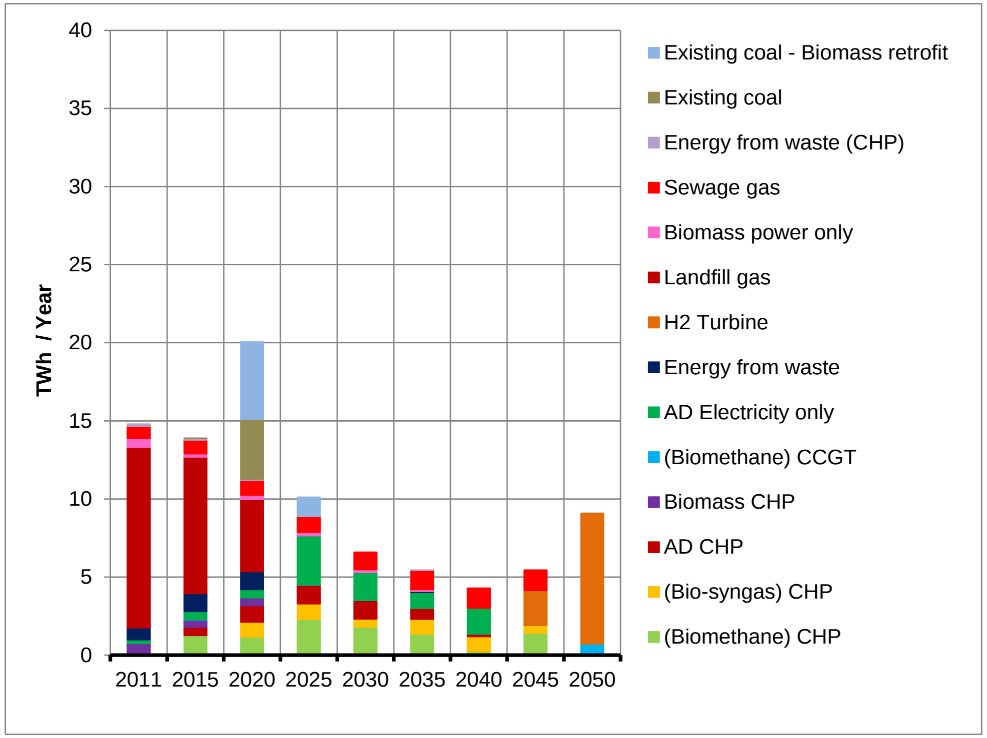
10 Annex A - Bioenergy use by technology

10.1 Bio-electricity generation including CHP electricity (1)

REDPOINT

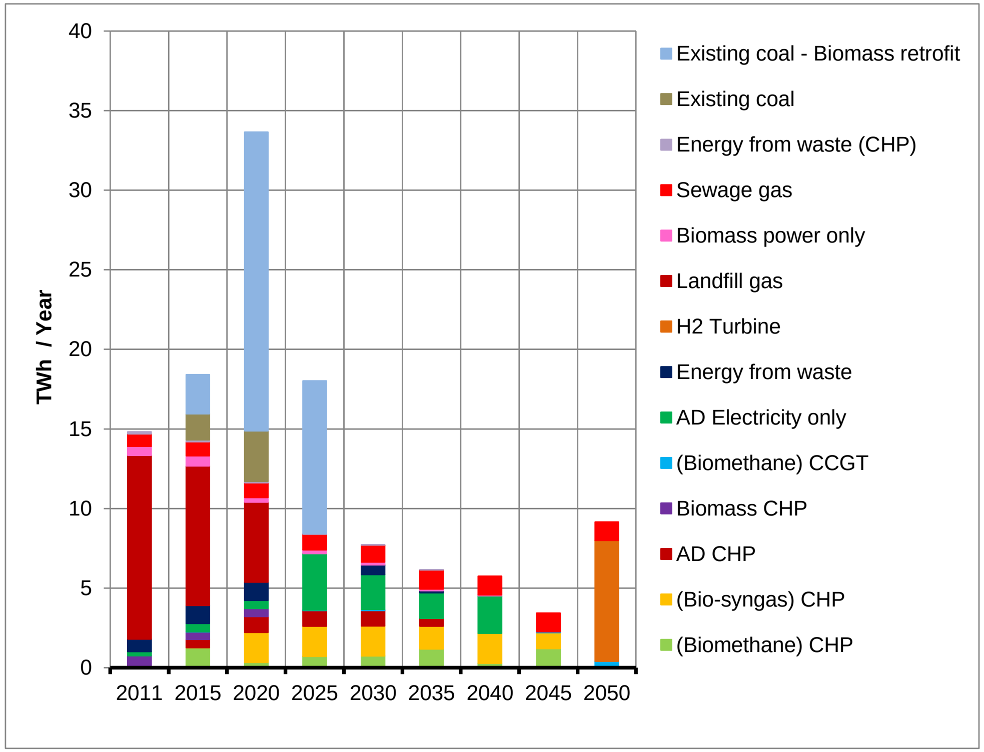
The figures below reflect the share of bio-related electricity generation chosen by the model, by technology (with the tranche for existing coal representing the bioenergy co-firing portion). Landfill gas has a high but declining near-term share of generation as resource availability decreases. There is also some additional co-firing and biomass retrofit as part of meeting the RED target. In the medium term there is a transitional role for AD and biomethane CHP generation. Sewage gas is used throughout until the final period when it is diverted away from dedicated electricity generation to AD biomethane to grid injection (BTG) to help decarbonise industrial process heat (with other low carbon alternatives for power used in its place). In 2045 there is also a switch towards bio-H_2, primarily for peak electricity.

Figure 35 Bio-electricity generation (Core - lower resource scenario)



A similar pattern is observed in the higher core resource scenario, the main difference being considerably higher generation from biomass retrofit of the existing coal stock (and which starts from 2015).

Figure 36 Bio-electricity generation (Core - higher resource scenario)



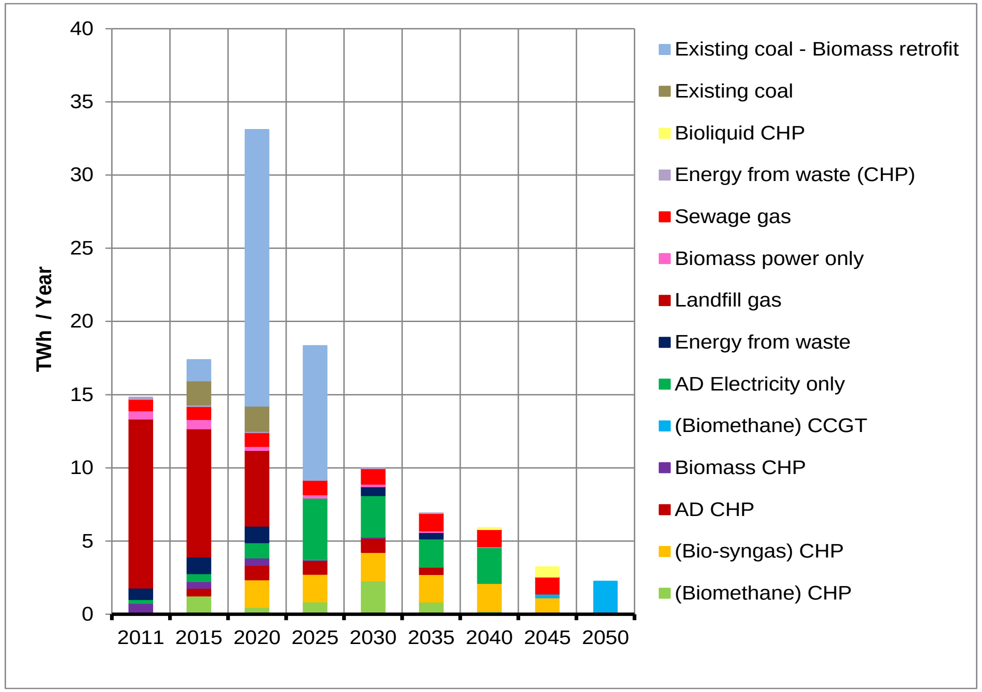
From the adjusted levelised cost calculations biomass retrofits under the core lower resource scenario are valued at approximately £-10/MWh for 2020 vintages. By contrast under the higher resource scenario the values are £-11 and £-12/MWh for 2015 and 2020 vintages – ie more negative and hence more valuable to the system overall. This is a result of the option being at the margin to help meet the RED, and with more resource available there is a higher preference for this technology.

10.2 Bio-electricity generation including CHP electricity (2)

REDPOINT

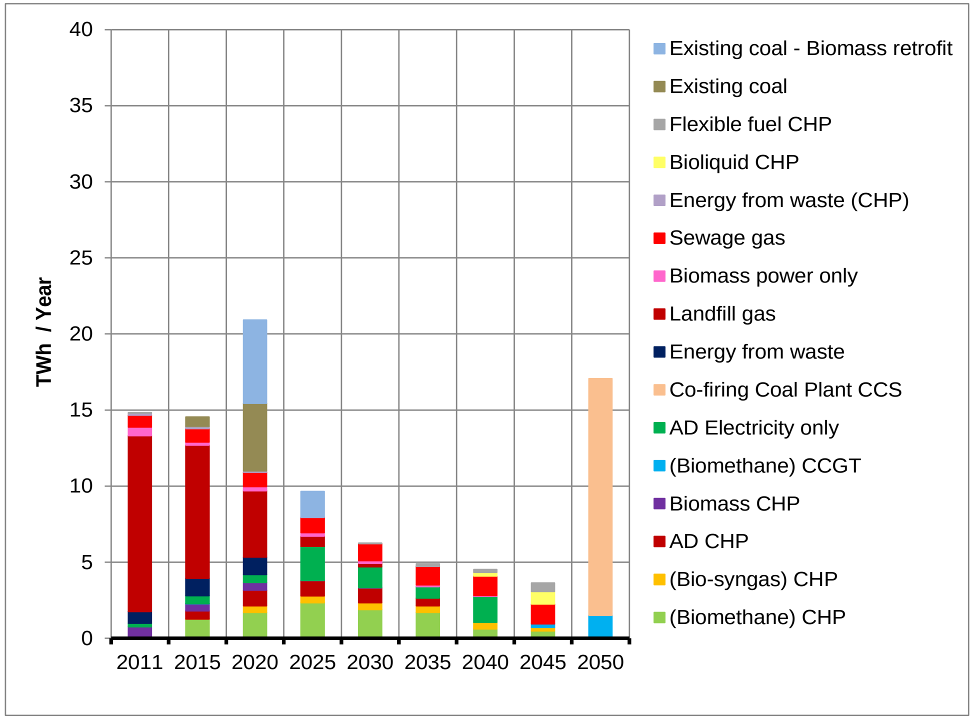
Without CCS the pattern of bioelectricity generation by technology is very similar to the equivalent core resource scenario up until 2040. After this point the more limited availability of bioH_2 (which is now being produced solely from electrolysis routes and almost all used in transport - see section 8.3) means that the bioelectricity production is restricted to biomethane in CCGTs in 2050. To supply the biomethane, the model diverts sewage gas (along with other biogas production) away from dedicated electricity generation to biomethane grid injection. This is predominantly to help decarbonise industrial process heat, with the side effect being that some is available for fuel switching in power generation (subject to the wider caveat from section 3.10 on the ability to direct energy carriers to specific end-uses).

Figure 37 Bio-electricity generation (No CCS - higher resource scenario)



The no H_2 scenario is broadly similar to the equivalent core resource scenario. However, without H_2 the system struggles to meet the overall emission target in 2050 (and needs to use the backstop option) and as a result has to explore all cheaper alternatives that are not restricted by technology build constraints or resource constraints. In this case it builds the equivalent of two new coal plant with CCS from 2045 to 2050, and runs these 100% on dedicated torrefied biomass (rather than co-firing with coal) to maximise negative emissions. Even though the adjusted levelised cost for this vintage of plant is over £500/MWh this is still cost-effective given that no other options outside of the backstop are available (due in part to build restrictions on the expansion of alternatives such as nuclear which is already at its scenario limit).

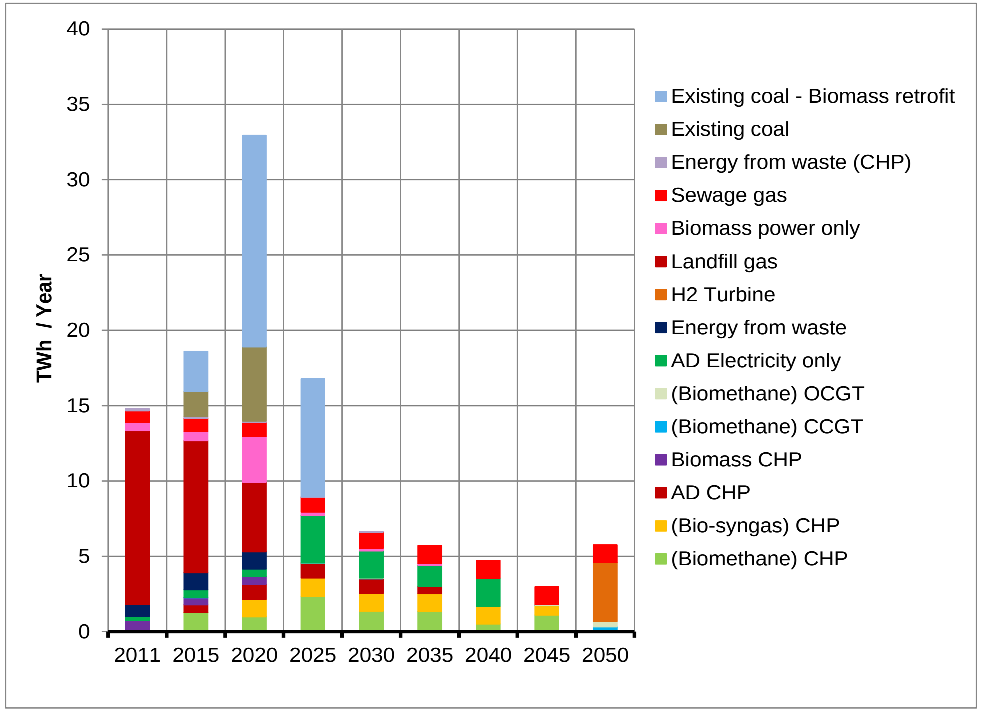
Figure 38 Bio-electricity generation (No H_2 - lower resource scenario)



10.3 Bio-electricity generation including CHP electricity (3)

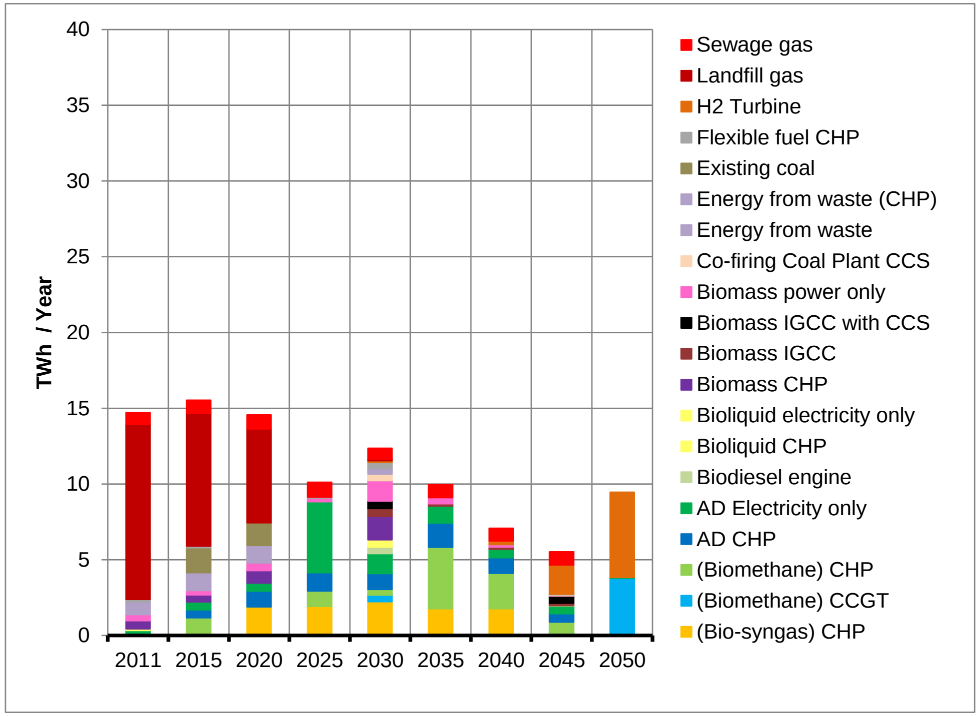
The high oil scenario is broadly similar to the equivalent core resource scenario, but there is lower H_2 generation in 2050 as bioenergy is diverted away from H_2 to use in non-surface transport. There is additional dedicated biomass generation in 2020 (resulting from higher utilisation of pre-existing plant rather than new build or further retrofit of existing coal), as in other scenarios this is too expensive to run in the near term due to a looser emissions target and more cost effective existing coal / gas generation. The adjusted levelised cost for the existing plant changes from ~£6/MWh in the equivalent core resource scenario, to just under £0.5/MWh in the high oil price scenario.

Figure 39 Bio-electricity generation (High oil - higher resource scenario)



The results for the myopic scenario show significant shifting in production of small quantities of bioelectricity generation throughout the middle part of the period, as the immediate focus for the most cost-effective use of bioenergy shifts. It is unlikely that some of this (eg biomass IGCC with CCS) would take place at such a small scale (an aspect which could be explored further via the lumpy investment mode). In the near term, the model does not retrofit the existing coal stock to use biomass. This is an indirect result of decisions in the first two periods leading to higher deployment of renewable heat and meaning that retrofit in 2020 is no longer a cost-effective option to meet the RED. In addition there is less bioH_2 generation in 2050 as the myopic scenario hits its build rate limits on new H_2 turbines.

Figure 40 Bio-electricity generation (Myopic - lower resource scenario)



10.4 Bio-heat production (1)

The figures below highlight the output of heat by technology type. It is important to note the minor role that the model finds for bioenergy within total heat demands and the relatively limited use for heating within all bioenergy uses. Hence the graphs highlight a number of relatively niche uses.

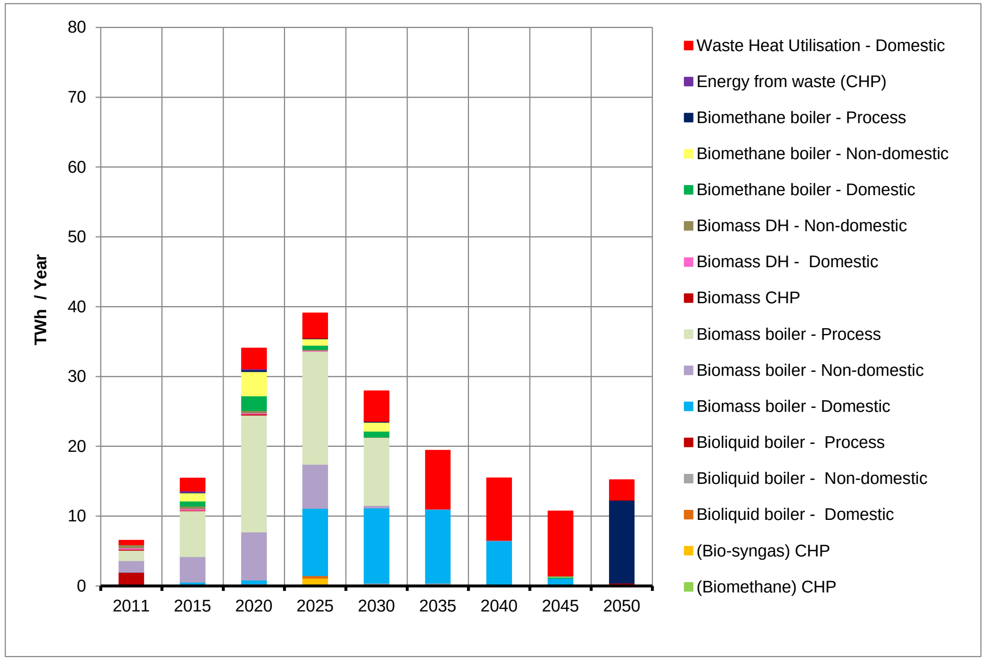
However, this is also a function of a lack of small-scale end-use CCS options within heating in the model, which mean that heating becomes a lower priority pathway as the emission constraint tightens as it is unable to provide negative emission credits. The model does not have the option to do this via a biomethane + CCS intermediate route either as large scale gasification + CCS technologies were not included in the current scenarios.

The core lower resource scenario, along with most other scenarios, shows a sizeable on-going use of 'recoverable' heat. Whilst this is nominally being assigned to 'sparse' domestic sector buildings the majority of the 'spare' heat in the model is being generated by AD heat plants and so could potentially be used in other local building (or low grade industrial heat) applications assuming these are available. However, there is general uncertainty around the costs of district heating networks, which can vary significantly between individual projects.

Other key transitions include use of biomass boilers for domestic and non-domestic buildings, with the latter driven by the RED and the former by use in the non-net bound sector. After the mid-2030s these transition back out due to more widespread use of heat pumps and more effective uses of bioenergy coupled to CCS.

The model uses some biomass for lower temperature industrial process heating in the near term, which is driven by the cost-effective contribution to the RED. This is via the use of waste wood chips in biomass boilers which are then phased out at the end of their life, as the bioresource is diverted to more valuable alternative uses. By contrast, as the emissions constraint tightens in the final periods, biomethane is used to provide high-temperature process heat, even without access to a CCS-based pathway, given the limited alternative options for reducing emissions.

Figure 41 Bio-heat output (Core - lower resource scenario)



10.5 Bio-heat production (2)

REDPOINT

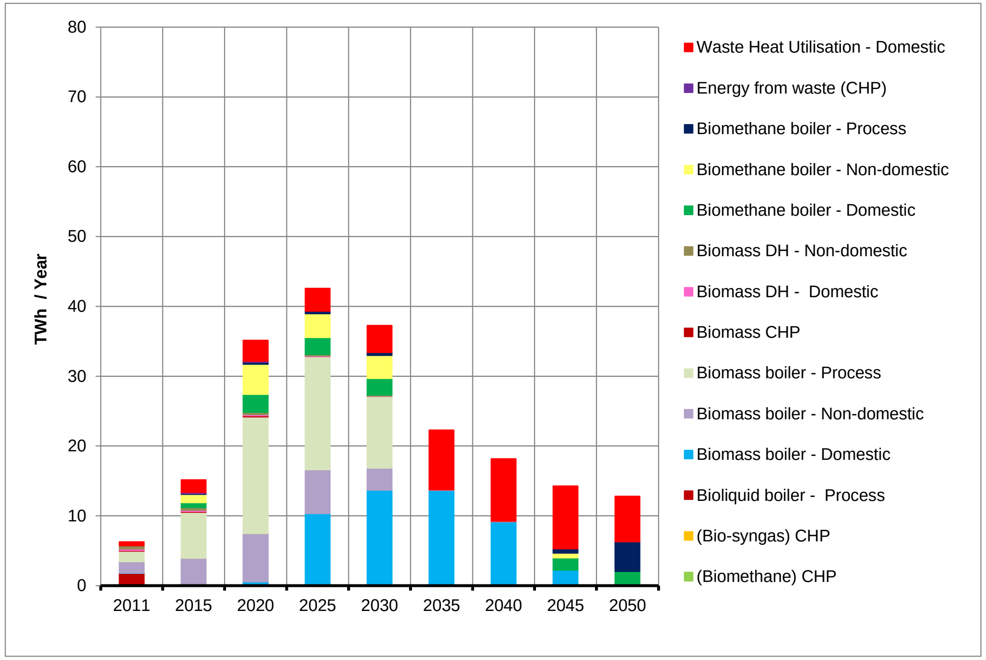
With higher resource availability the pattern is similar, but with marginally higher transitional domestic bioenergy use (both biomethane and solid biomass).

By 2050 there is a rebalancing of the output of AD plants (see section 9.4), which is split in the lower and higher core resource scenarios between localised space heat (or potentially other low temperature) uses and biomethane for high temperature industrial process heat.

This is partly a function of increased biomass availability leading to greater negative emissions from bioenergy + CCS use elsewhere in the energy system. This reduces the need to abate emissions in more difficult sectors such as heavy industry, which do not (at least in the current scenarios) have dedicated CCS options and hence cannot generate their own negative emissions.

This is reflected in the adjusted levelised costs for these bio heat options, which by 2050 are slightly less negative (and hence less favourable) under the higher resource scenario.

Figure 42 Bio-heat output (Core - higher resource scenario)

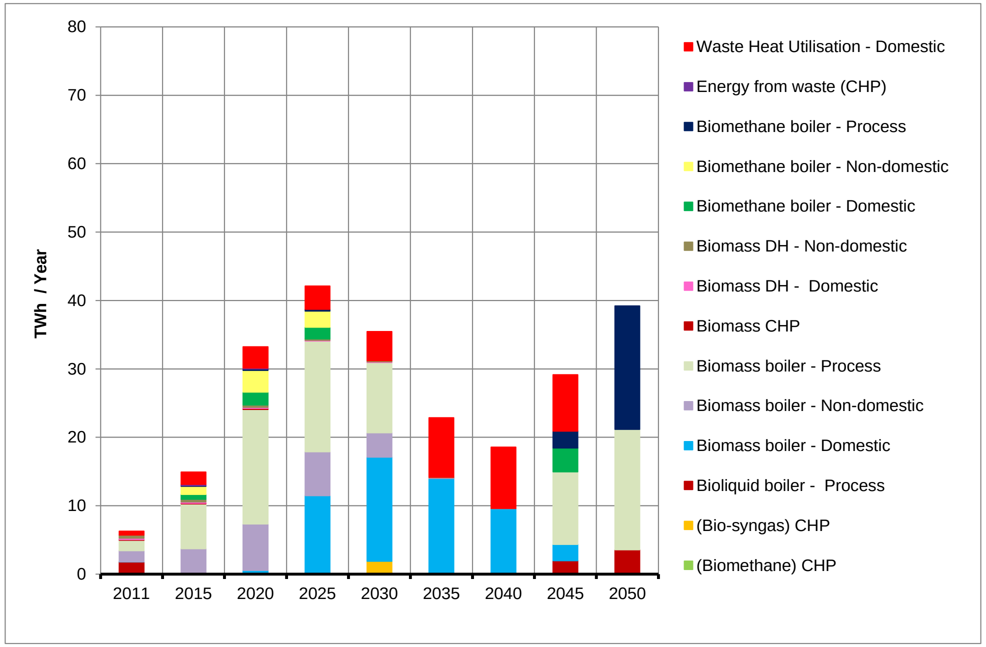


10.6 Bio-heat production (3)

Without access to CCS the pattern of bio-heat is similar to the equivalent core resource scenario, with the exception of a more substantial shift back towards industrial process heating from the mid-2040s onwards.

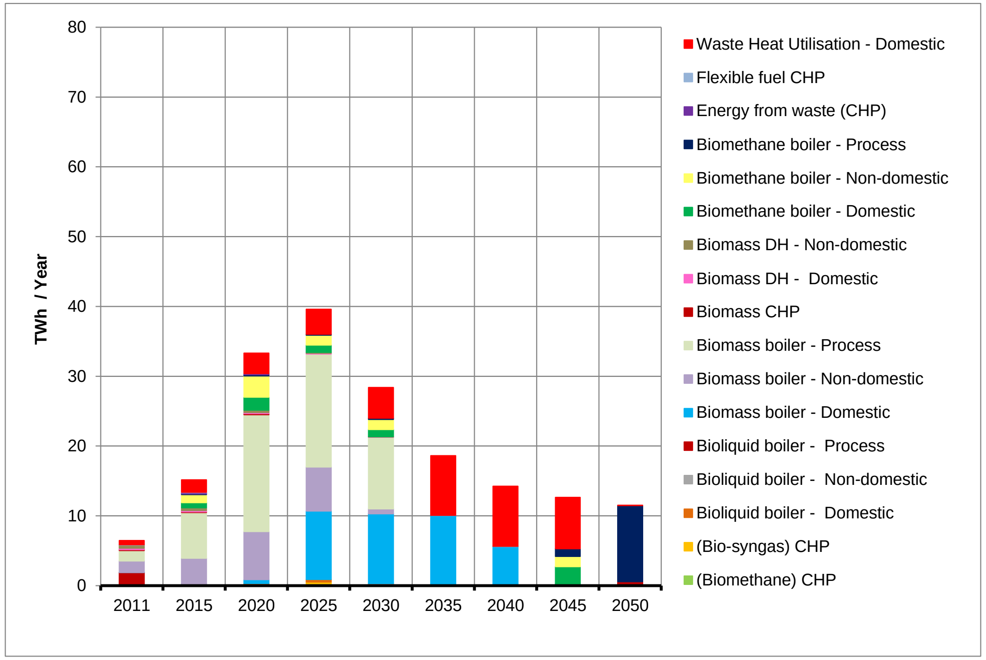
This heat is produced in the model with a mix of biomass boilers and biomethane, with the latter's availability limited by production from AD plants which switch almost exclusively to BTG in 2050 (see section 9.4). Large-scale diversion of bioenergy resources to produce biomethane via gasification (without CCS) does not appear cost-effective in this scenario given the overall conversion losses and that bioresources are at an even higher premium to try to meet the emission target without CCS (and therefore favour more direct solid biomass heat options).

Figure 43 Bio-heat output (No CCS - higher resource scenario)



Without H_2 options the overall pattern is similar to the equivalent core resource scenario. However by 2050, with the system struggling to meet the emissions target, the model is generally diverting bioenergy resource to other pathways with CCS (to generate negative emissions) such as power generation and bioliquid production with CCS. Large-scale biomethane production with CCS and small scale CCS in heating were not included in the scenarios. However, it is still cost effective to use some biomethane for industrial process (primarily higher temperature) heat given the limited alternative abatement options.

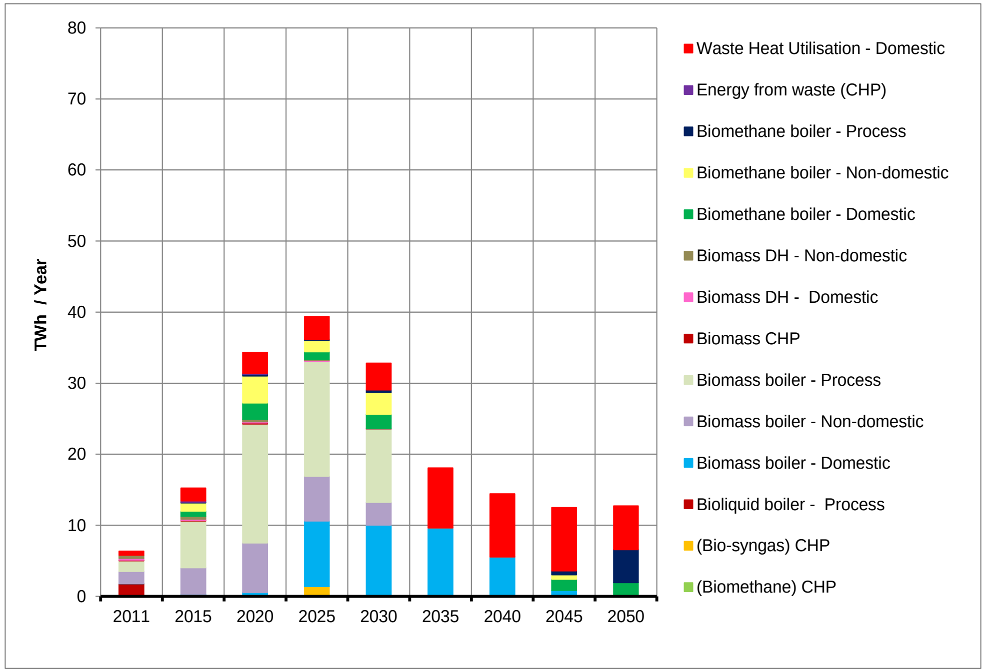
Figure 44 Bio-heat output (No H_2 - lower resource scenario)



10.7 Bio-heat production (4)

The high oil price scenario is virtually identical to the equivalent core resource scenario, but with marginally less use in biomass boilers in the domestic sector as some bioresources are shifted towards (non-surface) transport uses.

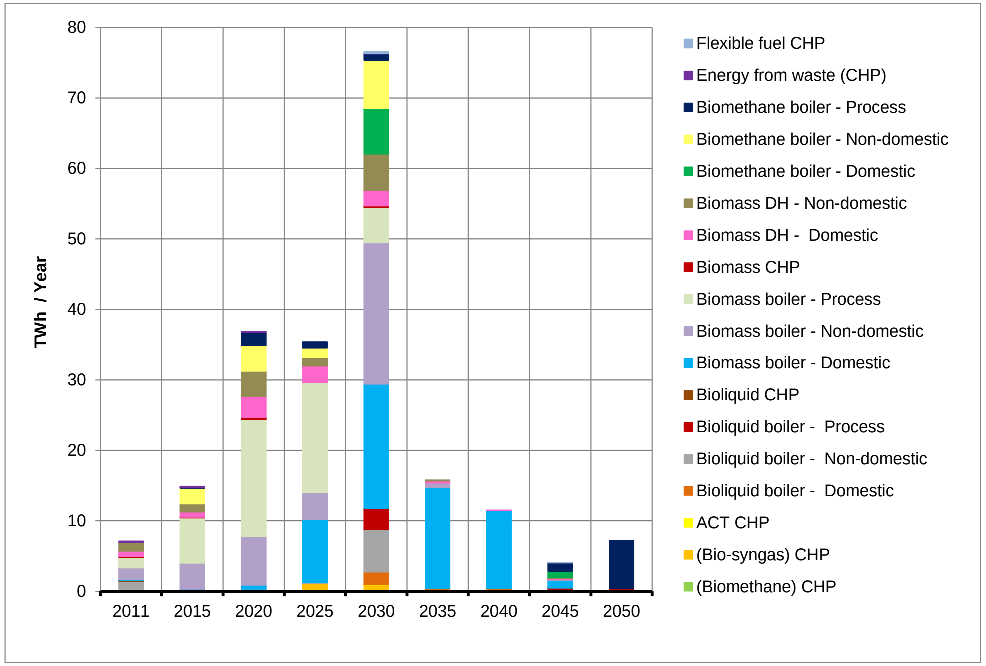
Figure 45 Bio-heat output (High oil - higher resource scenario)



The key difference under the myopic scenario is in the temporary mid-term transition to bioenergy for heating, focused primarily around solid biomass use in boilers and to a lesser extent biomethane use for heat.

The sudden jump in the model's bio-heat output in 2030 has to be seen within the context of both the appearance (albeit time limited) of a cost-effective route for bioenergy for heating, coupled with a roll-off of the existing stock which increases the scale of the transition. As heating devices typically have shorter lifetimes (eg 10-15 years) there are several replacement cycles of the stock to 2050, one of which coincides with a push for bio-heat in 2030[31]. However, bioenergy resources are rapidly diverted away from heating after 2030 as the emission target tightens and CCS options (which are not generally available for heating in the scenarios) are pursued.

Figure 46 Bio-heat output (Myopic - lower resource scenario)

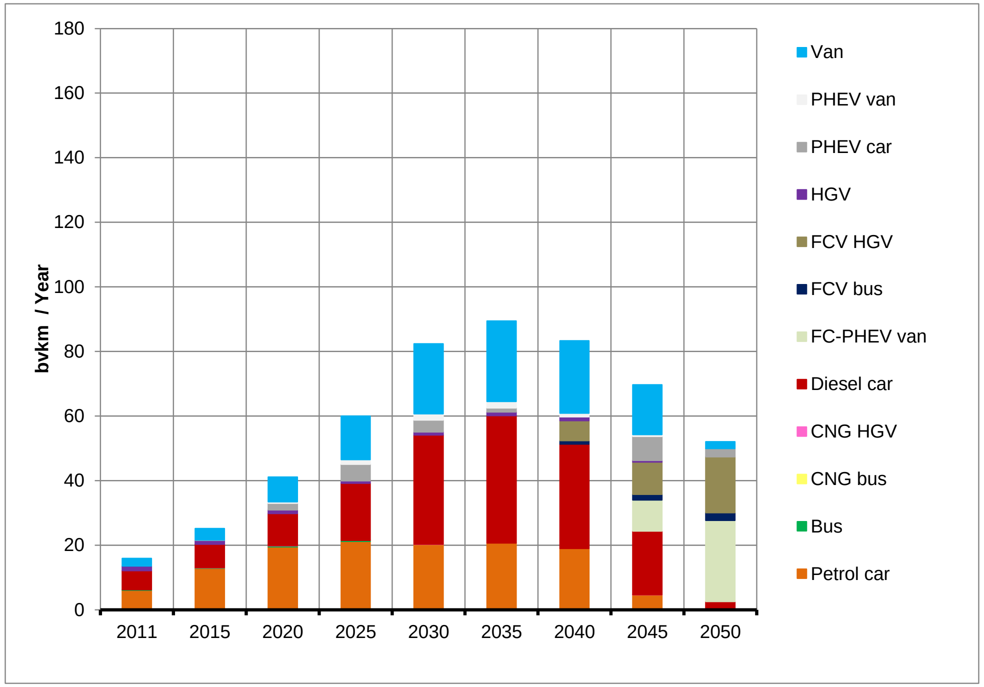


[31] The feasibility of the sudden ramp in installed capacity, of primarily biomass boilers, could be examined further by applying the % build rate constraint functionality which provides a better proxy for constraining the expansion of a supply chain.

10.8 Bioenergy road transport output (1)

The following graphs show the detailed output of road transport vehicle km by technology type. It is important to note that the use of bioenergy in specific vehicle types reflects a somewhat idealised application from the modelling, as in reality options such as biofuel blending in diesel would be difficult to target at specific vehicles. In addition, vkms of different vehicle types are not equivalent hence more energy intensive HGV vkms will be under represented in the total. Therefore the figures provide more of a breakdown of biofuel types delivering services in transport compared to the summary of input fuels already shown in section 8.5.

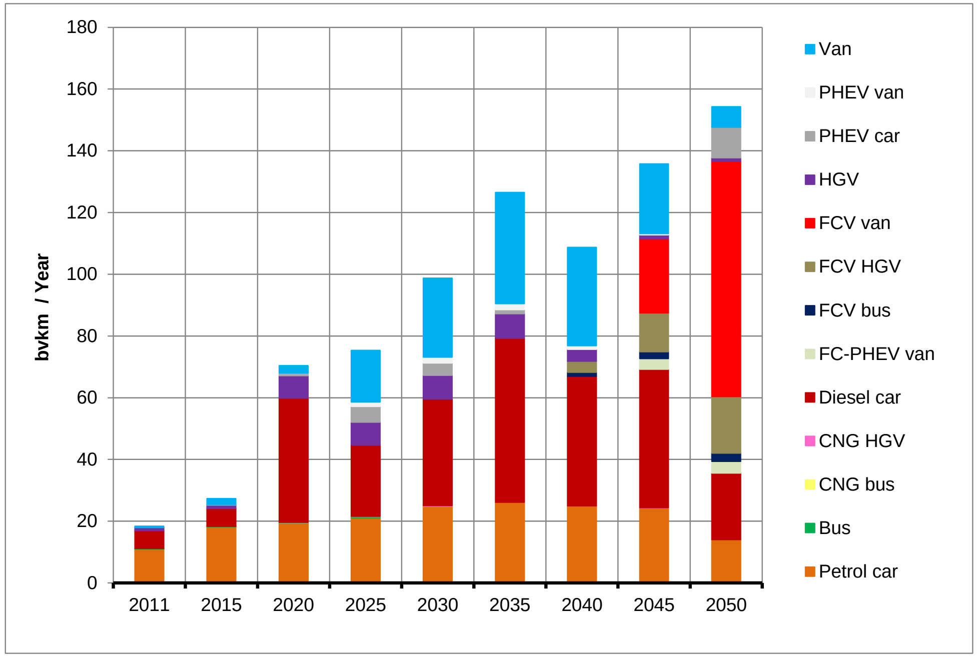
Figure 47 Bioenergy road transport vkm (Core - lower resource scenario)



In particular, the results show a transitional role for both biodiesel and bioethanol in light vehicles (including PHEVs), with a late stage move towards bioH_2 use in both lighter vehicles and dedicated heavier duty FCVs (eg HGVs or buses).

With higher bioresource availability there is generally higher, and continuing, use of biodiesel and bioethanol in lighter duty vehicles, but with a more significant overall shift to dedicated FCVs in the later periods as significant amounts of hydrogen are produced from bioenergy + CCS pathways (primarily via gasification – see section 8.3) to generate negative credits. However, it is important to note the general caveat around CCS costs, as an alternative preference for bioenergy in power + CCS would shift the balance away from FCVs towards electric vehicles.

Figure 48 Bioenergy road transport vkm (Core - higher resource scenario)



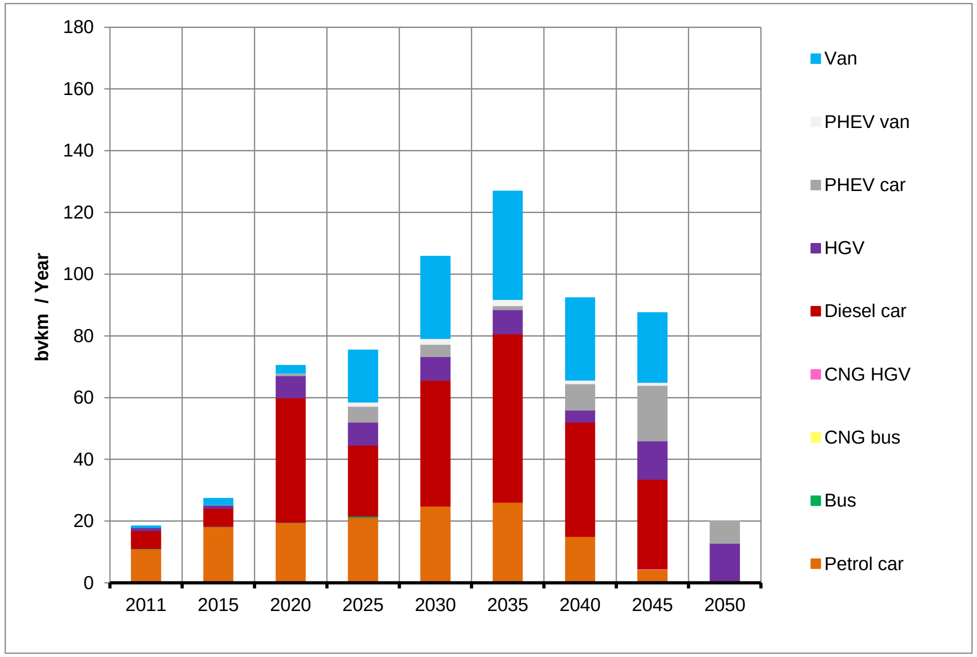
10.9 Bioenergy road transport output (2)

REDPOINT

Without CCS, the option for significant quantities of bioH_2 is reduced and by 2050 the model only finds a niche role for liquid biofuels in heavier duty vehicles, and to a lesser extent light vehicles.

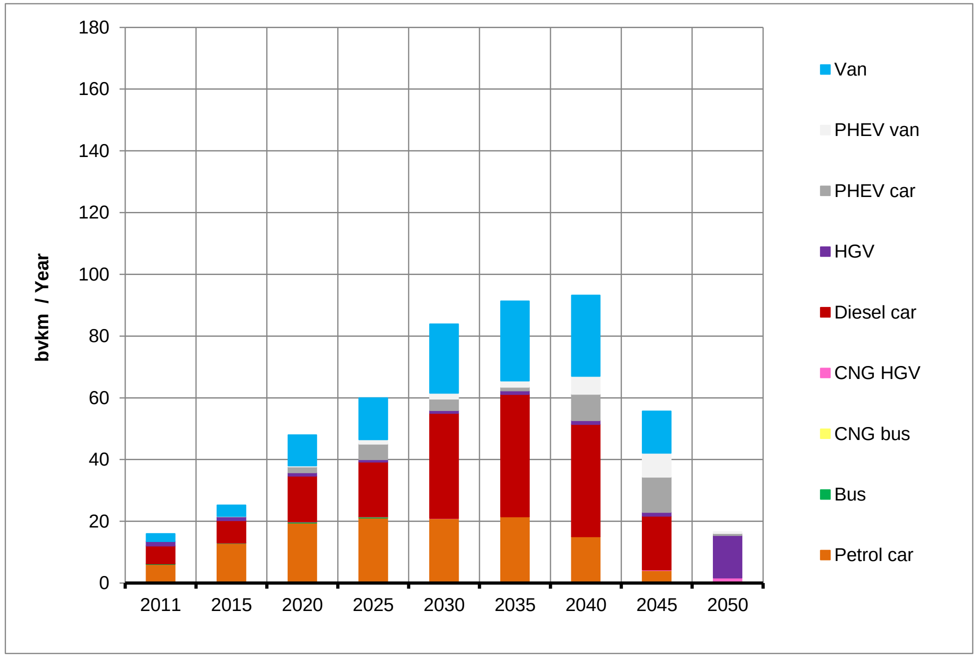
This to some extent reflects more limited abatement options in heavy duty vehicles without large-scale H_2 availability (H_2 from electrolysis routes is also limited as shown in 8.3), but use of bioenergy is now being diverted in 2050 towards non-surface transport uses.

Figure 49 Bioenergy road transport vkm (No CCS - higher resource scenario)



A similar situation is also reflected in the no-H_2 scenario (albeit with the slightly lower overall core resource availability assumptions) and by 2050, without H_2 more bioenergy resource is being diverted to non-surface biofuels. However, unlike the no-CCS scenario both the remaining road transport biofuels and non-surface biofuels are being produced primarily via CCS routes.

Figure 50 Bioenergy road transport vkm (No H_2 - lower resource scenario)

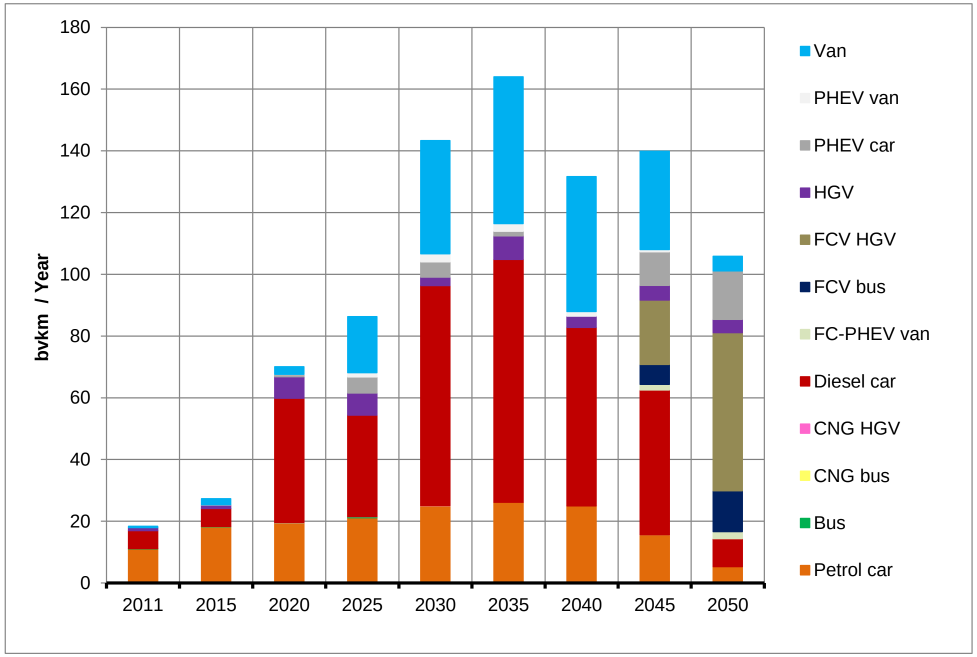


10.10 Bioenergy road transport output (3)

The overall pattern under high oil prices shows greater mid-term use of conventional bioliquid fuels for road transport, but a more limited late phase transition to bio-H_2 production as more bioenergy resource is diverted towards aviation and maritime transport fuels (as fossil prices for these end-uses increase proportionally more under the high oil scenario than diesel and petrol).

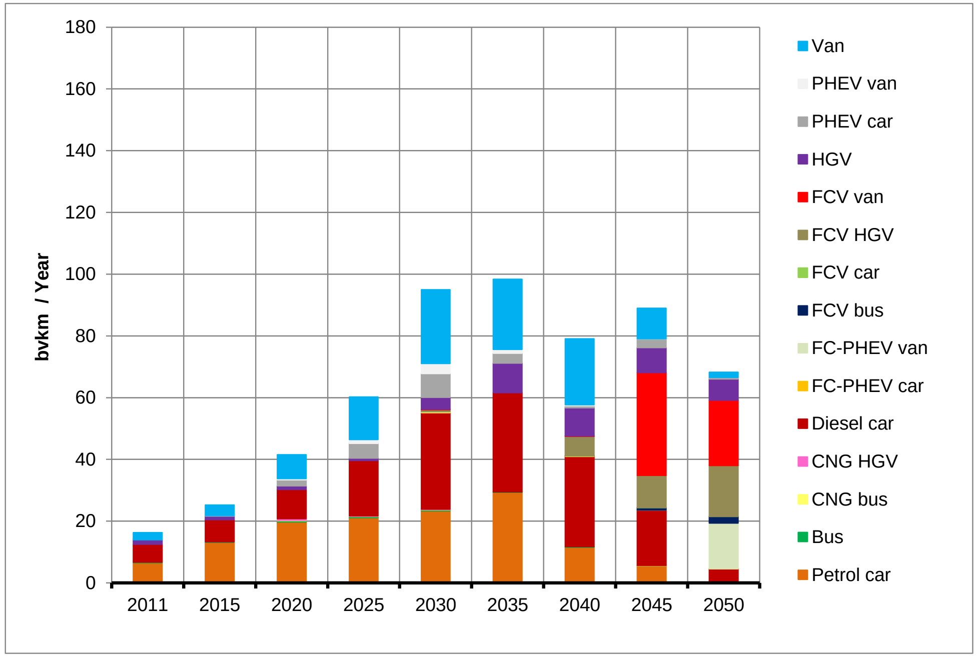
There is also more of a focused use of bioH_2 in heavier duty vehicles compared to the equivalent core resource scenario. By 2050 part of the limited remaining bioliquid fuel production for use in cars and vans is being produced via CCS production plants.

Figure 51 Bioenergy road transport vkm (High oil - higher resource scenario)



The myopic scenario is relatively similar to the equivalent core resource scenario until the last two periods, when there is a slightly more diversified use of H_2 across the different technology types. There is also a slightly higher overall use of bioH_2 by this point, which to some extent reflects build rate limitations on its potential use in power generation.

Figure 52 Bioenergy road transport vkm (Myopic - lower resource scenario)



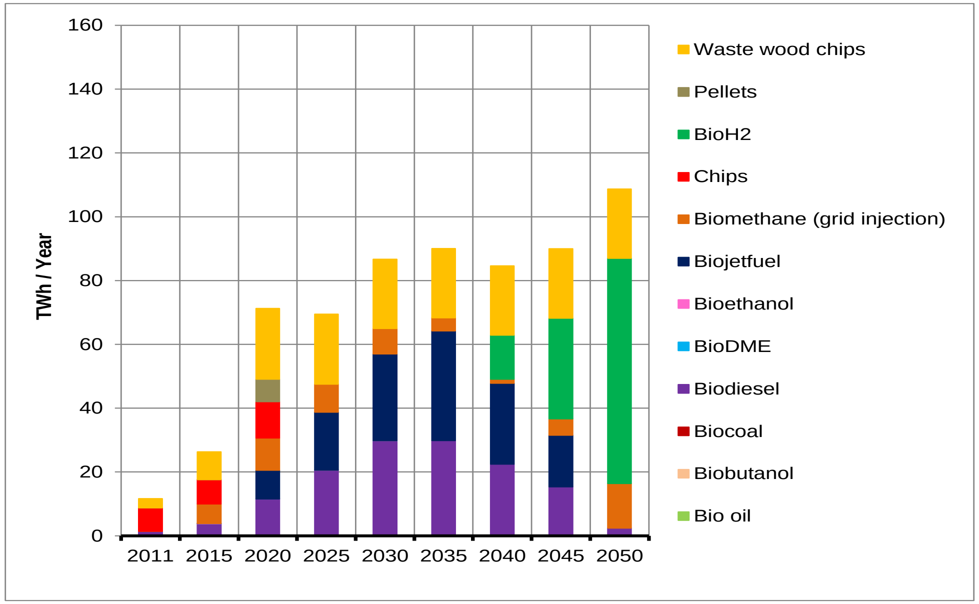
These results are partly a function of sunk costs in existing vehicles and fuel production infrastructure, as without the benefit of perfect foresight there is now a balance in each myopic period between making best use of already locked-in technology and transitioning to new capacity (subject to new build constraints).

11 Annex B - UK bioenergy carrier production and imports

11.1 UK bioenergy carrier production (1)

The key patterns in domestic production of bioenergy carriers reflect the sectoral trends described in the preceding sections[32]. In particular, the scenarios illustrate transitional roles for non-CCS liquid biofuels for transport - primarily biodiesel with bioethanol coming from imports[33] and biojetfuel - and a long term role for $bioH_2$. The majority of the biodiesel is used in road transport (but options are also available for use in bioliquid boilers, CHP and maritime).

Figure 53 UK bioenergy carrier (Core - lower resource scenario)

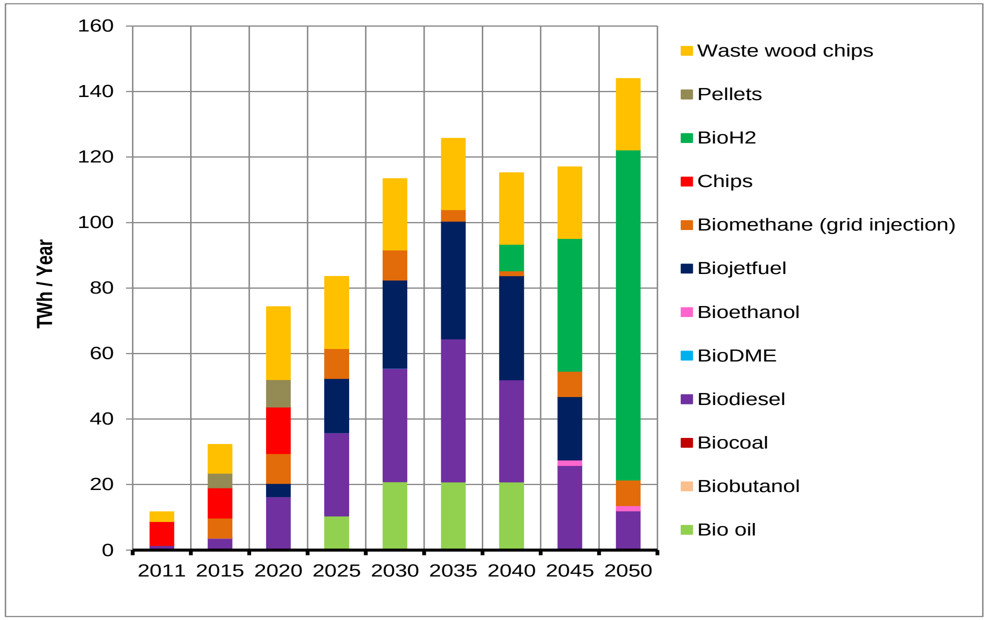


In the near term there is some use of chips and pellets in both the core lower and higher resource scenarios as part of the limited use of bioenergy in power generation and heating to help meet the RED target. The model uses waste wood chips to their maximum extent throughout all scenarios for industrial heat or large scale biofuel production given their low cost and lifecycle emissions.

[32] In terms of AD, only biomethane-to-grid is shown here. Other types of AD (where the biomethane produced is used directly at source for power and/pr heat generation) are shown in 9.4.
[33] The exact deployment in the modelling is a function of the cost and availability of imports, both of which are highly uncertain.

In comparison to the core lower resource scenario, with higher resource availability the model predicts significantly higher production of bioenergy carriers, although the broad pattern stays the same. With greater resource there is also transitional UK production of bio-derived fuel for use in maritime transport, before bioresources are diverted primarily towards $bioH_2$ produced via pathways with CCS to generate sizeable negative emissions.

Figure 54 UK bioenergy carrier (Core - higher resource scenario)

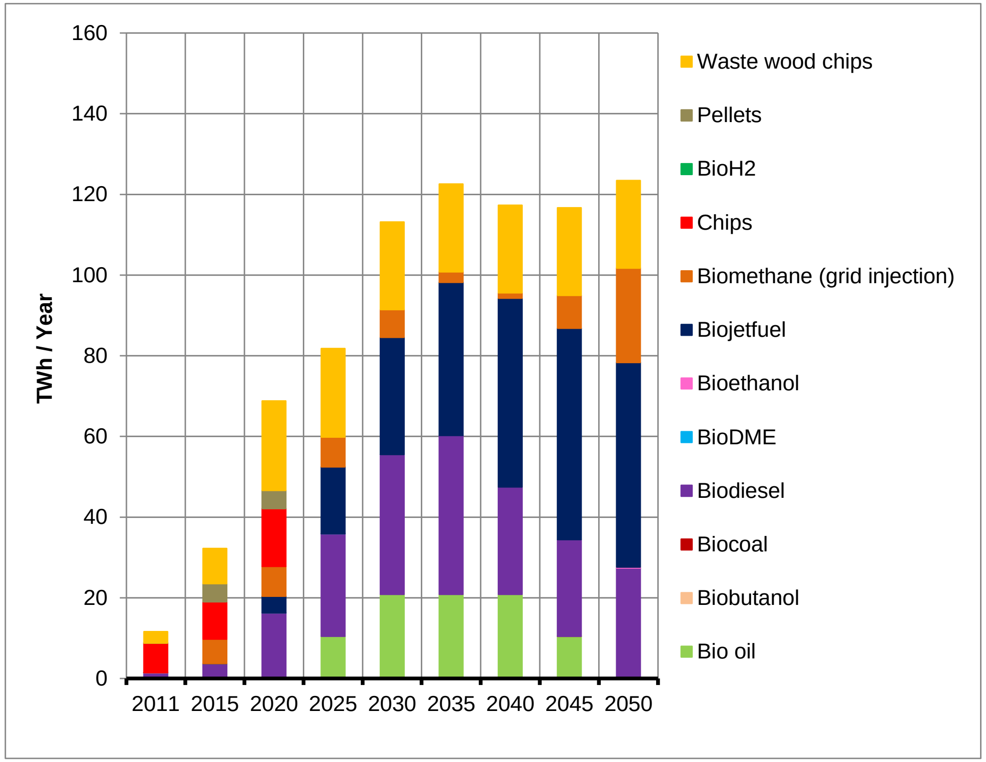


There is relatively limited use of biomethane grid injection in both the core lower and higher resource scenarios and produced primarily from smaller scale AD plants rather than larger scale use of gasification. However, it is important to note the there are no CCS options for gasification plants in the current scenarios due to data limitations. These could play a potentially significant role due to the flexibility of biomethane as an energy carrier, ie due to the wide range of potential gas end-uses and the existing delivery infrastructure.

11.2 UK bioenergy carrier production (2)

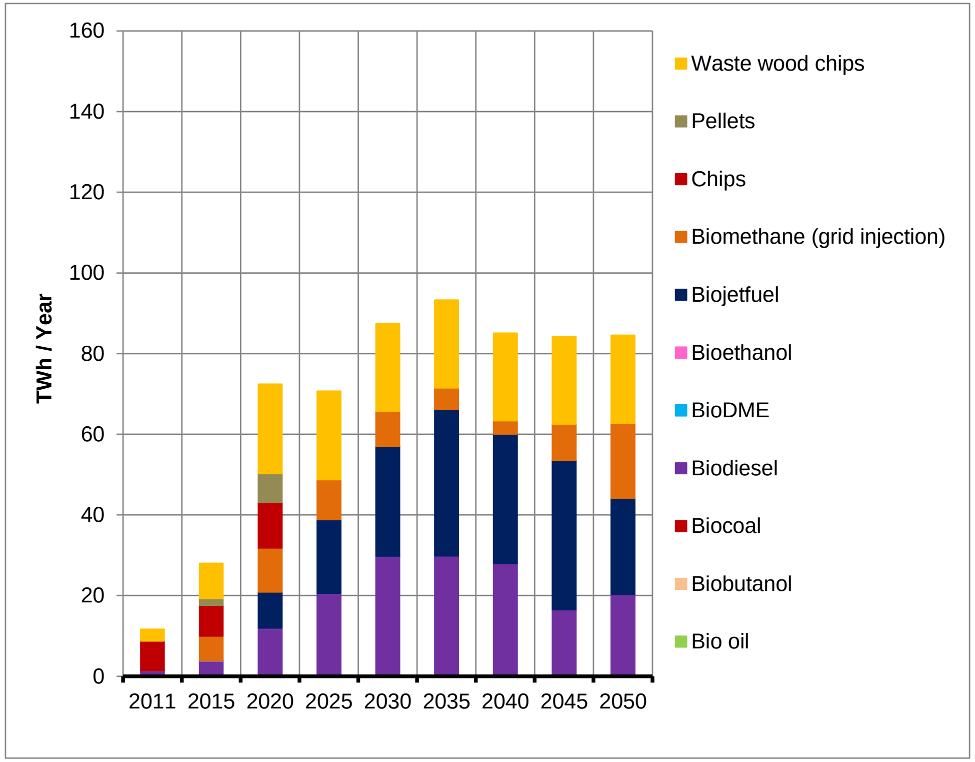
Without CCS, bioliquids retain a longer term role to 2050 as without CCS, H_2 production is no longer an effective option to meet the long-term emissions target. Biomethane also sees an expansion in 2050, primarily to help decarbonise industrial process heat, as the system struggles to meet the target.

Figure 55 UK bioenergy carrier (No CCS - higher resource scenario)



Without H_2 as an option, the pattern of bioenergy carrier production is very similar to the equivalent core resource scenario up until about 2035, after which there is continued production of liquid transport fuels in lieu of the transition to H_2, and slightly greater overall biomethane production. This additional amount is used in power generation, primarily CCGT for providing low carbon peak electricity (as opposed to H_2 turbines in other scenarios).

Figure 56 UK bioenergy carrier (No H_2 - lower resource scenario)

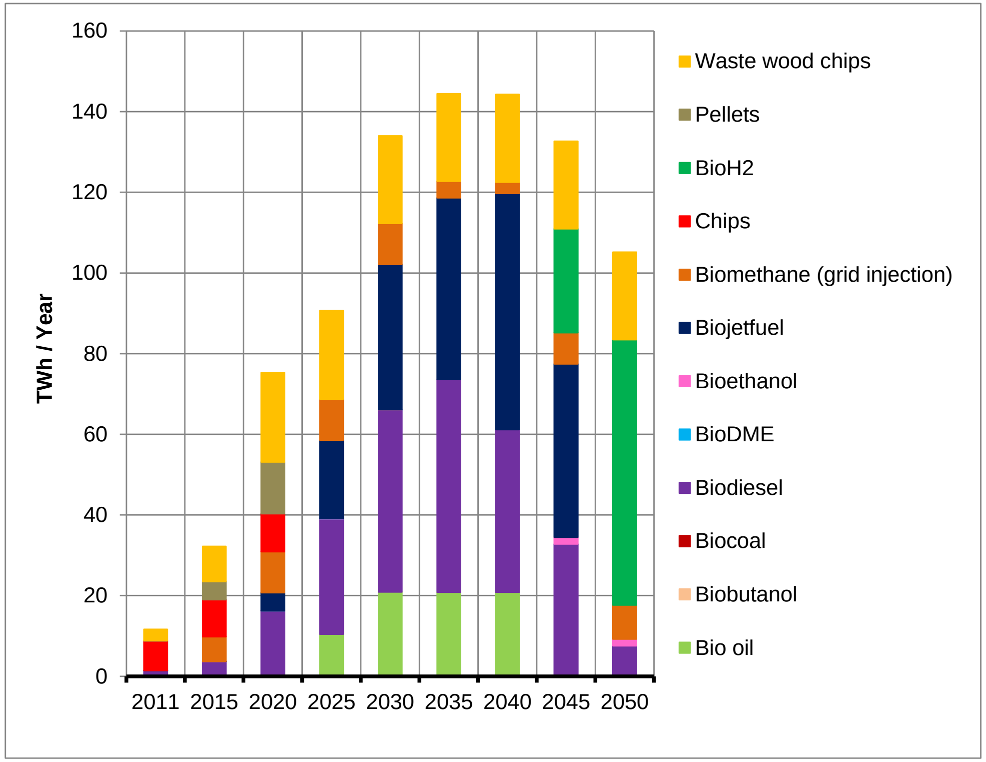


11.3 UK bioenergy carrier production (3)

In comparison to the equivalent core resource scenario, higher oil prices lead to higher overall production of bioenergy carriers (and hence greater use of available bioresources), primarily biojetfuel from the mid-2030s onwards.

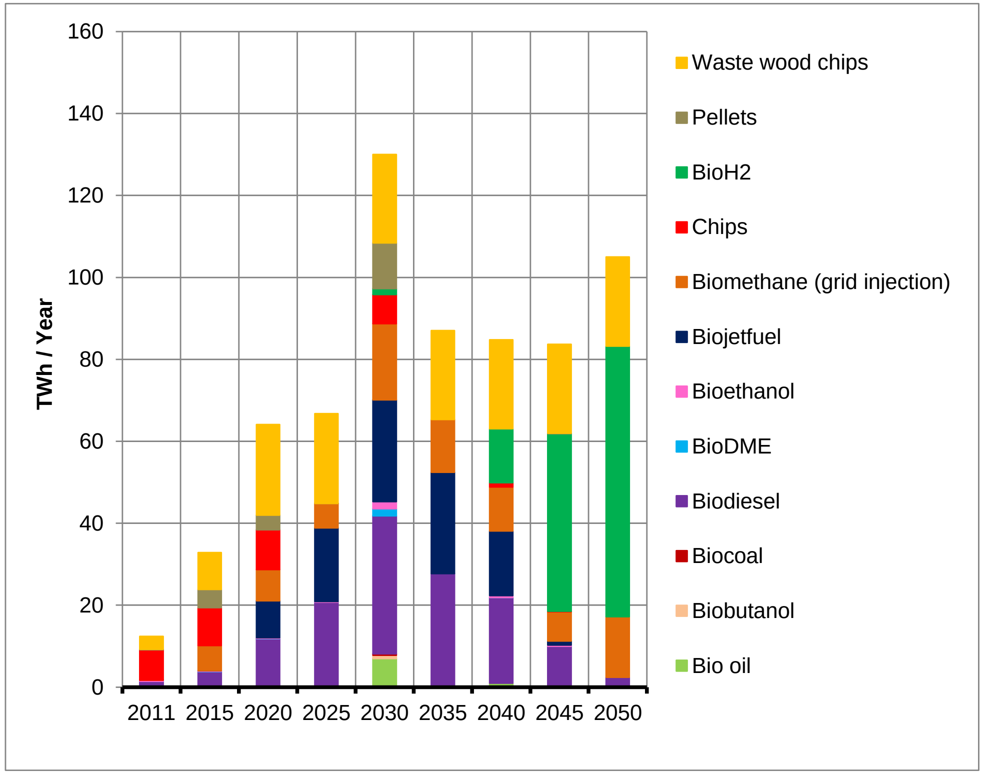
There is also substantially less bioH_2 production in 2050 as the higher oil price shifts the limited overall import availability away from woody biomass imports which were being used for H_2 gasification (with CCS) in the UK, to direct import of refined biojetfuel.

Figure 57 UK bioenergy carrier (High oil - higher resource scenario)



The overall pattern and level of bioenergy carrier production under the myopic scenario is broadly similar to that seen in the equivalent core resource scenario. However, there is a sizeable jump in 2030 in the production of intermediate carriers, such as chips, pellets and biomethane, which are used as part of the shift in bioenergy towards heating end-uses (see section 10.7). Clearly there are practical restrictions on the feasibility of such sizeable jumps and these could be further explored by using the proportional build rate constraint functionality in the model to better mimic the expansion of new technology supply chains

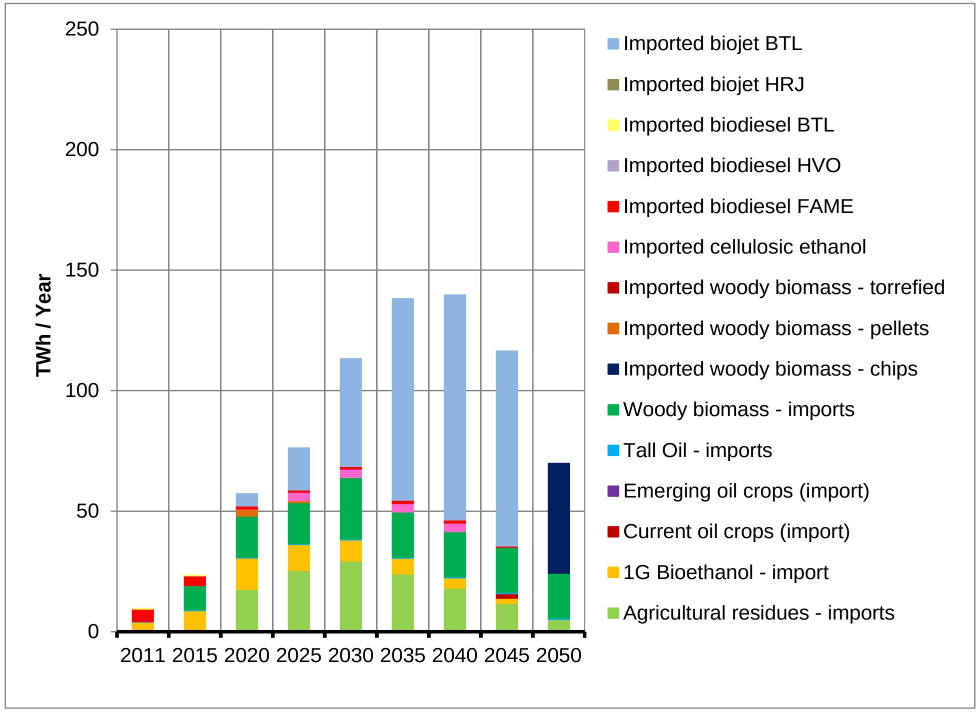
Figure 58 UK bioenergy carrier (Myopic - lower resource scenario)



11.4 Bioenergy imports (1)

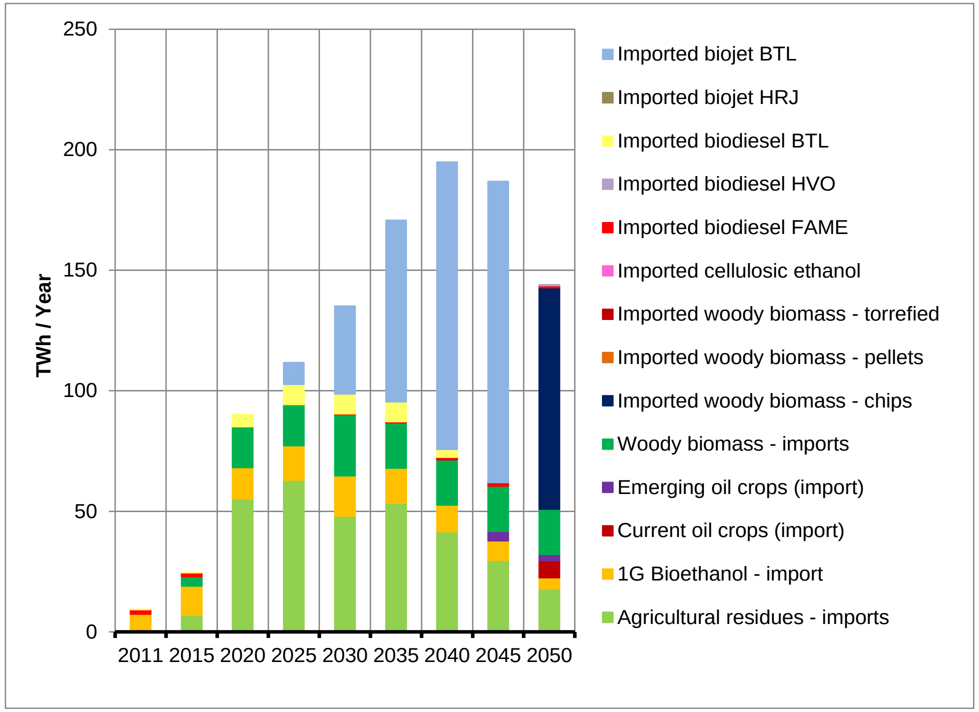
Both the core lower and higher resource scenarios show a number of key similarities with regard to imported bioenergy. After 2020 the model utilises all available agricultural residues due to a combination of low costs and lifecycle emissions) and there is also direct import of unrefined woody biomass for non-energy uses[34]. As part of the long-term transition to CCS applications, there are substantial imports of wood biomass chips

Figure 59 Bioenergy imports (Core - lower resource scenario)



The model also chooses to import a significant amount of biojetfuel (produced overseas from woody biomass)[35] as well as producing smaller quantities domestically as seen in section 11.1. However, it is important to note that the scale of UK domestic bioliquid production capacity will depend on the costs of 1G and advanced imports, which are very uncertain, and hence the broad scale of end-use in transport is the more important message from the analysis.

Figure 60 Bioenergy imports (Core - higher resource scenario)



[34] For these scenarios both the lifecycle emissions from imported bioenergy and savings from non-energy uses, even where the source originates from overseas, are included in the UK target.

[35] As described in section 3.7, dummy technologies exist in the model which allow it to choose how ideally to use available international resources e.g. for woody biomass, whether to import this in unrefined form or 'allow' it to be converted to liquid fuels overseas and import these. Obviously the feasibility of this would depend on international supply chains/markets.

11.5 Bioenergy imports (2)

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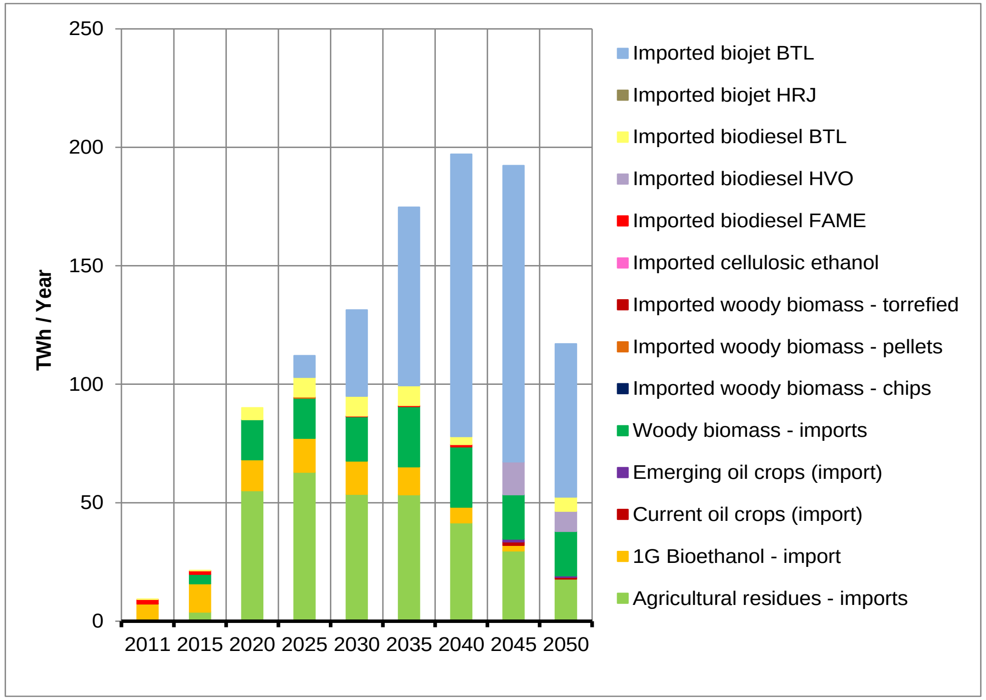
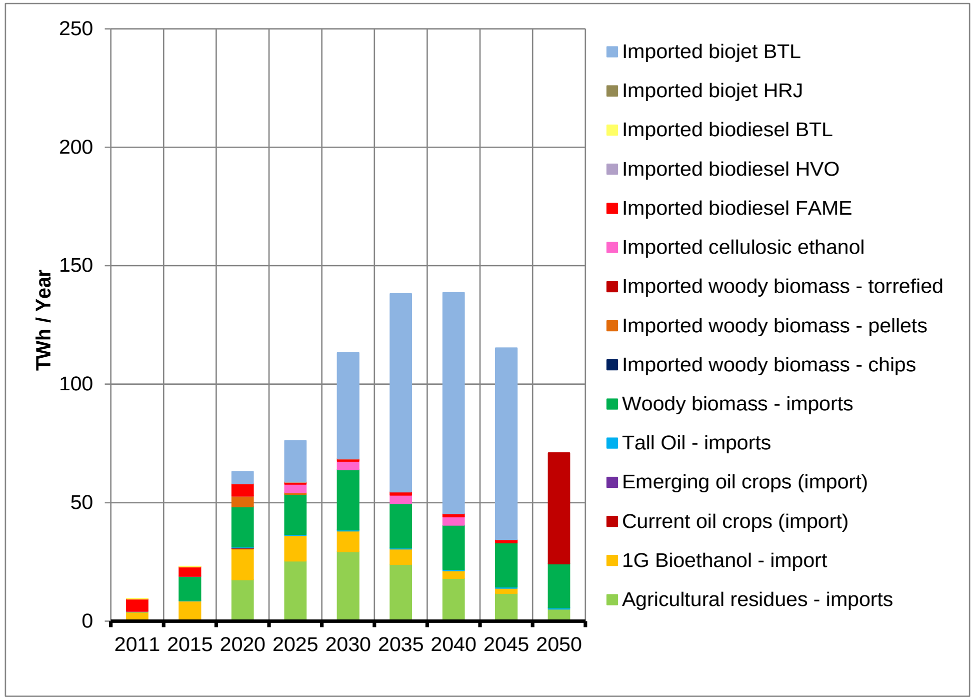
Without CCS the key difference to the equivalent core resource scenario appears in 2050. The option of using imported chips in H_2 gasification with CCS (with negative emissions) is no longer available and instead non-UK resource is diverted to produce refined biojetfuel for import.

Figure 61 Bioenergy imports (No CCS - higher resource scenario)



The overall pathway in the no-H_2 scenario is very similar to the equivalent core resource scenario, but without the option to produce H_2 the non-UK woody biomass resource in 2050 is diverted to torrefied biomass imports for dedicated use in (bio)coal CCS plants to generate negative emissions (there is no coal co-firing at this stage). It is important to note that the no-H_2 scenario still has to use the backstop option to meet the 2050 emissions target, hence the radical switch is a function of the model trying to find all other less costly routes to meet the target. Moreover it is likely that in practice, supply chains for this option would require more time to develop; the impact of this could be the subject of further work using the percentage build rate functionality in the model.

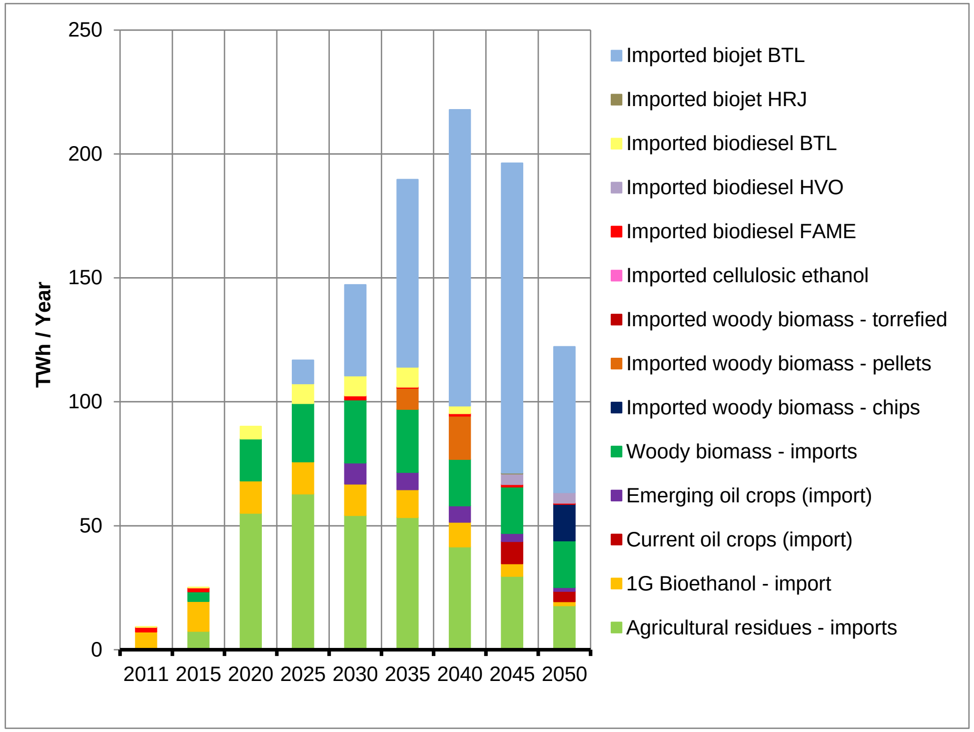
Figure 62 Bioenergy imports (No H_2 - lower resource scenario)



11.6 Bioenergy imports (3)

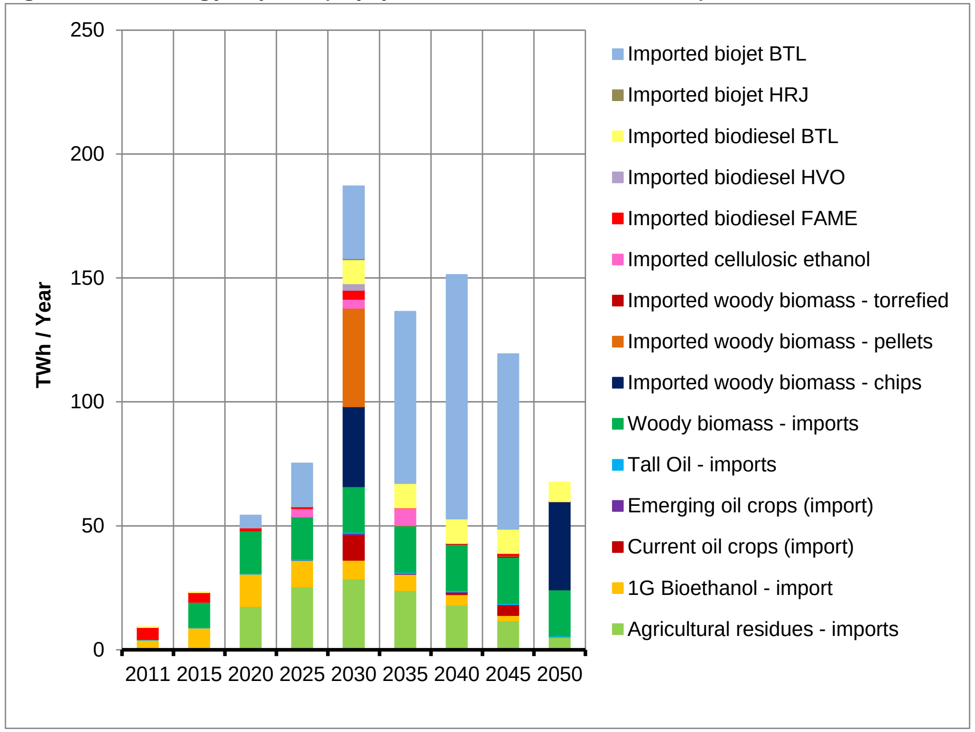
As noted in preceding sections, higher oil prices lead to continued, albeit still declining, use of liquid biofuels in aviation, compared to the equivalent core resource scenario, in lieu of imported bioenergy chips which were previously going to UK $bioH_2$ with CCS production plants.

Figure 63 Bioenergy imports (High oil - higher resource scenario)



The myopic scenario is similar in overall trends to the equivalent core resource scenario, albeit with some temporary mid-term use of imported woody biomass carriers that are being used as part of the increased (albeit temporary) shift in bioenergy use in heating. The jump in late period import of chips is part of the transition towards $bioH_2$ produced via CCS pathways. This is more cost-effective (including lifecycle emissions) than importing the raw woody biomass and converting fully within the UK, due to the lower transport emissions.

Figure 64 Bioenergy imports (Myopic - lower resource scenario)



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12 Annex C - Adjusted levelised cost calculation

12.1 Structure

The adjusted levelised cost of energy or service output in £/MWh or £/vkm from a technology =

Total (for each period over the lifetime of the plant) discounted

£ [

Core costs (capital + FOM + Outputs * VOM)

+ (Energy inputs * shadow price of inputs)

+ (Carbon emissions from plant[36] * shadow price of carbon)

- (Outputs * shadow price of outputs)

- (Contribution to RED * shadow price of RED target)

]

/

Total (for each year over the lifetime of the plant) energy or service outputs (MWh / vkm)

The calculation is based on the actual operation of the plant in the model, the associated fuel requirements and products produced (which may change over time) and the associated shadow prices produced in each period.

The more negative the adjusted levelised cost the more 'valuable' it is in the energy system relative to comparable alternatives.

[36] Including all bioenergy lifecycle emissions associated with technology (eg in operation or production of the energy inputs)

Example

For a new Biomass boiler - I-N-LLT-A-ALL[37], with 0.3 GW built in the 2015 period (with a 15 year lifespan) under Core Lower Resource Scenario

Element	Unit	2015	2020	2025
Core costs (CAPEX/FOM/VOM)	£M/year	17.7	17.7	17.7
Input costs	£M/year	12.8	17.7	32.7
Carbon cost[38]	£M/year	0.3	0.5	0.6
Output 'value'[39]	£M/year	47.6	52.1	47.7
RED 'value'[40]	£M/year		50.5	
Output	TWh/year	1.3	1.3	1.3
Years per period	year	5	5	5
Discount factor	%	0.84	0.70	0.59
Total costs per period	£M	-70.3	-233.8	9.8
Adjusted lifetime discounted levelised cost	£/MWh	-14.9		

[37] Industrial, Non-net bound, Large Low Temperature heat

[38] Shadow price of carbon 22, 38 and 47 £/tCO2 in periods from 2015 to 2025 respectively

[39] Shadow price of heat output 36,40 and 36 £/MWh in periods from 2015 to 2025 respectively

[40] Shadow price of RED £31/MWh in 2020