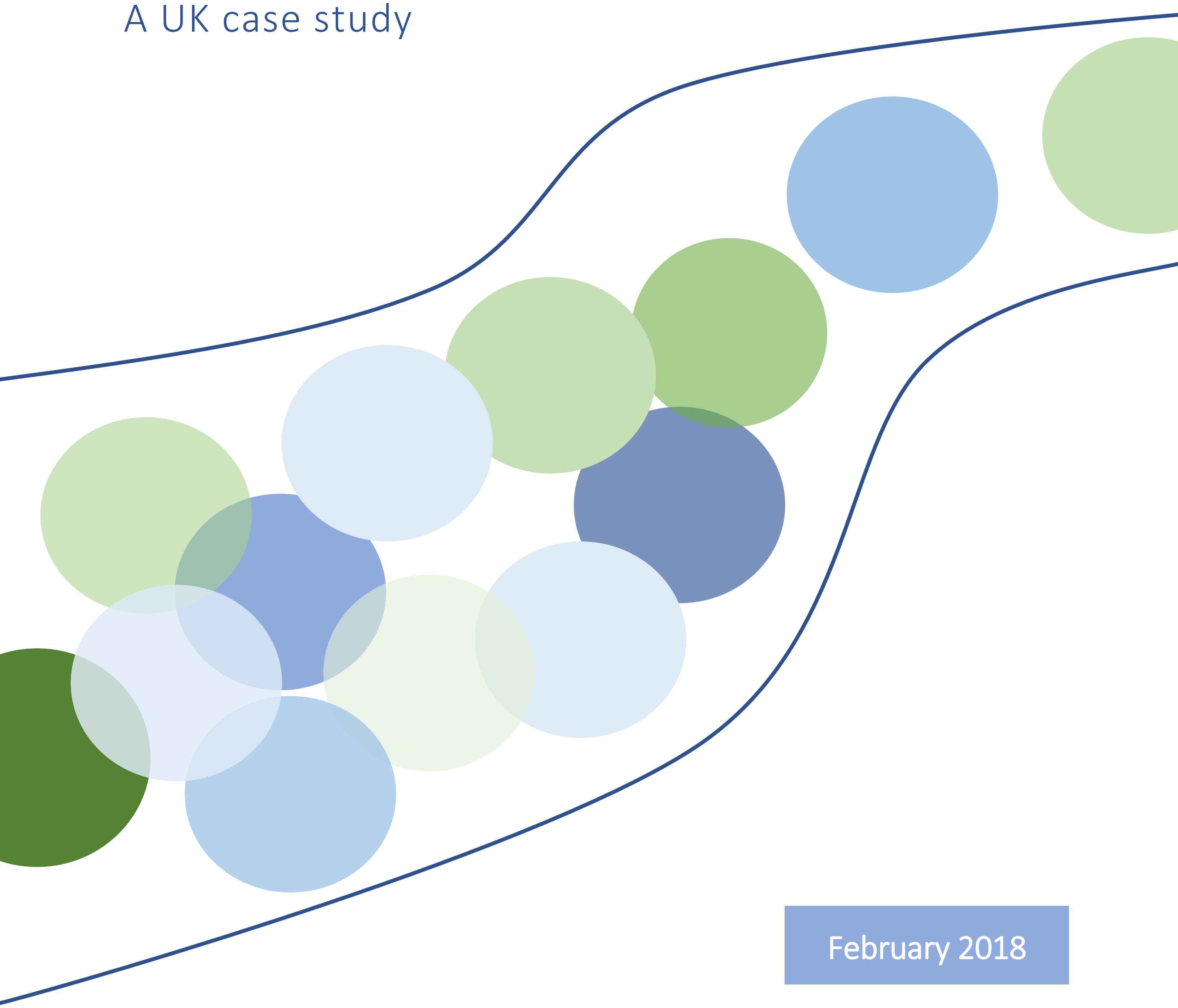
REEEM

Coevolution and competition of technologies in a low carbon system

A UK case study



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About this report

This report has been undertaken under WP2 of the REEEM project ‘Technology and Innovation’, and constitutes Deliverable 2.4 ‘Co-evolution of technologies Case Study report’.

Authors

Steve Pye, Ilkka Keppo

REEEM partners

About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

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Summary

To meet the stated ambition in the Paris Agreement, Europe's energy transition needs to be one that effects large-scale emission reductions at an unprecedented rate, with a system that has to be net-zero emissions by or soon after 2050. Critical to this transition will be the larges-scale deployment of existing and new technologies. However, many uncertainties are evident around future technology cost, performance, deployment, and socio-political feasibility. In this report, a case study for the UK is presented, which explores a range of these uncertainties using an integrated energy systems model, ESME. This integrated approach is key, because the objective of the research is to better understand, given the uncertainty, how different technologies are impacted both by the deployment of other technologies, and key system wide factors such as carbon price signal, resource availability etc.

A number of key insights emerge from the modelling. The large scale deployment of CCS drives down the costs of mitigation, both highlighting it as an option that requires much more consideration in policy. However, its effect on costs also means that it strongly shapes the take-up of options across the wider system. There is a danger that this influence is hidden in many analyses and that resulting strategies are not robust to the failure of this technology. Its dominance also precludes alternatives from receiving the necessary focus, and allows for 'buying time' to make the necessary investment to effect the longer term transition.

Under ambitious climate policy, the value of bioenergy increases. Whilst this usefully identifies the important role bioenergy can play, there are critical uncertainties concerning future availability, the sustainability of its use, and concerns of wider environmental impacts e.g. air quality. A final crucial insight is that a number of options are more robust to uncertainty in that they typically deploy at scale under a range of conditions, including offshore wind in the power system, and increased electrification both in the transport and building sectors. Other technologies remain much more contingent on other factors such as resource availability (bioenergy, influencing hydrogen use in transport) or technology costs (nuclear deployment where cost-effective alternatives may not be available).

Such insights, which are applicable to other Member States not just the UK, can help shape future strategy direction, but also give rise to further questions given the inherent uncertainty and the issues that fall outside of the model boundary e.g. broader sustainability concerns of bioenergy, legal and social acceptability of negative emissions. What is key is that firm insights can start to shape action now while issues of greater uncertainty are considered further and subjected to further research.

1. Introduction

1.1. Research context

The European Union (EU) faces the daunting challenge of moving from a fossil-heavy, carbon-intensive energy system to one that needs to be zero greenhouse gas (GHG) emission soon after 2050. The Commission's Clean Energy Package (European Commission, 2016a) states that '*The implementation of the EU's ambitious Paris climate change commitments is now the priority and depends to a large extent on the successful transition to a clean energy system as two thirds of greenhouse gas emissions result from energy production and use.*' In this transition, other central priorities for the EU include ensuring a participatory consumer model, with fair pricing and protection for the vulnerable, and ensuring security of supply.

The EU's low carbon roadmap published in 2011 highlights the objective of reducing GHG emissions by 80-95% by 2050 compared to 1990 (European Commission, 2011). This moves beyond some of the incremental policies to date to real structural change of the energy system (Spencer et al., 2017). Key to this structural change of the system will be large-scale investment in a range of low carbon technologies. To this end, the Commission has established the Strategic Energy Technology (SET) Plan, which prioritises research and innovation across a range of technology groups. Key actions are further elaborated in the *Progress in 2016* report (European Commission, 2016b). It is understood that the Commission is in the process of developing its Mid-Century Strategy to update the previous long-term strategy and reflect the goals of the Paris Agreement, requiring net zero emissions around or soon after 2050.[1]

The question is how do the many technologies recognised as important for the low carbon transition play out together in the same system? The uncertainty around R&D, commercialisation, policy support, and social acceptability means that there are numerous eventualities in terms of system design. If one technology subject to rapid cost reduction is deployed at scale, this will have an impact on the role of alternative competing technologies. Furthermore, inter-temporal dependencies may emerge, where specific technologies and their use in the system rely on earlier deployment of others.

In this study, we consider these issues for the UK energy system transition, investigating the interplay and interdependencies between different technologies by exploring the range of uncertainties through the simulation of a large number plausible pathways. Exploring future uncertainty in an integrated analysis can provide insights into the strategic planning process about the role of different technologies under different circumstances. In other words, for the high deployment of technology X, what are the characteristics of technology X, those of technologies Y and Z, and the broader system e.g. carbon price signal, resource availability

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[1] EU to aim for 100% emission cuts in new 'mid-century roadmap'. https://www.euractiv.com/section/climate-environment/news/eu-to-aim-for-100-emission-cuts-in-new-mid-century-roadmap/ [Access 15.01.18]. The European Parliament recently backed proposals for a net-zero emissions target by 2050, increasing ambition to be in line with the Paris Agreement goals, https://www.2050pathways.org/european-parliament-shows-strong-support-net-zero-target-2050/ [Access 15.01.18]

etc. In using the UK as a case study, we will consider the transferability of insights to other Member States, cognisant of the distinctive national circumstances.

1.2. Uncertainty in the role of energy technologies

Determining the future role of technologies used across the energy system is an important exercise for a number of reasons. Firstly, it can help demonstrate the feasibility of different systems to decision makers. This is important in the context of deep decarbonisation in the longer term (Bataille et al., 2016), as set out under Article 4.19 of the Paris Agreement, which is a timeframe that many countries have yet to fully consider. Modelling analysis in the 2000s in the UK certainly helped demonstrate that there were different technologies that could deliver 60% (Marsh et al., 2003) and then 80% (Pye et al., 2008) reductions in GHGs, relative to 1990 levels. Secondly, it can orientate the research and policy making community in a certain direction, as to what to focus R&D and demonstration budgets on. A recent example has been the increase in research on greenhouse gas removal (GGR) technologies, with the UK research council, NERC, launching a large programme of work.[2] This research direction is very much in response to the proliferation of such technologies in energy systems analysis, notably Integrated Assessment Models (IAMs) (Fuss et al., 2014; Vaughan and Gough, 2016).

However, many of the prospective technologies for the low carbon transition may be conceptual, part-demonstrated (at a very early stage of technology readiness), or only currently play a niche role in the system. There are therefore large uncertainties concerning the role that technologies play, driven by many different factors. Take the example of solar; when (Lewis, 2007) discussed the prospects of cost-effective solar, highlighting some of the key barriers for widespread use, including costs of $0.25-0.30 per kilowatt-hour (kWh) compared to other generators at $0.03-$0.05, he may have had difficulty envisaging this technology competing on costs 10 years later. Certainly, key scenario providers did not envisage such a role. In 2002, the IEA projected 2020 levels of 10 GW, from the current level of around 4 GW;[3] total global capacity for 2016 stood at 291 GW.[4] This has happened in large part due to large cost reductions, from initial large investment in R&D in the German and Japanese systems, followed by large scale production in China.

Improved performance and cost reduction across technologies and their deployment in different societies is complex, and covered extensively in the fields of technology innovation and socio-technical transitions (Gallagher et al., 2012; Geels, 2005; Smil, 2016). Energy system models, as used in this study, make assumptions about the improvements in costs and performance based on exogenous learning curves, and historical precedents in terms of deployment. In other words, there is no attempt to model the innovation and learning process, largely due its complexity, although some efforts have been made in the past to endogenise these effects (Anandarajah et al., 2013; Grübler et al., 1999).

Despite the relatively simplistic approach taken, it is still possible to capture the uncertainty of the assumptions on technology learning and deployment, using different approaches. While the modelling community in the UK

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[2] NERC GGR Research programme, http://www.nerc.ac.uk/research/funded/programmes/ggr/

[3] Solar energy has plunged in price—where does it go from here? Arstechnica, https://arstechnica.com/science/2017/04/whats-next-for-solar-energy/

[4] Renewable Energy Statistics 2017, IRENA, http://www.irena.org/publications/2017/Jul/Renewable-Energy-Statistics-2017

and elsewhere has historically overlooked the use of uncertainty analysis (Usher and Strachan, 2012), it has been increasingly recognised as critical part of ensuring modelling analysis help facilitate robust decision making, both by researchers (Pfenninger et al., 2014) and decision makers (McDowall et al., 2014). And the modelling community is responding. In the UK context, (Fais et al., 2016) undertook an uncertainty analysis to explore which low-carbon technologies and resources, focusing on nuclear, carbon capture and storage (CCS), bioenergy, and renewable electricity, had most influence on the long-term development of the energy system under emission reduction targets. The analysis highlighted complementarities and substitutability between technologies, critical options that are robust to uncertainty, wider system effects, and path dependencies.

(Pye et al., 2015) explored the potential for uncertainties across technologies and resources to undermine reduction targets, if policies were not robust to such uncertainties. The analysis also highlighted, via a global sensitivity analysis (GSA) using a multivariate regression analysis technique, which uncertainties had the largest influence on meeting decarbonisation goals. (Usher, 2015) undertook a similar analysis, using a GSA known as the Morris Method, to explore which model uncertainties across a range of technology and resource groups influenced the model solution the most. Similar to (Pye et al., 2015), biomass resource availability and gas price proved to be highly influential, as did the CO_2 emission constraint. A further analysis by (Pye et al., 2017) considered uncertainties across key technologies and resource under more stringent constraints, in meeting net-zero emission targets. They highlighted the critical role of bioenergy and CCS in particular, as confirmed by other global studies (Krey et al., 2014) but also the necessary changes to consumer demand if very tight carbon budgets were not to be exceeded.

While the above analyses focused on parametric uncertainty, other analyses have been undertaken to explore model structure uncertainty (Li and Trutnevyte, 2017) and that representing lack of foresight in planning (Usher and Strachan, 2012). In the first paper, using a Modelling to Generate Alternatives (MGA) technique, the authors show the many possible near-optimal pathways to decarbonising the power sector. In the second paper, the cost of uncertainty (limited knowledge) was shown to be very high for fossil fuels, and less so for biomass resources. Many of the papers on the uncertainty of technologies and resource assumptions provide important information about the impact of uncertainties on model results, and particularly from the GSA analyses, the ranking of uncertain assumptions based on solution influence. However, these analyses provide fewer insights into the relationships between technologies in different systems, and the impacts of deployment of one type of technology on another.

In the next section, we propose an approach to enhancing our understanding on coevolution (deployment together) and competition (substitutability) across technologies and resources. This paper is structured as follows; we first describe our approach to modelling different pathways, in view of the SET Plan priorities (section 2), before presenting the results (section 3). We then conclude with the key insights for policy making, in the UK and across other Member States (section 4).

2. Methodology

The objective of the modelling is to produce a wide range of plausible low carbon technology pathways that meet UK legislated targets, prior to and in 2050 (HM Government, 2008), their variation driven by the uncertainty in cost and performance across different technology groups. The UK ambition of at least an 80% reduction in GHGs relative to 1990 is consistent with the ambition at the EU level, allowing for comparability given similar climate policy ambition; however, in the mid-term the UK targets are arguably more ambitious, at 57% in 2030 compared to 40% for the EU.

To assess the deployment of technologies, it is crucial that a whole systems perspective is taken so that the impact of choices in one part of the system are captured in another part. We therefore use an integrated energy system model, ESME, which captures these interlinkages. This model is also technology-explicit, to provide a more detailed representation of different technology groups in order to better understand the characteristics that enable deployment. It is important to note that this modelling does not consider the innovation cycle as an endogenous process (as noted in the previous section), which could assess the impact of R&D expenditure, technology learning, and global spill over. The deployment and the resultant cost reductions that one might observe are not linked in the model. Rather the approach is to try to cover a large part of the uncertainty space, to explore the many combinations of technology costs, to better understand future deployment and costs of different technology portfolios.

While the analysis focuses on the UK, some of the insights from this case study will be transferable to other Member States. To try and facilitate transferability, the analysis considers i) similar levels of decarbonisation that have been proposed in the current EU roadmap, and ii) captures many of the technologies that will need to be deployed at scale in other Member States. However, it should also be recognised that the UK system is also quite distinctive, and in section 4.3, we further consider the transferability of insights.

2.1. The ESME model

The analysis used the ESME (Energy Systems Modelling Environment) model to simulate a range of different low carbon pathways. ESME is an integrated energy systems model for the UK, used to explore the different technology investments across conversion and end use sectors required for energy system decarbonisation (Heaton, 2014). It is spatially resolved, providing insights on the energy system change in different regions of the UK (Li et al., 2016). ESME also features a module for simulating large numbers of runs to explore parametric uncertainty of model inputs, through Monte Carlo sampling (Pye et al., 2015, 2014), and it is this feature that is used here. In addition to its use in research, ESME has been used to inform energy policy and strategy in the UK, both for the Department for Energy and Climate Change (DECC, 2011),[5] and the UK Committee on Climate Change (CCC) (CCC, 2013, 2011).

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[5] The department now covering the DECC function is the Department for Business, Energy and Industrial Strategy (BEIS).

Built in the AIMMS environment, the model uses linear programming to assess cost-optimal technology portfolios. It is across the technology groups that the exploration of uncertainty is focused; capital expenditure levels, fuel costs and resource potential e.g. biomass imports. The number of technologies total around 150, providing near complete coverage of the groups under the SET Plan. Energy sector representation is typical of other similar models, and includes power generation, industry, buildings, transport and other conversion sectors e.g. biofuel production, hydrogen production. The model endogenously determines how to meet a set of exogenous energy service demands in a cost-optimal manner, through investment in end use technologies (including efficiency measures), and the production and supply of different energy forms.

In the buildings sector, a rich characterisation of low carbon technologies is provided, particularly for heat pumps, district heating (incl. infrastructure) and building fabric retrofit. The transport sector also incorporates key low carbon technologies, and the different infrastructure required to deliver alternative fuels e.g. electricity charging infrastructure and hydrogen networks. The industry sector is characterised more simply, focusing on efficiency gains, fuel switching measures and carbon capture and storage (CCS). Transformation sectors (power generation, hydrogen production, biofuel production) represent the key low carbon technologies, and associated infrastructures (to enable inter-regional transmission). Primary resource supply is characterised by commodity price and resource availability, with no distinction between imports and domestic indigenous production (except for biomass), and no explicit representation of resource and upstream sectors.

It is worth noting a few characteristics of this type of model that have an important influence on deployment of technologies.

- *Delayed investment*. Due to the objective function formulation, to minimise discounted system costs over the model time period (NPV terms), investment decisions are taken as late as possible based on the use of a societal discount rate of 3.5%. For example, under a 3.5% discount rate, the value of an investment in 2050 is 25% of that same investment today, reflecting the difference in utility gained by investing now compared to the future. This means that sectors will try to decarbonise as late as possible, within the constraints of the system e.g. technology build rates.
- *Aggregate temporal structure.* The model provides a proxy representation of electricity system operation and supply-demand by timeslicing the 24 hour day into five periods – Overnight, Morning, Mid-Day, Early Evening and Late Evening. This aggregation means that the benefits of storage technologies, which allow for rapid discharge over very short periods to meet additional demand, are underplayed.[6] The option for timeslice resolution to be increased is an option in ESME but this increases model solution times by between 2-3 times making it problematic for large numbers of simulations, as undertaken in this research.

  Additional constraints such as electricity capacity reserve constraint, (ensuring capacity to meet peak demand), flexibility reserve (ensuring the system can ramp up quickly) and a ‘no wind’ constraint (to

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[6] In the next version of ESME, improvements will be made to better represent energy balancing services, which should result in an enhanced role for storage technologies.

ensure sufficient dispatchable generation to meet demand on an extremely low wind day) help to enhance the representation of system operation despite this aggregate temporal structure.

Note that the modelling presented in this report uses ESME v4.2. Further information on the data sources used in the model can be found in the ESME documentation (ETI, 2016).[7] However, it is important to note that the nuclear costs, and uncertainty distributions are based on our own work (see Annex A), and therefore the results produced in this report and insights should not be attributed to the official ETI version of ESME v4.2.

2.2. Technology group focus

The focus of the modelling analysis undertaken in this research has been determined by the SET Plan groupings (Table 1). A mapping exercise determined the extent of ESME's coverage of these different groups. In the main, the coverage is extensive. Annex A provides a listing of the technologies in ESME subject to uncertainty characterisation, and their classification according to SET Plan Groups. However, there is one priority area of the SET Plan that the model does not capture in the detail, which is smart systems in buildings. Further work is ongoing in ESME (outside of this research) to enhance this representation.

Table 1. SET Plan groupings based on objective, and mapping in ESME model

Objective	**ID**	**Description**	**ESME mapping**
No. 1 in renewables	1	Performant renewable technologies integrated into the system	Focus on renewable generation technologies in ESME, and technologies that allow for their system integration e.g. storage
	2	Reduce cost of technologies	
Consumers in the energy system	3	New technologies and services for consumers	Focus on new technologies used in the buildings sector, including district heating systems, solar PV / thermal, and electrification via heat pumps and resistive heating. The role of smart systems is not explciitly modelled in ESME.
	4	Resilience and security of energy system	
Efficient energy systems	5	New materials and technologies for buildings	Energy efficiency through retrofitting of buildings. Note that technologies under 3 could also in principal be categorised here.
	6	Energy efficiency for industry	Focus on energy intensity of production in the industrial sector.
Sustainable transport	7	Competitive in global battery sector and e-mobility	Focus on the role of electric mobility across the system. Note that the version used in this analysis (v4.2) does not include electrification of freight, although that has now been added to the latest version.
	8	Renewable fuels and bioenergy	Focus on the use of biofuels across the transport sector.
Carbon capture utilisation and storage	9	Carbon capture storage / use	Focus on the application of CCS in power generation, industry and for H_2 and biofuel production.
Nuclear safety	10	Nuclear safety	The focus in ESME is on the role of nuclear technologies in the system, not specifically on safety issues.

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[7] The data input parameters can be downloaded from the ETI website at http://www.eti.co.uk/programmes/strategy/esme. Note that these data inputs are for v4.3, and in the main, are consistent with the input assumptions for v4.2, which is the version used in this analysis. The key updates in v4.3 are shown in the 'change log' at the end of the document; all have been integrated into the version we are using (v4.2).

2.3. Parameter uncertainty

To explore the many different transition pathways, and technology deployment within each, key parameters across the different technologies groups are characterised as uncertain. The focus of parameter uncertainty is on costs, particularly the capital expenditure (capex) across energy technologies, and fuel prices. This makes sense when using a cost-optimising model, where the solution seeks the most cost-effective pathway, based on the aggregate discounted costs, subject to a range of constraints (climate policy targets, build rates, resource availability).

Figure 1 shows the number of uncertain parameters in the model, which total around 140, and their distribution across the different SET Plan Groups.[8] In addition to the focus on capex, uncertainty across resource costs is also considered, as is that associated with specific technology build rates and biomass resource availability. Build rate uncertainty for CCS and nuclear in particular reflects that many other factors determine deployment in addition to cost, as such technologies are unlikely to be market-driven in the same way as, for example, renewables. Resource limits on UK biomass and biomass imports are also included. Whilst ensuring that we consider uncertainty across all technology groups, previous analysis also provides a guide as to what our focus should be, in terms on what inputs influence the model the most based on global sensitivity analyses (Pye et al., 2015; Usher, 2015).

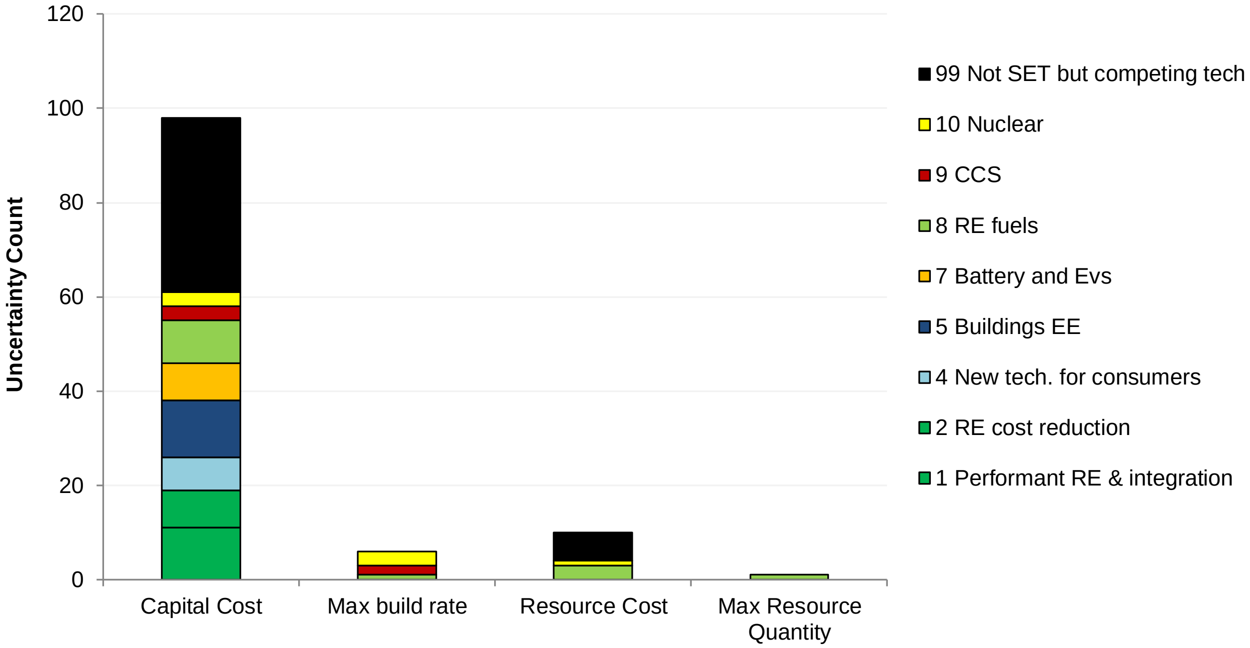

Figure 1. Mapping of parameter uncertainty across SET Plan Groups (see Table 1 for description of the categories)

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[8] Most of the key low carbon technologies in ESME (and higher carbon alternatives) are included in the uncertainty analysis, with the exception of the industry sector. There is also not explicit modelling of smart systems. A full list is provided in Annex A.

Characterising uncertainty in the ESME model is done by applying an uncertainty range to the 2050 parameter value. The approach does not attempt to determine probability distributions through formal elicitation approaches as done for example in (Usher and Strachan, 2013) but rather takes an approach that considers ranges that reflect the maturity or knowledge about a given technology. For example, a CCGT plant has a relatively narrow cost range, as it is well understood given its maturity, compared to CCGT w/ CCS, which has a much wider range. Therefore, for each parameter in question, a minimum and maximum value in 2050 is established, with a median value typically the central estimate used in often-run deterministic analyses. Using these three values, a triangular distribution is employed, valid for representing preferences over a certain value with symmetric or asymmetric variations around it, and in the absence of other data to formulate via elicitation actual probability distributions. All of the values used can be found in Annex A.

In the main, ranges are established for mature (+/-10%), new (+/-30%), and novel / emerging (+/-50% or more) technologies. The range distribution is sometimes asymetric, where for a technology it is unlikely that we would observe cost increases to the same extent as reductions. Given the deep uncertainty across many of these assumptions, over precision based on the use of subjective epert derived probability distribution functions does not seem merited, and for such long term analysis is often argued against (Lempert et al., 2003; Spiegelhalter and Riesch, 2011). (Morgan et al., 1992) describe at length some of the challenges of probability assignment.

The uncertainty distributions are sampled using the Monte Carlo technique. 600 simulations were undertaken to cover the uncertainty space. This again reflects earlier analyses, which have used a specific sample size to ensure a reasonable coverage of the uncertainty space (Morgan et al., 1992). While most of the distributions are independent, there are some that are correlated during the sampling procedure. This is to ensure that technologies that are similar in nature (for example, a light duty electric vehicle and an electric car) move in the same direction. While the distribution is applied to the 2050 value, earlier period values are estimated by interpolating the simulated 2050 value back to the historic estimate in 2010, using the existing trajectory. An example is provided in Figure 2, showing how the maximum and minimum value of an uncertainty range in 2050 is interpolated back to 2010, using the base trajectory (in the deterministic case).

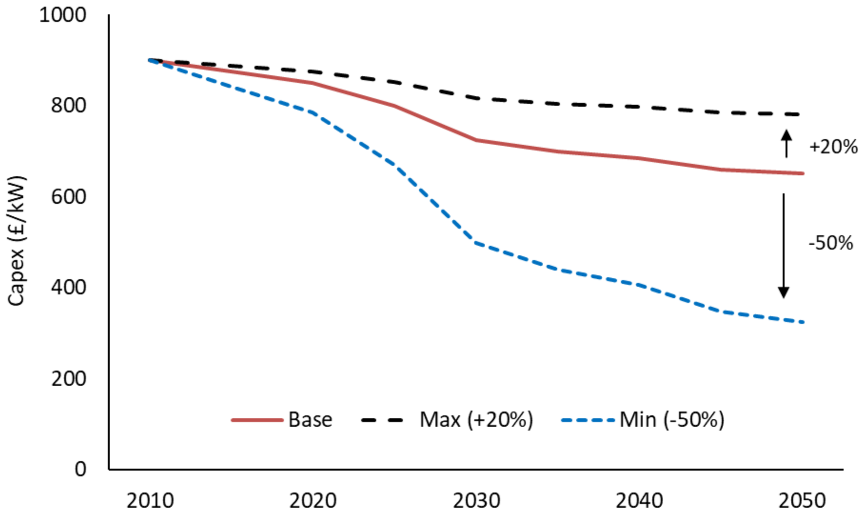

Figure 2. Uncertainty ranges, and interpolation of simulated values

2.4. Model scenarios

Using the above simulated uncertainties, three distinctive scenarios have been undertaken to explore the deployment of energy technologies in the UK system (Table 2). Scenarios reflect major areas of uncertainty that we want to hold constant due to their large impact on the system, in order to explore the impact of technology uncertainties under such conditions. Two scenario dimensions are represented – i) climate ambition, and ii) the availability of CCS.

The first scenario, RM,[9] meets the UK's legislated climate ambition of an 80% reduction in GHGs (relative to 1990), and the interim carbon budgets, which have been set on the basis of guidance by the CCC to deliver the long term emission reduction trajectory (CCC, 2017). The second scenario, RM-NCCS, reflects a scenario where no CCS is deployed in the system but in which the UK climate ambition still needs to be met. This is an important scenario in the UK context, where CCS is typically chosen in the model because it offers the most cost-effective pathway (ETI, 2015). This scenario provides the basis for considering the other pathways that would emerge in the event that CCS does not scale as envisaged in many scenarios, including implications for costs and for the deployment of other technologies. Such scenarios are critical as the credibility of CCS and BECCS comes under increasing scrutiny (Anderson and Peters, 2016; EASAC, 2018). Finally, RM-CP provides a lower climate ambition case. This case tests a 'failure to ratchet' scenario, to explore the impacts on deployment under weakening ambition which falls short of the long term legislated targets, resulting in lower incentives for abatement. The resulting level of ambition in 2050 is a only marginally higher to that that which is required in 2030, under the UK's 5th Carbon Budget.

It is worth highlighting a specific area of uncertainty that has not been considered in the scenario set but which we know has large impacts on meeting decarbonisation targets, namely energy service demand projections. Numerous uncertainties lie in the core drivers chosen (GDP, population), and in their relationship to demands, which is often premised on a historical time series and fails to account for how new models of service provision might come into play and impact demand for energy. Further research is needed to better understand the implications of uncertainty across energy service demand projections. The model was run for each scenario using the 600 Monte Carlo uncertainty simulations, resulting in 1800 individual model runs.

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[9] RM is an abbreviation for 'REEEM', to denote these scenarios being run as part of this EC-funded project.

Table 2. Scenarios for modelling

Scenario Name	Climate ambition*	Technology availability
RM	-80% GHG reduction in 2050 (rel. to 1990), -53% in 2030	All low carbon options
RM-NCCS	-80% GHG reduction in 2050 (rel. to 1990), -53% in 2030	No CCS
RM-F2R	-64% GHG reduction in 2050 (rel. to 1990), -48% in 2030	All low carbon options

* The 2030 value includes international shipping and aviation emissions, which is not included in the UK carbon budgets but is in the 2050 target. To ensure consistency, the 2030 reduction above is on the same basis as the 80% target, and include international transport emissions. This means that the reduction level is lower than the UK 5th Carbon Budget target of around 57% in 2030.

2.5. Results analysis

The challenge of generating large numbers of scenarios is then how to mine the resulting information to understand the factors driving the deployment of different technologies. Crucially, for ESME, we have a robust understanding of the influence of different input uncertainties on the model outputs from using different sensitivity analysis techniques (Multivariate Regression Analysis and Morris Method), referenced in section 2.3. This provides an understanding of the influence of different input uncertainties on the model results, as they relate to system costs and emission reduction objectives. These analyses enable us to better understand what drives technology deployment at the system level, and helps us avoid misreading trends and relationships in the data that may not be statistically proven.

What these sensitivity analysis techniques do not provide are more detailed insights into the trade-offs between technologies, either within sectors or between sectors. In this study we therefore try to develop our understanding of technology trade-offs through clustering analysis. The basic approach is as follows:

- Identify a set of metrics that characterise a potential low carbon pathway that also reflects some of the priorities in the SET Plan groups.
- For a given metric e.g. CCS deployment, deploy a clustering algorithm to group the simulations.
- Overlay the clusters on to different metrics to explore, for example, what a high CCS system cluster means in terms of biofuels in the transport sector, renewables deployment in the power sector, and energy provision in industry.

This a one-at-a-time approach to clustering, using the k-means formulation in Tableau. For a set number of clusters (k), in the case of this analysis k=5, the algorithm partitions the data into the said number of clusters. Each cluster is set around a central point that is the mean value of all the points in that cluster. K-means locates these points through an iterative procedure that minimizes distances between points in the cluster and the central point. This type of clustering produces partitional clustering, meaning that each data point is allocated to a specific cluster, and can’t be a member of more than one cluster (Tan et al., 2006). The research that emerges from this paper will consider multi-dimensional clustering, which aims to consider all system characteristics at the same time, and cluster accordingly. This approach is being worked on in parallel, and will be published as an academic paper in the near future.

The types of system characteristics considered for this clustering analysis are shown in Table 3.

Table 3. Pathways metrics subject to inter-metric comparison using clustering approach

Sector	**System characteristic relating to deployment level**
Power generation	CCS generation; Intermittent renewable generation (focus on wind); Nuclear generation; Storage capacity
Transport	Electrification level; Biofuel consumption; Hydrogen consumption
Buildings	Electrification level; Gas consumption; District heating deployment
Industry	CCS deployment; Low carbon fuels
Resources	Biomass consumption (system wide); Gas consumption; System wide CCS deployment

3. Results

This section presents the results across the SET Plan technology groups. Again the objective is to consider the conditions for deployment of these different groups whether that be related to system conditions (marginal abatement costs, climate constraints), or trade-offs between technologies.

We have structured the results section as follows:

3.1 Focuses on power generation, specifically on renewables, the role of storage, and the role of other large generators such as nuclear and CCS. This covers groups 1, 2, 9 and 10 in Table 1.

3.2 Focuses on buildings, predominantly the provision of heating services via low carbon technologies, and the conservation of heat via fabric retrofit measures. This therefore focuses on groups 3, 4 and 5 in Table 1.

3.3 Focuses on transport sector, through decarbonisation of fuels and new technologies. This therefore focuses on groups 7 and 8 in Table 1.

3.4 Focus on the industry sector, through decarbonisation of fuels, efficiency improvements and the deployment of CCS. This therefore focuses on groups 6 and 9.

3.5 Focus on cross sectoral indicators, including the use of fossil fuels and biomass across the system, and the role of CCS across all sectors.

3.1. Power generation

Numerous assessments have shown the criticality of early power sector decarbonisation, as often the most cost-effective and policy actionable sectors, and as a precursor to wider electrification of the energy system (Williams et al., 2012). This is what is currently being observed in the UK, as this sector leads in contributing to recent emission reductions. This has primarily been a result of coal falling out of the system, in large part driven by the carbon floor price[10] and the Government's decision to ban all coal generation by 2025 (BEIS, 2018a). The decommissioned coal plant capacity seen in recent years are being replaced by renewables (in the main) and gas generation.

In the UK context, three key technologies are often discussed as providing the platform for electricity system decarbonisation – renewables, notably wind, nuclear and CCS. On renewables, the UK has one of the largest offshore potentials in Europe, and is starting to see large reductions in offshore wind after some years of

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[10] Carbon Price Floor (CPF) and the price support mechanism. House of Commons Briefing paper, Number 05927. January 2018. http://researchbriefings.files.parliament.uk/documents/SN05927/SN05927.pdf (Accessed 31.1.18)

investment and Government support.[11] Nuclear has been an option promoted for many years although there are considerable doubts about the current Hinckley C project, whilst CCS has strong prospects due to the numerous storage options and offshore infrastructure to facilitate the storage of CO_2 but has been subject to lack of policy ideas resulting in limited prospects for technology demonstration, at least in the very near term (Poyry, 2016). From their latest projections (BEIS, 2018b), the Government's perspective is that renewables appear to be most promising of the three, accounting for 52% of generation in 2035, compared to 32% nuclear and 2% CCS. Current shares for renewables and nuclear are 26% and 21% respectively, with 42% of current electricity produced from gas generation.

What is clear from the modelling in this paper, and from other studies (ETI, 2014; Usher, 2015), is that the level of CCS deployment in the UK system has a strong impact on the costs of transition to a low carbon system. Figure 3 illustrates, for the year 2050 by which time CCS has had the opportunity to deploy, that higher abatement costs are observed for those simulations where CCS deployment is lower. This is for the RM scenario, under which UK policy ambition is achieved. The relative cost-effectiveness of this technology is illustrated by the high deployment even under relatively low carbon prices (in the RM-F2R scenario) of around £40/tCO_2. Deployment is in fact higher on average in this lower ambition case, as the emissions that do arise (i.e. not captured) can be managed within the permitted emissions under the lower ambition target; one-third of the RM-F2R sample have generation levels above 320 TWh, compared to only 4 simulations in the RM case. It is evident that the deployment of this technology, impacted by a range of factors (capex, build rate, gas price), is an important influence on the costs of abatement.

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[11] The latest auction in September 2017 produced a strike price for two offshore wind projects of £57.50 /MWh. See 'Contracts for Difference Second Allocation Round Results' at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/643560/CFD_allocation_round_2_outcome_FINAL.pdf (Accessed 31.1.18)

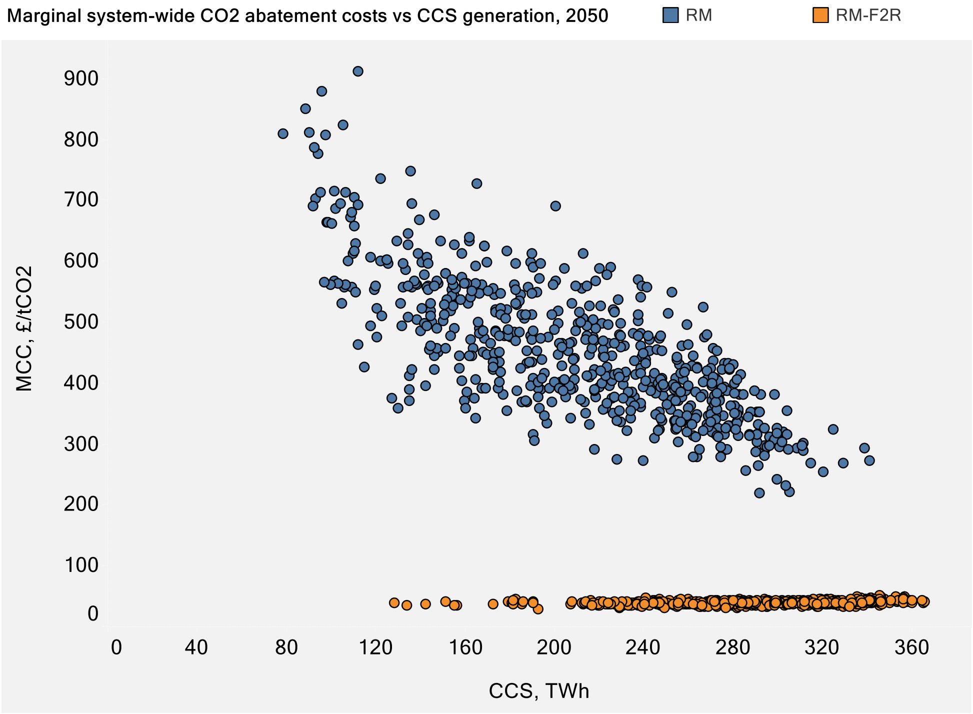

Figure 3. The impact of different levels of CCS generation (RM scenario) on marginal costs of CO_2 abatement in 2050

CCS deployment is understood to have an impact on the cost of decarbonisation, in effect reducing it as deployment increases (as highlighted also in Figure 5). This is of course due to the technology allowing for continued use of fossil fuels, and when used in combination with bioenergy (BECCS), offsetting hard-to-mitigate emission sources by the generation of negative emission credits.[12] Figure 4 compares CCS deployment (horizontal axis) against a range of other pathway metrics, to explore the role of other technology and fuel options in view of high or low CCS deployment. In the first instance, clusters are determined based on the distribution in the top left graph (a), plotting CCS against nuclear generation. The blue cluster is the high CCS-low nuclear group of simulations while the red-pink clusters are the high nuclear-low CCS simulations. These cluster groups are then overlaid across all other selected distributions.

While nuclear generation is sensitive to CCS deployment, wind generation levels remain at a similar level (b), highlighting the importance of this technology for the UK system. The high CCS-low nuclear cluster (blue) also sees higher gas use (c), with CCS allowing for its continued use in power generation, but also providing emissions

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[12] Negative emissions mean removing CO_2 from the atmosphere, in this case through bioenergy with carbon capture and storage (BECCS). It is based on the assumption of carbon-neutral bioenergy (that is, the same amount of CO_2 is sequestered at steady state by biomass feedstock growth as is released during energy generation), combined with capture of CO_2 produced by combustion and its subsequent storage in geological or ocean repositories. In other words, BECCS is a net transfer of CO_2 from the atmosphere, through the biosphere, into geological layers, providing in addition a non-fossil fuel source of energy.

headroom to enable increased or continued gas use in other sectors. Bioenergy use appears on average higher for these simulations (blue cluster) in (d) compared to the high nuclear-low CCS cluster, while hydrogen use in transport is lower (g). This lower level of hydrogen use reflects the need for less mitigation in end-use sectors in higher CCS deployment cases, notably the transport sector. Electricity consumption in end use sectors does not differ across different levels of CCS deployment (f and h), while gas in buildings is absent from the system in 2050, and biofuel production is not employed due to its relatively lower cost-effectiveness than estimated for other uses of bioenergy.

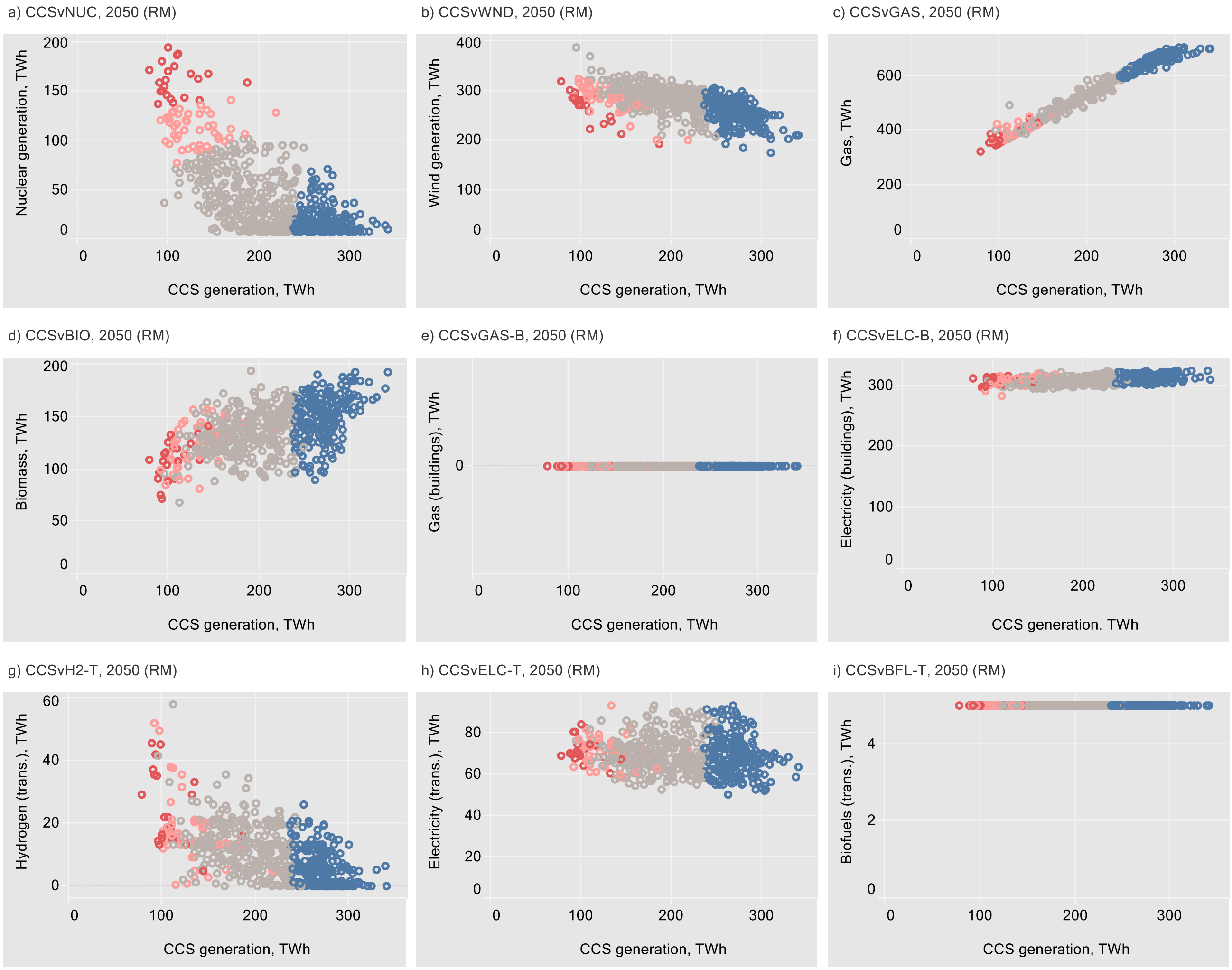

Figure 4. CCS generation compared to other pathway metrics (RM scenario). The red cluster denotes lower CCS generation and higher nuclear, with the opposite true for the blue cluster.

The global sensitivity analysis used in earlier ESME modelling suggests that bioenergy level and gas price account for the majority of the variation in system costs, and are therefore important underlying drivers of CCS deployment, not just in the power sector but also for hydrogen production, and in industry. For example, a lower gas price increases the cost-effectiveness of CCS deployment e.g. gas CCGT in the power sector, while more bioenergy resource provides increased potential for its use in combination with CCS, which in this modelling is for hydrogen production (Figure 19).

In the complete absence of CCS (under RM-NCCS), the system changes quite dramatically, in terms of the costs of decarbonising the energy system, and in respect of the deployment of competing technologies (Figure 5). Both wind (a) and nuclear (b) technologies see higher levels of deployment. For nuclear, its relatively high capital expenditure levels are no longer such a barrier in a system where abatement costs are considerably higher. Where climate ambition is weaker under RM-F2R (with an outturn carbon price of ~£40), lower levels of wind generation results, and no new investment in nuclear in the longer term is observed.

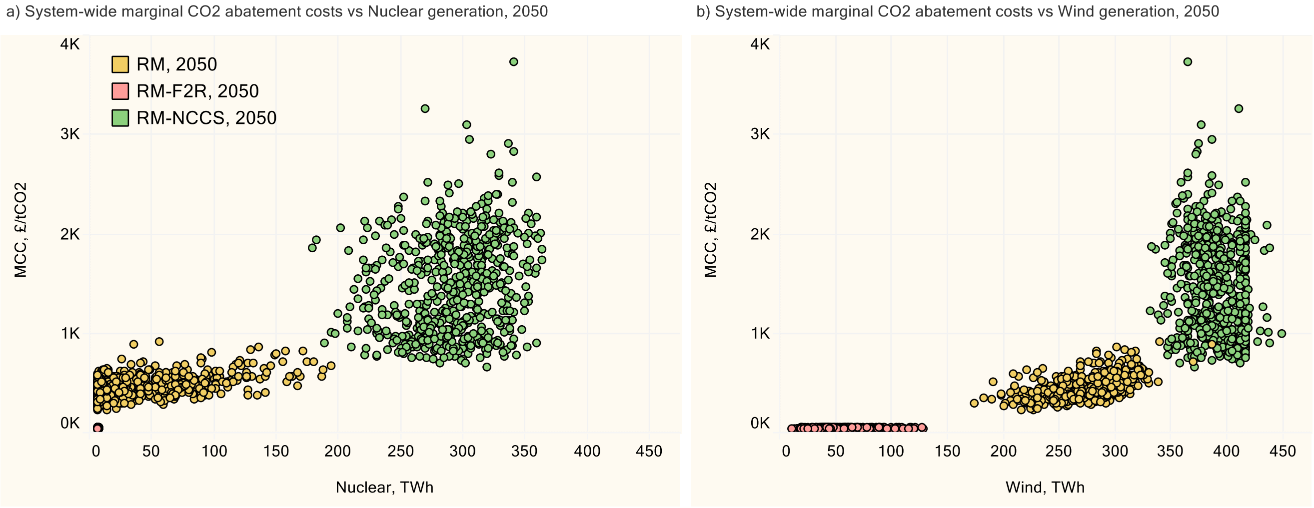

Figure 5. Marginal abatement costs of system, and level of nuclear (a) and wind generation (b) under all three scenarios, 2050. Two simulations in RM-NCCS had costs higher than £6000 /tCO$_2$, and have been omitted for presentational reasons.

These differences in median technology deployment based on generation are shown below in Figure 6, alongside the other options for electricity generation. What is particularly noticeable is the higher diversity of generation options in the RM-NCCS case, and dominance of CCS in RM-F2R, the level of which is quite surprising given the relatively low system abatement costs. This illustrates the cost-effectiveness of CCS in the ESME model. It also highlights the importance of considering zero or low CCS scenarios, given the influence this technology, with limited demonstration to date, has on the choices of the system.

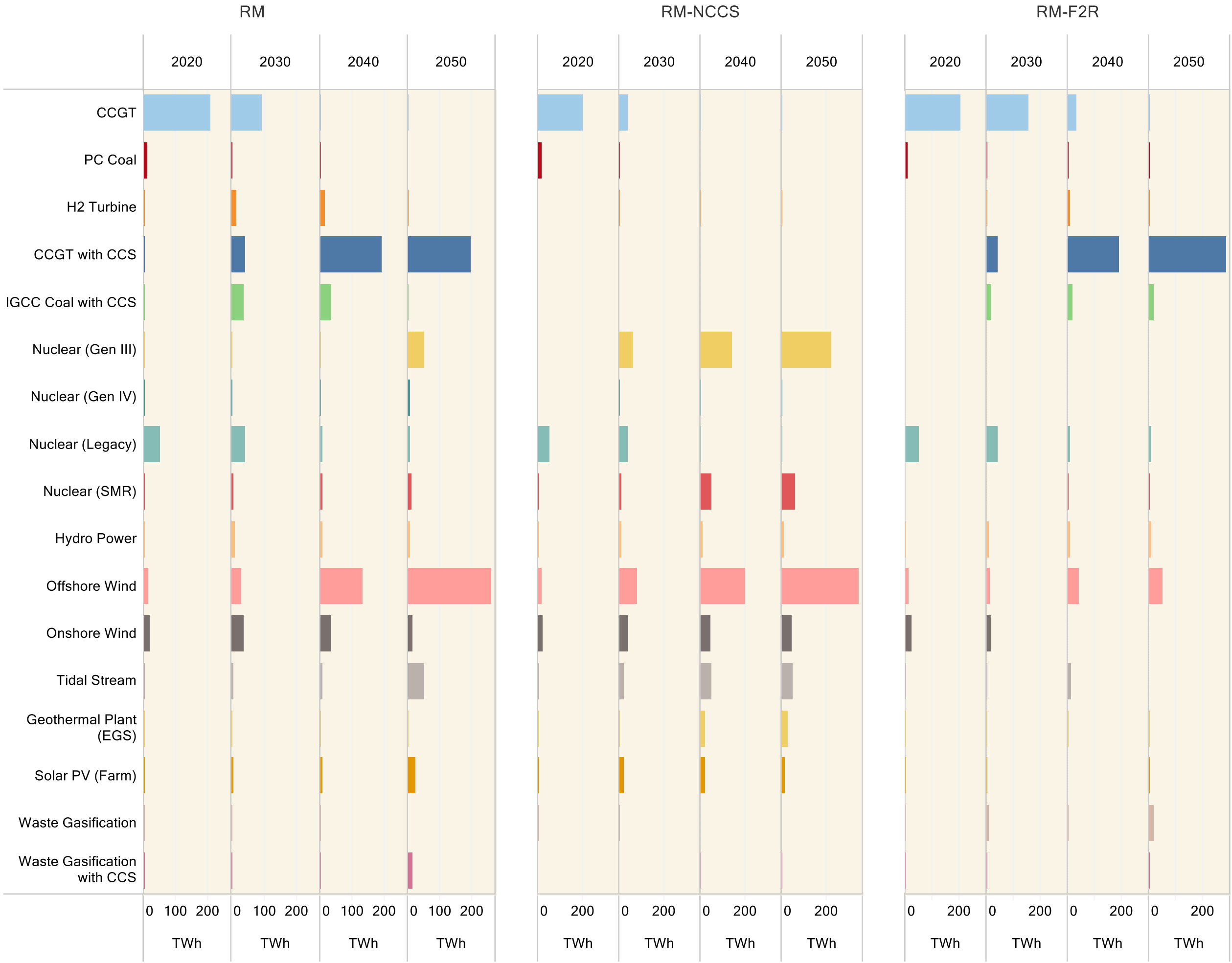

Figure 6. Median generation levels across power sector technologies between 2020 & 2050

Using the same approach as illustrated in Figure 4, Figure 7 compares wind deployment levels against the other metrics for scenario RM in 2050, although we have excluded the buildings metrics as these are not subject to change resulting from different mixes of power generation technology. A cluster distribution is first developed based on the wind-CCS distribution (a) and then overlaid on the other plots. Some patterns are observed although less clear than those for CCS; as shown in Figure 4, there is no emerging trends between the level of wind generation and CCS (a). Higher wind simulations (in the blue cluster) see lower gas use (c), lower biomass use (d) and higher levels of nuclear generation (b). Interestingly, the hydrogen use in transport for this cluster is higher than in the red cluster, resulting from the need to increase the level of decarbonisation in end use sectors in transport due to lower levels of CCS in the system. As implied earlier, the CCS driver shapes the role of the other metrics but not the deployment of wind.

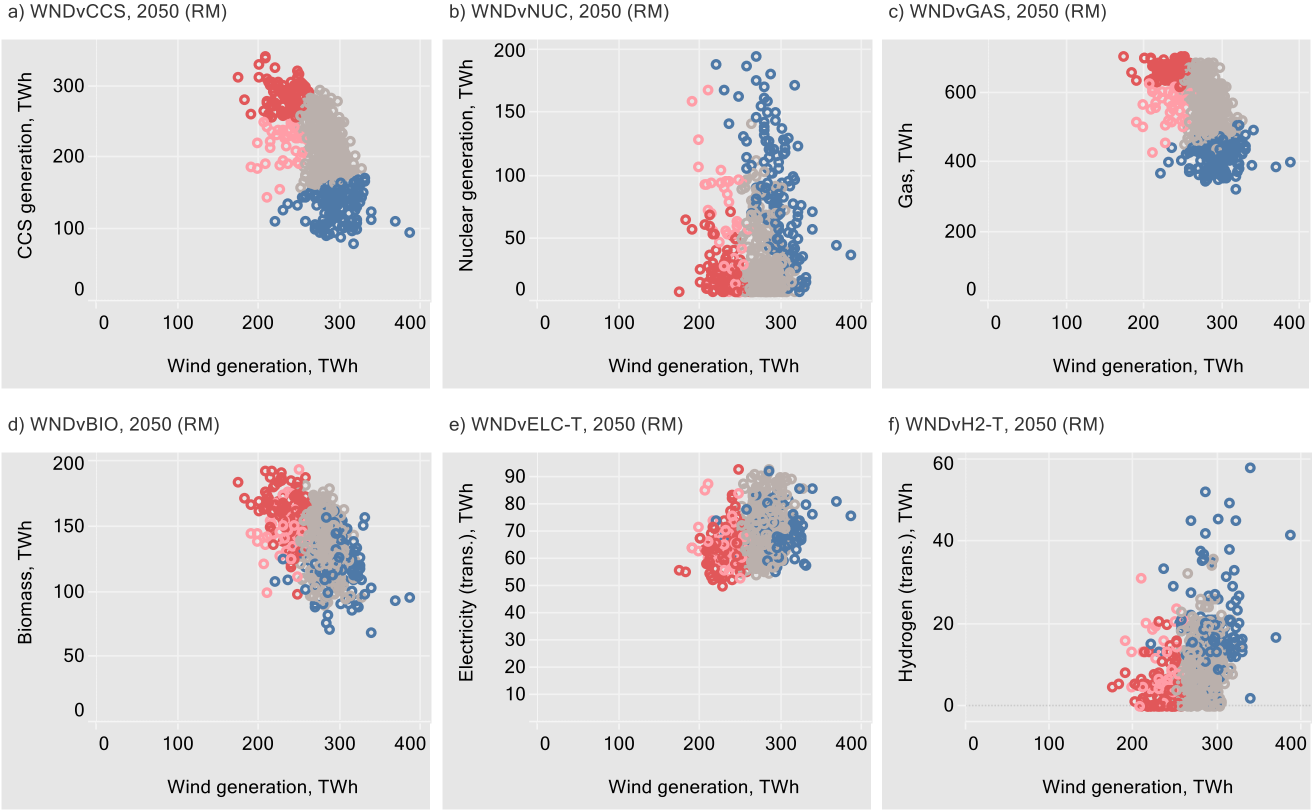

Figure 7. Wind generation compared to other pathway metrics (RM scenario). The Red cluster denotes lower wind generation and higher CCS, with the opposite true for the blue cluster.

The growth in wind generation over time (Figure 6) and increasing electrification of building heating (section 3.2) results in a more intermittent generation system while at the same time, increasing demand for electricity during peak periods of the day with high demand. Storage technologies can therefore play a crucial role in balancing demand and supply during the high demand periods. For RM (a) and RM-NCCS (b), the shift away from gas heating towards electric-based heating also sees investment in hot water storage alongside heat pumps and resistive heaters, to deal with the higher demand in mornings and evenings during the winter season. This additional building-based storage, plus the increase in the use of district heating, results in less electricity storage requirement on the system, as shown in the lower row of the panel ('Electricity system'). A different picture emerges for RM-F2R (c), where there is more investment in electricity storage. This results because more storage is needed due an increase in intermittent generation but with less investment in building system change (with gas heating remaining in place) and district heating, it makes more sense to have storage at the electricity system level.

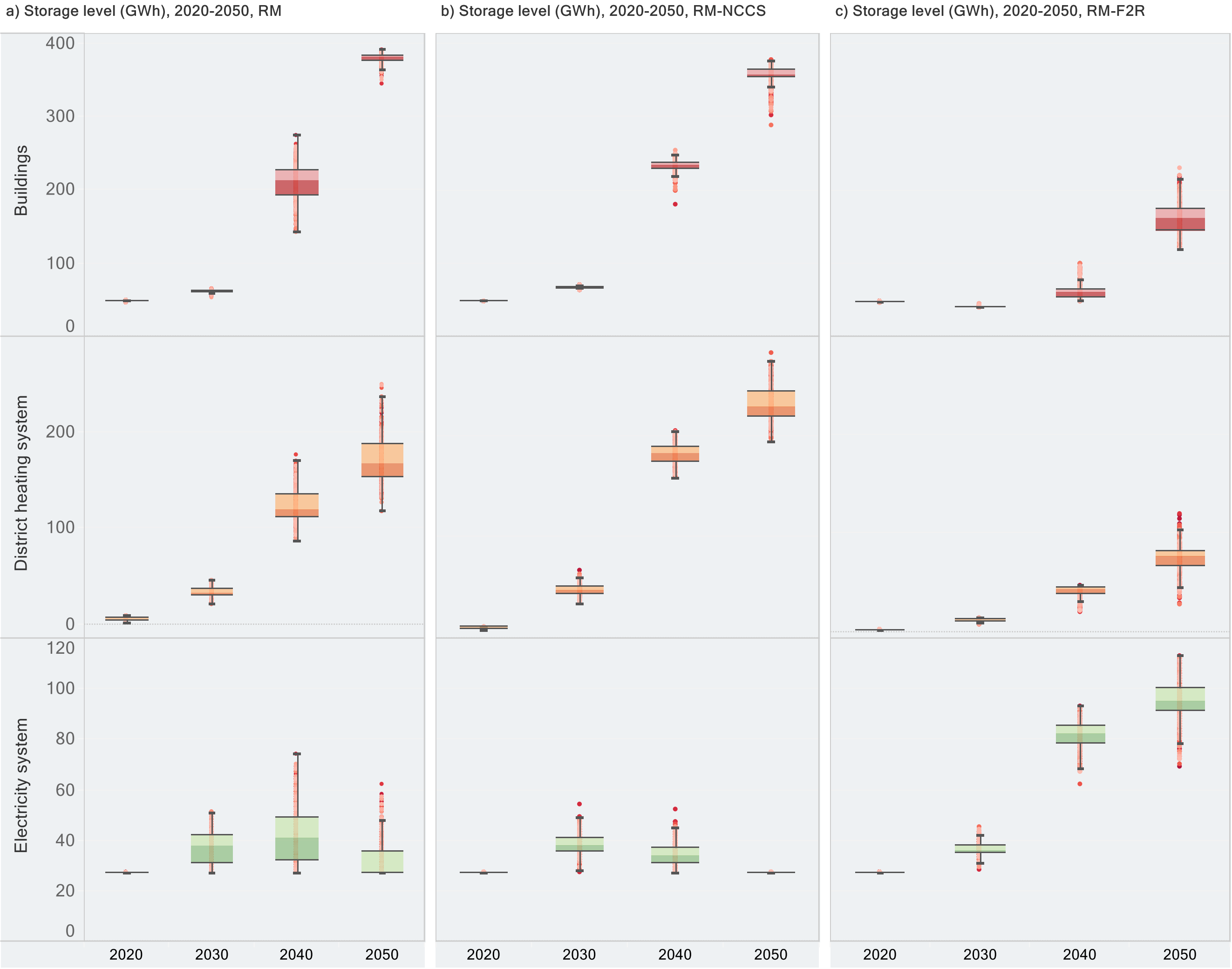

Figure 8. Storage level in the energy system for heating in buildings, district heating and on the electricity system, for three scenarios, 2020-2050. Box plots show interquartile range (IQR), while whiskers show data within 1.5 times the IQR.

As noted earlier, the aggregated temporal resolution of the model likely underplays the role of storage on the electricity system. A higher temporal resolution option has not been used due to the running of numerous simulations and computer resource needed. In addition, the model does not provide adequate representation of balancing services provided by storage technologies, in respect of services such as frequency containment, frequency replacement, and reserve replacement, to deal with system imbalances. Ongoing work to improve representation of such services should allow for an improved assessment of the role for storage.

Section summary – Power generation

A number of key points can be highlighted from this section:

- CCS deployment strongly influences the cost of mitigation, and therefore the power generation choices. This is important, as the modelling under RM/RM-F2R strongly steers towards a less diverse system of technology choices – and underlying this is the assumption that CCS will be deployed at scale. It is therefore crucial that decision makers understand the cost-effectiveness of this technology, and the influence it has on the insights that emerge.
- Offshore wind emerges as a key low carbon source of generation under both UK full ambition scenarios (RM/RM-NCCS), and is not particularly sensitive to level of generation from other low carbon sources. This suggests that it is a relatively robust choice, particularly given the recent success in UK deployment and ongoing cost reductions.
- Nuclear generation features on the system (under RM/RM-NCCS) where CCS deployment is low or absent. It does not compete on costs based on the assumptions used in this analysis. However, it needs to be recognised that this technology does not compete on the market in the same way as other technologies, and subject to political support, could flourish. However, the Government also recognises that costs of future nuclear projects need to be lower cost (BEIS, 2017) to be acceptable to society, particularly in view of falling renewable costs.
- Storage systems are needed in an increasingly highly intermittent system that sees strong levels of electrification across end use sectors, notably heating in buildings. The analysis points towards a role for building or district heating based storage as the role of gas declines, to manage any mismatch between supply and demand. In such a scenario, high levels of deployment of higher cost electricity storage are not observed.

3.2. Buildings

The building sector in the UK, including residential homes and commercial properties, is predominantly heated by natural gas, supplied through one of the largest distribution system in Europe. It is a legacy of discovery of natural gas in the North Sea in the late 1960s and a major programme through the 1970s to convert appliances from town gas to natural gas use. In the residential sector, of the 25 million centrally heated homes (out of a total stock of 27.4 million), 92% (23 million) are connected to the network.[13] The need to transition away from gas in this sector is well understood by policymakers (BEIS, 2017) and in the research community (McGlade et al., 2018), and reinforced by this analysis; in Figure 9, in both the higher ambition cases, gas is completely out of

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[13] United Kingdom housing energy fact file: 2013, https://www.gov.uk/government/statistics/united-kingdom-housing-energy-fact-file-2013 (Accessed 19.02.18)

use in building by 2050. This move away from gas remains one of the largest challenges to decarbonise the UK system, and in other Member States with a high dependency on oil and gas for heating in buildings.

Key pathways to heat decarbonisation considered in the UK include electrification, district heating, hydrogen and the retrofitting of buildings to improve energy efficiency (CCC, 2016). Hydrogen use in buildings is not a pathway considered in this modelling (despite garnering increased interest in recent years) but the other pathways feature prominently in the modelling analysis. Median fuel use levels under each of the scenarios (Figure 9) reflect the move towards low carbon fuels, with gas use starting to be displaced during the 2030s (as shown for the 2040 period) under the two scenarios meeting the Government's targets (RM/RM-NCCS). Under RM-NCCS, the rate of gas withdrawal is higher, while electrification (red) and district heating (orange) are deployed at faster rates. Biomass also plays an increased role as a source of energy, albeit at much lower levels, and only in the mid-term. Gas use persists under RM-F2R until the 2040s, when a decrease is observed (in 2050) alongside increases in low carbon alternatives.

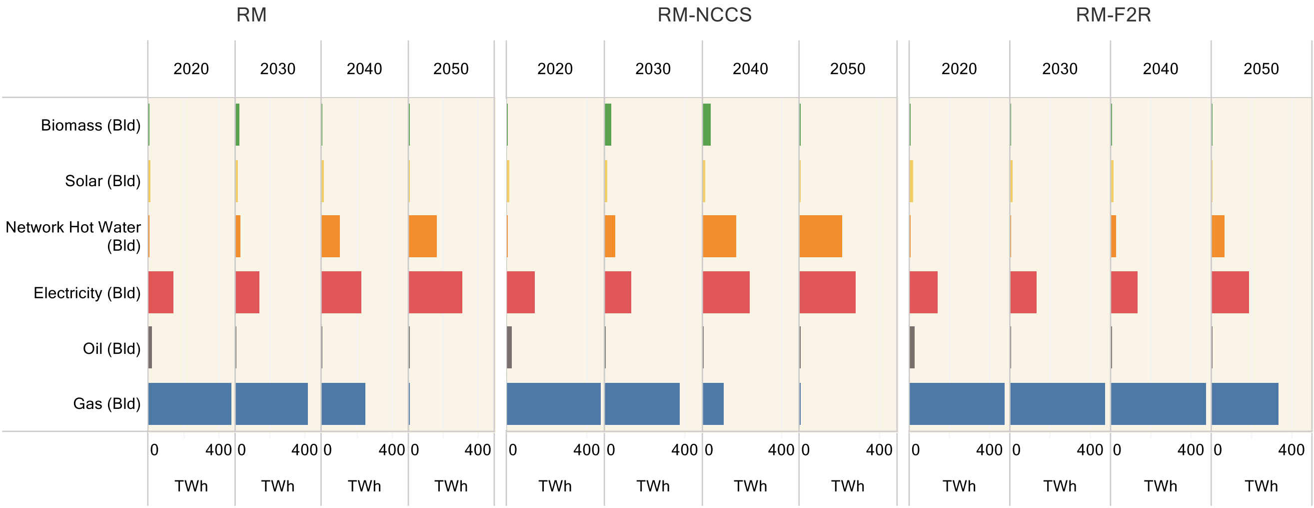

Figure 9. Median levels of fuel use by type in the buildings sector, 2020-2050

With gas being wholly absent from the building sector fuel mix in 2050, its use is compared to the other main competing fuels in the sector in 2040, under the RM scenario. Using the same approach as in the previous section, the modelled simulations are clustered based on the top-left distribution (a), with the red cluster showing high electricity and lower gas use, and typically higher levels of district heating (b). This cluster consists of simulations where CCS is playing a lower role across the system (red-pink cluster in Figure 4), resulting in a higher mitigation requirement across end use sectors. This is also indicated by the lower levels of gas use overall (c), and lower bioenergy level (d), also observed in low CCS simulations.

It is also worth noting the large spread of possible gas use levels in 2040, ranging from 150 to 300 TWh, which if put in dwelling terms would mean gas in either 12.5 or 25 million households (out of 34 million).[14] This suggests that the sector either has to reduce levels by 25% relative to 2030, or by 63%, a variation largely driven by the prospects for CCS and bioenergy. In the case without CCS (RM-NCCS), this level of variation in 2040 is not observed, with all simulations between 100-120 TWh. In the low ambition case (RM-F2R), the range for the same year is between 450-500 TWh. These large differences between scenarios illustrate the strong influence of climate ambition, and CCS deployment on the future role of gas.

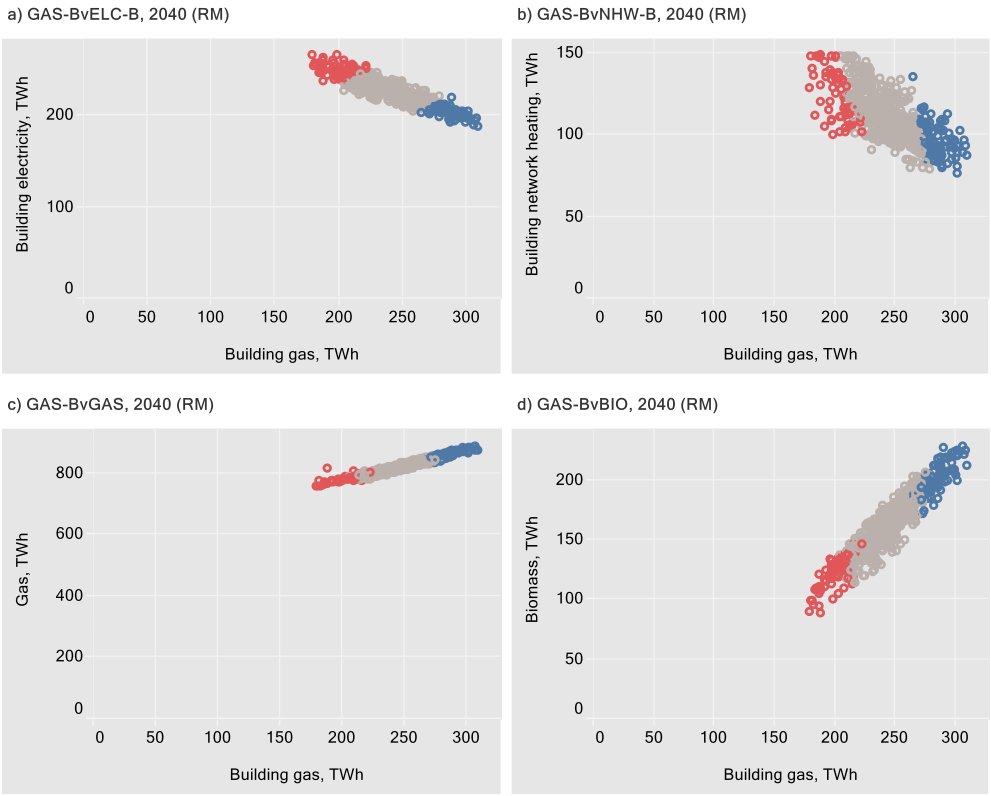

Figure 10. Alternative building fuel use compared to sectoral gas consumption in 2040 under the RM scenario

In parallel to the uptake of low carbon fuels, improvement to energy efficiency are undertaken to differing extents; new houses are built to improved standards, while existing homes are subject to retrofitting of building fabric. Given the poor energy efficiency of large parts of the existing stock, there is still significant potential for improving energy efficiency of building fabric (UKERC, 2017). Figure 11 shows the impacts of such measures on the reduction in the space heating requirement for different dwelling types under each of the three scenarios. A key insight is the stronger push to reduce energy service requirements under RM-NCCS; for example, the

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[14] Note that this is gas for all buildings, not just households. However, this is a useful way of understanding the difference in range. Note the estimate is based on an annual household consumption of 12 MWh of natural gas.

requirements for medium density homes in 2040 and high density homes in 2030 are much lower than in the other two scenarios. The variation in levels of space heating per dwelling are not large within scenarios, primarily because of the low uncertainty range assumed for costs of retrofits; hence the distribution of space heating levels are not shown here.

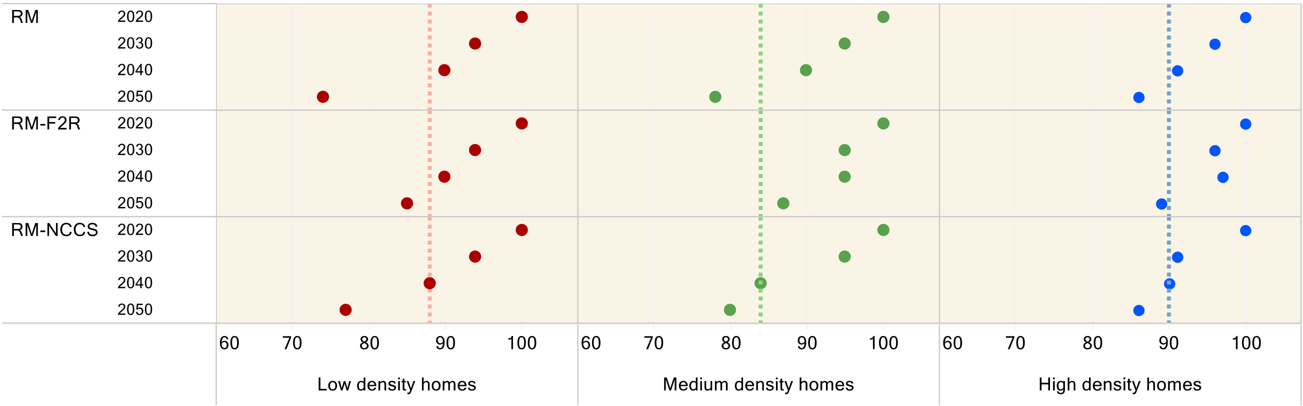

Figure 11. Median space heating requirement across the dwelling stock by building type and scenario, indexed against 2020 values (of 100). Dashed reference lines denote 2040 value for RM-NCCS

Section summary – Buildings

A number of key points can be highlighted from this section:

- The modelling suggest that all gas will need to be removed from the building sector by 2050 if the climate ambition is to be achieved, a huge challenge in the UK context – and in those Member States that are equally gas dependent.
- Key options for decarbonisation in the UK context include electrification and district heating. The latter option faces strong non-cost barriers due to the new infrastructure requirements, and other socio-cultural barriers due to limited use of such systems to date. Electrification will requires significant infrastructure reinforcement (partially modelled), and potentially changes to how building occupants use energy.
- Although not modelled here, these challenges of decarbonisation make the prospect of hydrogen for heating attractive, in the sense that it could potentially be delivered to homes using the existing infrastructure, and provide heating services not dissimilar to natural gas-based central heating. A key challenge how will be producing low carbon hydrogen at the quantities required to significantly displace gas.
- The mitigation level (or gas displacement) in the buildings sector prior to 2050 is influenced by the level of CCS in the system (under RM). Lower gas in the system in 2040 means higher levels of electrification, and district heating systems.
- In addition to alternative low carbon energy, the role of energy efficiency measures is key to reducing the energy service requirements of buildings in the UK. The sector contribution to mitigation again influences the rate of energy efficiency improvement.

3.3. Transport

The transport sector is heavily oil dependent, currently accounting for approximately a quarter of total domestic GHGs (120 $MtCO_2$).[15] Emissions have remain at the same level as observed in 1990, although the sector has of course grown significantly since that date, with road passenger and freight demands increasing from 410 billion vehicle kilometres (bvkm) in 1990 to 521 bvkm in 2016, a 25% increase.[16] However, international emissions from transport, based on bunker fuels (and included in this analysis) have seen an increase, from 24 to 41 $MtCO_2$, with the aviation component more than doubling, from 15 to 33 $MtCO_2$.

Few non-oil fuels contribute to the current energy mix, although under future emission reduction commitments this is projected to change, with increasing levels of alternative fuels in the mix by 2050, as shown in the modelling results (Figure 12). It is only during the 2040s, shown for the period 2050, that significant levels of mitigation are observed in this sector, with emission reduction options estimated to be more costly than in other sectors, and therefore not deployed in earlier periods. This is clearly highlighted in RM-F2R, where lower ambition fails to incentivise any shift in the sector. In 2050, where CCS is not available (RM-NCCS), a broader range of fuels play a role, notably biofuels and hydrogen. This reflects the increasingly level of mitigation required within this sector. However, despite this move away from oil, its use remains between 100-150 TWh; this consumption 'floor' reflects the difficulty in decarbonising the international transport and other freight sectors.[17]

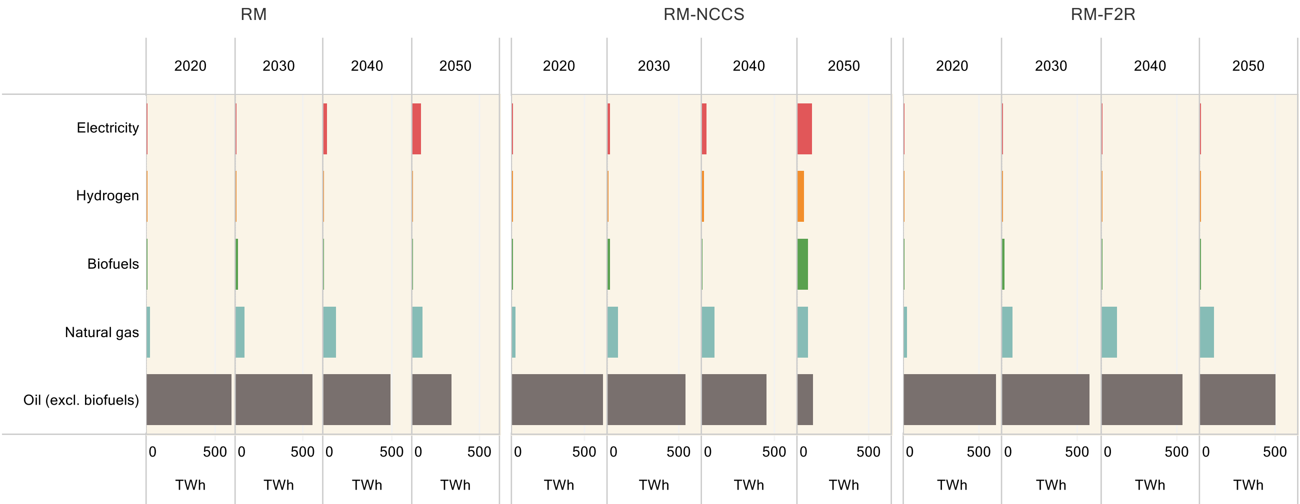

Figure 12. Median levels of fuel use by type in the transport sector, 2020-2050

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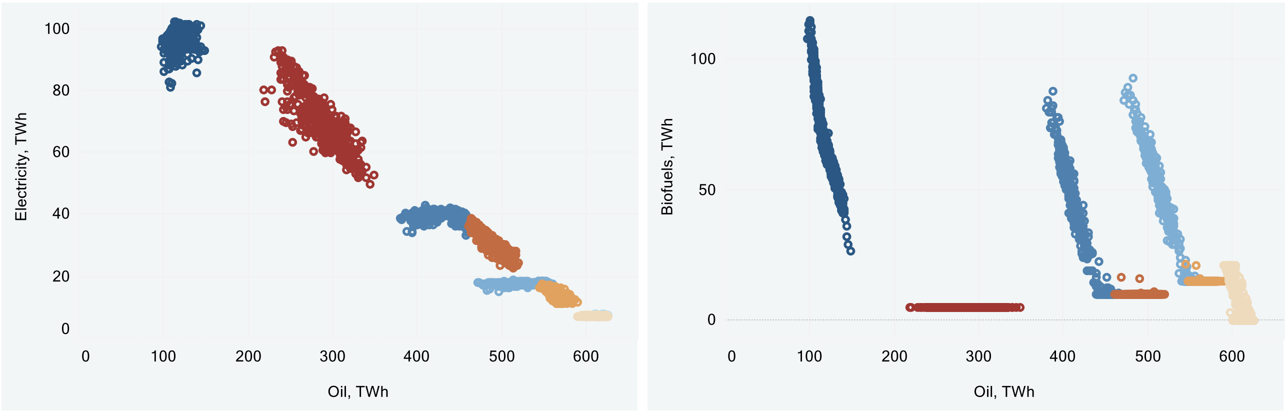
[15] Final UK greenhouse gas emissions national statistics: 1990-2015, Published by BEIS at https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-2015 (Accessed 09.01.18)

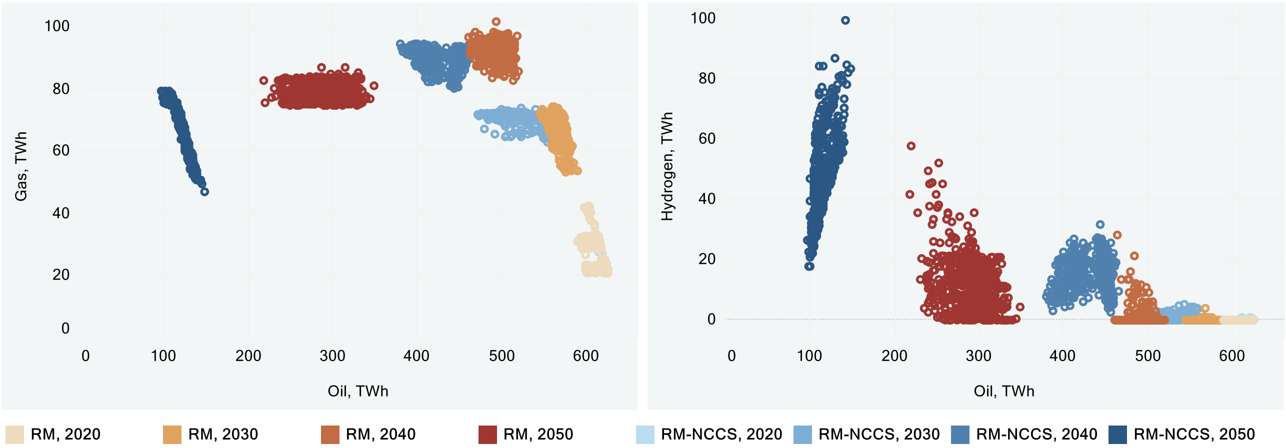
[16] Road traffic statistics, Table TRA0201, Department for Transport statistics, https://www.gov.uk/government/collections/road-traffic-statistics (Accessed 09.01.18)

[17] There are no options for the electrification in the road freight sector in the version of the ESME model used for this study (v4.2). However, they have been added subsequently in the latest version v4.4.

The spread of modelled simulations under each of the three scenarios for the above fuels are shown in Figure 13. These compare the use of alternative fuels against the level of oil consumption. Figure 13a shows how electricity use increases over time, particularly post-2030, displacing oil from the transport sector. There are larger reductions in oil use where CCS is not available and therefore more transport sector mitigation is required (blue markers, for RM-NCCS). This same logic is also true for higher levels of biofuels (b) and hydrogen (d). Where CCS is available (RM, 2050) the level of oil use (relative to electricity) shows a wider distribution, highlighting the sensitivity of oil use to the relative contribution of CCS i.e. higher oil use in simulations where CCS deployment is higher.


a) Transport fuel use, Oil vs. Electricity

b) Transport fuel use, Oil vs. Biofuels


c) Transport fuel use, Oil vs. Gas

d) Transport fuel use, Oil vs. Hydrogen

Figure 13. Alternative transport fuel use compared to sectoral oil consumption under the RM and RM-NCCS scenarios, 2020-2050

Biofuels use is minimal in RM, as the limited bioenergy resource in the system is used in other applications (Figure 13b). However, in RM-NCCS, its use is more prominent in the transport sector, with the bioenergy that would have been used with CCS now used for biofuel production. The high variability across all periods reflects the uncertainty of bioenergy resource availability. Hydrogen starts to play a role in the sector in 2040 under RM-NCCS, with a wide range of use levels in 2050 (Figure 13d). Where biofuel use is lower, hydrogen provides the alternative for road freight transport. In the case of RM, hydrogen use is low, primarily as biofuels use is low, as the relative contribution to decarbonisation from this sector is moderated by higher mitigation rates from CCS. Gas use (Figure 13c) acts as a transition fuel for the road freight sector, with a decline in 2050 from 2040 levels, as the emissions reduction stringency increases, and higher levels of mitigation are needed. Hydrogen and biofuels become important alternatives for gas, particularly under RM-NCCS.

The interplay between fuels in the transport sector can be illustrated, as demonstrated in the earlier sections of this report, by defining clusters and determining the use of fuels across these clusters. We first determine clusters based on the H_2-oil distribution for the RM-NCCS scenario (Figure 14), where the two blue clusters denote high hydrogen use and the red cluster low use. Simulations with lower levels of H_2 consumption (red cluster) have higher biofuels (c), while gas consumption is slightly higher (b) and oil consumption slightly lower (a). These simulations are also those that have higher bioenergy availability – and therefore see higher levels of biofuel production and supply. The system cost preference would be to produce biofuels where possible under RM-NCCS. Otherwise, it is increasingly reliant on hydrogen production via electrolysis, which is considerably more costly to produce (than other production processes, such as those that use gasification processes combined with CCS.

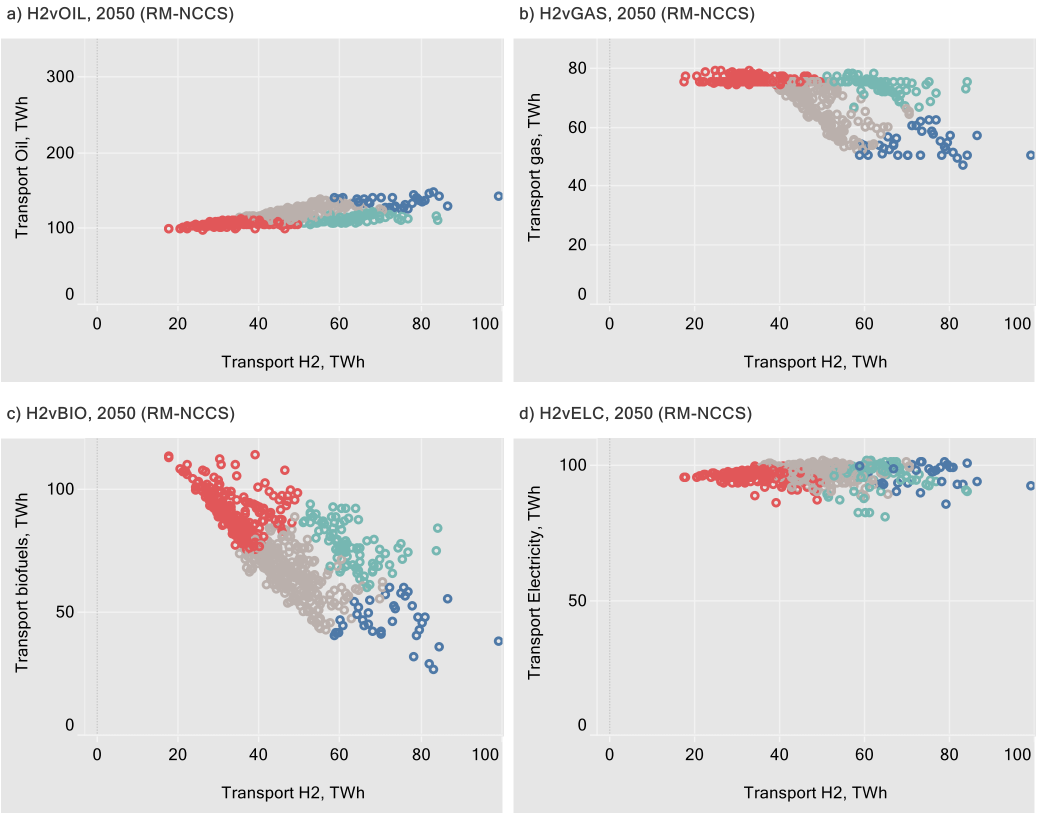


Figure 14. Alternative transport fuel use compared to sectoral hydrogen consumption in 2050 under the RM-NCCS scenario

The same clusters are overlaid on the 2050 distributions for the scenario RM. As indicated earlier, oil use is much higher in this scenario, with less use of alternative low carbon fuels, or no use in the case of biofuels. The red cluster again highlights high bioenergy-CCS simulations, allowing for more oil use in the sector (a) and and lower levels of electricity use (d) due to higher mitigation elsewhere, and offsetting via BECCS (primarily via hydrogen production).

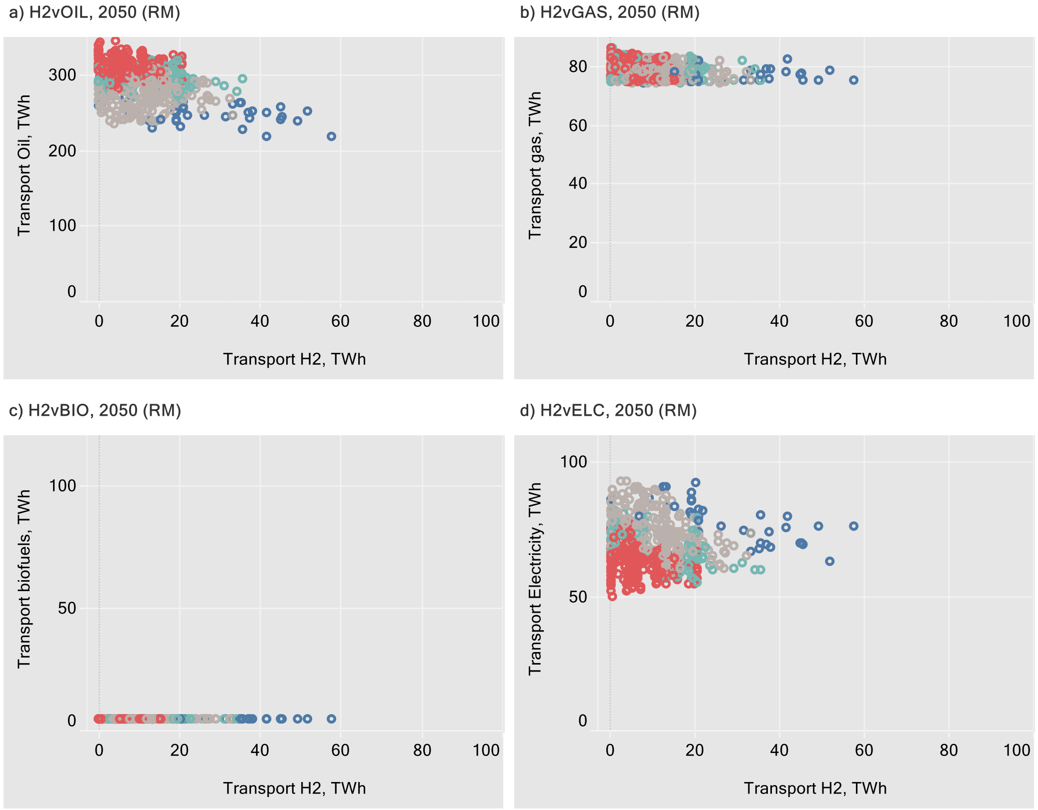


Figure 15. Alternative transport fuel use compared to sectoral hydrogen consumption in 2050 under the RM scenario

Section summary – Transport

A number of key points can be highlighted from this section:

- The transport sector is observed to be the sector which delays the emission reductions most, due to higher marginal costs of abatement, with serious decarbonisation only occurring in the 2040s.
- Electrification is an important pathway for passenger transport, under both higher ambition scenarios (RM / RM-NCCS), regardless of other technology / fuel options.
- Other low carbon fuels, however, only play a significant role in the long term where CCS deployment is limited, with the need for more end use sector mitigation. These are particularly needed for the freight sector, which does not have the option of electrification in the model.

- In the scenario with no CCS, biofuels are deployed as an important energy vector, although this is sensitive to overall bioenergy availability. In low bioenergy cases, hydrogen is shown to be the primary alternative, and produced through the process of electrolysis.
- Unlike in the buildings sector where all gas is removed by 2050, oil remains in the system under all scenarios. This consumption ‘floor’ is primarily due to international transport (aviation and shipping) that is more challenging to decarbonise than domestic road transport.
- With the need to move towards zero emission systems soon after 2050, addressing some of these hard to mitigate sectors, such as international transport and road freight, will require effective solutions, including demand side measures which can only be effected by policy action.

3.4. Industry

The industry sector currently accounts for about a fifth of total GHG emissions. Sectoral emissions have declined by 43% since 1990, resulting from a range of factors including improved energy intensity of production and a move to lower carbon fuels (1990-2007), a large reduction in manufacturing due to recession (2007-09), and structural change in energy intensity of the sector (2009-2014) (CCC, 2017). Large uncertainties as to how the industrial sector will change over time due to structural effects or as a result of economic cycles are evident, although not well represented in the model. Industrial energy demand for energy is driven by the exogenous future production output drivers, sourced from the Government’s own modelling (BEIS, 2018b), and the endogenous options to reduce energy intensity of production.

As illustrated in Figure 16, sector decarbonisation is characterised by a move away from oil and coal use, and an increase in the use of hydrogen and bioenergy. There are a few interesting differences to note across scenarios. As per other end use sectors which mitigate more in the absence of CCS, we observe greater reductions in fossil fuels by 2050 under RM-NCCS, and higher levels of bioenergy and hydrogen use compared to RM, which has the same ambition level. Similar trends are observed under RM-F2R, although lower emission reductions see lower investment levels in hydrogen for industrial heating, and a smaller reduction in the use of coal and gas by 2050.

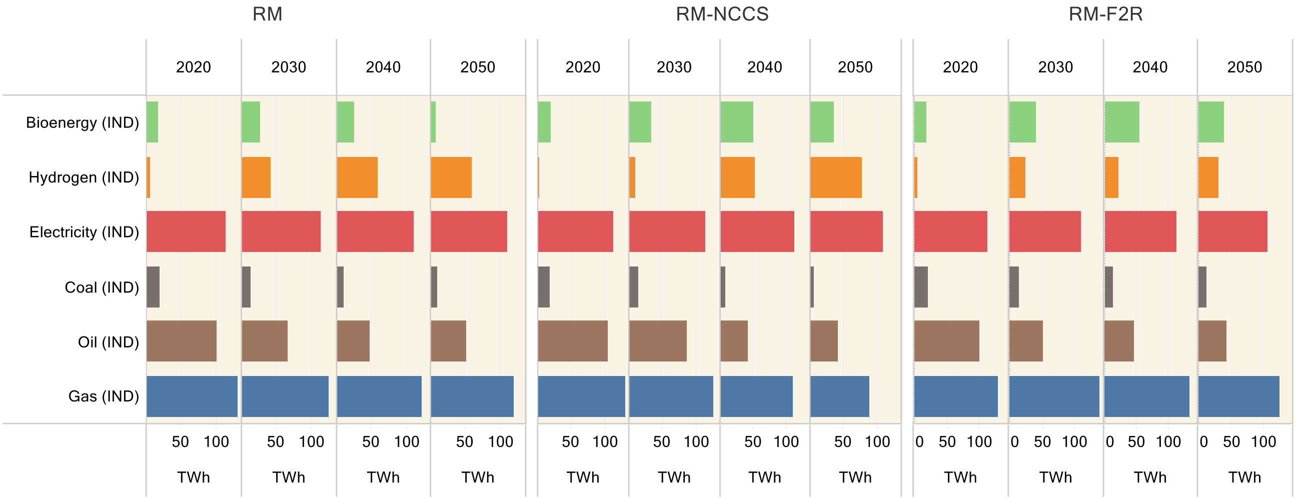


Figure 16. Median levels of fuel use by type in the industry sector, 2020-2050

Uncertainty representation across industry applies to build rates on CCS, and across the costs of energy resources used. However, the cost of specific technologies in the sector are not varied, in part due to their aggregated representation that does not capture the more detailed industrial processes. The limited representation of uncertainty, combined with fewer options for sector decarbonisation, results in a sector that shows no variation in 2050 at all under RM/RM-NCCS. Therefore, the simulation plots have not been presented. There is more variation under RM-F2R, due to lower emission reduction stringency, but restricted to lower bioenergy levels trading off with higher hydrogen use, and vice versa.

3.5. Cross-sectoral indicators

This section considers the wider cross-sectoral resource use across the energy system, and the capture of CO_2 via CCS technologies, which is not only confined to the power sector but used across industry, and in the production of other fuels, including biofuels and hydrogen.

System wide resource use

The metrics for the power and end use sectors (in the preceding sections) highlight the need for a system moving towards stringent decarbonisation goals to reduce its use of fossil fuels in all cases. The distribution of consumption across the main energy resources by scenario is shown in Figure 17. On gas, the level of use by 2040 in a system that has no CCS (b) is half of that in the RM case for the equivalent period, and halves again by 2050 (relative to 2040), to around 150 TWh. This contrast with RM (a), where gas use remains relatively higher, albeit with wide variation. The lower ambition level under RM-F2R sees gas use increase over the period, albeit with increasing variation in the longer term.

Unlike gas, which is not subject to supply constraints, the bioenergy distributions reflect the uncertainty in resource availability. Post 2030, all available bioenergy is used by the system, across all scenarios. Its use continues to increase to 2040 before decreasing in 2050, reflecting an assumption that the rest of the world will also be competing for biomass, reducing import availability. Oil use sees a decline across all scenarios, albeit a larger drop under RM-NCCS (b) and smaller under RM-F2R (c). There is limited distribution across simulations, reflecting the dominance of oil in the transport sector that persists until the longer term due to higher marginal abatement costs in that sector (as discussed in section 3.3).

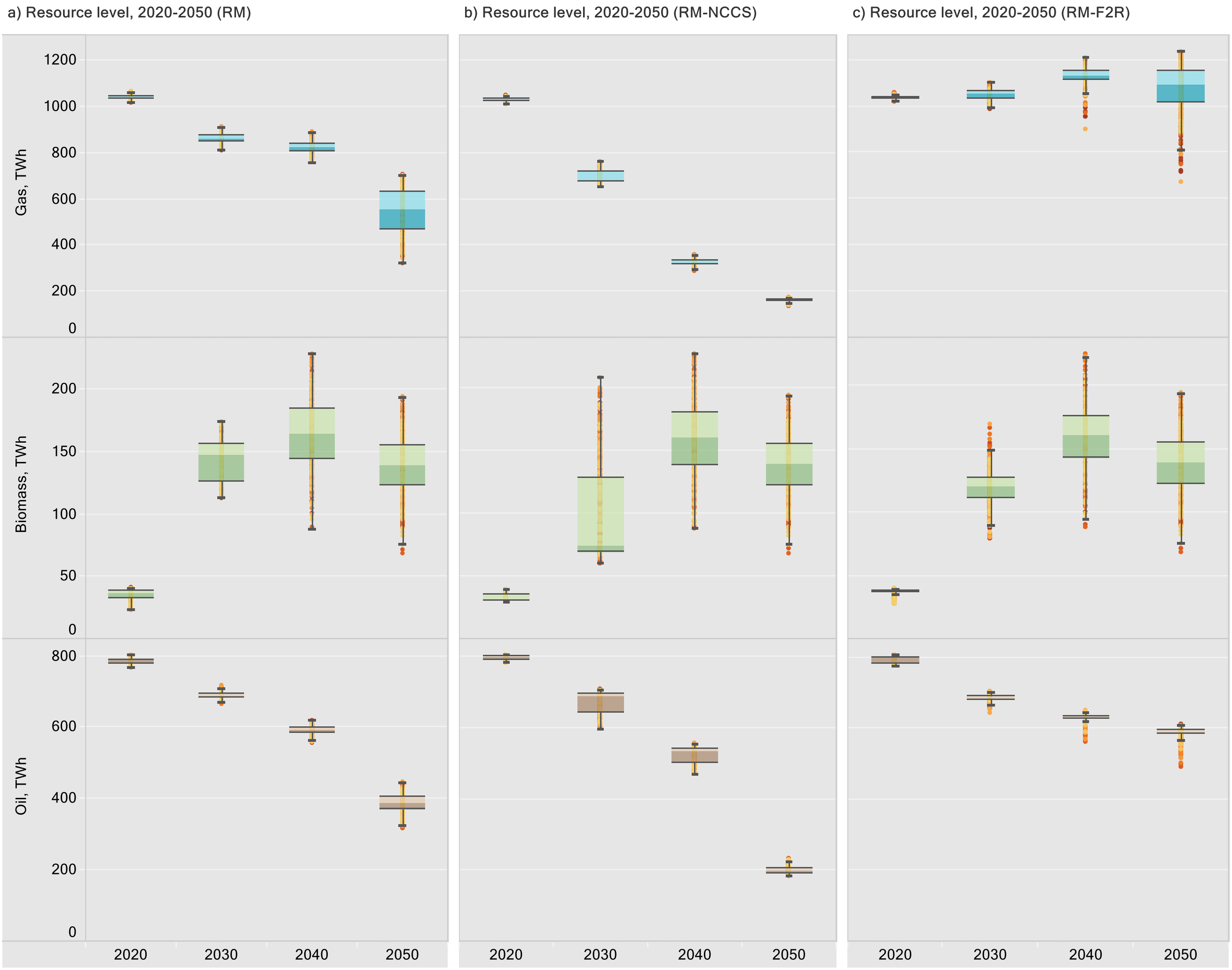


Figure 17. Level of consumption across key energy resources, 2020-2050. Box plots show interquartile range (IQR), while whiskers show data within 1.5 times the IQR

It is of interest to consider how the costs of mitigation compare for simulations with different levels of resource use (Figure 18). This provides some insights, combined with knowledge from previous global sensitivity analysis, into how resource level impacts costs. Where CCS is available (RM scenario), higher mitigation costs in the longer term are associated with lower bioenergy availability (b), and lower levels of gas use (a). For bioenergy, this relationship strengthens in RM-NCCS, where CCS is not available (e). However, for gas, due to the much lower levels of use (given the absence of CCS) and its use only in sectors where it is hard to displace, no correlation is observed (d). The spread of oil consumption levels in 2050 under both scenarios is relatively narrow (as shown in Figure 17). Marginal costs are slightly higher in the lower oil consumption simulations under RM (c), reflecting more mitigation effort in end use sectors due to lower CCS i.e. mirroring the pattern observed in (a) and (b).

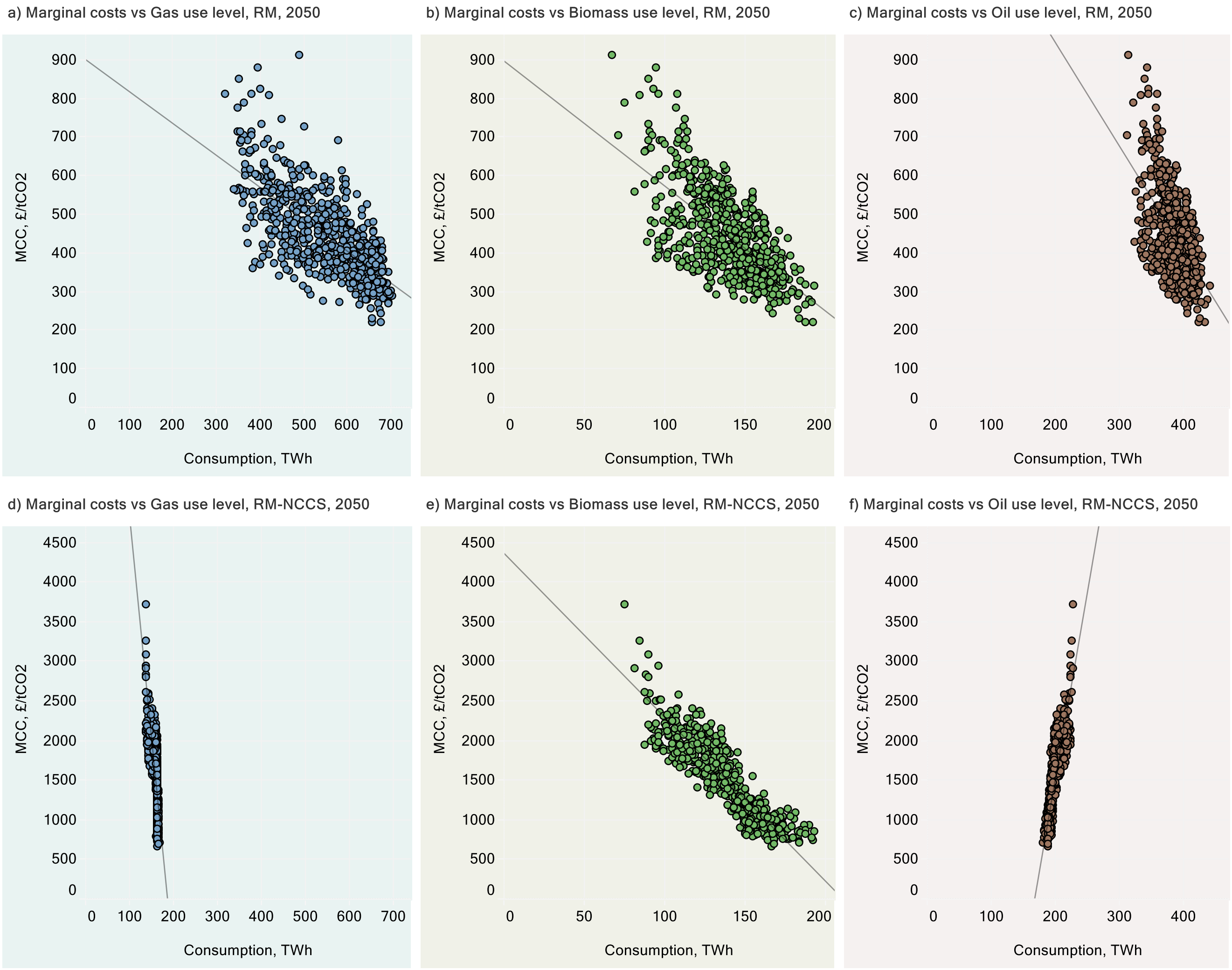


Figure 18. Level of resource consumption versus marginal system cost of abatement, 2050

The role of CCS

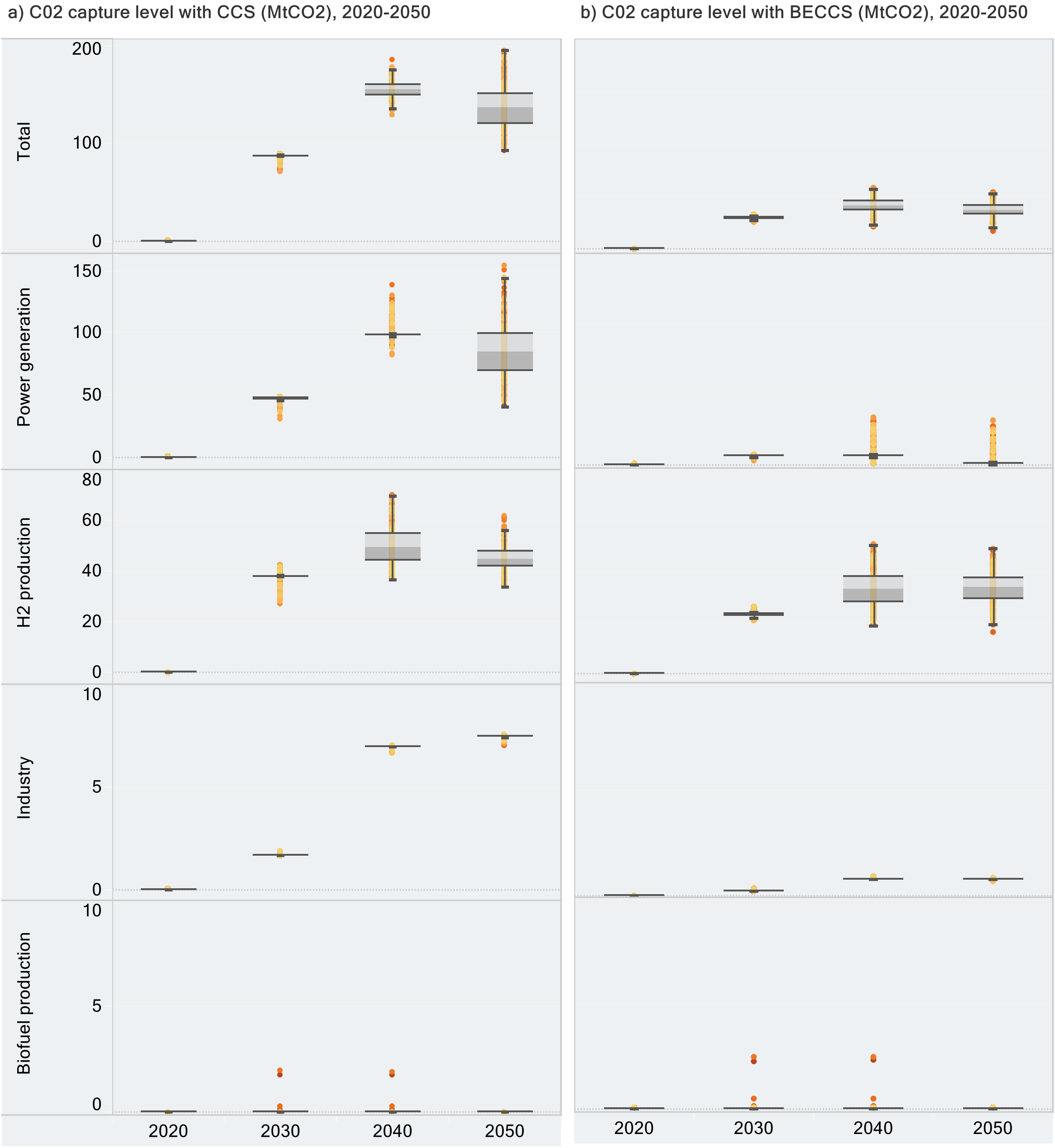
Across the results section, the role of CCS in RM, and its absence in RM-NCCS, have been an important feature of the discussion. In this section, we consider further the role of CCS is providing ‘emissions headroom’ for the system, and helping shape the different options and technology choices across sectors. Figure 19a shows the CCS use across sectors, based on the amount of CO_2 captured and sequestered. The ‘Total’ plot suggests a median capture level of around 130 $MtCO_2$ in 2050 against a target of 105 $MtCO_2$. In other words, CCS technologies are allowing for a level of CO_2 to be captured and stored that is greater than the emissions level permitted in 2050, in effect doubling the ‘space to emit’. About 35 $MtCO_2$ is from the use of bioenergy with CCS (Figure 19b), while the rest (95 $MtCO_2$) is from the continued use of fossil fuels, primarily gas in power generation and for the production of hydrogen via fossil gasification technologies. The BECCS component, while only 27% of the total, is extremely important for offsetting the emissions of sectors in which few cost-effective options exist for mitigation. CCS in the industry and biofuel production sectors is relatively low in comparison to other sectors, although it is worth noting that industry benefits in large part from hydrogen produced in plants using CCS.

Given the emissions headroom the technology provides, it is not surprising that the absence of CCS increases the marginal costs of mitigation significantly, and provides quite different pathways and options for decarbonisation. In effect, the target under RM-NCCS is twice as stringent. The key insight is that assumptions on CCS have a strong influence and therefore need to be transparent. If the technology can be deployed as per the RM scenario, the cost benefits are likely to be significant. However, decision makers need to be aware of this influence and understand the available pathways that are robust to this technology not scaling, as shown under RM-NCCS.

Section summary – Cross sectoral indicators

A number of key points can be highlighted from this section:

- Under the UK climate targets, gas use is highly sensitive to the availability of CCS. Without CCS, its role is heavily restricted. Even with CCS, there is no role for gas in the buildings sector by 2050, under any of the simulations. These types of insight is crucial in view of investment in new infrastructure, and the development of strategies for long term decarbonisation.
- Bioenergy resources are used to the maximum. The constraints on availability have the largest influence on the costs to the system in meeting emission reduction targets.
- The reduction in oil use is most prominent under RM-NCCS, when the transport sector has to affect stronger emission reduction options. Where CCS is available, high levels of oil use remain in the system until the very long term.
- The role of CCS for emission reduction provides significant headroom for continued use of fossil fuels, and via BECCS, potential for offsetting. There are significant barriers to scaling to this level, and it is arguably an optimistic outlook for the technology here, particularly for the prospects of deployment in 2030. It is critical that the no CCS case (RM-NCCS) is considered, and the different pathways that emerge when considering robust strategies that are not wholly reliant on CCS at scale.



a) C02 capture level with CCS (MtCO2), 2020-2050

b) C02 capture level with BECCS (MtCO2), 2020-2050

Figure 19. Level of CO_2 capture by CCS across different sectors under RM scenario, 2020-2050. Box plots show interquartile range (IQR), while whiskers show data within 1.5 times the IQR. a) includes all CO2 captured by CCS, and stored, while b) relates to capture via the use of bioenergy with CCS, known as BECCS.

3.6. Cost outliers

Finally, it is useful to consider the ‘outlier’ simulations, those that are at the extreme ends of the mitigation cost range under the different scenarios. Analysing such simulations allows for an understanding of the characteristics of a system that produces such outliers. For the scenarios RM and RM-NCCS, simulations were selected that were furthest from the median value and typically not clustered with other simulations. This includes those with marginal costs (£/tCO_2) lower than £270 (9) and £750 (11), and higher than £730 (11) and £2500 (15) under RM and RM-NCCS respectively. The bracketed values are the number of each simulations in each group.

Figure 20 shows the percentage difference from the median value (for all 600 simulations) for the low and high cost simulation group under the RM scenario (a), and for the highest and lowest individual simulations (b), where the black line is the median, normalised to 100. The low cost simulations see higher levels of bioenergy, gas and CCS, and lower levels of nuclear and wind. Differences in model inputs (based on the Monte Carlo sampling) for average (c) and lowest / highest simulations (d) are indicative of the key drivers; for lower mitigation costs, higher bioenergy availability and lower CCS capex, while for higher costs, the opposite. For the lowest cost simulation (d), despite higher commodity costs, similar to the pattern for the average in c) but with higher build rates for non-industry sector CCS.

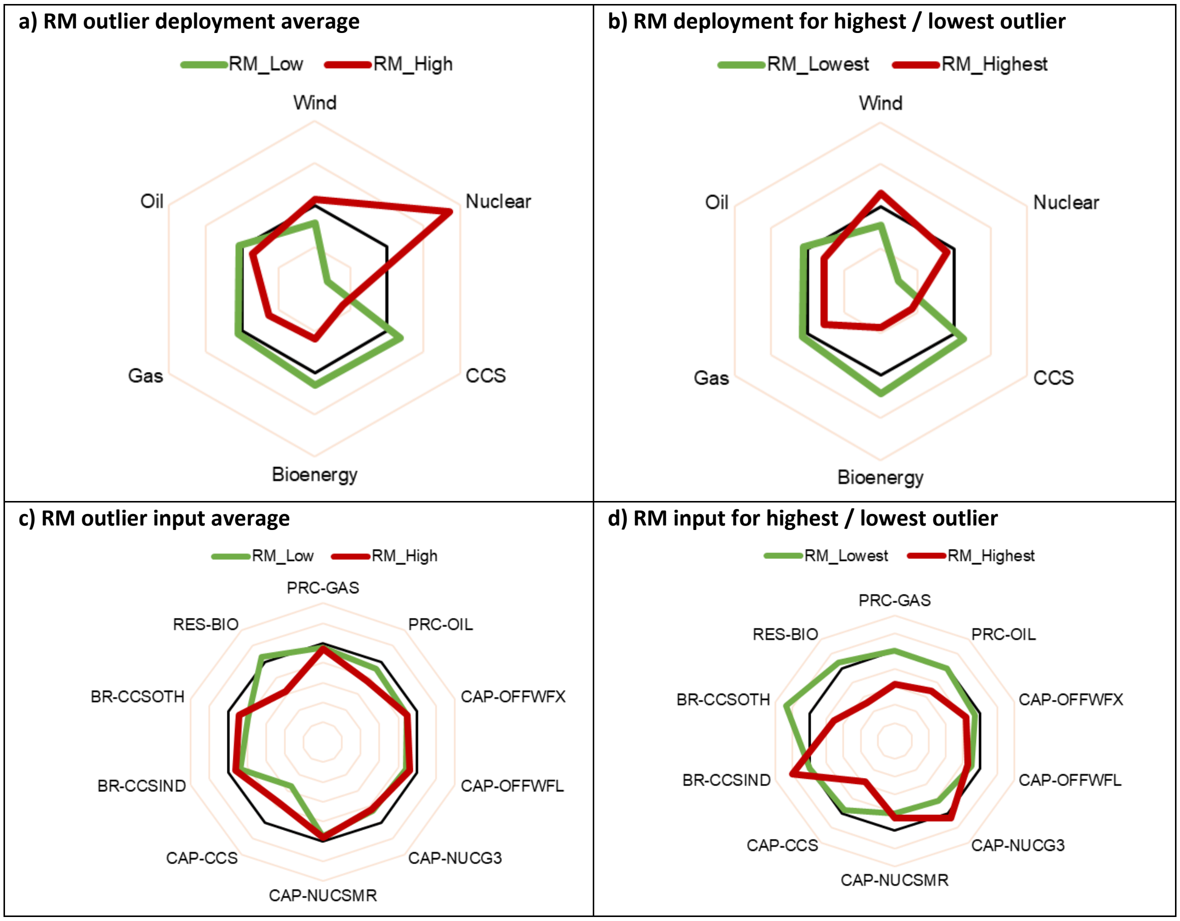


Figure 20. Difference in deployment levels across indicators and input assumptions for simulation outliers in scenario RM in 2050. a) Average deployment difference compared to scenario median (black line) for low (<£270 /tCO$_2$) and high (>£730 /tCO$_2$) simulation groups, where gridline increments represent 50%. b) as per a), except differences for the lowest and highest cost simulation (not the average). c) Average input parameter difference compared to scenario median (black line), where gridline increments represent 20%. The label meanings are as follows: BR=Build rate; PRC=resource cost; CAP=Capex; RES=resource availability; OFFWFX=offshore wind (fixed); OFFWFL=offshore wind (floating); NUCG3=Nuclear Gen. III; NUCSMR=Nucelar small modular reactors; CCS=carbon capture and storage; CCSIND=CCS in industry; CCSOTH=CCS other than industry. d) as per c), except differences for the lowest and highest cost simulation (not the average).

Figure 21 creates the same plots for RM-NCCS. In terms of the average across outlier simulations (a), the main difference is the use of bioenergy, with higher availability (c). For the lowest cost simulation (b), bioenergy deployment is higher (relative to the highest cost simulation). Despite having higher resource cost and capex input assumptions (d), the lowest cost simulation has much lower costs due to higher bioenergy availability, underlining the impact of this assumption on the model solution.

This analysis of outliers reinforces the importance of bioenergy as a key driver of mitigation cost in both scenarios, and the role of CCS in providing more cost-effective solutions.

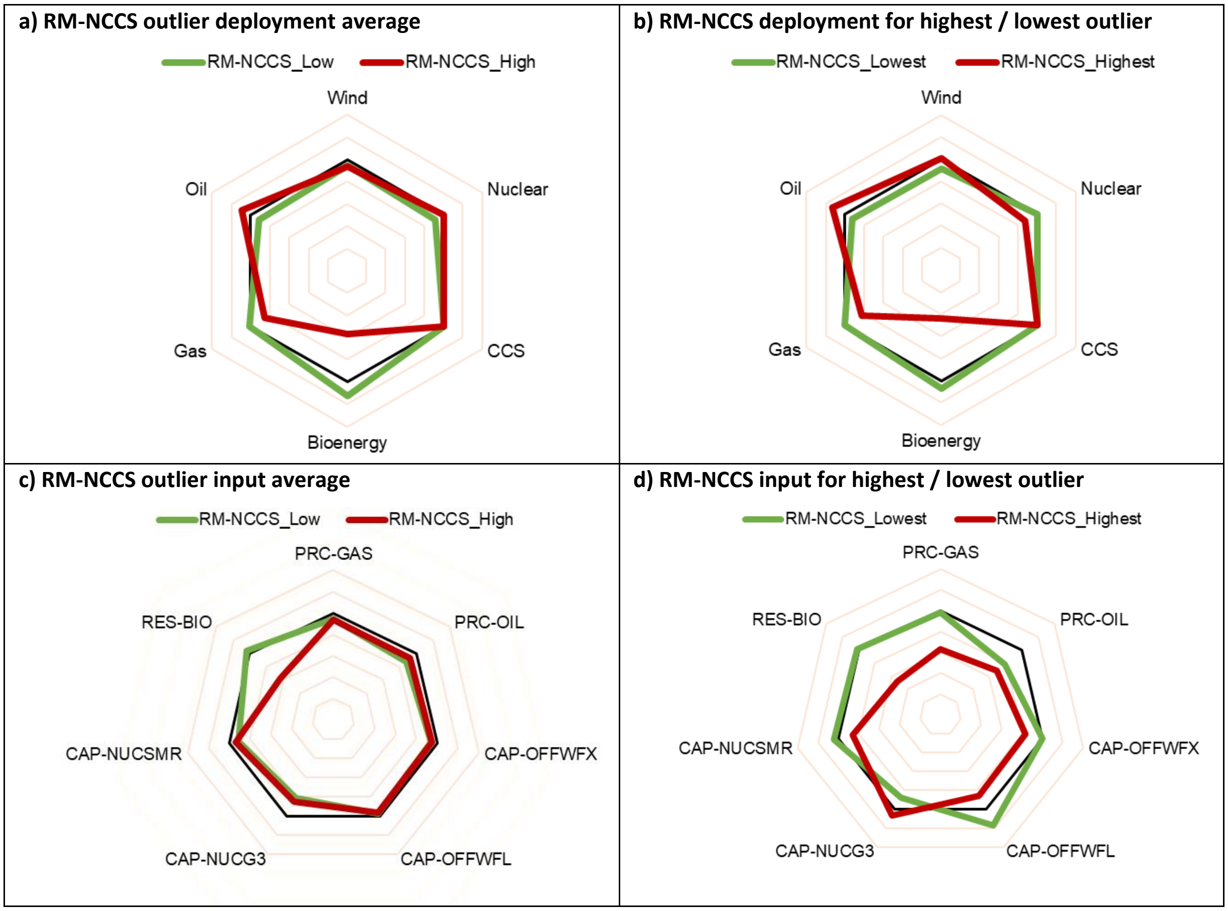


Figure 21. Difference in deployment levels across indicators and input assumptions for simulation outliers in scenario RM-NCCS in 2050. a) Average deployment difference compared to scenario median (black line) for low (<£750 /tCO$_2$) and high (>£2500 /tCO$_2$) simulation groups, where gridline increments represent 20%. b) as per a), except differences for the lowest and highest cost simulation (not the average). c) Average input parameter difference compared to scenario median (black line), where gridline increments represent 20%. The label meanings are as follows: BR=Build rate; PRC=resource cost; CAP=Capex; RES=resource availability; OFFWFX=offshore wind (fixed); OFFWFL=offshore wind (floating); NUCG3=Nuclear Gen. III; NUCSMR=Nuclear small modular reactors; CCS=carbon capture and storage; CCSIND=CCS in industry; CCSOTH=CCS other than industry. d) as per c), except differences for the lowest and highest cost simulation (not the average).

4. Discussion, conclusions and insights for policy

4.1. Discussion of results

The modelling presented in this report explores distinctive scenarios and many of the underlying technology and resource level uncertainties, providing some clear insights into the evolution of different low carbon pathways. In the power system, the availability (or not) of CCS shapes other generation choices, notably of nuclear deployment but also in terms of the diversity of options, which increase in the absence of CCS. In the UK context, the deployment level of wind is pretty stable across different scenarios and uncertainties, highlighting its cost-effectiveness, and the robustness of any strategy to facilitate and fast track deployment of this technology.

The modelling provides a perspective on deployment according to costs and availability, within climate constraints. It is interesting to note for CCS that this is an attractive technology option irrespective of uncertainty around costs, as illustrated in the RM-F2R scenario, where even under low mitigation costs, deployment is as high as that observed for RM. However, this scaling in the modelling potentially overlooks the other barriers to deployment, which likely sit in the political and societal realm. In particular, developing the incentives or public sector support via policy to develop the necessary shared infrastructure will be a significant challenge, as will garnering public buy-in and support. The same may also be true for nuclear power; while cost is shown as a barrier in this modelling, with political support for a nuclear programme, deployment could be scaled. This is particularly shown in the absence of CCS.

All end use sectors have significant decarbonisation challenges of their own; in transport, this is a transition away from an oil-based mobility model, while in buildings, it is about finding an alternative to gas-based heating that provides the same levels of comfort and convenience. In industry, the challenge concerns making a transition that again addresses high fossil fuel use but protects the sector from the competitive pressure of international markets, a factor that is likely to gain increasing visibility in the age of Brexit. A key finding is emission reductions across all end use sectors increase where CCS is not available, resulting in a more diverse set of pathways.

For transport, which delays mitigation action the most, electrification for passenger road transport is a key pathway under both high ambition scenarios (RM / RM-NCCS). For road freight, while gas can play a transition role, in the long term biofuels or hydrogen feature, the latter more so in a system where bioenergy availability is lower. Oil use does persist in the longer term, although the level is strongly determined by the level of ambition and CCS availability. In the most stringent case (RM-NCCS), it is at about 20% of current levels, a consumption 'floor' that is maintained across cases due to growing international transport demand, particularly aviation.

Building decarbonisation results in no gas use by 2050, a radical departure from the system of today. This is an important insight; while gas persist in other sectors, it completely disappears from the buildings sector in both UK climate policy compliant scenarios, reflecting that unabated (without CCS) gas use is not possible in this sector. The high gas-based system is replaced by electrification and district heating, both of which have challenges. Electrification will requires significant infrastructure reinforcement, and potentially changes to how building occupants use energy, while district heating faces strong non-cost barriers due to the new infrastructure requirements, and other socio-cultural barriers reflecting limited deployment to date. In addition to a low carbon heating supply, increasing energy efficiency is also identified as a key measure. Deployment levels of all low carbon options in 2040 is dependent on level of bioenergy availability and CCS; higher bioenergy and CCS sees lower levels of deployment, and higher gas use. It is also worth noting that the building sector transition also sees large investment in storage (hot water, district heating), to deal with higher electrification and a more intermittent system. The model results show more storage at the building level than via batteries on the grid.

There are also a number of important cross-sectoral insights. The role of gas is heavily restricted without CCS at scale under UK targets, although no longer features in the buildings sector in 2050 under either RM or RM-NCCS. However, where CCS is available and / or climate ambition is reduced, the role of gas at the system wide level is robust. Under these scenarios, bioenergy resource level is a key driver of system costs, and used to the maximum. For oil use, the level (as with gas) is highly variable, based on the deployment of CCS and the level of climate ambition. For all three resources, CCS provides significant headroom for continued use of fossil fuels, and via BECCS, potential for offsetting associated emissions.

4.2. Insights for policy makers

The critical question is what insights can be determined from this modelling for decision makers seeking to develop robust and ambitious strategies. While we focus on the UK context, the level of ambition set out here and the types of pathways required to meet that ambition hold strong relevance across many Member States; in the next section we further set out the transferability of these insights.

A first key insight relates to the role of CCS. The large scale deployment of this technology drives down the costs of mitigation. Therefore, decision makers should be focusing policy action towards demonstration programmes to better understand the challenges of deployment at scale, and what policy mechanisms may be needed. However, this is not happening at the level required as implied by what is in the models, and remains absent from much of the policy debate (Peters and Geden, 2017). In the UK, some more funding has been pledged for this technology as part of the Clean Growth Strategy (BEIS, 2017) but not to the level previously committed under the CCS demonstration competition. Recent Government projections perhaps underlie fading optimism as to the role this technology can play in the next 20 years, with almost no deployment envisaged prior to 2035 (BEIS, 2018b).

A second insight relates to how CCS shapes the options across the system. Very different systems emerge depending on CCS being largely absent or deployed at scale. There is a danger that this influence is hidden in many analyses and that resulting strategies are not robust to failure of this technology. Its dominance also precludes alternatives from receiving the necessary focus, and allows for ‘buying time’ to make the necessary investment to effect the longer term transition. In other words, the modelling can delay near term investment because the role of fossil fuels is partially safeguarded by CCS. This is reinforced by the use of discount rates, which kick low carbon investment further down the road. Arguably there needs to be a more pluralistic perspective (recognising the influence of CCS on modelling results), not reliant on specific technology groups, which allows for dynamic policy making as the situation changes (Mathy et al., 2016). Caution is also needed in relation to BECCS, which generates negative emissions to offset emissions from other sectors. Again the level of deployment and reliance for mitigation need careful scrutiny (Anderson and Peters, 2016; EASAC, 2018).

A third insight is the importance of bioenergy availability in scenarios with and without CCS. There are critical uncertainties concerning future availability, which increases by four times from current use in the scenarios, and the sustainability of that resource (Brack, 2017). There are also concerns about the impacts on air quality from the use of biomass for energy in specific sectors, particularly buildings (Lott et al., 2017). The importance of this resource for decarbonisation (as per the modelling) needs to be carefully considered against these other issues of sustainability and air quality.

A fourth insight suggests that some technologies play a role irrespective of the deployment of other technologies, and therefore could be considered robust options. This includes offshore wind in the power system, and increased electrification both in the transport and building sectors. Other technologies are much more contingent on other factors such as resource availability (bioenergy, influencing hydrogen use in transport) or technology costs (nuclear deployment where cost-effective alternatives may not be available). Another robust finding of this modelling is the complete move away from gas in the buildings sector by 2050, while more uncertainty surrounds the extent to which full decarbonisation of transport (displacement of oil) takes place.

Such insights can help shape future strategy direction, but also give rise to further questions given the inherent uncertainty and the issues that fall outside of the model boundary e.g. broader sustainability concerns of bioenergy, legal and social acceptability of negative emissions. What is key is that firm insights can start to shape action now while issues of greater uncertainty are scrutinized further and subjected to further research. In other words, the multiple uncertainties need not be an excuse for inaction. In fact, the action needed is likely to be more ambitious, as countries look to move towards net-zero emission systems (Pye et al., 2017). As the Commission looks towards the development of its mid-century strategy, a net-zero objective would be preferable to ensure that near term action and infrastructure investment is all in line with this ultimate objective (Geden, 2016). However, the issue of increasing reliance on CCS/BECCS as we consider net zero systems must not be at the expense of a more diverse set of solutions.

4.3. Transferability to other Member States

As a case study in the REEEM project, it is important that the transferability of insights to other Member States is considered. Arguably, all of the insights from this analysis are relevant across other EU Member States except where they are predicated on the specifics of the current or emerging UK system. It is therefore worth highlighting some of the distinctive characteristics of the UK system; i) a power system that is rapidly changing, from one that was thermal-dominated to an increasingly renewables-based system, primarily wind, with an ever decreasing share of coal plant. Going forward, it has the prospects of access to high renewable resource potential (wind, marine) and CCS storage, further facilitated by strong expertise in offshore industries; ii) a building stock primarily heated by natural gas through connection to an extensive gas grid, and with large potential across the existing stock for further improvements in energy efficiency through building fabric retrofit; iii) an industry base which is dominated by services, with only 10% from manufacturing.[18] The transport sector is potentially less

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[18] Industries in the UK: A UK parliament briefing paper. Number 06623, August 2016.
http://researchbriefings.files.parliament.uk/documents/SN06623/SN06623.pdf (Accessed 26/02/18)

distinctive, except that the UK has the largest aviation sectors in terms of passenger numbers of any Member State.[19]

A key insight relates to the role of CCS, which typically is not needed in lower ambition systems. When Member States start considering high emission reduction targets post-2030, the role of this type of technology, where potential is available, is likely to play a more prominent role. It is therefore imperative that the ability of such a system to shape the transition is well understood to ensure robustness of strategies, but also to recognise that this technology, if viable and deployed, can reduce costs considerably. It therefore needs serious recognition in the technology demonstration programmes and policy planning. Member States that are likely to benefit from such a technology are those situated in reasonable proximity of the storage sites in North West Europe, or to tge the CO_2 transportation infrastructure.[20]

A similar region (for countries such as UK, Denmark, the Netherlands, Germany and France) also benefits from strong offshore wind potential, the deployment of which has been shown to be stable across all scenarios and uncertainties in this UK analysis. One trade association assessment suggests that up to 25% of EU electricity demand could be met (in theory) by the offshore wind, in some locations at prices similar to the auction strike prices realised in the UK last year (~€55-60/MWh) (BVG, 2017). Prospects for the role of nuclear, on the other hand, look less favourable, particularly if the costs and technical problems of recent (and ongoing) builds cannot be overcome in the medium term. Such a technology currently generates nearly 30% of all EU electricity produced from 130 nuclear plants across 14 EU countries so no replacement will see a large capacity gap to fill (although France accounts for half of this generation so it is largely concentrated). This analysis suggests difficulties in deployment at current costs, particularly in view of cost-effective renewables and if and when CCS can be deployed at scale.

The UK also constitutes a Member State will high gas dependency, particularly in the residential sector. Other countries that have high gas use (over 50% of energy needs) in homes include Netherlands, Italy, Hungary and Slovakia. At a level of over 35%, Belgium, Luxembourg and Germany are also highly dependent. This is also a relevant issue for specific gas-connected urban centres too, even where national gas dependency for home heating is lower. Removing gas from the system by 2050, as in the case of the UK, will either need a highly strategic intervention, such as continued use of existing infrastructure but piping low carbon hydrogen or biomethane, or more pluralistic solutions, taking account of the needs of different localities. This could include greater use of bioenergy, electrification and / or low carbon district heating. Whatever pathway, the challenge of heat decarbonisation is huge, and will require strong near term action in order to transition this sector by the middle of the century.

The other insight is the increasing importance of bioenergy to the system. Its importance to European renewable policy is evident, with bioenergy accounting for around 60%. As emission reduction targets increase, the value

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[19] Air transport statistics, 2016. Eurostat.
http://ec.europa.eu/eurostat/statistics-explained/index.php/Air_transport_statistics (Accessed 26/02/18)

[20] Assessment of the CO2 Storage Potential in Europe (CO2Stop project)
https://ec.europa.eu/energy/en/studies/assessment-co2-storage-potential-europe-co2stop (Accessed 09/02/18)

of bioenergy increases, both as direct fuel and in the provision of negative emissions via BECCS. However, large uncertainties around the its role are crucial to flag, including availability across Member States, particularly where increased competition for imports is observed, the sustainability of feedstocks, and the potential externalities arising from air pollution, depending on the sector in which it is used, and if not combusted efficiently and using appropriate technologies. A recent letter to the Guardian newspaper by a host of eminent scientists warned against too much reliance on bioenergy to meet sustainable energy targets, particularly due to risks for deforestation.[21]

In conclusion, many of the insights from this UK case study have a broader application to other Member States, also grappling with the deep decarbonisation of their energy systems. A final thought; ultimately Member States will need to push even deeper than the targets in this analysis, requiring net zero systems soon after 2050. It is important to stress that such a 100% reduction system is quite different from an 80% one, because of the lack of headroom to manage sectors that are very difficult to decarbonise (Pye et al., 2017). Further work is needed on this issue, which can then be effectively shared between Member States. Some country exercises and interactions on modelling have already been started in recent years to facilitate learning across Member States (Spencer et al., 2017; van Sluisveld et al., 2017). Development in energy and climate policy and planning could also help facilitate such analysis, by adopting net zero emission targets (Geden, 2016), something that Sweden have moved towards but that the UK has so far put on hold (Committee on Climate Change, 2015).

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[21] EU must not burn the world's forests for 'renewable' energy, Guardian Letter, December 2017 https://www.theguardian.com/environment/2017/dec/14/eu-must-not-burn-the-worlds-forests-for-renewable-energy (Accessed 16.01.18)

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Annex A: ESME technology information

Technology type	Technology	SET Plan Priority	Parameter type	Values			2050 distribution range	
				2010	2050	Units	Low	High
Storage	Battery - Li-ion	1	Capital Cost	668	267	kWh	-50%	50%
	Battery - NaS	1	Capital Cost	241	229	kWh	-10%	10%
	Compressed Air Storage of Electricity	1	Capital Cost	10	10	kWh	-30%	30%
	Flow battery - Redox	1	Capital Cost	443	266	kWh	-50%	50%
	Flow battery - Zn-Br	1	Capital Cost	280	252	kWh	-10%	10%
Power	Biomass Fired Generation	99	Capital Cost	2417	2357	kW	-10%	10%
	CCGT	99	Capital Cost	589	496	kW	-10%	10%
	CCGT with CCS	9	Capital Cost	997	777	kW	-42%	60%
	Gas Macro CHP	99	Capital Cost	562	489	kW	-10%	10%
	Geothermal Plant (EGS) Electricity & Heat	1	Capital Cost	9507	8556	kW	-50%	50%
	Geothermal Plant (HSA) Electricity & Heat	1	Capital Cost	25869	23282	kW	-30%	30%
	Geothermal Plant (HSA) Heat Only	1	Capital Cost	1459	1313	kW	-10%	10%
	H2 Turbine	2	Capital Cost	590	500	kW	-10%	10%
	IGCC Biomass	2	Capital Cost	1911	1507	kW	-50%	50%
	IGCC Biomass with CCS	2	Capital Cost	4069	2661	kW	-50%	50%
	IGCC Coal	99	Capital Cost	1827	1369	kW	-30%	30%
	IGCC Coal with CCS	9	Capital Cost	2343	1719	kW	-25%	100%
	Incineration of Waste	2	Capital Cost	1712	1472	kW	-10%	10%
	Nuclear (Gen III)	10	Capital Cost	6000	4200	kW	-20%	50%
	Nuclear (Gen III)	10	Max build rate	1000	2000000	kW	-90%	25%
	Nuclear (Gen IV)	10	Capital Cost	6000	4200	kW	-20%	50%
	Nuclear (Gen IV)	10	Max build rate	100	240000	kW	-90%	25%
	Nuclear (SMR)	10	Capital Cost	6500	6500	kW	-20%	50%

	Nuclear (SMR)	10	Max build rate	100	1200000	kW	-100%	20%
	Offshore Wind (fixed)	2	Capital Cost	3000	1500	kW	-30%	15%
	Offshore Wind (floating)	2	Capital Cost	3000	1261	kW	-30%	15%
	Onshore Wind	2	Capital Cost	1489	1250	kW	-30%	30%
	PC Coal	99	Capital Cost	1565	1326	kW	-10%	10%
	PC Coal with CCS	9	Capital Cost	2868	2232	kW	-42%	60%
	Severn Barrage	1	Capital Cost	2330	2330	kW	-30%	50%
	Solar PV (Domestic)	2	Capital Cost	3300	673	kW	-30%	30%
	Solar PV (Farm)	2	Capital Cost	1400	449	kW	-30%	30%
	Tidal Range	1	Capital Cost	3030	2580	kW	-50%	50%
	Tidal Stream	1	Capital Cost	1890	1050	kW	-50%	50%
	Waste Gasification	2	Capital Cost	3750	3750	kW	-50%	50%
	Waste Gasification with CCS	2	Capital Cost	5800	5800	kW	-50%	50%
	Wave Power	1	Capital Cost	7810	3540	kW	-50%	50%
Fuel production	Biodiesel Production	8	Capital Cost	168	168	kW	-30%	30%
	Biokerosine Production	8	Capital Cost	219	219	kW	-50%	50%
	Biopetrol Production	8	Capital Cost	883	641	kW	-30%	30%
	Biopetrol Production with CCS	8	Capital Cost	883	671	kW	-30%	30%
	H2 Plant (Biomass Gasification with CCS)	8	Capital Cost	1204	828	kW	-50%	50%
	H2 Plant (Biomass Gasification)	8	Capital Cost	1061	763	kW	-50%	50%
	H2 Plant (Coal Gasification with CCS)	8	Capital Cost	950	698	kW	-50%	50%
	H2 Plant (Electrolysis)	8	Capital Cost	1266	611	kW	-30%	30%
	H2 Plant (SMR with CCS)	8	Capital Cost	553	459	kW	-50%	50%
	SNG Plant (Biomass Gasification with CCS)	8	Capital Cost	1209	831	kW	-50%	50%
	SNG Plant (Biomass Gasification)	8	Capital Cost	969	764	kW	-50%	50%
Transport	Bus (BEV)	7	Capital Cost	182574	117300	vehicle	-50%	50%
	Bus (Dual Fuel Direct Flywheel Hybrid)	99	Capital Cost	152920	112579	vehicle	-30%	30%
	Bus (Dual Fuel Direct)	99	Capital Cost	146002	108100	vehicle	-30%	30%
	Bus (Dual Fuel Port)	99	Capital Cost	146002	110300	vehicle	-30%	30%
	Bus (Flywheel Hybrid)	99	Capital Cost	138085	110615	vehicle	-30%	30%

	Bus (Gas SI Flywheel Hybrid)	99	Capital Cost	148570	109252	vehicle	-30%	30%
	Bus (Gas SI)	99	Capital Cost	141002	104400	vehicle	-30%	30%
	Bus (Hybrid)	99	Capital Cost	224700	156600	vehicle	-30%	30%
	Bus (Hydrogen FCV)	8	Capital Cost	520000	153800	vehicle	-50%	50%
	Bus (ICE)	99	Capital Cost	130000	106400	vehicle	-10%	10%
	Bus (Wireless PHEV)	7	Capital Cost	165000	112700	vehicle	-30%	30%
	Car Battery (A/B Segment)	7	Capital Cost	18200	7567	vehicle	-10%	75%
	Car Battery (C/D Segment)	7	Capital Cost	25373	13161	vehicle	-10%	75%
	Car CNG (A/B Segment)	99	Capital Cost	10667	8186	vehicle	-10%	10%
	Car CNG (C/D Segment)	99	Capital Cost	16781	12949	vehicle	-10%	10%
	Car Hybrid (A/B Segment)	99	Capital Cost	10348	6125	vehicle	-10%	15%
	Car Hybrid (C/D Segment)	99	Capital Cost	15603	9146	vehicle	-10%	15%
	Car Hydrogen FCV (A/B Segment)	8	Capital Cost	33064	8192	vehicle	-10%	75%
	Car Hydrogen FCV (C/D Segment)	8	Capital Cost	52221	14234	vehicle	-10%	75%
	Car Hydrogen ICE (A/B Segment)	8	Capital Cost	29927	9207	vehicle	-10%	50%
	Car Hydrogen ICE (C/D Segment)	8	Capital Cost	47488	14847	vehicle	-10%	50%
	Car ICE (A/B Segment)	99	Capital Cost	7631	5662	vehicle	-10%	10%
	Car ICE (C/D Segment)	99	Capital Cost	11123	8456	vehicle	-10%	10%
	Car PHEV (A/B Segment)	7	Capital Cost	17710	6832	vehicle	-10%	25%
	Car PHEV (C/D Segment)	7	Capital Cost	26594	10328	vehicle	-10%	25%
	HGV (Dual Fuel Direct Flywheel Hybrid)	99	Capital Cost	97212	64767	vehicle	-30%	30%
	HGV (Dual Fuel Direct)	99	Capital Cost	92228	59253	vehicle	-30%	30%
	HGV (Dual Fuel Port)	99	Capital Cost	81807	58143	vehicle	-30%	30%
	HGV (Flywheel Hybrid)	99	Capital Cost	81109	60965	vehicle	-30%	30%
	HGV (Gas SI Flywheel Hybrid)	99	Capital Cost	83286	62200	vehicle	-30%	30%
	HGV (Gas SI)	99	Capital Cost	71807	56698	vehicle	-10%	10%
	HGV (Hydrogen FCV)	8	Capital Cost	1728053	455325	vehicle	-10%	75%
	HGV (ICE Euro 6)	99	Capital Cost	72337	57578	vehicle	-10%	10%
	LGV (BEV)	7	Capital Cost	65865	21200	vehicle	-10%	75%
	LGV (Dual Fuel Direct)	99	Capital Cost	39140	38640	vehicle	-10%	10%

	LGV (Dual Fuel Port)	99	Capital Cost	38140	37640	vehicle	-10%	10%
	LGV (Gas SI)	99	Capital Cost	31120	30620	vehicle	-10%	10%
	LGV (Hybrid)	99	Capital Cost	30290	16680	vehicle	-10%	10%
	LGV (Hydrogen FCV)	8	Capital Cost	84780	25737	vehicle	-10%	75%
	LGV (Hydrogen ICE)	8	Capital Cost	81911	28773	vehicle	-10%	50%
	LGV (ICE)	99	Capital Cost	21871	15350	vehicle	-10%	10%
	LGV (PHEV)	7	Capital Cost	36335	17050	vehicle	-10%	25%
	MGV (Dual Fuel Direct Flywheel Hybrid)	99	Capital Cost	61302	43621	vehicle	-30%	30%
	MGV (Dual Fuel Direct)	99	Capital Cost	59721	38369	vehicle	-30%	30%
	MGV (Dual Fuel Port)	99	Capital Cost	56350	40050	vehicle	-30%	30%
	MGV (Flywheel Hybrid)	99	Capital Cost	49446	39621	vehicle	-30%	30%
	MGV (Gas SI Flywheel Hybrid)	99	Capital Cost	52339	41928	vehicle	-30%	30%
	MGV (Gas SI)	99	Capital Cost	46350	36597	vehicle	-30%	30%
	MGV (Hydrogen FCV)	8	Capital Cost	1728053	455325	vehicle	-10%	75%
	MGV (ICE Euro 6)	99	Capital Cost	44779	35643	vehicle	-30%	30%
Buildings	District Heating (HD)	4	Capital Cost	3376-7059	3376-7059	dwelling	-30%	30%
	District Heating (MD)	4	Capital Cost	5818-9906	5818-9906	dwelling	-30%	30%
	District Heating (LD)	4	Capital Cost	8365-12903	8365-12903	dwelling	-30%	30%
	Retrofix (LD)	5	Capital Cost	16363	10187	dwelling	-20%	10%
	Retrofix (MD)	5	Capital Cost	11904	7284	dwelling	-20%	10%
	Retrofix (HD)	5	Capital Cost	7629	4917	dwelling	-20%	10%
	Retroplus (LD)	5	Capital Cost	25495	18237	dwelling	-20%	10%
	Retroplus (MD)	5	Capital Cost	18974	13608	dwelling	-20%	10%
	Retroplus (HD)	5	Capital Cost	14765	10246	dwelling	-20%	10%
	Heat Pump (Air Source, Hot Water)	4	Capital Cost	750	585	kW	-30%	30%
	Heat Pump (Air Source, Space Heat)	4	Capital Cost	750	585	kW	-30%	30%
	Heat Pump (Ground Source, Hot Water)	4	Capital Cost	1200	936	kW	-30%	30%
	Heat Pump (Ground Source, Space Heat)	4	Capital Cost	1200	936	kW	-30%	30%
	Heat Pump (Large Scale Marine)	1	Capital Cost	300	300	kW	-30%	30%
	Solar Thermal (Domestic non south facing)	4	Capital Cost	3046	2264	kW	-50%	50%

	Solar Thermal (Domestic south facing)	4	Capital Cost	1616	1249	kW	-50%	50%
Resources	Biomass Importing	8	Max build rate	1.08E+10	3.40E+10	kWh	-100%	200%
	Biofuel Imports	8	Resource Cost	6.01	5.46	p/kWh	-31%	50%
	Biomass Imports	8	Resource Cost	1.94	2.27	p/kWh	-21%	58%
	Coal	99	Resource Cost	0.78	0.61	p/kWh	-22%	51%
	Gas	99	Resource Cost	1.41	1.86	p/kWh	-39%	16%
	Liquid Fuel	99	Resource Cost	4.62	4.20	p/kWh	-31%	50%
	Nuclear	10	Resource Cost	0.16	0.34	p/kWh(th)	0%	39%
	UK Biomass	8	Resource Cost	1.87	1.87	p/kWh	-30%	30%
	UK Biomass	8	Max Resource Quantity	1.89E+10	1.17E+11	kWh	-30%	30%
CCS	Industry CCS	9	Max build rate	1	100000	industrial units	-90%	50%
	Other CCS	9	Max build rate	100	20000000	kW	-90%	50%