energy
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An ETI Strategy report

Comparing Generating Technologies

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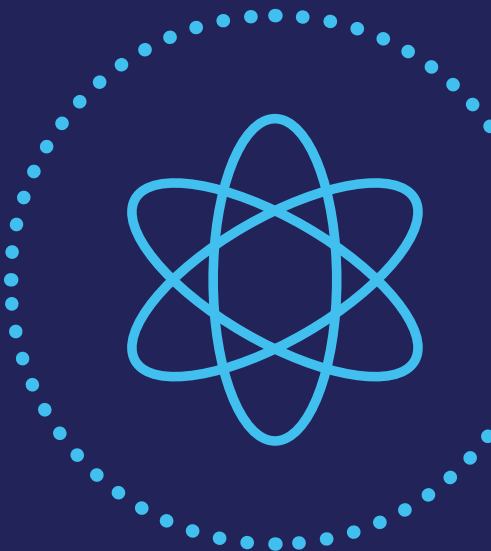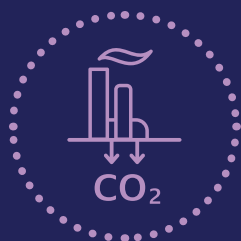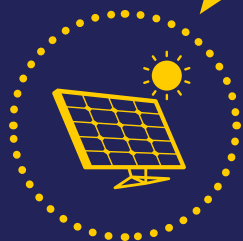
Summary

Differing generating technologies are often compared using simple Levelised Cost of Energy (LCOE) analysis. Whilst useful in some circumstances, LCOE analysis can be misleading and hide the true system costs incurred by different technologies under different conditions. In practice, the average cost achieved may be very different to the theoretical LCOE.

Simple LCOE analysis is therefore often not an effective way of robustly comparing the real overall system cost of various generating technologies.

System Operators are tasked with matching instantaneous supply with demand at the lowest cost to consumers and society. This requires a degree of system flexibility using a mix of primary and secondary generating and balancing technologies. For example, the achieved cost (and carbon intensity) for renewable generation is actually dependent upon its intermittency (how much power can be generated due to weather conditions and availability), and its instantaneous supply performance against instantaneous demand (the difference will need to be filled by a secondary generation or back-up technologies such as batteries or gas turbines).

The ETI has developed an easy to use Excel spreadsheet Technology Comparator Tool that allows users to compare how well a number of different generating technologies match half hourly electricity demand through a number of sample years. The tool cost optimises the selected generation technologies, together with either batteries or gas turbines as back-up, deployed to match demand through the year.

The spreadsheet is designed to allow users to make various choices and to input their own data, for example for carbon price or technology costs. The user manual describes how the spreadsheet is organised for anyone who wants to add another technology, or a new demand year or any other changes to the structure. Users can also test the sensitivity of the cost-optimised combination of the selected technology and backup technology to the assumptions, by using different data.
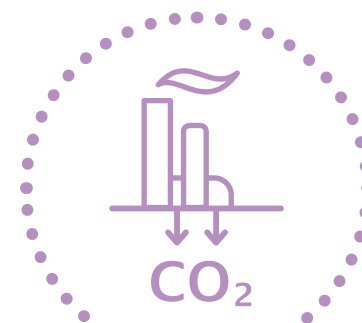
The tool calculates the (expected) LCOE for each chosen technology, as well as the average annual cost of electricity with and without a carbon price. In addition to the basic costs of the generation technology, the average cost includes the cost of the gas turbines or batteries, as well as fuel costs and the notional cost of emitted greenhouse gases.

This report describes the structure and operation of the tool and includes a number of examples of its use. Using the default data that comes included in the tool, the user will see from the examples that deep decarbonisation of electricity production using renewables alone is more expensive than a simple LCOE analysis would suggest. Users will also see how the relative attractiveness of various technologies changes as battery prices reduce, as well as the required scale of batteries that enable those generation technologies to become a major supplier of electricity in a fully decarbonised world.

Users of this tool will gain insight into the profile of different technologies and their potential system impact out to around 2030. The large differences between the LCOE of some technologies and the annual average cost of supply may be surprising and this suggests that a note of caution should be raised in using

LCOE as the basis of technology neutral competitions, auctions etc.

Using LCOE or the average cost from this tool alone will not show what the optimum contribution of any generating technology is, within a mix that includes multiple design options for supply, demand management, storage and interconnection. Transport and heating are becoming increasingly electrified and the UK is more strongly connected to other electricity systems. This means that the variability and manageability of demand and the variability of price and embedded emissions of imported electricity will become at least as important as the variability of supply. For example, once heating is electrified, the relatively low cost of heat storage becomes a significant factor.

While this tool will therefore provide the user valuable insight, the ETI recommends that analysis of potential future energy systems should be undertaken using whole systems tools. Other relevant ETI publications based on this whole system approach include an analysis of two potential future UK energy systems[1] and also a detailed report on valuing generation technologies[2].

> **"Users of this tool will gain insight into the profile of different technologies and their potential system impact out to around 2030."**

1   Options Choices Actions – UK scenarios for a low carbon energy system, Milne, ETI, March 2015

2   Assessing the Value for Money of Electricity Generating Technologies, Deasley and Thornhill, Frontier Economics for ETI, March 2018

Introduction

Differing generating technologies are often compared using simple LCOE analysis. This is often not an effective way of comparing the real overall system cost of the generating technologies. The impact of variable renewables has frequently been used as an example to illustrate this, with the cost of the required back-up generation to cope with intermittency, or the costs of storage usually ignored in the calculation. A very thorough analysis of relevant publications has been undertaken by the UK Energy Research Centre (UKERC)[3].

A UKERC review in 2016 highlighted the wide range of possible estimates that could be made of hidden system costs; the very location specific, and supply-demand mix specific, nature of these estimates; and also that whole systems optimisation is the gold standard for understanding the LCOE points at which different generating technologies compete, given their different characteristics.

Work which looked at a whole energy system approach has shown that UK electricity systems designed with high levels of renewables penetration have additional costs for flexibility that may be hidden and as high as £8bn[4] per annum by 2030. A later piece of work from the same team showed that there are a wide range of competing solutions to create system flexibility but that these are hard to cost. It also found that there is a lack of evidence on their impact to date[5].

The ETI has created a whole energy system analysis and modelling capability and has developed a number of tools to explore these issues from different perspectives. Our most ambitious and challenging project – EnergyPath Operations – seeks to develop a tool that can model at a local level the whole system behaviours of complex supply-demand mixes (including storage) with real-world representation of factors such as market rules, IT and communications costs and bottlenecks (ie real control algorithms and hardware), weather and the behaviours of building occupants and vehicle drivers[6].

For most people these complex tools are black boxes from which answers emerge. Simplified tools provide a way to get a quick sense of how the system works and what the important factors are without needing to undertake complex modelling studies. For example, the DECC *2050 Calculator*[7] fills the need for a simplified tool for overall energy system design and is widely used as a communications and teaching aid. The ETI's Technology Comparator Tool is intended to be a simple tool that captures some of the important aspects of short-term variations in both supply and demand but which is simple enough for non-experts to use and modify themselves.

The ETI has produced the tool to enable anyone with a basic understanding of electricity balancing to explore the effect of different assumptions on the total cost of meeting electricity demand, as it varies through the year. In scope it is a much less ambitious project than the 2050 Calculator (or the ETI's whole systems analysis tools) but it has enough functionality to be useful and to allow non-expert users to explore themes and trends. The tool looks at meeting electricity demand from a single generating technology with the flexibility to match supply to demand provided either through batteries or combined cycle gas turbines (CCGTs). It is intended to allow engineers, policy makers and the public to get a feel for what might happen, for example, as batteries become ever cheaper or why it is not currently cost-effective to fully decarbonise the electricity supply in the UK with only renewables.

> ❝ The tool looks at meeting electricity demand from a single generating technology with the flexibility to match supply to demand provided either through batteries or combined cycle gas turbines (CCGTs). ❞

3 The costs and impacts of intermittency – 2016 update: A systematic review of the evidence on the costs and impacts of intermittent electricity generation technologies, Heptonstall, Gross and Steiner, UKERC, February 2017

4 Value of Flexibility in a Decarbonised Grid and System Externalities of Low-Carbon Generation Technologies, Strbac et al, Imperial College and Nera (for the Committee on Climate Change), October 2015

5 An analysis of electricity system flexibility for Great Britain, Carbon Trust and Imperial College, November 2016

6 http://www.eti.co.uk/programmes/smart-systems-heat/energypath-operations

7 http://2050-calculator-tool.decc.gov.uk/#/home

Introduction

The tool itself is an Excel spreadsheet which is freely downloadable from our website, along with a user guide. It is licensed for anyone to use and modify although any modifications to the structure for other than private use must be made generally available to other users under the same terms.

The tool is intended to provide a starting point for a common resource we can all use, share and build on. Users of the tool will be better informed to engage in discussions about the relative advantages of different generating technologies and to take a broader view of their impact than a single LCOE can provide.

This report will explain at a high level how the tool works and show examples of different results that can be derived from it by using the built-in data, at the same time illustrating some of the weaknesses of using LCOE in isolation. The real value of the tool comes from users using their own data to understand sensitivities to assumptions.

This report deliberately has no findings or recommendations, other than to use the tool freely and thoughtfully.

In practice, all real world scenarios will have a mix of different technologies, and also demand which responds to supply costs and availability. The challenge is to combine different supply, demand and control technologies in a way that meets the need for services such as comfort, cleanliness, mobility, security, food preparation and preservation etc in the most affordable, secure, sustainable and equitable way. This requires a whole system analysis and the final section of this paper touches on this.

We will now look at worked examples to gain insight into the characteristics of each generating technology as a starting point for thinking about how to combine them. These worked examples illustrate how the tool may be used.
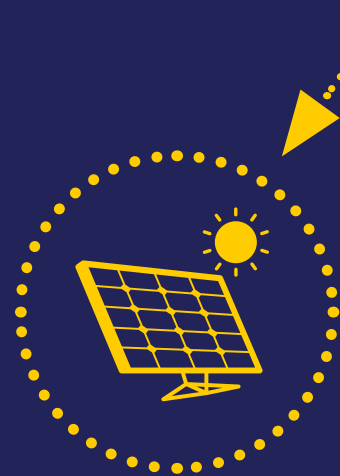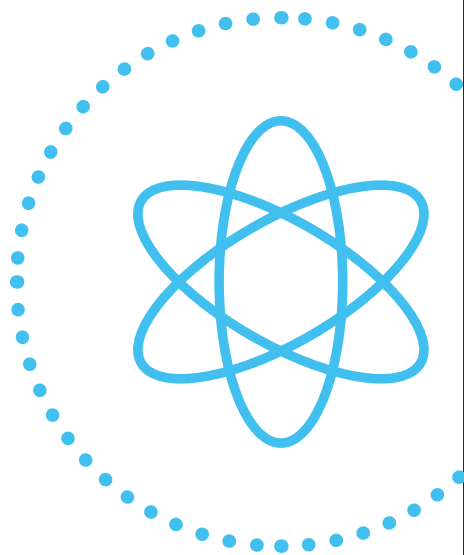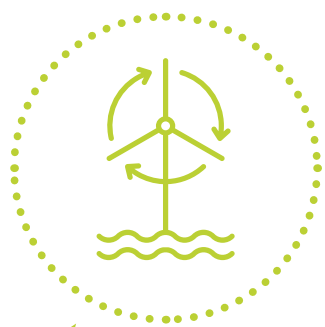
> " Users of the tool will be better informed to engage in discussions about the relative advantages of different generating technologies and to take a broader view of their impact than a single LCOE can provide. "

Evaluating electricity technologies for the future

LCOE often does not work as an effective way of comparing costs because it assumes that a unit of electricity has the same value wherever and whenever it is produced, i.e. it can be stored and transported at no cost. It is an *energy* (kWh) based cost measure rather than a *power* (kW) based one. Electricity distribution is expensive and electricity storage is very expensive. If batteries were a thousand times cheaper and a hundred times smaller than today, then the use of LCOE may be a reasonable measure of the value of any generating technology, especially distributed ones. Even at ten times cheaper and a quarter the size, batteries will make a significant difference to how the UK system operates. How much impact this might have on direct competition between generating technologies could be explored using the tool.

The tool is based on historic data from the GB System Operator. It allows the user to test how well wind, PV, nuclear, gas turbines etc on their own could have matched demand in a number of historic years. This automatically allows for correlations between supply and demand, driven by the time of day and weather conditions. It also will allow investigation into how much the answer changes depending on which year is used.

Current discussions about variable supply have been prompted by increasing levels of variable renewables. What is often less well recognised is that variable demand for electricity will also become more important, especially as travel and heating are electrified. Nearly all envisioned scenarios for decarbonising the UK energy system show significant levels of electrification of heat and transport beyond 2030.

Successful energy storage, both of heat and electricity, will revolutionise the operation of the electricity system over the next twenty years, provided that markets and enabling governance are altered to enable stronger innovation and technology-neutral competition.

The availability of storage will break the direct connection between supply and demand, which will change the optimum mix of generating technologies, and the average costs achieved.

The UK Smart Meter project aims to install smart remotely readable gas and electricity meters in 80% of UK homes and commercial premises by 2020. This, together with other Smart Grid changes, has the potential to enable innovation and competition between technologies, including storage. Unlocking this innovation will require changes to market arrangements to take account of advanced metering in combination with storage. How smart meters could enable these kinds of innovation is beyond the scope of this tool. Despite it's rather tongue-in-cheek title, the reference is a useful source of information[8].

For example, it would be possible to use the distributed capacity of domestic hot water tanks with immersion heaters fitted to store quite large renewable surpluses in the form of stored heat. A domestic hot water tank enables a 3kW immersion heater to provide hot water, that would otherwise require a 30kW gas combi-boiler. Similarly, a storage radiator uses electricity overnight and provides heat during the day, smoothing energy demand. Electrifying the delivery of domestic heat could also help with absorbing short-term surpluses, for example using summer PV peaks to provide hot water. A second, often cited example would be to use the distributed resource of electric vehicle battery storage to store surplus supply. These innovations alone are unlikely to be able to solve the real problem in trying to meet peak winter heating demand.

Although the ETI has not created robust <u>detailed</u> future time series demand pattern estimates with electrified heating and transport, our whole systems high-level optimisation tool ESME[9] does perform a cross-vector co-optimisation of supply and demand technologies based on a <u>reduced</u> set of characteristic time slices, importantly including explicit peak closure and a flexibility (system services) model. This has highlighted that automated demand management is inevitable at some stage and demand therefore responds to supply in complex ways (as ESME shows). Current ETI projects are looking to address this knowledge gap.

In general however, electric vehicle charging provides positive flexibility to the energy system, providing that charging is managed by automated systems. Heating on the other hand presents a tremendous challenge.

Using today's electricity demand patterns can still give useful insight out to 2030 but by 2040 electrification of heating and transport will require a different modelling approach.

It is therefore prudent for users of this comparator tool to avoid generalising findings from current patterns of demand to systems where heat and travel are much more electrified.

8 Smart Metering Implementation Programme (SMIP) for Dummies, Chris Beard, https://www.cgi-group.co.uk/article/SMIP-for-dummies

9 Modelling Low-Carbon Energy System Designs with the ETI ESME Model, Heaton, ETI, April 2014 and ESME data references book – http://www.eti.co.uk/library/esme-data-references-book

Description of the Technology Comparator Tool

This section describes in outline how the tool is constructed and what effects it does and doesn't include. The user guide describes this in more detail.

Concept structures

The Technology Comparator Tool minimises the total cost of meeting demand for electricity by optimising the combination of a primary technology and either a fleet of CCGTs or batteries to meet the half hour demand through the year. The optimisation also includes a notional "carbon tax" on the emissions from back up CCGTs and the residual emissions from CCGTs with Carbon Capture and Storage (CCS). The optimised solution will find the lowest cost combination. Note however that it will not necessarily have a low average carbon intensity of electricity unless it is cost-effective to deliver that.

There is a simplified commitment process for thermal plants around the concepts of cold start and hot start. There are constraints about the rate at which thermal plants like nuclear can be ramped up. Thermal plants have part-load capacities and efficiencies. Batteries have round trip efficiencies but no long-term self-discharge.

The tool has tables with GB[10] electricity demand averaged over each half hour period through the year for a number of years, all based on historic data. Over shorter periods than half an hour, the GB electricity System Operator is assumed to buy services to match instantaneous power supply and demand and the cost of these services does not depend on the primary generating technology. Although there will be small differences in the cost of these services between different technologies, this should be a secondary effect, except in extreme cases. The large back up fleets of CCGTs or batteries can provide services at small additional costs.

The tool has an option to include embedded emissions in the optimisation. Embedded emissions are found in materials used in the construction of the primary and secondary technologies, and also in natural gas when used as fuel. Methane is a potent greenhouse gas and fugitive emissions during production and transport can significantly increase system-wide emissions. These embedded emissions are real because increasing deployment of a technology will increase them, until the supply chain itself is significantly decarbonised. The user of the tool can switch this option on or off according to their own purposes.

It is possible for both inflexible and variable technologies to produce more electricity than actual demand requires. Reducing the output from variable technologies will require System Operator action and potentially compensation to the generator. Managing the potential for over-frequency events from inflexible technologies will require both System Operator actions and design features in the generating technology to allow for some of the primary energy to be "dumped" on command. These are unlikely to contain significant costs and the tool represents both types of surplus as electricity that is produced at zero or very low marginal cost but not used.

In a real world outcome, especially beyond 2030, this surplus electricity would represent an opportunity for market and systems design to enable interconnectors, the control of immersion heaters and vehicle charging (and many other uses) to add value to the overproduction state. But the tool does not attempt to value this unused capacity nor does it have an additional cost above and beyond the cost of investing in and operating the equipment.

Demand shaping in response to supply (Demand Side Response or DSR) is an inevitable feature of future electricity systems. The main sources of this currently are contracts for interruptible supply with large industrial users and tariffs such as Economy 10 working in combination with large loads such as night storage heaters, immersion heaters and vehicle chargers. The ETI's whole system tools include many forms of DSR as inherent features of system design and optimisation. However, this is beyond the scope of this Technology Comparator Tool.

Interconnectors can make an important secondary contribution to electricity economics and operation through a series of market and technical effects. These effects are very hard to predict as both the supply and demand mixes will continue to develop across Europe. Fully understanding these effects for the UK would require a complex whole system model of a large part of Europe. The tool itself does not allow for interconnectors.

10 Great Britain operates as a single synchronised electricity system and market. The island of Ireland is a separate and internally integrated system.

Description of the Technology Comparator Tool

Data sources

The default data set supplied with the tool is one view of costs for new projects at the point of Final Investment Decision (FID) in or around 2030 and has been chosen to illustrate how the tool works.

Forecasting short-term costs is almost impossible, as any review of costs and cost projections over the last ten years will show. Although the course of cost and performance development over longer periods is easier to relate to underlying technological, competitive, economic and social factors, there remain very large uncertainties. In undertaking whole system analysis, the ETI uses probability distributions to account for these uncertainties, but including uncertainty in this tool would have made it too complicated. Predicting how the whole UK energy system will evolve out to 2050 is almost impossible – there are too many decisions to be made by too many actors. Even reasonably short-term cost developments are hard to quantify, as any auction or competition to supply electricity will show.

Recognising this, users of the tool can substitute their own data for any of the current inputs, as well as using ranges and scenarios to test the sensitivity of their conclusions to uncertainties in the data. The cost data in the tool will likely be wrong; we just don't know by how much and in which direction, but it allows the user to outline broader thinking and investigate trends and sensitivities.

The tool also has data for embedded carbon within materials of construction and fuels. These emissions may or may not be in the UK, depending on where the materials are produced. The data in the tool is consistent with available references[11,12] but used in a different form. The ETI has used its own sources for the embedded emissions of natural gas in the UK[13] and has verified the estimates in the reference through independent calculation from primary references.

The embedded carbon estimate for lithium-ion batteries is consistent with other sources. BYD, a leading high tech multinational company[14] is supplying batteries into the UK for Enhanced Frequency Response, but there may be more uncertainty over the carbon intensity of batteries, depending on the supply chain[15].

A capture rate of 95% is assumed for CCS plants, although ETI technology analysis suggests that the long-term optimum level will be slightly higher than that. Analyses that use very low capture rates, such as 90%, do not in our opinion reflect the real potential of CCS technologies. However, it is possible that these low rates could become a self-fulfilling assumption that limits the application of CCS.

> " Predicting how the whole UK energy system will evolve out to 2050 is almost impossible – there are too many decisions to be made by too many actors. Even reasonably short-term cost developments are hard to quantify, as any auction or competition to supply electricity will show. "

11 Carbon Footprint of Electricity Generation, POSTnote 383, Allen et al, Parliamentary Office of Science & Technology, June 2011

12 GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China, Han et al, Tsinghua University, April 2017

13 An ETI Perspective – Natural Gas Pathway Analysis for Heavy Duty Vehicles, Matthew Joss, November 2017 – http://www.eti.co.uk/library/an-eti-perspective-natural-gas-pathway-analysis-for-heavy-duty-vehicles

14 http://www.byd.com/pv/ess.html

15 Cleaner Cars from Cradle to Grave, Union of Concerned Scientists, Nealer et al, November 2015

Worked Examples

Please note that the tool requires Visual Basic to be installed, as well as Excel. Refer to the User Guide for details of tool use.

Tool Configuration

For the worked examples, the tool has been run with unmodified data, apart from the exceptions noted in the text.

The embedded carbon emissions input was turned off, although its use is briefly reviewed later. Instead, the embedded carbon is included within the data inputs as supplied. Excluding carbon emissions that have occurred outside the UK is consistent with most analyses. However, as the global economy decarbonises, emissions will be driven down by the decarbonisation activities of the producing nations. It is not plausible to believe that this will have occurred to any significant extent by 2030.

The analysis starts with a carbon price of £200/Te CO_{2e}. The sensitivity of this will be tested later.

First we note the LCOE for the various technologies, using 2014 supply data and the notional 2030 costs in the spreadsheet for each generating technology. The LCOE of renewable technologies depends on how much resource is available during the year.

Worked Example – Year to Year variation

The first worked example considers the cost variations year to year resulting from matching demand and weather for wind and PV, when these are backed up by a CCGT fleet. Note that the tool re-optimises the capacity of PV and wind for each year.

Table 2
Variation of annual average cost and carbon intensity for Solar PV and Offshore Wind

Year At £200/Te CO_{2e}	Solar PV		Offshore Wind	
	Average cost £/MWh[16]	Average carbon intensity g/kWh	Average cost £/MWh	Average carbon intensity g/kWh
2012	115	241	104	148
2014	109	224	104	142
2015	110	222	104	139
2016	111	227	105	130

Table 1
"2030" Levelised Cost of Energy based on 2014 renewable resource availability

LCOE	£/MWh
Onshore Wind	68
Offshore Wind	72
Solar PV	53
Nuclear	73
CCGT with CCS	94
Unabated CCGT	59

Although there is some variation in the costs and carbon intensity from year to year, it is not dramatic. However, the generating capacity varies more. For example, the optimised Offshore Wind capacity in 2014 is 52GW whereas in 2016 it is 57GW, as 2016 was less windy than 2014.

16 Note that the cost of electricity includes a notional "carbon tax" on the emissions from the gas turbines. This represents the marginal cost of finding additional savings outside the power sector. Since decarbonised electricity is often key to carbon savings elsewhere, these costs might be higher than the £200/Te used here.

Worked Examples

The CCGT back-up capacity to provide the required system flexibility depends on the year. For example, the optimised capacity for a selection of years is:

Table 3
Variation of required back-up capacity for Solar PV and Offshore Wind

Year	Required CCGT capacity GW	
	PV	Offshore Wind
2012	56.2	53.8
2016	51.6	46.4

The table shows how much PV and back-up CCGT capacity would have been required in 2012 and 2016, given the profile of electricity demand and the weather in those years.

The demand profile changed between 2012 and 2016, so less capacity was required. The availability of wind <u>at peak</u> was also much better in 2016 than in 2012. The availability of PV at peak in the UK is and probably always will be nothing, because peak is on cold dark weekday evenings in winter.

By convention, the capacities used in this report are the rated or design capacities of the assets, sometimes written as GW_{peak} (or MW_{peak}). GW_p is a common abbreviation of this. The capacity or utilisation factor is the number of GWh produced in a year compared to the amount that would have been produced at rated capacity.

Capacity factors are less than a hundred percent because of planned maintenance, unplanned outages and variation of the availability of renewable sources or fuels. Where the output is less than the theoretical maximum because of constraints or market forces, the capacity factor is sometimes called the utilisation (ie how much of time the asset was needed rather than how much of the time it was available). Both of these have been combined in the capacity factors used in the following analysis. They were calculated using Equation 1.

The different availabilities of renewable resource and maintenance requirements lead to very different capacity factors. For example, in the UK the capacity factor for a baseload thermal generator should be around 90%. Whereas PV is around 11% and a UK Offshore Wind fleet might vary between 35% and 45%, depending on the year. Crudely, $1GW_p$ of nuclear is equivalent to $8GW_p$ of PV or $2.2GW_p$ of Offshore Wind in terms of energy production. As will become clear later, this is only one aspect of the differences between them.

For any real system design the System Operator will have to award sufficient capacity contracts to ensure that it can cope with the coincidence of moderately rare demand peaks and moderately rare low wind supply. The costs highlighted above are therefore slightly lower than they should be in practice, since in most years there would be more back-up capacity than required in that particular year. Within this tool we are using historic data, whereas the design of future systems must consider using price signals and control systems to flatten profiles and manage peaks.

As vehicle and heating electrification advances, this will become very important to system costs and performance. As already discussed, diversifying heating is challenging, not least because large parts of the UK are all cold at once, especially in periods of high pressure with very low overnight temperatures coupled with low wind and sunny but short days.

Based on Tables 2 & 3, it seems that 2014 would be a reasonable year to pick as a worked example in terms of technology comparison. Electricity demand in 2014 is similar to later years and the availability of wind and solar energy looks typical.

Equation 1
Calculation of Capacity Factor from rated capacity GW_p and annual electricity production in GW^h

$$\text{Capacity Factor} = \frac{GW^h}{GW_p} * 8760$$

Worked Examples

Worked Example – Operating flexibility provided by CCGTs

This table compares the results when CCGTs are the secondary technology. (The counterfactual of the tool is always using CCGTs as the only generating technology.)

Table 4
Cost optimised technology deployments with CCGT fleet for demand matching

2014 data at £200/Te	Solar PV	Offshore Wind	New Nuclear	CCGT + CCS	Counterfactual CCGT only
Primary capacity GW	96	52	35	35	–
CCGT capacity GW	53	47	18	18	53
Average Cost without "carbon tax" £/MWh	64	76	76	94	59
Average Cost with "carbon" tax £/MWh	109	104	81	101	121
LCOE of Primary Technology £/MWh	53	72	73	94	59
Average carbon intensity g/kWh	224	142	28	37	309
% electricity from primary technology	29%	55%	92%	92%	–
% electricity unused (of primary output)	12%	7%	0%	0%	–

It may seem surprising that while PV has the lowest cost per MWh, it has the highest cost after carbon emissions from the turbines are included. This is due to the fact that increasing the PV capacity beyond the optimum only has a very marginal impact on the amount of carbon produced, because PV simply cannot supply electricity when it is dark. CCGTs therefore must be used for at least half the hours in the year. Deploying infinite PV capacity cannot make up this shortfall. Note that with lower carbon prices PV looks more attractive than at high carbon prices.

With zero carbon prices, PV is still more expensive than CCGTs. The CCGTs still have to be built to meet peak demand and PV therefore only saves fuel costs.

There is a similar effect for wind, where it is not economic to increase capacity only to get a little more power during those times when wind power is low across the UK. In the UK wind output is much better matched to demand than PV. Therefore it is possible to get deeper decarbonisation with wind than with PV (when the flexibility is provided by CCGTs).

Although nuclear and CCGT with CCS both still show some back-up CCGT capacity to create operating flexibility and meet infrequent peaks, the required time periods are short. Therefore it is possible to achieve deep decarbonisation with these low carbon technologies. The total installed capacity of dispatchable technologies is 53GW, which matches peak demand.

Which of these is therefore the lowest cost? As you can see it depends on how the question is interpreted. Nuclear, unabated CCGTs and PV could all claim to be lowest cost. However, PV on its own cannot ever meet carbon targets if the flexibility is to be provided by CCGTs. Nuclear, on the other hand, cannot be built fast enough to meet the carbon targets. Offshore Wind and CCGT with CCS could both claim to be deployable at scale and therefore lowest practical cost.

In order to build enough low carbon generation in time, we are therefore likely to need several of these technologies operating together.

CCGT with CCS and Offshore Wind also both have the highest potential for further cost reductions through learning. CCS has the potential for rapid savings through network scale reducing transport and storage costs.

Of course different input data for the tool will produce different outputs, but the qualitative drivers of these patterns would not change. These costs do not include land (or seabed) rental and resource licences which would affect all the technologies differently, especially those with a large area of "footprint".

Using the tool, we can plot the effect of nominal carbon price on system carbon intensity and optimum capacity. This is different for PV and wind.

Worked Examples

Figure 1
Effect of carbon price on carbon intensity with CCGT fleet for demand matching
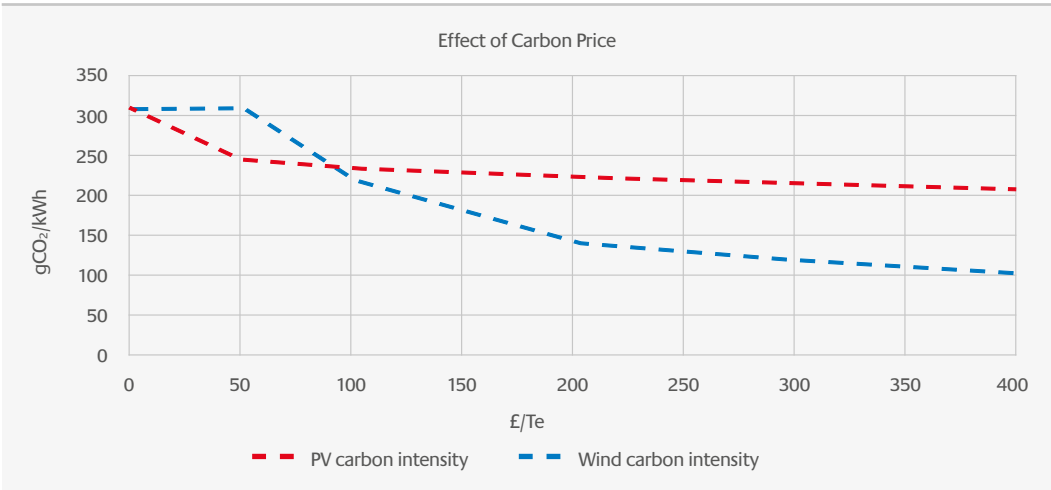
Most of the benefit of PV occurs with low carbon prices; PV is very cost-effective but its limited time window of operation creates a ceiling for its impact on carbon intensity. Wind has an impact in the range £100-300/Te. It requires a higher price than PV to stimulate its introduction but has a greater potential for decarbonisation.

Figure 2
Effect of carbon price on cost optimised deployment levels with CCGT fleet for demand matching
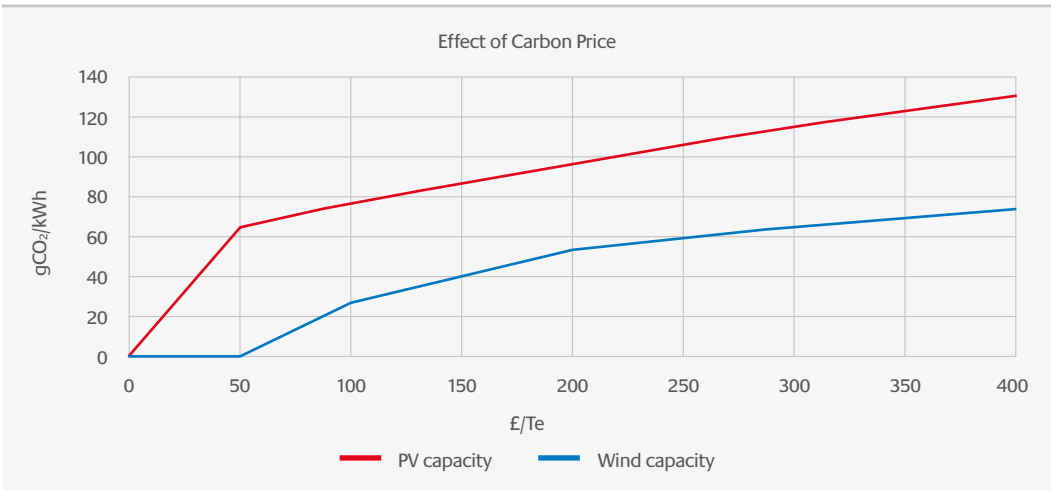
The scale of deployment for each at the point where their contribution when backed up by CCGTs starts to diminish is still significant. This analysis looks at each technology on its own but it does suggest that current levels of deployment are not excessive.

This particular example illustrates why batteries (or other storage technologies), rather than unabated CCGTs are essential if renewables are to deliver deep decarbonisation. Electricity needs to be moved from the times when it is available in excess of demand to times when it is in deficit. Wind in general is more available in the winter, when demand is high, but there is always the risk to the overall system that wind resources may be low for several days in a row.

Worked Example – Operating flexibility provided by batteries

Another useful worked example is to use the tool to look at the use of batteries to provide flexibility and balancing, instead of CCGTs.

The following table shows the results of the tool using the default data – as before, these are the combinations which are found to minimise the total cost of meeting the electricity demand profile.

Table 5
Cost optimised technology deployments with batteries for demand matching

2014 data at £200/Te	Solar PV	Offshore Wind	New Nuclear	CCGT + CCS	Counterfactual CCGT only
Primary capacity GW	1,346	246	51	53	53
Battery capacity GWh	2,600	1,325	11	0.01	–
Battery max power GW	510	100	2	0.03	–
Average C rating	0.2	0.1	0.2	3	–
Average Cost without "carbon tax" £/MWh	360	253	93	104	59
Average Cost with "carbon" tax £/MWh	360	253	93	108	121
LCOE of Primary Technology £/MWh	53	72	73	94	59
Average carbon intensity g/kWh	0	0	0	10	309
% electricity from batteries	48	4	<1	<1	–
% electricity unused	77	64	1	<1	–

Worked Examples

Although batteries are a more expensive way of providing flexibility than gas turbines, they do make it possible to remove direct carbon emissions from all technologies, apart from residual emissions from CCS. It becomes economic to shave off less frequent peaks with some battery capacity supporting nuclear and also CCGT with CCS generation. The optimum level of batteries in a given energy system will depend very much on the details of the technology operating characteristics, costs and market arrangements which the simple Technology Comparator Tool cannot fully represent.

The ETI expects that the broader system benefits of using batteries would justify somewhat higher levels of investment than that shown for CCS or nuclear, and at higher "C" ratings[17] to provide system services. Baringa have estimated for the ETI that batteries might provide cost-effective system services at levels up to around 1GW by 2030.

The level of batteries required to support variable renewables technologies is on a different scale, even allowing for dramatic overbuild of the primary technology. Wind justifies more than 20 hours of storage at peak demand and PV nearly 50 hours. The power rating of the batteries is either similar for both charge and discharge or driven by charging requirements. The charging windows for

PV are short and a large charging power is required only at certain times of year. In summer most of the output cannot be used and the charging windows are wider. With wind it tends to be extended periods in winter when the power cannot be used (once the batteries are charged).

The role of most of the batteries in the fleet is energy shifting (storage) rather than power support (frequency response). This is shown by the low C-ratings which are well below 1. Frequency response systems tend to have C-ratings of 5 or higher. Systems with this scale of batteries can control frequency very well, provided that a mechanism is available to constrain surplus production.

The required scale of these battery supported systems can be understood from some dimensions:

- The required installed PV capacity of 1,346 GW would take 24,500 sqkm of ground mounted PV across Southern England and Wales. This is about 20% more than the total area of Wales and would therefore cover most of the agricultural land in these locations.

- To reach the required 3,925 GWh of installed battery capacity would require the equivalent of over 180M Tesla Powerwall II batteries or more than 6 each within dwellings across England, Scotland and Wales (at an aspirational installed cost quoted

by Tesla as around £4,500 each or £800bn, which is rather more than the default costs in the tool and not yet demonstrated by large scale sales).

- The required installed wind capacity of 246 GW is a significant fraction of the physically available wind resource in the UK and accessing sufficient resource would require the development and operation of floating platforms in very hostile marine environments.

There is a widespread belief that batteries will drop dramatically in price and physical size over the next thirty years. The default battery costs in the tool for 2030 and used in this worked example are well below the costs projected by a variety of commentators for 2020. There are likely to be other

technologies available after 2030 that could reduce the cost of electricity storage, for example novel redox flow batteries or devices based on storing heat in different forms.

We can use the tool to test the effect of very dramatic falls in battery costs. This chart shows the effect of falls in cell costs and the power conversion equipment costs beyond the default data in the spreadsheet. For each reduction in cell cost by a factor of ten, it is assumed the cost of the power conversion is reduced by a factor of two (since power conversion technologies are more mature, with less headroom). As cell costs fall the optimum capacity of the primary technology falls and the cost of power conversion therefore becomes less important in any case.

Figure 3
Effect of battery costs on cost optimised deployment levels of renewables
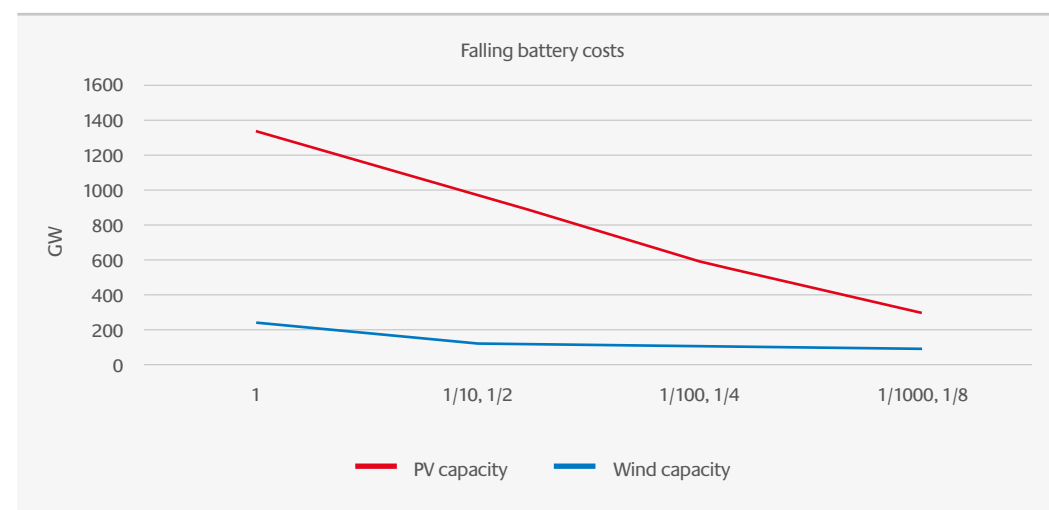
17 The C rating of a storage technology is the ratio of Power to Capacity (in units of "per hour"). A high C store can be operated at high power but charges and discharges in a short time.

Worked Examples

As batteries become cheaper, the economic optimum capacity of the renewable falls towards the minimum required to meet the annual demand, including losses.
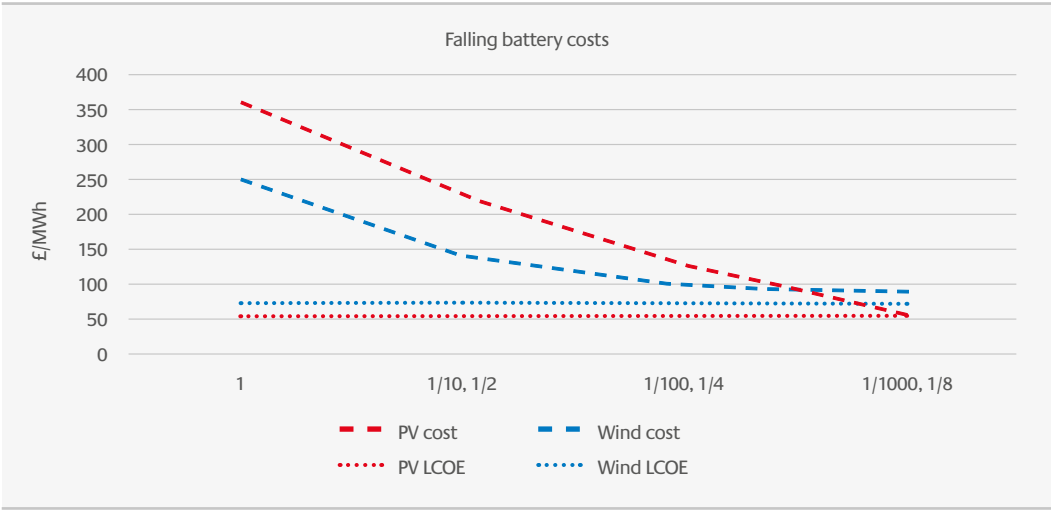
The average cost of delivered electricity falls as less primary capacity is required, and as the battery cost falls. The cost of electricity never quite falls to the LCOE, since there are losses involved in using the batteries (which require more primary capacity) and also the installed battery capacity is so large that the costs are still a small increment over LCOE. For example, PV has an LCOE of £53/MWh, based on this data. At 1/1000th the base cell cost for 2030, the delivered cost over the year is £60/MWh.

At 1/1000th of the nominal 2030 battery pack costs, the optimum capacity to support generation by PV alone would amount to around 235 Powerwall II's on average for each UK dwelling. That would take about the same space as a 20ft standard shipping container (maybe more to allow for cooling) and weigh perhaps 40 tonnes. The stored energy would be colossal – fully charged lithium-ion batteries have about the same explosive potential as plastic explosives.

Illustrating the impact of relying entirely on battery storage back-up in combination with renewables illustrates the need to consider the energy system as a whole, comprising a mix of generating and storage technologies.

Within the wider system there are already low carbon energy storage technologies for heat, as well as hydrogen which can be deployed between now and 2030 much more cheaply.

Worked Example – Accounting for embedded carbon

Including the embedded carbon in the optimisation and technology comparison with CCGTs providing back up, shows some differences in the results compared to excluding embedded carbon.

Table 7
Optimised capacities with CCGT back-up, accounting for embedded carbon

2014 data at £200/Te (with embedded carbon)	Solar PV	Offshore Wind	New Nuclear	CCGT + CCS	Counterfactual CCGT only
Primary capacity GW	93	55	36	36	–
CCGT capacity GW	53	47	17	18	53
Average Cost without "carbon tax" £/MWh	63	76	77	94	59
Average Cost with "carbon" tax £/MWh	120	112	85	115	133
LCOE of Primary Technology £/MWh	62	77	76	94	59
Average carbon intensity g/kWh	283	178	41	105	368

Table 7 shows some differences in the optimisation compared to Table 4. The increased attractiveness of Offshore Wind is the most notable difference.

A typical impact of embedded carbon in batteries can be seen by comparing the results for offshore wind at battery costs of (1/10, 1/2), with and without embedded carbon.

Worked Examples

Table 8
Optimised Offshore Wind capacities with battery back-up, showing effect of embedded carbon

2014 data at £200/Te (battery costs at 1/10, 1/2)	Offshore Wind without embedded C	Offshore Wind with embedded C
Primary capacity GW	129	137
Battery capacity GWh	9,105	7,399
Charging capacity GW	102	109
Average Cost without "carbon tax" £/MWh	140	141
Average Cost with "carbon" tax £/MWh	140	173
LCOE of Primary Technology £/MWh	72	77
Average carbon intensity g/kWh	0	161

The differences apparent between Tables 4 & 7 and within Table 8 are large enough to suggest that reflecting embedded carbon in policy and market mechanisms would have two beneficial effects:

- It would avoid medium-term technology choices that have significantly higher lifecycle global emissions than is apparent if embedded carbon is not accounted for

- It would reward suppliers that deliver cost-effective greenhouse gas reductions, for example for natural gas supplies or batteries

The analysis also points to Offshore Wind as a least likely regrets generating technology investment in the medium term in the UK in terms of overall global greenhouse gas emissions impact.

Worked Examples – Conclusions

The worked examples have shown some of the ways the tool can be used to compare individual generating technologies from different perspectives. Although meeting electricity demand from a single generating technology plus a single back-up technology is over-simplistic, it does provide insight into the characteristics of individual generating technologies and how system plans need to be put together.

The tool has shown that LCOE is only one perspective on an individual generating technology, and that on its own LCOE does not reflect the system impacts of a technology.

No single technology is likely to be the answer to decarbonisation and a system energy analysis approach is vital in developing a complementary mix of technologies to reduce emissions across multiple sectors.

It is imperative to understand how the choices made in one form of energy affect what needs to happen elsewhere. While many sources have made this point, this tool enables users to explore it.

Whole systems analysis – discussion

Whole systems analysis was described in the UKERC report[18] (referenced in the Introduction) as the gold standard for understanding the complex interactions of different generating technologies at high levels of renewables penetration. The system challenge will increasingly be to manage supply-demand interactions, including storage of different kinds throughout the system, and using demand scheduling to match demand to available supply. As electrification of heating and transport gathers pace, the variability and management of demand will become more important than the variability of the renewables part of the supply mix.

It really is not possible to do this in a meaningful way without considering energy forms other than electricity and the flexibility and predictability of consumer needs. We examined in the worked examples in the previous section how electricity storage might impact on supply balancing as storage technology becomes dramatically cheaper. A full system analysis would recognise that the storage of hydrogen and heat are both already much cheaper than batteries,

using well-proven technologies. Given the very large capacity of heat storage already available in hot water tanks across the UK, the challenge in utilising this becomes one of market structures and control, not about technology and cost.

We can however make some comments about how a mix of generating technologies could provide a better solution than any one generating technology alone. In a 2030 time frame this is a pragmatic approach, since only heat storage could conceivably be implemented at the scale of significant fractions of a TWh by then.

Intuitively, combining wind and PV creates a better mix than operating either on its own. Wind is more available in the winter and PV in the summer. PV is more consistent when it is available and also likely to have a significantly lower LCOE. The Energy Transitions Commission has undertaken an analysis[19] of how the optimum PV:wind ratio to minimise interday storage varies with the geographic location of countries and the coincidence of demand with supply.

For countries as far north as Germany, they found a ratio of 30:70 was around optimum. A similar ETI analysis for the UK indicates that a ratio of 15:85 may be optimum. This ratio is for average annual electricity production (ie GWh). The ratio of rated capacities would depend on local capacity factors.

The worked examples from running the Technology Comparator Tool show that both batteries and fossil fuel generation (ideally with CCS) can support renewables in matching the characteristics of the generating mix to the profile of demand. Using the ETI's ESME whole system model, it is

possible to study unconstrained optimum pathways out to 2050, pathways that are constrained by scale-up of the supply chain capacity, and pathways influenced by the preferences of various stakeholders. Unless ESME is prevented from using most of the available generating technologies, it invariably selects a mix of several technologies in order to combine their characteristics to produce a better solution than any one or two technologies alone. The same is true of demand side technologies.

18 The costs and impacts of intermittency – 2016 update: A systematic review of the evidence on the costs and impacts of intermittent electricity generation technologies, Heptonstall, Gross and Steiner, UKERC, February 2017

19 Low-cost, low-carbon power systems: how to develop competitive renewable based power systems through flexibility, Climate Policy Initiative for ETC, January 2017

Conclusion

The worked examples have shown us:

- How significant hidden systems costs and carbon emissions can be

- The risks that might arise through not estimating potential global impacts of embedded greenhouse gas emissions, whether in fuels, construction materials or even electricity supplied through interconnectors

Other work by ETI and systems analysts shows that effective energy systems designs need to include a mix of supply and demand side technologies, including interconnectors and batteries.
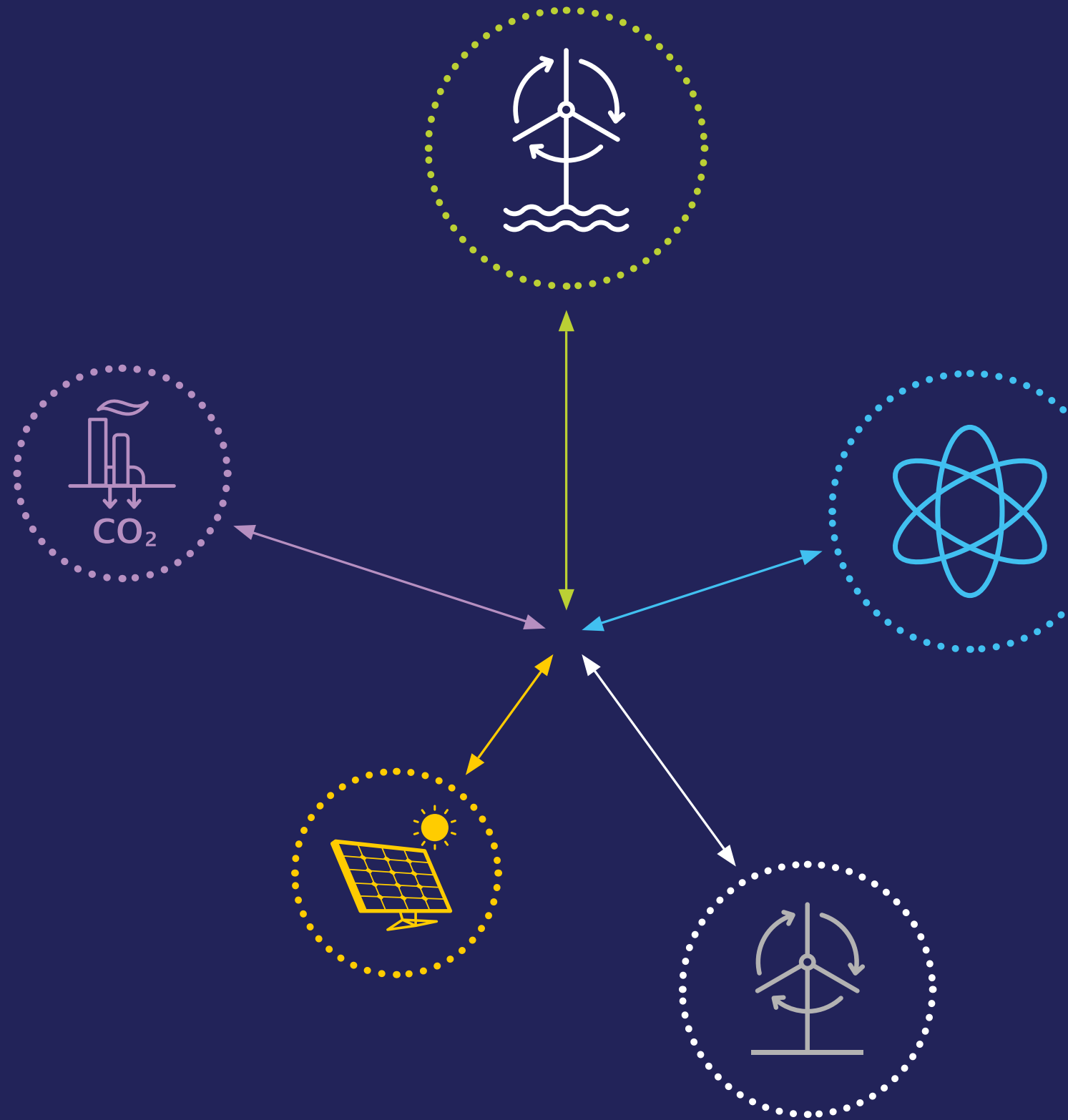
Further Reading

Options, Choices, Actions –
UK scenarios for a low-carbon energy system

Targets, technologies, infrastructure and investments –
Preparing the UK for the energy transition

These reports are available via the dedicated insights report page of the ETI website –
www.eti.co.uk/insights

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