Contents

Section P: Electricity balancing

Context

The electricity system must be continually balanced to match supply and demand. This section sets out the range of options to ensure the electricity system can operate securely to supply peak demands and manage second-by-second variations. There is a range of existing and future technology options available to meet changing requirements. The transition to new forms of balancing on a low carbon electricity grid will need to be well managed in order to ensure that sufficient power is delivered, and delivered reliably.

Balancing supply and demand

To achieve the required balance in the electricity system from the timeframe of a few seconds through to daily, weekly and seasonal variations we need to ensure there is adequate means to flex generation and demand.

Balancing has historically been achieved by varying the output of generation (including existing pumped storage and interconnection) to meet indicated demands for electricity. To date, sufficient flexibility for second-by-second through to weekly balancing has been available from coal- and gas-fired generating stations. The existing UK nuclear fleet is less flexible over shorter timescales, but all sources of supply take some account of seasonal changes in demand when scheduling station output. Where possible, for example, nuclear plants will carry out maintenance and fuelling shutdowns during the lower demand periods of the summer. In addition, demand is already seen to respond to price signals in the market, moving demand to lower priced periods and avoiding high priced periods of the day (for example overnight storage heating).

Looking ahead, it is likely that daily and seasonal electricity demand trends will change with the potential changes driven by the growth in electric vehicles and water and space heating supplied by electric heat pumps.

At the same time, the transition to low carbon electricity generation sources (nuclear, CCS and renewables) introduces two additional challenges. First, some renewable sources, such as wind, have a more variable output; second, the low carbon sources of nuclear and fossil fuel with CCS due to come on stream between now and 2050 are perceived to be less flexible than existing coal and gas stations.

The analysis undertaken to date identifies that balancing can be managed on a technical level to deliver security of supply, but that there are a number of questions as to how this can be best optimised to ensure efficiency.[399] This optimisation covers both the development of technology and physical measures, such as flexible generation

399 See, amongst others, Ofgem (2009) *Project Discovery*; Poyry (2008) *Impact of Intermittency*; National Grid (2008) *Operating the Electricity Markets in 2020*

sources and smart demand, and the development of commercial arrangements for the electricity market and for new innovations such as smart demand and smart grids.

Analytical approach

This analysis considers the options that will provide flexibility in the electricity system to balance against a varying level of (in particular) wind output. This flexibility must be adequate to cover both the routine variability of wind output across hours and days; and periods of low wind winter cold spells associated with anticyclone weather systems, sometimes also called blocking events, that can last for a number of days.

For this analysis, the Government has sought to identify the range of capabilities for each technology group that could help to balance the electricity system. It has then assessed this capability against the requirement for balancing flexibility in each pathway. The analysis has not included an assessment of the impact on plant load factor.

Drivers

The requirement for flexibility can be broken down into a number of time bands as follows:

- **Instantaneous**: Instantaneous flexibility refers to continual management of frequency and is needed to smooth the continual second-by-second fluctuations in supply demand balance. In addition this flexibility must also secure the system from a sudden loss of a generator or large demand block. Typically this requirement is set by the largest generation loss and/or the requirement for short term spinning reserve.
- **Hourly**: Variations across timeframes of an hour to several hours are currently driven by changes in demand, such as the increase in demand in the early morning, and as lights are turned on in the evening. In the future this requirement will also be driven by varying levels of wind generation.
- **Daily variations**: Currently the UK has a lower electricity demand level at night, with higher demand during the day. This repeating daily pattern of demand is met by altering generation output.
- **Weekly variations**: The weekly demand cycle sees higher demands during the typical working week (Monday to Friday) and lower demands at weekends.
- **Seasonal variations in demand**: Typically, average UK electricity demand is higher in the winter than the summer due, for example, to increased lighting and heating load. Currently only around 10% of heating load is provided by electricity, typically powering storage heaters in areas that are not connected to the gas network. In the future the electrification of additional heat load may increase winter electricity demands.

In the current electricity market more than 98% of supply/demand matching is completed by the functioning of the electricity market ahead of time. A residual of less than 2% is completed by the system operator, National Grid, as it balances the system in real time. Whilst there will be new challenges in achieving supply/demand balance, this analysis assumes that a similar split will exist in the future, with the system operator taking a perhaps larger but still very small minority of actions to balance the system.

Sector segmentation used

Electricity balancing can be segmented into different sectors, as considered in several analytical assessments of 2050 as well as the IEA 2009 working paper on electricity storage.[400] Broadly, these fall into four categories.

1. Flexibility designed into generating stations

A number of analyses assume that future nuclear and CCS generating sources will not be flexible. It is not clear that this will be the case and it can be expected that some flexibility will be provided by these stations.

The current UK nuclear fleet is inflexible in its output, perhaps for historical reasons, due to the alternative flexibility available from coal and gas units. However, the current French nuclear fleet does provide some fast flexibility to manage fluctuations. It also provides some flexibility to match weekly and seasonal demand variations through careful management of refuelling and maintenance work across the fleet as a whole.

It is expected that a future UK nuclear fleet would be able to provide similar levels of flexibility to the existing French fleet and will therefore be a significant contribution to the flexibility required for short term, near instantaneous regulation as well as weekly and seasonal variability.

The technical potential for CCS plant flexibility is less clear as these stations are in earlier development. Whilst there are concerns as to the flexibility that can be provided from post-combustion CCS stations, there are design options that may allow these stations to provide fast flexibility at least equivalent to that of future nuclear stations and greater flexibility to regulate output over weekends and overnight. However, this work is still at an early stage. Improvements in flexibility would mirror the development of existing coal and gas stations, both of which became more flexible as the technology developed. Pre-combustion CCS stations are generally expected to be at least as flexible as existing gas-fired power stations.

A key point noted in some analyses is that the higher capital cost and lower operating cost, in particular of nuclear plant but also CCS, may mean that the financial model for investment in these stations is less suited to flexibility. This is because flexing the units will tend to reduce the high load factors needed to fund the capital cost.

In summary therefore, it is reasonable to expect, for all levels, a minimum level of flexibility from future nuclear and CCS plant similar to current French nuclear levels, providing some short term, weekly and seasonal balancing. For low load factor operation, alternative solutions are likely to prove more economic than nuclear or CCS. It is assumed that thermal stations can enhance availability during winter cold spells by taking short-term measures to move planned shutdowns or improve short term reliability. As a result, thermal power stations are assumed to be able to provide on average 5% more energy in the winter than their average annual output.

400 IEA (2009) *Prospects for Large-Scale Energy Storage in Decarbonised Power Grids*, www.iea.org

2. Storage: conventional pumped storage and new technology solutions

At present there are several pumped storage stations in the UK, the largest being Dinorwig in North Wales with a storage capacity of approximately 10 GWh and a peak output of 2 GW. These stations have long lifetimes and can be expected to be still operational in 2050. The development of new stations is also possible within the UK.

Future flexibility and storage requirements may lead to different specifications that have a higher storage capability relative to peak output. If pumped storage were to provide longer term, multi-day or weekly storage then it is likely that storage capacities would need to be significantly larger than current designs. Such projects would be a major capital undertaking and the impact on the local environment can be expected to be a key concern. Dinorwig, for example, was approved via an Act of Parliament rather than through the local planning system. Pumped storage lagoons, built in the sea or estuary areas, have also been proposed as an alternative to large scale land-based pumped storage.

There are a number of alternative forms of storage which, by 2050, may provide large scale storage, including batteries and heat stores. Multi-MW scale battery systems have been installed at a number of sites worldwide. These technologies have not yet been proven on a scale required for national balancing but would provide an alternative to large scale storage at level 3 or 4.

3. Interconnection

Interconnection already forms part of the existing market mix. It allows power sharing between interconnected systems, in particular the large European power markets via the existing 2 GW connection to the French system. There is also an existing 0.5 GW link between Scotland and Northern Ireland.

A new 1 GW connection with the Netherlands is under construction and there are plans to build interconnectors with a number of other countries including Ireland, Belgium, Norway and France. Both existing and planned projects mean that capacity could grow by 200–500% over the next 15 years.

Interconnection can adjust flows very quickly (within seconds to minutes) and can also provide longer term support across hours or days. For example, power could be exported during high wind periods and imported during low wind periods. Imported power could be used immediately, offsetting local supplies or stored, through pumping or offsetting generation in the large scale hydro power resources of the Alps or Norway. Key to any assumptions about the flexibility interconnection might provide is the level of diversity we can expect to see across Europe in terms of demand variation, generation use and in particular wind output. This diversity and the benefits of integrating offshore wind with interconnectors are being studied further as part of existing work on interconnection. In this analysis we assume that interconnector transfers would be somewhat linked to variable power sources, for example periods with high wind output would lead to increased exports and low wind output would lead to increased imports of electricity across interconnection. For very low wind conditions in the UK, it is assumed that flows to the UK would be up to 75% of available interconnection capacity, driven, for example, by diversity of generation and wind output across continental Europe and the larger hydroelectric storage capability of Norway and the Alps.

4. Flexible demand

Flexible demand, which may form part of a smart grid system, could play a major role in matching supply and demand. The development of this sector may be facilitated by the roll-out of smart metering, which may provide metering of shorter time periods, for example use in each half hour. This would allow demand to target low priced periods, for example when the wind is blowing. Smart grids may also play a key role in more complex optimisation solutions for flexible demand.

The amount of flexible demand assumed in different 2050 analyses varies but the assumption used is generally between 20% and 30%. With the right incentives there may be many opportunities to develop flexible demand across the domestic, industrial and commercial sectors. The level of actual accessible flexible demand and the period over which demand can be flexed will depend heavily on the path taken by technology development in each sector. This analysis focussed on the potential flexibility from electrified transport and domestic and commercial electric heat demand. Both are discussed below.

Car charging

There are a wide range of possible scenarios but the key drivers are battery size and pattern of future use:

- If electric vehicles (EV) or plug-in hybrid electric vehicles (PHEV) car batteries remain of similar capacity to daily usage requirements, we expect to see regular charging patterns, particularly overnight, which could be flexed to provide short term variations in demand during the charging period.
- At the high end, a growth in car battery capacity, perhaps to 40 kWh, may see less regular charging by many users and the ability to provide significant weekly flexibility through selective charging. Fuel switching of PHEVs to run solely on their liquid fuel source could also be used to reduce electricity demand. This assessment does not include the further option to re-export power from the battery to the grid.

Electric heat

Flexing heat demand is likely to be able to provide large quantities of short term flexibility if it can be incorporated into heat pump operation without major reductions in efficiency.

Space heating may be able to provide demand flexibility from a few minutes to a number of hours whilst preserving required heating levels, but this would be dependent on the level of insulation and the thermal mass of the heated source. For example, a well-insulated house with under-floor heating installed in a concrete floor with high thermal mass may be able to flex heating demand for many hours, or even days. An air-to-air heat pump in a poorly insulated home may provide flexibility over a few tens of minutes only. If incentives were present, it is possible that longer term heat stores could become widespread. Based on existing technology these would allow greater flexibility of heat demand, perhaps over several days.

It should also be noted that the volume of electric heat flexibility will vary with the season. In the winter large volumes of space heating could potentially be flexed. During the summer the only demand available from heating will be lower levels of water heating demand unless there is significant growth in air cooling, which could provide similar flexibility to heat. Increased penetration of solar thermal heating would reduce electric water heating demand flex capability in the summer.

For this analysis it is assumed that there is flexibility of up to 12 hours for space heating in a well insulated home, to avoid peak demand periods, or up to 12-24 hours for water heating.

The levels

Levels chosen in 2050 Pathways Calculator are presented as a combination of ranges between storage, interconnection and flexible demand.

Level 1

- Storage: remains at today's level.
- Interconnection: according to current plans, interconnection increases to 4 GW, but then remains stable from 2015 onwards.
- Flexible demand: no shiftable demand provided by any form of car charging.

Level 2

- Storage: up to two or three projects to develop storage capacity at existing stations or small new stations may be developed. Storage capacity peak output gradually increases from today's 3.5 GW to 4 GW.
- Interconnection: increases significantly over the coming two decades and stabilises at 10 GW.
- Flexible demand: around a quarter of all EVs and PHEVs have a shiftable electricity demand capacity.

Level 3

- Storage: significant step change with the development of at least two large pumped storage stations or lagoons, each with six times the storage capacity of Dinorwig. Storage capacity peak output increases to 7 GW in 2050.
- Interconnection: increases to 15 GW in 2050.
- Flexible demand: around a half of all EVs and PHEVs have a shiftable electricity demand capacity.

Level 4

- Storage: development of two very large pumped storage sites and two pumped lagoons, giving a total storage capacity of 400 GWh or 0.4 TWh, approximately forty times that of Dinorwig. Storage capacity peak output reaches 20 GW. Alternatively, a significant proportion of this capacity could be provided by a new storage source, such as battery or heat storage.
- Interconnection: very high levels of up to 30 GW could be achieved, which may include some integration of interconnection with large offshore wind farms. This figure is in line with other analyses of the potential for a highly interconnected European grid.

- Flexible demand: 75% of all EVs' and 90% of all PHEVs' storage capacity are being utilised for shifting demand.

Table P1: Development of storage capacity peak output, GW

Storage: Peak Power										GW
Level	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
1	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
2	3.5	3.5	3.5	3.8	3.8	3.8	3.8	3.8	3.8	4.0
3	3.5	3.5	3.5	3.8	7.0	7.0	7.0	7.0	7.0	7.0
4	3.5	3.5	3.5	3.8	7.0	10.0	15.0	15.0	20.0	20.0

Table P2: Development of storage capacity, TWh

Storage: energy storage										GW
Level	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
2	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
3	0.03	0.03	0.03	0.03	0.04	0.08	0.10	0.10	0.10	0.10
4	0.03	0.03	0.03	0.03	0.04	0.15	0.30	0.35	0.40	0.40

Table P3: Development of interconnection capacity, GW

Innerconection: Peak Power										GW
Level	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
1	2.5	2.5	4	4	4	4	4	4	4	4
2	2.5	2.5	4	6	8	10	10	10	10	10
3	2.5	2.5	4	6	10	15	15	15	15	15
4	2.5	2.5	4	9	15	25	30	30	30	30

Table P4: Electric cars – shiftable demand

Electric cars: shiftable demand	% of average	
Level	EV	PHEV
1	–	–
2	25%	30%
3	50%	59%
4	75%	90%

Back-up supply

In addition to the four options above, a number of studies highlight scope for back-up generation or fuel switching to a non-electric back-up supply to allow supply and demand to match.

Back-up generation could be bio- or fossil-fuel fired generators, similar to back-up generation used today, or other measures such as CCS plants shutting down the CCS plant load during periods of peak demand to increase station output. This analysis assumes construction of back-up generation if insufficient flexibility is available elsewhere. Because of the high level of shorter term flexibility available under most scenarios, significant back-up plant is only likely to be required under pathways with the majority of electrical power coming from wind.

There are a number of options for fuel switching during periods of high demand or low wind. These include:

- PHEVs running on their liquid fuel rather than plugging in to charge the battery;
- bio or fossil fuel gas top-up for heating to reduce electrical heating demand; and
- other economic responses to peak power demands.

Discussion

There are a wide range of sources of flexibility that are proven or could be developed. At a high level the use of flexible demand, together with flexible generation and interconnection, would appear the most immediately available route for balancing demand and generation. In terms of storage options, pumped storage or pumped lagoons could also provide significant additional capacity but are identified in many studies as potentially more expensive options. Other storage technologies such as batteries, heat stores or greater demand flexibility have the potential to be in large scale use before 2050.

There remain a number of technical uncertainties – the flexibility of new plant; new storage technologies including seasonal heat stores; the roll-out of smart metering; and development of smart demands – but against these uncertainties, there is significant diversity of potential solutions. As such, it is clear that balancing is achievable, but that the cost will vary and will be dependent on the development of new infrastructure, storage technologies and smart demand.

However, it is likely that the requirement for flexibility will rise in the shorter term, ahead of 2050 and ahead of the development of smart demand volumes. As such, the role of flexible units such as non-CCS coal and gas, and back-up reserve plant will continue to play an important role, at least in the near term.

Analysis

The 2050 Pathways Calculator tests the ability of the system to meet demands for electricity during a five day anticyclone blocking event, with five days of low wind output and a peak in heating demand associated with the cold weather.

This is a constraint identified by many commentators and other reviews of future balancing issues. If sufficient flexibility is available to meet the winter low wind period then it is expected there will be sufficient capability from the same and other sources to manage more routine, shorter term fluctuations from day to day and hour to hour.

To ensure the test fully reflects the supply demand conditions, it additionally assumes that a portion of the increase in electricity demand resulting from colder than average weather during the five days would have to be met by flexible sources. In all levels it assumes that this increase during an occasional cold spell is equal to 20% of annual average daily domestic and commercial heating demand, or approximately 10% of peak daily heating demand.

Grids

Discussions with stakeholders indicate that networks will be able to facilitate the potential growth in electricity demand, even if national annual demand was to more than double to over 800 TWh. Clearly there are important issues that need further consideration such as how to coordinate and plan for this growth given the uncertainty of some demand technologies, the timing of growth and the balance of small and larger scale generation, all of which will place different requirements on networks.

There is evidence of close working between network companies and, for example, developers of electric vehicles, to look at how these can be integrated into the current demand mix. Further working across industries will be important to ensure robust integration of potential new demands such as vehicles and heat pumps. This and the associated development of networks could perhaps be further facilitated under the auspices of groups such as the Electricity Networks Strategy Group (ENSG), which is already looking at future grid development.

Section Q: Negative emissions

Context

Negative emissions could assist the UK in achieving its 2050 emissions reduction target. Negative emissions remove CO_2 directly from the atmosphere. Over the coming decades, many experts believe that negative emissions technologies could play a role in a global mitigation strategy, particularly for emissions that are hard to tackle at source. [401]

This section focuses on new and emerging technologies and processes for negative emissions, most of which are currently at the research and demonstration phase. Each negative emissions technology has its own dynamics and each needs to be analysed as to its capacity to store CO_2 securely in the long term; its potential to be scaled up; its material and energy requirements; and its impacts on the environment.[402]

Drivers and enablers

The majority of negative emissions technologies require the ability to store CO_2 securely underground; without this, most negative emissions technologies become unfeasible. Energy demand is high for most engineered air capture technologies. However, many are flexible as to their location, since CO_2 can be captured anywhere on the globe. For those processes that require heat, this means that technologies could be deployed in regions where there is unused excess heat or significant solar heat. Any cost estimates depend heavily on the energy these processes tap into.

Sector segmentation used

The 2050 Pathways Calculator segments the generation of negative emissions into two sectors: bio-energy plus carbon capture and storage (BECCS); and geo-sequestration. BECCS takes advantage of nature's capacity to capture CO_2 directly from the atmosphere and is dependent on the development of a CCS infrastructure in the UK, as well as on the amount of biomass being utilised in the UK's CCS plants. Geo-sequestration focuses on engineered air capture technologies.

The levels chosen in this analysis reflect a segmentation of negative emissions technologies by their technological difficulty, energy demand and potential environmental impacts. The analysis of these technologies is still at an early stage, and needs to reflect not only their potential to deliver real sequestration, but also the impacts in terms of wider sustainability and policy practicality (including the potential for funding), and the systems which might be needed to deploy them.

401 For instance, IPCC Fourth Assessment Report 2007; Royal Society (2009) *Geo-engineering the climate. Science, governance and uncertainty*; Institute of Mechanical Engineers (2009) *Geo-engineering – giving us the time to act*; DECC/Met Office AVOID programme (www.avoid.uk.net) *The potential for the deployment of negative emissions technologies in the UK*.

402 Carbon sequestration in the form of forestry is covered in Section E.

Bio-energy plus carbon capture and storage

Plants sequester CO_2 from the atmosphere and store it in the form of biomass. BECCS assumes that the UK can take advantage of nature's capacity to capture CO_2 from the atmosphere by harvesting the biomass and burning it in electricity generation plants which are fitted with CCS infrastructure. This would ensure that the CO_2 sequestered from the atmosphere by plants would be stored underground in designated CCS facilities. The CCS power plants could either be only biomass or co-fired coal and biomass plants to generate electricity.

To generate negative emissions from BECCS the 2050 Pathways Calculator necessitates several inputs.

- First, CCS needs to be presumed to be in operation within the UK. BECCS obviously is dependent on CCS infrastructure to operate. Levels 2 to 4 in the section 'Combustion plus CCS' need to be chosen for BECCS to operate.
- Second, bioenergy could be used in several forms – solid, liquid or as a biogas. The section 'bioenergy production from agriculture and waste' presents these options. BECCS is maximised in trajectory B (solid).
- Third, once the BECCS infrastructure is existent and the usage of solid biomass is being prioritised, the 2050 Pathways Calculator user needs to decide on the amount of biomass being utilised within the UK. The country can either produce biomass domestically or import it. The domestic option depends on how much land is being dedicated to biomass production under the 'agriculture' section. With a CCS capture rate of around 90%, the 2050 pathways calculator assumes a carbon capture rate of $18tCO_2$ per year for each hectare of biomass production. The biomass levels for 2050 range between 350,000 hectares and 4.2 million hectares of domestic production. UK biomass imports are determined in the section 'Bioenergy imports'.

These inputs into the 2050 Pathways Calculator determine the overall level of negative emissions generated by BECCS within the UK. If for all inputs the maximum possible is assumed, the UK could generate up to 165 $MtCO_2$ per year from BECCS in 2050.

Geo-sequestration levels

Besides BECCS, geo-sequestration could become an additional driver of negative emissions for the UK. Also referred to as carbon dioxide removal techniques, geo-sequestration aims to reduce the amount of greenhouse gases in the atmosphere via, for instance, engineered air capture technologies or enhanced weathering processes.

The geo-sequestration levels presented in the 2050 Pathways Calculator describe a gradual build-up of mostly engineered air capture technologies. Levels 2 and 3 assess the negative emissions potential of these techniques within the boundaries of the UK. The most ambitious geo-sequestration activity is described in level 4. This entails the UK participating in an international initiative to deploy air capture technologies anywhere in the world wherever they are most effective. All negative emissions technologies can take advantage of the fact that CO_2 travels freely in the atmosphere. The technologies can be installed wherever it is the most practical to do so. Level 4 maximises this strategic advantage.

Level 1

As a baseline, level 1 assumes that no action on geo-sequestration is taken over the coming decades. Any geo-sequestration options that do emerge prove to be technologically unfeasible, financially unattractive, unacceptable to the public and/or insignificant in terms of their contribution to mitigation.

Level 2

Level 2 on geo-sequestration assumes the UK generates 1MtCO_2 per year of negative emissions. These would be generated by business opportunities either in the form of biochar being linked to financial incentive structures or some business opportunities linked to negative emissions, such as the production of chalk or bio cement.

Level 3

Level 3 assumes the construction of engineered air capture technologies within the UK geographical boundaries. A ten year demonstration phase would lead to a gradual build-up of engineered air capture technologies starting in 2025. Some engineered negative emissions technologies currently in R&D stage could possibly be deployed in the UK. Options include 'forced draft contactors'[403] and 'induced air flow towers'.[404] As an example, each induced air flow tower, approximately 20 meters tall, is expected to capture 4tCO_2 per day. Thus, induced air flow towers capturing 30 MtCO_2 per year in 2050 would necessitate the operation of roughly 20,000 towers.

All the engineered air capture methods are presumed to necessitate CCS infrastructure and locations close to power stations as well as significant energy supplies. Level 3 assumes an engineered air capture technology contribution of 30 MtCO_2 per year in 2050 with an energy demand of 100 TWh per year. The possibility of utilising excess heat from power stations as well as probable efficiency gains could reduce this energy demand.

Level 4

Level 4 assumes as in level 3 that the UK constructs its own air capture infrastructure in the 2020s, but also participates in an international negative emissions initiative. With international partners the UK would push for a global negative emissions effort to assist a worldwide mitigation strategy. Negative emission technologies would be deployed anywhere in the world wherever they are most cost effective. The UK holds a certain percentage share of negative emissions and counts them towards national mitigation targets. This level assumes that such an operation is in demonstration phase in 2020 with roll-out starting in 2030. It estimates that by 2050 the contribution of this negative emissions approach will deliver around 80 MtCO_2 per year to the UK's mitigation effort. It is also assumed that the energy cost of concentrating and compressing CO_2 from the air is in line with statements of some experts in the field. These energy demand projections are significantly lower than the ones used in level 3. For 80 MtCO_2 captured per year the technologies listed below estimate an energy cost of between 40 TWh to 130 TWh per year.

403 'Calgary Carbon Capture Machine' developed by Prof David Keith (Canada Research Chair for Energy and Environment at University of Calgary).

404 'Fast Trees' Process via induced air flow towers being developed and commercialized by Carbon Cycle in the UK.

All engineered negative emissions proposals would need to be investigated as to their suitability for deployment in specific regions of the world, their efficiency at capturing and storing CO_2 and their impact on the environment. It is impossible to state which technology will ultimately be chosen following a decade-long demonstration phase. Some contenders could include:

- Artificial 'carbon trees' that capture CO_2 via an ion exchange resin. The resin absorbs CO_2, which is released when exposed to water vapour.[405] The technology must be deployed in regions with a lot of dry air, with access to water and with a CCS capability. Possible locations are Canada, Africa or the Middle East. The container sized carbon trees are predicted to capture around 1 tCO_2 per day. 80 $MtCO_2$ per year would necessitate approximately 250,000 'carbon trees'.
- 'Solar scrubber'[406] technology pumps air into a tube full of calcium oxide pellets. The tubes are heated via parabolic mirrors. At 400 degrees the CO_2 reacts with the pellets to form calcium carbonate. Heated to 1000 degrees, pure CO_2 is driven out of the pellets. Solar scrubbers would only operate in conjunction with solar energy and would be most effective in desert regions with CCS infrastructure.
- Adding alkalinity to seawater is another possible means of capturing CO_2. This involves decomposing heated limestone into lime and CO_2.[407] The CO_2 is sequestered and the lime is added to seawater, where it acts to enhance the capacity of the oceans as a carbon sink by drawing CO_2 out of the atmosphere and storing it as bicarbonate ions in the ocean. The process requires large amounts of limestone, energy, CCS infrastructure and access to the ocean. Possible locations include Australia, Namibia and Oman. 80 $MtCO_2$ per year would require approximately 120 Mt of limestone.

The two engineered air capture technologies of level 3 could also be deployed on a global scale under level 4.

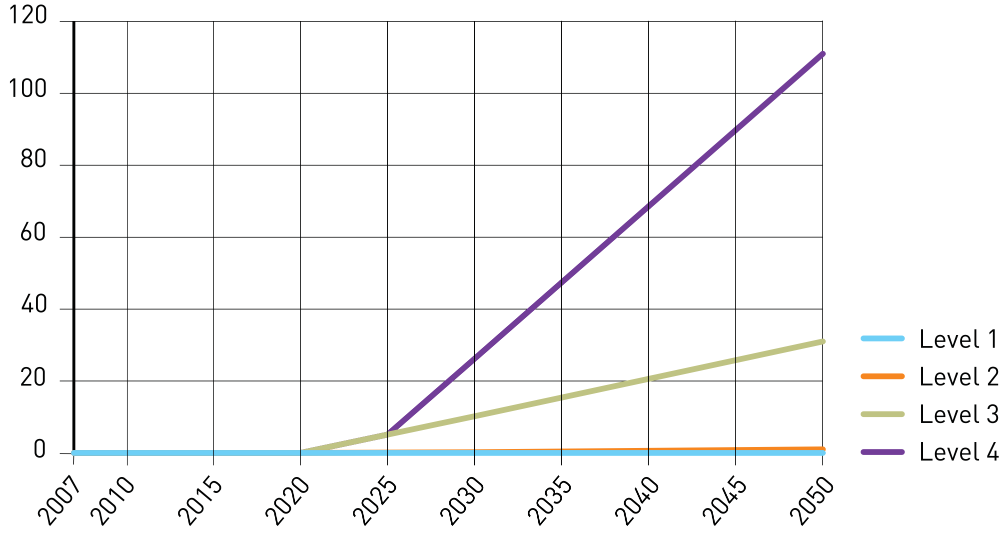
In summary, this level 4 of geo-sequestration estimates a negative emissions potential of 111 $MtCO_2$ per year in 2050 (80 $MtCO_2$ per year from international geo-sequestration processes plus 30 $MtCO_2$ per year from UK engineered air capture techniques and 1 $MtCO_2$ per year from other UK sources). As the energy cost of the international engineered negative emissions have such a significant range and will not need to be covered by UK production, the 2050 Pathways Calculator does not account for them. A significant UK financial contribution to any such international negative emissions programme is to be expected.

405 Global Research Technologies and Columbia University – www.grestech.com/ . Technology also referred to as 'Carbon Carousel'. Also see *Scientific American* (June 2010) 'Washing Carbon out of the air'.

406 ETH Zurich University– http://solar.web.psi.ch/

407 Cquestrate (University of Oxford in collaboration with Shell, AEA technology and Plymouth Marine Laboratories) – www.cquestrate.com

Figure Q1: Trajectories for negative emissions from geo-sequestration under four levels of deployment, in $MtCO_2$



Section R: Electricity imports

Context

Low carbon and/or renewable electricity could not only be produced domestically in the UK but also be imported from abroad. This will necessitate other countries to significantly oversupply their electricity and be willing to export. It will also require a much strengthened continental grid infrastructure to deliver electricity from the generation point to the areas of consumption.

Low carbon electricity could come from various sources to the UK. Geothermal energy from Iceland, wind capacity from Norway's North Sea or solar energy from southern Europe including northern Africa are just some examples. The levels proposed in this analysis focus on the potential of electricity imports from solar, especially concentrated solar power, from the south. Concentrated solar power uses mirrors or lenses to focus sunlight. It has an electricity generation capacity of around 15 W/m^2 and is considered as a 'proven' technology. It is around five times more efficient per square meter than wind and over twice as efficient as tidal stream. Concentrated solar power also has the advantage of being comparably simple to construct and to maintain, compared to, for example, offshore wind. Moreover, large scale projects are feasible for concentrated solar power as the technology is best deployed in areas with very low population density. Deserts in northern Africa as well as southern Europe could be utilised to construct large concentrated solar electricity generation capacities which would have a significant impact on the whole of the African as well as European system.[408] Such a project would need substantial international cooperation.

For the UK to benefit from large scale concentrated solar power it needs to be connected to the generation plant. This will necessitate a cross European grid system connecting the south – possibly also across the Mediterranean – with the UK. The most likely interconnector would be high-voltage direct-current (HVDC). HVDC is preferred over AC lines because it requires less material and power losses are smaller. Such a grid infrastructure would need to be developed in close cooperation with other European countries. The 2050 electricity import levels used in this analysis assume that the UK participates with other European and Mediterranean countries in a common project for large scale concentrated solar power stations. Depending on the level of engagement of the UK in this international project, a 'fair share' of the generated electricity would become UK imports.

408 See one example of a plan for a large scale concentrated solar power generation project: www.desertec.org. Also, see German Aerospace Center (DLR), Institute of Technical Thermodynamics, Section Systems Analysis and Technology Assessment (2006) '*Trans-Mediterranean Interconnection for Concentrating Solar Power*' or Franz Trieb (2009) *Global Potential of Concentrating Solar Power*..

Levels for electricity imports

Level 1

This level assumes that the UK does not import electricity, other than for balancing.

Level 2

This level assumes that the UK imports 30 TWh, gradually beginning in 2020. Electricity originates mostly from concentrated solar power projects in southern Europe. The interconnector between the UK and the European mainland is strengthened with an additional 4 GW designated for electricity imports.

Level 3

The UK imports 70 TWh. An international project constructs concentrated solar power in northern Africa, close to equivalent to the ambition of desertec. The whole project would require an area of around 5000 km^2 of concentrated solar power infrastructure – roughly a quarter the size of Wales. Starting in 2020, this level of action would require the international project to achieve a build rate of roughly 0.5 km^2 per day of concentrated solar power equipment for 30 years until 2050.

This level 3 assumes the UK's project share to be 10%. Therefore, to import 70 TWh per year, the UK's share of the international project would need to occupy an area of around 500 km^2 – that is roughly equivalent to one third of the area of Greater London. A significant grid infrastructure in Europe would need to be constructed with a UK interconnector of an additional 8 GW designated for electricity imports.

Level 4

The UK imports 140 TWh. The same project as in level 3 constructs concentrated solar power in northern Africa. The whole project area would require an area of over 5,000 km^2 of concentrated solar power infrastructure – roughly a quarter the size of Wales. Starting in 2020, this level of action would require the international project to achieve a build rate of roughly 0.5 km^2 per day of concentrated solar power equipment for 30 years until 2050.

This level 4 assumes the UK's project share to be 20%. Therefore, to import 140 TWh per year, the UK's share of the international project would need to occupy an area of around 1,000 km^2 – that is roughly equivalent to two thirds of the area of Greater London. A significant grid infrastructure in Europe would need to be constructed with a UK interconnector of an additional 20 GW designated for electricity imports.

Table P5: Electricity import levels[409]

Trajectory assumptions											
Imports, Desertec											TWh
Trajectory	Description	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
1	Concentrated solar power	–	–	–	–	–	–	–	–	–	–
2	Concentrated solar power	–	–	–	2	6	10	15	20	25	30
3	Concentrated solar power	–	–	–	6	15	23	35	47	59	70
4	Concentrated solar power	–	–	–	12	30	46	70	94	118	140

409 The Desertec Foundation, *Clean Power From Deserts, Whitebook, 4th edition*. Assumes UK share is 10%

Annex A: Costs assumptions

Fuel cost assumptions (2009 prices)

	2010	2020	2030	2040
Low oil (£/bbl)	51	61	61	61
Central oil (£/bbl)	71	81	91	91
High oil (£/bbl)	85	122	122	122
High-High oil (£bbl)	104	152	152	152
Low coal (£/tonne)	81	51	51	51
Central coal (£/tonne)	111	81	81	81
High coal(£/tonne)	122	101	101	101
High-High coal (£/tonne)	132	132	132	132
Low gas (p/therm)	33	34	35	35
Central gas (p/therm)	59	68	75	75
High gas (p/therm)	71	98	98	98
High-High gas (p/therm)	85	121	121	121

Source: DECC fossil fuel price assumptions

Capital cost assumptions (2009 prices)

Capital cost, £/kW	2020			2030			2040		
	Low	Central	High	Low	Central	High	Low	Central	High
CCS (coal, ASC[410], FGD[411])	1,530	2,035	2,500	1,440	1,943	2,500	1,387	1,914	2,500
Nuclear (PWR[412])	2,114	2,686	3,125	1,983	2,584	3,125	1,924	2,549	3,125
CCGT	470	588	688	454	580	688	440	572	688
Tidal range	2,000	2,600	3,100	2,000	2,600	3,100	2,000	2,600	3,100
Tidal stream	1,698	2,043	2,462	1,024	1,239	1,466	637	768	921
Wave	1,979	2,380	2,771	904	1,097	1,284	532	644	754
Onshore wind	997	1,258	1,500	966	1,241	1,500	934	1,223	1,500
Offshore wind	1,900	3,000	3,250	1,627	2,369	3,250	1,559	2,328	3,250
Oil	853	1,075	1,266	741	1,002	1,266	715	987	1,266
Hydro	1,438	1,594	1,688	1,438	1,594	1,688	1,438	1,594	1,688

Sources: CCS, nuclear, CCGT, onshore wind and offshore wind costs from UK Electricity Generation Costs Update: A report by Mott MacDonald (June 2010)

Oil, Hydro, wave, tidal stream and tidal range costs are DECC estimates

410 Advanced supercritical.
411 Flue gas desulphurization.
412 Pressurised water reactor.

Department of Energy and Climate Change. www.decc.gov.uk