

# Decarbonising UK energy: Effective technology and policy options for achieving a zero-carbon future

A conference report of the *Science-plus* meeting organised for the Royal Society in partnership with the British Academy and Royal Academy of Engineering by Professor John Shepherd CBE FRS, Professor Corinne Le Quéré FRS, Professor Cameron Hepburn, Nick Winser CBE FREng and Professor Richard Parker CBE FREng.

This paper has been compiled by the organisers and reviewed by the session chairs, and is not intended to represent either an agreed consensus of the participants or the official views of the convening institutions.

## Synopsis

The UNFCCC Conference in Paris (COP21) reached agreement not only to hold global warming to “well below 2°C above pre-industrial levels” but also “to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gas (GHG) in the second half of this century” (Article 4.1). This means that global net GHG emissions need to be reduced to zero by some time before 2100. In turn, achieving net zero GHG emissions globally entails that emissions in the UK and other nations are also reduced to net zero after accounting for traded carbon. The implications of the Paris Agreement goals, and the magnitude of the task of achieving them while maintaining energy security, are not yet at all widely understood. Achieving net zero GHG emissions would require near complete decarbonisation of industrial and energy systems, accompanied by the deployment of Carbon Capture and Storage (CCS) and greenhouse gas removal technology to balance intractable emissions from remaining sources such as aviation and agriculture.

The means for achieving net zero GHG emissions and the consequences of doing so need to be explored and understood. Some previous and existing energy policies have not been fully effective or have had perverse consequences. The advantages and disadvantages of various future technology and policy options need to be debated by a broad community of experts. This meeting brought together scientists, engineers, social science experts and policy-makers to discuss the need for decarbonisation of the UK energy supply, the technology and policy options for achieving this, the consequences of doing so, and the incentives that may be necessary.

## Headline views expressed at the meeting

- The present UK policy targets are broadly consistent with the level and rate of decarbonisation required to meet international commitments, but new technologies and incentives will be needed if the targets are to be met.
- Carbon pricing could play an important role in driving decarbonisation. Simplifying carbon prices across electricity markets and strengthening the carbon price floor would incentivise further action.
- A decarbonised energy system will need new developments, including storage, to balance load and ensure energy security. Batteries can provide effective and efficient short-term storage, but chemical energy storage is likely to be required for longer time periods.
- Transport provides a complex challenge for decarbonising and will likely require both improvements to the efficiency of the system and both technological and behavioural changes.
- Substantial deployment of carbon capture and storage (CCS) will almost certainly be required to decarbonise the UK energy supply and will continue to require significant pre-competitive support until price incentives become adequate.
- Low-carbon hydrogen is likely to play a significant role in energy storage and transport, not least for decarbonising heat which remains a major challenge. Steam reformation of methane with CCS and electrolysis both hold promise.
- Given the UK emissions targets it would be undesirable to build long-lived assets that would commit us to emissions for decades into the future, and that may thus become stranded (eg. new coal, or gas infrastructure without CCS).
- Restoration and management of forests and increased use of timber in buildings could be implemented relatively quickly and easily and could play a significant role in carbon storage in the UK for the next few decades, but do not provide secure long-term storage.
- To achieve the Paris goals, and compensate for intractable emissions, active removal of greenhouse gases from the atmosphere, by both biological and technological means, will likely be required by mid-century.

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## Presentations

Abstracts of the presentations to the meeting are compiled in Annex A, and information on the speakers, audio recordings and copies of the slides for some presentations are available online at [royalsociety.org/events](https://royalsociety.org/events)

# Summary of discussion

## General

1. The Paris Agreement now provides a clear signal of the magnitude and rates of decarbonisation that will need to be achieved by all nations during this century.
2. Global emissions of carbon dioxide would need to peak and decline rapidly to limit climate change to levels consistent with the ambition of the Paris Agreement.
3. There is at present a known and substantial gap between the sum of the Nationally Determined Contributions (NDCs) declared and the global carbon budget, and much more ambitious NDCs will be required in future.
4. Trends in China are largely responsible for both the rapid rise in global emissions of the 2000s and their recent stalling during 2014-2016, but decarbonisation of energy systems is occurring in many industrial economies.
5. Substantial amounts of greenhouse gas removal from the atmosphere ('negative emissions') will likely be required in the latter part of the century to achieve the Paris goals, and to compensate for intractable sources of GHG emissions (especially agriculture and aviation).
6. The present UK policy targets are broadly consistent with the level and rate of decarbonisation required, but there is a significant 'implementation gap' in the policy instruments (mechanisms, regulations, incentives and technological options) required to achieve these and future targets.

## Technology development (general)

7. China has made a major contribution to driving down the cost of solar photovoltaics (PV) panels and making PV a cost-effective means of electricity generation in many parts of the world, and has also had a similar influence on wind turbine prices. China is likely to be an increasingly active proponent of global emission reductions.
8. Pre-competitive support for promising technologies (including preferential procurement) is likely to be needed to enable them to move beyond the 'valley of death' in technology development, and progress to be tested operationally at full-scale.
9. There are many potential low-carbon technologies (see below) that have not yet been tested at large-scale, and it is difficult to determine a priori which are likely to be successful.

10. Large-scale deployment of many promising future low-carbon technologies is very unlikely to occur in the absence of adequate financial and/or regulatory incentives (such as a substantial carbon price, >\$80/tCO<sub>2</sub>).
11. Substantial deployment of Carbon Capture and Storage (CCS) will almost certainly be required both to achieve the necessary emissions reductions and to enable several of the prospective 'negative emissions' technologies (NETs).
12. It may be less difficult to deploy CCS before rather than after combustion, and this could enable a number of additional low-carbon technologies to be deployed.
13. Resumption of pre-competitive support for CCS is likely to be necessary to enable it to be further developed, demonstrated and deployed at full-scale.
14. The outlets for captured CO<sub>2</sub> (Carbon Capture and Utilisation, CCU) other than for enhanced oil recovery, or 'natural climate solutions' that use (enhanced) natural processes to remove CO<sub>2</sub>, are likely to remain small markets (below 1 Gt CO<sub>2</sub> p.a.) with the possible exception of use in building materials, and if it becomes feasible and economic, use of CO<sub>2</sub> for large-scale carbon-neutral fuel synthesis (see below).
15. In order to bring CCS and other emerging technologies to market it is likely that a significant increase in technology development spending will be required, in addition to market incentives (see #10 above). For example a 5-fold increase in RD&D spending in the UK and Europe across a diverse portfolio of promising projects would be required to achieve a level comparable to that of the USA and China.

## Energy systems

16. The costs of solar PV and off-shore wind electricity have fallen unexpectedly fast, and deployment of much greater capacity of these technologies is to be expected. The limit to this is likely to be the difficulty of managing very high dependency on intermittent sources.
17. The seasonal fluctuations in energy demand for heating (mostly from gas) are very large and much greater (~ five-fold) than those for electric power.

18. A very large expansion (>> doubling) of electricity generation capacity would therefore be required to enable replacement of gas exclusively by electricity for heating, even using heat pump technology, and such expansion is unlikely to be feasible or optimal.
19. Balancing energy use – including by energy storage – on all time-scales, from seconds to seasonal would therefore be necessary to facilitate both the integration of large-scale intermittent electricity and replacement of natural gas for heating.
20. To avoid the risk of unacceptable blackouts the UK needs to be able to dispatch (or reliably import) around 50GW(e) of power for at least several days. This need is currently met by gas and nuclear plant, but the inefficient use of capital invested, due to using expensive plant only to meet peak demand, needs to be addressed.
21. It is very unlikely that emissions reduction targets can be met unless the emissions from remaining gas-fired plant are also abated in future by deploying Carbon Capture and Storage.
22. Demand management should have considerable potential for smoothing diurnal fluctuations of supply and demand, but is unlikely to be very effective on shorter, or longer time-scales.
23. Given the UK emissions targets it would be undesirable to build long-lived assets that would commit us to emissions for decades into the future, and that may thus become stranded (eg.. new coal, or gas infrastructure without CCS).
27. For longer term storage, conversion of surplus electricity to chemical energy (by electrolysis in the first instance) is likely to be required (see below)
28. It is unlikely that pumped hydro storage has much scope for expansion in the UK, but other unconventional forms of energy storage (eg. compressed air storage) are at an early stage of R&D, hold promise for deployment in the future and would benefit from additional support.

### Hydrogen and chemical fuels

29. Production of low-carbon hydrogen by electrolysis is now adequately efficient for widespread deployment, but cost reduction and sufficient low carbon energy sources will be essential. In the long term it would be desirable to capture and use the oxygen too (eg. for oxy-fuel combustion)
  30. Efficient production of hydrogen directly from sunlight (without conversion to electricity and electrolysis) is the subject of considerable research and could be a break-through technology
  31. Steam reformation of methane (with CCS, when available) would provide a potential source of low-carbon hydrogen without major new technological developments.
  32. Conversion of hydrogen to gaseous (eg. ammonia), or liquid (eg. methanol, using captured CO<sub>2</sub>) fuels by catalytic conversion processes could provide alternative fuels for transport and longer-term storage.
  33. The production of ammonia from hydrogen and nitrogen by the Haber-Bosch process requires substantial medium-grade heat energy (500 C) and electricity for compression (to ~ 200 bar) that could be provided by nuclear plant when not supplying electricity to the grid.
  34. The use of hydrogen as an alternative to methane in domestic gas supplies is feasible but limited by potential corrosion and leakage problems in the present distribution network that would need to be addressed.
- Energy storage**
24. Batteries are highly effective and efficient for short-term storage of electricity. They are being rapidly improved (notably for electric vehicles) and are capable of significant (but probably not massive) further development. Cost will be the prime issue for large scale storage.
  25. Effective utilisation of the likely future large battery storage capacity in electric vehicles for grid balancing will be desirable, but will require innovative network management and appropriate financial (contractual) arrangements.
  26. Other technologies that would allow the time-shifting of large amounts of energy and meet energy system needs have largely been neglected.

## Low-carbon electricity, nuclear etc

35. UK electricity markets are extremely complicated, with multiple and inconsistent implicit carbon prices, and would benefit from simplification (eg. based on a single substantial carbon price of >\$80/ tCO<sub>2</sub> to remove unintended and/or perverse incentives).
36. The electrification of transport, and the widespread deployment of wind turbines and photo-voltaics will result in dramatic changes in the amount of energy that we need to move around on our energy networks and may increase potential instability of the grid.
37. The UK is likely to need a minimum of 13 GW(e) of new zero-carbon firm generation capacity just to meet a CO<sub>2</sub> intensity target of 50 g/kWh, let alone achieve zero. This could be new nuclear, biomass or gas with CCS.
38. Problems with deployment of new nuclear capacity have been mainly due to on-site construction. A new approach from the construction sector, using modern techniques involving much more modularity and factory build as have already been applied in other sectors, could reduce such problems.
39. Government intervention in financing of new nuclear build (as indicated in the 2017 National Audit Office report on Hinkley Point) could lead to lower interest rates enabling a significant reduction of electricity cost.
40. Fragmentation of electricity supply is leading to a seriously sub-optimal configuration of nuclear power infrastructure: i.e. a small number of (planned) large plants all of a different design, rather than a substantial number (a 'fleet') of smaller plants of the same (or similar) design. This inefficiency is estimated to have led to additional £20/MWh on the strike price.
41. Small modular reactors (SMRs) may be a better fit for a future high-renewable energy mix. At less than 500MW(e), these power plants could in principle be rapidly assembled on site from factory-produced modules. There could be a significant export opportunity if the UK were to move rapidly to develop this capability.
42. A stable long-term incentive for innovation from the nuclear and other low-carbon energy sectors, through an on-going funded programme of RD&D, would further contribute to their success and sustainability.

## Transport

43. A major transition to electric cars for personal road transport in the next few decades now seems very likely. Availability of fast charging at scale will be needed to meet demand and this will place further pressures upon the grid but could provide storage opportunities.
44. For Heavy Goods Vehicles however the most appropriate technology and/or fuel is still unclear, but may include liquefied natural gas (LNG) and biofuels in hybrid electric configurations.
45. For passenger vehicles the load factor (i.e. the number of people per vehicle) is the single biggest variable that can reduce the carbon footprint in use and the growing availability of car sharing services has the potential to influence this, especially with associated incentives.
46. It will be necessary to improve the efficiency of transport by integrating the different modes of transport, increasing load factors, consolidating journeys and improving the marginal choices that people are able to make with better information.
47. Widespread electrification of road transport has a significant political dependency, since the Treasury receives £25 – 30bn p.a. from vehicle fuel duty, so alternative sources of taxation may eventually be required. Some sort of differential payment per mile ('road pricing') could be implemented using existing technology.
48. The ICAO and IMO have not so far proposed effective regulatory frameworks for limiting emissions from aviation and shipping.
49. Aviation remains technologically difficult, and is likely to become a high priority market for bio-fuels and/or 'green' carbon-neutral liquid fuels (i.e. those synthesised from captured CO<sub>2</sub>), but this may not be the most effective use of scarce biomass. Demand management may also be required.
50. An early priority for shipping would be to phase out the use of Heavy Fuel Oil, possibly by substituting Liquefied Natural Gas in the near term. There are several potential technological options for long term decarbonisation of shipping (for example, nuclear, 'green' liquid fuels, on-board CCS, wind assist), but active development of these is proceeding very slowly and would benefit from additional incentives.

## Biological systems

51. Carbon storage by biological systems in biomass (eg. forests) and/or soils requires little or no technological development and could in principle be implemented or augmented without delay at potentially large scale.
52. The potential capacity of carbon storage in soils is large\* (maybe ~ 1 GtC for the UK), but it is generally difficult to measure the amounts of carbon stored in biomass and/or soils, and such stores are vulnerable to degradation if appropriate management is not maintained indefinitely.
53. Soil carbon storage may be increased by a number of agricultural practices, and potentially also further augmented by application of basic minerals, including lime and silicates such as basalt (this is a form of enhanced weathering).
54. Restoration and management of forests could be implemented relatively quickly and easily and could play a significant role in carbon storage in the UK for the next few decades.
55. The use of timber in buildings constitutes an easily implementable and significant medium-term store of carbon, but the retention time is limited by the finite (< centennial) lifetime of most buildings. Greater re-use of materials from buildings could significantly extend retention time.
56. The scope for production of biofuels in the UK is likely to be limited by its less than optimal climate, and by the availability of agricultural waste and of non-agricultural land for growing energy crops.
57. The use of biofuels in the UK (eg. for transport and electric power generation) is likely to depend on imports, and current methods for assessing their true carbon footprint may lead to misleading and uncertain results (see EASAC 2017 (5) and Royal Academy of Engineering 2017 (6))

## Heating, cooling and industrial processes

58. Use of hydrogen produced by steam reformation of methane (with CCS) may provide an effective route to decarbonising heat for industrial processes.
59. It is far simpler to manage heat efficiently in new-build homes, cities and industrial complexes than to retro-fit lower carbon solutions to existing buildings.

60. Wherever possible, combining heat and power would increase efficiency and so reduce waste.
61. Emissions from the manufacture of cement could be substantially reduced by promoting greater efficiency in its use, through lifespan extension and reuse, eliminating waste of cement and concrete during construction, and improved engineering design.
62. Alternative forms of cement that lead to lower or even possibly negative emissions (eg. those based on silicate minerals, including fly ash and slags) could also be used for less demanding applications.

## Policy mechanisms

63. The EU Emissions Trading Scheme has been ineffective, as the carbon cap has been set too high so that EU-ETS certificates are still too cheap to incentivise deployment of alternative technologies, including new CCS. The EU-ETS also does not yet allow credit for CO<sub>2</sub> storage.
64. For CCS, one possible alternative in the absence of an appropriate carbon price is a Certificate of Storage for each tonne of carbon produced or imported, that carries an obligation to store the CO<sub>2</sub> generated within some predefined deadline.
65. The failure of the Green Deal shows that complex promises of future benefits do not necessarily provide adequate incentives, in the absence of adequate up-front benefits.
66. Regulators could embolden action by providing assurance of long-term strategic direction, without cutting across their existing statutory objectives or adding new ones. If actions to respond to, and restrain, climate change are fully understood to be integral to economic performance, then there is much less risk of an apparent conflict of regulatory objectives.
67. Tighter building regulations towards zero-carbon homes would be effective, with increased monitoring and inspections, supported by massive artisanal up-skilling in all low-carbon trades (especially energy efficiency and low-carbon heat)
68. The demise of coal in the UK has been in large part due to the (rather modest) UK carbon price floor (at £18/tCO<sub>2</sub>). Maintaining or strengthening the carbon price floor would provide an incentive to drive further decarbonisation in the UK.

\* This is reflected in the '4 per mille Soils for Food Security and Climate' initiative, see <http://nora.nerc.ac.uk/517116/>

69. The energy system in the UK is quite diverse and energy policies and regulation could exploit this by focussing on managing the demand for energy services rather than fuels.
70. It would be desirable for businesses to follow the risk disclosure recommendations of the Task Force on Climate-related Financial Disclosures report, to help investors have a full understanding of the risks of holding stranded assets from climate policy or climate impacts.
71. Additional policy interventions are likely to be needed to further encourage clean innovation, promote energy efficiency, overcome barriers to clean finance and deal with any unintended socio-economic consequences (for example on fuel poverty and employment opportunities). Current innovative proposals around the so-called Circular Economy will provide new opportunities for change.
72. Rigorous analysis of proposed policies for energy production, distribution and usage prior to their implementation would help to avoid perverse and unintended consequences. Such analyses need to take into account the widest possible range of scientific, technical, economic, environmental, human, social, political and ethical issues.
73. In broad terms people generally express a strong desire to see a long-term commitment by society to move towards a more sustainable energy system, involving a reduced reliance upon finite fossil fuels and minimization of waste.
74. People also emphasise efficiency, capturing technological opportunities, and environmental protection, alongside cultural values including justice and equity, energy affordability for those on low incomes, personal freedom and autonomy.
75. A successful transition to a zero-carbon energy supply will be as much about meeting these values for change as it will be about finding appropriate technology solutions or economic instruments.
76. Public concern about climate change as expressed to politicians is low compared to other political issues. Policies need to be meaningful to people and communities, and ideally lead to other positive outcomes, as well as providing a material contribution to carbon reduction.
77. Reducing emissions to manage climate change is a public benefit it is therefore appropriate for Government to continue to contribute public funds to achieve this.
78. Achieving UK targets for emissions reduction would be facilitated by a longer-term energy strategy involving consistent application of appropriate mechanisms, to enable businesses to plan.
79. Available policy levers include taxation, subsidy and regulation and used appropriately these can allow industry to build credible business cases for major investment in new carbon reduction technology (eg. Small nuclear reactors, CCS, etc.).
80. Timescales are long and to have any prospect of achieving national targets cost-effectively it is urgent to make a start now. If the UK moves now there is the prospect of an export market for UK experience and hardware.



## Notes and references

1. The Royal Society produced a Policy Briefing Note *The potential and limitations of using carbon dioxide* in May 2017, <https://royalsociety.org/~media/policy/projects/carbon-dioxide/policy-briefing-potential-and-limitations-of-using-carbon-dioxide.pdf>
2. The Royal Society is currently preparing a Policy Briefing Note on Negative Emissions Technologies.
3. The Parliamentary Advisory Group on Carbon Capture and Storage (CCS) published a report *Lowest Cost Decarbonisation for the UK: The Critical Role of CCS* in September 2016, available at [http://www.ccsassociation.org/index.php/download\\_file/view/1043/508/](http://www.ccsassociation.org/index.php/download_file/view/1043/508/)
4. The House of Commons Committee of Public Accounts published a report entitled *Carbon Capture and Storage* in April 2017, available at <https://publications.parliament.uk/pa/cm201617/cmselect/cmpubacc/1036/1036.pdf>
5. EASAC (2017) *Multi-functionality and sustainability in the European Union's forests* EASAC policy report 32, April 2017, [http://www.easac.eu/fileadmin/PDF\\_s/reports\\_statements/Forests/EASAC\\_Forests\\_web\\_complete.pdf](http://www.easac.eu/fileadmin/PDF_s/reports_statements/Forests/EASAC_Forests_web_complete.pdf)
6. The Royal Academy of Engineering published a report titled *Sustainability of liquid biofuels* in July 2017 available at <https://www.raeng.org.uk/publications/reports/biofuels>