

Royal Society of Chemistry response to the Innovation, Universities and Skills Select Committee inquiry into renewable electricity-generation technologies

The Royal Society of Chemistry (RSC) welcomes the opportunity to comment on the Select Committee on Science and Technology inquiry on renewable electricity-generation technologies.

The RSC is the largest organisation in Europe for advancing the chemical sciences. Supported by a network of 43,000 members worldwide and an internationally acclaimed publishing business, our activities span education and training, conferences and science policy, and the promotion of the chemical sciences to the public.

This document represents the views of the RSC. The RSC's Royal Charter obliges it to serve the public interest by acting in an independent advisory capacity, and we would therefore be very happy for this submission to be put into the public domain.

The document has been written from the perspective of the Royal Society of Chemistry and consequently our comments relate to only parts of the consultation document.

The evidence submitted was for the most part published in an RSC report entitled "Chemical Science Priorities for Sustainable Energy Solutions"
| [\[www.rsc.org/Gateway/Subject/EnvEnergy/\]](http://www.rsc.org/Gateway/Subject/EnvEnergy/).

If you would like further information or need anything in this document clarified, please do not hesitate to contact me.

Yours sincerely,

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Executive Summary

1. Solar power has the potential to provide a significant proportion of the UK electricity needs, but current shortcomings have to be addressed. The chemical sciences will be crucial in reducing the cost and increasing the efficiency of solar technology through improvements to current design and manufacture and through the development of the next generation of technology. Ideally it will become routine to integrate solar power into buildings through the use of specialised construction materials.
2. Biofuels have great potential for reducing carbon emissions but it is vital that energy used in their production is minimised or derived from renewable resources. Bioethanol from lignocellulosic biomass (such as wheat straw) could improve the economics and reduce land use for biofuels in the medium term. However significant research and development challenges remain for chemists, biochemists and engineers. The chemical sciences and engineering disciplines are critical in developing efficient catalysts, separation processes, high throughput systems and additives to maximise the effectiveness and efficiency of biofuels.
3. In order for hydrogen to become a commercial energy vector in the future many technical barriers will have to be overcome. In the short term it is important to develop materials that allow safe storage and distribution of hydrogen. As demand grows for hydrogen, it is important to develop an efficient way of producing hydrogen that is carbon neutral in itself. Since it is expected that steam reforming of methane with subsequent release of CO₂ is likely to be the predominant production route in the medium-term, the development and deployment of carbon capture and storage is vital.
4. With wider use of renewables, the need for energy storage will increase significantly. Research into batteries is very important, especially into cheaper and safer electrode and electrolyte materials with better performance. Additionally, batteries for hybrid vehicles need to become smaller, lightweight and have a higher energy density.
5. It is important that there are sufficiently trained and committed scientists and engineers to carry out the research, development, demonstration and deployment of renewable energy-generating technologies. It is also important that the Research Councils, Technology Strategy Board, Energy Technologies Institute and BERR work together to ensure that there are collaborative funding mechanisms throughout the technology development pathway that allow scientists, engineers and technologists to work together to bring basic research through to developed products.
6. Two alternative technologies for future energy generation could be artificial photosynthesis and blue energy (salinity-gradient energy). This requires a long-term research and development effort beginning now before a commercial process can be envisaged. The technology for blue energy

needs to be produced much more cheaply for it to be competitive with existing energy sources.

Recommendations for Government

7. Long-term funding is required for fundamental and application specific chemistry to stimulate and encourage energy related research. Chemical sciences can play a major role in delivering cost effective and highly efficient renewable energy sources. Research into more efficient and less expensive materials to construct systems for solar energy conversion into heat and electricity are needed as well as research into improved feedstock conversion and lightweight, durable materials and coatings for turbines. Basic research needs to be undertaken into materials that can be used for fuel-cells and on-board storage of hydrogen in vehicles.
8. Additional government support (bank loans, tax reduction, etc) is needed to help end-users transfer to low carbon energy. Important areas of applications could be the installation of domestic solar power devices, the replacement of obsolete domestic electrical equipments. The government should also introduce policies that allow net metering, by which consumers can sell surplus electricity back to the grid.
9. It is important that there are sufficiently trained and committed scientists and engineers to carry out research, development, demonstration and deployment of renewable energy-generating technologies. This could be achieved through incentives to recruit and maintain outstanding, internationally competitive scientists to work on energy related research in the UK. It is also important that the Research Councils ensure that there are collaborative funding mechanisms throughout the technology development pathway that allow scientists, engineers and technologists to work together to bring basic research through to developed products.

The current state of UK research and development in, and the deployment of, renewable energy-generation technologies including: offshore wind; photovoltaics; hydrogen and fuel cell technologies; wave; tidal; bioenergy; ground source heat pumps: and intelligent grid management and energy storage.

Photovoltaics (solar power)

10. Solar power has the potential to provide a significant proportion of the UK electricity needs. The chemical sciences will be crucial in reducing the cost and increasing the efficiency of solar technology through improvements to current design and manufacture and through the development of the next generation of technology, such as technology that takes advantage of biological methods of harvesting and storing energy from light. The UK has a strong research base in areas including understanding and mimicking photosynthesis systems and also in dye-sensitised and organic solar cells. Ideally it will become routine to integrate solar power into buildings through the use of specialised construction materials (for example roof tiles and windows) coupled to energy storage and low energy demand devices.
11. Photovoltaic (PV) devices consist of a semi-conducting material, currently most commonly silicon, which convert photons into electrical current by means of the photoelectric effect. They were developed in the 1950s to power space satellites, but their potential for providing remote power for telecommunications, water pumping and refrigeration rapidly increased demand for terrestrial applications. The drawbacks of early photovoltaic technology also became obvious, namely cost, low power density and intermittency of operation.
12. Although prices are coming down PV systems currently cost around 55 pence/kWh which is more than a factor of 10 greater than current gas, coal and nuclear power plants. A number of different technologies are at various stages of development to both reduce the cost of solar modules and to increase their efficiency. Over 80% of modules are currently based on crystalline silicon. Silicon is an excellent material for solar cell production since its technology has become highly developed as a result of the global semiconductor market. In addition, its supply is virtually inexhaustible and it is non-toxic, although its manufacture is currently highly coupled to semiconductor demand. In the late 1970s and early 1980s thin films of inorganic semiconductors made from indium tin oxide (ITO), cadmium selenide (CdSe), copper indium diselenide (CuInSe₂), amorphous silicon, thin film silicon and titanium oxide (TiO₂) were developed as potentially cheaper PV materials. Innovative research on very thin (less than 20 atomic layers), high efficiency silicon devices is now in progress.
13. One of the factors that keeps system costs high for these technologies is the requirement of high temperature processing of the semiconductor material. This, and the rapid growth of the organic light emitting diode market, have resulted in considerable research on PV materials based on molecular,

polymeric and nanocomposite materials. Although commercially viable efficiencies have yet to be demonstrated, progress is rapid. In 2004 at least two manufacturers claimed efficiencies of 5% for organic PV materials that can be printed or sprayed on to a thin support, flexible backing film, potentially offering considerable production cost reductions.

14. Dye sensitised solar cells (DSCs) offer a near market alternative system to silicon cells. These cells were invented by Michael Grätzel and Brian O'Regan at the École Polytechnique Fédérale de Lausanne in the 1990s. DSCs currently have a sunlight conversion efficiency of 11%, which is lower than that of silicon based solar cells, however, they have a lower cost base which allows them to compete. There is significant potential to improve the efficiency and further reduce the cost of DSCs.
15. The growing number of uses for photovoltaic devices, and the considerable improvements in reliability and price have generated a market that is growing at about 25% per annum. Although PV began by providing power to remote locations that had no grid connection, over 50% of today's world market is for building integrated photovoltaic (BIPV) devices that are incorporated into the roofs and structures of buildings. Providing governments continue to support the installation of BIPV and introduce policies that allow net metering, by which consumers can sell surplus electricity back to the grid, it is likely that the demand for PV will continue to grow. As a result, many independent studies suggest that the costs of PV will continue to fall and that it is plausible to reduce module costs by a factor of seven or greater by 2020 – this would allow BIPV to provide electricity below today's retail price in sunny areas of the world.
16. Useful amounts of electricity can also be generated directly from infrared radiation using a process called thermophotovoltaics. It is unlikely that the power of the sun will be harnessed directly using this technology, but it is theoretically possible. It is more likely that thermophotovoltaics will be used to generate electricity from waste heat to boost the efficiency of conventional thermal power generation technologies.

Hydrogen and fuel cell technologies

17. The hydrogen economy is the name given to an economy based on hydrogen rather than carbon based fuels. The transition to the hydrogen economy represents the biggest infrastructure project of the 21st Century. A sustainable hydrogen economy would offer enormous economic, social and environmental benefits and this justifies the significant investment of resources and capital.
18. When hydrogen (H₂) is burned or used as fuel to generate electricity in a fuel cell, the major by-product is water. Whilst hydrogen is abundant on Earth, it is not abundant in the form H₂ and must be produced in a way that uses energy. Therefore, H₂ is potentially a significant fuel source and the key

challenges are to minimise the energy used in producing H₂ and ultimately to produce H₂ from sustainable sources.

19. There are technical barriers throughout the supply chain of the hydrogen economy, and the key challenges for the chemical sciences are highlighted in the following sections.

Hydrogen production

20. Energy is required to produce hydrogen and therefore as a fuel it is only as clean as the process that produced it in the first place. Currently the most common method is steam reforming of natural gas in two-step catalytic process, producing a mixture of H₂ and CO₂. There are concerns over the economics of the process and over the release of CO₂. In the future it will be possible to employ carbon capture and storage (CCS) technology to safely store the CO₂, however, this will add to the cost of the hydrogen production and the energy required. There are a number of medium and long-term options for producing hydrogen:
- Coal and oil residues or biomass gasification. The high temperature of the process and the need to separate nitrogen from air (presumably cryogenically) are barriers which add to the cost of this process.
 - Using electricity (preferably from renewables) to split water via electrolysis can be seen a method of storing (renewable) power. Further work is still needed to develop improved electrode surfaces for electrolyzers and also the materials of construction. Uses for the by-product O₂ also need to be found.
 - Thermochemical splitting of water in the next generation of high temperature nuclear reactors or concentrating solar power plants. There is a need for new materials and an understanding of the fundamental high temperature kinetics and thermodynamics in order to achieve this.
 - Biochemical hydrogen generation. Green algae and cyanobacteria utilise light to split water, producing both H₂ and O₂. Currently O₂ concentration in the system and the rate of reaction are limiting factors. New natural microorganisms and genetically modified organisms may hold the key to increased efficiency.
 - Photocatalytic water electrolysis is where the energy of sunlight is used to split water into H₂ and O₂. The system, and current R&D priorities, are focussed on two basic principles. Firstly, the light harvesting system must have suitable energetics to drive the electrolysis. Secondly the system must be stable in an aqueous environment.

Hydrogen storage and distribution

21. Hydrogen is the lightest element and occupies a larger volume than other fuels. Currently, in prototype vehicles, compressed hydrogen is used, but this is relatively bulky. Liquid hydrogen would be a more efficient way to store H₂ (850 times denser than gaseous H₂) but with a boiling point of -

253°C it is very energy intensive to maintain the very low temperature required to store hydrogen in this form. Finding mechanisms to store hydrogen in a form that is safe, suitable for intended use and regenerable (if applicable) is therefore a key research priority that the chemical sciences must rise to meet. Some of the key technologies and issues are summarised below:

- a. High surface area nanostructured materials, such as carbon nanotubes, have been shown to be able to store and release significant quantities of H₂. Such materials are as yet unproven and much scientific endeavour is required to fully assess their potential.
 - b. Certain metal complexes absorb H₂ reversibly to form metal hydrides. Numerous compounds have been and continue to be studied. Key requirements of a suitable metal hydride include, high H₂ content, low cost, favourable kinetics, resistance to poisoning and the materials should not ignite in air.
 - c. There are a number of options for chemical carriers of H₂; this means that the H₂ is bound into the chemical structure of the carrier. Organic liquids, such as cyclohexane and methanol, inorganic complex hydrides such as 3Na[AlH₆] and chemical hydrides such as NaBH₄ all have potential to carry H₂. Key challenges include the mechanism of releasing H₂, recharging the materials, H₂ density and cost. R&D programmes continue to explore these issues.
22. There are a number of worldwide examples of pipeline networks for safely moving pressurised hydrogen, thus demonstrating that a larger scale network is possible. However, there is an issue of compatibility of H₂ with existing natural gas infrastructures both in terms of the materials employed (potential for leakage) and the need for a faster flow rate (requiring more energy). The chemical sciences have a key role to play in material design for hydrogen carrying infrastructures.
23. Hydrogen may potentially be stored in large quantities in depleted oil and gas fields and aquifers. There is a significant parallel here with work being carried in the field of carbon capture and storage.
24. There have been concerns over release of molecular hydrogen into the lower atmosphere, for example through leakage. The presence of H₂ may lead to a reduction in the levels of hydroxy radicals (•OH). Since •OH is a sink of methane (CH₄) this may lead to an increased level of CH₄ in the atmosphere. Clearly it is important that the role of H₂ in the atmosphere is better understood.

Hydrogen use

25. Aside from direct combustion, fuel cells are the main method for obtaining energy from hydrogen. Fuel cells (FCs) fall broadly into three categories:
- Low Temperature (50-150°C): alkaline (AFC), proton-exchange membrane (PEMFC) and direct methanol (DMFC) fuel cells;
 - Medium Temperature (around 200°C): phosphoric acid fuel cell (PAFC);

- High temperature (600-1000°C): molten carbonate (MCFC) and solid oxide (SOFC) fuel cells.
26. The DMFC differs from the other FCs because it uses methanol as fuel, rather than H₂. Each of the six systems has preferred uses (for example stationary and mobile power generation), advantages and disadvantages and specific research priorities that need to be addressed. For chemical scientists there are numerous technical challenges to be overcome including:
- Membrane design
 - Materials for construction
 - Understanding the fundamental thermodynamics and kinetics
 - Tolerance to impurities
 - Electrocatalyst design
 - Cost
 - Speed of start-up
27. On-board storage of hydrogen is posing significant obstacles to delivering hydrogen-powered vehicles. The development of materials for hydrogen storage is a key challenge for chemical scientists.
28. The cost of fuel cells versus that of the internal combustion engine is also a problem, with the latter typically costing \$50 for each kilowatt of power it produces while fuel cells cost a hundred times more. Technical challenges such as making fuel cells rugged enough to withstand the stress of driving, reducing their size and weight while increasing power density, fuel flexibility and fuel cell poisoning still exist.
29. The RSC believes that for the hydrogen economy to become a reality, major scientific and engineering challenges need to be addressed in terms of the generation of hydrogen on a large scale, storage, cost-effective safe transportation and the next generation of materials and technology for hydrogen fuel cells. We recommend that the Government supports the science and engineering research that will ultimately deliver a sustainable hydrogen economy at a level where the UK is in competitive position in a world perspective.

Bioenergy

30. First generation biofuels, that is those derived from starch or sugar crops (bioethanol) or those derived from vegetable or animal oils (biodiesel) are already a mature technology. There are certain technological advances, for example pervaporation membranes for bioethanol purification and high throughput continuous reactors for biodiesel production, that could improve the efficiency of their production.
31. It is the belief of the RSC that second generation biofuels (e.g. bioethanol, biobutanol and fuels produced from synthesis gas such as gasoline and

diesel) that are derived from lignocellulosic biomass (such as cereal straw, trees, waste paper, etc.) offer far greater potential for reducing cost and environmental impact compared to first generation biofuels. Furthermore, second generation biofuels do not necessarily compete with food production unlike first generation biofuels. There are a number of key technological barriers that must be overcome before second generation biofuels are realised and these are addressed in our response. The chemical sciences and engineering disciplines are critical in developing efficient catalysts, separation processes, high throughput systems and additives to maximise the effectiveness and efficiency of biofuels.

32. There are currently many options for the generation of energy from potential materials. The best of these, including the biorefinery approach, not only produces matter for power generation but also potentially valuable co-products. Given the restriction of available land area, there is great potential in exploiting the extensive marine resources at the disposal of the UK for biomass production, a process which serves multiple beneficial roles beyond that served by the end product.
33. Carbon emissions from the use of biomass or derived products should ideally be equal to that sequestered during the growth of the source material making the process carbon neutral. However, this depends crucially upon the energy used in processing and production, and the logistics and efficiency of agricultural, chemical, biochemical and engineering practices employed. Biomass is most effective in reducing CO₂ when the supply chain distance is minimal. This means that importing biomass should be considered carefully in this respect in addition to the ethical and security implications involved. Furthermore, achieving sustainability during production would be greatly helped by the publication of best practice guidelines for agriculture.
34. Economic factors will drive the success of bioenergy so making this option competitive is essential. Research into the practicalities of scale, efficiency and logistics as well as the creation of an appropriate long-term policy and finance framework based upon this research to support bioenergy in the UK is clearly needed. The potentials for bioenergy are unlikely to be exploited under prevailing economic conditions and sectorial approaches. There must be strong links between all those involved including academic research, agricultural production, industrial refining and end users be they public retailers or power companies.
35. The RSC has recently submitted evidence to two relevant inquiries, the EFRA Committee inquiry into bioenergy (appendix A) and the Royal Society inquiry into biofuels (Appendix B). Both documents are attached to this submission as appendices.

Energy Storage- Batteries

36. Rechargeable batteries offer the most direct means of storing electrical energy and as a result are highly efficient.
37. Lithium-ion batteries represent the most important development in rechargeable battery technology for a hundred years. They have three times the energy density of conventional rechargeable batteries and have had a major impact in consumer electronics. A lithium-ion battery occupying some 10 m³ could store 4.5 MWh of energy and with a charge/discharge efficiency of over 99.9%. This technology is already the storage solution of choice in a number of energy research centres around the world.
38. Lithium-ion technology presents one of the greatest challenges for chemists. Scale up to larger batteries requires:
- fundamental advances in new cheaper, safer electrode and solid polymer electrolyte materials with better performance;
 - new non-flammable liquid electrolytes or ionic liquids.
39. Moreover, Li-ion batteries for vehicles are comprised of hundreds of cells, if any of these fails the whole system is compromised.
40. Cobalt oxide is a key material for producing lithium ion batteries. The world estimated cobalt reserves are relatively small; less than a tenth of that of nickel and just over a hundredth of that of copper. Cobalt accounts for a quarter of the mass of lithium ion batteries. If 30 million battery packs capable of powering electric vehicles were made annually the world cobalt reserves would be depleted in six years (provided the global estimates are accurate). The majority of cobalt reserves are located in politically unstable regions - the top three sources of cobalt are Congo, Cuba and Zambia. This could raise a major security of supply issue. To address this electrodes based on cheaper more abundant materials must be synthesised.
41. A further possible driver for the development of novel battery technology at the smaller scale end of battery technology is regulation. In the EU, measures have already been taken to limit the mercury content of batteries. Further regulation will aim to reduce other heavy metals, including cadmium, nickel and lead. Also options for disposal of batteries will be limited to encourage collection and recycling.

Energy Storage - Superconductors

42. In superconducting magnetic energy storage devices (SMES), energy is stored in the magnetic field of a coil within which a current flows. The device consists of a superconducting coil, typically made of niobium with titanium or tin, in a copper matrix, a power conditioning system (PCS), a refrigeration system for cooling the coil and a cryostat vacuum vessel. Efficiency losses are mainly due to the cryogenic system, which has to keep the coil below the critical superconducting temperature of around -268°C.

43. Chemists are needed to address the identification and development of new superconducting materials with higher critical temperatures, preferably room temperature, and with suitable mechanical properties for processing into coils and wires.

Wind, tidal and wave power

44. Advances in materials science to develop high strength, lightweight materials for turbine blades and towers are required in order to facilitate the construction and continued operation of large wind and tidal power turbines. Long lasting protective coatings will also be required to reduce maintenance costs and prolong the operating life of wave and tidal energy devices.

The feasibility, costs, timescales and progress in commercialising renewable technologies as well as their reliability and associated carbon footprints.

45. No comment.

The UK Government's role in funding research and development for renewable energy-generation technologies and providing incentives for technology transfer and industrial research and development.

46. It is important that there are sufficient trained and committed scientists and engineers to carry out the research, development, demonstration and deployment of renewable energy-generating technologies. It is also important that the Research Councils, Technology Strategy Board, Energy Technologies Institute and BERR work together to ensure that there are collaborative funding mechanisms throughout the technology development pathway that allow scientists, engineers and technologists to work together to bring basic research through to developed products.
47. The relatively short timescales (3 years) of research council funding is seen as a major weakness in the context of the long-term challenge of sustainable energy research. It leads to a lack of continuity in academic research and a short term attitude. In terms of funding, responsive mode funding is viewed as being of vital importance to foster new discoveries and support high quality research. Such responsive mode funding needs to be long term 5 – 8 years rather than 2 – 3 years. However, responsive mode funding alone cannot address the strategic imperatives in research for sustainable energy technologies. It is felt that responsive mode funding must be complemented with more targeted, focussed funding and especially long term support to stimulate more materials research for sustainable energy technologies.
48. There is a real need to bridge the 'development' gap between academic research and prototyping. Large-scale collaboration is required to drive breakthroughs. As well as the cultural divide, the 'development gap' is linked to a lack of funding for development. Whilst the decline in large-scale corporate R&D investment reflects a global trend, this decline is felt particularly acutely in the UK where large-scale industrial research was previously very strong. Opportunities to collaborate with industry and the availability of additional industry funding are no longer as widely and readily available. Funding is required to support research as it moves from the laboratory into technology development. Tax breaks and other financial incentives should be offered to encourage industry to invest in sustainable energy technologies.
49. The RSC has recently submitted responses, relevant to this inquiry, to the Sainsbury review of science and technology consultation (Appendix C) and the EPSRC knowledge transfer and economic impact consultation (Appendix D) – these are attached as appendices.

Other possible technologies for renewable energy-generation.**Artificial photosynthesis**

50. Artificial photosynthesis is a research field that attempts to replicate the natural process of photosynthesis, converting sunlight, water and carbon dioxide into carbohydrates and oxygen. The process essentially comprises two steps one involving a light reaction and other a dark reaction. In the first step light is captured and the energy used to split water into oxygen and hydrogen. In the second "dark" step hydrogen is combined with carbon dioxide to make carbohydrates (or possibly other products). The potential of artificial photosynthesis is huge as it offers a route to sustainable hydrogen production and also potentially to a process that removes carbon dioxide from the atmosphere and creates useful products. The scientific and technical challenges, however, are equally large – in essence this is because the natural process is incredibly complex and comprises of numerous interlinked processes. Artificial photosynthesis will require a number of years of research and development before a commercial process is envisaged.

Blue energy

51. A significant potential to obtain clean energy exists from mixing water streams with different salt concentrations. This salinity-gradient energy, also called blue energy, is available worldwide at estuaries where fresh water streams flow into the sea. The global energy output from estuaries is estimated at 2.6TW, which represents approximately 20% of the present worldwide energy demand. Large amounts of blue energy can also be made available from natural or industrial salt brines.
52. Blue energy can work either on the principle of osmosis (the movement of water from a low salt concentration to a high salt concentration) or electro dialysis (the movement of salt from a highly concentrated solution to a low concentrated solution) where the saline water and fresh water be separated by a selectively permeable membrane. In the osmosis process water pressure is created that can drive a turbine. In the electro dialysis case the movement of ions creates the electricity. The by-product of blue energy is brackish water. Brackish water is simply a combination of fresh and salt water which naturally occurs in an estuary.
53. Though the technology of blue energy has been understood for quite sometime, manufacturing the membranes was far too expensive for this to become a practical energy alternative. Recently, more economical membranes have been developed which will allow blue energy technology to begin being implemented in suitable environments. Further developments that reduced the cost or improved the efficiency of membranes would significantly improve the economics of this process. Currently blue energy is being used successfully in the Netherlands.