Institute of Physics Report

The Role of Physics in Renewable Energy RD&D

A report produced for the Institute of Physics by Future Energy Solutions

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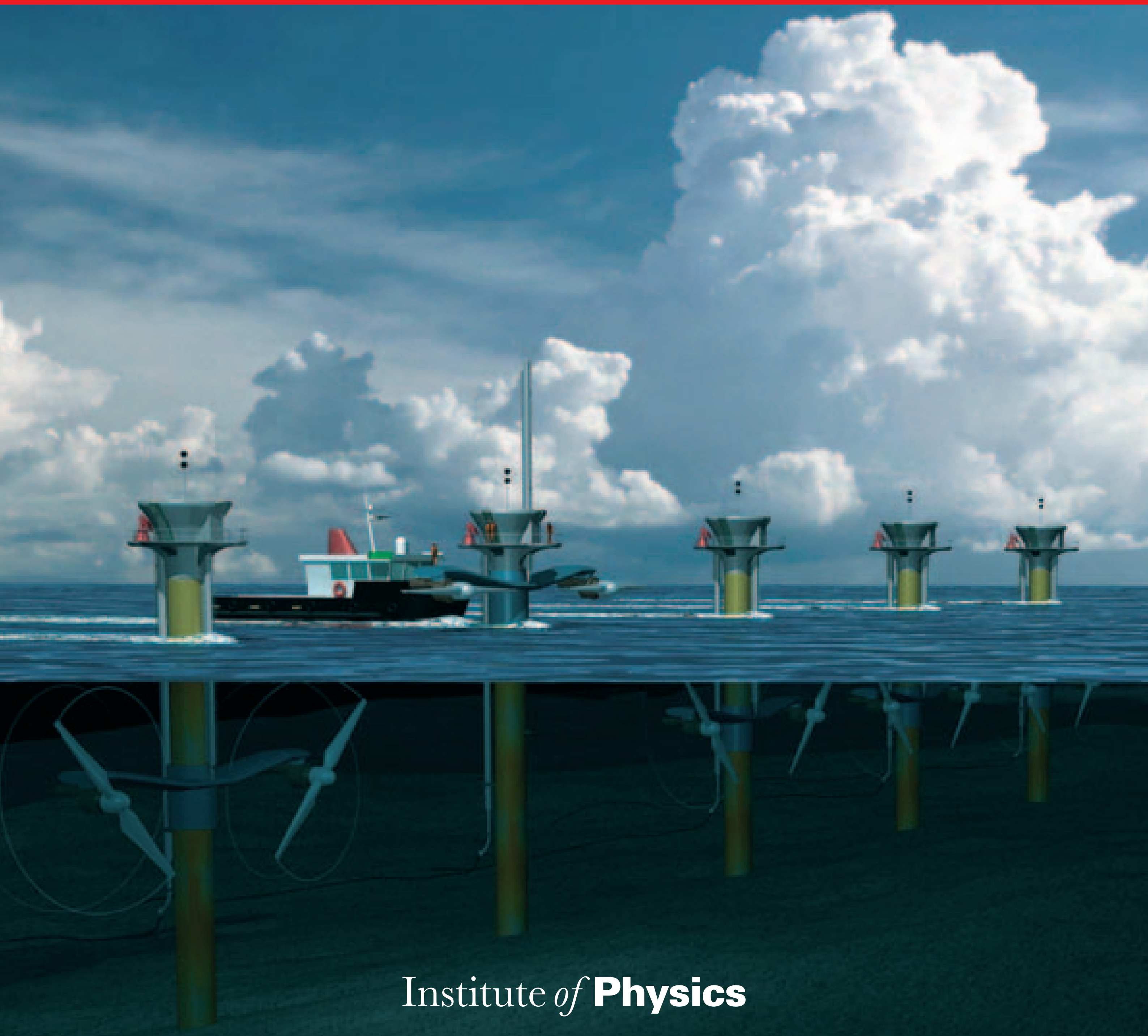

Institute *of* **Physics**

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Preface

Achieving the UK's long-term aspiration to create a low-carbon economy, as set out in the government's 2003 Energy White Paper "Our energy future: creating a low-carbon economy", will require significant improvement in energy efficiency to reduce energy demand at the point of use, together with the promotion of low-carbon energy supplies, such as renewable energy, combined heat and power generation, nuclear power, and fossil-fuel plant equipped with carbon capture and storage technologies. The contribution that physicists make in the development of nuclear power is clear, but their contribution to other technologies has not previously been examined.

The Institute of Physics therefore commissioned Future Energy Solutions to prepare this report, setting out the challenge facing renewable-energy technologies, the important role of research, development and demonstration (RD&D) in meeting this challenge, and areas where physicists currently, or could in the future, contribute to this RD&D. In preparing the report, Future Energy Solutions consulted technology experts in industry and academia, physics departments in the UK and Ireland, and those involved in running RD&D programmes, as well as reviewing the literature on RD&D.

The most obvious area where physicists are contributing to RD&D is in photovoltaics, where they are carrying out much of the fundamental research required to develop novel types of cell

Achieving the UK's long-term aspiration to create a low-carbon economy requires the promotion of low-carbon energy supplies as well as significant improvement in energy efficiency to reduce energy demand. This report, commissioned by the Institute of Physics from Future Energy Solutions, examines the contribution that physics and physicists can make to the development of one type of low-carbon energy supply – renewable-energy technologies. It also examines fuel cells, developments required to move to using hydrogen as a fuel, and supporting technologies that are necessary to allow the grid integration of renewables.

Renewable-energy RD&D

A wide range of disciplines and skills are involved in renewable-energy technologies research, development and demonstration (RD&D). They include mechanical and electrical engineering, materials science, physics, chemistry, and the biological sciences, and in many cases a multidisciplinary team is required to tackle the multifaceted problems posed. The most obvious area where physicists are contributing to RD&D is in photovoltaics, where they are carrying out much of the fundamental research required to develop novel types of cell that may result in step changes in the cost of photovoltaic generation. They can also make particularly strong contributions to RD&D in marine technologies, hydrogen storage, fuel cells and grid integration. As well as contributing to RD&D through the direct application of physics and physics principles, physicists have transferable skills such as simplification by approximation, systems analysis and problem solving, which allow them to make useful contributions in teams tackling engineering problems, or in areas requiring detailed mathematical understanding or statistical analysis.

Supporting the RD&D base

Contacts with technology and project developers for this study confirmed the findings from other recent studies: that there is a lack of necessary skills in the UK, both general technical skills and more specialist skills. To date, developers have remedied the situation through either in-house training or recruiting internationally. A solution that is more beneficial to the UK's competitive position is to estimate future skills and educational needs, from R&D through to applied engineering, and to ensure suitable education and training are available and taken up to provide an adequate supply of appropriately qualified personnel.

Encouraging physicists, and indeed other scientists and engineers, to consider a career in renewable energy could help to plug the skills gap identified above. Awareness and interest in the physics element of these technologies could be raised by promoting the inclusion of examples of the physics of renewable-energy sources and fuel cells in teaching on undergraduate physics courses, A-level physics courses and other A-level science courses. Careers advice material for physicists, at both graduate and postgraduate level, and for mid-career changes could also identify opportunities for physicists in these areas. Better facilitation of specialisation in renewable-energy technologies and fuel cells at the postgraduate level would also help to ensure a better supply of suitably qualified researchers. The multidisciplinary nature of many of these research areas means that obtaining funding or training bursaries can be difficult, and a more flexible approach from funding bodies may be required. An additional barrier is that PhD research topics may not sit easily within university department structures. In this case the development of "energy technology centres" to act as a focus for such activities could help.

Two key areas where the UK has an opportunity to take a research lead are in:

- the new generation of photovoltaic energy technologies, although this would require a strong RD&D effort;
- wave and tidal energy, where there are a number of universities with significant research capability.

Ensuring that these RD&D strengths are developed would bring the UK substantial environmental benefits from reduced carbon dioxide emissions, and financial benefits from export earnings as technologies are deployed globally. This will require support of RD&D and the availability of suitably qualified personnel to work in these areas.

The current landscape for public sector funding of renewable energy RD&D in the UK is complex: funding bodies include the DTI; the Carbon Trust; the EPSRC (mainly through the SUPERGEN programme); and the EU's Sixth Framework programme. A clearer overall strategy for UK RD&D in both renewable-energy technologies and other new energy technologies, together with a clearer map of RD&D funding and clearer demarcation of roles of different funding bodies, would be useful. These could be potential activities for the new UK Energy Research Centre. A clearer research "atlas" indicating institutions and developers carrying out relevant RD&D would also encourage graduates and postgraduates to consider working in this field by clearly showing the variety of career opportunities available.

Summary of recommendations

- Estimate future skills and educational needs in all disciplines (e.g. engineering, physics, materials science) from R&D through to applied engineering in new and renewable-energy technologies and make an effort to ensure that appropriate training is available to ensure an adequate supply of suitably qualified personnel.
- Develop a clearer overall strategy for UK RD&D in renewable energy and other new energy technologies, together with a clearer map of RD&D funding and a clearer demarcation of the roles of different funding bodies.
- Support the UK's significant research capability in wave and tidal RD&D and its potential lead in RD&D in third-generation photovoltaic devices with adequate R&D funding and an adequate supply of suitably qualified personnel.
- Ensure that the funding bodies (e.g. the EPSRC) should appreciate the multidisciplinary nature of much R&D in renewable-energy technologies and take a more flexible approach to the funding of MScs and PhDs in this area.
- Persuade universities to consider setting up "energy technology centres" to encourage and facilitate the multidisciplinary RD&D required for the development of many renewable-energy technologies.
- Encourage physicists (and other scientists and engineers) to consider a career in renewable energy by raising awareness of the science and engineering principles and challenges involved in renewable-energy technologies. This could be done in A-level and undergraduate teaching courses, through continuing professional development activities in professional bodies and through articles on renewable-energy research activities in their member journals.

Contents

1: The challenge for renewable energy

1.1: The need for renewable energy

The government's 2003 energy White Paper "Our energy future: creating a low carbon economy" [1] recognised that climate change, largely caused by the burning of fossil fuels, threatens major consequences in the UK and worldwide, most seriously for the poorest countries, who are least able to cope with the impacts of climate change. It set out a long-term aspiration to create a low-carbon economy, setting the UK on a path to reduce carbon dioxide (CO_2) emissions by 60% by 2050, and making a commitment to substantial progress towards the target by 2020.

Achieving these demanding cuts in CO_2 emissions will require significant improvements in energy efficiency to reduce energy demand at the point of use, together with the promotion of low-carbon energy supplies, such as:

- renewable energy;
- combined heat and power generation;
- nuclear power;
- fossil-fuel plant equipped with carbon-capture and storage technologies.

The energy White Paper saw renewable energy as having a vital role to play in a future low-carbon economy. The UK already has a target that 10% of its electricity should come from renewable-energy sources by 2010, and the White Paper sets an additional aspirational target of 20% by 2020. The equivalent targets for Scotland alone are 18% by 2010 and 40% by 2020. These targets represent a significant challenge given that, in the UK, only 3.6% of electricity was generated from renewable energy in 2004 (table 1.1).

In the longer term the contribution from renewables could be even higher. Analyses carried out to support the White Paper [2, 3] suggested that about a third of electricity might be supplied by renewables by 2040, although this could be substantially higher if some of the other options for low-carbon energy supply were not adopted. For example, renewables might be required to supply up to two-thirds of electricity demand if no new nuclear plants were built and carbon capture and storage for fossil-fuel-fired plant were not implemented.

The modelling work suggested that wind – in particular, offshore wind – and biomass would account for a significant proportion of renewable energy generation. However, technologies with a higher cost but sizable potential resource (e.g. solar photovoltaics and wave) could also contribute significantly if there were other constraints on the energy system (e.g. if no new nuclear plant were built). The forecast electricity generation from each of the renewable-energy technologies in the modelling work is shown in figure 1.1, together with the additional generation that might be expected if other low-carbon options were not available.

Table 1.1: UK electricity generation from renewable energy in 2004

Source	GWh	%
hydro	4930	35
biomass	7302	52
landfill gas	*4004*	*28*
sewage sludge digestion	*379*	*3*
municipal solid waste combustion	*971*	*7*
cofiring of biomass with fossil fuels	*1022*	*7*
other biofuels	*927*	*7*
onshore wind	1736	12
offshore wind	199	1
solar photovoltaics	4	0.03
total	**14 171**	**100**

Source: Digest of United Kingdom Energy Statistics, 2005.

Looking outside the UK the same pattern emerges. The EU has a target to increase the proportion of electricity supplied from renewable energy from 14% in 1997 to 21% by 2010, [4] and the increased use of renewable energy is a key element of many EU member states' strategies to reduce CO_2 emissions. Figure 1.2 shows that, worldwide, the practical resource for renewable energy is huge, and that, even taking into account constraints on availability of sites, practical renewable-energy resources are significantly greater than world energy demand.

Globally, renewable energy currently supplies about 8% of world primary energy, predominantly through large-scale hydroelectric plants,[1] but in the future its contribution could rise enormously. Energy demand is likely to rise sharply as less-developed countries become more industrialised and prosperous, and energy use per capita rises to levels approaching those of the developed world. Meeting these energy needs while limiting CO_2 emissions is likely to require a substantial contribution from renewables.

In general, scenarios examining the potential of renewables estimate that they might contribute 20–50% of global energy supplies in the second half of the 21st century. [6] In some low-carbon future scenarios, this is even higher. For example, in some scenarios considered by the Intergovernmental Panel on Climate Change (IPCC), where global CO_2 emissions fall to below 2000 levels by the end of the century (allowing stabilisation of CO_2 emissions in the atmosphere[2] to be achieved), renewables accounted for up to 80% of world energy supply by 2100. [7] Once again, wind, biomass and photovoltaics are likely to make significant contributions to electricity supply, with hydropower, wave and tidal also being important (figure 1.3). Renewable energy technologies can also make significant contributions to other types of energy demand: biomass can also be used to supply heat, and to produce liquid transport fuels

1. This rises to about 14% if traditional uses of biomass (e.g. wood collecting for cooking and heating in developing countries) is included. [6]

2. At about 500 ppm by the last decades of the century.

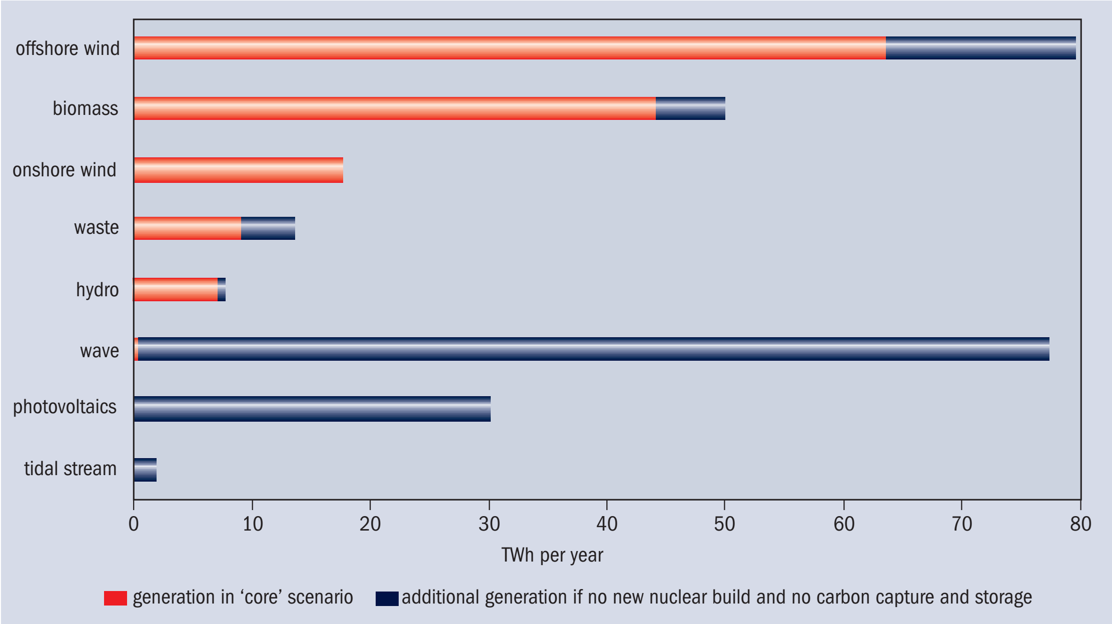
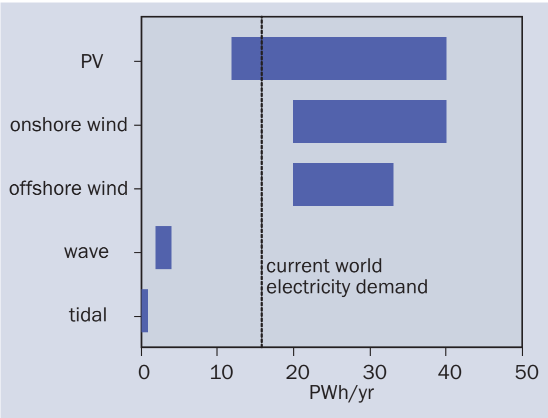


Figure 1.1: Potential UK electricity generation from renewable energy in 2040. Source: Derived from modelling work [3] carried out in support of the energy White Paper, and assuming that a 60% cut in CO_2 emissions is achieved. Electricity demand was forecast to be about 400 TWh per year in 2040.



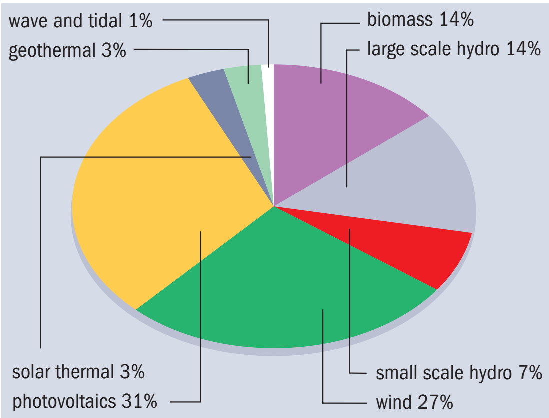


Figure 1.2 (left): Estimated global practical resource potential of some renewable-energy technologies. Source: Derived from [5].

Figure 1.3 (right): Potential contribution of renewable energy to global electricity supply in 2040. Source: Based on [8].

(e.g. biodiesel and bioethanol).

As well as being low-carbon energy sources, renewables have a number of other advantages. They can enhance diversity in energy-supply markets, secure long-term sustainable energy supplies, reduce dependency on imported energy supplies and reduce emissions of local air pollutants. Their standalone nature also makes them particularly suited for use in remote locations, which are not connected to energy networks.

1.2: Can renewable energy meet the challenge?

Realising the large potential benefits that renewables and other advanced technologies, such as fuel cells, could make to a low-carbon economy requires a number of technical, economic, institutional and social constraints to be overcome (box 1.1). Overcoming the technical and economic barriers requires substantial research, development and demonstration (RD&D) to improve performance and reliability, bring down costs and overcome issues of grid integration. This needs to go hand in hand with policy support to remove institutional and social barriers.

The remainder of this report provides an overview of ongoing RD&D to tackle these barriers in renewable-energy technologies used for electricity generation, and other emerging energy technologies such as fuel cells and hydrogen. In particular, it highlights areas where physics is making a contribution to this RD&D. The report focuses on electricity generation technologies, and the developments necessary to move to a hydrogen economy as these were found to be the technologies where physics was making the greatest contribution. The emphasis of the report is also on technologies likely to be deployed in the UK, or where there may be significant export opportunities for the UK. The current trend of rapidly rising energy demand in industrialising countries such as India and China is likely to continue, and the provision of renewable-energy technologies to help to meet increased demand, could provide a significant export opportunity for the UK.

Box 1.1: Barriers to the deployment of renewable energy

Maturity

The maturity of renewable-energy technologies varies considerably. While a number are commercially proven, others are still at a precommercial stage and some still require quite fundamental R&D (figure A).

Cost

In the UK, at current gas prices and under current market structures, mature technologies are not yet competitive with existing gas-fired combined cycle gas turbine (CCGT) plant without subsidy[3] [4,9] although in the medium term (2020) some technologies (e.g. on and offshore wind) could be (figure B). Technologies such as solar photovoltaics (PVs) are unlikely to be cost-competitive with centralised generation unless a step change in cost-effectiveness is achieved by the new types of PV cells currently under development. They may, however, become competitive in remote off-grid locations, where the cost of other standalone systems, such as diesel generators, is high. It is also worth noting that as governments seek to reduce CO_2 emissions, they will acquire an economic "cost". For example, the EU Emissions Trading Scheme, which is now operational, will determine a monetary value per tonne of CO_2 for the trade of CO_2 emissions. If this additional cost of emitting CO_2 from fossil-fuel-based power sources is taken into account in the future, then the competitiveness of renewables will improve.

Intermittency

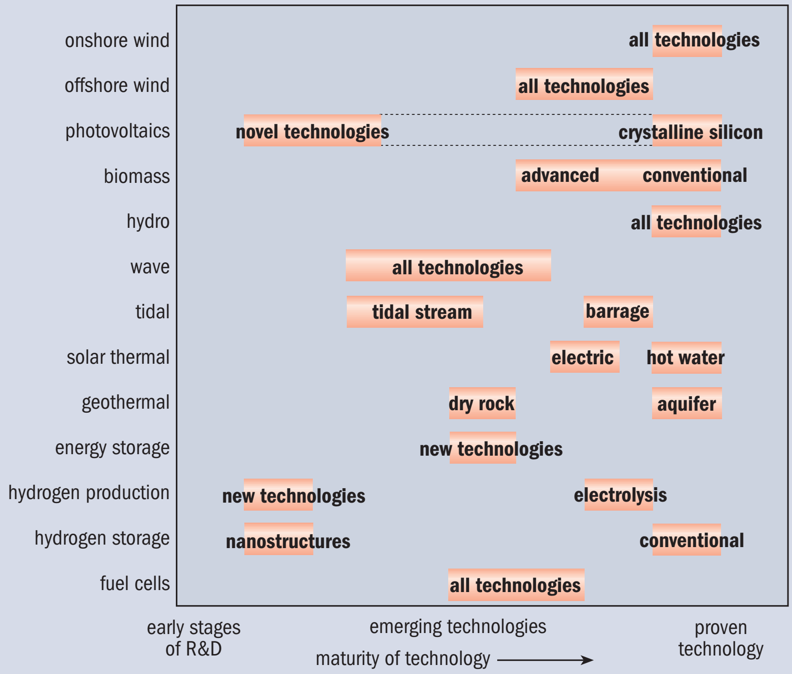
Many of the technologies, such as wind power, are intermittent and thus require energy storage or back-up-generating capacity to be available on the electricity network.

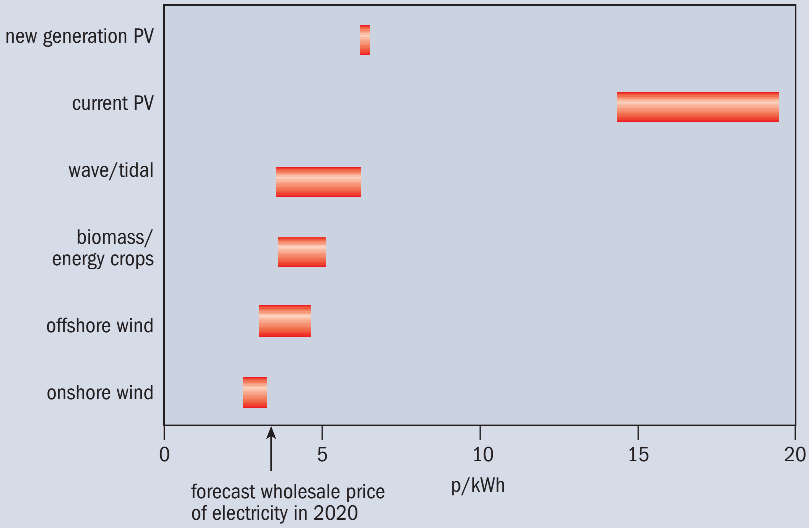
Distributed nature

Renewable energy plant are currently generally small in scale – from a few kilowatts for individual PV installations to tens of megawatts for biomass plant – compared with conventional power stations (a gigawatt or so). The small scale has advantages for use in some situations (e.g. for standalone applications) but, in a country like the UK where the transmission grid is designed for distribution of power from a small number of large power stations, the incorporation of small, distributed sources raises some technical issues. Renewable-energy resources may also occur in locations that are remote from regions with large energy consumptions (e.g. remote parts of Scotland), and where grid infrastructure to transport the power does not exist.

Social and institutional constraints

Issues that may hamper development include public acceptability, planning constraints and institutional barriers (e.g. lack of clarity over planning consents, permitting of plants, skills issues and investment regimes). While renewable-energy technologies are environmentally benign in that emissions of CO_2 and other air pollutants associated with them are typically very low (even after allowing for their manufacture), they do have a number of other local environmental impacts. For example, wind turbines may be visually intrusive, particularly if they are located in areas that are highly prized for their beauty or isolation. This can cause considerable local opposition, and care is needed to ensure that technologies are located sensitively, and that techniques to mitigate impacts are used where possible. Public education so that the environmental benefits of the scheme at the more global level are appreciated may help. It is also important to ensure that an adequate understanding of these new technologies and appropriate guidance on evaluating plant is developed with the planning process and other regulatory processes.





Note: The cost of new generation photovolatic cells is very uncertain.

Figure A (top): Status of renewable-energy technologies. Source: Future Energy Solutions.

Figure B (bottom): Forecast costs of renewable-energy technologies. Source: Derived from [10].

3. The cost estimates considered in [9] have been the subject of some debate, with some suggesting that not all technologies considered are assessed on an equal basis.

2: The role of physics in renewable-energy RD&D

The following sections provide a review of areas of RD&D in the main renewable-energy technologies, other advanced energy technologies (fuel cells), the development of hydrogen infrastructure and also supporting technologies, such as energy storage, which are necessary to allow grid integration of renewables. Within the renewable-energy technologies the focus is on technologies for electricity generation, because these were found to be the technologies where physicists were making the greatest contribution, although fuel cells can also be used in the transport sector. Solar and biomass can also provide heat, and hydrogen and liquid biofuel produced from biomass are both potential energy sources for the transport sector. The sections are based on a review of existing literature, as well as consultation with government, academic and industry stakeholders.

In general, RD&D in the more mature, proven technologies, such as wind and biomass, is aimed at incremental improvements in performance and reliability though improvements to components (e.g. rotors) or control (e.g. of the combustion process) and cost reduction. For emerging technologies, such as marine, the emphasis is on demonstration, testing of prototypes and scaling up of technologies. For some technologies, more fundamental research is being carried out. For example, in PVs, new types of cell are being developed that may lead to step changes in performance and cost.

The main research areas for each of the technologies were identified through a literature review and discussions with technology experts in both academia and industry, and these are summarised in table 2.1, with a qualitative assessment of the potential contribution that physicists could make to that RD&D area.[4] Several technology experts reviewed a draft of the table, which was modified to reflect their comments. It is intended to provide an overview only.

The research underpinning table 2.1 showed that a wide range of disciplines and skills are involved in RD&D in renewable-energy technologies, including mechanical and electrical engineering, materials science, physics, chemistry and, in some cases, the biological sciences. In many cases an interdisciplinary or multidisciplinary team will be required to tackle the multifaceted problems posed. Physics and physicists can make a significant contribution in a number of areas. The most obvious is in PVs, where physicists are carrying out much of the fundamental research required to develop novel types of cells. There are, however, several others:

- development of marine technologies require the modelling of flows and thus the use of computational fluid dynamics;
- physics underpins the new technology of nanoscience, and nanostructures are one option for hydrogen storage;
- development of high-temperature superconducting materials could allow changes to the electricity transmission system that would allow better integration of large renewable energy resources located remotely from the grid.

In addition to the direct applications of physics and physics principles, physicists have a number of transferable skills, such as simplification by approximation, systems analysis, mathematical modelling and problem solving, which allow them to make useful contributions in teams tackling engineering problems, or in areas requiring detailed mathematical understanding or statistical analysis.

It is worth noting that in the two technology areas where physicists could make substantial contributions – PVs and marine technologies – the UK is in a strong position with respect to RD&D and has the opportunity to lead in these areas.

The remainder of this section summarises RD&D areas. Developing technologies are covered in section 3, and more mature technologies in section 3.7. The boxes highlight specific examples of the application of physics and provide more technical details of a particular research effort.

4. At its most fundamental, physics can be defined as "the science of the properties, other than chemical, of matter and energy" [11], and ideas and techniques from physics drive developments in many disciplines, including computing, engineering, materials, science, mathematics, medicine and the life sciences, meteorology and statistics. [12] Physicists can apply problem-solving techniques and skills such as mathematical modelling to a variety of situations. For the purposes of this report, it was agreed with the Institute of Physics to define the contribution that physics could make to RD&D areas using the working definition of "any area where physicists could work and provide physics expertise".

Table 2.1: Potential contribution of physicists to the main areas of renewable-energy RD&D

Technology	Little potential contribution	⟶		Very significant potential contribution
Photovoltaics			● molecular organic solar cells	● thin-film solar cells ● dye-sensitised photochemical solar cells ● conducting polymer cells ● quantum solar cells
Marine	● design for low-cost construction ● design for survivability and low maintenance costs ● deployment and recovery methods ● seaworthiness and survival	● flexible cables and connections ● material selection and coatings ● grid connections	● instrumentation for performance assessment and control ● instrumentation for resource assessment ● dynamic systems modelling/control ● fluid dynamics and turbomachinery ● current flow description, modelling and device optimisation ● tidal flow modelling with details such as turbulence levels ● rotor design for vortices and cavitation ● power take-off systems/ smoothing	● wave-field characterisation and hydrodynamics ● met-ocean forecasting/hindcasting
Fuel cells	● microbial fuel cells	● fuel-cell and component manufacture ● fuel-cell design and optimisation ● integration of fuel-cell stacks ● catalyst development ● membrane materials	● material and component development ● electrode development	
Hydrogen infrastructure		● advanced electrolysis ● reforming of carbonaceous gases ● storage systems (liquid, solid, metal hydride, glass microspheres) ● pipeline transport ● delivery/refuelling systems	● photolytic production ● thermal decomposition of water	● carbon nanostructures for storage
Electricity transmission and distribution	● modelling and simulation tools	● network management and control ● power conditioning ● network and generator protection	● current fault limiting	
Energy storage technologies		● physical storage (pumped storage, compressed air, flywheels)	● electrical storage (redox flow , cells batteries, super capacitors)	● electrical storage (superconducting magnetic storage)
Wind	● windfarm development and management ● integration of wind power	● wind turbines ● blades and rotors ● wind resources forecasting and mapping		
Biomass	● primary fuel sourcing ● primary fuel processing		● combustion, gasification and pyrolysis processes	
Hydroelectricity	● improved turbine control ● integrated forecasting and reservoir management	● microscale and low head systems ● advanced turbine systems		
Geothermal energy	● field verification of small-scale geothermal power plants	● reservoir modelling and microseismology ● heat exchanger linings ● air-cooled condensers ● alternative non-condensable gas removal methods	● condensation of mixed working fluids	

3: RD&D in renewable-energy technologies

3.1: Photovoltaics

Also known as solar cells, photovoltaic (PV) cells work by transforming the photon energy in solar radiation (light from the Sun) directly into electrical energy without an intermediate mechanical or thermal process. PV generation has expanded steadily over the last few years, recording an average of around 30% annual growth globally, [8] but it still only makes a very small contribution to energy supply owing to its high cost. It is generally agreed that, unless the market is backed by aggressive R&D, this growth may not continue and PV will not achieve the potentially substantial contribution that it could make to energy supplies. The main focus

Box 3.1: Novel semiconductor solar cell structures

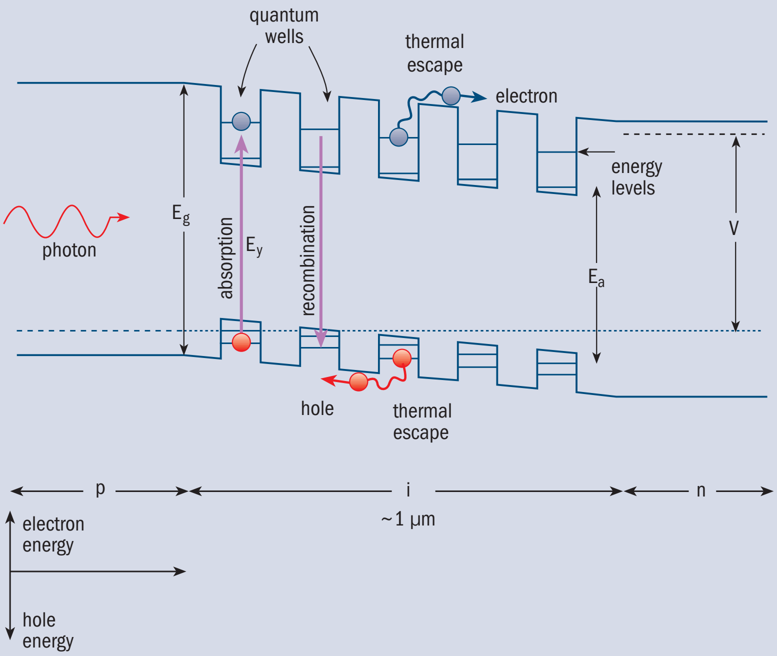


Figure A (top): Schematic of a quantum-well solar cell.

Our group has pioneered the use of nanostructures in novel strain-balanced third-generation quantum-well solar cells (SB-QWSC). Such cells are expected to generate electricity at twice the efficiency and half the cost of second-generation thin-film cells and are already deployed on satellites. Before the technology can enter the terrestrial solar-cell market, costs must be reduced with relatively cheap, light-concentrating systems. Our SB-QWSCs offer significant advantages in high-concentration systems.

The quantum wells, which are nanometre-wide regions of a low-bandgap semiconductor (figure A), absorb low-energy photons of light that would otherwise pass through the host cell, and thus extend the absorption band-edge of high-efficiency GaAs cells to longer wavelengths to generate significant current enhancement while preserving good voltage performance. We have shown that the resulting carriers escape from the well with high efficiency. This leads to extra current at a voltage above that achieved by conventional cells made from the well material, as long as this material has the same lattice constant as the host cell. The world's highest-efficiency cells are monolithic, tandem cells formed of GaInP and GaAs. The performance of this tandem is limited by the current produced by the lower bandgap GaAs cell.

We have recently demonstrated that were our SB-QWSC to replace the GaAs cell, it would increase the world's highest-efficiency tandem from 34 to 36% at around 200 Suns concentration. Our current primary research aim is to optimise such tandem cells grown by MOVPE at the EPSRC III-V Facility at Sheffield in collaboration with a leading European space cell company. We intend to demonstrate the cell in a concentrator system, in collaboration with experts in UK and European universities and a UK concentrator manufacturer.

We are also developing a novel, non-tracking concentrator, which uses the luminescence and quantum-confinement properties of quantum dots. We have developed a thermodynamic model to optimise concentrator performance, which demonstrates that separation between luminescence and absorption can be optimised by changing the spread of quantum-dot sizes. We are researching the properties of quantum dots, such as their stability, high luminescence efficiency and the possibility of tailoring their absorption edge, which make them good candidates to replace the organic dyes of conventional luminescence concentrators.

We are also applying our strain-balanced cell ideas to thermophotovoltaics (TPV). In this case, low-bandgap solar cells are used to convert the radiant energy from conventional power sources directly to electricity. We are collaborating with Italian researchers to design an efficient and environmentally friendly TPV system to extend the range of Fiat's electric car. In collaboration with BP Solar we are also studying epitaxially grown films of silicon to investigate the ultimate efficiency that can be achieved by thin-film silicon cells. In addition, we have recently extended our fundamental work on the determination of the quasi-Fermi level separation in quantum-well systems to the light-biased situation. This work has important implications for questions about the ultimate efficiency enhancement possible with quantum-well cells.

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5. The percentage of the incident energy from the light that is converted into electrical energy.

of PV R&D is on cost-reduction issues, [13] because at least a three-fold reduction in cost per kWh is required to make it competitive with centralised generation. PV may become competitive more quickly in other markets (e.g. in remote off-grid locations), where the cost of other standalone systems, such as for diesel generation, is high, or in building integrated systems.

About 90% of world solar-cell production is based on silicon technology, of which over 80% uses wafer technology (so-called first-generation solar PV) [13] to produce crystalline silicon solar cells. Commercially produced cells typically have efficiencies of around 17%, well below the efficiencies of 25% or more that have been reached in the laboratory. The challenge is therefore to develop fabrication processes and devise structures for manufacture that will enable laboratory-cell performance features and efficiencies to be achieved at competitive costs. [14]

A major impediment to the rapid expansion of the PV industry is the dependence on the supply of electronic-grade silicon for crystalline solar cells. European research is therefore:

- exploring new and innovative technologies to change the way in which current materials are used;
- exploring the use of different materials;
- exploring the transfer or development of new manufacturing technologies.

The current front-runner is the development of medium-thickness polycrystalline ribbon silicon and thin-film based devices (also referred to as second-generation solar PV). Thin-film solar cells can be based on amorphous silicon (a-Si), gallium arsenide (GaAs), cadmium telluride (CdTe) and the copper indium diselenide (CIS) family of compounds. These allow the use of manufacturing technologies already demonstrated in other industries (e.g. large-scale production of architectural glass) [13] and use considerably less raw material than crystalline silicon cells. Commercial thin-film solar cells currently have a conversion efficiency of about 7%, but much higher efficiencies (up to 12%) have been achieved in pilot manufacture. [14] R&D efforts are concentrated on improving film crystallinity, thickness and growth rate.

One route to high efficiency is through the use of multi-junction cells, where several layers of PV cells are stacked on top of one another. Each successive layer has a lower bandgap energy and thus responds to different parts of the electromagnetic spectrum (of which visible light is a small part), allowing absorption of a wider range of the spectrum. Efforts are being made to increase the efficiency of a multi-junction cell from the current record of 34% up to 40%. Such cells are expensive and thus not suitable for large areas. The possibility of using them in a solar concentrating system, where sunlight is focused onto a small area of cells, could, however, be cost-effective and is currently being researched.

In addition, a number of novel emerging (third-generation) PV material systems could provide step-change decreases in production costs. These include:

- *Dye-sensitised photochemical solar cells:* In these cells, inexpensive nanocrystalline titanium dioxide is used, giving a large effective area of titanium dioxide. The cells and organic dyes are immersed in an electrolyte, and electrons from the dye molecules are excited onto the substrate. It is anticipated that simple production technology will be possible, giving low manufacturing costs. Efficiencies of up to 11% have been achieved in the laboratory and 8% in real devices. [13]
- *Conducting polymer cells:* Based on the conductive property of some organic materials (conjugated polymers), promising structures include those containing fullerene (C_{60}) as the acceptor material. This is expected to lead to low-cost manufacturing and the possibility of solar-cell production via modification of the properties of organic molecules. The challenge is to improve the stability of cells in outdoor conditions and to increase cell efficiencies (currently 2–5%).
- *Molecular organic solar cells:* These are based on the utilisation of organic molecules and, like polymer cells, they are expected to benefit from low-cost manufacturing. Challenges include increasing the low cell efficien-

Box 3.2: Key RD&D areas in photovoltaics

Fundamental research:
- basic research (i.e. electronic materials and devices, processing science, etc);
- high-performance advanced research (e.g. tandem or multi-junction solar cells);
- measurement and characterisation.

Advanced materials and devices:
- materials (i.e. crystalline silicon, thin films);
- advanced PV concepts (e.g. organic, dye-sensitised, quantum/third-generation cells);
- building and other integration concepts.

Systems technology development:
- systems modelling and analysis (i.e. understanding of PV market potential);
- systems engineering (e.g. benchmarking and validation, system performance and standards);
- concentrator PV systems (i.e. optical elements, tracking structure, electronics and software).

Performance and reliability testing:
- type testing and development of standards.

Manufacturing and deployment:
- techniques to upscale throughput and device size while maintaining performance and cost targets.

Box 3.3: Dye-sensitised solar cells and self-assembled nanostructures

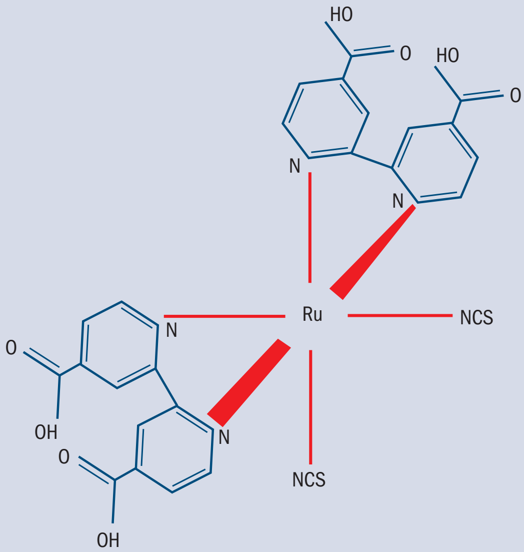

Figure A: Schematic of the N3 dye molecule (cis-bis(4,4-dicarbosy-2,2-bipyrifine)-bis9isothiocyanoto)-ruthenium(II).

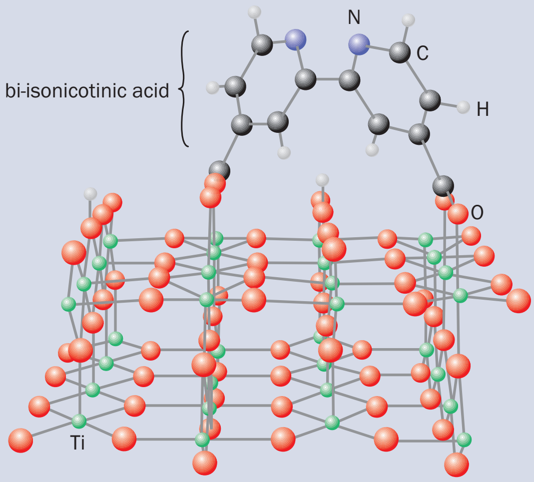

Figure B: Structure of the adsorbed "anchor" molecule bi-isonicotinic acid (4.4-dicarboxy-2,2-bipyridine) on a rutile of TiO_2(110) surface.

Our laboratory is part of the closely collaborative Nanoscience Group within the School of Physics & Astronomy, which focuses on the interaction of molecules with surfaces for a wide range of nanoscale applications. Our specific research interests are directed towards understanding the fundamental science of dye-sensitised solar cells and self-assembled nanostructures using a range of electron spectroscopy and scanning probe microscopy techniques.

At the most fundamental level, one of the key processes in dye-sensitised PV devices is the transfer of electrons from the molecule to the substrate (after first being excited by the Sun's light). The dynamics of this charge-transfer depend strongly on the coupling of the molecule to the surface in terms of both the geometry of adsorption and the overlap of the molecular electronic orbitals and the substrate density of states. The challenge is to correlate the efficiency of working PV systems to processes on the molecular level through a combination of electron spectroscopy and surface probe techniques. Owing to the nature of the molecules most relevant to these studies we are also developing novel ways to deposit dye molecules relevant to solar cells onto substrates in an ultra-high vacuum (UHV) environment. Tracking the movement and energetics of electrons in solar-cell systems is carried out using electron spectroscopy methods both at large-scale European synchrotron facilities and in our own laboratories.

We have recently been involved in a range of research relating to the fundamental science of organic and dye-sensitised PVs. In particular the application of synchrotron techniques, such as photoemission, X-ray absorption and resonant photoemission reported in *Nature*, [16] *Surface Science* [17, 18, 19] and *Journal of Physical Chemistry*, [20] has led to ground-breaking insights into the workings of the Grätzel solar cell. [21] The experimental method used to gauge how well a dye molecule might couple to the substrate essentially involves using synchrotron light to excite an electron in the "anchor" ligand of a dye molecule (figure A) and measuring the timescale of electron injection from the molecular orbitals into a TiO_2 substrate conduction band (figure B).

We have no doubt that solar cells based on organic and inorganic molecules will play an important role in renewable energy generation over the next 50 years. They offer a cost-effective alternative to other sources of power, and efficiencies are increasing all the time as we gain a deeper understanding of exactly how these systems work. Our laboratory will continue working to improve our understanding of dye-sensitised solar cells, and how best to get the Sun's energy to excite the electrons on the dye molecules to a point where they are injected into the oxide support to produce a usable form of energy. With novel UHV preparation techniques there should also be no limitations placed on the molecules that we can investigate using electron spectroscopy, whichever direction the field takes over the next few decades.

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cies, which are currently 2–3%.

- *Quantum/nanotechnology solar cells:* These include the application of quantum wells and quantum dots to PV, using quantum confinement to modify the electronic structure in order to decouple current voltage and the increased efficiency of the cells. These high-efficiency solar cells have good potential for solar PV concentrators, particularly in building integrated applications. Finding low-cost systems that can use the same principle as those currently being researched is a challenge. More information on one group's work in this area is provided in box 3.1.

Thermophotovoltaics (TPV) are a subset of PV technology where electricity is generated in low bandgap solar cells by utilising the waste radiant heat (infrared radiation) emit-

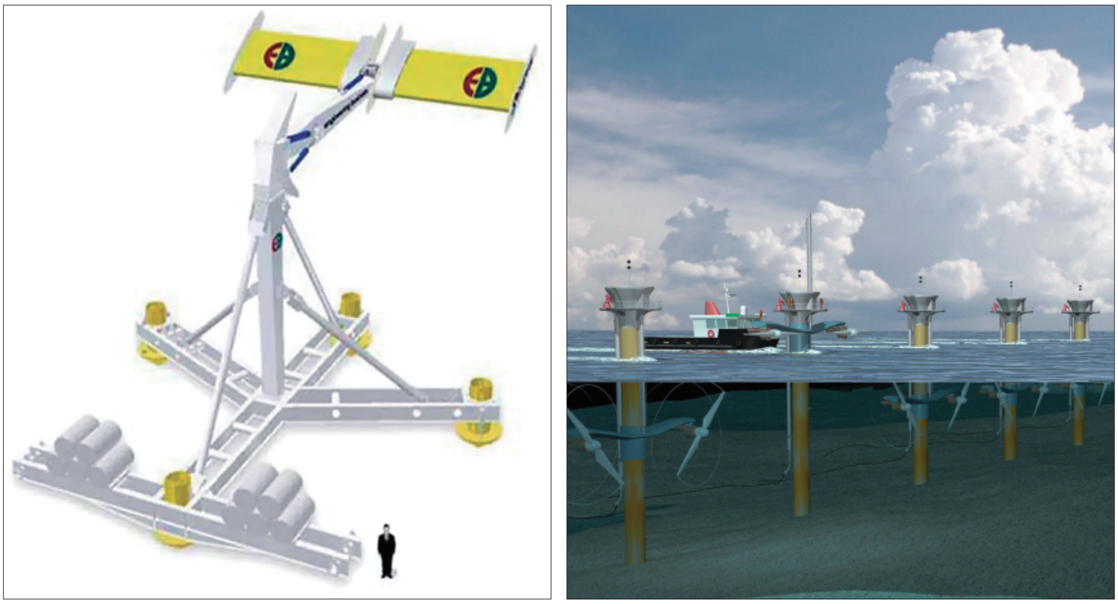


Figure 3.1: Stingray (left) and Seaflow (right) tidal stream technology prototypes. Source: Images supplied courtesy of the Engineering Business (Stingray), http://www.engb.com/home.html, and Marine Current Turbines (Seaflow), http://www.marineturbines.com/home.htm.

ted by conventional sources of heat (e.g. car engines, power stations). By using infrared radiation from a radiant source, rather than sunlight, the overall power output of the heat source devices can be improved. [15] Quantum solar cells are thought to be particularly promising in this area.

The key areas of solar PV RD&D are summarised in box 3.2. Physicists have played a significant part in fundamental research into the basic principles of solar cells and they continue to play a large role in research into advanced materials and devices (particularly bandgap engineering and surface properties of materials). The UK technology base for current-generation solar PV is small in the global context, but the country's competitive position in advanced solar PV is stronger (see boxes 3.1 & 3.3). Fundamental research is seen as essential for attaining the step-change improvements in solar cell efficiency and manufacturing cost reduction needed for solar PV to compete effectively on a cost basis with existing fossil-fuel-based energy technologies.

3.2: Marine energy

Tides, ocean currents, waves, heat storage and salinity gradients all provide potential sources of renewable energy from the marine environment.

3.2.1: Tidal and ocean current power

Ocean currents represent a huge energy resource. There is an estimated 3000 GW of available tidal energy worldwide, but less than 3% of this is located in an area suitable for power generation. [22] There are two main approaches to collecting energy from tidal flows:

- *Building barrages across high tidal range estuaries:* Barrages across estuaries with closable sluices trap water at high tide and release it through turbines at low tide.
- *Harnessing offshore tidal streams:* Tidal streams can be harnessed using offshore underwater devices similar to wind turbines.

Tidal-barrage technology is well established. Constraints to development are high capital costs and the identification of suitable sites, many of which are far from energy users and/or have a high ecological value. Interest has therefore turned to the potential offered by coastal currents using tidal fences and tidal turbines. Tidal-stream technologies are in their infancy, with only two prototype machines currently operational (both in the UK): the Engineering Business's 150 kW rated Stingray and Marine Current Turbine's 300 kW Seaflow (figure 3.1). With some of the largest tidal ranges in the world, the UK is one of the top commercial markets for such systems, together with Norway and the USA. [22]

Tidal-stream devices have been proposed in a variety of forms, including both horizontal- (e.g. Seaflow) and vertical-axis turbines (similar to wind turbines), reciprocating-hydroplane machines (e.g. Stingray) and systems exploiting the Venturi effect. A problem common to all of these designs is the characterisation of tidal current flows. Another problem is the robustness of designs, as some fail or break up in certain weather conditions. Further work on fluid dynamics will be necessary to optimise the designs of tidal-stream generators and to define the range of applicability of these systems.

Admiralty charts provide basic tidal data, but their detail and accuracy is usually limited to the needs of navigators. An excellent example of applied physics in practice is the acoustic doppler current profiler (ADCP), which can be used to assess new tidal-stream generation sites. This technology permits accurate determination of the flow effects and also provides data of sufficient accuracy for use in project financial models. The ability to provide commercial justification for a project is particularly important while tidal-stream generation systems make the transition between

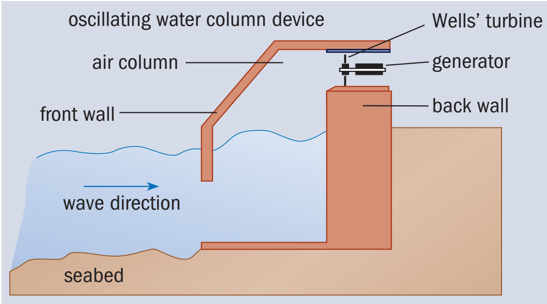


Figure 3.2: Schematic of an oscillating water column device. Source: EC ATLAS Project website: http://europa.eu.int/comm/energy_transport/atlas/htmlu/wavint2.html.

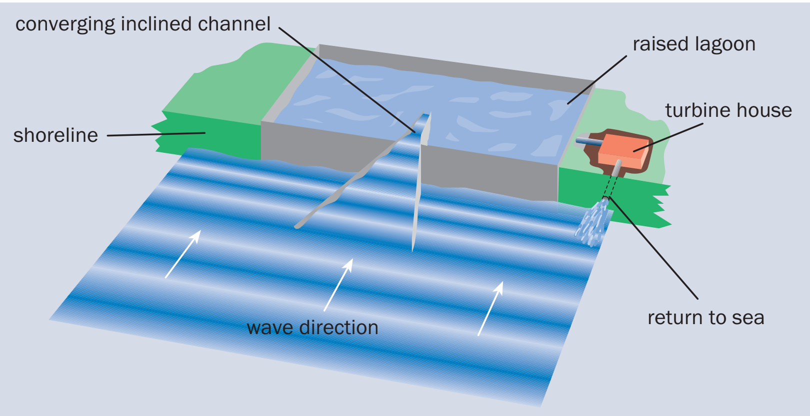


Figure 3.3: Schematic of a tapered channel (tapchan) device. Source: EC ATLAS Project website: http://europa.eu.int/comm/energy_transport/atlas/htmlu/wavint2.html.

R&D and the generation of bulk power. Tidal-stream device developers in the UK are currently investigating ADCPs.

3.2.2: Wave-energy conversion systems

The total power of waves arriving at the world's coastlines is estimated at 2000–3000 GW. In favourable locations the average wave-energy density can reach 65 MW per mile of coastline. A variety of devices have been, or are being, developed, though they generally fit into one of three broad categories:

- *Floats or pitching devices:* These generate electricity from the bobbing (heave) or pitching action of a floating object. This can be mounted to a floating raft or to a device fixed on the ocean floor. Examples of development in the UK include the PS Frog developed by Lancaster University (box 3.4), the Duck wave energy device at the University of Edinburgh (box 3.5) and Ocean Power Delivery's (ODP) Pelamis.
- *Oscillating water columns:* These generate electricity from the wave-driven rise and fall of water in a cylindrical shaft (figure 3.2). The rising and falling water column drives air into and out of the top of the shaft, powering an air-driven Wells turbine (e.g. Wavegen's 500 kW Limpet).
- *Wave surge or focusing devices:* These shoreline devices, also called "tapered channel" or "tapchan" systems, rely on a shore-mounted structure to channel and concentrate the waves, driving them into an elevated reservoir (figure 3.3). Water flow out of this reservoir is used to generate electricity, using standard hydropower technologies.

More than 60% of worldwide development expenditure is accounted for by the UK and Japan. [22] Much of the technology that has been deployed worldwide is of UK origin and involves UK companies. The UK is the world leader in the development of new wave technology and is, for example, currently undertaking full-scale field testing of one of the most developed of all nearshore/offshore wave devices: OPD's Pelamis floating wave energy converter. Rated at 750 kW, each Pelamis is expected to be sufficient to meet the annual electricity needs of more than 500 UK households. [23]

The shoreline-fixed wave electricity generation prototypes have been mainly of the oscillating water column type (e.g. Wavegen's Limpet). The main operational challenge is to balance optimal site location (in water sufficiently deep to minimise dissipation of energy by seabed friction) while minimising the cost of construction work and hence energy prices. There have also been a number of design challenges for this technology.

One particular difficulty has been the measurement of energy in waves incident to the oscillating water column collector. The kinetic energy of the approaching wave train ultimately becomes the potential energy of the internal water column, with some losses as large waves "overtop" the external structure. These energy characteristics are both difficult to describe in physical terms and difficult to measure. While statistical approaches are appropriate to describe wave conditions over long periods of time, real-time measurements are needed to control the turbine/generator to produce greatest maintainable power.

Computational fluid dynamics has been applied in the analysis of the behaviour of the "trapped" air column above the surface of the water, sometimes using turbine models in a rotating frame of reference. The fixed-pitch Wells turbine and the more advanced variable-pitch versions have been proposed, owing to their ability to rotate in the same sense with axial flow in either direction. However, such turbines are relatively inefficient at energy transfer and considerable effort is currently being made to optimise turbine designs.

Devices for offshore generation have the important advantage that the waves are more energetic close to land, but the obvious disadvantage is that the power needs to be conveyed over greater distances. Transmission along high-voltage subsea cables is the preferred method, although high-pressure hydraulic fluid transfer has been considered. Owing to numerous applications in the oil and gas industry, and more recently offshore windfarms, electrical connection now presents only a minor difficulty.

The major challenge here is to design a large-scale generation system with low maintenance costs that can survive the extreme conditions of open seas. Research into hydrostatics and hydrodynamics, in the context of naval architecture, is well advanced. However, traditionally the aim has been to keep vessels stable and to minimise their displacement or rotation, especially by avoiding resonant conditions in heave, surge, pitch and roll. The purpose of most

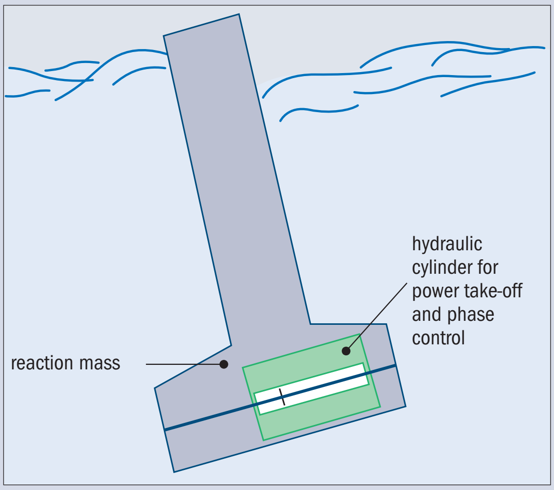
Box 3.4: PS FROG

PS Frog, a wave-energy converter invented and developed at Lancaster University and intended to work in offshore locations, offers a real prospect of economic power from sea waves for the UK and other countries. The energy density in sea waves is much higher in the oceans offshore than it is close to the shore. The shell of PS Frog is shaped like a large buoyant paddle, afloat and facing the oncoming waves, with the handle downwards and a large mass at the bottom end. The force of the waves acts on the face and causes the device to pitch to and fro. Inside the shell are movable reaction masses whose weight and inertia resist the pitching motion. This is the means of converting energy of the waves to useful work.

Conceptual design (figure A) and development involved detailed investigations into the mechanics (including linearised hydrodynamics in monochromatic waves and the effect of resonant mode shape), hydrodynamics coefficients and power capture calculations for PS Frog.

Current research on PS Frog Mk 5 (figure B) includes both experimental work on models in the engineering department's wave tank and computer-based simulation, and the results are very promising. We are planning to move up to a larger scale in the near future. PS Frog has been selected by the Carbon Trust as one of eight wave-energy converters for more detailed work on costs under the Marine Energy Challenge Programme.

George Aggidis, Engineering Department, Faculty of Applied Sciences, Lancaster University.



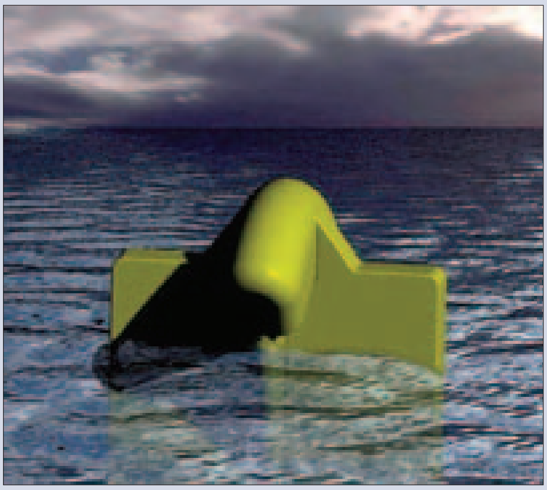


Figure A (left): PS Frog device concept.

Figure B (right): Visual representation of the current PS Frog.

offshore wave devices is, in contrast, to encourage the large forces and displacement, and to operate close to resonance with the most energetic waves in order to maximise output. It is in these conceptual stages that the tasks of wave diffraction modelling and time/frequency domain simulation undertaken by applied physicists are most valuable.

There are other areas where applied physics can make an important contribution to renewable wave-energy research. These include:

- *Dynamic systems modelling/control:* Certain wave device designs can be modelled as mass, spring, damper systems, the optimisation of which can follow similar approaches to those used in electrical engineering design, by analogy with circuits including resistance, inductance and capacitance. However, there are many constraints to this approach and there is a need for more detailed and complex modelling to aid understanding and improve system design.
- *Meteorological ocean forecasting/hindcasting:* Some control strategies for offshore wave devices require incident wave conditions to be known or estimated before they occur to allow an optimum damping level to be set.

3.2.3: Ocean thermal-energy conversion systems

A large quantity of thermal energy is stored in the world's oceans. Each day the oceans absorb enough heat from the Sun to equal the thermal energy contained in 250 billion barrels of oil. Ocean thermal-energy conversion (OTEC) systems convert this thermal energy into electricity, often while producing desalinated water. Sites could be located inshore, nearshore or offshore. The greatest potential for application lies in equatorial and tropical locations. The majority of research has been carried out in the US, India and Japan [24] with very little related research carried out in the UK. Funding is currently more focused in academia rather than commercial areas and OTEC device generation costs are currently very high, and a long way from commercial application.

3.2.4: Salinity gradient

About 1 MW of electricity can be generated from 1 m^3/s of fresh water meeting seawater (or high-salinity water in lakes). Fresh water passes through a membrane and dilutes salt water on the other side because it is drawn by an osmotic gradient, generating a hydraulic pressure that can be exploited in conventional turbines. There was some R&D in this area in the 1970s and 1980s, but this petered out

Box 3.5: Tank testing of a free-floating sloped IPS buoy

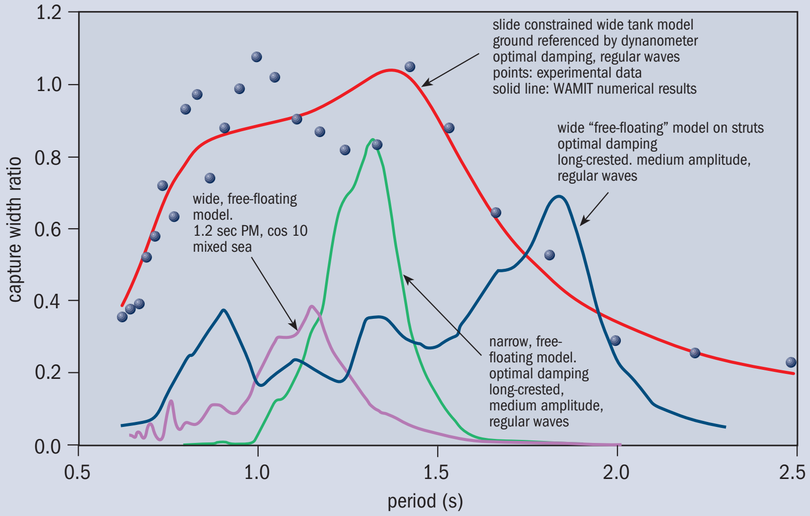


Figure A (above): Summary of measured power capture for representative configurations of the free-floating model and the original constrained model.

Figure B (left): Free-floating model.

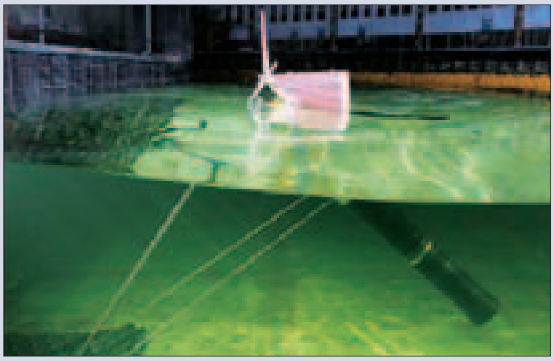


Figure C (left): Strut-mounted module.

Background/context

The deep-water "terminating" Duck wave energy device, with its three intelligently controlled degrees of freedom and maximum usage of the wave resource, remains the preferred concept of the University of Edinburgh wave energy group. However, it became clear that it would be helpful to gain interim experience from the development and operation of a "solo" device. Three such devices have so far been proposed and investigated: the Solo Duck, the Swinging Mace and the Sloped IPS Buoy.

Considerations from analysis of the Solo Duck and the Swinging Mace suggested a new kind of device in which the float would be constrained by some means to move at an angle intermediate between surge and heave so that its hydrostatic stiffness, and hence natural period, could be "tuned" to longer waves. The current project has sought to investigate experimentally the performance of models of a free-floating device constrained to move at an angle by a self-contained "slope-plate", which has high added mass in the direction perpendicular to the slope. The experiments will also provide the opportunity to develop numerical models by using WAMIT – a well established hydrodynamics analysis package. The new device incorporates the piston-damped water-filled inertia tube of the Swedish IPS device as the power-take-off mechanism, so it is referred to as the Sloped IPS Buoy.

Performance of the free-floating model compared with the slide-constrained model

Figure A summarises measured power capture for representative configurations of the free-floating model (figure B) with a water-referenced dynamometer, along with data from an earlier slide-constrained model with a ground referenced dynamometer. The capture width ratio of the vertical axis is computed by dividing the power absorbed in the dynamometer by the power measured in an incident wave of the same width as the float. To allow fair comparison, the horizontal (period) scale of the data for the slide-constrained model have been transformed to those of the new model, in the ratio of the cube root of their respective displacements.

The power capture characteristics of the free-floating model (figure B) are modest in comparison to those of the slide-constrained model. This difference illustrates the familiar challenge to wave-energy engineers of going from an artificially constrained laboratory concept to a fully realistic design capable of full-scale implementation in the ocean. To understand the power capture issue further, additional tests were made with an intermediate "strutted" configuration (figure C). This gives a wider bandwidth and higher power capture but, most important, it improves performance in the higher-energy longer-wave periods.

The high-power capture and wide bandwidth of the slide-constrained Sloped IPS Buoy model are impressive and there is some way to go before these can be matched by its free-floating model counterpart. Further work will concentrate on understanding and improving the motion constraint provided by the slope plate and of the power-take-off reaction provided by the water-referenced piston. A major part of the next phase of the work will use a linear numerical model of the device, which is now running within the WAMIT hydrodynamic analysis package. A separate project is under way to build a six degree-of-freedom variable dynamics constraint rig for the multidirectional wave tank. On its completion it will provide a unique and important experimental tool for improving the performance of both the free-floating sloped IPS buoy and other wave-energy devices.

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owing to the high costs predicted for some systems. Recently there has been a small resurgence of interest and Norwegian hydroelectric company Statkraft has opened a laboratory dedicated to salt power.

3.3: Fuel cells

Fuel cells are electrochemical devices, similar in principle to primary batteries, that convert the energy of a chemical reaction directly into electricity, with heat and water as by-products (figure 3.4). They are different from batteries in that the fuel and oxidant (oxygen or air) are stored externally, enabling them to continue operating for as long as fuel and oxidant are supplied. In the short to medium term (2015–2030) fuel cells are likely to use fossil fuels such as natural gas, coal, gasoline and methanol, but in the long term they may use hydrogen and biofuels. These fuels would produce no CO_2 emissions at the point of use and, although there would be CO_2 emissions associated with hydrogen production from fossil fuels, these could be sequestered, or hydrogen could be produced using "carbon-free energy sources" (i.e. renewables or nuclear power).

Fuel cells offer higher efficiencies than conventional thermal combustion technologies, operate quietly and cleanly (giving localised air-quality benefits compared with conventional combustion engines) and have a modular construction that is easily scalable. These features mean that fuel cells are attractive for a range of potential applications, including combined heat and power (CHP), distributed power generation and transport. Fuel cells are also attracting interest for providing portable power for laptop computers, mobile telephones, etc.

The main types of fuel cell being developed in Europe are summarised in box 3.6. The different fuel-cell technologies all face similar development challenges.

Fuel-cell performance depends fundamentally on the electrochemical reactions that occur within the core fuel-cell stack. Fuel-cell systems are complex and currently costly, because of the expensive materials required for catalysts, electrodes and membranes, and because of the numerous peripheral devices required.

Key areas of R&D are:

- solid-state properties (including electrical properties) of materials;
- new materials for membranes, catalysts and other components (e.g. specialised substrates, ceramics);
- physical forces, mechanical forces, micromechanical properties and particle technology;
- modelling of mass and heat transfer;
- scale-up of fuel-cell stacks and systems.

3.4: Hydrogen infrastructure

Hydrogen is not a primary fuel but it can be used as an energy carrier, with the advantage that it has no emissions of CO_2 or other pollutants at the point of use. Whether there are CO_2 emissions at the point of production depends on the method used (box 3.7). Hydrogen is widely considered to be an essential part of a low-carbon future because of its potential role (in conjunction with fuel cells) in the transport sector. The UK has a very strong fundamental research base that is active in the fields of materials science, catalysis and bioengineering.

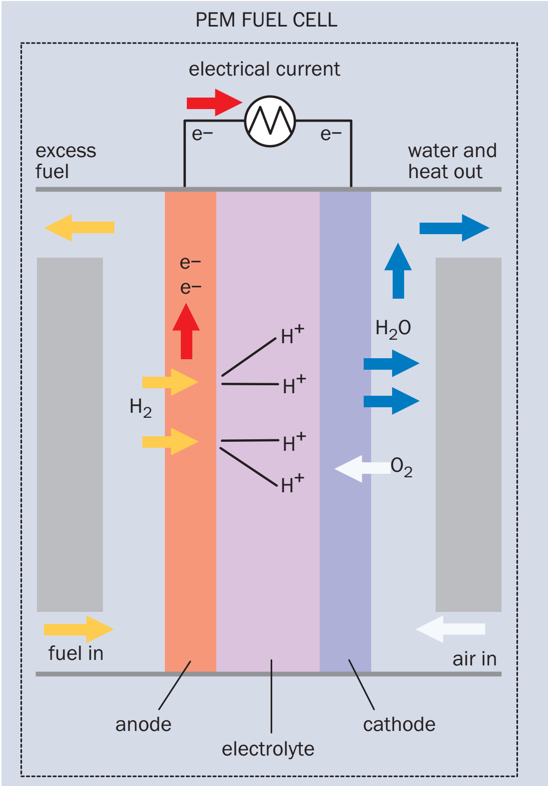

Figure 3.4: Schematic of a proton exchange membrane fuel cell. Source: US Department of Energy Efficiency and Renewable Energy website: http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html.

At least 22 UK universities have been involved in researching issues associated with hydrogen and a large number of these are currently carrying out research into chemical and physical hydrogen storage. In addition, companies located in the UK, such as BP, Shell and BOC, have been active in assessing safety issues related to the storage and distribution of hydrogen.

The EU has made hydrogen a priority technology, along with fuel cells, and has recently established a technology platform on fuel cells and hydrogen that it hopes will accelerate EU RD&D activities such that they can compete effectively with North American and Japanese programmes.

3.4.1: Hydrogen storage

Established methods of hydrogen storage are compression, adsorption in metal hydrides, and liquefaction (box 3.8). [25] Disadvantages of liquefaction and compression are the energy requirement (up to 30% of the energy in the hydrogen) and significant safety concerns. R&D priorities are the development of new materials and systems to enhance the efficiency of storage and to reduce costs. A new method, still at an early stage of development, is a solid-state storage solution in which hydrogen is reversibly chemisorbed (at near-ambient pressures and temperatures) into a lightweight material with a large specific surface area like activated or nanostructured carbon and

Box 3.6: Fuel cell types

- *Polymer Electrolyte or Proton Exchange Membrane Fuel Cells (PEMFCs)* operating at 100–120 °C and fuelled by hydrogen are being developed for transport, stationary and portable power applications. Transport applications include fuel-cell engines to drive cars and buses, and auxiliary power units (APUs) powering the electronics on a vehicle.
- *Direct Methanol Fuel Cells (DMFCs)* are similar to PEMFCs, except that they operate directly on methanol without the need to reform it to hydrogen first. DMFCs are at an earlier stage of development but may offer advantages in transport and portable applications where the weight and volume of systems is important.
- *Molten Carbonate Fuel Cells (MCFCs)* operating at about 650 °C are being developed for combined heat and power (CHP) and distributed generation applications. They are typically fuelled by natural gas although there is also some research being undertaken into biogas systems.
- *Solid Oxide Fuel Cells (SOFCs)* are also being developed for CHP and distributed generation applications, where their high temperature operation (800–1000 °C) gives the opportunity of combination with gas turbines to give very high electrical efficiencies of up to 70%. A lower-temperature version of the SOFCs operating at 650–750 °C is being developed for vehicle APUs and stationary power applications. There is currently little interest in Europe in operating MCFs or SOFs on coal gas, unlike the situation in the US.

There are also a number of Phosphoric Acid Fuel Cell demonstration plants and some research activity on Alkaline Fuel Cells.

Box 3.7: Hydrogen production methods

- *Reforming of carbonaceous gases (e.g. natural gas):* This is a mature technology. CO_2 is produced during this process.
- *Electrolysis of water:* New steam electrolysis systems that reach higher total energy efficiency compared with existing alkali and proton exchange membrane electrolysis are being developed. Their main advantage is that a substantial part of the process energy is added as heat, which is much cheaper than electric energy. R&D for these systems includes thermodynamic systems modelling and materials development (including catalysts). If electricity from renewables or nuclear sources is used for electrolysis then there are no associated CO_2 emissions.
- *Biological production:* Several types of algae and bacteria can also produce hydrogen by photosynthesis or by fermentation. Particularly interesting possible applications include use in sewage treatment works. Biological methods based on these are generally, however, still at relatively early R&D stages.
- *Photoelectrolysis:* This is another prospective technology for hydrogen production, still at the early stages of R&D, and it involves the use of a solar cell to split water directly, without the use of electricity.

carbon nanotubes, or nanoporous materials such as zeolites (box 3.9). [26] The best materials currently have a hydrogen storage density of 150 $kg{\cdot}m^{-3}$), but theoretically this can be improved by 50%.

3.4.2: Hydrogen transport and distribution

At present, hydrogen is generally transported in the form of liquid hydrogen, but an alternative to high-volume transport is by pipeline. Hydrogen is expensive to transport over long distances by pipeline owing to the high pressure required – energy consumption is about 0.9% of energy in the hydrogen flow per 100 km, compared with 0.2% for natural gas. The existing natural-gas network cannot be used for hydrogen because of diffusion losses, brittleness of materials and seals, incompatibility of pump lubrication with hydrogen, and other technical issues. However, there is some discussion about the possibility of diluting gas with hydrogen (up to 10%) for use in conventional applications and using the existing network for distribution. Hydrogen stored in compressed gas cylinders, cryogenic liquid storage tanks and metal hydrides can obviously be transported by road, rail and ship.

3.5: Electricity transmission and distribution

Electricity in the UK is currently moved at high voltages (400 and 275 kV) through the transmission network from generating stations to distribution companies, and to a small number of large industrial customers. Electricity is then provided to the majority of customers through the lower-voltage (from 132 kV to 230V) and more localised distribution networks.

The key characteristic of many renewable-energy technologies is that they are small in scale (compared with conventional fossil-fuel and nuclear power stations) and are connected directly to the lower-voltage distribution networks – "embedded generation plant". [27] While the current distribution network does have some capacity for adding new embedded generation plant, locations where generation can be added often do not coincide with the optimum location for the proposed plant. In the longer term, incorporating a large number of plant will require changing to a pattern of "embedded" electricity generation and will require the reconfiguration of existing electricity networks into a "distributed electricity system" (figure 3.5).

Several avenues are being explored to help to adapt the UK transmission and distribution network to the needs of renewable-energy sources:

- *Current fault limiters:* Improvements to fault-level management in particular are needed for embedded generation. Most current fault-limiter technologies work by mechanical switching, so if they fail they can create dangerous operating conditions. Superconducting current fault limiters offer a promising solution because

Box 3.8: Established hydrogen-storage methods

- *Compressed hydrogen*: The storage of hydrogen in pressurised tanks is the most commonly used technology for large-scale storage. Limitations of compressed hydrogen storage relate to the materials' permeability to hydrogen and to their mechanical stability under pressure.
- *Liquid hydrogen*: The storage of hydrogen as a cryogenic liquid has been used for many years. It is a much more weight-efficient means of storing hydrogen than as a compressed gas in steel cylinders, though the temperature required is very low because the boiling point of liquid hydrogen is only 20 K (−253 °C) at 1 bar. Extremely efficient tank insulation is required to maintain this low temperature. Liquid hydrogen is stored in Dewars, which are insulated spherical or cylindrical containers. A disadvantage is that the liquefaction process requires about 30% of the total energy content of hydrogen. R&D is still needed on thermodynamic cycles of hydrogen liquefaction to explore the various ways to increase efficiency.
- *Metal hydrides*: These compounds, which are obtained through the direct reaction of certain metals or metal alloys to hydrogen, are capable of absorbing the hydrogen and restoring it when required. In the future, metal hydrides may be favoured for stationary applications because they guarantee a good level of safety and a high degree of modularity.

they acquire high resistance if they fail, creating safe operating conditions in their failed state.

- *Energy storage:* Electricity storage devices are needed for the integration of intermittent renewables generation into the existing network. They allow better use of efficient baseload generation by reducing requirements for spinning reserves to meet peak power demands. They also allow greater use of intermittent renewable-energy technologies. Energy storage technologies are discussed further in section 3.6.
- *High-voltage DC (HVDC):* For renewable-energy resources such as wind, wave and tidal, the location of plant is determined by the availability of the physical resource, and may be far from locations of high power requirement. For example, there is a substantial wind resource in remote parts of Scotland and much of the marine resource is off the northwest coast of England. A potential option for the bulk transmission of power from such schemes to load centres in the centre and south of England is the use of HVDC rather than conventional alternating current systems. This has a number of technical advantages but is more expensive owing to the high-cost additional equipment that is required for high-voltage rectification and inversion. Improvements in the cost and efficiency of HVDC power converters and cables are thus needed to facilitate movement to a HVDC-based network. Interest in HVDC links is growing. For example, the recent, very large Three Gorges hydroelectric project in China will be connected to the network by a HVDC link.
- *Network management and control:* Intelligent network management and control equipment is needed to automate the network as it becomes more complex.
- *Power conditioning:* Improvements are needed to overcome the effects of embedded generation plants in the network, such as transient voltage variations and harmonic distortion.
- *Network and generator protection:* Improvements are needed in the understanding and management of the impact of a faulty generator in the network.
- *Modelling and simulation tools:* More complex tools are needed for assessing power flows, faults and system stability as embedded power plants are integrated into the network.

A key multidisciplinary area where physics is making a contribution is the development of high-temperature superconducting materials (box 3.10) for cables. These also have important potential applications in electrical machines, current fault limiters and energy storage. Another area where physicists are making important contributions is in the development of components for HVDC voltage converter technologies. For example, silicon-based thyristor valves, which have a low operating temperature, have been superseded by the development of thyristor valves based on silicon carbide ceramics, which operate at much higher junction temperatures and current density.

3.6: Energy storage

Energy storage will play a critical role in helping to combine intermittent renewables, such as wind and PV, with fossil-fuel energy sources. In the short term the wider availability of energy storage would allow a reduction in the amount of "spinning reserve" maintained by fossil-fuelled plant on the transmission system.[6] In the longer term the presence of a store would allow plants to be run at baseload for longer, with consequent savings in fuel and CO_2 emissions. In the UK the Department of Trade and Industry (DTI) has allocated £4 million of the new and renewable-energy R&D budget to energy storage as a "priority area". In the EU more than €30 million has been allocated to more than 20 projects in the field of energy storage during the past few years.

Energy storage can be used for:

- *Maintaining power quality:* Stored energy is only applied for seconds or less, to assure continuity of quality power, such as to maintain frequency control or to guarantee uninterruptible power supplies.
- *Bridging power:* Stored energy is used for seconds or minutes to assure continuity of service when switching from one source of energy generation to another.
- *Energy management:* Storage is used to decouple the generation and consumption of electric energy. The capacity to store many MWh of energy may be required

6. Spinning reserve is a partly loaded plant that is kept running so that it can be very quickly called upon should there be a trip at another power station or a rapid pick-up in demand for electricity (over a timescale of minutes).

Box 3.9: Nanostructured materials for hydrogen storage

In one area of our research at the University of Birmingham, we are employing High Velocity Ball Milling (HVBM) to synthesize a range of nanoscale materials under different gas atmospheres.

With a theoretical reversible hydrogen uptake value of 7.6 weight%, magnesium is a prime candidate for use as a storage medium. However, the absorption temperature first needs to be reduced (from 350 °C) and the sorption kinetics need to be accelerated. HVBM-treated Mg-based powders (under argon or hydrogen) exhibit greatly improved sorption kinetics (figure A) due to the introduction of a nanocrystalline microstructure (figure B) with an increased volume of grain boundaries, which act as preferred pathways for hydrogen diffusion. Further improvements in kinetics have been achieved by introducing trace amounts of Ni and certain PGM catalysts at different stages of the HVBM process, to activate the surface of the powders.

HVBM is also a highly effective method for preparing defective structures of carbon. This route shows great promise in generating a new class of carbon-based materials for effective hydrogen storage. After graphite is HVBM in hydrogen, a hydrogenated structure with a reduced grain size is produced (figure C). Heating HVBM graphite under vacuum up to 700 °C demonstrates (figure D) that significant amounts of hydrogen can be stored (up to 7 weight%). We are examining the nature of these milled materials in more detail, using a number of techniques (XRD, TEM and ESR), and are studying the effect of additional elements with the aim of radically reducing the desorption temperature and introducing a significant degree of reversibility (i.e. to allow hydrogen to be reabsorbed).

Dr David Book, Dr Allan Walton, Dr Vicky Mann, Dr John Speight and Prof. Rex Harris, Department of Metallurgy and Materials, School of Engineering, University of Birmingham, Birmingham B15 2TT.

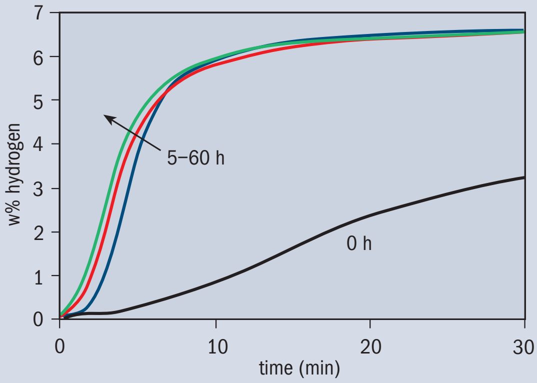

Figure A: HVBM Mg hydrogen uptake at 300 °C and 10 bar H_2.

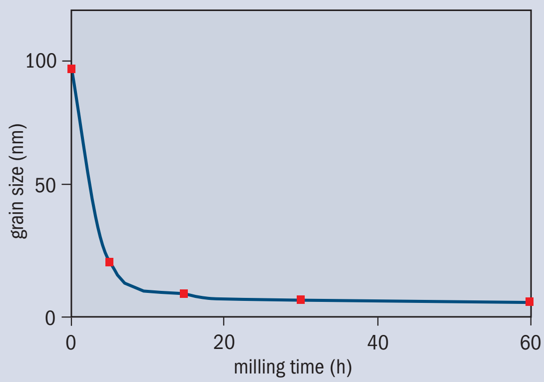

Figure B: Estimated grain size, from XRD peak broadening, of HVBM Mg.

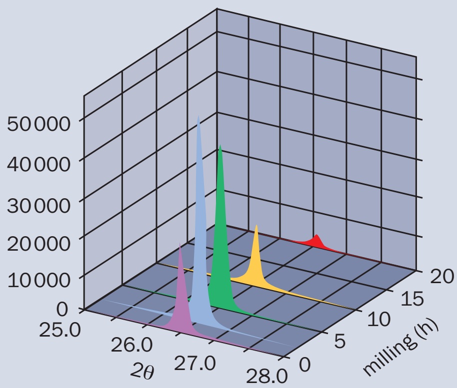

Figure C: XRD 002 peak of HVBM graphite.

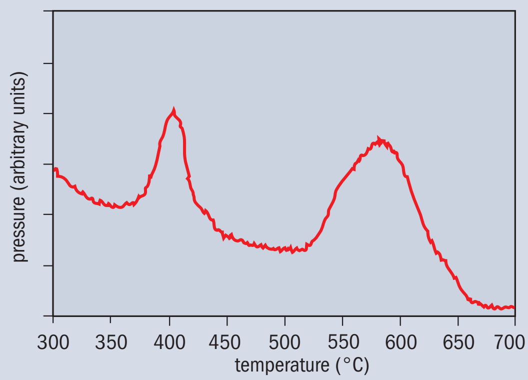

Figure D: Thermal desorption spectrum from HVBM graphite (20 h in 8 bar H_2).

to store output from renewables at a time of low demand to provide power at a time of peak demand some hours later.

Figure 3.6 shows energy-storage systems that are already available or are under development. Other media under investigation include methanol, chemical hydrides, hot water, ceramics, molten salt/steam and even ice. As discussed in section 3.4, there is also significant interest in the use of hydrogen systems because of their potential for integration with highly intermittent renewable-energy sources and as an energy carrier for the future. [28]

3.6.1: Power quality and bridging power

Flywheels: These are kinetic energy storage devices and they store energy in a rotating mass (rotor), with the amount of stored energy (capacity) dependent on the mass and form (inertia), as well as the rotational speed, of the rotor. A flywheel spinning at very high speeds can be used to store energy by combining it with a device that operates either as an electric motor driving the flywheel to store energy or as a generator producing electricity from the stored energy in

Box 3.10: High-temperature superconducting materials

Superconducting materials have the ability to transport high currents without electric losses, when they are cooled to very low temperatures (−269 °C), with liquid helium as the cooling material. The discovery of high-temperature superconducting material (HTS) in 1986 was a breakthrough. HTS material becomes superconducting at the temperature of liquid nitrogen (−196 °C). Cooling at this temperature is one thousand times less expensive than liquid helium cooling (at 269 °C). Thus new cost-effective applications can be envisaged in electricity transmission.

Power cables based on the HTS materials can offer several advantages over conventional power cable technology due to the unique properties of the HTS material and the perfect magnetic shielding (for some designs).

At present, HTS cables are still in a prototype state and further research and investment will be required to bring down the cost of the wire before the technology can be used economically on a large scale. This requires new research into superconductivity models, promising new (lower-cost) superconducting materials and improved (lower-cost) manufacturing techniques.

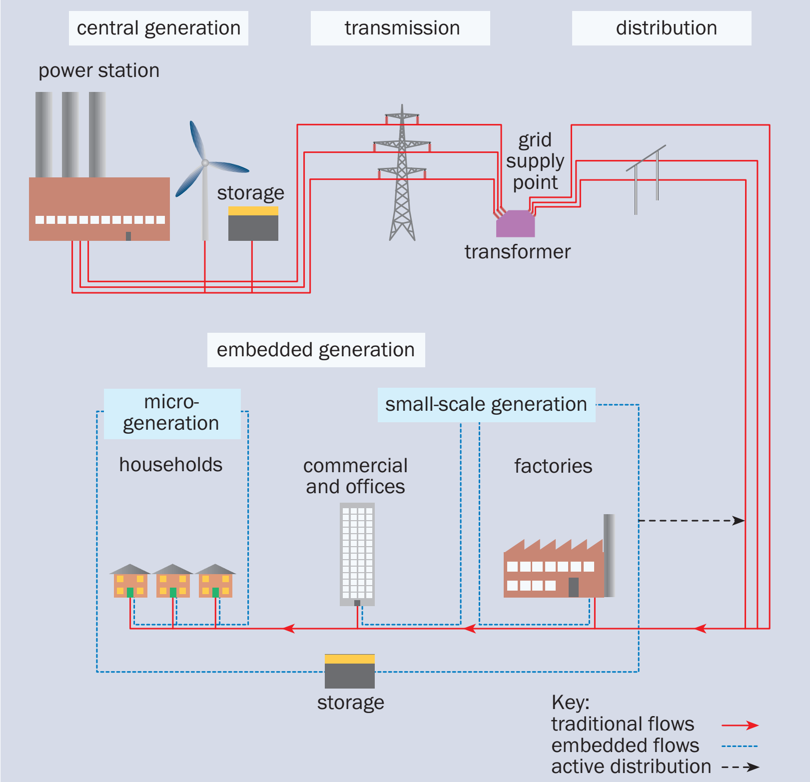

Figure 3.5: Schematic of a distributed electricity system. Source: Postnote no. 163 UK Electricity Networks: http://www.parliament.uk/post/home/htm.

the flywheel. Most modern flywheel energy-storage systems use composite rotors made from carbon fibre materials and superconducting electromagnetic bearings virtually to eliminate energy losses through friction. Flywheels can bridge the gap between short- and long-term storage, and they reduce the cost of materials and manufacturing. Reducing operational losses and increasing storage times could make flywheel systems competitive with batteries in standalone renewable-energy systems. [29]

R&D areas include:

- improvement of rotor materials and manufacturing technology;
- magnetic and mechanical bearings;
- power electronics interface and control;
- hybrid storage topologies (e.g. with battery);
- control strategies and instrumentation;
- condition monitoring;
- lifetime prediction.

Supercapacitors: Also known as electrochemical capacitors, double-layer capacitors and ultracapacitors, these possess characteristics of both batteries and capacitors. They store electrical energy in the two series capacitors of the electric double layer, which is formed between each of the electrodes and the electrolyte ions. The capacitance and energy density of these devices is thousands of times as large as those of electrolytic capacitors. [30] Compared with lead-acid batteries, supercapacitors have a lower energy density, but they are much more powerful than batteries and possess fast charge and discharge capability. They also have a virtually unlimited service life and show very low leakage of current.

Supercapacitors are being developed for transportation applications and uninterruptible power supplies with ambitious energy and power density targets. While small units are well developed, the larger units with energy densities of more than 20 kWh/m^3 are still under development. Current research covers materials development to improve performance and reduce cost and optimisation of energy management in applications.

Superconducting magnetic energy storage (SMES): These systems store energy in a magnetic field created by the flow of direct current in a coil of cryogenically cooled superconducting material. They have the advantage of being a very highly efficient energy storage medium (>95%) with a very fast response capability. In addition, their deep discharge capacity allows for significant damping of power station instability and provides an efficient protection against voltage sags or small power breakdowns.

SMES systems are currently expensive to install and run compared with other technologies, and R&D is focused on improvements to system design and the use of better/cheaper materials.

3.6.2: Energy management

Batteries: Existing utility battery storage systems primarily use lead-acid batteries, but there are a number of other promising types, including lithium-ion, nickel cadmium and sodium sulphur batteries. The UK possesses a significant capability in the design, development and manufacture of

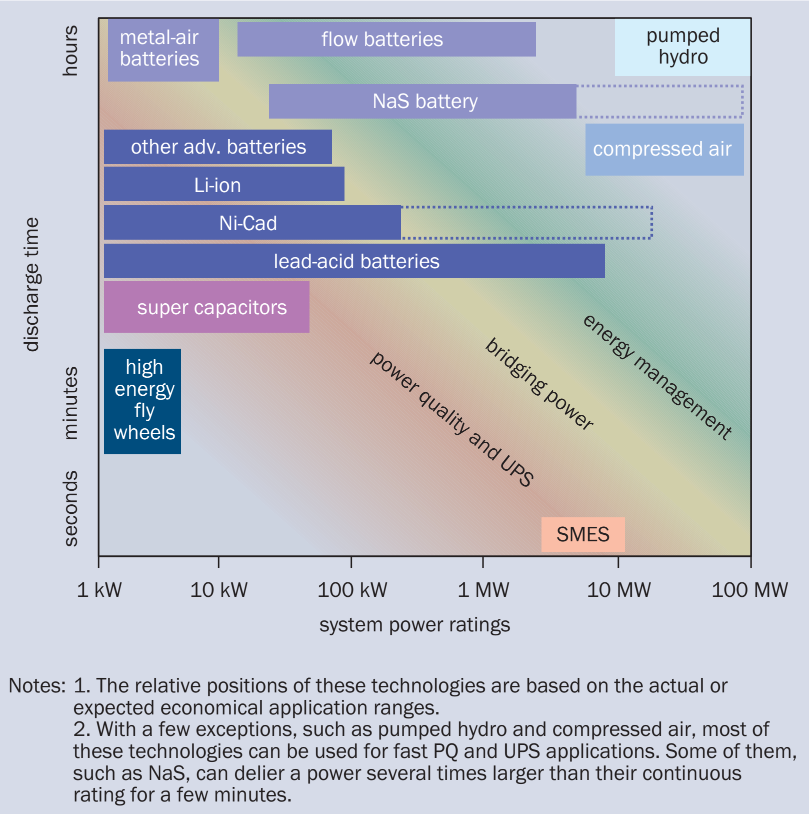

Figure 3.6: Types of energy storage by primary role. Source: The Electricity Storage Association: http://www.electricitystorage.org.

a variety of battery systems, ranging from traditional lead acid systems [28] to small-scale lithium devices for portable power applications.

High-performance power conditioners are being developed to provide optimised control of charge and discharge currents in renewable-energy-source applications. The aim is to improve the lifetime of lead-acid batteries through a better understanding of operating conditions and the introduction of active control of charge/discharge to avoid degradation.

Development of novel materials to increase battery life, without increasing cost, is particularly important for PV applications. Such R&D needs to include improvements in:

- active material composition;
- battery design and technology;
- energy management systems.

Metal-air systems: Metal-air batteries couple a reactive metal anode to an air electrode to provide a battery with an inexhaustible cathode reactant from the oxygen in atmospheric air. These batteries are typically used for standby or emergency power. Their usefulness in renewable-energy storage depends largely on successful development of bifunctional air electrodes, which requires advances in material science and catalyst technologies, and relies on improving system efficiency.

Redox flow cell: Like classical batteries, redox flow cells are based on chemical storage (figure 3.7). They have two different electrolytes, separated by an ion-permeable membrane, and an electrochemical ion-exchange reaction occurs when a voltage is applied across the electrodes. Reversing the flow of the electrolyte produces a voltage across the external electrodes of the cell, discharging the energy stored. To ensure their continuous flow the electrolytes are stored separately (in bulk storage tanks). Redox flow cell systems are mainly used for grid-connected systems, [32] but there are some examples of their use for renewable-energy storage. Smaller systems could potentially be used for standalone applications. They are also useful for energy management in utilities (e.g. load levelling, increasing utilisation efficiency and voltage control).

R&D is aimed at improving overall system design, reducing capital and operational costs, and improving efficiencies (e.g. losses from energy-consuming devices). Specific needs are improvement of electrolytes, materials for membranes and electrodes, and optimisation of flow geometries to minimise losses.

Pumped hydro storage: During off-peak hours, water is pumped from one reservoir to another at a greater height. When additional electricity is required, the water flow is reversed to generate electricity. Pumped storage is a developed technology that is valued in electricity systems around the world. However, it is very capital intensive with a cost of £0.5–1.0 million per installed MW. More important is that significant schemes require large areas of land and can only be sited in hilly regions. Areas of R&D include development of advanced turbines and flow modelling.

Compressed air: Low-cost electricity from the power grid at off-peak times is used to compress air, which is later expanded through a combustion turbine to create electricity, as needed. The compressed air is often stored in appropriate underground mines or caverns created inside salt rocks. Use of the technology is limited to helping to meet peak demands. The system has a poor adaptability to fluctuating input and output power, and it is not suitable for use with renewable-energy technologies.

3.7: Mature technologies

A number of renewable-energy technologies have reached conceptual maturity (i.e. the fundamental underlying science is well understood). These include biomass generation and bioenergy, geothermal energy, hydroelectricity, solar thermal and wind energy. Here the challenges in the medium to long term tend to be towards incremental improvements in performance, reliability and cost, rather than new concepts or step-change improvements to the technologies. These tend to require engineering solutions, with R&D focusing on improvements in system/plant design, control and scaling, together with optimisation of manufacturing processes. However, there are still several areas where physicists can make a contribution, such as in new materials development (enhancing performance and reducing costs) and computational fluid dynamics, as well as physical modelling in order to refine understanding and improve efficiencies.

3.7.1: Wind energy

The UK has a large potential wind resource – in fact, 40% of Europe's total resource, although much of it remains largely untapped, currently meeting only 0.5% of our electricity requirements. This is expected to increase to at least 5% by 2010. [33] Utilising wind energy involves converting the power within a moving air mass (wind) into rotating shaft power. Modern wind turbines contain rotors fitted with aerodynamic blades, which rely on lift forces caused by the wind on the blades to turn the shaft and drive a generator (located behind the rotor and blades). Although significant advances have been achieved in turbine efficiency and reliability, further improvements are possible, and blade and rotor design is an important research area.

To date, most wind turbines have been installed onshore, but a large part of the wind potential lies offshore, and this is now beginning to be exploited, bringing additional challenges. Turbines will be bigger – up to 10 MW turbines are being considered – so blades and their components need to be larger and foundations need to be stronger. Materials also need to be more durable to withstand the harsh marine environment. In the longer term, larger, more robust offshore turbines may even require radical and fundamental design changes. Also, deeper offshore locations are being considered, which will require new techniques for mooring the turbines, probably using techniques and skills developed in the offshore oil and gas industry. Access to offshore locations is more difficult, so it is desirable to reduce the frequency of maintenance, such as by using remote monitoring to detect when maintenance is required rather than maintaining on a routine basis. One particular application being developed is the use of optoelectrical sensors for monitoring strain in the blades.

Areas where physicists could make valuable contributions include aerodynamics and aeroelastics, meteorological modelling/forecasting, and materials development. Physics is also essential in tackling the issue of interference of wind turbines with radar, which has proved a major obstacle for many proposed sites in the UK. Possible solutions include the development of stealth materials for the blades and using software to filter out the radar profile produced by wind turbines from the screen viewed by the operator.

3.7.2: Bioenergy

Biomass can be used to produce energy by:

- combustion gasification of biomass to produce electricity and/or heat;
- pyrolysis of fuels to produce electricity/heat and/or products such as oils;
- extraction or hydrolysis and fermentation to produce liquid biofuels (bioethanol and biodiesel) for the transport sector;
- anaerobic digestion to produce biogas, which can subsequently be burned to produce electricity and/or heat.

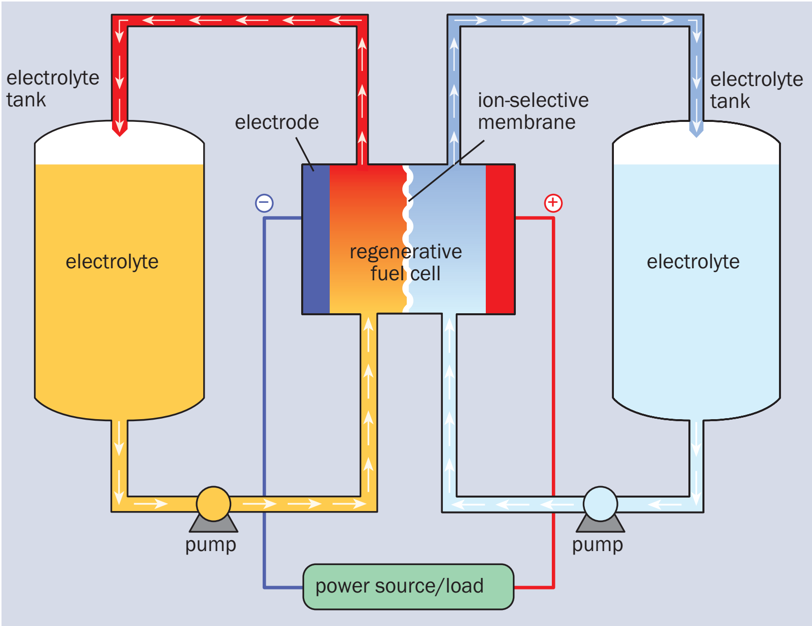

Figure 3.7: Schematic of redox flow battery. Source: [32].

A variety of biomass feedstocks can be used, including:

- forestry residues (as a by-product of timber and pulp production);
- agricultural residues (e.g. straw from cereal production);
- agroprocessing residues (from crop processing);
- energy crops grown especially for use as a fuel (e.g. in the UK, short-rotation coppice and miscanthus for combustion, and oil-seed rape, wheat and sugar beet for conversion into liquid biofuels).

Conventional combustion technology is expensive and has limited development potential for biomass electricity. However, advanced technologies that convert the biomass to gas or liquid before combustion show the potential for lower overall costs. In the short term, co-utilisation with fossil fuels in an existing boiler is potentially the lowest-cost option, though it is limited to areas with existing coal plant. Technologies are mature, with major challenges being of an engineering nature in process/plant design and cost reduction (particularly for gasification and pyrolysis). However, physicists still have an important input in some areas, such as modelling systems, improving combustion characteristics and computational fluid dynamics.

3.7.3: Hydroelectricity

Hydroelectric power is a mature and proven technology – the potential energy stored in water held at height is converted to kinetic energy as it falls, turning a turbine to generate electricity. It is probably the oldest method of harnessing renewable energy, and is currently the world's largest renewable source of electricity, accounting for 15%

of the world's electricity. [34] The majority of this comes from large-scale hydro plant, where large reservoirs, created by building large dams and flooding areas of land, provide water storage and therefore a constant supply of electricity. There are a number of environmental impacts and population displacement issues associated with such schemes, and a number of planned hydroelectric schemes are coming up against a great deal of opposition from environmental groups and indigenous people. Small-scale hydro plants tend to be "run-of-river" without appreciable water storage and are typically less than 10 MW. Improvements in small turbine and generator technology mean that micro (<100 kW) and picohydroelectric schemes have become more attractive and allow useful power to be produced from even a small stream.

R&D challenges are primarily to improve the engineering of hydroelectric systems, although there are areas where physics can contribute (e.g. in advanced turbine systems, flow modelling and water resource forecasting).

3.7.4: Geothermal energy

The geothermal resources currently exploited commercially are hydrothermal resources – hot water and/or steam trapped in fractured or porous rocks at shallow to moderate depths. Lower-temperature resources can be used for space heating, district heating, greenhouses and heat pumps, and higher-temperature resources for electricity generation, either directly or by using a binary fluids system. The potential for geothermal energy in the UK is low because the temperature just a few metres below the surface is generally around 12 °C. This heat can be used to power individual houses using ground source heat pumps, and there are a few areas where the temperature is high enough to make local-area heating possible (e.g. the city of Southampton). [35] Low-temperature resources dominate throughout Europe, with the main high-temperature resources for electric power generation being in Italy and Iceland, and with more minor sources found in France, Portugal and Switzerland.

The cutting edge of geothermal technology is the enhanced geothermal system (EGS) or hot dry rock concept, which aims to create artificial geothermal systems by injecting water underground at high pressure so as to produce fractures in deep, hot rocks. One borehole is drilled to inject the water and another to recover the hot water after its passage through the artificial natural fractures in the deep hot rocks. The attraction of EGS technology is that it could be applicable to many countries (including the UK) that are currently regarded as effectively having no geothermal resource. The energy sources are not truly renewable, however, because eventually the rocks cool and the water is then not hot enough for efficient power generation. The plant would then have to be shut for decades while the Earth's core reheated the rocks. [36]

Key disciplines for solving R&D challenges in this area are engineering and geology, although physics can contribute in helping to reduce the thermodynamic inefficiencies in plants, modelling energy cycles and developing more effective materials for heat exchangers.

3.7.5: Solar thermal

In solar thermal systems the warmth absorbed from the Sun's rays by a collector is used to heat water or another working fluid, or to make steam. The most common use is for small-scale systems to provide hot water for use in homes, but larger systems can be used to provide hot water for commercial buildings and industrial processes. Steam is used for process heat or for operating a turbine generator to produce electricity or industrial power.

Solar thermal power plants reflect and concentrate the Sun's rays to heat a fluid to a high temperature. Depending on the design (parabolic trough, solar dish or solar power tower) the working fluid can be used to produce steam to drive a turbine, or used directly in a small engine generator (e.g. Stirling engine). Some designs have been commercially deployed but others are still at the pilot stage. Solar thermal power plants are not suitable for the UK because they depend on direct sunlight and must be sited in areas with high direct solar radiation, such as steppes, bush savannahs, semi- and true deserts, within ± 40 ° latitude.

Being relatively well developed technologies, the R&D challenges facing solar thermal heat and power are mainly engineering. However, physicists do have involvement in areas such as modelling and materials development. For example, new developments in advanced silicon carbide ceramics that can withstand the high temperatures required for efficient solar thermal power generation are being utilised in a prototype solar thermal power plant currently being trialled in southern Spain. [37]

4: Supporting the RD&D base

4.1: The skills base

The previous section has shown that enabling renewable and other emerging low-carbon energy technologies to contribute to a low-carbon future requires advances in a variety of research areas, and contributions from scientists and engineers from many disciplines, often working in interdisciplinary or multidisciplinary teams. This echoes findings from other studies, which found that the renewables industry requires a wide range of skills. [38] Physics and physicists can make useful contributions to some aspect of RD&D in almost all of the technologies, and there are several areas where their skills and knowledge could enhance the research effort, and might bring an additional perspective to solving the challenges that these technologies face. For example, their involvement is critical to bringing about step changes in the cost of PV cells in the medium to long term by developing novel PV technologies. There are also varied and interesting opportunities for physicists in marine energy, and they could make a valued input to experimental and computational physics areas to fuel-cell development.

Quantitative information about the number of researchers from different disciplines, or indeed the total number of researchers involved in renewable-energy RD&D, is not available, nor are forecasts available of the number of engineers and scientist required to help to develop renewable-energy technologies. Recent studies that have examined the renewable-energy supply chain have reported that several technology and project developers have found a lack of necessary skills in the UK – both general technical skills and also more specialist skills, [38, 39] which developers have remedied either through in-house training or by recruiting internationally. A solution that could be more beneficial to the UK's competitive position in new and renewable-energy technologies is to estimate future skills and educational needs, from R&D through to applied engineering, and to make an effort to ensure that these are then provided.

Although the total number of graduates has risen over the last few years, the number of physics graduates has declined slightly (figure 4.1). Data on the first destination of graduate physicists also shows that the number entering science- and engineering-related employment has fallen since the turn of the century, although this may not be a true picture of long-term career choice.[7] Encouraging physicists, and indeed other scientists and engineers, to consider a career in renewable energy could help to plug the skills gap identified above. One option would be to raise awareness of and interest in the physics element in the development of these technologies. This could be achieved by promoting the inclusion of examples of "the physics" of renewable-energy sources and fuel cells in teaching on undergraduate physics courses, or even on A-level physics and other A-level science courses. Another option would be to raise awareness of opportunities for physicists in these areas in careers advice material for physicists, at both graduate and postgraduate level, and in advice provided for mid-career changes. Articles in physics journals (such as *Physics World*) about physics research areas in renewable-energy technologies or profiles of physicists now working in these areas could also highlight these areas as a career choice. Relevant professional bodies could also consider providing continual professional development courses in the areas of renewable-energy technologies and fuel cells.

The lack of suitably qualified postgraduates was also commented on by academics and developers contacted in this study. They mentioned that there is a shortage of opportunities at postgraduate level for physicists wishing to specialise in these areas. There are a few MSc courses in renewable-energy technologies and fuel cells, but these are, by their very nature, multidisciplinary, and obtaining funding or training bursaries for such courses can be difficult. There are also few PhD research opportunities, again partly due to the difficulty of obtaining funding for interdisciplinary or multidisciplinary research topics. A more flexible approach from funding bodies may be required. An additional difficulty can be that such research topics may not sit easily within university department structures. In this case the existence of "energy technology centres", which can act as a focus for such activities, can help.

Two key areas where the UK has an opportunity to take a research lead are:

- in the new generation of PV energy technologies, although this would require a strong RD&D effort; [40]
- wave and tidal energy, where there are a number of universities with significant research capability.

Ensuring that these RD&D strengths are developed could bring substantial benefits to the UK, both in terms of enabling deployment of these technologies, with subse-

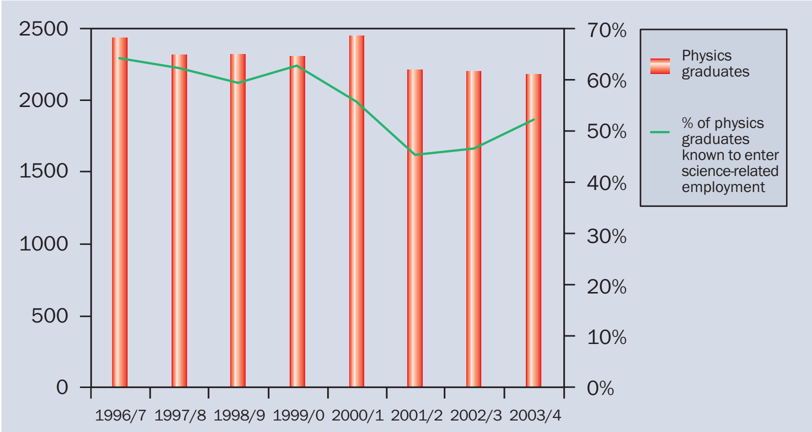

Figure 4.1: Physics first degree graduates and their first destinations. Source: Derived from Higher Education Statistics Agency data. Science-related employment is taken as professional occupations, associate professional and technical qualifications, and plant and machine operatives. Statistics on employment relate only to graduates where first destination is known, and therefore may not present a very accurate picture of longer-term career choice. Statistics on career choice based on information from about 40% of physics graduates.

7. Data are only available for the first job after graduation and will thus include temporary jobs in a variety of types of employment. Data are also only available for a proportion of physics graduates and the percentages shown in figure 4.1 are based on this subset.

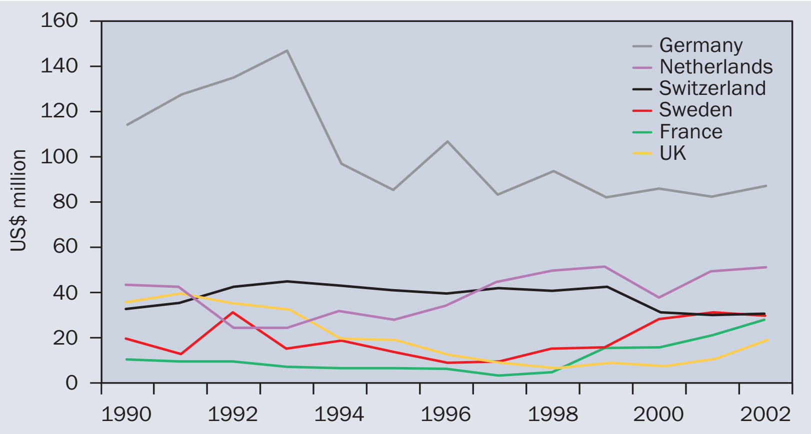

Figure 4.2: Annual RD&D budget for renewable energy (millions US$). Source: International Energy Agency.

quent environmental benefits in terms of reducing CO_2 emissions, and in terms of financial benefits from export earnings as technologies are deployed globally. This will require support of RD&D and the availability of suitably qualified personnel to work in these areas.

4.2: RD&D funding

Renewable-energy RD&D in the UK is funded through a number of routes. The main ones supported by government and the public sector, together with EU funding opportunities, are described briefly in box 4.1. In addition, there is industry-funded RD&D, and commercial deployment of renewables in the UK is supported by the Renewables Obligation – a market-based mechanism in which a requirement for all electricity suppliers to purchase a certain amount of energy from renewable energy creates a premium price for renewably generated electricity.

It has been suggested by some that the level of funding for RD&D is not sufficient if the UK is to meet its renewable-energy targets. [41] While UK expenditure has increased in recent years, it is still lower than in several other European countries (figure 4.2). US expenditure is about $250 million per annum.

A recent DTI/Carbon Trust review [10] found that there appears to be a funding gap in moving renewable-energy technologies to the pre-commercial stage, and from the pre-commercial to the supported commercial stage. It also considered that the current landscape for renewables funding is complex, which suggests that a clearer overall strategy for UK RD&D in both renewable-energy technologies and other new energy technologies, together with a clearer map of RD&D funding and clearer demarcation of roles of different funding bodies, could be useful. This could be a potential activity for the new UK Energy Research Centre. A clearer research "atlas" indicating institutions and developers carrying out relevant RD&D could also encourage graduates and postgraduates to consider working in this field by clearly showing the variety of career opportunities available.

For physicists currently wishing to work in this area, the main source of public UK funding is the EPSRC's SUPERGEN programme. Renewable-energy R&D could be funded through the EPSRC Physics Programme, but it would compete with other physics research. Physicists need to be made aware of the funding opportunities offered by SUPERGEN and other public sector funding, and encouraged to consider working in multidisciplinary teams to take advantage of the funding. EPSRC has been tasked with taking a clear lead in driving forward the sustainable energy agenda and covering the full spectrum of energy research issues, and it was given extra funds in the 2004 spending review to expand support for research and training necessary to underpin future energy options (including renewables). [42] It will be putting in place a coordinated energy programme.

4.3: Summary of recommendations

This report has made a number of recommendations about ways to strengthen the UK's RD&D base for renewable energy and other new energy technologies, such as fuel cells, and more specifically ways to ensure that the important contribution that physicists might make to that RD&D base is realised. In brief they are:

- Estimate future skills and educational needs in all disciplines (e.g. engineering, physics, materials science) from R&D through to applied engineering in new and renewable-energy technologies, and make an effort to ensure that appropriate training is available to ensure an adequate supply of suitably qualified personnel.
- Develop a clearer overall strategy for UK RD&D in renewable-energy and other new energy technologies, together with a clearer map of RD&D funding and a clearer demarcation of the roles of different funding bodies.
- Support the significant research capability in wave and tidal RD&D and its potential lead in RD&D in third-generation PV devices with adequate R&D funding.
- Ensure that the funding bodies (e.g. EPSRC) appreciate the multidisciplinary nature of much R&D in renewable-energy technologies and take a more flexible approach to the funding of MScs and PhDs in this area.
- Ensure that universities consider setting up "energy technology centres" to encourage and facilitate the multidisciplinary RD&D required.
- Encourage physicists (and other scientists and engineers) to consider a career in renewable energy by raising awareness of the science and engineering principles and challenges involved in renewable-energy technologies. This could be done in A-level and undergraduate teaching courses, through continuing professional development activities in professional bodies and through articles on renewable-energy research activities in their member journals.

Box 4.1: Funding of RD&D in renewable and other emerging energy technologies

The main sources of public funding for renewable-energy RD&D are:

Department of Trade and Industry (DTI)
The DTI's latest competition round for renewable-energy RD&D has allocated an indicative budget of £7 million for collaborative R&D projects in bioenergy, fuel cells, wave power, tidal stream, offshore wind power and PVs. This RD&D is now managed as part of the DTI's Technology Strategy programme.

The DTI also funds the commercialisation and demonstration of renewable energy, mainly through a series of capital grant type schemes, which include:

- marine renewables;
- offshore wind projects;
- projects generating electricity from energy crops;
- small-scale biomass heating schemes;
- PVs;
- community and household renewables.

The Carbon Trust
One of the Carbon Trust's principal programmes is the Low Carbon Innovation Programme to support the development and commercialisation of new and emerging low-carbon technologies. Areas that it has identified where its investment may have a significant impact include biomass for local heat generation, fuel cells and hydrogen infrastructure. £18 million (over three years) is allocated to RD&D in the programme.

EPSRC: Sustainable Power Generation and Supply (SUPERGEN)
This initiative is a large, collaborative programme of research based on the assembly of research consortia that tackle the large challenges of sustainable power generation and supply. £25 million of funding has been earmarked for the initiative over a five-year period. Research themes identified to date are:

- *SUPERGEN I:* In collaboration with BBSRC, ESRC and NERC, SUPERGEN I provided £12 million of funding for four consortia in the following themes:
  Networks: Research into the transmission and distribution of power.
  Biomass and biofuels: Using renewable, fast-growing crops as a sustainable energy source.
  Marine: Harnessing the power of the oceans around our coastline for renewable energy.
  Hydrogen technology: Exploring the options for hydrogen as the clean fuel of the future.
- *SUPERGEN II:* Under this initiative, two research themes have been identified:
  PV devices, materials and technology: Harnessing the power of the Sun for electricity generation.
  Lifetime extension of conventional power plant: Ensuring current fossil-fuelled plant remains efficient.
- *SUPERGEN III:* The three themes for this are:
  Fuel-cell technologies: Silent, clean, efficient energy generation.
  Energy storage and recovery systems: Maintaining an uninterrupted supply from intermittent sources.
  Distributed power systems and devices: Exploring networks and the control of small-scale generating systems.
- *SUPERGEN IV:* This round will explore next-generation PV devices that may offer increased efficiencies and lower production costs. The technologies included in this consortium will be novel organic and dye-sensitised PV systems.

The EPSRC delivery plan for 2005/6–2007/8 [42] has announced that research consortia will also be established in wind energy and biofuels cells.

EU
The Sixth Framework Programme (FP6) is the European Commission's programme for Research, Technological Development and Demonstration activities for the period 2002–2006. Within the programme, which has a total budget of €17.5 billion, €810 million has been allocated to sustainable energy systems. Funding is available for both short-medium-term and medium-long-term activities.

Short-medium-term energy research themes relevant to renewable energy are:

- *clean energy*, in particular renewable-energy sources and their integration into the energy system, including storage, distribution and use;
- *alternative motor fuels*.

Research should be aimed in principle at bringing the next generation of more cost-effective renewable-energy technologies to the market, with particular emphasis on markets in Europe.

Relevant medium-long-term energy research activities in the programme are:

- *fuel cells*, including their application;
- *new technologies for energy carriers/transport and storage*, in particular hydrogen;
- *new and advanced concepts in renewable-energy technologies*, including PV cells and biomass;
- *new and advanced concepts in renewable-energy technologies*, in particular PVs and biomass.

This R&D is more focused on the validation of technical and economic feasibility of pilot plants and prototypes, with commercial exploitation not expected until after 2010.

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Physics World magazine
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University of Birmingham, Department of Metallurgy and Materials, School of Engineering
University of Edinburgh, School of Engineering and Electronics
University of Edinburgh, Wave Energy Group, Institute for Energy Systems
University of Glamorgan, Hydrogen Research Unit
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University of Reading, Energy Group

Acoustic Doppler current profiler (ADCP) A current-measuring instrument employing the transmission of high-frequency acoustic signals in water. Utilising the Doppler effect, it allows development of a profile of current speed and direction over the entire water column.

Aeroelastics Study of flexible structures situated in a flowing fluid (such as air or water). Aeroelasticity is the study of the mechanics of coupled aerodynamics structure systems.

Carbonaceous gases Carbon-containing gases, such as methane, propane and LPG.

Diffraction The bending of waves around the edges of objects.

Fluid dynamics The branch of applied science that is concerned with the movement of gases and liquids.

Hindcasting In wave prediction, the retrospective forecasting of waves using measured wind information.

Hydrodynamics The study of fluids in motion and the movement of objects through fluid.

Hydrostatics The study of the mechanical properties of fluids that are not in motion.

Luminescence The emission of light, usually by chemical or electrical means (e.g. from LEDs), by sources other than a hot, incandescent body (where emission of light is due to high temperature of the emitting material, such as from lightbulbs).

Nanotechnology Science/technology based on very small structures, typically built on the atomic scale.

Photolytic decomposition Using solar radiation (sunlight) to break chemical bonds within materials at the atomic level or to catalyse (speed up) a chemical reaction.

Photovoltaics Photovoltaic (PV) cells, also known simply as solar cells, which work by transforming the energy in solar radiation (light from the Sun) into electrical energy.

Pyrolysis The thermal decomposition of organic material (e.g. fossil fuels or biomass) through the application of heat in the absence of oxygen.

Quantum The smallest discrete amount (of energy, momentum or angular momentum).

Quantum confinement When applied to low-dimensional semiconductors, this describes the confinement of the exciton (an electrically neutral excited state) within the physical boundaries of the semiconductor. This is an inherently quantum phenomenon, hence the names “quantum well”, “quantum wire” and “quantum dot”, which describe confinement in one, two and three dimensions, respectively.

Quantum dots Also known as nanocrystals, these are a special class of material known as semiconductors, where an atom is so confined and isolated that the removal or addition of a single electron can be detected.

Quantum Well See **Quantum confinement**

Resonant conditions Conditions inducing resonance; “resonant frequency”.

Spinning reserve Generating capacity connected to the system (in service) and ready for immediate response to load variations.

Superconductivity The ability of certain materials to carry an electric current with zero electrical resistance, usually at supercold temperatures.

Thermodynamics The study of the processes that involve the transformation of heat into mechanical work, of mechanical work into heat or the flow of heat from a hotter body to a colder body.

Venturi effect The speed up of a fluid through a constriction due to the pressure rise on the upwind side of the constriction and the pressure drop on the downwind side as the fluid diverges to leave the constriction.

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