

RENEWABLE ENERGY

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ABSTRACT

The expansion and commercialisation of renewable energy technologies is one of the key challenges for energy in the 21st Century and many countries have set challenging targets for renewable use and deployment. A range of arguments favouring the development and deployment of renewable energy technologies can be made based on their environmental, sustainability and security benefits. Renewable generating technologies vary significantly in their geographical and operational characteristics and there are difficulties in integrating these variable and often intermittent generating sources into existing electrical networks. Although changes will need to be made to future network operation and design, renewables can also bring benefits through application in new low-carbon energy vectors as well as direct-use in a range of industrial processes. When compared to conventional generating sources the economics of renewable energy often appear inferior. However, traditional methods for comparing them can be shown to be limited and more robust techniques indicate that rather than raising energy prices, the increasing use of renewables will actually lower them.

KEYWORDS

Renewable, energy, hydropower, wind, wave, grid-connected, economics, storage, conversion, alternative fuels.

INTRODUCTION

Climate change is widely regarded as one of the most significant global challenges in the 21st Century. With conventional fossil fuel generation a major culprit, the expansion of renewable energy use is a critical element of the strategy to lower emissions of greenhouse gases. Many countries have set challenging targets for renewable use and deployment driven by the environmental, sustainability and security benefits that may be attributed to renewables.

Here, these arguments are reviewed along with the renewable technologies available. The challenges for integrating these variable and often intermittent generating sources are highlighted and alternative applications in creating new energy vectors and in direct-use are explored. Finally, the economics of renewables are examined with particular reference to the limitations of traditional comparisons with conventional sources and the impact of more robust techniques on the relative cost of fossil fuels and renewables.

THE DRIVE FOR RENEWABLE ENERGY

The case for promoting renewable energy revolves around the three key benefits associated with it:

1. Non-polluting
2. Infinite reserves
3. Security of supply

Pollution

The primary argument in favour of renewable energy is that it does not entail the release of chemical pollutants to convert the energy. This is in contrast to fossil fuels which emit a range of pollutants from carbon dioxide (CO₂) to the components of acid rain to ash. Table 1 shows the pollutants from typical 2000 MW plants

Pollutant	Conventional coal (no FGD)	Conventional oil	Combined-Cycle Gas Turbine
Carbon dioxide	11,000	9,000	6,000
Sulphur dioxide	150	170	~0
Nitrogen oxides	45	32	10
Airborne particulates	7	3	~0
Solid waste and ash	840	~0	~0
Ionising radiation (Bq)	10 ¹¹	10 ⁹	10 ¹²

Table 1: Typical emissions from 2000 MW fossil fuelled power stations in kt/yr, adapted from (1).

The combustion of fossil-fuels produces the majority of anthropogenic CO₂ with transport and power generation the largest sources. CO₂ is widely accepted as the major cause of climate change which – if left unchecked – is forecast to lead to global temperature rise of between 1.5 and 5.8°C by the end of century (Figure 1) (2). This, and accompanying changes in other climate variables (precipitation, wind speed, etc.) will have impacts on many sectors ranging from agriculture to human health that will be seen at local, regional and global scales. In responding to this, many industrialised countries have signed the Kyoto Protocol requiring cuts in CO₂ and other gases by 2010 which will become legally binding on participants once it is ratified by Russia. This is the beginning of a longer process, with the United Kingdom (UK) Royal Commission on Environmental Pollution recommending CO₂ cuts of 60% by 2050 to limit the eventual rise of greenhouse gas concentrations to twice the pre-Industrial level (3). Achieving the reductions required by Kyoto and the longer-term targets will not be straight-forward. To date, modest CO₂ emissions have been achieved through switching to less carbon intensive fuels like natural gas (albeit on a cost-basis) but ultimately, emission-free energy is required. While continued fossil-fuel use will be possible if large-scale capture and sequestration of carbon can be achieved, the development and deployment of truly carbon-free energy sources like hydrogen, nuclear and renewables will be critical.

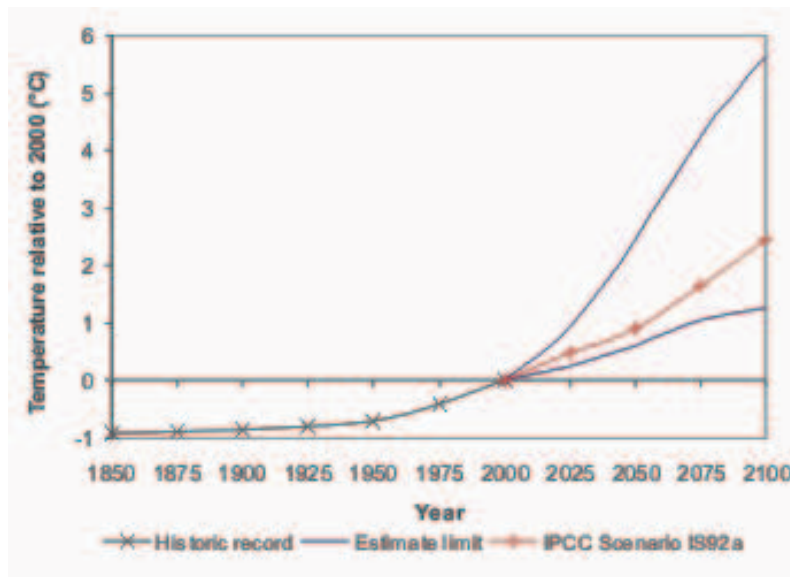


Figure 1: Historic and range of future temperature rise, adapted from (2)

Fossil-fuelled power stations produce significant quantities of sulphur dioxide (SO_2) and nitrogen oxides (NO_x) which are precipitated as 'acid rain' across wide areas and legislation such as the European Union Large Combustion Plant Directive has imposed emissions limits in response. SO_2 emissions can be reduced by a range of techniques including the treatment of coal before ignition, combustion processes that collect sulphur in the ash and SO_2 removal from the combustion product gases, known as Flue Gas Desulphurisation (FGD). Although effective, FGD is expensive, particularly so for retro-fit, and reduces station efficiency (4). While road transport is the major cause of NO_x emissions, power stations still contribute a significant fraction. A wide variety of NO_x control technologies have been developed (e.g. flue gases scrubbing with alkalis) but again are expensive. Despite not deploying NO_x scrubbing, the UK has achieved reductions with greater use of gas-fired plant and the retro-fit of low- NO_x burners to existing coal stations. Use of renewables can avoid these costly removal processes.

Radiation is emitted from nuclear and, due to the presence of trace elements, from fossil-fuelled power stations. The amounts are generally small, with public exposure similar to that of background radiation levels. However, the major issues surrounding nuclear power are how to deal with radioactive waste products and avoid proliferation of radioactive material. Until these issues are resolved and a clear lead given by Governments, new nuclear plant is unlikely to be built, particularly not by the private sector. Once again, renewables can begin to fill the gap.

Finite Resources

There is also the issue of sustainability of fuel supplies. Fossil-fuels are the product of sedimentation processes over millions of years, but they will have been consumed in a matter of centuries. Table 2 shows recent estimates of global proven fossil fuel reserves and an estimate of their remaining lifetime assuming current usage rates. While there is uncertainty over remaining reserves particularly given that further oil and gas fields will be identified, there is little doubt that with rapidly increasing demand for oil and gas and increasing exploitation costs (in financial and energy terms) supplies will be limited to a several decades.

Fuel	Proven Reserve	Reserve to Production Ratio
Oil	156 billion tonnes	41
Gas	176 trillion m ³	67
Coal	984 billion tonnes	192

Table 2: Proven fossil fuel reserves and reserve/production ratio (5)

Fortunately, there are sufficient renewable energy resources to meet our energy needs many times over, although in many cases the means of doing this in a technically and economically efficient manner is still under development. Table 3 shows an estimate of the power available from a range of renewables. To put these in perspective, global installed electrical capacity is currently just over 3000 GW (3 TW) and is anticipated to grow by some 120 GW per year.

Resource	Estimate of Recoverable Resource	Resource Base
Solar radiation	1000 TW	90 000 TW
Wind	10 TW	1200 TW
Wave	0.5 TW	3 TW
Tides	0.1 TW	30 TW
Biomass	1,150 TW	450 TW years

Table 3: Estimate of global renewable energy resource (6)

Although biomass is currently the most heavily used renewable in overall energy terms very little is used to generate electricity. Accordingly, hydropower is the number one renewable in electricity terms and contributes around 19% of global supply. Installed capacity is currently around 650 GW with a further 100 GW under construction. In recent years wind has seen the largest growth, and with 8 GW added in 2003 alone, global installed capacity is now almost 40 GW; forecasts suggest an installed capacity of 1250 GW by 2020 meeting 12% of electrical needs (7).

Security

An increasingly strong argument in favour of renewables is their positive effects on security by spreading risk. At the crudest level this can be interpreted as increasing energy self-sufficiency and lowering risk of supply interruptions either by accident, terrorist activity or the actions of politically unstable fossil fuel exporting nations. The UK fuel diversity is often indicated using the Shannon-Weiner index which measures the logarithmic weighting of fuel technologies. Hence, by increasing the variety of fuel sources through new types and increasing volumes of renewables, diversity and, by implication, security rises.

Security can also be measured in terms of the economic implications of exposure to volatile fossil fuel prices. Studies suggests that fossil fuel price volatility has a range

of negative effects on economic activity including impacts on employment levels and asset values; for example, a 10% oil price spike is estimated to reduce economic growth in the US alone by as much as \$200 billion over the following year (8). This totally dwarfs current and future investment to commercialise renewables estimated at around \$125 billion between 2001 and 2010 (9). The deployment of renewables reduces exposure to fossil price risk and this can be shown to lower overall cost (10). This perhaps surprising result arises as the costs of renewables do not have any correlation with fossil fuel price changes. The addition of renewables creates a diversified generation portfolio that serves to lower overall generating costs for a given level of risk.

BRIEF REVIEW OF RENEWABLE ENERGY

There are a range of renewable energy sources currently in use in electricity systems or with the potential to contribute significantly in the future. The following energy sources are briefly reviewed and their merits explore:

- Hydropower
- Solar Energy
- Wind Energy
- Biomass
- Tidal
- Wave

Hydropower

Hydropower is the conversion of the gravitational potential energy of water into electricity. The power generated depends on the water flow rate and the height through which the water falls – the ‘head’ – and is roughly 10 times the product of the two quantities. Global installed capacity is approximately 650 GW and produced 2,700 TWh in 2003 (5) (around 19% of primary energy). The estimated technical potential is around 14,000 TWh/year but the economically exploitable potential is between 40 and 65% of that, with much of the more economic plant already installed. The pattern of availability and exploitation varies significantly with countries like Norway producing 99% of their electricity from it while others little or none. The more developed regions have exploited far greater proportions of their resource while only around a small fraction of Asia’s much larger potential has been tapped.



Figure 2: Typical embankment dam in Texas, USA

Hydropower is characterised by high initial capital costs offset by a long lifetime (civil engineering works often last more than 50 years), high reliability and low operational costs. Hydro is generally defined on the basis of its installed capacity as Table 4 indicates.

Type	Capacity
Micro Hydro	< 100 kW
Mini Hydro	< 1 MW
Small Hydro	< 20 MW
Large Hydro	> 20 MW

Table 4: Hydro capacity definitions

Large hydro is often defined as a grid-connected scheme in excess of 20 MW capacity and would normally possess a dam and a storage reservoir. The largest scheme, the Three Gorges project on the Yangtze will shortly have a capacity of 18 GW. Most large-scale schemes were developed prior to 1990 and the potential for new large schemes is now rather limited given that there are fewer commercially attractive sites still available, but perhaps more importantly due to opposition on environmental grounds mainly as a result of the flooding of land to create the storage reservoir.

Pumped storage schemes are large hydro schemes that are designed with a storage reservoir that is larger than justified by the natural flow of water into it. Alternatively they may consist of a pair of reservoirs that are connected by appropriate penstocks. They operate such that when electricity demand is high, water is released from the upper reservoir driving the generators and exporting power to the grid; when electricity demand is low, the generators draw electricity from the grid (i.e. become motors), which are used to drive the turbines in reverse and pump water back into the reservoir. Pumped storage schemes play a major role in many countries in smoothing out imbalances between supply and demand and providing rapid response capabilities that help stabilise the grid. Their economics are based partly on these balancing and response capabilities but also on the fact that electricity at low demand is cheaper than at peak.

Schemes of less than 20 MW are relatively common and can be extremely competitive with minimal environmental impacts. While these smaller schemes currently contribute only about 3% to global hydro power capacity, they make a significant contribution in many regions of the world, especially in rural or remote regions where other conventional sources of power are less readily available. Small schemes can be associated with a dam and storage reservoir or can consist of short diversions schemes that are termed “run-of-river”. Small and micro hydro can also provide competitive power and while per-unit capital costs are higher than for larger schemes these can often be reduced by use of existing structures or by refurbishing existing plant and equipment. The cost of generating power from smaller hydro schemes depends on site characteristics and the hydraulic head with economic viability decreasing as the head reduces.

Solar Energy

Most renewable energy sources are ultimately concentrated forms of solar energy. However, there are two distinct approaches to generating electricity directly:

- Solar thermal engines
- Photovoltaic (PV) cells

Solar thermal engines use a solar collector to create a temperature sufficient to raise steam and drive a turbine-generator. There are a wide range of prototype stations around the world which, unsurprisingly, tend to be in areas that are hot, dry and sunny. The schemes use some form of solar collector to concentrate the sun's rays to a point or series of points. These arrangements include parabolic dishes, solar collector fields that use long lines of planar parabolic mirrors and power towers that rely on surrounding heliostats to reflect light into the power chamber. The devices range from a few hundred kW to several hundred MW schemes that are co-fired with gas. A different approach makes use of the smaller temperature differential at the ocean surface and at great depth. Ocean thermal energy (OTEC) pumps water from both 1000 m at low temperature and at the surface in order to drive a power-vapour cycle (11).

Photovoltaic cells are semi-conductor devices that convert sunlight directly into electricity. It is a well established technology particularly for sites that are far from the distribution network. The cost of PV has dropped significantly and is a promising, low-risk technology – a fact indicated by the involvement of oil companies in their large scale manufacture. The greatest potential for developing PV is to integrate it into buildings as PV modules can substitute for roof or façade elements hence reducing net costs, can be operationally integrated and, being relatively unobtrusive, are unlikely to face public opposition (12).

Wind Energy

Winds are the product of pressure differences in the atmosphere and the wind speed at a given location continuously varies. The power available in from the wind is proportional to the cube of the wind speed. Accordingly, wind turbines are generally sited in areas of high mean wind speed and development of taller, larger capacity turbines has occurred to harness the greater wind speeds at height (due to the wind shear effect near the ground). Wind speed is quite unpredictable and at a given point

fluctuates second by second and over longer periods of time; given the power law, individual wind turbine output varies significantly. Fortunately, wind turbines are commonly connected in substantial groups with aggregation having a marked smoothing effect (12). An enormous variety of designs have been created to extract power from the wind but the three-bladed horizontal axis (HAWT) model is now the industry standard (Figure 3).



Figure 3: Lamb Rigg wind farm, UK.

A desire for economies of scale and the harnessing of higher wind speeds has seen turbine capacities grow significantly to the current standard of around 2 MW. The increase in blade diameter has pushed the overall height of these machines to around 130 m. Larger machines are being used for offshore wind developments of which there are several in the UK and Denmark. Offshore sites tend to benefit from higher wind speeds and lower turbulence levels, resulting in higher energy capture. There are several other advantages of offshore wind as well as a number of negative aspects as Table 5 indicates.

Advantages	Disadvantages
Reduced visual impact	Higher capital costs
Higher mean wind speed	Access restrictions in poor weather
Reduced wind turbulence	Submarine cables required
Low towers due to low wind shear	

Table 5: Advantages and disadvantages of offshore wind (13)

Despite the trend towards larger generators there are a wide range of smaller devices available, including those in the tens of kW range as well as a number of micro-

turbines for battery charging, water heating as well as newer grid-connected versions (e.g. (14)) which are designed to be connected to domestic property.

A number of different approaches have been taken by wind turbine manufacturers in converting the rotational motion into electricity. Some of the main differences include:

- fixed or variable speed operation
- direct drive generators or the use of a gearbox
- stall or pitch regulation

Fixed-speed wind turbines usually use an induction generator via a gearbox and capacitors are required to improve the poor power factor (13). Variable-speed operation increases energy capture by allowing maximum efficiency over a wide speed range. This necessitates a power electronic converter and while this increases losses the rotor acts as a flywheel smoothing the output. Power limitation in high wind speeds is achieved by shedding load either by stall control which relies on the aerodynamics or pitch control which actively turns the blade away from the optimal position. Beyond the cut-out speed which is normally around 25 m/s the turbine shuts down to minimise damage.

Biomass

Biomass is the Earth's living matter and is an enormous store of energy. Historically, biomass was the sole fuel source with material burned for heat and animal and vegetable fats used for lighting. The primary technology was the processing of wood to produce charcoal and allowed temperatures sufficient to extract metals from their ores. While such technologies have been largely superseded in the developed world, bio-fuels still represent around 14% of global primary energy consumption and over a third in developing nations consumption (15).

A whole range of materials can be used as biomass including wood, straw and sewage. The majority decompose quickly so are not very good long term energy stores. In addition, their low energy density (relative to fossil fuels) increases transport costs. This means that biomass power generating units are relatively small compared to conventional plant, relying on local supply chains for feedstock. A range of processes can be used to extract the energy in the biomass (15):

- Direct combustion of raw biomass
- Combustion following physical processing (e.g. chipping, drying)
- Thermal/chemical processing to concentrate the fuel.
- Biological processing such as anaerobic digestion or fermentation.

The direct product of each of these products is heat which may be used locally for heating or chemical processing, to raise steam to generate electricity or a combination of the two as Combined Heat and Power (CHP). As such, modern biomass generation will use electrical technologies common in other thermal generating plant. This is particularly true where biomass (e.g. solid processed sewage) is co-fired with coal; this is becoming increasingly common in the UK.

While biomass generally involves the burning of material it differs from fossil fuels in that no more heat or carbon dioxide is produced than would be produced by natural

processes. As such, it is referred to as 'carbon neutral'. However, it still produces CO₂ and a range of other pollutants including nitrogen oxides, ash but virtually no SO₂. A further environmental benefit is that the combustion of landfill gas avoids accidental explosions and prevents the release of methane which is more potent as a greenhouse gas.

Tidal Power

Tidal power can use either conventional or new technology to extract energy from the tides. It is usually best deployed in areas where there is a high tidal range which includes many areas of the UK as well as the US, New Zealand and parts of the west coast of India.

The conventional approach to extracting tidal energy is to construct a barrage across an estuary or a bay. As the tide rises (floods) and falls (ebbs), it creates a height differential between the inner and outer walls of the barrage. Water can then flow through turbines installed in the barrage and drive generators. Some tidal barrages operate on both the rising and falling tide, but others, particularly estuarine barrages, are designed to operate purely on the falling tide. With basic ebb or flood generation the installed capacity is used for only short periods of three to six hours in each tidal cycle producing a block of power that may or may not coincide with high demand. Fortunately a degree of smoothing of the power output can be achieved and tides can be predicted to a high degree of accuracy. Technology for tidal barrages is essentially the same for hydro schemes with the barrage and axial flow turbines of similar construction to those used in low-head dams.

Very few tidal barrages are in existence worldwide with the exception of the 240 MW La Rance scheme in France and smaller installations in Nova Scotia, Russia and China. The UK has a number of attractive sites due to its high tidal ranges including the Severn (8 GW potential) and the Mersey (700 MW) (16). The scale of these installations and the associated high capital costs mean that the necessary investment is unlikely to be forthcoming within the current privatised electricity supply industry. Their environmental impact is also a major constraint on large-scale developments.

The construction of a large barrier across an estuary would have a major impact on the local estuary although there would be benefits as well as detrimental effects. The La Rance scheme caused the local ecosystem to collapse although it has regenerated (16). There would be a tendency for the water behind the barrage to become less saline as a result of lower sea-water inflows which would tend to allow freshwater flora and fauna to extend seawards. Lower tidal current velocities, particularly on the ebb tide, will tend to reduce sediment erosion or increase sedimentation. A reduction in suspended sediments allows increased sunlight penetration stimulating biological productivity and water level changes would also impact on the mud flats, home to wading sea birds (16).

A more benign approach is to extract energy from the tidal flows that occur between headlands and islands or in and out of estuaries. The power available in these tidal streams varies with the cube of the current velocity and while sea currents are typically around 3 m/s, much lower than minimum velocities required for wind turbines (~7 m/s), the density of seawater is such that the output of tidal stream

devices is much higher than equivalently sized wind generators. The energy flows are significant with around 7.5 GW of accessible resource in Scotland alone (17).

Tidal stream technology, which directly exploits these currents is relatively new but is presently generating considerable interest. Turbine rotors can be used to extract energy from the flows, much as a wind turbine does. Alternative designs use oscillating aerofoils or rotating vertical hydrofoils (Figure 4) to pump oil and generate power. Prototype devices currently on test in the UK include the 300 kW SeaFlow turbine possessing and 11 m diameter rotor attached to a monopile (18). The tidal turbines can be arranged singly or in arrays, allowing a range of power outputs that avoid the massive bursts of power associated with barrage technology. In common with barrages, the output will be variable but to a great extent predictable. In addition to monopiles, tidal devices can be moored to the seabed or perhaps more cleverly secured by an 'active' mooring device designed to allow the easy recovery of the tidal device itself. The 'Snail' (developed at the UK's Robert Gordon University) possesses hydrofoils that press the device onto the seabed.

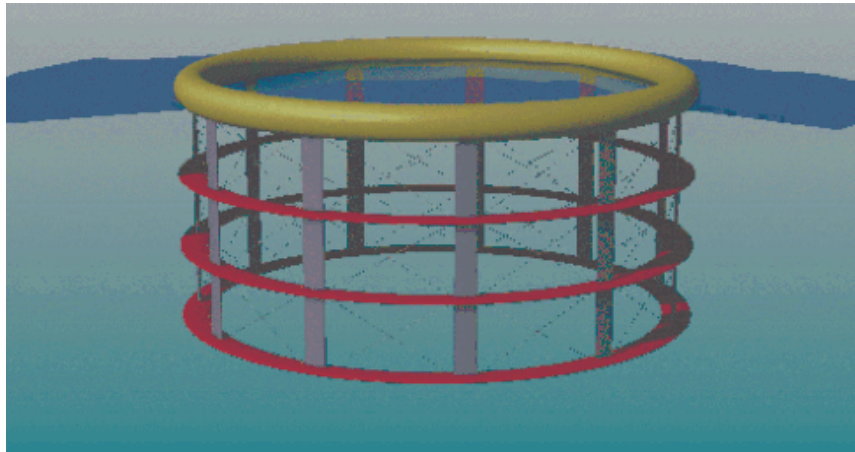


Figure 4: Impression of a large-scale vertical-axis tidal rotor.

Wave Energy

The worldwide wave power resource potential is huge with global power potential estimated to be up to 10 TW, which is the same order of magnitude as world electrical energy consumption. The power in the waves varies with the square of the wave height and is proportional to the period. Island countries are well placed to exploit wave energy with what is considered a huge accessible resource. However when account is taken of practical constraints such as conversion efficiency, shipping lanes and environmental restrictions the resulting practicable resource is significantly reduced.

Waves are primarily driven by the wind with the best wave climates found in the temperate zones (30-60 degrees latitude) where strong storms occur. Among the best locations include the UK, Ireland, Portugal and the Canadian west coast (19). Attractive wave climates are also found within ± 30 degrees latitude where trade winds blow as the lower power levels are compensated by the lower wave power variability.

Since the early 1970s there has been research into developing means of harnessing the power of the waves and various machines have been developed. These fall broadly into three categories:

1. Oscillating Water Column (OWC) devices channel waves into constricted chambers such that as the waves flow in and out of the chamber, they force air in and out of the chamber. These air flows are in turn channelled through a Wells turbine (which turns in the same direction irrespective of the air flow direction) that is used to drive a generator. This type of machine is generally designed to be fixed on or near the shore (or for incorporation into breakwaters) although several floating OWCs are at prototype stage. This kind of machine is the most advanced and is particularly advantageous when incorporated into coastal protection. The UK-based company 'Wavegen' built a shoreline OWC device known as the 'Limpet' on the coast of Islay in Scotland, the first grid-connected wave device.

2. Fixed or semi-fixed machines which harness the hydraulic head in the water that occurs at a submerged point as the wave passes over that point. The pressure differential is used by a variety of means to cause a fluid to flow in a circuit, which is then used to drive a turbine and generator. The Archimedes Wave Swing (AWS) is such a device.

3. Devices which use buoyancy to cause relative movement in order to indirectly drive a generator. Examples include the heaving buoy, rafts and the original wave device, the 'Duck' designed by Professor Stephen Salter at the University of Edinburgh (Figure 5). An example of An Edinburgh spin-out company, Ocean Power Delivery (20) has developed the 'Pelamis', which resembles (and indeed is named after) a sea snake in that it is a long articulated series of tubes that flex as waves run long the length of the device. This device has recently been connected to the grid at the European Marine Energy Test Centre (EMEC) in Orkney.



Figure 5: Early artist's impression of Salter's Duck

Wave Energy Converters (WECs) will be among the least environmentally harmful energy sources (19) with minimal chemical and shipping hazard risk and zero visual impact for offshore devices (although some with shoreline-based devices). There are, however, as yet unconfirmed suggestions of low-frequency effects on marine mammals.

EFFECTIVE USE OF RENEWABLES

Grid Connected

There are difficulties in absorbing the variable and often unpredictable energy of renewable energy sources into the electrical system (21). At the root of the problem is the fact that electrical networks were designed to convey power from large, centrally dispatched thermal and hydropower plants via the high voltage supergrids to customers at lower voltages. The capacities of many renewable sources and their geographical locations means they are being connected at lower voltage distribution levels. The design of the networks together with geographic remoteness from load centres creates a range of technical difficulties such as changes to power flows, voltage variations and rising fault levels among others. A significant academic and industrial research and development effort is concerned with identifying and mitigating the impact of embedded or distributed generation on the electricity network.

A further issue relates to the intermittent nature of the resources, particularly wind, and the ability of the electrical system as a whole to respond to rapidly changing power input. Studies in the UK (22) suggest that at penetrations of 10% there is virtually no impact on network operation. At 20% and above there are issues of raised reserve in the form of part loaded conventional generators as well as standing capacity required for periods of calm and this has economic implications. Denmark currently has well in excess of 20% although this to some extent is due to their connections with the German and Nordic networks that provide much of the response required. The introduction of other renewables is anticipated to partly mitigate the issue of wind intermittency as they are generally more predictable and less variable. Further research is underway in the UK (23) and elsewhere, although it should be noted that other renewables will take many years to make a significant contribution.

Overall, the needs of current electricity systems to maintain power balances on a second-by-second basis and the current approach of trying to get renewable generators to mimic thermal generation creates a range of technical and economic problems for renewables. These range from strict technical requirements for generator capability to network planning and protection which conspire to make the connection of renewables appear fairly expensive. This is compounded by electricity markets that operate around 'firm' power and penalise intermittent sources. An alternative approach that does not try to 'shoehorn' renewables into conventional generation in embracing a more decentralised network will serve to mitigate many of these problems (24).

Alternative Energy Vectors

One of the means of tackling the intermittency issue is to provide a degree of energy storage that accepts fluctuating inputs whilst providing a firm electrical output. A

range of storage technologies are in development including flywheels, superconducting coils and compressed air and oil. While these offer storage solutions on relatively short time frames, the energy density of chemical fuels provides a longer term storage opportunity with the added benefit of creating new energy delivery vectors.

The most commonly mentioned is hydrogen in the context of a new hydrogen economy to supplant the existing carbon-based economy. Iceland has set itself the target of becoming the first all-hydrogen economy and has one of the first hydrogen refuelling stations. Recently, Norsk Hydro has developed one of the Norwegian islands into an all hydrogen system.

While it is possible to create hydrogen (H₂) by reforming natural gas this will require the release of CO₂ which will be difficult to sequester if it is performed on a decentralised basis. However, the electricity from carbon-free nuclear and renewables can be used to electrolyse water (H₂O) forming oxygen (O₂) as a by-product:



The process is appealing as H₂ is excellent for fuel cells in both electricity generation and in vehicles and overall energy conversion efficiencies are over 60% (25). The downside is that large-scale storage and transport of H₂ is difficult although research is looking into how best to store hydrogen, e.g. in carbon nanotubes and prototype H₂-fuelled vehicles are in existence.

An alternative or intermediate approach to the development of a full-scale hydrogen economy would be to convert the hydrogen into hydrogen-rich liquid fuels such as methanol (25), ethanol or even longer chain hydrocarbons. These methods are proven to pilot stage or further (26). Each approach requires a readily available source of CO₂ – in the flues of fossil fuel power stations. This would not only assist in achieving high levels of renewables through chemical buffering but would allow continued use of fossil fuel plant and recycle CO₂ as a hydrogen carrier fuel. However, it would still require the capture of CO₂ from flue gases.

Direct Use

Renewables can also be used directly to provide useful work in chemical processes and elsewhere without the need to integrate with the electrical network. One approach is to use the mechanical energy from renewables such as wind to drive heat pumps to abstract thermal energy from the ambient airstream (or other low-grade heat source such as the ocean). The resulting heat may be delivered at a useful temperature for drying, steam-raising or other thermal processes (27). Processes such as desalination that currently require significant fossil fuel usage could be achieved using renewables such as wind (28) and wave (29).

ECONOMICS OF RENEWABLE ENERGY

Probably the most controversial aspects of renewable energy is their apparent cost relative to conventional forms of generation. It is commonly stated that fossil fuelled generation has a lower cost than renewables with, for example, combined-cycle gas turbines (CCGT) costing 2-3 p/kWh while wind costs 4-5 p/kWh and other

renewables more. Figure 6 shows such a comparison as carried out for the UK's Royal Academy of Engineering (30); these suggest that it would be more economic to invest in gas and nuclear rather than wind and renewables and that the increasing use of renewables will raise electricity prices. There are several critical flaws underlying such interpretations and analyses.

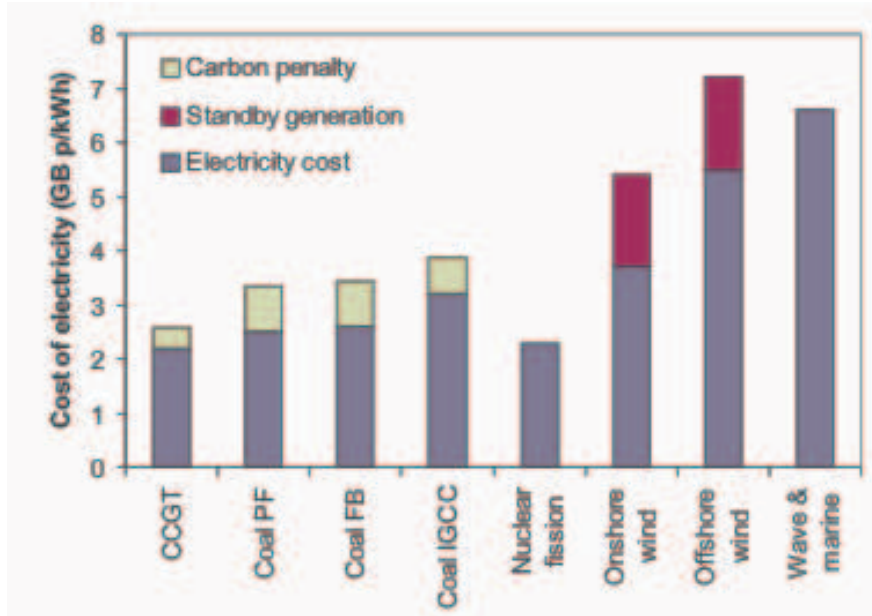


Figure 6: Levelised electricity cost for generating technologies with/without carbon and standby generation for periods of no wind (30).

Firstly, the analyses consider the direct costs associated with generation and ignore the social and environmental cost associated with them. The exclusion of these 'external' costs means that fossil fuels appear cheaper than their true cost. Inclusion of damage costs for SO₂, NO_x and importantly CO₂ make a large difference even if they might be difficult to predict. Estimates of the 'cost' of CO₂ vary significantly but £30 per tonne – at the lower end – is often used in comparisons such as that in Figure 6 which is seen to raise coal generating costs by almost 1 p/kWh (30).

Secondly, the issue of subsidy for renewables is often used as an argument against their deployment and development and that it should be removed to 'level the playing field'. It should be remembered that fossil fuels and particularly nuclear power are mature technologies and have benefited from many decades of development and public subsidy. Although hydro is mature, wind is only just approaching maturity and newer renewables like wave and tidal stream are yet to receive significant development funding. As such, expecting these newer technologies to compete directly is not a reasonable or socially responsible approach; once developed subsidy will not be required.

Thirdly, the standard approach of comparing technologies is inappropriate given the diversity of technologies and an increasingly market-orientated power sector. It is common practice to use the discounted cash flow methodology to calculate the levelised unit cost (p/kWh) of a given technology. It is given by the ratio of the capital and recurring cost stream and the energy output stream, where both streams are discounted at the same rate. The International Energy Agency favours a 7% discount rate while it is common in the UK to use 8 and 15% to represent nominal state and

private sector discount rates. Renewables are, in general, characterised by relatively high capital costs but compensated by low recurring operations and maintenance and zero fuel costs. The use of discounting in this manner means that the full renewable capital costs are seen while the often significant fossil fuel costs are reduced; this automatically biases the outcome in favour of the fossil technology. While nuclear also has large capital costs, discounting lowers the deferred decommissioning costs to a negligible level – again biasing the outcome.

Historically, the levelised cost methodology was used to compare financially similar alternatives, that of hydro with high capital cost and zero fuel costs and coal with similar capital costs and very low fuel costs. As fuel prices have risen and different technologies have become available the comparison has become less and less appropriate and is creating perverse outcomes. The problem stems from the fact that discount rate is, by definition, a reflection of risk. By applying the same discount rate to each generating technology it implies that the risks for each technology are identical. This is clearly not the case.

A more sophisticated approach is to use risk-adjusted discounted cash flow methods that properly account for the non-diversifiable risk associated with fossil fuel price volatility and the lower diversifiable risk associated with capital projects (10). Application of this more robust financial analysis leads to a significant change in the costs of technologies. Table 6 suggests that the renewable technologies become slightly less costly while nuclear and fossil fuels, particularly gas, become significantly more expensive (in some cases the cost more than doubles). Furthermore, the cost rank order alters such that, with the exception of solar thermal, renewables become cheaper than the fossil fuelled and nuclear options.

Technology	Standard approach (US c/kWh)	Risk-adjusted approach (US c/kWh)	% change
Biomass	2.8	3.2	14
Wind	4	3.6	-10
Large hydro	5	4.7	-6
Nuclear	4	5.5	38
Pulverised coal	3.2	6.7	109
CCGT	3	7.2	140
Solar thermal	11.9	11.1	-6

Table 6: Standard and risk-adjusted levelised generation costs (31)

CONCLUSION

This paper outlines the arguments in favour of developing and deploying renewable energy technologies in terms of its environmental, sustainability and security benefits. A range of technologies are briefly examined before the difficulties of integrating these variable and often intermittent generating sources are highlighted along with alternative uses for creating new energy vectors and in direct-use applications. Finally, the economics of renewables were explored with reference to the limitations in traditional comparisons with conventional sources.

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