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CARBON FOOTPRINT OF ELECTRICITY GENERATION

All electricity generation systems have a 'carbon footprint', that is, at some points during their construction and operation carbon dioxide (CO_2) is emitted. There is some debate about how large these footprints are, especially for 'low carbon' technologies such as wind and nuclear. This POSTnote compares the life cycle CO_2 emissions of different electricity generation systems currently used in the UK, including fossil-fuelled and 'low carbon'.

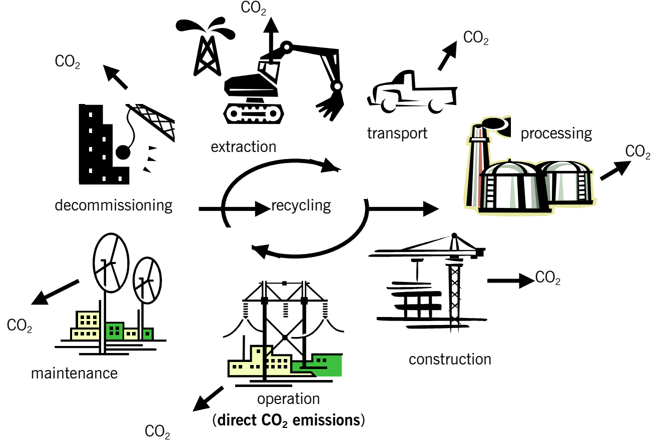
Background

All electricity generation technologies generate carbon dioxide (CO_2) and other greenhouse gas emissions. To compare the impacts of these different technologies accurately, the total CO_2 amounts emitted throughout a system's life must be calculated. Emissions can be both direct – arising during operation of the power plant, and indirect – arising during other non-operational phases of the life cycle. Fossil fuelled technologies (coal, oil, gas) have the largest carbon footprints, because they burn these fuels during operation. Non-fossil fuel based technologies such as wind, photovoltaics (solar), hydro, biomass, wave/tidal and nuclear are often referred to as 'low carbon' or 'carbon neutral' because they do not emit CO_2 during their operation. However, they are not 'carbon free' forms of generation since CO_2 emissions do arise in other phases of their life cycle such as during extraction, construction, maintenance and decommissioning (Fig 1).

What is a carbon footprint?

A 'carbon footprint' is the total amount of CO_2 and other greenhouse gases, emitted over the full life cycle of a process or product.[1] It is expressed as grams of CO_2 *equivalent* per kilowatt hour of generation (gCO_2eq/kWh), which accounts for the different global warming effects of other greenhouse gases. This POSTnote deals only with life cycle CO_2eq emissions from electricity generation. All other emissions are outside the scope of this study.

Figure 1. Life cycle CO_2 emissions for electricity generation technologies



Calculating carbon footprints

Carbon footprints are calculated using a method called life cycle assessment (LCA), and is also referred to as the '*cradle-to-grave*' approach (Box 1).[2] This method is used to analyse the cumulative environmental impacts of a process or product through all the stages of its life. It takes into account energy inputs and emission outputs throughout the whole production chain from exploration and extraction of raw materials to processing, transport and final use. The LCA method is internationally accredited by ISO 14000 standards. The robustness of the method means that although carbon footprints vary between individual power plants, the *ranking* of electricity generation technologies does not change with different sources of data.

Box 1. Life Cycle Assessment (LCA)

A complete LCA consists of four phases: **1**) Goal and scope (boundary) definition; **2**) Inventory analysis (LCI); **3**) Impact assessment (LCIA), and **4**) Interpretation/Improvement. The 'carbon footprint' is just one output from the life cycle inventory (LCI) step.

Life Cycle Inventory (LCI)
The inventory table is the most objective result of a LCA study, referring mainly to measures of mass and energy, i.e. raw materials and energy consumption, and the emission of solid, liquid and gaseous wastes.[3] However, it does not say anything about the environmental *impact* of a particular emitted substance.

Life Cycle Impact Assessment (LCIA)
In this phase all the LCI phase outputs are analysed to determine their impacts.[4] The outputs contribute to impact categories such as global warming potential.

Use of other evidence-based tools
Life cycle assessment cannot replace the decision making process itself. The information needs to be complemented by other considerations such as social and economic aspects. For example, despite the small carbon footprint that LCA of nuclear shows, these analyses are not always sufficient to answer criticisms of the safety and security of nuclear power.

Policy context

The Energy Review

In June 2006, the UK Government's Department of Trade & Industry (DTI) published its Energy Review, assessing progress towards its policy goals set in the 2003 White Paper.[5] However, the broader rationale was also to consider options for the UK's future energy mix in the face of two long-term challenges - climate change and energy security. The review concluded that in order to meet these challenges, diversity of energy supply is essential. In this context, the future role of all kinds of energy supply is currently being debated in the UK.

The Energy Review has attracted parliamentary interest with several select committees looking at the range of options open to the Government in order to meet its White Paper targets. The Commons Environmental Audit Committee has examined options for meeting future requirements for electricity generating capacity, while the Trade and Industry Committee considered new nuclear build.[6] There is also wider European parliamentary interest in energy policy. In March 2006, the European Commission published a Green Paper calling for a common, coherent European energy policy.

Carbon footprints

Fossil fuelled technologies

The carbon footprint of fossil fuelled power plants is dominated by emissions during their operation. Indirect emissions during other life cycle phases such as raw material extraction and plant construction are relatively minor.

Coal burning power systems have the largest carbon footprint of all the electricity generation systems analysed here. Conventional coal combustion systems result in emissions of the order of >1,000 gCO_2eq/kWh. Lower emissions can be achieved using newer gasification plants (<800gCO_2eq/kWh), but this is still an emerging technology so is not as widespread as proven combustion technologies. In 2003 there were only four coal gasification plants operating worldwide and none yet in the UK (POSTnote 235, Cleaner Coal). Future developments such as carbon capture and storage (CCS) and co-firing with biomass have the potential to reduce the carbon footprint of coal-fired electricity generation (see Issues).

Oil accounts for only a very small proportion (1%) of the electricity generated in the UK. It is primarily used as a back-up fuel to cover peak electricity demand periods. The average carbon footprint of oil-fired electricity generation plants in the UK is ~650gCO_2eq/kWh.

Current gas powered electricity generation has a carbon footprint around half that of coal (~500gCO_2eq/kWh), because gas has a lower carbon content than coal. Like coal fired plants, gas plants could co-fire biomass to reduce carbon emissions in the future.

Low carbon technologies

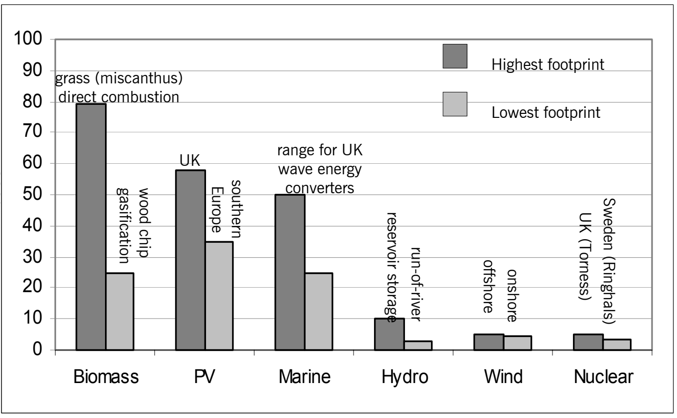
In contrast to fossil fuelled power generation, the common feature of renewable and nuclear energy systems is that emissions of greenhouse gases and other atmospheric pollutants are 'indirect', that is, they arise from stages of the life cycle other than power generation.

Biomass

Biomass is obtained from organic matter, either directly from dedicated energy crops like short-rotation coppice willow and grasses such as straw and miscanthus, or indirectly from industrial and agricultural by-products such as wood-chips. The use of biomass is generally classed as 'carbon neutral' because the CO_2 released by burning is equivalent to the CO_2 absorbed by the plants during their growth. However, other life cycle energy inputs affect this 'carbon neutral' balance, for example emissions arise from fertilizer production, harvesting, drying and transportation.

Biomass fuels are much lower in energy and density than fossil fuels. This means that large quantities of biomass must be grown and harvested to produce enough feedstock for combustion in a power station. Transporting large amounts of feedstock increases life cycle CO_2 emissions, so biomass electricity generation is most suited to small-scale local generation facilities, or operating as combined heat and power (CHP) plants.[7] The range of carbon footprints for biomass is related to the type of organic matter and the way it is burned (Fig 2). Combustion of low density miscanthus results in higher life cycle emissions (93gCO_2eq/kWh), than gasification of higher density wood-chip (25gCO_2eq/kWh).[8] Biomass can also be 'co-fired' with fossil fuels in conventional power stations. Replacing a component of the fossil fuel with 'carbon neutral' biomass reduces the overall CO_2 emissions from these power stations (see Issues).

Figure 2. Range of carbon footprints for UK & European 'low carbon' technologies



*Source: DTI, UK Elsayed et.al., **2004***

*Source: Northumbria Uni UK, **2006** (based on Utrecht Uni study **2000**)*

*Source: Carbon Trust UK **2006***

*Source: WEC non-alpine European **2004***

*Source: Vestas, Denmark & BWEA, UK **2005***

*Source: Torness, UK **2006** Ringhals, Sweden **2004***

Photovoltaics (PV)

Photovoltaics (PV), also known as solar cells, are made of crystalline silicon, a semi-conducting material which converts sunlight into electricity. The silicon required for PV modules is extracted from quartz sand at high temperatures. This is the most energy intensive phase of PV module production, accounting for 60% of the total energy requirement. Life cycle CO_2 emissions for UK photovoltaic power systems are currently 58gCO_2eq/kWh (Fig 2). However, future reductions in the carbon footprint of PV cells are expected to be achieved in thin-film technologies which use thinner layers of silicon, and with the development new semi-conducting materials which are less energy intensive (see Issues). Life cycle CO_2 emissions are lower for PV systems operating in southern Europe, (35gCO_2eq/kWh), because there is more sunlight, so overall operating hours are greater and energy output is higher.

Marine technologies (wave and tidal)

There are two types of marine energy devices; wave energy converters and tidal (stream and barrage) devices. Marine based electricity generation is still an emerging technology and is not yet operating on a commercial scale in the UK. Some prototypes are being tested at the European Marine Energy Centre (EMEC), in Orkney. Because these technologies are still at this early stage, no formal life cycle analyses have been carried out. However, the Carbon Trust's 2006 report on *Future Marine Energy* gives an example of life cycle analysis for a wave energy converter. Most CO_2 is emitted during manufacture of the structural materials, and a wave converter device presently requires 665 tonnes of steel. Life cycle emissions for this type of marine technology is estimated between 25-50gCO_2eq/kWh, roughly equivalent to life cycle CO_2 emissions from current PV technologies (Fig 2).

Hydro

Hydropower converts the energy from flowing water, via turbines and generators, into electricity. There are two main types of hydroelectric schemes; storage and run-of-river. Storage schemes require dams. In run-of-river schemes, turbines are placed in the natural flow of a river. Once in operation, hydro schemes emit very little CO_2, although some methane emissions do arise due to decomposition of flooded vegetation. Storage schemes have a higher footprint, (~10-30gCO_2eq/kWh), than run-of-river schemes as they require large amounts of raw materials (steel and concrete) to construct the dam.[9] Run-of-river schemes have very small reservoirs (those with weirs) or none at all so do not give rise to significant emissions during their operation. Carbon footprints for this type of hydro scheme are some of the lowest of all electricity generation technologies (<5gCO_2eq/kWh).

Wind

Electricity generated from wind energy has one of the lowest carbon footprints. As with other low carbon technologies, nearly all the emissions occur during the manufacturing and construction phases, arising from the production of steel for the tower, concrete for the foundations and epoxy/fibreglass for the rotor blades.[10] These account for 98% of the total life cycle CO_2 emissions. Emissions generated during operation of wind turbines arise from routine maintenance inspection trips. This includes use of lubricants and transport. Onshore wind turbines are accessed by vehicle, while offshore turbines are maintained using boats and helicopters. The manufacturing process for both onshore and offshore wind plant is very similar, so life cycle assessment shows that there is little difference between the carbon footprint of onshore (4.64gCO_2eq/kWh) versus offshore (5.25gCO_2eq/kWh) wind generation (Fig 2).[11] The footprint of an offshore turbine is marginally greater because it requires larger foundations.

Nuclear

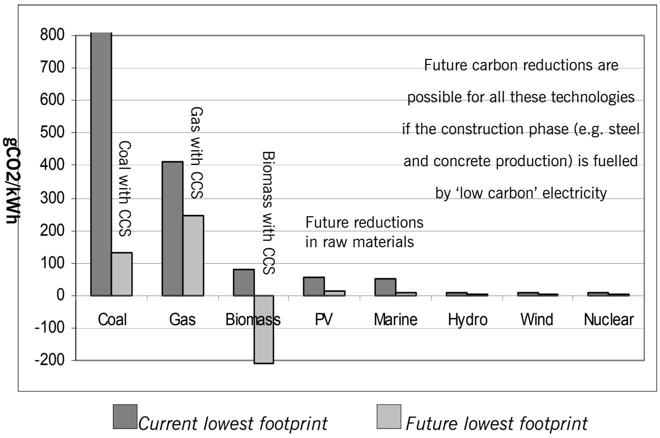
Nuclear power generation has a relatively small carbon footprint (~5gCO_2eq/kWh) (Fig 2). Since there is no combustion, (heat is generated by fission of uranium or plutonium), operational CO_2 emissions account for <1% of the total. Most emissions occur during uranium mining, enrichment and fuel fabrication. Decommissioning accounts for 35% of the lifetime CO_2 emissions, and includes emissions arising from dismantling the nuclear plant and the construction and maintenance of waste storage facilities.[12] The most energy intensive phase of the nuclear cycle is uranium extraction, which accounts for 40% of the total CO_2 emissions. Some commentators have suggested that if global nuclear generation capacity increases, higher grade uranium ore deposits would be depleted, requiring use of lower grade ores. This has raised concerns that the carbon footprint of nuclear generation may increase in the future (see Issues)

Issues

Future carbon footprint reduction

The greatest potential for carbon footprint reduction is in conventional fossil fuelled electricity generation, using improved combustion technologies, carbon capture and storage and co-firing with biomass (Fig 3). All the technologies examined here have the potential to reduce their carbon footprint.

Figure 3. Current and future carbon footprints



(UK, European, USA and Australian power plants)

Fossil fuel generation – future carbon footprint

Technology improvements could increase the energy efficiency of existing coal fired plants from current levels of ~35% (where only 35% of the fuel energy is converted into electricity) to over 50%. Improvements in energy efficiency can halve life cycle carbon emissions in both coal and gas fired plants (Fig 3). Carbon capture and storage (CCS) could potentially avoid 90% of CO_2 emissions to the atmosphere in the future (POSTnote 238, Carbon capture and storage). However, this technology has not yet been demonstrated within the electricity generation industry.

Co-firing fossil fuels and biomass

Co-firing biomass along side fossil fuels in existing power plants can also significantly lower their carbon emissions, because the fossil fuels are replaced by 'carbon neutral' biomass. Trials of wood co-firing with coal are ongoing at coal-fired power stations in the UK, for example, at Drax. Biomass energy crops are currently more expensive than coal, although by co-firing biomass, power stations operators can earn Renewables Obligation Certificates (ROCs) which makes co-firing economically viable. In 2001 a dedicated biomass gasification plant (ARBRE) was constructed in the UK, but technical difficulties forced it closure. In 2005, E.ON announced plans to a build the UK's largest dedicated biomass plant (44MW) in Lockerbie, Scotland due to commence operation in 2007.

Future carbon footprint reductions in all technologies

Carbon footprints could be further reduced in all electricity generation technologies if the manufacturing phase and other phases of their life cycles were fuelled by low carbon energy sources. For example, if steel for wind turbines were made using electricity generated by wind, solar or nuclear plants. Using less raw materials would also lower life cycle CO_2 emissions, especially in emerging technologies such as marine and PV. New semi-conducting materials (organic cells and nano-rods), are being researched for PV as alternatives to energy and resource intensive silicon.[13] Biomass has the potential to generate electricity with 'negative' CO_2 emissions (Fig 3). Burning 'carbon neutral' biomass and capturing the emissions using carbon capture and storage (CCS) technologies would result in a net removal of CO_2 from the atmosphere. Studies show that a 'negative emission' of up to -410gCO_2/kwh can be achieved.[14] However, some researchers suggest that CCS, intended for large fossil-fuelled plants (>1,000MW), would not be adopted for smaller capacity biomass plants, typically <50MW.[15]

Future nuclear footprint & global uranium resources

Some analysts are concerned that the future carbon footprint of nuclear power could increase if lower grade uranium ore is used, as it would require more energy to extract and refine to a level usable in a nuclear reactor. However, a 2006 study by AEA Technology calculated that for ore grades as low as 0.03%, additional emissions would only amount to 1.8gCO_2eq/kWh. This would raise the current footprint of UK nuclear power stations from 5 to 6.8gCO_2eq/kWh (Fig 3). If lower grades of uranium are used in the future the footprint of nuclear will increase, but only to a level comparable with other 'low carbon' technologies and will not be as large as the footprints of fossil fuelled systems.

Overview

- All electricity generation technologies emit CO_2 at some point during their life cycle. None of these technologies are entirely 'carbon free'.
- Life cycle inventory analysis is used to measure the amount of CO_2 emitted by each technology.
- Fossil fuelled electricity generation has the largest carbon footprint (up to 1,000gCO_{2eq}/kWh). Most emissions arise during plant operation.
- 'Low carbon' technologies have low life cycle carbon emissions (<100gCO_2eq/kWh). Most CO_2 is emitted during non-operational phases.
- Future carbon footprints can be reduced for all electricity generation plants if high CO_2 emission phases are fuelled by low carbon energy sources.

Endnotes

1 Carbon Calculations over the Life Cycle www.surrey.ac.uk/CES/CCalC/
2 World Energy Council Report 2004, *Comparison of energy systems using life cycle assessment.*
3 www.pre.nl/life_cycle_assessment/life_cycle_inventory.htm
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5 www.dti.gov.uk/energy/energy-policy/energy-white-paper/
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15 *pers. comm.* Prof Roland Clift, University of Surrey, 2006

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