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Carbon Footprint of Electricity Generation

In 2006, POSTnote 268 outlined the "carbon footprints" of a variety of electricity generation technologies. Footprint data were scarce at that time, particularly peer-reviewed estimates. This POSTnote provides an updated overview of the evidence base in 2011, including estimates from more than 30 peer-reviewed studies.

Overview

- All electricity generation technologies emit greenhouse gases at some point in their life cycle and hence have a carbon footprint.
- Fossil-fuelled generation has a high carbon footprint, with most emissions produced during plant operation. "Carbon capture and storage" could reduce these significantly, though this is unproven at full scale.
- Nuclear and renewable generation generally have a low carbon footprint. Most emissions are caused indirectly, such as during the construction of the technology itself.
- Carbon footprints are sensitive to factors including the technology's operating conditions and country of its manufacture.
- Further studies for the UK would improve the evidence base.

Background

International negotiations and national targets seek to reduce greenhouse gas (GHG) emissions significantly and limit the risks of dangerous climate change. In the UK, the Climate Change Act (2008) requires a reduction in emissions of 80% by 2050 compared with 1990 levels. It also expects Parliament to set successive five-year "carbon budgets" to limit emissions along the way. The fourth budget equates to a reduction in annual emissions of 50% from 1990 levels for the period 2023-27.[1]

The electricity sector has a key role to play in meeting these budgets. Average emissions from electricity generation fell from 718 gCO_2eq/kWh in 1990 to 500 gCO_2eq/kWh in 2008 (Box 1).[2] The Committee on Climate Change (CCC) recommends a further reduction to just 50 gCO_2eq/kWh by 2030 to support achievement of the national budgets.[3]

These figures consider only the emissions caused directly at the point of electricity generation, such as when coal is burnt in a coal-fired power station. To provide a more complete picture of the emissions caused by generation technologies, all stages of their life cycles must be considered. These include their construction and maintenance; the extraction, processing and transport of their fuels (if applicable); and their ultimate decommissioning and disposal.

Box 1. Quantifying Greenhouse Gas (GHG) Emissions
The units 'gCO_2eq/kWh' are grams of carbon dioxide equivalent per kilowatt-hour of electricity generated. Carbon dioxide is the most significant GHG and is produced, for example, when fossil fuels are burnt. GHGs other than carbon dioxide, such as methane, are quantified as equivalent amounts of carbon dioxide. This is done by calculating their global warming potential relative to carbon dioxide over a specified timescale, usually 100 years.

Carbon Footprints

A *carbon footprint* aims to account for the total quantity of greenhouse gas emitted over the whole life cycle of a product or process. It is calculated by the method of *life cycle assessment* (POSTnote 268). In practice, it can be difficult to analyse the complete life cycle because some stages, such as end-of-life management, may be uncertain. The analysis nevertheless provides a more comprehensive view than considering only direct emissions in isolation.

This POSTnote describes the carbon footprints of a variety of electricity generation technologies. Box 2 describes how data have been selected and presented in the figures. Data generally refer to existing rather than future technology, and are international in their scope rather than specific to the UK. The footprints aim to consider all emissions up to and including the process of electricity generation, and ignore:

- downstream emissions, such as those caused by the construction of transmission cables and consumer appliances, and;
- alternatives to direct electricity generation, such as heating technologies and combined heat-and-power plants. These offer further and sometimes alternative ways of providing energy services to consumers.

Box 2. Data Selection and Presentation
Carbon footprint estimates are influenced by the conditions and assumptions of each study, including:

- the scope and methodology of the analysis;
- the specific design of the technology within each broad category;
- the country of manufacture of the technology and its components;
- the operating conditions and lifetime of the technology.

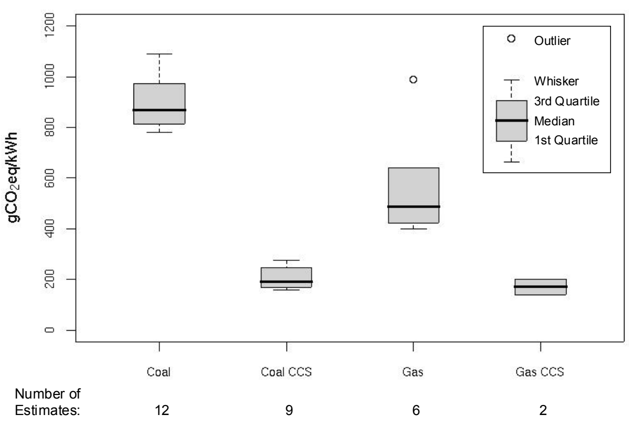
These often vary between studies, making it difficult to compare and summarise results. With the aim of providing a pragmatic and impartial summary of the evidence:

- only footprint data from published, peer-reviewed studies were included in the main analysis summarised by the figures. Peer review does not guarantee integrity of results but does mean that studies have been formally and independently reviewed. The data search was international in scope due to a scarcity of peer-reviewed UK studies.
- the data are displayed as box plots[4] to show their spread and to indicate outliers. (Outliers are defined as estimates that reside further than 1.5 times the inter-quartile range from the median.[4]) The number of footprint estimates given in each figure is greater than the number of referenced studies because some studies consider multiple scenarios (e.g. different deployment conditions). The figures do not necessarily reflect true maximum or minimum values or any central tendency for conditions in the UK.
- where there was a lack of peer-reviewed data for the UK, non-peer reviewed studies are quoted in the text but excluded from the figures.

Fossil-Fuelled Technologies

Figure 1 gives carbon footprint data for coal and gas-fired electricity generation, with and without potential carbon capture and storage (CCS) technology. The footprints are dominated by the emissions produced directly as fuel is burnt during plant operation, as opposed to indirectly, such as those arising during construction. Direct emissions are influenced mainly by generating efficiency but also the specific type of fuel (e.g. lignite vs higher-grade coal).

Fig 1. International Carbon Footprints of Fossil-Fuel Electricity



Coal

Within the range of international carbon footprint estimates shown on Figure 1,[5,6,7,8,9,10,11,12] three studies give figures for existing UK plant of 786,[10] 846,[11] and 990[12] gCO_2eq/kWh. In general, the improved generation efficiencies of newer designs of plant (POSTnote 253) give footprints at the lower end of the range shown in Figure 1.

Gas

Figure 1 shows footprint estimates for six European gas generation scenarios from three studies.[7,8,13] The lowest carbon footprints are achieved by the most efficient generation technology – combined cycle gas turbines (CCGT) – which predominate in the UK. One UK study[8] gives a footprint of 488 gCO_2eq/kWh for a CCGT. More recent research from Imperial College London[14] and separately at the University of Manchester[15] is indicating that UK CCGT footprints can be as low as 365 gCO_2eq/kWh for modern technology, but these estimates are excluded from the figure because they have not yet been peer-reviewed and published.

The type and source of gas used for electricity generation can have a significant effect on the carbon footprint. Domestic supplies of North Sea gas are in decline and so imports are increasing, reaching 32% of UK supply in 2009. These come either by pipeline or, as liquefied natural gas (LNG), by ship. Research in the USA estimates that the footprint of electricity from imported LNG is 20-25% higher than from US-produced gas[16,17] due to the additional energy requirement and hence emissions associated with its processing and shipping. This is an active area of research in the UK: recent but unpublished estimates suggest that the use of 100% LNG would increase the footprint of modern CCGTs, though figures vary widely from 4%[14] to 31%.[15]

Natural gas is composed mainly of methane, which is itself a greenhouse gas (Box 3). The footprint of gas generation is influenced by the “fugitive” emissions of methane that arise during its production and transport, for example via pipeline leakages. Researchers have found fugitive emissions to be greater than previously thought in the USA, increasing the footprint of US natural gas.[18] They also found that the fugitive emissions and hence footprint of US “shale gas” (POSTnote 374) to be greater than those of “conventional” gas. Shale gas has gained much recent attention, including in the UK, following its major exploitation in the USA.[19]

Box 3. The Global Warming Potential of Methane
Methane is a more potent greenhouse gas than the CO_2 produced when it is burnt for electricity generation, but it also has a tenfold shorter residence time in the atmosphere so its effect reduces more rapidly.[18] The common practice is to quantify the global warming potential of GHGs relative to carbon dioxide over a one hundred year timescale (Box 1), reflecting the aim of minimising long-term climate change. In this case, the warming potential of methane is generally taken to be 25 times that of CO_2,[20] and each unit of methane is therefore counted as 25 units of CO_2 equivalent. (Recent modelling has suggested that the ratio should be as high as 33.[18]) By contrast, a shorter 20 year timescale gives a global warming potential of methane of 72[20] to 105[18] times that of CO_2.

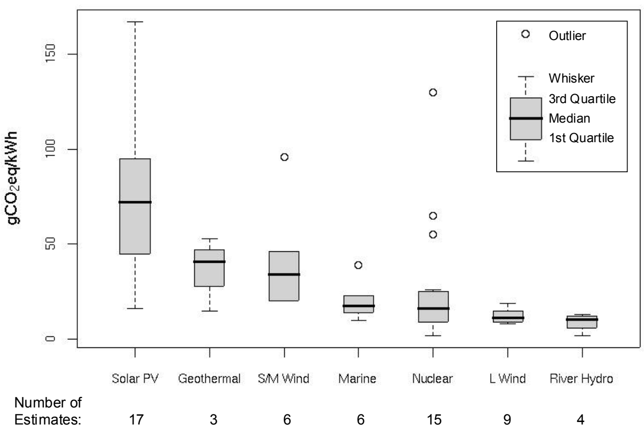
Carbon Capture and Storage (CCS)

CCS technologies (POSTnote 335) have the potential to reduce emissions from fuel combustion considerably, but are yet to be proven feasible at full scale.[21] Modelling of future coal-fired generators with CCS has produced carbon footprints ranging from 160 to 280 gCO_2eq/kWh (Figure 1).[7,8,9,10,11] For gas, the carbon footprint of a modelled CCGT with CCS was 200 gCO_2eq/kWh in a UK study[8] and 140 gCO_2eq/kWh in a German study[7] (Figure 1). Recent but as yet unpublished research at Imperial College London has modelled gas CCS with a much lower footprint of 56 gCO_2eq/kWh.[14]

Low-Carbon Technologies

Figure 2 summarises footprint data for “low carbon” generation technologies. In many cases, emissions do not arise directly from the operation of the generators and so footprints are dominated by indirect emissions, such as those produced during construction and the production of fuels (where applicable). For generators based on ambient energy flows, such as solar energy, the local energy resource also has an important influence on the footprint. This is because higher electricity outputs cause lower footprints, as total emissions are spread over a greater amount of electricity.

Fig 2. International Carbon Footprints for Low-Carbon Electricity



Solar

A range of international footprints for solar photovoltaic (PV) systems is represented in Figure 2.[6,22,23,24,25,29] One UK study[22] gives a figure of 88 gCO_2eq/kWh for a residential PV system in a typical UK installation, which ranges from 75 to 116 gCO_2eq/kWh under different operating conditions. The PV cells of this system were made of mono-crystalline silicon – a dominant technology. Carbon footprints for such systems have been falling due to improvements in production techniques.[26] Some novel alternatives to mono-crystalline silicon technologies are demonstrating carbon footprints at the lower end of the range shown in Figure 2.[25,29] Many studies ignore the disposal stage for PV, often citing the uncertainty that arises because few installed systems have yet reached the end of their lives.

Geothermal

Geothermal electricity plant use heat from deep underground to drive conventional steam-powered generators. Three recent international studies estimated footprints of 15 to 53 gCO_2eq/kWh (Figure 2).[6,24,27] One of these[27] suggests that footprints are very much influenced by the geological conditions at the plant’s location, reporting ‘best case’ and ‘worst case’ scenarios of around 6 and 750 gCO_2eq/kWh respectively. However, these extremes are unlikely in real-world settings[27] and so neither value was included in Figure 2. They nevertheless highlight that, as with all technologies, plant must be constructed and operated effectively to ensure that they produce ‘low carbon’ electricity.

Nuclear

Figure 2 summarises carbon footprint estimates for various countries and operating conditions, but not for the UK.[6,13,28,29,30,31,32] The majority of estimates fall below 26 gCO_2eq/kWh, though the outliers indicate that footprints can be higher. This variation arises from the general factors outlined in Box 2 and also from nuclear-specific issues, particularly the grade of the uranium ore and the method of uranium enrichment.[30,33,34] There are also uncertainties regarding waste disposal and decommissioning.[34] For current UK conditions, recent but unpublished research from the University of Manchester[15,35] estimates a footprint of 6.4 gCO_2eq/kWh for a new build plant. Non-peer reviewed estimates produced by AEA Technology for existing UK plants are 5.5 gCO_2eq/kWh for Sizewell B[36] and 7 gCO_2eq/kWh for Torness.[37]

Marine (Wave and Tidal)

Marine technologies are based on wave power (caused by the wind) or tidal power (POSTnote 324). Figure 2 shows carbon footprint estimates from two UK studies carried out by researchers in Edinburgh. One is of a first-generation wave device (“Pelamis”), with a baseline estimate of 23 gCO_2eq/kWh and a range of 12 to 39 gCO_2eq/kWh.[38] The other is of a first-generation tidal stream turbine (“Seagen”), with a baseline estimate of 15 gCO_2eq/kWh and a range of 10 to 20 gCO_2eq/kWh.[39] The researchers included recycling as a disposal option, and reduced the carbon footprint of each device by the amount of carbon saved by recycling its components at the end of its lifetime. Recycling may create carbon savings because it usually takes less energy to produce recycled materials than raw materials. International standards (POSTnote 268) allow this approach to carbon footprinting. If the credit is excluded, the estimated footprints are the upper value of each range quoted above.

Tidal barrages are another option for marine electricity generation (POSTnote 324). For the UK, a feasibility study for various possible Severn barrages included non-peer reviewed estimates of carbon footprints among a range of environmental impacts.[40] These vary between -20 and 50 gCO_2eq/kWh. The negative footprints (net emissions reductions) arise from a high level of assumed carbon sequestration, resulting from a deposition of silt upstream of the barrage.[40]

Wind

Figure 2 shows international footprint estimates for onshore wind turbines, distinguishing broadly between large (greater than 500 kW in rated power) and smaller scales.[5,24,31,41,42,43,44] As with all generation technologies that depend on the local energy resource, location can have an important effect on the carbon footprint. For example, figures from one UK study[44] indicate that a micro-wind turbine would have a carbon footprint of around 38 gCO_2eq/kWh for locations with an average annual wind speed of 4.5 m/s. This is the minimum wind speed recommended for small wind systems by the industry trade body, RenewableUK.[45] The same study indicated that locations with average wind speeds of 6 m/s would give footprints of 20 gCO_2eq/kWh, while locations of 3 m/s would give 96 gCO_2eq/kWh (the outlier shown on Figure 2).

For offshore wind, two peer-reviewed studies give footprints of 9 and 13 gCO_2eq/kWh.[24,41] These are excluded from Figure 2 due to space constraints; they are within the range shown for large onshore wind. The Thanet offshore wind farm, which opened in September 2010 off the coast of Kent, is made up of 300 Vestas V90 turbines. A recent study by Vestas,[46] which was reviewed by an external consultant but not formally peer-reviewed, estimated the carbon footprint of an offshore V90 turbine to be 5.2 gCO_2eq/kWh for an installation off the coast of Denmark.

Hydro

Hydro-electric plant produce electricity from flowing water, either within a river ("run-of-river" technologies) or from water released from a dammed reservoir. Figure 2 summarises four international estimates for run-of-river hydro technologies, which range from 2 to 13 gCO_2eq/kWh.[6,24,47] Reservoir schemes appear to have higher carbon footprints than run-of-river devices due to the extra materials required for dam construction (POSTnote 268). In addition, in areas flooded when the reservoir fills, decaying plant material can produce methane. Uncertainty remains over such emissions and reservoir hydro has thus been excluded from Figure 2.

Bioenergy

Bioenergy is a fuel obtained from organic matter. It can come either from dedicated energy crops or as a by-product or waste of other processes. Depending on the source, bioenergy is processed to produce solid biomass (e.g. wood chips), biogas (e.g. from landfill) or bioliquids (e.g. biodiesel). The significant diversity of bioenergy options and methods of production gives rise to wide variation in carbon footprints,[48] and researchers have emphasised the need for location-specific assessments.[49] Because of this and the scarcity of UK-specific, peer-reviewed studies, bioenergy is excluded from Figure 2.

Reports for the government[50] and the Environment Agency[48] have found that the carbon footprint of electricity from bioenergy is generally, but not always, lower than the least carbon intensive fossil-fuel option, gas-fired CCGTs. For example, electricity generated through combustion of short-rotation coppice wood chips has an estimated carbon footprint of 60 to 270 gCO_2eq/kWh,[48] which in all cases is below the lowest UK CCGT figure of 365 gCO_2eq/kWh reported above. For straw, however, footprints range from 200 to 550 gCO_2eq/kWh.[48] An earlier report for the government[51] suggested that electricity generated via two alternatives to direct combustion – gasification and pyrolysis – has a lower carbon footprint. It gave footprints as low as 25 gCO_2eq/kWh for electricity from the gasification of wood chips from forestry residue or short rotation coppice.

In addition to being used on its own for electricity generation, biomass can be blended and "co-fired" with coal.[52] Recent research has considered various options for replacing up to 10% of coal with biomass.[53] It found that the biomass component reduces GHG emissions by 88 to 97% compared to the coal it displaces.

If used in conjunction with CCS, bioenergy-based electricity has the scope to provide net reductions in emissions. Atmospheric carbon dioxide is absorbed by vegetation as it grows, and, using CCS, could be captured and stored when it is subsequently burnt for electricity generation.

The government is introducing a limit of 285 gCO_2eq/kWh in 2013 for electricity generated from solid biomass and biogas. It is part of a set of sustainability criteria that generators will have to meet to be eligible for financial support in the form of Renewables Obligation Certificates.[54]

Concluding Remarks

Most of the carbon footprints summarised in this POSTnote are based on data for existing processes and technologies; these data will change over time. For example, energy is used for construction, and a reduction in the emissions from that energy would reduce the footprints of future technology. Footprints would also be reduced by improved operating performance, which are likely as technologies develop. The method of life cycle assessment can be used to identify these trends. The general need for location-specific and up-to-date analysis suggests that further studies for the UK would improve the evidence base for policy makers.

The composition of carbon footprints and their sensitivity to underlying assumptions varies among technologies and further work could investigate this. For example, the construction stage is a significant contributor to the footprint of most low-carbon technologies. In such cases, footprints are sensitive to the inclusion of recycling credits. This was illustrated by the marine example described above, where this significance was made apparent by a clear sensitivity analysis in the underlying research.

There are many other impacts of electricity generation beyond the emission of greenhouse gases. LCA assesses a wider range of environmental impacts, such as the production of particulates or requirements for water, and can be combined with other techniques from the physical sciences and from economics to provide more comprehensive assessments.[22,55]

Endnotes

For references please see http://goo.gl/2DXRB

POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of policy issues that have a basis in science and technology.
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