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Sustainability indicators for the assessment of nuclear power

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A B S T R A C T

Electricity supplies an increasing share of the world's total energy demand and that contribution is set to increase. At the same time, there is increasing socio-political will to mitigate impacts of climate change as well as to improve energy security. This, in combination with the desire to ensure social and economic prosperity, creates a pressing need to consider the sustainability implications of future electricity generation. However, approaches to sustainability assessment differ greatly in their scope and methodology as currently there is no standardised approach. With this in mind, this paper reviews sustainability indicators that have previously been used to assess energy options and proposes a new sustainability assessment methodology based on a life cycle approach. In total, 43 indicators are proposed, addressing the techno-economic, environmental and social sustainability issues associated with energy systems. The framework has been developed primarily to address concerns associated with nuclear power in the UK, but is applicable to other energy technologies as well as to other countries.

1. Introduction

Sustainable development has, as its key tenet, the concept of continuing prosperity for all people in both current and future generations [1]. Its relevance to the electricity sector is abundantly clear when the pervasive nature of electricity is considered: as an extremely adaptable 'high-grade' energy source [2] it has become fundamental to almost all aspects of modern life. Commerce, government, households and many forms of recreation rely on it, and this reliance has increased considerably in the last four decades [3]. Indeed, it is set to increase further, principally due to changes in the transport sector: projected trends in policy and vehicle production [see Ref. [4]] point towards an increase in the proportion of battery- and hydrogen-powered vehicles, both of which depend on electricity.

It is extremely important, therefore, that more sustainable energy options are identified and pursued in order to maximise the welfare of society, environment and economy. To work towards this goal, the current electricity supply must first be considered.

In the UK, the total electricity demand in 2009 was approximately 380 TW h, constituting 18% of total energy consumption [5] and approximately a third of national CO_2 emissions [6]. The UK's electricity mix, shown in Fig. 1, is currently dominated by coal (27%), gas (45%) and nuclear (17%), with renewable sources (predominantly hydroelectricity and wind) playing a much smaller role (~7%) [5].

Due to the current socio-political prominence of climate change, progressive emissions regulations and the advent of carbon trading, fossil fuels are gradually becoming less favourable as a source of energy. This is accentuated by the UK government target to reduce CO_2 emissions by 80% by 2050 [7]. As fossil fuels currently provide approximately 75% of UK electricity and the government anticipates only 15% of production coming from renewable sources by 2020 [8], a decline in fossil fuel power stations would leave a large deficit in installed capacity. At the same time, nuclear power has become a point of increasing interest due to its low life cycle carbon emissions and its perceived reliability: for example, the pressurised water reactor (PWR) at Sizewell B (Suffolk) has an average availability factor of 89% [10]. Although other, older UK reactors such as some advanced gas cooled reactors (AGRs) operate less reliably, the two reactor designs currently proposed for new build in the UK are both PWRs [11,12] and might therefore be expected to behave similarly to Sizewell B.

At the time of writing, National Grid has agreed 16.7 GW of potential grid connections at eight proposed nuclear sites in the UK by 2025 [13]. Utility companies currently have 19 GW of new nuclear capacity planned or proposed in the UK [14]. These figures compare to the current UK net operating capacity of around 10 GW (see Table 1). This apparent shift towards a more nuclear-intensive grid requires a thorough assessment of the potential of nuclear power to contribute to sustainable development.

There are many frameworks for sustainability assessment. One of the more prominent and widely used is that developed by the Global Reporting Initiative (GRI) [17]. However, although sector specific GRI

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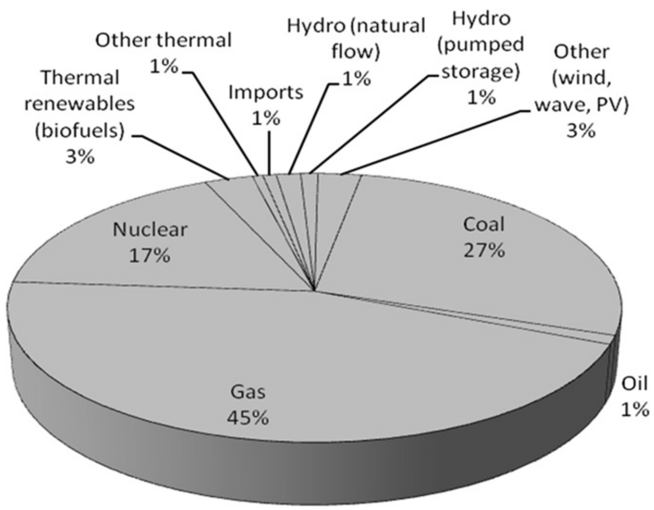

Fig. 1. Breakdown of the UK electricity supply in 2009, by fuel type (based on data from Ref. [5]).

indicators are available [18], the framework is aimed at measuring corporate sustainability and is less applicable to assessment at the project, technology or policy level. Other sustainability frameworks are similarly unsuitable for the examination of electricity-generating technologies. For example, the UN, the International Atomic Energy Agency (IAEA) and at least 15 countries have proposed sustainability indicators for the assessment of national development [19–35]. However, there is currently no framework by which the sustainability of nuclear power and alternative electricity options might be assessed for use in the UK. In an attempt to address this gap, we present a novel indicator framework designed specifically for that purpose. Although the work is motivated by the need to assess the sustainability of nuclear power in the UK, the framework is generic and applicable to any electricity technology regardless of its location.

2. A framework for assessing the sustainability of nuclear power in the UK

It is widely recognised and accepted that sustainability assessments should take a life cycle approach, taking into account all relevant techno-economic, environmental and social sustainability issues. Therefore, the framework proposed here follows this approach. This ensures that alternatives to nuclear power can be compared on an equivalent basis and also allows identification of ‘hot spots’, indicating opportunities for improvement from ‘cradle to grave’.

Table 1
Nuclear plants currently operating in the UK [15].

Power Station	Type	Net MW_e	Commercial operation	Expected closure date
Oldbury, Gloucestershire	Magnox	434	1967	2011
Wylfa, Anglesey	Magnox	980	1971	2012
Dungeness B, Kent	AGR	1090	1983	2018
Hinkley Point B, Somerset	AGR	860	1976	2016
Hunterston B, North Ayrshire	AGR	840	1976	2016
Hartlepool, Hartlepool	AGR	1190	1984	2019[a]
Heysham 1, Lancashire	AGR	1160	1984	2019[a]
Heysham 2, Lancashire	AGR	1230	1988	2023
Torness, East Lothian	AGR	1250	1988	2023
Sizewell B, Suffolk	PWR	1188	1995	2035

[a] Originally expected to close in 2014 but recently extended by five years by operator EDF Energy [16].

The proposed framework comprises 43 indicators, reflecting key techno-economic, environmental and social issues; these are summarised in Table 2. Their relevance to each life cycle stage of energy generation is also indicated. The indicators are discussed in turn in the rest of the paper. First, a brief overview is given of the nuclear life cycle and related sustainability issues relevant to the UK. For a more detailed account of the sustainability issues associated with nuclear power, see, for example, Azapagic and Perdan [36].

2.1. Nuclear fuel cycle and sustainability issues

The life cycle of nuclear power is shown in Fig. 2. The UK does not have indigenous uranium reserves, so all fuel is imported. Mining of uranium currently takes place in 18 countries, with Kazakhstan, Canada and Australia providing over 60% of total uranium supply from mines [37]. Uranium can therefore be imported into the UK from any of these countries, also ‘importing’ the related sustainability impacts. These include issues such as leaching of toxic substances, worker health and safety, distribution of revenues, local community benefits and indigenous peoples’ rights; for more detail on sustainability issues associated with mining see, for example, Azapagic [38] and GRI [39]. It should be noted that approximately 13% of global uranium supply is currently derived from diluted military material rather than from primary repositories [40]. This is an illustration of the link between civil nuclear fuel and nuclear weapons: each can be created from the other. This raises questions related to nuclear weapons proliferation, which is one of the sustainability indicators discussed further below.

Imported uranium is then converted into uranium hexafluoride before being enriched and finally converted into fuel. Most of this activity takes place in the UK, although some processes currently take place elsewhere. For example, fuel for Sizewell B is currently manufactured in two stages taking place in Russia and Germany, rather than in the UK’s own Springfields fuel fabrication site [41,42]. Similar sustainability issues that might be of concern to any other industrial process also apply to this part of the fuel life cycle, including environmental and social impacts (see Table 2).

Construction and operation of a nuclear power plant can take between 5–10 and 40–60 years, respectively. Specific issues of relevance to these stages include public concern that investment in nuclear power could divert investment away from renewables [43] along with lingering doubts over the safety of nuclear reactors. However, it is clear that the key determinants of UK policy are climate change and energy security [8,44–46] and these form the prime operational concerns of new power plants.

The end of the nuclear life cycle – waste storage and disposal – is arguably the most contentious issue for nuclear power. No country currently has a final repository for high-level waste (HLW), although plans in the UK have progressed in recent years following the reports of the Committee on Radioactive Waste Management (CORWM) [47]. Moreover, the UK’s Drigg facility for low-level waste (LLW) storage is currently thought to be almost full, although a new LLW storage vault and separate recycling facility should help to alleviate this problem [48,49].

Another issue specific to nuclear waste is the potential for nuclear proliferation. In the context of civil nuclear power in the UK, this is affected by factors such as reactor design and choice of fuel cycle. For instance, while it is increasingly acknowledged that all reactor-grade plutonium is weapons usable, the safety, predictability and yield are improved if the fuel is withdrawn early (at low burn-up) [50,51]. This is easier to achieve with a Canadian deuterium uranium (CANDU) reactor than with a PWR or boiling water reactor (BWR) due to its ability to refuel whilst online, not to mention the fact that it does not require enrichment facilities [52].

Table 2
Proposed indicators and their applicability to the life cycle stages of nuclear power.

Category	Issue addressed	Indicator	Unit	Life cycle stage											
				Mining and milling	Conversion	Enrichment	Deconversion	Fuel fabrication	Operation	Waste storage	Waste disposal	Reprocessing	MOX fabrication	Construction	Decommissioning
Techno -economic	Operability	Capacity factor (power output as a percentage of the maximum possible output)	Percentage (%)	–	–	–	–	–	✓	–	–	–	–	–	–
		Availability factor (percentage of time a plant is available to produce electricity)	Percentage (%)	–	–	–	–	–	✓	–	–	–	–	–	–
		Technical dispatchability (ramp-up rate, ramp-down rate, minimum up time, minimum down time)	Summed rank	–	–	–	–	–	✓	–	–	–	–	–	–
		Economic dispatchability (ratio of capital cost to total levelised generation cost)	Dimensionless	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Lifetime of global fuel reserves at current extraction rates	Years	–	–	–	–	–	✓	–	–	–	–	–	–
	Technological lock-in	Ratio of plant flexibility (ability to provide trigeneration, negative GWP and/or thermal/ thermochemical H_2 production) and operational lifetime	$Years^{-1}$	–	–	–	–	–	✓	–	–	–	–	–	–
	Immediacy	Time to plant start-up from start of construction	Years	–	–	–	–	–	–	–	–	–	–	✓	–
	Levelised cost of generation	Capital costs	Pence/kWh	–	–	–	–	–	–	–	–	–	–	✓	✓
		Operation and maintenance costs	Pence/kWh	–	–	–	–	–	✓	✓	✓	–	–	–	–
		Fuel costs	Pence/kWh	✓	✓	✓	✓	✓	–	–	–	✓	✓	–	–
		Total levelised cost	Pence/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

(*continued on next page*)

Table 2 (*continued*)

				Life cycle stage											
Category	Issue addressed	Indicator	Unit	Mining and milling	Conversion	Enrichment	Deconversion	Fuel fabrication	Operation	Waste storage	Waste disposal	Reprocessing	MOX fabrication	Construction	Decommissioning
	Cost variability	Fuel price sensitivity (ratio of fuel cost to total levelised generation cost)	Dimensionless	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Financial incentives	Financial incentives and assistance (e.g. ROCs, taxpayer burdens)	Pence/kWh	–	–	–	–	–	✓	✓	✓	–	–	✓	✓
Environmental	Material recyclability	Recyclability of input materials	Percentage (%)	–	–	–	–	–	–	–	–	–	–	✓	✓
	Water eco-toxicity	Freshwater eco-toxicity potential	kg 1,4-DCB[a] equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Marine eco-toxicity potential	kg 1,4-DCB[a] equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Global warming	Global warming potential (GHG emissions)	kg CO_2 equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Ozone layer depletion	Ozone depletion potential (CFC and halogenated HC emissions)	kg CFC-11 equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Acidification	Acidification potential (SO_2, NO_x, HCl and NH_3 emissions)	kg SO_2 equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Eutrophication	Eutrophication potential (N, NO_x, NH_4^+, PO_4^{3-} etc.)	kg PO_4^{3-} equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Photochemical smog	Photochemical smog creation potential (VOCs and NO_x)	kg C_2H_4 equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Land use and quality	Land occupation (area occupied over time)	m^2 yr/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Greenfield land use (proportion of new development on previously undeveloped land relative to total land occupied)	Percentage (%)	–	–	–	–	–	–	–	–	–	–	✓	–
		Terrestrial eco-toxicity potential	kg 1,4-DCB[a] equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Social	Provision of employment	Direct employment	Person-yrs/GWh	–	–	–	–	–	✓	–	–	–	–	✓	✓
		Total employment (direct + indirect)	Person-yrs/GWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Human health impacts	Worker fatalities	No. of fatalities/GWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Human toxicity potential (excluding radiation)	kg 1,4-DCB[a] equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Worker human health impacts from radiation	DALY[b]/GWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Total human health impacts from radiation (workers and population)	DALY[b]/GWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Large accident risk	Fatalities due to large accidents	No. of fatalities/GWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Local community impacts	Proportion of staff hired from local community relative to total direct employment	Percentage (%)	–	–	–	–	–	✓	–	–	–	–	–	–
		Spending on local suppliers relative to total annual spending	Percentage (%)	–	–	–	–	–	✓	–	–	–	–	–	–
		Direct investment in local community as proportion of total annual profits	Percentage (%)	–	–	–	–	–	✓	–	–	–	–	–	–
	Human rights and corruption	Involvement of countries in the life cycle with known corruption problems (based on Transparency International Corruption Perceptions Index)	Score (0–10)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Energy security	Amount of imported fossil fuel potentially avoided	toe/kWh	–	–	–	–	–	✓	–	–	–	–	–	–
		Diversity of fuel supply mix	Score (0–1)	–	–	–	–	–	✓	–	–	–	–	–	–
		Fuel storage capabilities (energy density)	GJ/m^3	–	–	–	–	✓	✓	–	–	–	–	–	–

(*continued on next page*)

Table 2 (*continued*)

Category	Issue addressed	Indicator	Unit	Life cycle stage: Mining and milling	Conversion	Enrichment	Deconversion	Fuel fabrication	Operation	Waste storage	Waste disposal	Reprocessing	MOX fabrication	Construction	Decommissioning
	Nuclear proliferation	Use of non-enriched uranium in a reactor capable of online refuelling; use of reprocessing; requirement for enriched uranium	Score (0–3)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Inter-generational equity	Use of abiotic resources (elements)	kg Sb equiv/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Use of abiotic resources (fossil fuels)	MJ/kWh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Volume of radioactive waste to be stored	m^3/kWh	–	–	–	–	–	–	–	✓	–	–	–	–
		Volume of liquid CO_2 to be stored	m^3/kWh	–	–	–	–	–	–	–	✓	–	–	–	–

[a] DCB – dichlorobenzene.
[b] DALY – disability-adjusted life years.

However, its lack of enrichment requirements can also be argued to reduce proliferation risks by negating the perceived need for enrichment technology in prospective nuclear nations.

As shown in Fig. 2, spent fuel can be reprocessed into mixed oxide fuel (MOX) to reduce the amount of nuclear waste generated and increase the energy recovered from the original nuclear fuel by up to 30% [53]. MOX can also be manufactured from ex-military plutonium, providing a way of reducing weapons-usable stockpiles [see, for example, Ref. [54]]. In the UK, reprocessing is carried out at the Thermal Oxide Reprocessing Plant (THORP) facility, although MOX is not currently used in Sizewell B [55]. Moreover, the continuation of reprocessing activities is not certain for the near-future: the government currently recommends that any nuclear power stations that might be built in the UK should proceed on the basis that spent fuel will not be reprocessed [45]. Despite this, both reactor designs currently undergoing the Generic Design Assessment prescribed by Health and Safety Executive (HSE) are able to utilise MOX fuel [56,57]. As such, the possibility of future reprocessing of used fuel and the manufacture of MOX for UK use cannot be ruled out. If spent fuel was reprocessed, the total amount of waste would decrease but plutonium separation may raise nuclear proliferation concerns under certain technical scenarios (especially those using Plutonium URanium EXtraction (PUREX)).

Various sustainability issues associated with different parts of the nuclear fuel cycle are discussed further in the next section, in conjunction with the related indicators. The indicators are, where possible, expressed per kWh electricity generated in order to enable equivalent comparisons between nuclear and other energy options.

The proposed indicators framework draws on some of the previous approaches to sustainability assessment [such as Refs. [18,25,38,58–66]] as well as on direct stakeholder input, obtained as part of this research. The latter included face-to-face interviews with over 30 stakeholders representing the energy industry (nuclear, fossil and renewables), NGOs and the government, as well as experts from academia. Therefore, the developed framework arguably represents the concerns of a range of stakeholder groups in the UK.

Although the indicators are divided into techno-economic, environmental and social, it is acknowledged that this is somewhat an artificial division, as in all other sustainability assessment frameworks, due to the inherent interconnections between different sustainability issues and their respective indicators.

2.2. Techno-economic indicators

Techno-economic aspects are arguably some of the most important factors for consideration in any sustainability assessment as they determine how well and in what way a technology can be integrated into the electricity mix. If, for example, reliability of a technology is poor, other generators will be needed to compensate for the inoperable unit(s), potentially changing the overall impacts of electricity generation dramatically. Equally, in a competitive market, financial viability is a prerequisite. However, the overall cost of an energy option is not the only important consideration. Firstly, the cost structure (how much cost is attributable to capital, operation and other relevant stages) can affect viability and the resultant operational characteristics. Secondly, economic impacts of electricity generation are broader than this, including possible taxpayer burdens.

To account for the above factors, the following categories of techno-economic indicators have been identified in this work as most important for nuclear and other electricity-generating technologies:

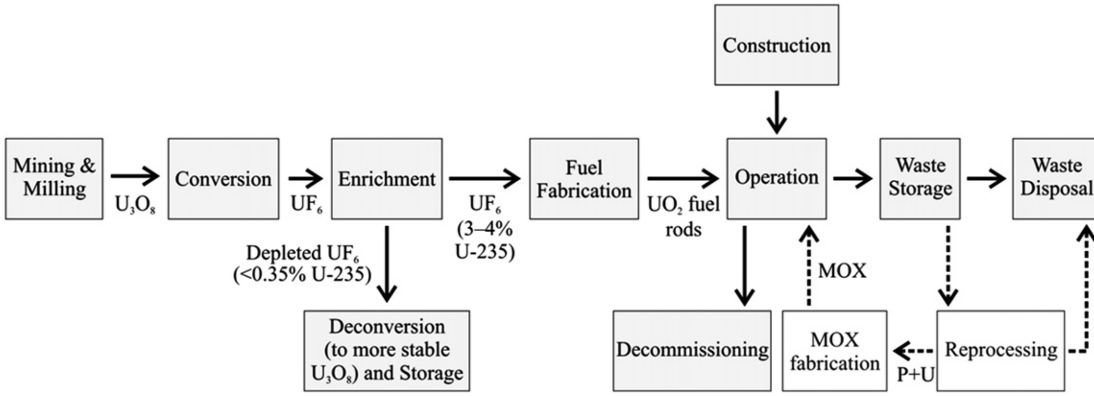

Fig. 2. The life cycle of nuclear power (HLW: high-level waste; MOX: mixed oxide fuel).

- operability;
- technological lock-in;
- immediacy;
- levelised cost of generation;
- cost variability; and
- financial incentives.

2.2.1. *Operability*

Operability concerns the way in which a technology works within an integrated electricity mix. As large-scale electricity storage in the UK is currently limited to the 2.7 GW of pumped storage capacity installed [5], generation is mostly dictated by demand which fluctuates minute by minute. Therefore, generation must be managed to follow that demand, and this depends on the technical abilities of the generating fleet. To capture the different technological properties needed for smooth operation of the grid, the indicators considered here are capacity factor, availability factor, technical and economic dispatchability and lifetime of fuel reserves at current extraction rates. They all apply to the operational stage of the power plant, although economic dispatchability requires consideration of full life cycle costs (see Table 2). For estimation of the operability indicators, see Appendix.

Capacity factor is the power output of a plant in a specified time expressed as a percentage of the maximum possible power output over the same time period had the plant been running continuously at full power [9]. It should be noted that capacity factor may vary from one time period to the next as the operator responds to external factors like changes in fuel price or baseload requirements. There may not, therefore, always be a preference associated with capacity factor. However, capacity factor does give an indication of the capabilities and characteristics of a technology. For instance, nuclear power, as discussed in Section 2.2.4, has relatively high capital costs and low fuel costs, meaning it is advantageous to run the plant at consistently high loads, giving a high capacity factor (around 86% for Sizewell B [10]). Lower capacity factor suggests reliability problems, as is the case in the older AGR fleet (50.2% fleet average in 2008 [calculated from Ref. [10]]). In the case of wind power, capacity factors are typically between 25 and 35% [5], with higher capacity factors suggesting excellent site characteristics and/or reliability.

Availability factor is the percentage of time that a plant is available to produce electricity [9]. This is fundamentally different to capacity factor as it includes times when the plant is fully functioning but is not being used. As such, it is a general measure of reliability. In the case of nuclear power, the operational fuel cycle of light water reactors (apart from CANDU) typically necessitates a period of (very roughly) 40 days every 18 months in which the reactor must be shut down to refuel [67], giving a highest theoretical availability factor of around 93%. Technologies that do not require shutting down to refuel may be able to achieve higher availability factors, although maintenance requirement and unforeseen down time normally preclude this.

Dispatchability is the ability of a generating unit to increase or decrease generation, or to be brought on line or shut down as needed [68]. This is a difficult characteristic to evaluate succinctly, being determined by many technical and economic characteristics. We therefore propose two indicators: technical dispatchability and economic dispatchability. The former applies only to the operational stage and can be determined by ramp-up rate, ramp-down rate, minimum up time and minimum down time. For instance, open cycle gas turbines (OCGTs) typically have ramp-up rates of 90–100% of P_{max} per minute, coupled with minimum down times of 8–10 min [69]. As a result, they can change their output quickly and need only short periods offline before being started again. In contrast, due to their greater complexity and thermal constraints, combined cycle gas turbines (CCGTs) typically have ramp-up rates of around 2–3% P_{max} per minute and minimum down times of 300 min [69]. Modern nuclear power stations are able to follow load reasonably well: some reactors in the current French fleet reduce their output to 25% of maximum every day [70]. Similarly, the Westinghouse AP1000 claims a ramp-up rate of 5% per minute [71], which compares favourably with a typical coal power station [72]. We suggest ranking the technologies on each of the four technical dispatchability criteria described above (ramp-up rate, ramp-down rate, minimum up time and minimum down time), then summing the rankings to derive a total technical dispatchability ranking (see Appendix).

Despite the technical potential of nuclear power plants to load-follow, due to their high capital and low operating costs it is normally uneconomic to do so: the cost profile means that generating at maximum capacity is desirable at all times in order to reduce the payback time. We therefore suggest quantifying economic dispatchability based on the life cycle costs of electricity generation: the ratio of capital cost to total levelised cost (see Section 2.2.4 and Appendix) expresses the economic detriment of load-following, where low ratios suggest technologies better suited to varying output. The fact that this is based on total levelised costs means the whole life cycle must be considered. Approximately 70% of the levelised cost of nuclear electricity arises from capital costs, whereas this figure is normally less than 20% for CCGTs [73]. This is reflected in the typical decision of current utility companies to use nuclear stations exclusively for baseload while CCGTs operate on intermediate load cycles.

The lifetime of fuel reserves at current extraction rates is a reflection of current usage rates compared to identified economically recoverable resources (see Appendix). Figures currently stand at approximately 100 years for uranium [74], 120 years for coal [75], 55 years for natural gas and 41 years for oil [76] (although of course these quantities depend on what is classed as economic to extract). The indicator is a best estimate of the global longevity of fuel supplies, but is accompanied by unavoidable caveats. It does not try to predict any changes in demand which might occur over the coming decades; nor does it consider future reserve discoveries or improvements in extraction technology that would make currently uneconomic reserves exploitable. It also assumes that fuels currently used to provide several services (such as natural gas, which is used for heating as well as electricity production) continue to be allocated between those services in their current proportions. It should also be noted that certain fuels (primarily fossil) have been the subjects of more extensive exploration than others, meaning that the estimated lifetimes of fossil fuel reserves are probably more realistic than those of, for example, uranium. This is reflected in the fact that investment in uranium exploration was very low from 1980 to 2003, but is now expanding, resulting in an expectation that the current economically recoverable reserves are underestimated [74,77].

2.2.2. Technological lock-in

This indicator, also applicable to the operational stage, describes situations which cause an economic system "gradually to lock itself in to an outcome not necessarily superior to alternatives, not easily altered, and not entirely predictable in advance" [78]. In the context of electricity generation, this can be interpreted as the extent to which a choice of technology in the present day prohibits future changes in energy provision. For example, it is often argued that the development of large, centralised power stations with long lifespans might be expected to subdue the growth of small-scale, decentralised power generation [see, for example, Ref. [79]]. This is because the former situation 'locks' the energy system into a regime which has characteristics that do not favour widespread small-scale generation: for instance, the existence of large utility companies and an extensive, well maintained national grid would, arguably, not be required at such a scale if decentralised generation had dominated the market at an earlier stage.

Clearly this is a difficult subject to address from the perspective of present-day energy choices: as already mentioned, the attributes of a locked-in system are not entirely predictable in advance. Moreover, attempts to explain technological lock-in tend to ascribe it primarily to social and economic phenomena rather than to characteristics of the technologies themselves. Examples include the bounding of thought by 'incremental' innovation [80], increasing returns to adoption (the preference to adopt technologies that are already widespread, or at least perceived to be) [78,81] and the network externalities caused by technological 'clusters', whereby one technology becomes linked in some way to others, giving it an advantage through association [80–82] rather than to characteristics of the technologies themselves. We suggest instead the use of two basic, measurable criteria that significantly affect the extent to which certain technologies cause lock-in: lifespan and flexibility.

The former criterion is relatively easy to quantify in terms of years of expected lifetime. The latter is slightly more subjective, but can be described in terms of the ability to cater for different energy requirements, if needed, in the future. Key abilities, identified by the stakeholders in this research that may be useful in the future include the potential to provide heating and cooling as well as electricity (trigeneration), to operate with net negative carbon emissions (by burning biomass with carbon capture and storage (CCS)), and to produce hydrogen via thermal/thermochemical processes for use in fuel cells.

A high degree of flexibility and a short lifespan are preferable from the perspective of technological lock-in: the former widens the boundaries of the energy provision paradigm, while the latter reduces the inertia of the system by diminishing economic ties to legacy assets and providing more points at which new technologies can be brought online [83]. Naturally, a short lifespan is not preferred from the investment point of view, particularly for capital-intensive technologies such as nuclear; however, this indicator does not attempt to capture the cost aspects, which are addressed by different indicators, as discussed further below.

Table 3
Levelised energy costs for different generating technologies in the UK for 2010 [88] (discount rate = 10%).

Technology	Cost range (pence/kWh)
Nuclear	5.5–8.5
CCGT	5.5–11.0
CCGT with CCS	6.0–13.0
Onshore wind	8.0–11.0
Biomass	6.0–12.0
Coal with CCS	10.0–15.5
Offshore wind	15.0–21.0
Tidal power	15.5–39.0

Therefore we suggest that the lock-in indicator be defined as a ratio of the square of the flexibility index and the lifespan of technology (see Appendix). The 'flexibility index' is scored on an ordinal scale (0–30) in which the three key services identified above (trigeneration, negative CO_2 emissions and H_2 production) are allocated 10 points each. This equal scoring is suggested because the index attempts to account for overall flexibility rather than to predict which of the services will be most important in the future. The index is then squared to reduce the indicator's sensitivity to technology lifespan.

As an example, a PWR reaches temperatures of around 325 °C [84], much of which is wasted, and could therefore provide trigeneration, assuming any acceptance issues surrounding proximity to the reactor and use of nuclear heat were overcome. However, significantly higher temperatures are required for thermal hydrogen production, and nuclear power cannot provide negative CO_2 emissions. Its flexibility index is therefore 10. With a lifespan of 60 years [11,12], its technological lock-in score is 1.67 ($T = 10^2 \div 60$; see Appendix for the equation). In contrast, a theoretical biomass CCS power plant might be able to provide trigeneration and negative net carbon emissions while operating at a high enough temperature to produce hydrogen thermally. This gives a flexibility index of 30. Given a lifetime of 40 years, this yields a technological lock-in score of 22.5 ($T = 30^2 \div 40$). Therefore, in terms of technological lock-in, the biomass CCS plant would be more sustainable than the PWR.

2.2.3. Immediacy

Immediacy addresses the potential problems caused by technologies with long lead times in terms of time to plant start-up.

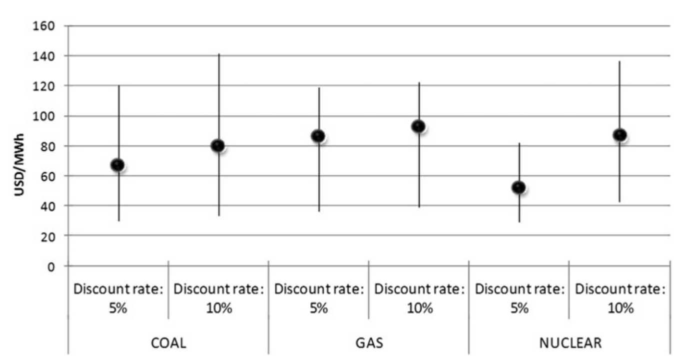

Fig. 3. Levelised cost estimate ranges and medians for coal, gas and nuclear power at 5% and 10% discount rates (based on data from the IEA [73]).

Therefore, this indicator is defined here as the overall time taken from start of construction to start-up of the plant and is thus relevant to the construction stage of a power plant. For instance, the so-called UK 'energy gap', resulting from the retirement of older nuclear power stations and the effect of the European Large Combustion Plant Directive (directive 2001/80/EC), is likely to begin in 2016 when combustion plants that opted out of the above directive will be forced to close [85]. Given that nuclear power stations have long construction times, generally 5–7 years without additional licensing considerations [45,73], none can be completed by then as no new build has started yet. This makes the option of new nuclear build less appropriate in situations where generating capacity is required in the near-term. In contrast, a large CCGT is likely to take 3–4 years to complete [see, for instance, Ref. [86]], providing a much quicker response to changing power requirements.

2.2.4. Levelised cost of generation

The levelised electricity cost (LEC) represents the average price that consumers would have to pay for the investor to break even. It is calculated as the ratio of total costs of generation and the total electricity generated during the lifetime of a power plant, taking into account an appropriate discounting factor [87] (see Appendix).

Therefore, the LEC is relevant to the whole life cycle of the power plant (see Table 2). Table 3 gives examples of the LEC ranges for some generating technologies in the UK for 2010 [88]. As can be seen, nuclear power has an LEC of 5.5–8.5 pence/kWh, of which around 70% is due to the capital costs. The LECs of CCGT and biomass are similar albeit slightly more expensive at the top of the range, but in contrast to nuclear, the main contributor to the costs (70%) is fuel. The other renewables have higher levelised costs than nuclear, ranging from 8 pence/kWh for wind to 39 pence/kWh for tidal, but similar to nuclear, the capital investment contributes more than 70% of the LEC [88].

Obviously, LECs are sensitive to the discount rate assumed. This is illustrated by Fig. 3, which is based on the IEA's projection of costs of different technologies [73]: as nuclear power is dominated by capital costs and has relatively low operational costs, raising the discount rate from 5% to 10% dramatically changes its LEC, while that of coal or gas remains similar. It is important, therefore, to state explicitly the discount rate used for estimation of LEC.

Discounting rates are also a controversial topic for sustainable development, as they effectively neglect costs (and benefits) experienced by future generations (for discussion, see for instance Ref. [89]). An alternative approach would be to avoid discounting completely by giving undiscounted costs for different life cycle stages: Polatidis and Haralambopoulos [90] and Cavallaro and Ciraolo [91], for example, give undiscounted installation costs and operational costs. However, there are at least two advantages to using discount rates, both pragmatic. Firstly, power stations in the UK are privately owned and operated (although some public contribution often exists), meaning they will be commissioned or otherwise on a market basis. In this context, making decisions based on a very low (or zero) discount rate is economically unrealistic as it neglects both the opportunity cost of investment and the financial risk to the investor. Secondly, discounting is a universally established corporate financial management tool and, as such, its use enhances the communicability of the assessment. We do, however, propose the use of several different discount rates as part of sensitivity analysis in order to explore the interaction between economic costs and intergenerational issues. Low discount rates are favoured if the goal is to avoid transferring costs to future generations; this in turn favours high capital, low running cost options such as nuclear power and most renewables. In contrast, high discount rates diminish future costs and accentuate near-term costs, thereby favouring energy options with less capital investment but higher running costs.

2.2.5. Cost variability

Fuel price volatility and its impact on cost variability of energy have been identified as major drivers of UK energy policy [44,45]. Fuel price sensitivity as an indicator of cost variability has been included in at least two previous sustainability assessments of electricity-generating options [63,66]. It is expressed as the ratio of fuel cost to total LEC (see Appendix), providing a measure of financial risk due to price fluctuations. Therefore, as shown in Table 2, it is relevant to the whole life cycle of a power plant. Its value varies greatly between different technologies. For example, using IEA data [73], the mean estimated levelised costs of coal and gas electricity in the OECD countries are 77 and 86 USD/MWh respectively (at 10% discount rate, no carbon tax), of which 27 and 64 USD/MWh are fuel costs. This gives coal a fuel price sensitivity of 0.35 and gas 0.74: figures which are broadly in line with other estimates [e.g. Refs. [87,92,93]]. The difference between the two is a result of significantly higher capital costs associated with coal plants [73]. In contrast, fuel costs make up approximately 10% of overall costs for nuclear power [45,93], so that fuel price fluctuations have a limited impact. This effect is amplified by the fact that a large proportion of the fuel cost is due to fuel processing, with less than half being the actual cost of uranium [94]. This contrasts with other fuels because uranium undergoes many processing stages (mining, milling, conversion, enrichment and fuel fabrication) before it becomes usable fuel assemblies. Fossil fuels, on the other hand, involve only the processing of the fuel itself, meaning fuel price fluctuations are buffered less by subsequent processing steps.

2.2.6. Financial incentives

This indicator takes account of non-market financial incentives and assistance for the generation of electricity in the UK. It therefore includes all subsidies incurred at the development, construction, operation, decommissioning and waste disposal stages and is expressed in pence/kWh (see Table 2). With global energy subsidies (direct and indirect) estimated at US$ 300 billion per year, of which around 77% goes to fossil fuels [95], concerns are often voiced over their distribution between different technologies, and whether this constitutes a fair market. Nuclear, renewables and fossil fuels have all been subject to criticism in this respect [see, for example, Refs. [96–99]].

The issue is complicated by many factors, including: state funding of legacy assets and operations (such as the eventual decommissioning and disposal of UK nuclear liabilities, estimated by the NDA to cost £44.5 billion [100]); indirect consumer burdens (such as the Renewable Obligation Order [101]); the global nature of the subsidies, meaning imported fuels are subsidised differently depending on their origin; and historical support enjoyed by previously nationalised industries. The latter often serves as a supporting argument for renewables which, as incumbent technologies, have not benefitted from the subsidies given to the non-renewables that dominated electricity markets prior to their widespread decentralisation in the 1990s [95].

In the UK context, this indicator should include all the policy instruments that manipulate the liberalised electricity market as well as their administrative costs. The main considerations are therefore Renewables Obligation, site selection studies, HSE design assessments and any direct payments from government to generators (such as in the newly proposed 'contract for difference' system in which the government would guarantee long-term feed-in tariffs, topping up payments with public money [102]).

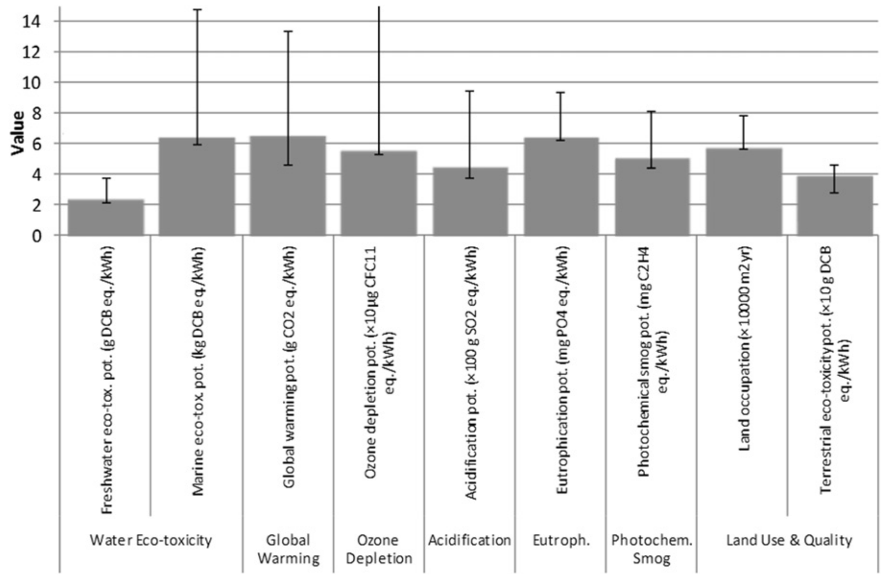

Fig. 4. Life cycle environmental impacts of nuclear power (based on Ref. [113]) (The values shown have been scaled by multiplying the original values with the factors shown in the brackets; the upper value for ozone depletion potential = 72.8 μg CFC-11 equiv/kWh.).

2.3. Environmental indicators

Electricity generation contributes around a third of the UK's carbon emissions [6] and, along with road transport, is the UK's biggest source of environmental pollution [103]. It is important to consider all environmental impacts despite the current focus on global warming, as trade-offs often apply. For instance, it has been estimated that the UK Low Carbon Transition Plan will result in an increase in NO_x emissions and therefore in acidification and human health impacts [103].

To ensure as broad coverage of environmental impacts as possible, the following environmental indicators are included in this sustainability assessment framework (see Table 2):

- material recyclability;
- water eco-toxicity;
- global warming potential (GWP);
- ozone layer depletion potential;
- acidification potential (AP);
- eutrophication potential (EP);
- photochemical smog creation potential; and
- land use and quality.

They span the whole life cycle of electricity generation and are estimated using life cycle assessment (LCA) as a tool, following the CML impact assessment method [104] (see Appendix). The exceptions to this are material recyclability and some aspects of the water eco-toxicity indicator, as explained below.

2.3.1. Material recyclability

This indicator measures the extent to which materials used in the construction of a power plant are recycled and is therefore relevant to the construction and decommissioning parts of the life cycle. It is calculated as the total percentage (by mass) of the power plant that is recyclable. Certain materials, such as steel, aluminium and glass, can be recycled many times without significant loss of quality [105,106]. In contrast, materials such as concrete can only be partially recycled, for example, by being broken down into aggregate and used for construction [107]. Consequently, certain technologies offer a far greater potential to be recycled than others, ultimately reducing resource consumption and increasing sustainability of materials. In most wind turbines, for example, steel is by far the dominant material, being used for the foundations, tower and various nacelle components [108,109]. This contrasts with a nuclear power station, which uses predominantly concrete [110], reducing its recyclability (although much of the other materials are not recyclable anyway due to their acquired radioactivity).

2.3.2. Water eco-toxicity

Electricity generation accounts for over 50% of all water usage in the industrialised and developing world [111]. Impacts on water quality are diverse, ranging from the emission of toxic compounds to temperature increase. Two indicators are proposed to account for these impacts: freshwater and marine eco-toxicity potentials (Table 2). They are expressed in 1,4-dichlorobenzene (DCB) equivalents per kWh and are calculated according to the CML method [112] (see Appendix). For example, as shown in Fig. 4, the life cycle freshwater toxicity of nuclear energy is 2–4 g DCB equiv/kWh, the majority of which is from the mining and milling of uranium and waste disposal; marine eco-toxicity is approximately 6–15 kg DCB equiv/kWh and is mainly due to mining and milling.

2.3.3. Global warming

With the introduction of the Climate Change Act, which legally binds the UK to an 80% carbon emission reduction by 2050, global warming has become a key driver of UK energy policy. On a life cycle basis, nuclear power emits approximately 5–10 g CO_2 equiv/kWh (Fig. 4), compared to 5–15 for offshore wind and 900–1500 for pulverised coal. The low carbon emissions of nuclear power and renewables are the main reason for high interest in these technologies.

As global warming has wide-ranging impacts, both intra- and intergenerational, affecting the environmental, society and the economy, it is perhaps best described as an integrated indicator [38]. However, due to its inclusion as an environmental indicator in LCA, it is considered under the environmental category within this framework.

2.3.4. Ozone layer depletion

Ozone layer depletion refers to the thinning of the stratospheric ozone layer by chlorofluorocarbons (CFCs), which results in increased transmission of UVB radiation to the earth's surface.

Despite the ban of CFCs under the Montreal Protocol [114] some ozone depleting substances are still manufactured in various non-signatory countries for use in signatory countries. As such, ozone depletion is still a relevant issue. As shown in Fig. 4, nuclear power emits around 0.55 μg CFC-11 equiv/kWh, most of which is normally attributable to mining and milling, although the figures can also vary widely depending on the enrichment technology used.

2.3.5. Acidification

Acidification causes increased mortality of aquatic organisms in lakes and rivers as well as erosion of buildings due to emissions of acid gases such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), hydrogen chloride (HCl) and ammonia (NH_3). Power generation has been identified as responsible for affecting species composition at several sites in the UK, often reducing overall biodiversity (see, for example, Ref. [115]). AP of the nuclear power life cycle is approximately 40–90 mg SO_2 equiv/kWh (Fig. 4), the majority of which occurs during mining and milling.

2.3.6. Eutrophication

Eutrophication refers to the promotion of biomass growth in an ecosystem owing to an influx of nutrients such as nitrogen and phosphorus. This then depletes local oxygen and affects aquatic organisms. Currently, in the UK, critical loads are exceeded in 60% of habitats sensitive to eutrophication from nitrogen deposition [103]. This has also been highlighted, along with acidification, as an issue of increasing importance given that power stations with CCS release more NO_x and NH_3 than current fossil fuel stations [116]. The main cause of this is oxidation of the monoethylamine solvent used in the carbon capture process. Given the potential future prominence of CCS in power generation, this is an important consideration. Regarding nuclear power, throughout its life cycle, it emits around 6–9 mg PO_4^{3-} equiv/kWh (Fig. 4), mostly due to mining and milling.

2.3.7. Photochemical smog

It has been estimated that, in the year 2000, ground level ozone (the main constituent of photochemical smog) caused 6.7 billion Euros of lost arable crop production in the EU [117]. NO_x, volatile organic compounds (VOCs), CH_4 and CO are all ozone precursors, with power generation mainly contributing via NO_x: power stations produce around 20% of anthropogenic NO_x emissions in the UK [117]. As is the case with eutrophication, this is of particular interest if coal CCS becomes widespread, due to its higher NO_x emissions [116]. Nuclear power is responsible for 5–8 mg C_2H_4 equiv/kWh (Fig. 4), the majority of which is from mining and milling.

2.3.8. Land use and quality

Land is a limited commodity, particularly in countries with high population densities like the UK (which houses around 250 people per square kilometre [118]). Three indicators are included under this category: land occupation, greenfield land use and terrestrial eco-toxicity.

Land occupation is a measure of the total land occupied throughout the life cycle and the period for which it is unavailable for other use (see Appendix). This reflects the extent to which land is 'locked' for other uses and cannot enhance biodiversity by succession or cultivation. As shown in Fig. 4, the nuclear life cycle occupies around 6×10^{-4} m^2 yr/kWh, with the unit reflecting the fact that land is occupied for many years (for example, the site of the power plant itself is, in this case, occupied for 40 years during the operational stage, followed by several more years during decommissioning).

Greenfield land use represents the percentage of land converted from a near-natural state relative to the total amount of land used for the construction of a power plant (see Appendix). It is a rough proxy for loss of biodiversity. The results of this indicator depend on the sites being proposed for new build. For example, despite all eight of the proposed sites for nuclear new build being adjacent to existing power stations, seven of the plots themselves are currently greenfield, including farmland, woodland, drained marsh and a golf course [13].

Neither of the above indicators takes into account toxic emissions to land, which are covered by the life cycle terrestrial eco-toxicity indicator, estimated by a method similar to that for marine and freshwater eco-toxicity (see Appendix). As shown in Fig. 4, the life cycle terrestrial eco-toxicity from the nuclear life cycle is around 0.4 g DCB equiv/kWh, most of which is attributable to construction of the power plant.

2.4. Social indicators

While techno-economic and environmental indicators for energy systems are relatively well established, social indicators are less well developed. This is mainly owing to the complexity and variety of social issues pertinent to energy systems as well as their mainly qualitative and subjective nature. To account for some of the social issues relevant to electricity generation, and particularly nuclear power in the UK [44,119], the following eight categories of social indicators are proposed within this framework (Table 2 and Appendix):

- provision of employment;
- human health impacts;
- large accident risk;
- local community impacts;
- human rights and corruption;
- energy security;
- nuclear proliferation; and
- intergenerational equity.

2.4.1. Provision of employment

The construction of a single new nuclear reactor provides over 1000 jobs for approximately six years [120] in addition to other jobs in the manufacture of components. It then supports around 500 jobs on-site throughout its operating life of 60 years [120,121] as well as more, indirect, employment throughout the fuel cycle. In several cases in the UK, areas with aging power stations are heavily reliant on the prospect of new build to replace as many jobs as possible when the current station closes. For instance, Anglesey is working towards realising the Government 'Energy Island' vision, by securing a significant fraction of its total employment in nuclear and renewable energy generation [122].

Therefore, to account for both direct and indirect employment, two indicators are included in this category: direct and total employment (Table 2). The former refers to employment created in the life cycle of the power plant, i.e. construction, operation, maintenance and decommissioning. Total employment also includes indirect employment which exists up and down the supply chain as a result of the plant's existence. This includes jobs required in fuel mining, fuel production, waste management and other services to the plant over its lifetime. Indirect employment is not to be confused with induced employment, which is the employment created outside the supply chain as a result of increased disposable income. Induced employment can be estimated using a multiplier so that, for example, 0.25 induced jobs are assumed to result from every one direct or indirect job [as in Ref. [123]]. However, induced employment is not considered within this framework due to the uncertainties associated with such estimations.

Since the employment provided by a power plant varies greatly by life cycle stage, it is more meaningful and informative to express this indicator in terms of person-yrs (per total electricity generated) rather than absolute number of jobs (per total electricity generated). For instance, as mentioned above, if 1000 people are employed for six years during the construction of a reactor, and 500 people are employed during the operation of the plant over 60 years, then the total employment expressed in person-yrs is 36,000 $[=(1000 \times 6)+(500 \times 60)]$ divided by the total electricity output over the lifetime of the plant. The alternative would be to simply sum the number of jobs to 1500 (and divide with the electricity output), regardless of the duration of the employment, thus providing only partial employment information.

2.4.2. Human health impacts

Electricity generation incurs many types of human health impacts, ranging from workplace accidents to the more widespread detriments associated with toxic emissions. For instance, the Institute of Occupational Medicine estimates that eliminating all anthropogenic PM2.5 emissions would result in gains in life expectancy three or four times higher than those that would be achieved by eliminating all motor traffic accidents or passive smoking [124].

In order to assess human health impacts as fully as possible, we propose the following three indicators, applicable along the whole life cycle of electricity generation (Table 2):

- worker fatalities;
- human toxicity potential (excluding radiation); and
- human health impacts from radiation (HIR) (workers and population).

These indicators cover normal operation only, excluding large accidents, which are covered by the accident risk indicator (see next section).

The first indicator is related to worker safety, including contractors and subcontractors, and it measures the number of deaths per unit electricity generated (Table 2 and Appendix). It does not take into account non-fatal incidents or near-misses as fatalities are more widely documented, making the information provided by this indicator more accurate. For instance, the Namibian Chamber of Mines reports that, from 2005 to 2009, its two uranium mines (Rossing and Langer Heinrich) had a cumulative output of 21,234 t (unenriched) UO_2 [125] and one fatality [126]. This gives a fatality rate of 4.7×10^{-5} fatalities/t UO_2 for the mining stage of the nuclear life cycle. Since ~0.02 t of UO_2 are required for 1 GWh of electricity, then the worker fatality rate from mining would be equal to 9.4×10^{-7} deaths/GWh.

Human toxicity potential expresses the potential harm to humans from toxic substances emitted in the life cycle of energy generation. It excludes impacts from radiation, which are accounted for by the indicator discussed below. Similar to the environmental eco-toxicity potentials discussed in the section on environmental indicators, it is calculated according to the CML methodology [127] and expressed in DCB equiv/kWh (see Appendix).

Finally, HIR are measured for both workers and the general population. They are expressed in terms of disability-adjusted life years (DALY), in line with the World Health Organisation's 'burden of disease' measurements [128] (see Appendix). The nuclear power life cycle results in approximately 0.02 DALY/GWh, but this increases if reprocessing is included, resulting in around a 10% increase if 8% of power is derived from MOX (based on Ref. [113]). This is a result of the radioactive emissions resulting from treatment of used fuel and manufacture of MOX.

2.4.3. Large accident risk

This indicator measures the number of fatalities due to large accidents over the life cycle of electricity generation and is expressed per unit of electricity generated (Table 2 and Appendix).

Large accidents in energy generation are perhaps most associated in the public psyche with nuclear power. This is, in part, due to the widespread public suspicion and fear engendered by Chernobyl and Three Mile Island, particularly the large number of deaths ultimately caused by the former. Estimates including latent deaths range from around 8250 [129] to over 200,000 [130]: numbers only rivalled in the energy sector by the Banqiao dam failure in China in 1975, which caused at least 25,000 deaths [131] (possibly 230,000 including subsequent disease and famine [132]). However, it is important to recognise the fact that, in terms of large accident fatalities from nuclear plants, Chernobyl is the only data point. Large accidents occur at a higher frequency in other energy chains, but with fewer consequences per incident. This is illustrated in Fig. 5 which compares the maximum number of fatalities and fatality rate for the nuclear, gas, coal, hydro, photovoltaics (PV) and wind supply chains based on historical OECD data and probabilistic safety assessment [133]. While the fatality rate for coal is around 25 times higher than that of nuclear power (0.18 fatalities/GW yr for coal compared to 0.007 for nuclear), the total number of ultimate fatalities from a nuclear accident (here, under Swiss conditions) estimated using probabilistic risk assessment (PSA) is about 24 times higher than that from coal-related accidents (10,240 fatalities for nuclear versus 434 for coal). However, PSA is based on many assumptions and its resulting estimates can carry the same uncertainty as those based on a single accident. Nevertheless, in the absence of more reliable data and estimation approaches, these results can be used as an indication of the ranges of possible fatalities from a large accident related to nuclear power compared to other electricity options.

2.4.4. Local community impacts

This category aims to assess the impacts of a power station on local community (see Table 2). Some of the possible impacts include provision of employment to local communities as well as contribution to their development and welfare. Therefore, the following three indicators are proposed under this category: proportion of staff hired from local community; proportion of spending on local suppliers; and direct investment in local community (see Appendix). Similar indicators have been suggested by several other authors [see, for example, Refs. [18,38,134]].

Proportion of staff hired from local community is expressed relative to the total direct employment provision. Spending on local

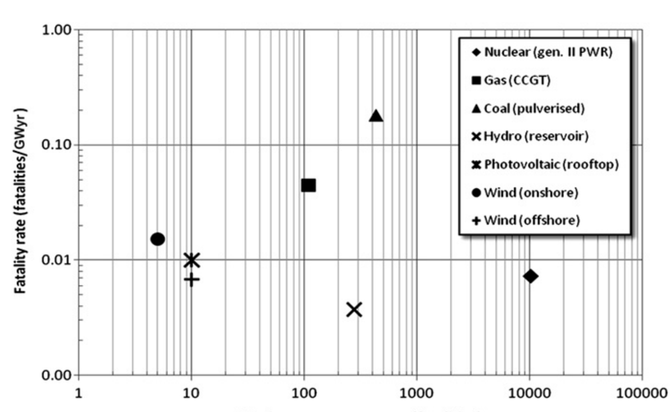

Fig. 5. Fatalities associated with different energy chains based on actual data and probabilistic safety assessment for nuclear power (based on data from Ref. [133]).

suppliers measures the percentage of spending in the local community and is expressed relative to the total spend each year. Finally, direct investment in local community aims to promote equitable distribution of wealth through direct returns to the local community [38]. This includes investments in local schools, hospitals, infrastructure, environmental projects, etc. This indicator is expressed as percentage investment relative to the total company revenue.

Ideally, these indicators should span the construction, operation and decommissioning stages, but it is unlikely that information on all three stages will be available at the same time and data for construction and decommissioning may not be available at all. Besides, different companies may be involved in these three life cycle stages making it even more difficult to obtain meaningful information. Therefore, it is suggested that these indicators only cover the operation stage of a power plant. Furthermore, given that these indicators are company – rather than technology-specific, they can only be used by individual companies with specific knowledge of impact on and contribution to the local communities. Alternatively, it may be possible to use industry average data, but this would incur further data collection problems and would contribute little to distinguishing between different technologies.

2.4.5. Human rights and corruption

Ethical problems surrounding human rights and corruption are a major concern in some countries where the social and regulatory regimes are lax. However, it is difficult to assess this indicator in an unbiased fashion since evidence of rights violations and corruption is not readily available. Moreover, value judgements are inherent in the definition of terms like 'violation' and 'corruption'. For this reason, we suggest using a simplified indicator based on the Corruption Perceptions Index (CPI) developed by Transparency International [135]. The CPI scores countries on a scale from 0 to 10 based on the level of corruption of their politicians and official administration, whereby 0 means extremely corrupt and 10 means completely clean. For example, Denmark, New Zealand and Singapore top the league with a score of 9.3 while Somalia is at the bottom with a CPI of 1.1. Although CPI admittedly only considers corruption and not human rights violations, it is arguably a reasonable proxy, as public corruption and human rights issues are often closely correlated.

Within this framework, it is proposed to calculate the human rights and corruption indicator as an average CPI of the countries involved in the life cycle of an energy system (see Appendix). For instance, if a nuclear fuel cycle involved uranium mining in Namibia (CPI = 4.4), conversion, enrichment and fuel fabrication in Germany (CPI = 7.9) and waste storage and disposal in the UK (CPI = 7.6), the average CPI for this life cycle would be 6.6.

As is the case with the local community indicators discussed in Section 2.4.4, human rights and corruption will depend mainly on company sourcing policy rather than on energy technology, although inevitably the technology may dictate where the fuels and raw materials are sourced from.

2.4.6. Energy security

Energy security is clearly one of the main objectives of UK energy policy [44,45]. The UK currently relies on coal and gas for around 75% of its electricity [5], both of which are finite resources and require substantial imports, reducing the UK's energy security.

Previously, energy security has been assessed by estimating the amount of imported fossil fuel avoided by non-fossil fuel generation technologies [90], calculating global fuel availability [62,63,66] or via qualitative assessment [136–138]. Here, we use three different but related indicators to assess the level of energy security associated with different energy options (Table 2):

– amount of imported fossil fuel potentially avoided (adopted from Ref. [90]);
– diversity of fuel supply (DFS); and
– fuel storage capability.

The indicator imported fossil fuel potentially avoided applies only to the operational stage and is expressed in terms of the amount of fossil fuel that would have to be burned to provide the equivalent electrical output of a non-fossil source, using the current fossil fuel fleet as a benchmark. The installed capacity of fossil fuel stations (gas, coal and oil) in the UK and their average efficiencies [139] allow calculation of the overall conversion efficiency of the fossil fuel fleet, which is approximately 43%. Therefore, producing 1 kWh of electricity from that fleet requires around 0.2 kg of oil-equivalent. Thus, this amount of fossil fuels would be avoided by using non-fossil fuel electricity technologies. It should be noted that, since the UK produces oil, coal and gas indigenously, not all of this amount would necessarily be imported. However, given that the UK is currently a net importer of all three of those fuels [140], it is reasonable to assume that a reduction in demand equates to a reduced need to import. In reality, a reduction in fossil fuel demand might simply mean that import levels are maintained while more indigenously produced fuels are exported.

In addition, we propose a simple, novel indicator on DFS mix based on Simpson's Index of Diversity (SID) [141,142] and expressed as a score on a scale from 0 to 1 (see Appendix). This indicator applies to the operational stage (see Table 2) and takes into account the proportions of national fuel demand supplied domestically and imported (see Appendix), corrected for SID. In ecological studies, SID is used to quantify the biodiversity of a habitat by taking into account the number of species present (richness) as well as the abundance of each species (evenness). Here, we use it to indicate the diversity of fuel imported to a particular country. The SID of the import mix is then multiplied by the proportion of the fuel that is imported, which in turn is added to the proportion produced indigenously. In this way, the overall result of the indicator increases in situations where: a greater proportion of fuel is produced indigenously; the same proportion of fuel is imported from a greater number of exporters; or the import mix is split more evenly between exporters. Cases in which fuel supplies depend heavily on one exporter will therefore score badly as security of supply is too vulnerable.

For instance, in 2009 the UK produced 17.1% of its steam coal (used for electricity generation) indigenously while the remainder was imported from various countries, predominantly Russia (56% of imports) (based on Ref. [140]). The SID of the steam coal import mix for 2009 was 0.65 (see Appendix), giving an overall DFS mix of 0.71 ($=0.179 + (0.821 \times 0.65)$). In contrast, the EU (and UK) supply mix for uranium is more diverse and evenly split, coming from a total of more than 12 countries, with the main suppliers (Russia, Australia and Canada) contributing roughly equal amounts [143]. The SID for uranium supply is 0.84 (based on Ref. [143]). Since no uranium is produced in the UK, this is also the overall UK DFS ($=0 + (0.84 \times 1)$). It should be noted that this value assumes the EU supply mix is equivalent to that of the UK – given that UK nuclear plants are currently owned by EDF Energy and will, for the foreseeable future, remain the property of large, Europe-wide utilities [15], this is arguably a reasonable assumption. Therefore, even though coal is produced indigenously in the UK and uranium is not, over-reliance on Russia for coal imports results in uranium being more sustainable than coal in terms of diversity of supply (DFS of 0.84 vs 0.71).

Finally, fuel storage capability is quantified as the energy density of the fuel and applies to two life cycle stages: fuel fabrication and operation (Table 2). This indicator can be expressed either in terms of energy content per mass or volume of fuel and provides information on the ease of storage of different types of fuels. For example, both coal and gas have relatively low net energy densities (approximately 21 GJ/m^3 and 0.035 GJ/m^3, respectively [calculated from Ref. [144]]), making stockpiling difficult. With current storage capacity and assuming average demand, the UK has just under 17 days' supply of natural gas stockpiled [calculated from Refs. [145,146]] (although this is set to increase over the next decade [147]). Similarly, the largest coal power station in the UK, Drax, requires around 140 train loads of coal per week to operate [148]. This means that, especially in the case of gas, disruptions in the supply chain can leave the country vulnerable to supply shortages. A more recent example of such a situation was the 2005–2006 Ukraine/Russia gas dispute – although the majority of UK gas imports are in fact from Norway [145], this highlighted the security of supply issues associated with fuel imports. In contrast, assuming burn-up of 50 GW d/t U, a PWR fuel assembly has an energy density of approximately 10 million GJ/m^3, allowing stockpiling between 476,000 to 287 million times more energy in the same area compared to coal and gas, respectively. On the other hand, most renewables do not require fuel (apart from biomass) and are therefore not subject to supply disruptions (although they may produce energy intermittently).

2.4.7. Nuclear proliferation

Based on the objectives of the Treaty for Non-Proliferation of Nuclear Weapons (NPT) [149], nuclear proliferation can be defined as the spread of nuclear weapons and weapons technology. In recent years the phrase has also become associated with the potential targeting of civil nuclear facilities by terrorist groups, although this is a separate issue. The UK, as a nuclear power, has already 'proliferated' and subsequently signed the NPT. Consequently, non-proliferation objectives must be considered from a different perspective. For instance, several measures of proliferation resistance use the existence or non-existence of safeguards in the country of operation as a criterion [150,151]. This is not informative in this framework because of the focus on the UK which signed the NPT in 1968 [152]. Similarly, while the NPT aims for nuclear disarmament, the existence of civil nuclear reactors in the UK is of no direct relevance to the reduction in number of the UK's approximately 200 nuclear warheads [153], as this would be dictated solely by defence policy. There are, however, three main factors which are simultaneously of concern from a proliferation perspective and of relevance to energy systems:

- the ease by which nuclear weapons material might be produced from power reactors;
- the ease by which nuclear weapons material might be obtained from the chosen fuel cycle; and
- the effect of possessing certain technologies on global non-proliferation efforts.

The first criterion addresses the fact that certain reactors provide weapons-usable plutonium more readily than others. CANDU and Magnox, for example, do not require enriched fuel, circumventing the need for enrichment facilities. CANDU reactors also allow fuel unloading while still online, making extraction of low burn-up spent fuel easier (although this would require operation outside of safeguards).

The second criterion addresses the products of the fuel cycle: reprocessing involves the separation of uranium and/or plutonium from spent fuel, leading to various risks such as theft and detonation (discussion of which, in relation to the UK plutonium stockpile, can be found in Ref. [154]). Indeed, plutonium production (in terms of weapons-usability, mass produced and ease of appropriation) is the usual focus of nuclear proliferation resistance indicators [see, for example, Refs. [50,51,155]]. However, these indicators are often over-complicated, requiring large amounts of data that are not freely available. Moreover, detailed assessment of plutonium alone seems increasingly redundant given the fact that almost any grade of plutonium, including that extracted by so-called proliferation-resistant reprocessing techniques (such as COEX, UREX and THOREX), could be used to create a nuclear weapon with relative ease, albeit a potentially low-yield one [51].

Regarding the third criterion, if enrichment technology, for instance, is taken as a requirement for civil nuclear power, it is diplomatically and politically difficult for a possessor of that technology to deny it to a country that does not possess it. This is echoed by the public concern expressed in response to the 2006 UK energy White Paper [44]: many respondents stated that possessing nuclear power in the UK was undesirable because it encouraged other countries to pursue nuclear technology in general.

Considering these three concepts, it is suggested that the nuclear proliferation indicator be based on the following considerations (Table 2):

- use of non-enriched uranium in a reactor capable of online refuelling, such as CANDU;
- use of reprocessing, and;
- requirement for enriched uranium.

It spans the whole life cycle of nuclear power. It is expressed as a score on a scale from 0 to 3 with all the three criteria equally weighted; the lower score is preferred. To capture all three criteria, the enrichment, operation, reprocessing and MOX fabrication stages of the life cycle must be considered. Therefore, a PWR in a reprocessing fuel cycle would score 2 because PWRs require enriched fuel (indirectly promoting the spread of enrichment technology) and, in this case, involve reprocessing (leading to risks of theft and weapons manufacture). While we recognise that this is a simplistic evaluation, we suggest that it is sufficient for consideration of current nuclear options for the UK. It is not, however, appropriate or sufficiently detailed for application to future (Generation IV) nuclear technologies.

2.4.8. Intergenerational equity

Maintaining resources for future generations is a notion at the centre of sustainable development. Unfortunately the nature of these 'resources' is extremely hard to define in a universally acceptable manner, being open to interpretation depending on the substitutability of different forms of capital. Moreover, the timescales involved are highly debatable, although they are certainly long enough to provide exceptionally low certainty about future contexts and conditions. These issues, along with four different models of intergenerational equity, are discussed in more detail by Brown Weiss [156]. As a result of these difficulties, intergenerational equity is rarely considered. Nevertheless, it is crucial that it be included in sustainability assessments.

In the context of electricity generation, we suggest that there are three main issues related to intergenerational equity that should be considered: climate change, abiotic resource depletion and long-lived hazardous waste. Of these, only the latter two are considered here. Abiotic resource depletion applies to the whole life cycle, whereas long-lived hazardous waste is only relevant to the waste disposal stage of the life cycle (Table 2). Regarding climate change, we must differentiate between global warming (as a result of life cycle GHG emissions, as discussed in Section 2.3.3) and climate change itself (a complex phenomenon of which average global warming is only a part [see Ref. [157]]). In the context of energy policy in the UK and elsewhere, GWP is used as a proxy for climate change, so this approach is also followed within this framework. Since GWP is normally considered an environmental problem and estimated using LCA, it is included within this framework under the environmental indicators (see Section 2.3.3). Thus, to avoid double counting, it is not considered again as part of the intergenerational equity category.

The depletion of abiotic resources indicator comprises depletion of minerals and fossil fuels, and is quantified using the CML methodology [158] (see Appendix). It is split into two indicators to allow for the fact that fossil fuels, as energy vectors, are essentially substitutable, whereas elements and the substances containing them perform very different functions and are not interchangeable [158]. The fossil fuel depletion indicator is expressed in MJ/kWh. The elements indicator takes into account differences in reserve sizes and usage rates of different resources by normalising to antimony (since this is not a widely used metal and therefore has a relatively constant reserve lifetime).

The long-lived hazardous waste indicator comprises two types of waste: radioactive waste from nuclear power and CO_2 captured from fossil (and biomass) fuel technologies. Both types of waste have obvious consequences for future generations due to the possibility of accidental leaks and the burden of monitoring for long time periods. The risk of accidental leaks cannot be quantified sufficiently at this stage due to the lack of operating repository experience and site-specific information as well as the difficulties in establishing an agreed timeframe. The long-term monitoring burden, however, can be expressed by using the volume of waste (or waste storage facilities) that requires monitoring as a rough proxy. For instance, over its life cycle, it has been estimated that Sizewell B produces 4.88×10^{-8} m^3 of LLW, 1.55×10^{-8} of intermediate-level waste (ILW) and $1.42 \times 10-9$ of spent fuel per kWh [42] which, under current expectations, should be treated as high-level waste (HLW) [45]. Assuming half of the LLW is recycled, this gives 4.132×10^{-8} m^3 per kWh of waste requiring long-term geological storage. In the case of coal CCS for instance, assuming 90% CO_2 capture at a plant emitting 800 g CO_2/kWh, followed by supercritical (liquid) storage at a density of 950 kg/m^3 [159], approximately 7.6×10^{-4} m^3 of waste per kWh requires long-term storage. This is roughly 18,000 times greater than the volume of nuclear waste given above. Direct comparison of these waste streams does, of course, neglect differences in the potential severity of their release into the environment and in their specific characteristics whilst in storage. However, given that a large release of either could be disastrous, the monitoring burden is arguably similar per unit volume.

3. Conclusions

The UK electricity sector is changing rapidly to meet the demands of the 21st century. Energy security and climate change appear to be driving towards an electricity mix with a significant contribution from nuclear power and various renewable technologies. However, energy security and climate change are not the only criteria by which sustainable development should be gauged. The aim of this research has been to identify all other appropriate sustainability criteria in the context of UK electricity generation, particularly with regard to possible new nuclear build. As a result, a new sustainability framework has been developed, comprising 43 techno-economic, environmental and social indicators assessed on a life cycle basis wherever appropriate. Although the framework has been developed primarily to address concerns associated with nuclear power in the UK, it enables sustainability assessments and comparisons of other energy technologies; it is also applicable to other countries.

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Appendix. Definition and estimation of indicators

Techno-economic indicators

Operability: capacity factor; availability; dispatchability; fuel reserves

Capacity factor is the power output of a plant in a specified time expressed as a percentage of the maximum possible power output over the same time period had the plant been running continuously at full power:

$$CF = \frac{P_{out}}{P_{max}} \times 100 \quad (\%)$$

CF – capacity factor (%)
P_{out} – power output of a plant (MWh)
P_{max} – maximum possible power output (MWh)

Availability is the percentage of time that a plant is available to produce electricity and is calculated as follows:

$$A = \frac{t_A}{t_{max}} \times 100 \quad (\%)$$

A – plant availability (%)
t_A – time over which the plant is available for generation of electricity over one year (h/yr)
t_{max} – maximum operating time over one year (h/yr)

Dispatchability is the ability of a generating unit to increase or decrease generation, or to be brought on line or shut down as needed. Two types of dispatchability are distinguished here: *technical* and *economic*.

Technical dispatchability: ramp-up rate; ramp-down rate; minimum up time; minimum down time

Ramp-up rate:

$$RU = \frac{RU_{max}}{P_{max}} \times 100$$

RU – ramp-up (%)
RU_{max} – maximum rate of power increase (MW/min)
P_{max} – maximum power output (MW)

Ramp-down rate:

$$RD = \frac{RD_{max}}{P_{max}} \times 100$$

RD – ramp-down rate (%)
RD_{max} – maximum rate of power decrease (MW/min)
P_{max} – maximum power output (MW)

Minimum up time: minimum time for which a unit must operate at power before being shut down.

Minimum down time: minimum time for which a unit must remain shut down before returning to power.

The overall technical dispatchability is estimated by ranking the electricity-generating technologies on each of the four technical dispatchability criteria defined above and then summing the rankings to derive a total technical dispatchability value:

$$TD = R_{RUR} + R_{RDR} + R_{MUT} + R_{MDT} \quad (-)$$

TD – technical dispatchability value (–)
R_{RUR} – ranking for ramp-up rate
R_{RD} – ranking for ramp-down rate
R_{MUT} – ranking for minimum up time
R_{MDT} – ranking for minimum down time

Economic dispatchability is the ratio of capital to total levelised electricity costs (for the estimation of the latter, see further below):

$$ED = \frac{CC}{LEC} \quad (-)$$

ED – economic dispatchability (–)
CC – capital component of total levellised costs (pence/kWh)
LEC – levelised electricity costs (pence/kWh)

Lifetime of fuel reserves represents a ratio of economically recoverable resources and the current rate of usage of fuel reserves:

$$LFR = \frac{ERR}{UR} \quad \text{(years)}$$

LFR – lifetime of fuel reserves (years)
ERR – economically recoverable resources (t)
UR – current usage rates of fuels (t/yr)

Technological lock-in

This indicator is defined by two parameters: lifespan and flexibility and is estimated as:

$$T = \frac{f^2}{l} \quad \left(\text{years}^{-1}\right)$$

T – technological lock-in score (years^{-1})
f – flexibility index (0–30)
l – lifespan of the technology (years)

The flexibility index is related to the ability of a technology for trigeneration, negative CO_2 emissions and H_2 production. Each of these three options is allocated 10 points, so that f ranges from 0 to 30.

Levelised electricity cost

This indicator expresses the cost of generating electricity, throughout the full life cycle of a power plant, discounted at an appropriate rate. It is calculated as:

$$LEC = \frac{\sum_{n}^{N} \frac{CC_t + M_t + F_t}{(1+r)^t}}{\sum_{n}^{N} \frac{E_t}{(1+r)^t}} \times 10^{-2} \quad \text{(p/kWh)}$$

LEC – levelised electricity cost (p/kWh)
CC_t – capital costs (investment) in year t (£)
M_t – operations and maintenance expenditure in year t (£)
F_t – fuel expenditure in year t (£)
E_t – electricity generation in year t (kWh)
r – discount rate
N – lifetime of the power plant

Cost variability: fuel price sensitivity

This indicator represents the ratio of fuel cost to total levelised generation cost:

$$CV = \frac{FC}{LEC} \quad (-)$$

CV – fuel cost variability (fuel price sensitivity) (–)
FC – fuel cost (p/kWh)
LEC – levelised electricity costs (p/kWh)

Environmental indicators

Material recyclability

This indicator estimates the proportion of a power plant that is recycled at the end of its lifetime as follows:

$$MR = \frac{\sum_{j}^{J} R_j}{M_p} \times 100 \quad (\%)$$

MR – overall material recyclability (%)
R_j – amount of material j that can be recycled (t)
M_p – total amount of materials contained in the power plant (t)

Water eco-toxicity: Freshwater and marine eco-toxicity potential

These two indicators are based on the maximum tolerable concentrations of toxic substances by different organisms in the freshwater and marine environments. The reference substance is 1,4-dichlorobenzene (DCB) and the indicators are calculates as:

$$FWETP = \sum_{j}^{J} FWETP_j \times B_j \quad (\text{kg } 1,4-\text{DCB equiv/kWh})$$

FWETP – total freshwater eco-toxicity potential of energy technology (kg 1,4-DCB equiv/kWh)
$FWETP_j$ – freshwater eco-toxicity potential of substance j (kg 1,4-DCB equiv/kg)

$$METP = \sum_{j}^{J} METP_j \times B_j \quad (\text{kg } 1,4-\text{DCB equiv/kWh})$$

METP – total marine eco-toxicity potential of energy technology (kg 1,4-DCB equiv/kWh)
$METP_j$ – marine eco-toxicity potential of substance j (kg 1,4-DCB equiv/kg)
B_j – emission of substance j to freshwater or seawater (kg/kWh)
J – total number of toxic species

Global warming potential (GWP)

GWP expresses the potential of different greenhouse gases (GHGs) to cause climate change. GWP factors for different GHGs are expressed relative to the GWP of CO_2, which is defined as unity. It is calculated as:

$$GWP = \sum_{j}^{J} GWP_j \times B_j \quad (\text{kg } CO_2 \text{ equiv/kWh})$$

GWP – total GWP of energy technology (kg CO_2 equiv/kWh)
GWP_j – GWP factor for GHG j (kg CO_2 equiv/kg)
B_j – emission of GHG j (kg/kWh)
J – total number of GHGs

The values of GWP depend on the time horizon over which the global warming effect is assessed. GWP factors for shorter times (20 and 50 years) provide an indication of the short-term effects of GHGs on the climate, while GWPs for longer periods (100 and 500 years) are used to predict the cumulative effects of these gases on the global climate. GWP100 is used more widely and therefore is within this framework.

Ozone layer depletion potential

Ozone layer potential (ODP) indicates the potential of emissions of chlorofluorocarbons (CFCs) and other halogenated hydrocarbons to deplete the ozone layer. It is expressed relative to the ozone depletion potential of CFC-11 and calculated as:

$$\text{ODP} = \sum_{j}^{J} \text{ODP}_j \times B_j \quad (\text{kg CFC}-11\ \text{equiv/kWh})$$

ODP – total ozone layer depletion potential of energy technology (kg CFC-11 equiv/kWh)
ODP_j – ODP of ozone depleting gas j (kg CFC-11 equiv/kg)
B_j – emission of ozone depleting gas j (kg/kWh)
J – total number of ozone depleting substances

Acidification potential (AP)

AP represents the contribution of SO_2, NO_x and NH_3 to acid rain and related impacts. It is expressed relative to the AP of SO_2 and calculated according to the equation:

$$\text{AP} = \sum_{j}^{J} \text{AP}_j \times B_j \quad (\text{kg SO}_2\ \text{equiv/kWh})$$

AP – overall acidification potential of energy technology (kg SO_2 equiv/kWh)
AP_j – acidification potential of acid gas j (kg SO_2 equiv/kg)
B_j – emission of acid gas j (kg/kWh)
J – total number of acid gases

Eutrophication potential

EP is defined as the potential of nutrients such as N, NO_x, NH_4^+, PO_4^{3-} and P to cause over-fertilisation of water and soil, which can result in increased growth of biomass (algae). It is expressed relative to PO_4^{3-} and calculated as:

$$\text{EP} = \sum_{j}^{J} \text{EP}_j \times B_j \quad \left(\text{kg PO}_4^{3-}\ \text{equiv/kWh}\right)$$

EP – overall eutrophication potential of energy technology (kg PO_4^{3-} equiv/kWh)
EP_j – eutrophication potential of nutrient j (kg PO_4^{3-} equiv/kg)
B_j – emission of nutrient j (kg/kWh)
J – total number of nutrients

Photochemical oxidant creation potential (summer smog)

This indicator is related to the potential of VOCs and NO_x to generate photochemical or summer smog. It is usually expressed relative to the photochemical oxidation creation potential (POCP) of ethylene and can be calculated as:

$$\text{POCP} = \sum_{j}^{J} \text{POCP}_j \times B_j \quad (\text{kg C}_2\text{H}_4\ \text{equiv/kWh})$$

POCP – total photochemical oxidant creation potential of energy technology (kg ethylene equiv/kWh)
POCP_j – POCP potential of species j (kg C_2H_4 equiv/kg)
B_j – emission of substances j contributing to the formation of summer smog (kg/kWh)
J – total number of substances contributing to the formation of summer smog

Land use and quality: impacts of land use; greenfield land use; terrestrial eco-toxicity

Impact of land use (ILU) is calculated as:

$$\text{ILU} = A \times t \quad \left(\text{m}^2\text{yr/kWh}\right)$$

ILU – total impact of energy technology on land use over time ($m^2 \cdot$yr/kWh)
A – land area occupied (m^2)
t – time over which land is occupied (yr)

Greenfield land use is expressed as the percentage of the area of greenfield land that needs to be converted for the construction of power plant, relative to the total amount of area that will be occupied by the plant. It is calculated as:

$$\text{GF} = \frac{\text{GFA}}{\text{TLA}} \times 100\ (\%)$$

GF – percentage of greenfield land used for construction of power plant (%)
GFA – area of greenfield land used (m^2)
TLA – total land area occupied by the power plant (m^2)

Terrestrial eco-toxicity potential (TETP) is based on the maximum tolerable concentrations of toxic substances by different organisms in terrestrial environment. The reference substance is 1,4-dichlorobenzene and it is calculated as:

$$\text{TETP} = \sum_{j}^{J} \text{TETP}_j \times B_j \quad (\text{kg } 1,4-\text{DCB equiv/kWh})$$

TETP – terrestrial eco-toxicity potential of energy technology (kg 1,4-DCB equiv/kWh)
TETP_j – terrestrial eco-toxicity potential of toxic substance j (kg 1,4-DCB equiv/kg)
B_j – emission of substance j to land (kg/kWh)
J – total number of toxic substances emitted to land

Social indicators

Employment provision: direct and total

This indicator measures employment provision in the life cycle of an energy technology. It is expressed in person-yrs per total amount of electricity generated over the lifetime of energy technology.

Direct employment measures number of person-yrs/GWh directly employed in the life cycle of energy technology and is calculated as follows:

$$\text{DE} = \frac{\sum_{j}^{J} \text{DE}_j \times t_j}{P_{\text{tot}}} \quad (\text{person}-\text{yrs/GWh})$$

DE – direct employment provision over the life cycle of an energy technology (person-yrs/GWh)
DE_j – direct employment provision in life cycle stage j (no. of people employed)
t_j – duration of employment in life cycle stage j (yrs)
P_{tot} – total amount of energy generated over the lifetime of energy technology (GWh*)
J – total number of life cycle stages

(*GWh rather than kWh to avoid small numbers)

Indirect employment is related job creation owing to the activities related to electricity provision and is calculated in the same way as DE.

Total employment represents the sum of direct and indirect employment: DE = DE + IE (person-yrs/GWh).

Human health impacts: worker fatalities; human toxicity potential (excluding radiation); human health impacts from radiation (workers and population)

Worker fatalities represents the total number of worker deaths per unit of electricity generated in the whole life cycle of electricity generation and is calculated as:

$$\mathrm{WF} = \sum_{i}^{I} \mathrm{WF}_i \quad (\mathrm{no./GWh})$$

WF – total number of worker fatalities (no./GWh)

WF_i – number of worker fatalities in life cycle stage *i* scaled per GWh electricity produced (no./GWh)

Human toxicity potential (HTP) is calculated by taking into account releases toxic to humans to three different media, i.e. air, water and soil:

$$\mathrm{HTP} = \sum_{j}^{J} \mathrm{HCA}_{\mathrm{A}j} \times B_{\mathrm{A}j} + \sum_{j}^{J} \mathrm{HCW}_{\mathrm{W}j} \times B_{\mathrm{W}j} + \sum_{j}^{J} \mathrm{HCS}_{\mathrm{S}j} \times B_{\mathrm{S}j} \quad (\mathrm{kg\ 1,4-DCB\ equiv/kWh})$$

HTP_{Aj}, HTP_{Wj}, and HTP_{Sj} – toxicological potentials for substances emitted to air, water and soil, respectively (kg 1,4-DCB equiv/kg).

B_{Aj}, B_{Wj} and B_{Sj} – emissions of different toxic substances into the three environmental media (kg/kWh).

J – total number of substances toxic to humans.

Human health impacts from radiation (HIR): This indicator is divided in two indicators to distinguish between the impacts from radiation on workers and total impact on workers and general population. Both indicators are expressed in terms of disability-adjusted life years (DALY) lost due to the effects of radiation. This includes the years of life lost due to cancer and hereditary disease as well as the years in which individuals live with disease/disability. The severity of each disease is based on evaluations by a panel of health experts using a scale from 0 to 1, where '0' is perfect health and '1' is death. HIR is calculated as follows:

$$\mathrm{HIR} = \frac{\sum_{d}^{D} \mathrm{YL}_d + D_d S_d}{P_{\mathrm{tot}}} \quad (\mathrm{DALY/GWh})$$

HIR – human health impacts from radiation for workers or total impacts for both workers and general population (DALY/GWh)

YL_d –life lost due to disease *d* (yr)

D_d – average duration of disease *d* (yr)

S_d – average severity of disease *d*, as estimated by health experts (0–1)

P_{tot} – total amount of energy generated over the lifetime of energy technology (GWh)

Large accident risk

This indicator measures the number of fatalities due to large accidents over the life cycle of electricity generation and is expressed per unit of electricity generated as follows:

$$\mathrm{LAR} = \sum_{i}^{I} \mathrm{LAR}_i \quad (\mathrm{no./GWh})$$

LAR – total number of fatalities (no./GWh)

LAR_i – number of worker fatalities in life cycle stage *i* per GWh electricity produced (no./GWh)

I – total number of life cycle stages

Local community impacts: proportion of staff hired from local community; proportion of spending on local suppliers; and direct investment in local community

Proportion of staff hired from local community is expressed relative to the total provision of direct employment during the operation stage of a power plant. It is calculated as follows:

$$P_{\mathrm{LS}} = \frac{\mathrm{LS}}{\mathrm{DEO}} \times 100 \quad (\%)$$

P_{LS} – proportion of staff hired from local community during the operation stage of a power plant (%)

LS – number of staff hired from local community per unit of electricity generated during the operational lifetime of a power plant (person-yrs/GWh)

DEO – total number of staff directly employed per unit of electricity generated during the operational lifetime of a power plant (person-yrs/GWh)

Proportion of spending on local suppliers is expressed relative to the total spend each year:

$$P_{\mathrm{LSUP}} = \frac{S_{\mathrm{LSUP}}}{S_{\mathrm{tot}}} \times 100 \quad (\%)$$

P_{LSUP} – proportion of spending on local suppliers each year (%)

S_{LSUP} – annual spend on local suppliers (£/yr)

S_{tot} – total annual spend related to the operation and maintenance of the plant (£/yr)

Direct investment in local community is expressed as percentage investment relative to the total annual revenue:

$$P_{\mathrm{LDI}} = \frac{\mathrm{LDI}}{R_{\mathrm{tot}}} \times 100 \quad (\%)$$

P_{LDI} – proportion of direct investment in local community each year (%)

LDI – annual investment in local community (£/yr)

R_{tot} – total annual revenue (£/yr)

Human rights and corruption

This indicator is calculated as an average CPI [142] of the countries involved in the life cycle of an energy system:

$$\mathrm{CPI} = \frac{\sum_{c}^{C} \mathrm{CPI}_c}{C} \quad (\mathrm{score\ 0-10})$$

CPI – average corruption perceptions index (score 0–10)

CPI_c – corruption perceptions index for country *c* in the life cycle of an energy technology

C – total number of countries

Energy security: imported fossil fuel avoided; diversity of fuel supply (DFS); fuel storage capacity

Imported fossil fuel avoided

This indicator measures the amount of imported fossil fuel potentially avoided by non-fossil fuel electricity-generating technologies, calculated as follows:

$$\mathrm{IFA} = \frac{100}{\eta_a} \times K \quad (\mathrm{koe/kWh})$$

IFA – imported fossil fuel potentially avoided (koe/kWh)

η_a – average efficiency of the fossil fuel fleet (%)

K – conversion for kilowatt-hour to kilograms oil equivalent (koe/kWh)

DFS mix is based on the proportions of national fuel supply imported and exported, where the import mix is assessed for diversity using the Simpson Diversity Index (SID). It is calculated as follows:

$$\text{DFS} = P_{\text{in}} + P_{\text{im}}\left(1 - \frac{\sum_{c}^{C} n_c(n_c - 1)}{9900}\right) \quad (\text{score } 0\text{–}1)$$

P_{in} – proportion of national fuel demand produced indigenously
P_{im} – proportion of national fuel demand imported
n_c – percentage of fuel imports supplied by exporting country c

Fuel storage capacity is related to the fuel storage capacity expressed in unit of energy per unit storage volume. For conventional fuels, it is simply the net calorific value of the fuel (GJ/m^3). In the case of nuclear power, the relevant criterion is the energy density per fuel assembly volume rather than per uranium volume. This can be calculated as:

$$\text{ED} = \frac{\text{MA}_\text{u} \times \text{BU}}{\text{VA}_{tot}} \quad \left(\text{GJ/m}^3\right)$$

ED – volumetric energy density of nuclear fuel (GJ/m^3)
MA_u – mass of uranium in one fuel assembly (t)
BU – assumed 'burn-up' of uranium in fuel (GJ/tU)
VA_tot – total volume of one fuel assembly (t)

Intergenerational equity: abiotic resource depletion; long-term storage of hazardous waste

Abiotic resource depletion potential (ADP) represents depletion of fossil fuels and minerals. It is expressed in MJ/kWh and kg Sb/kWh, respectively for fossil fuels and minerals. The total impact is calculated as:

$$\text{ADP}_\text{F} = \sum_{j}^{J} \text{ADP}_{\text{F}j} \times B_{\text{F}j} \quad (\text{MJ/kWh})$$

ADP_F – abiotic resource depletion potential for fossil fuels (MJ/kWh)
$\text{ADP}_{\text{F}j}$ – abiotic depletion potential for fossil fuel j (MJ/kg)
$B_{\text{F}j}$ – quantity of fossil fuel j used (kg/kWh)

$$\text{ADP}_\text{M} = \sum_{j}^{J} \text{ADP}_{\text{M}j} \times B_{\text{M}j} \quad (\text{kg Sb equiv/kWh})$$

ADP_M – abiotic resource depletion potential for minerals (kg Sb equiv/kWh)
$\text{ADP}_{\text{M}j}$ – abiotic depletion potential for mineral j (kg SBb equiv/kg)
$B_{\text{M}j}$ – quantity of mineral j used (kg/kWh)

Long-term storage of hazardous waste represents the long-term waste monitoring burden resulting from nuclear power and CCS. Nuclear waste is normally expressed volumetrically, whereas CO_2 is normally expressed in mass terms and therefore requires conversion to storage volume as described below.

$$\text{LSW}_\text{NUC} = \sum_{i}^{I} w_i \quad \left(\text{m}^3/\text{kWh}\right)$$

LSW_NUC – long-term storage of nuclear waste (m^3/kWh)
w_i – quantity of nuclear waste destined for geological disposal produced in life cycle stage i (m^3/kWh)

$$\text{LSW}_\text{CAR} = \frac{\sum_{i}^{I} c_i}{d} \quad \left(\text{m}^3/\text{kWh}\right)$$

LSW_CAR – long-term storage of supercritical carbon dioxide from CCS (m^3/kWh)
c_i – quantity of carbon dioxide removed for long-term storage in life cycle stage i (kg/kWh)
d – density of carbon dioxide under supercritical conditions at storage site (kg/m^3)

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