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LCA FOR ENERGY SYSTEMS

# Life cycle environmental impacts of decommissioning Magnox nuclear power plants in the UK

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**Abstract**
*Purpose* Full life cycle assessment (LCA) impacts from decommissioning have rarely been assessed, largely because few sites have been decommissioned so that the impacts of decommissioning are currently uncertain. This paper presents the results of an LCA study of the ongoing decommissioning of the Magnox power plant at Trawsfynydd in the UK. These results have been used to estimate the potential environmental impacts for the whole UK Magnox fleet of 11 reactors that will have to be decommissioned during this century.
*Methods* The functional unit is defined as 'decommissioning one Magnox power plant'. The system boundary considers all stages in the life cycle of decommissioning, including site management, waste retrieval, plant deconstruction, packaging and storage of intermediate- and low-level wastes (ILW and LLW). High-level waste, i.e. waste fuel is excluded as it was being removed from the site to be reprocessed at Sellafield. The environmental impacts have been estimated using the CML 2001 methodology. Primary data have been sourced from the Trawsfynydd site and the background from Ecoinvent.
*Results and discussion* Most impacts from decommissioning are due to the plant deconstruction (25–75 %) and ILW storage and disposal (25–70 %). For the example of global warming potential (GWP), estimated at 241 kt $CO_2$ eq./functional unit, or 3.5 g $CO_2$ eq./kWh of electricity generated during the lifetime of the plant, 55 % of the impact is from plant deconstruction and 30 % from ILW disposal. The results for the whole UK Magnox fleet indicate that the impacts vary greatly for different sites. For example, the GWP ranges from 0.89 to 7.14 g $CO_2$ eq./kWh. If the impacts from storage of waste fuel at Sellafield are included in the estimates, the GWP increases on average by four times. Overall, decommissioning of the UK Magnox reactors would generate 2 Mt of $CO_2$ eq. without and 11 Mt of $CO_2$ eq. with the waste from Sellafield. This represents 0.4 and 2 % of the total UK annual emissions, respectively.
*Conclusions* The impacts of decommissioning can vary greatly at different sites depending on the amount of waste and electricity generated by the plants. Delaying decommissioning to allow the energy system to decarbonise could reduce the environmental impacts, e.g. GWP could be reduced by 50 %. The impacts could also be reduced by reducing the volume of waste and increasing recycling of materials. For example, recycling 70 % of steel would reduce the impacts on average by 34 %.

**Keywords** Decommissioning · Life cycle environmental impacts · Magnox reactors · Nuclear waste

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## 1 Introduction

There is currently an international drive to build new nuclear power plants, bringing about a 'nuclear renaissance'. At the same time, a significant number of nuclear plants are coming to the end of their lifetime and will need to be decommissioned. In the UK, all but one of the present reactor fleet will reach the end of their lifetime by 2023. At the time of writing, 14 nuclear power plants have either been closed down or are being decommissioned, including ten of the 11 Magnox[1] power plants. Decommissioning these plants and the related infrastructure is expected to cost UK £73 billion over the next 100 years (NAO 2008) and it could also cause significant environmental impacts.

The environmental impacts of the nuclear life cycle (Fig. 1) have been the subject of a number of life cycle assessment (LCA) studies (e.g. Fthenakis & Kim 2007; Lenzen 2008; Sovacool 2008; Vattenfall 2010a; Vattenfall 2010b; Simons & Bauer 2012). However, the full impacts from decommissioning have rarely been assessed, largely because few sites have been completely decommissioned (Fthenakis & Kim 2007); Jazayeri et al. 2008; van Leeuwen and Smith 2005). In the absence of data, most studies have considered either the energy required for construction of power plants (e.g. Voorspools et al. 2000) or decommissioning costs (e.g. van Leeuwen and Smith 2005) as a proxy for estimating the environmental impacts of decommissioning. These are usually expressed only in terms of $CO_2$ emissions and estimates have varied widely (Beerten et al. 2009). Therefore, the life cycle impacts of decommissioning remain uncertain.

In an attempt to provide a further insight into the subject, this paper presents the results of an LCA study of the ongoing decommissioning of the Magnox power plant at Trawsfynydd in the UK. These results are then used to estimate the potential environmental impacts for the whole UK Magnox fleet that will have to be decommissioned over the next decades.

## 2 Goal and scope of the study

The main goal of the study is to estimate the life cycle environmental impacts of decommissioning Magnox nuclear power plants. The functional unit is defined as 'decommissioning one Magnox power plant'. The Trawsfynydd plant based in Wales and currently being decommissioned is used as a case study. This is discussed in Sections 2, 3 and 4. A further goal is to estimate the potential impacts of decommissioning of all Magnox reactors in the UK based on the results obtained for the Trawsfynydd plant. For these purposes, the second functional unit is defined as 'decommissioning of the whole UK Magnox fleet'. This is the subject of Section 5.

[1] Magnox is a British-designed pressurised reactor, which uses natural (unenriched) uranium as fuel, graphite as moderator and carbon dioxide as coolant. Magnox (magnesium non-oxidising) alloy is used for cladding; hence the name. For description of Magnox reactors, see, e.g. (Jensen & Nonbøl 1999). Magnox reactors have only ever been used in the UK and are no longer built. The last Magnox plant is scheduled to close by September 2014.

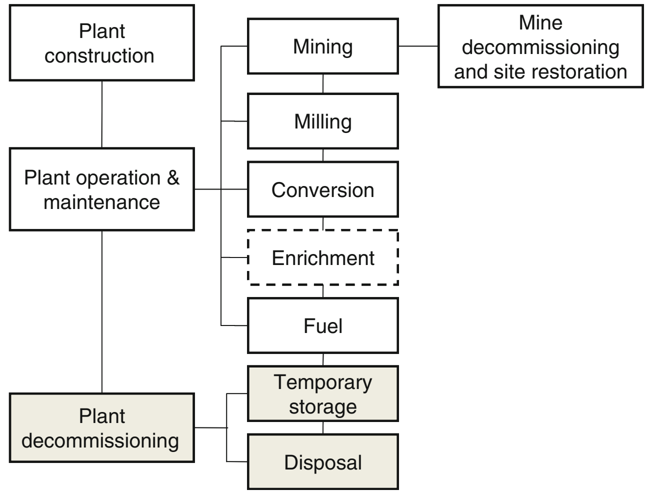



**Fig. 1** The life cycle of nuclear power. The *shaded boxes* indicate the life cycle stages included in the decommissioning study considered in this study. For full detail, see Fig. 2. Fuel enrichment is not carried out for Magnox reactors

Two 390 MW Magnox reactors at Trawsfynydd based in the Snowdonia national park in North Wales operated for 24 years until 1993. The lifetime energy output of the site was 69 TWh (NDA 2006) and defuelling operations were completed by August 1995. Under the current decommissioning plans, all operational wastes and peripheral fixtures are currently being removed, with completion expected in 2015. Thereafter, the buildings housing the reactor cores will be sealed for a period of 'care and maintenance' (also known as 'safestore') lasting at least 70 years. During this time, no further decommissioning is carried out and no specific site management (other than periodic monitoring) is required. This will allow radioactive contamination to decay to lower levels, simplifying the final demolition and site clearance, which is scheduled to occur between 2088 and 2098 (NDA 2006).

Therefore, the system boundary (Figs. 1 and 2) includes all site activities after the completion of defuelling and comprises:

- Site management and research and development of decommissioning methods, which continue throughout the decommissioning period
- Waste retrieval
- Plant deconstruction, which involves dismantling and decontamination of the power plant structure as well as construction and demolishing of the supporting structures used for the deconstruction
- Separation of recyclable materials
- Packaging of waste
- Interim storage, transport and final disposal of wastes
- Land remediation.

Further description of these activities is given in the next section. Note that storage of spent fuel is excluded from the system boundary as it was being removed from the site for

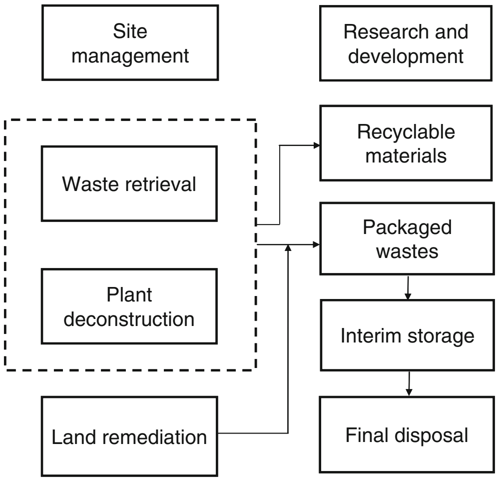



**Fig. 2** System boundary for decommissioning

reprocessing at Sellafield throughout the lifetime of the power plant.

## 3 System description, assumptions and data

### 3.1 Site management

Site management will be required over 30 years to support early stages of decommissioning from 1995 to 2015 and then demolition from 2088 to 2098 (NDA 2006). No significant active site management is anticipated during the period of care and maintenance in between these two phases, so resource consumption in this period is considered negligible. Site management involves administrative and service functions such as surveying, planning, costing, timetabling and approvals; in other words, typical office operations. Therefore, typical values for resource consumption in offices have been assumed in this study (Table 1), taking into account staff numbers and floor space (OGC 2009).

### 3.2 Research and development

Research and development (R&D) includes designing and testing new decommissioning techniques as well as further development of existing techniques (Versemann 2008). In each case, test facilities or 'dummy' structures may need to be constructed. At Trawsfynydd, R&D includes trialling electrochemical treatment of radioactive oil (Magnox North 2010c), testing waste retrieval methods (e.g. Magnox North 2010a) and modification of tools and fixings to increase the speed and reliability of pond scabbling[2] (Magnox North 2009a, 2010b). As the R&D and active decommissioning are similar in nature, they are assumed here to require similar but lower resources (as described in Sections 3.3 and 3.4) and for only a fraction of the time (see Table 1).

### 3.3 Waste retrieval

In UK, nuclear wastes are categorised into three types (Bayliss and Langley 2004):

- Low-level waste (LLW): waste with radioactivity levels not exceeding 4 GBq/tonne (alpha) or 12 GBq/tonne (beta/gamma), which are placed in managed surface disposal facilities
- Intermediate-level waste (ILW): waste with higher beta/gamma activity, potentially also some alpha emitters, whose heat production is sufficiently high to require managed disposal
- High-level waste (HLW): heat-generating wastes which require managed disposal.

Presently, ILW and HLW decommissioning wastes are placed in interim storage at each nuclear site until long-term disposal becomes available [for the UK (CoRWM 2006) and the European Commission (2010), preference is for a sealed facility, 500 m or more below the surface]. As already mentioned, no HLW will be generated from decommissioning the Trawsfynydd site as no spent fuel remains at the site. ILW or LLW will arise in decommissioning operations, depending on the initial level of contamination and subsequent treatment of the waste during decommissioning.

Waste retrieval involves recovery from the concrete vaults beneath the site buildings of materials, which were radioactively contaminated during the operation of the power plant. This is typically carried out using remotely controlled heavy machinery. Various wastes are recovered and treated separately, according to their material and radiological characteristics; however, the principal elements of all waste recovery are similar and involve:

- Accessing of waste, possibly requiring construction work
- Its mobilisation, if required, using jetting or stirring by pneumatic, mechanical or chemical means (IAEA 2006; IAEA 2007; Parsons 2007)
- Retrieval by manipulator arms or robotic vehicles with grabs, suction tools or pumps (IAEA 2006; IAEA 2007; Wall & Shaw 2002)
- Transfer to waste processing by winches, hoist and conveyors (Wall & Shaw 2002).

Retrieval of the following five types of waste is carried out concurrently at Trawsfynydd (Parsons 2007) and will continue for approximately 10 years (NDA 2006):

[2] Scabbling is the process of abrading the surface of concrete in the ponds with a rotating drill head to remove contamination.

**Table 1** Equipment and resource used for site management and R&D over 30 years

| Life cycle stage | Equipment/ resource | Included in the study | Use | Quantity/ size | Assumptions | Source | LCA data source (age), region[f] |
|---|---|---|---|---|---|---|---|
| Site management | | | | | 350 staff (average) over 30 years [a] | Own estimate[a] | |
| | Electricity | Electricity generation | Electricity used in offices and administrative buildings | 8,118 GJ | 2 MWh per person per year [b] | Own estimate[b] | Ecoinvent (2002), UK |
| | Tap water | Production of tap water | Water used in offices and administrative buildings | 225 million litres | 50 l per person per day | British Water (2011) | Ecoinvent (2000), Eur |
| | Paper | Material manufacture | Retained documents | 110 tonnes | 10 % of office paper use | Hawken et al. (1999) | Ecoinvent (2000), Eur |
| | Waste: | Material manufacture | Materials used in normal office operation | 1,580 tonnes | 150 kg per person per year [c] | Own estimate[c] | |
| | Paper/card | | Paper and card | 1,100 tonnes | 70 % of waste[d] | Own estimate[d] | Ecoinvent (2000), Eur |
| | Organics | | Food wastes | 250 tonnes | 16 % of waste [d] | Own estimate[d] | Ecoinvent (2000), Eur |
| | Plastic | | Packaging and plastics | 80 tonnes | 5 % of waste [d] | Own estimate[d] | Ecoinvent (2000), Eur |
| | Glass | | Glass | 60 tonnes | 3.5 % of waste[d] | Own estimate[d] | Ecoinvent (2000), Eur |
| | Metal (Al) | | Metals, assumed tins/cans | 50 tonnes | 1.5 % of waste[d] | Own estimate[d] | Ecoinvent (2002), Eur |
| Research and development | | | | | | | |
| | Building | Construction of small contained area | Small purpose-built research facility | 50 $m^2$ | Reasonable area for experimental work | Own estimate | Ecoinvent (2001), CH |
| | Electricity | Electricity generation | Electricity used in testing | 756 GJ | 7,000 h at 30 kW[e] | Own estimate[e] | Ecoinvent (2002), UK |
| | Electronics | Material manufacture | Experimental control and monitoring systems | 0.1 tonnes | Fewer control systems required than actual decommissioning | Own estimate | Ecoinvent (2005), Eur |
| | Heavy machinery | Construction of machinery | Equipment used in testing new methods | 5 tonnes | Weight of a typical decommissioning machine[e] | Own estimate[e] | Ecoinvent (2001), Eur |

[a] Based on 200 permanent staff and half the current 300 temporary or contract staff during early stage decommissioning (1995–2015) and demolition (2088–2098) (NDA 2006)

[b] Within estimated range based on 10 $m^2$ floor area (OGC 2009) and 100–kWh/$m^2$ (CIBSE 2000)

[c] Based on the range of 125–200 kg per person (PACE 2000; Hilton undated; Mouchel 2010)

[d] Based on office waste data from Resource NSW (2002) and Waste online (2004)

[e] Based on a 5 tonne, 30 kW 'Brokk', a typical remote control vehicle used in decommissioning

[f] LCA data considered applicable to UK, Switzerland (CH) or Europe (Eur)

- Miscellaneous activated components (MAC): metal and wire, which have become radioactive (activated) following exposure to radiation
- Fuel element debris (FED): fragments of the magnesium oxide alloy casings from uranium fuel rods and potentially also fuel debris, removed when preparing the fuel for reprocessing
- Active waste vaults (AWV): various contaminated items, including rags, paper, metals and asbestos cladding from operations and maintenance work
- Resins: ion-exchange resin used to clean and decontaminate components during the power plant operation
- Sludges: liquid wastes from the cooling ponds and effluents, containing corrosion products from Magnox fuel

rods and other materials such as grit, paint flakes, oils and grease.

Data and assumptions for the waste retrieval stage related to the use of machinery and waste quantities can be found in Tables 2 and 3, respectively.

## 3.4 Plant deconstruction

### *3.4.1 Dismantling and decontamination*

Dismantling of nuclear power plants involves the removal and possible decontamination of recoverable structural elements such as walkways, fences and cabling and finally the demolition of structures. With on average 160,000 and 40,000 t, concrete and steel are respectively by far the largest components of the structure of a nuclear power plant (Bryan & Dudley 1974; White & Kulcinski 2000). The estimates for Trawsfynydd waste (NDA 2007) indicate that approximately 80,000 t of concrete and 13,500 t of steel will be consigned as radioactive waste upon final demolition. It is also estimated that 30,000 t of steel will be available for recovery and recycling (see Table 3). The other major waste component is the graphite moderator of the reactor core, amounting to 3,500 $m^3$ of mostly ILW, which must be removed prior to demolition.

All steel and other metalwork must be cut for removal, transport, packaging for disposal and/or recycling. Data for metal cutting at Trawsfynydd are not available; however, detailed calculations describing the cutting required to extract and dispose of 21 tonnes of pipework and vessels from a small (250 $m^3$) nuclear industry facility have been obtained from Sellafield (as confidential information) and used in this study. Although the facilities differ, the requirements for packaging and disposal of the material are assumed to be the same and hence also the necessary cutting regimes for the steelwork. These have been extrapolated for the total amount of 43,500 t of steel assumed in the study (13,500 t as radioactive waste + 30,000 t available for recycling).

Up to 80 % of metalwork requires some decontamination (Steiner, 20 December 2010, by email), mostly

**Table 2** Equipment and resources used for waste retrieval, scabbling[2] and decontamination over the lifetime of decommissioning

| Infrastructure component | Equipment/ resource | Included in the study | Use | Quantity | Assumptions | LCA data source (age), region[e] |
|---|---|---|---|---|---|---|
| Ventilation | Ventilation unit (720 $m^3$/h) | Manufacture, transport, operation and disposal of unit | Ventilation and vacuum/ pressure systems operations | 500 $m^2$ years | 50 $m^2$ space, ventilated for 10 years[a] | Ecoinvent (2003), CH |
| Electronics | Electronics for control systems | Manufacture and transport of electronics | Control systems and devices for site safety, operations and monitoring equipment; including fire safety, CCTV, robotic and remote control systems | 1 tonne | All high-tech electronic equipment consists of similar material components | Ecoinvent (2005), Eur |
| Heavy machinery | Heavy equipment | Manufacture | Remote vehicles, cranes, hoists, grabs, conveyors for waste handing | 10 tonnes | Two 5-tonne remote control machines[b] | Ecoinvent (2001), Eur |
| Electricity usage | Electricity | Electricity generation | Consumption by all electronic and mechanical machinery | 3.77 TJ | 30 kW per heavy machine[b]<br>5 kW per tonne of electronics[c] | Ecoinvent (2002), UK |
| Routine cleaning | Electricity and water | Electricity generation and tap water production | Power and water used in routine decontamination of staff and equipment | 54 GJ | 4 kW washing machine[c]<br>8 kW shower unit[c] | Ecoinvent (2002), UK |
| | | | | 8.8 million litres of water | Water consumption of domestic machines[c,d] | Ecoinvent (2000), Eur |

[a] Estimated average size of typical cells and vaults

[b] Based on a 5-tonne, 30 kW Brokk, a typical remote-controlled decommissioning vehicle

[c] Based on observed consumption of typical consumer electronic products

[d] Water estimate includes an allocated share based on water consumption at Trawsfynydd in 2004 (NDA 2010a)

[e] LCA data considered applicable to UK, Switzerland (CH) or Europe (Eur) cases

**Table 3** Summary of resources used for decommissioning and waste management

| Life cycle stage | Process/tool/material | Use | Quantity | Assumptions | Source | LCA data source (age), region[i] |
|---|---|---|---|---|---|---|
| Waste retrieval | Typical decommissioning equipment and resources | Decontamination operations | See Table 2 | Typical equipment and resource used in decommissioning | Own estimate | See Table 2 |
| Decontamination | Typical decommissioning equipment and resources | Decontamination operations | See Table 2 | Typical equipment and resource used in decommissioning | Own estimate | See Table 2 |
| | Soap | Decontaminant | 5 tonnes | 1 l per 3 $m^3$ of metal | Own estimate | Ecoinvent (1995), Eur |
| | Tap water | Decontaminant | 8,800 tonnes | Known site water use, allocated amongst decommissioning operations | NDA (2010a) | Ecoinvent (2000), Eur |
| Construction and demolition of temporary structures and demolition of plant | Transport (20 tonne lorry) | Movement of materials | 500,000 km | 500×50 km journeys per year[a] | NDA (2010a) | Ecoinvent (2003), Eur |
| | | | | | | Ecoinvent (2000), GLO |
| | Concrete | Demolition and disposal of demolition waste | 80,000 tonnes | Assumed to be uncontaminated waste based on 160,000 tonnes of concrete in a typical plant | Bryan & Dudley (1974) | Ecoinvent (2002), GLO |
| | Excavation | Landscaping and backfilling | 70,000 $m^3$ | Equivalent to concrete volume | Own estimate | Ecoinvent (2001), Eur |
| | Concrete | Construction | 2,000 tonnes | 100 tonnes per year[a] | NDA (2010a) | Ecoinvent (2001), CH[j] |
| | Electricity | Tool use | 9,690 GJ | 50 kW/$ft^2$ for building 50,000 $m^2$ | Arnold (2008) | Ecoinvent (2002), UK |
| | Steel | Construction | 4,000 tonnes | 200 tonnes per year[a] | NDA (2010a) | Ecoinvent (2002), CH[j] |
| Cutting | Typical decommissioning equipment and resources | Cutting operations infrastructure | See Table 2 | Typical equipment and resource used in decommissioning | Own estimate | See Table 2 |
| | Power saws | Cutting tools | 5 | Typical metal saws, 2–7.5 kW | Own estimate | Ecoinvent (2001), Eur |
| | Electricity | For cutting | 1,260 GJ | 100,000 h based on steel volume [b] | Own estimate | Ecoinvent (2002), UK |
| Graphite retrieval | Typical decommissioning equipment and resources | Decontamination operations | See Table 2[c] | Typical equipment and resource used in decommissioning | Own estimate | See Table 2 |
| Scabbling | Decommissioning resource (Table 2) | Concrete scabbling operations | See Table 2 | Basic safety and machinery requirements for decommissioning operations | Own estimate | See Table 2 |
| Recycling | Steel (electric furnace) | Steel recycling | 30,000 tonnes | Potentially recoverable for recycling[d] | Parsons (2007) | Ecoinvent (2001), Eur |
| Interim storage | Concrete | Building store | 13,333 $m^3$ | Concrete used in Trawsfynydd ILW store | Magnox North (2009b) | Ecoinvent (2001), CH[j] |
| | Steel | Building store | 1,770 tonnes | Modified Ecoinvent data[e] | Dones et al. (2009) | Ecoinvent (2002), CH[j] |
| | Transport rail | Movement of materials | 735,000 tkm | Modified Ecoinvent data[e] | Dones et al. (2009) | Ecoinvent (2000), Eur |
| | Road transport | Movement of materials | 42,300 tkm | Modified Ecoinvent data[e] | Dones et al. (2009) | Ecoinvent (2005), CH |
| | Diesel | Construction machinery | 6,120 GJ | Modified Ecoinvent data[e] | Dones et al. (2009) | Ecoinvent (2001), GLO |
| | Electricity | Construction use | 972 GJ | Modified Ecoinvent data[e] | Dones et al. (2009) | Ecoinvent (2002), UK |
| | Disposal concrete | Demolition of store | 33,700 tonnes | Modified Ecoinvent data[e] | Dones et al. (2009) | Ecoinvent (2002), CH |
| ILW disposal | Final Repository | Building, filling, closing deep repository | 13,200 $m^3$ | UK repository design for 168,000 $m^3$ of ILW is used to scale the reference Swiss design | Nirex (2003); Dones et al. (2009) | Ecoinvent (2002), CH[j] |
| | Electricity | Running storage facility | 25,000 GJ | 0.5 TJ/year[f] | Chan et al. (1998) | Ecoinvent (2002), UK |
| LLW disposal | LLW treatment | Excavation for construction of store | 75,000 $m^3$ | Surface storage | Dones et al. (2009) | Ecoinvent (2000), CH |
| | Concrete | Construction of store | 3,000 $m^3$ | | Own estimate | Ecoinvent (2001), CH[j] |
| | Electricity | Running storage facility | 25,000 GJ | 0.5 TJ/year[f] | Chan et al. (1998) | Ecoinvent (2002), UK |
| | Water | Running storage facility | 50,000 tonnes | 1,000 $m^3$/year for 50 years | Own estimate | Ecoinvent (2000), Eur |

**Table 3** (continued)

| Life cycle stage | Process/tool/material | Use | Quantity | Assumptions | Source | LCA data source (age), region[i] |
|---|---|---|---|---|---|---|
| Land remediation | Excavation | Soil movement | 60,000 $m^3$ | Double the soil stockpile for landscaping | Magnox Electric (2005) | Ecoinvent (2001), Eur |
| Transport | Freight transport (road) | Packaged waste to disposal site (assuming a distance of 300 km) | $6.64\times10^7$ tkm | 300 km×30 tonnes per package×824 packages | Own estimate | Ecoinvent (2005), Eur |
| | Freight transport (rail) | Packaged waste to disposal site (assuming a distance of 1 km) | 18,000 tkm | 1 km×30 tonnes per package×6,357 packages | Own estimate | Ecoinvent (2000), Eur |

[a] Data for 2004/2005 from a Strategic Environmental Assessment at Trawsfynydd (NDA 2010a) are extrapolated for the 20-year retrieval period only, as demolition implicitly accounts for these activities

[b] To decommission and package 16 tonnes of vessels and 5 tonnes of piping in a small nuclear facility required a total of 575 m of cuts, which has been scaled up for a 30,000 tonne steel volume and energy use calculated according to a reported cutting rates of 5–10 cm/min (IAEA 2001)

[c] This has been scaled to last only 5 years as graphite retrieval is not expected to take the 10 years assumed in defining the basic decommissioning resource

[d] Based on up to 20,000 tonnes already recovered from plant (Parsons 2007) plus additional boilers and construction use (approximately 10,000 t). Assumes 900 kg of steel is produced per tonne steel recycled

[e] Figures are scaled up by the ratio of the concrete volumes in (Dones et al. 2009) and the Trawsfynydd ILW: 8,300–13,333 $m^3$

[f] Based on 1–2 W/$m^3$, typical of underground car parks (Chan et al. 1998); around 5 % of the 13 TJ used annually at the Drigg LLW repository (NDA 2010b)

[i] LCA data considered applicable to UK, Switzerland (CH), Europe (Eur) or global (GLO) cases

[j] Swiss production data amended to account for UK electricity mix in steel and concrete production

by wiping or washing with water, detergents or alcohol. Estimated requirements for Trawsfynydd steel are given in Table 3. More aggressive decontamination by blasting or chemical treatment (NEA 1999) could allow for either reuse or waste reclassification (i.e. cleaning ILW to create LLW). Such methods may eventually be used during final dismantling on the more contaminated metals forming the reactor core, but presently, this is expected simply to be disposed of as untreated waste.

Concrete in the fuel cooling ponds is decontaminated by scabbling. For decommissioning, the ponds have been sealed with a roof and fitted with ventilation and appropriate safety systems (see Table 2), while scabbling is performed using two remotely controlled vehicles (Brokks). Work commenced in 2005 and is ongoing, with refinement of methods and periodic replacement of equipment, e.g. the pond ventilation system (Madog-Jones 2006) and the scabbling heads and crane (Magnox North 2009a). Scabbling thus appears to require a similar range of typical equipment and resources for decommissioning as described for waste retrieval (see Table 2) so these data have been used to characterise scabbling in the LCA model (see Table 3). There are no plans to decontaminate any other structural concrete prior to disposal as LLW after demolition.

Graphite retrieval is currently expected to resemble other retrieval operations, in so far as requiring remotely operated heavy machinery under similar containment measures and hence is also represented by the typical equipment and resources for decommissioning. Current plans are to package and dispose of graphite as ILW, but alternative treatments and waste reduction methods are currently sought (von Lensa et al. 2008). Despite the likelihood of change, it is assumed here that disposal will proceed according to the current plan.

### *3.4.2 Construction and demolition*

Throughout decommissioning, construction work is required to provide access or exit pathways, new temporary buildings or other infrastructure in which to carry out various decommissioning operations, e.g. lowering the reactor roof at Trawsfynydd in preparation for the care and maintenance period. Construction material use has been estimated using data from the Strategic Environmental Assessment of Trawsfynydd (NDA 2010a); these data are shown in Table 3.

Following the care and maintenance period, all power plant buildings and remaining temporary structures will be demolished. As residual radioactivity will have diminished to safe levels, demolition will only require standard construction methods. However, since the reactor structure is specifically designed to resist destruction, demolition may require considerably more energy than a similarly sized standard building (see Table 3).

**Table 4** Summary of data for different decommissioning stages used in the LCA model (based on the data in Tables 1, 2 and 3)

| | Project life (years) | Total electricity use (TJ) | Mean annual electricity use (TJ) | Total water use ($m^3$) | Mean annual water use ($m^3$) | Total steel use (t) | Total concrete use (t) | No. of ILW packages | No. of LLW packages |
|---|---|---|---|---|---|---|---|---|---|
| Site management | 30 | 87.30 | 2.91 | 225,000 | 7,500 | – | – | 0 | 0 |
| Plant deconstruction | – | – | – | – | – | – | – | 92 | 6,032 |
| Scabbling | 10 | 3.77 | 0.42 | 9,300 | 930 | – | – | 4 | 118 |
| Cutting | 10 | 5.08 | 0.51 | 9,300 | 930 | – | – | – | – |
| Graphite retrieval | 5 | 1.89 | 0.42 | 4,650 | 930 | – | – | 211 | 3 |
| Decontamination | 20 | 7.19 | 0.36 | 8,805 | 880 | – | – | – | – |
| Civil Engineering | 20 | 9.69 | 0.48 | – | – | 3,000 | 2,250 | – | – |
| Waste retrieval | – | – | – | – | – | – | – | – | – |
| MAC | 10 | 3.77 | 0.42 | 9,300 | 930 | – | – | 20 | 0 |
| FED | 10 | 3.77 | 0.42 | 9,300 | 930 | – | – | 115 | 0 |
| Sludge | 10 | 3.77 | 0.42 | 9,300 | 930 | – | – | 6 | 0 |
| Resins | 10 | 3.77 | 0.42 | 9,300 | 930 | – | – | 0 | 6 |
| AWV | 10 | 3.77 | 0.42 | 9,300 | 930 | – | – | 376 | 38 |
| R&D | 30 | 1.52 | 0.05 | – | – | – | – | – | – |
| Land remediation | – | – | – | – | – | – | – | 0 | 360 |
| Waste packaging | – | – | – | – | – | – | – | – | – |
| ILW | – | 11.81 | – | – | – | 1,892 | 100,116 [b] | – | – |
| LLW | – | 1.48 | – | – | – | 26,036 | 12,162 [b] | – | – |
| ILW management | – | – | – | – | – | – | – | – | – |
| Interim storage | – | 25.97 | 0.5 | – | – | 2,000 | 32,000 | – | – |
| Repository | – | 25 | 0.5 | – | – | – | – | – | – |
| LLW management | – | – | – | – | – | – | – | – | – |
| Total | – | 200 | – | 303,555 | 15,820 | 32,928 | 146,528 | 824[c] | 6,557[c] |

[a] Total reported energy consumption in 2007 was 7 TJ/year (NDA 2010b). For comparison, consumption at some other decommissioning Magnox plants was: Hunterston A—0.8TJ in 2004 and 17 TJ in 2007; Hinkley Point—30 TJ in 2007; and Bradwell—19 TJ in 2007 (NDA 2010c; NDA 2010d; NDA 2010e). This is because decommissioning activities at each site vary considerably

[b] Each box is assumed to contain a standard volume of concrete grout: 8.48 $m^3$ for LLW (Entec 2010) and 8.2 $m^3$ for ILW

[c] Total volume of ILW=13,400 $m^3$; total volume of LLW=60,700 $m^3$

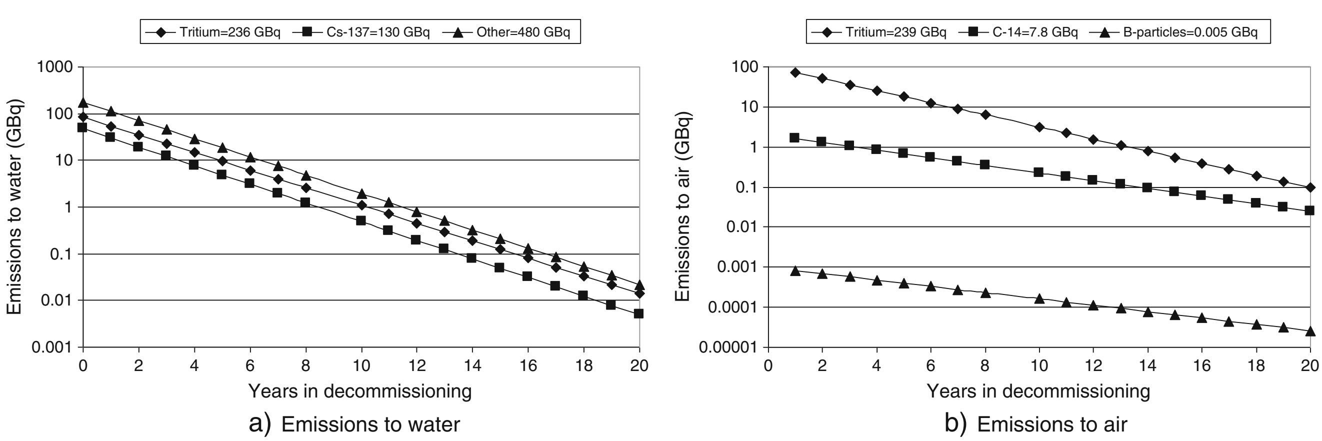



**Fig. 3** Radioactive emissions to water and air from closed Magnox power stations Magnox Electric (2005). Total emissions over the decommissioning period are shown in the legend

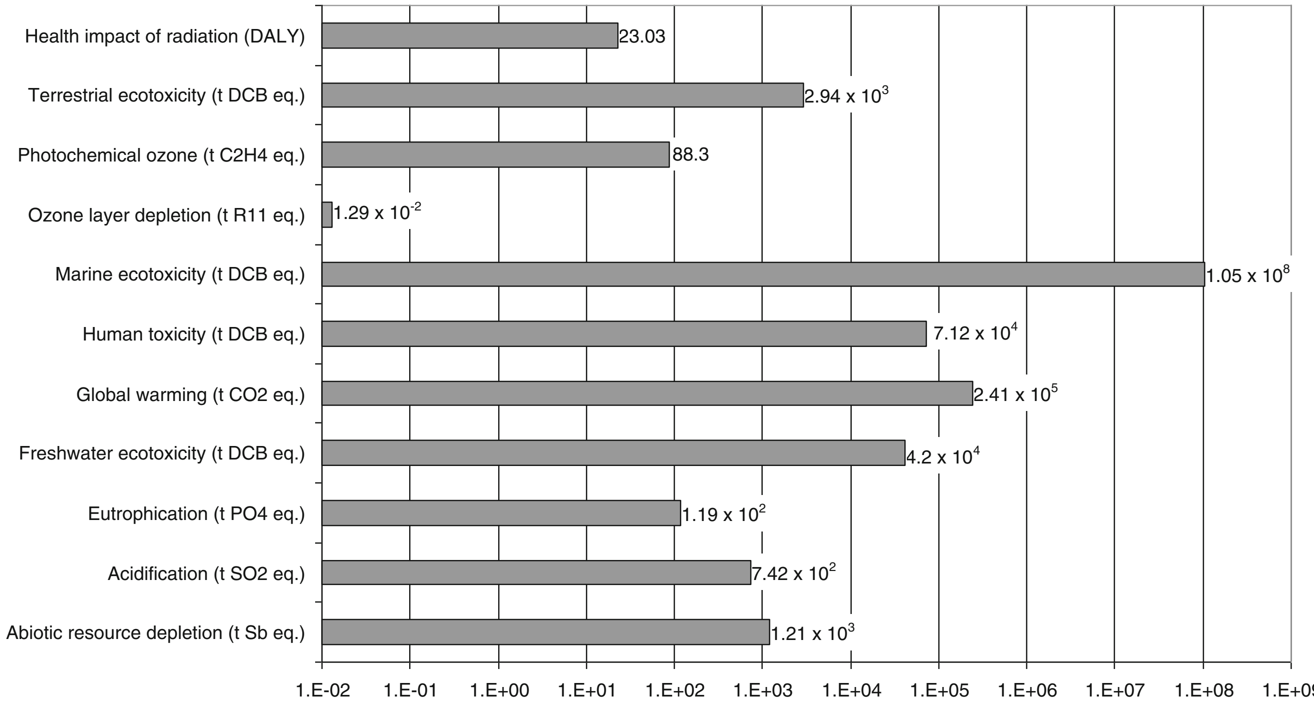



**Fig. 4** Total environmental impacts of decommissioning of Trawsfynydd over the lifetime of the decommissioning process. The results shown in the figure are the rounded off total results in tonnes shown in Table 5

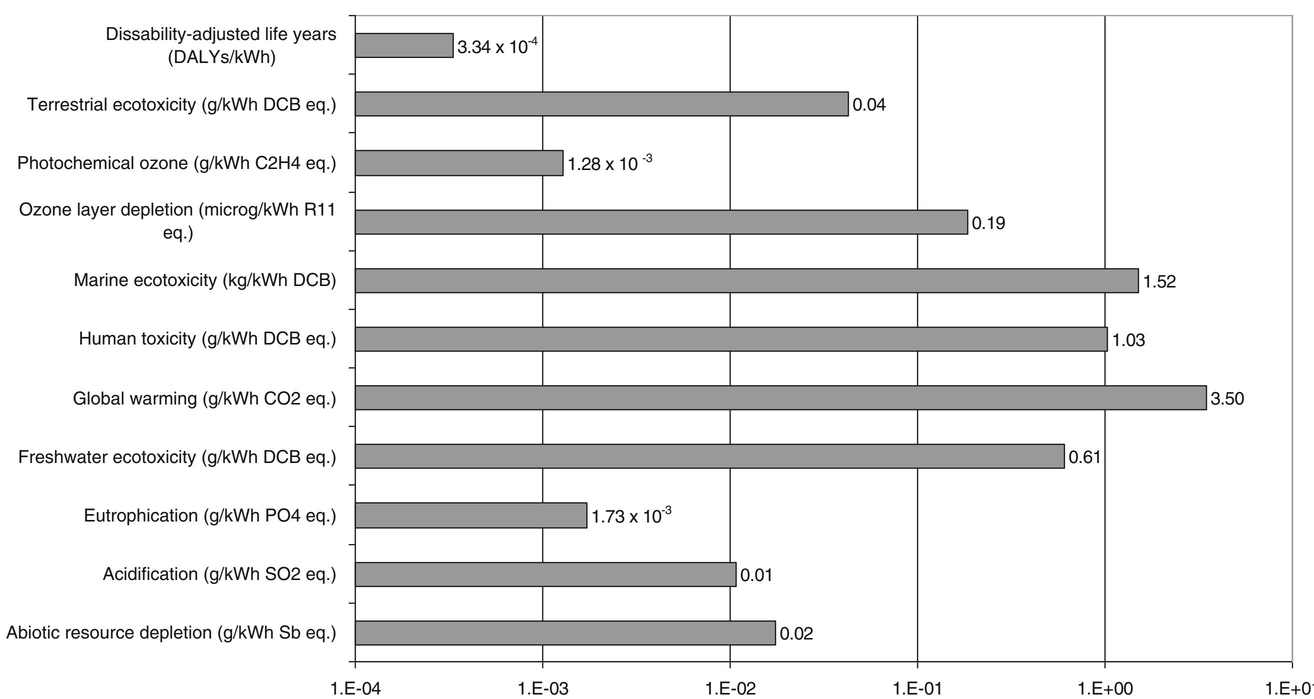



**Fig. 5** Environmental impacts of decommissioning expressed per kilowatt hour of electricity generated by the Trawsfynydd power plant over its useful lifetime (69 TWh). The results shown in the figure are the rounded off results per kilowatt hour shown in Table 5

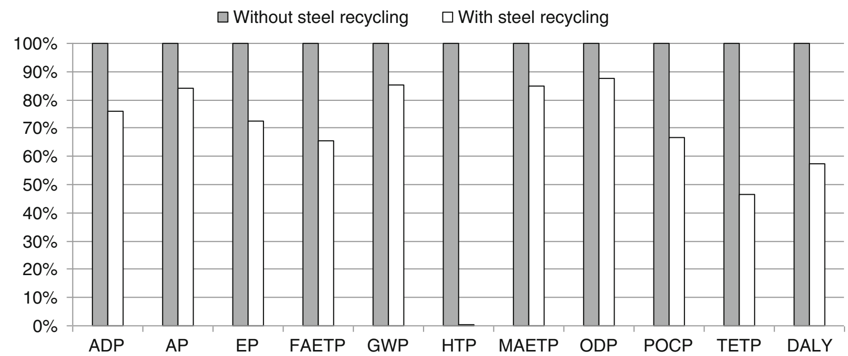



**Fig. 6** Sensitivity analysis: effect of steel recycling on the impacts from decommissioning. Percentage of total steel recycled: 70 %. The system has been credited for the avoided impacts from the equivalent amount of 'virgin' steel using the Ecoinvent data, which are based on the European mix of 'virgin' steel production consisting of 63 % primary steel and 37 % recycled steel. For full names of impact categories, see Table 5

## 3.5 Land remediation

There is an estimated 9,500 m$^3$ of radiologically contaminated soil at Trawsfynydd (NDA 2010a). Currently, this is expected simply to be dug up and packaged for disposal as radioactive waste (see Fig. 2); hence, this stage is characterised as excavation works (see Table 3).

## 3.6 Recyclable materials

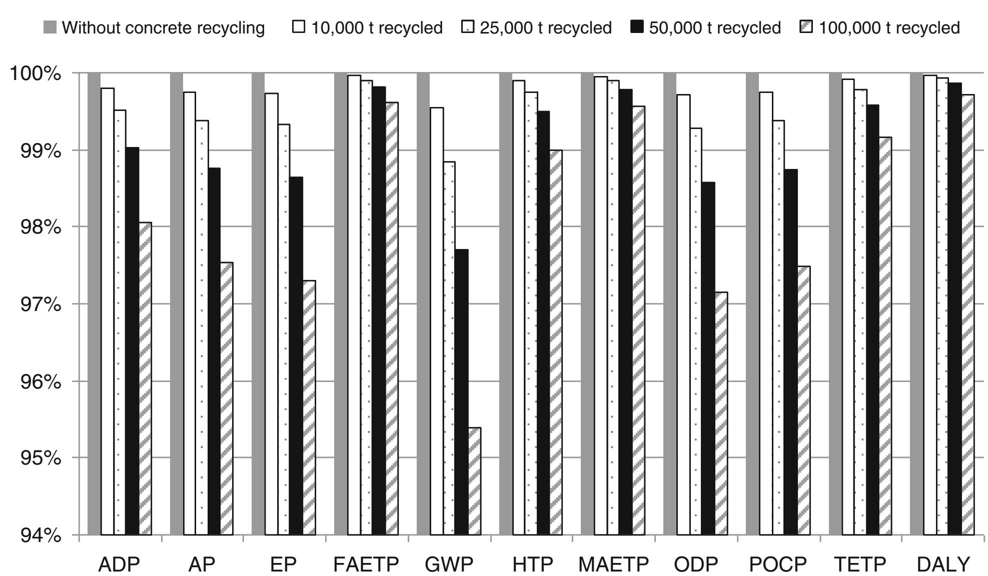
Although recyclable materials are being recovered during the decommissioning process (Parsons 2007), no recycling is considered in this study as it is not clear at this stage if and how much will actually be recycled. However, the potential effect of steel and concrete recycling on the total impacts are considered as part of the sensitivity analysis, by crediting the system for avoiding the impacts from virgin steel and concrete, respectively. As previously mentioned and shown in Table 3, a total of 30,000 tonnes of steel is assumed to be available for recycling—this represents approximately 70 % of the estimated 43,500 t of steel embodied in the plant (see Section 3.4.1).

The total amount of concrete at a nuclear power plant is estimated at around 160,000 t (see Section 3.4.1), with half of that arising from deconstruction of temporary structures (see Table 3). However, it is not clear how much of the total amount of concrete could be recycled so the sensitivity analysis considers a range between 10,000 and 100,000 t, assuming that not all of the concrete would be available for recycling. The results of the sensitivity analysis are presented in Section 4.

## 3.7 Packaged waste

Conditioned nuclear wastes are packaged in various containers appropriate to their form and level of radioactivity and

**Fig. 7** Sensitivity analysis: effect of concrete recycling on the impacts from decommissioning. The system has been credited for the avoided impacts from the equivalent amounts of virgin concrete. For full names of impact categories, see Table 5



suitable for long-term storage or disposal. These are generally steel boxes or drums, possibly lined with concrete and then also possibly placed within a concrete 'overpack'. Drums may be crushed into 'pucks' and placed into larger boxes. Containers are filled with 'grout' (usually concrete) to immobilise and separate the wastes. The UK radioactive waste inventory (NDA 2007) has been used to calculate the cumulative resource requirements for packaging all expected wastes from Trawsfynydd (Table 4).

To simplify calculations, the number of waste packages generated by each decommissioning activity (see Table 4) is based solely on the steel volume needed for packaging. A typical waste package is defined for LLW (one package requiring 2.2 t of steel) and another for ILW (one package requiring 4.2 t of steel). For the volume of waste and cement grout in each package, a typical average value is assumed (see Table 4). Each ILW package is also assumed to contain 150 kg of secondary wastes, i.e. material contaminated in decommissioning, such as latex gloves, air filters, tools and paper towels (NDA 2007).

### 3.8 Interim storage

Currently, ILW is packaged at each decommissioning site and then stored in temporary surface storage. Trawsfynydd's newly built temporary storage will eventually be demolished once a final disposal facility becomes available for the UK (see Section 3.9). Data used for storage and disposal can be found in Tables 3 and 4.

### 3.9 Final disposal

Trawsfynydd waste arisings make up 5 % of UK's current legacy waste and are estimated to be 13,200 m$^3$ of packaged ILW and 72,900 m$^3$ of packaged LLW (Defra and NDA 2007). This waste will eventually be disposed of in a deep geological disposal facility, together with all other UK HLW and ILW waste. At present, no finalised designs for waste disposal exist, but it is expected that a disposal facility will be developed by around 2040. However, the location and final design are not yet known so that no data are available. The extant UK generic repository design studies (Nirex 2003) indicate that a dedicated ILW repository will be approximately 600 m below ground, which, in terms of size and depth (and hence engineering requirements), is similar to the Swiss design. Therefore, the data for the Swiss repository in clay-based rocks (Dones et al. 2009) have been used and scaled for the amount of ILW waste from Trawsfynydd; for details, see Table 4.

It is also assumed that transport of all packaged waste from Trawsfynydd to final disposal will be by road, with a short rail transfer (see Table 3). Distances of 300 km by road and 1 km by rail have been assumed.

**Table 5** Environmental impacts over the life cycle of decommissioning showing contribution of different life cycle stages

| | Abiotic depletion potential (ADP) (t Sb eq.) | Acidification potential (AP) (t $SO_2$ eq.) | Eutrophication potential (EP) (t $PO_4$ eq.) | Freshwater aquatic ecotoxicity potential (FAETP) (t DCB eq.) | Global warming potential (GWP) (t $CO_2$ eq.) | Human toxicity potential (HTP) (t DCB eq.) | Marine aquatic ecotoxicity potential (MAETP) (Mt DCB eq.) | Ozone layer depletion potential (ODP) (kg R11 eq.) | Photochemical ozone creation potential (POCP) (t $C_2H_4$ eq.) | Terrestrial ecotoxicity potential (TETP) (t DCB eq.) | Health impact of radiation (DALY) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Site management | 121 | 61.377 | 6.628 | 671.807 | 15,041 | 2,087 | 10,546 | 0.536 | 4.328 | 42.76 | 0.181 |
| R&D | 1.076 | 0.617 | 0.072 | 13.121 | 151 | 40.189 | 92.744 | 0.005 | 0.047 | 1.016 | 0.004 |
| Waste retrieval | 49.1 | 28.107 | 3.922 | 1,032 | 10,023 | 1,579 | 3743.57 | 0.418 | 2.684 | 75.51 | 0.113 |
| Plant deconstruction | 480 | 293 | 49.615 | 18,435 | 124,005 | 16,640 | 36,575 | 6.175 | 34.27 | 1,265 | 17.21 |
| LLW disposal | 33.393 | 17.684 | 1.952 | 96.863 | 5,336 | 474.6 | 2421.25 | 0.165 | 1.362 | 8.628 | 0.050 |
| ILW storage and disposal | 447 | 288 | 44.895 | 20,598 | 72,376 | 48,812 | 48,841 | 3.958 | 37.56 | 1,466 | 5.299 |
| Land remediation | 24.040 | 14.919 | 2.568 | 830.434 | 6,591 | 789 | 1650.378 | 0.329 | 1.786 | 54.98 | 0.042 |
| Transport | 56.704 | 37.648 | 9.663 | 321.894 | 7,746 | 746.549 | 869.795 | 1.269 | 6.282 | 22.84 | 0.136 |
| Total | 1,212 t | 741 t | 119 t | 41,999 t | 241,269 t | 71,168 t | 104,740 t | 12.86 t | 88.32 t | 2,937 t | 23.04 DALY |
| Total per kWh electricity generated over the lifetime of power plant | $1.76\times10^{-2}$ g | $1.07\times10^{-2}$ g | $1.73\times10^{-3}$ g | 0.61 g | 3.50 g | 1.03 g | 1,518 g | $1.86\times10^{-7}$ g | $1.28\times10^{-3}$ g | $4.26\times10^{-2}$ g | $3.34\times10^{-10}$ DALY |

### 3.10 Radioactive emissions from decommissioning

At around 1 % of permitted limits, radioactive emissions from decommissioning are far lower than from an operating Magnox plant (Magnox Electric 2005). The most significant aqueous nuclides, deriving from decontaminating fuel cooling ponds and processing and packaging of ILW, are tritium and cesium-137. Aerial discharges diffusing from the reactor core are also relatively low but include tritium, carbon-14 and beta particles. Levels vary significantly with decommissioning activity.

Radioactive emissions to water and air from decommissioning several Magnox sites are plotted in Fig. 3. As can be seen, most of the emissions occur in the first 20 years of decommissioning; these data have been used to estimate the impacts from radiation (see next section). The emissions from the LLW and ILW repositories are negligible (Bayliss and Langley 2004; LLWR Repository and NDA (2012) and have therefore not been considered in this study.

## 4 Impact assessment and interpretation of results

The study follows the ISO 14040/44 LCA guidelines (ISO 2006a; ISO 2006b). The LCA software Gabi v4.4 (International 2011) has been used for modelling the system and estimating the environmental impacts following the CML 2001 methodology (Guinée et al. 2001). The Ecoinvent (2011) database has been used for the background LCA data for the UK conditions (see Tables 1, 2 and 3 for details).

The total impacts over the lifetime of decommissioning, assuming no recycling of recyclable materials, are shown in Fig. 4; the impacts per kilowatt hour of electricity generated by the power plant during its useful lifetime (69 TWh) are given in Fig. 5. For example, the total global warming potential (GWP) is estimated at 241 kt $CO_2$ eq., equating to 3.5 g $CO_2$ eq./kWh. By comparison, the GWP values reported by previous studies for the whole life cycle of nuclear power range from 1 to 527 g $CO_2$ eq./kWh, but the vast majority report 5–10 g $CO_2$ eq./kWh (Weisser 2007; Fthenakis & Kim 2007; Lenzen 2008). Taking the latter range as a basis would suggest that the contribution of decommissioning to the whole nuclear life cycle GWP, as estimated in the present study, is significant. This agrees well with the findings of Voorspools et al. (2000) who report the GWP from decommissioning in the range of 2–4 g $CO_2$ eq./kWh despite, like here, not considering the spent fuel within the system boundary. However, other studies (White & Kulcinski 2000; Weisser 2007; Sovacool 2008; Vattenfall 2010a; Vattenfall 2010b) report lower GWP values for decommissioning, ranging between 0.01 and 1.4 g $CO_2$ eq./kWh. There could be a number of reasons for the difference in the results between different studies, including not only different assumptions, reactors considered and data used but also the level of detail at which this part of the life cycle of nuclear power has been assessed. As far as the authors are aware, this is the first study to consider decommissioning of nuclear plants in as much detail, and particularly for Magnox plants, which may explain the higher GWP results compared to other, less detailed, studies of decommissioning. Furthermore, most studies consider a generic case of a 1,000-MW pressurised water reactor (PWR) from the 1970s, with an assumed lifetime of 40 years and an operating capacity of 80–85 %, whereas different sites and reactors have unique operational and decommissioning histories. For example, the lifetime electricity output of Trawsfynydd was only 30 % of the typical generic values assumed in other studies, which translates to three to four times higher impacts per kilowatt hour of

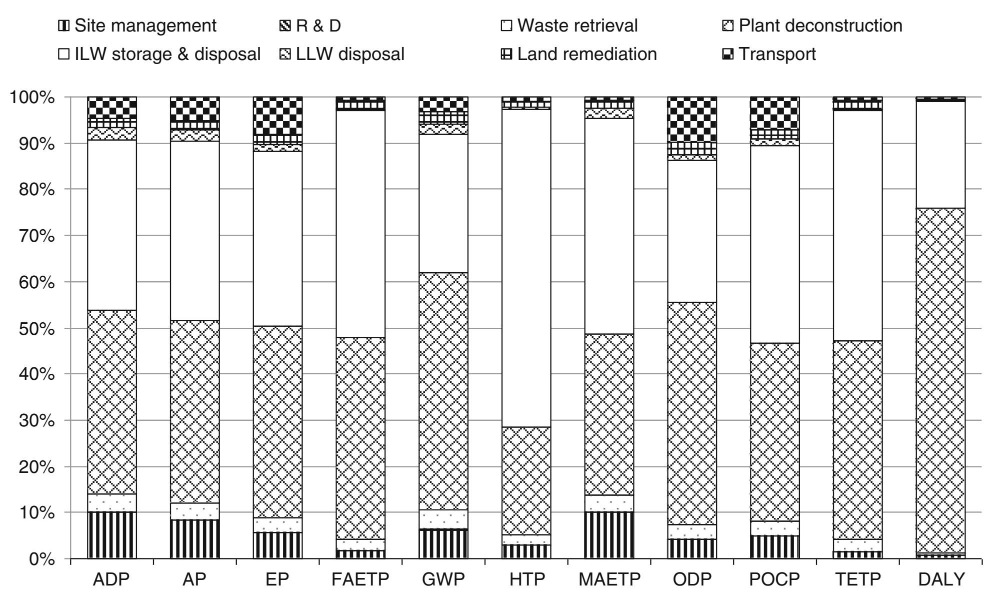



**Fig. 8** The relative contribution of different decommissioning stages to the overall environmental impacts. Waste retrieval and Plant deconstruction include the packaging of the wastes. For the full names of impact categories, see Table 5]

electricity generated. In addition, decommissioning of the Trawsfynydd plant is expected to produce waste volumes five to six times greater than decommissioning of the UK's only PWR reactor at Sizewell B (NDA 2010f). Therefore, varied lifetime outputs of legacy plants (Fig. 6) as well as the amounts of waste can make comparisons between different plants difficult.

Furthermore, recycling of materials such as concrete and steel can also affect the results, as shown in Figs. 6 and 7. For example, assuming that 70 % or 30,450 t of steel is recycled (as mentioned in Section 3.6), reduces GWP by 15 % and human toxicity potential (HTP) by more than 99 %. Recycling of concrete, e.g. in packaging for radioactive waste, leads to more modest reductions in the environmental impacts. For instance, by recycling the maximum amount of 100,000 t of concrete assumed available for recycling, the average reduction of all impacts is just under 2 % with the greatest reduction of 4.6 % achieved for GWP. The modest savings are due to the need to crush the concrete before it can be re-used in packaging and the impacts associated with this activity.

Comparison with literature for the other impacts from decommissioning is difficult as other studies either consider only GWP or do not provide enough detail to allow meaningful comparisons.

As indicated in Table 5 and Fig. 8, most impacts from decommissioning are due to the plant deconstruction (25–75 %) and ILW storage and disposal (25–70 %). Around 85 % of the impacts from deconstruction of the plant are due to the steel and concrete used to package the LLW and ILW wastes. Construction of the repository accounts for 90 % of the impacts from ILW storage and disposal. Site management and transport contribute between 1 and 10 % to the impacts, while waste retrieval (up to 4 %), R&D (up to 1 %), LLW disposal and land remediation (up to 3 % each) have relatively low impacts.

The exception to this trend is the health impact of radiation as measured by disability-adjusted life years (DALYs)

**Table 6** Magnox plants and their closure dates

| Power station | Net power (MWe) | Operation started | Closure |
|---|---|---|---|
| Berkeley | 276 | 1962 | 1989 |
| Bradwell | 246 | 1962 | 2002 |
| Calder Hall | 200 | 1959 | 2003 |
| Chapelcross | 240 | 1960 | 2004 |
| Dungeness A | 450 | 1965 | 2006 |
| Hinkley Point A | 470 | 1965 | 2000 |
| Hunterston A | 300 | 1964 | 1990 |
| Oldbury | 434 | 1968 | 2012 |
| Sizewell A | 420 | 1966 | 2006 |
| Trawsfynydd | 390 | 1965 | 1991 |
| Wylfa | 980 | 1972 | 2014 |

**Table 7** Allocation of environmental impacts from Trawsfynydd per volume of waste as a basis for estimation of decommissioning impacts from other UK Magnox sites

| | ADP | AP | EP | FAETP | GWP | HTP | MAETP | ODP | POCP | TETP | DALY |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total (t/f.u.)[a] | 1,212 | 741 | 119 | 41,999 | 241,269 | 71,168 | 104,740 | 12.86 | 88.32 | 2,937 | 23.04 |
| ILW disposal (%)[b] | 36.86 | 38.84 | 37.63 | 49.04 | 30.00 | 68.59 | 46.63 | 30.79 | 42.53 | 49.93 | 23.01 |
| Waste retrieval and plant deconstruction (%)[b] | 43.68 | 43.34 | 44.87 | 46.35 | 55.55 | 25.60 | 38.49 | 51.29 | 41.84 | 45.63 | 75.20 |
| Packaging (85 % of the above; %)[b] | 37.12 | 36.84 | 38.14 | 39.40 | 47.22 | 21.76 | 32.72 | 43.59 | 35.56 | 38.79 | 63.92 |
| Other decommissioning activities (%)[b] | 26.02 | 24.32 | 24.23 | 11.56 | 22.78 | 9.65 | 20.65 | 25.62 | 21.91 | 11.28 | 13.07 |
| ILW disposal (kg/m$^3$ or DALY/m$^3$ of waste)[c] | 33.35 | 21.51 | 3.35 | 1537.18 | 5401.21 | 3642.66 | 3,644,853 | 2.95E−04 | 2.80 | 109.44 | 3.95E−04 |
| Packaging (kg/m$^3$ or DALY/m$^3$ of waste)[c] | 6.07 | 3.69 | 0.61 | 223.31 | 1537.43 | 208.99 | 462,489 | 7.56E−05 | 0.42 | 15.37 | 1.99E−04 |
| Other decommissioning activities[c] (kg/m$^3$ or DALY/m$^3$ of waste) | 4.26 | 2.44 | 0.39 | 65.51 | 741.83 | 92.72 | 291,878 | 4.44E−05 | 0.26 | 4.47 | 4.06E−05 |

[a] The results as shown in Table 5

[b] The results as shown in Fig. 8. Packaging contributes around 85 % to the total impacts from waste retrieval and plant deconstruction (see Section 4)

[c] An example calculation for GWP for Trawsfynydd: GWP due to ILW disposal : $241,269(\text{total GWP, t } CO_2 \text{ eq.}) \times 0.3(\text{contribution of ILW disposal})/13,400(m^3 \text{ILW}) = 5.4012 \text{ t } CO_2 \text{ eq.}/m^3 = 5401.2 \text{ kg } CO_2 \text{ eq.}/m^3$; GWP due to packaging : $241,269(\text{total GWP, t } CO_2 \text{ eq.}) \times 0.47(\text{contribution of packaging})/74,100(m^3 \text{LLW + ILW}) = 1.5374 \text{ t } CO_2 \text{ eq.}/m^3 = 1537.4 \text{ kg } CO_2 \text{ eq.}/m^3$; GWP due to other decommissioning activities: $241,269(\text{total GWP, t } CO_2 \text{ eq.}) \times 0.228(\text{contribution of other decommissioning activities})/74,100(m^3 \text{LLW+ILW}) = 0.748 \text{ t } CO_2 \text{ eq.}/m^3 = 741.83 \text{ kg } CO_2 \text{ eq.}/m^3$

**Table 8** Potential environmental impacts of decommissioning the UK Magnox reactors[a]

| Magnox site | Lifetime output (TWh) | ILW arising[b] ($m^3$) | LLW arisings [b] ($m^3$) | ADP (g Sb eq./kWh) | AP (g $SO_2$ eq./kWh) | EP (g $PO_4$ eq./kWh) | FAETP (g DCB eq./kWh) | GWP (g $CO_2$ eq./kWh) | HTP (g DCB eq./kWh) | MAETP (g DCB eq./kWh) | ODP (μg R11 eq./kWh) | POCP (g $C_2H_4$ eq./kWh) | TETP (g DCB eq./kWh) | DALY (DALY/kWh) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Berkeley [c] | 43 | 6,910 | 30,300 | 0.014 | 0.009 | 0.0014 | 0.497 | 2.840 | 0.846 | 1,239 | 0.151 | 0.0010 | 0.035 | $2.71\times10^{-10}$ |
| Bradwell | 60 | 5,770 | 51,400 | 0.013 | 0.008 | 0.0013 | 0.423 | 2.691 | 0.638 | 1,069 | 0.143 | 0.0009 | 0.029 | $2.66\times10^{-10}$ |
| Calder Hall | 60 | 9,410 | 51,000 | 0.016 | 0.010 | 0.0015 | 0.532 | 3.142 | 0.875 | 1,331 | 0.167 | 0.0011 | 0.037 | $3.03\times10^{-10}$ |
| Chapelcross | 60 | 6,230 | 167,000 | 0.033 | 0.020 | 0.0032 | 0.993 | 7.141 | 1.249 | 2,556 | 0.377 | 0.0023 | 0.069 | $7.32\times10^{-10}$ |
| Dungeness A | 115 | 6,940 | 34,900 | 0.006 | 0.004 | 0.0006 | 0.198 | 1.155 | 0.330 | 494 | 0.062 | 0.0004 | 0.014 | $1.11\times10^{-10}$ |
| Hinkley point A | 103 | 7,270 | 57,400 | 0.009 | 0.005 | 0.0009 | 0.290 | 1.812 | 0.447 | 731 | 0.096 | 0.0006 | 0.020 | $1.78\times10^{-10}$ |
| Hunterston A | 74 | 8,350 | 57,600 | 0.013 | 0.008 | 0.0013 | 0.431 | 2.641 | 0.680 | 1,084 | 0.140 | 0.0009 | 0.030 | $2.58\times10^{-10}$ |
| Oldbury | 125 | 6,120 | 32,900 | 0.005 | 0.003 | 0.0005 | 0.165 | 0.976 | 0.273 | 414 | 0.052 | 0.0004 | 0.012 | $9.41\times10^{-11}$ |
| Sizewell A | 110 | 6,140 | 38,700 | 0.006 | 0.004 | 0.0006 | 0.204 | 1.231 | 0.326 | 511 | 0.065 | 0.0004 | 0.014 | $1.20\times10^{-10}$ |
| Trawsfynydd [d] | 69 | 13,400 | 60,700 | 0.018 | 0.011 | 0.0017 | 0.609 | 3.497 | 1.031 | 1,518 | 0.186 | 0.0013 | 0.043 | $3.34\times10^{-10}$ |
| Wylfa | 225 | 8,430 | 59,500 | 0.004 | 0.003 | 0.0004 | 0.145 | 0.890 | 0.228 | 364 | 0.047 | 0.0003 | 0.010 | $8.71\times10^{-11}$ |
| Average | | | | 0.012 | 0.008 | 0.001 | 0.408 | 2.547 | 0.629 | 1,028 | 0.135 | 0.001 | 0.028 | $2.50\times10^{-10}$ |
| Total | 1,044 TWh | 84,970 $m^3$ | 641,400 $m^3$ | 10,298 t | 6,465 t | 1,016 t | 340,474 t | 2,114,384 t | 528,862 t | 752,920,740 t | 99,329 t | 725 t | 23,722 t | 207 DALY |

[a] Extrapolated based on the findings for Trawsfynydd presented in Section 4

[b] NDA (2010f)

[c] Example calculation of GWP for Berkeley: GWP due to ILW disposal : $5401.2\ \text{kg}\ CO_2\ \text{eq.}/m^3 \times 6910\ m^3\text{ILW} = 37,322\ \text{t}\ CO_2\text{eq.}$; GWP due to packaging : $1537.4\ \text{kg}\ CO_2\ \text{eq.}/m^3 \times (6910 + 30,300)m^3\text{LLW} + \text{ILW} = 57,207\ \text{t}\ CO_2\ \text{eq.}$; GWP due to other decommissioning activities: $741.83\ \text{kg}\ CO_2\ \text{eq.}/m^3 \times (6910 + 30300)\ m^3\text{LLW} + \text{ILW} = 27,603\ \text{t}\ CO_2\ \text{eq.}$; Total GWP: $(37,322\ \text{t}\ CO_2\ \text{eq.} + 57,207\ \text{t}\ CO_2\ \text{eq.} + 27,603\ \text{t}\ CO_2\ \text{eq.}) \times 1,000,000\ \text{g}/43,000,000,000\text{kWh} = 2.84\ \text{g}\ CO_2\ \text{eq.}/\text{kWh}$

[d] Environmental impacts as shown in Table 5; a slight difference due to rounding off

where plant deconstruction is the main contributor (75 %). The next largest contributor is ILW storage and disposal (23 %); the other life cycle stages have negligible impact. The majority of radioactive releases contributing to this impact occur during the decommissioning work. However, a significant proportion of the health impact from radiation (around 25 %) is due to the ‘background’ radioactive releases, including steel and concrete manufacture, power generation and, most importantly, excavating the repository during which the naturally occurring radioactive emissions are released. The latter should be considered when designing and building the repository in order not to counterbalance the efforts for containing anthropogenic radioactive waste.

With respect to the repository, its estimated contribution to the impacts should be treated with caution as the data are based on the Swiss repository design (see Section 3.9). Although the UK design is expected to be similar, the Swiss repository is housed in clay rocks, but potential alternatives to clay for the UK also include sites with hard crystalline rocks or salt. Each rock type presents different construction challenges, which could lead to different resource consumption and therefore the environmental impacts from this life cycle stage. In addition, the Swiss design is a co-located repository for HLW and ILW (Dones et al. 2009), whilst the UK generic design studies refer to a potential dedicated ILW repository (Nirex 2003). This could alter the scaling and allocation assumptions, again changing the overall impacts. However, despite this uncertainty, the volumes of rock removed and structural engineering required for the Swiss design are likely to be representative of the UK repository. Thus, the results reported here should provide a meaningful baseline, in the context of the wider uncertainties inherent in a decommissioning process, which extends over the whole of the next century (some of which are also addressed in Section 6).

## 5 Potential impacts of decommissioning the UK fleet of Magnox power plants

Given that the UK has 10 Magnox plants in addition to Trawsfynydd that will need to be decommissioned over the next decades (Table 6), this section considers the potential impacts of their decommissioning by extrapolating the LCA results estimated for Trawsfynydd. Because the majority of the impacts depend directly on the volume of waste, determining how much packaging and repository volume for disposal is required, the extrapolation is based on the expected ILW and LLW waste arisings from these plants estimated by NDA (2010f). Table 7 shows the basis used for the extrapolation of the impacts and Table 8 specifies the waste volume data for the whole UK Magnox fleet.

As shown in Table 7, to estimate the impacts from decommissioning of other UK Magnox sites the total environmental impacts from Trawsfynydd have first been estimated per volume of waste for three types of decommissioning activity: ILW disposal, packaging of LLW and ILW waste, and the remaining decommissioning activities. These values have then been multiplied by the volumes of waste for each decommissioning site. An example calculation for GWP is shown below Tables 7 and 8; the latter also shows the results of extrapolation of the environmental impacts for all the sites.

Using GWP as an example, Fig. 9 shows a great variability in this impact for different sites, which ranges from 0.89 g $CO_2$ eq./kWh for Wylfa to 7.14 g $CO_2$ eq./kWh for Chapelcross. A similar trend is noticed for the other impacts (see Table 8). As suggested in Section 4, this variability is perhaps to be expected, since different sites generate different volumes of waste as well as energy outputs over their lifetime. However, it is the first time that such an estimate has been attempted confirming that the decommissioning impacts at different sites could be very different.

The results are yet different if the waste fuel generated at different Magnox sites and stored at Sellafield is also included in the estimates. Using the same method as above to allocate the Sellafield’s impacts amongst the different Magnox reactors according to the volume of waste generated at each site, the GWP of decommissioning increases on average by four times; in the case of Trawsfynydd, it goes up from 3.5 to 15.95 g $CO_2$/kWh (Fig. 10).

Overall, the results obtained here indicate that decommissioning of the UK Magnox reactors would generate in total around 2 Mt of $CO_2$ eq. (see Table 8). This would increase to

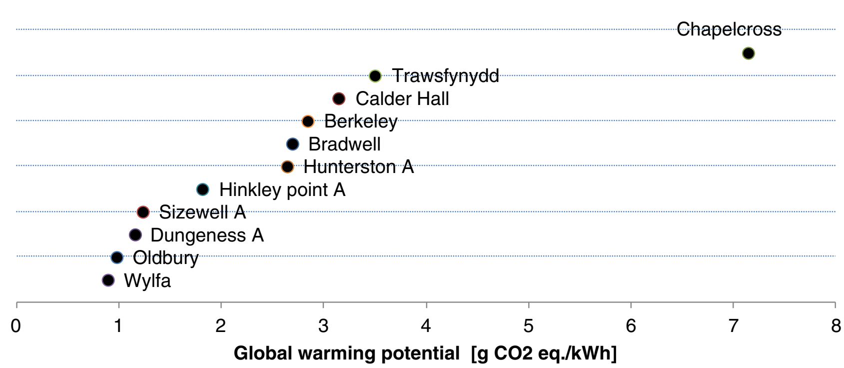



**Fig. 9** Global warming potential of decommissioning the UK Magnox reactors

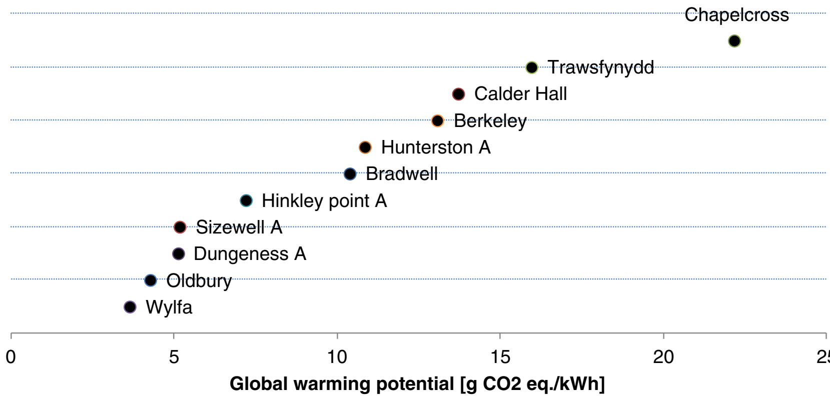



**Fig. 10** Global warming potential of decommissioning the UK Magnox reactors including waste at Sellafield. Estimates based on the total amount of waste at Sellafield of 3.462 million $m^3$

11 Mt of $CO_2$ eq. if the waste from Sellafield is included. To put these results in context, the UK annual GHG emissions in 2011were around 549.3 Mt of $CO_2$ eq. (DECC 2012). Therefore, the GWP from decommissioning the UK Magnox legacy sites would contribute around 0.4 % to the total UK annual emissions without and 2 % with the Sellafield waste. This is assuming that the decommissioning process is completed within 1 year, which, of course, is not the case as it takes place over very long time periods (around 100 years) so the contribution to the GHG emissions from decommissioning per year would be much lower. Nevertheless, as the emissions of GHG are cumulative and GWP is estimated over 100 years, the overall contribution of decommissioning to climate change is arguably not negligible.

The long duration of decommissioning or even delaying it could potentially be advantageous in terms of the environmental impacts. For example, the GWP could potentially be reduced by delaying decommissioning to allow the energy system to be substantially decarbonised, as envisaged by the UK Government (2006). Figure 11 illustrates the potential reduction in GWP from decommissioning the reactor at Trawsfynydd if the UK 2050 carbon reduction targets of 80 % were met (UK Government 2006). As indicated, the total GWP of 241 kt $CO_2$ eq. could potentially be reduced by 50 % by the end of the decommissioning process in around 2100 if the process was delayed to around 2030. Other impacts may also be reduced particularly as more advanced decommissioning methods become available through the ongoing R&D, but these should be assessed properly before drawing any conclusions. On the other hand, the benefits of early decommissioning include more rapid reduction of safety and environmental hazards and reduced short-term costs (although the long-term financial costs of waste management remain unknown). Therefore, there is a conflict between the potential environmental benefits of delay and the accelerated decommissioning at Trawsfynydd funded by the UK Nuclear Decommissioning Authority (NDA).

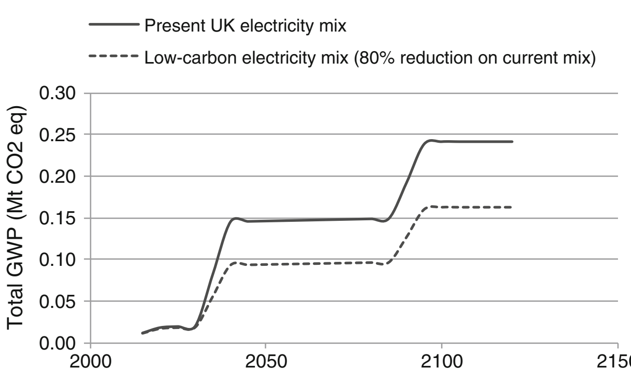



**Fig. 11** Cumulative global warming potential of decommissioning the reactor at Trawsfynydd over time depending on the UK electricity mix. It is assumed that the carbon intensity of the UK electricity mix reduces from the current 500 to 50 g $CO_2$ eq./kWh by 2030. This is congruent with the UK Government's target of 80 % carbon reduction in the whole energy sector, which would require almost complete decarbonisation of the electricity sector

Furthermore, social aspects of decommissioning must also be taken into account before decisions are made on the decommissioning methods and the time scales. For example, delaying the decommissioning process would lead to further accumulation of waste requiring on-site storage, also risking accidental release of hazardous material into the environment. If it is eventually decided that all the waste should be stored in a single, central repository (which is the current preferred option in the UK), this would imply significant radioactive waste transport (of many tens of thousands of packages nationwide), which is an issue that the public objects to (see, e.g. Hall 2010). Any method aimed at segregating (and hence concentrating) waste to reduce the amount of packaging and therefore the environmental impacts also increases risk, possibly including security and nuclear proliferation concerns. Therefore, in addition to the environmental sustainability of decommissioning discussed here, economic and social assessment should be carried out to explore fully the sustainability implications of decommissioning the nuclear reactors in the UK.

## 6 Conclusions and recommendations

This paper has presented an in-depth analysis of life cycle environmental impacts of decommissioning the Magnox nuclear reactors in the UK. All stages in the life cycle of decommissioning have been considered, including site management, R&D activities, waste retrieval, plant deconstruction, packaging and storage of waste. The study is based on the case of Trawsfynydd reactor currently being decommissioned.

The GWP of decommissioning the whole plant is estimated at 241 kt $CO_2$ eq., equating to 3.5 g $CO_2$ eq./kWh of electricity generated during the lifetime of the plant. By comparison, typical GWP values reported in the literature for the whole life cycle of nuclear power are in the range of 5–10 g $CO_2$ eq./kWh, suggesting that the contribution of decommissioning as estimated in the present study is significant.

Recycling of concrete and steel could reduce the environmental impacts significantly. For example, if 70 % of steel embodied in the plant is recycled, GWP is reduced by 15 % and human toxicity potential by more than 99 %. The environmental benefits from recycling 60 % of concrete are more modest, with the greatest reduction of 4.6 % achieved for GWP; this is due to the impacts associated with its crushing before it can be re-used.

Most impacts from decommissioning are due to the plant deconstruction and ILW storage and disposal, each contributing on average around 40 % to the total. Site management and transport contribute on average 5.5 and 4 % to the total, while waste retrieval, R&D, LLW disposal and land remediation contribute little to the impacts (1.5–3 %). Around 85 % of the impacts from plant deconstruction are due to the steel and concrete used to package the LLW and ILW wastes. Construction of the repository accounts for 90 % of the impacts from ILW storage and disposal.

Therefore, as these results indicate, the majority of the impacts (over 80 %) from decommissioning are directly related to the amount of waste that needs to be packaged and stored. These results have been used to extrapolate the environmental impacts to the whole of the UK Magnox fleet and the results suggest a great variability in the impacts for different sites. For example, the GWP ranges from 0.89 to 7.14 g $CO_2$ eq./kWh; a similar trend is noticed for the other impacts. This is due to different volumes of waste and the energy output generated by different reactors.

If the impacts from storage of waste fuel generated at different Magnox sites and stored at Sellafield are also included in the estimates, the GWP of decommissioning increases on average by four times; in the case of Trawsfynydd, it goes up from 3.5 to 15.95 g $CO_2$/kWh.

Overall, decommissioning of the UK Magnox reactors would generate 2 Mt of $CO_2$ eq. without and 11 Mt of $CO_2$ eq. with the waste from Sellafield. This represents 0.4 and 2 % to the current total UK annual emissions, respectively.

The study also shows that delaying the decommissioning process to allow the energy system to decarbonise could reduce the environmental impacts. For instance, delaying until 2030 could reduce the GWP by 50 % by the end of the decommissioning process around 2100. Other technological improvements, both in the decommissioning process and in the background, are also likely to happen over the time that could potentially reduce the impacts from decommissioning. However, economic and social aspects of any delays should be assessed fully before making any such decisions.

Regardless of the timelines, the environmental impacts of decommissioning would be reduced substantially by reducing the volume of the waste to be disposed of through appropriate waste management strategies and increasing recycling of materials, particularly steel.

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## References

Arnold AG (2008) Development of a method for recording energy costs and uses during the construction process. PhD thesis, Texas A&M University

Bayliss C, Langley K (2004) Nuclear decommissioning, waste management and environmental site remediation. London, Butterworth-Heinemann (Elsevier), 330pp.

Beerten J, Laes E, Meskens G, D'haeseleer W (2009) Greenhouse gas emissions in the nuclear life cycle: a balanced appraisal. Energ Policy 37:5056–5068

British Water (2011) Code of practice: Flow and loads—3. Sizing criteria, treatment capacity for small wastewater treatment systems. British Water, London. http://www.britishwater.co.uk/publications/Publications_and_Technical_Guides.aspx

Bryan RH, Dudley IT (1974) Estimated quantities of materials contained in a 100-MW(e) PWR power plant. Oak Ridge National Laboratory, Oak Ridge

Chan MY, Burnett J, Chow WK (1998) Energy use for ventilation systems in underground car parks. Build Environ 33: 303–314

CIBSE (2000) Energy use in offices. Chartered Institute of Building Services Engineers, Energy Consumption Guide 19. www.cibse.org/pdfs/ECG019.pdf

CoRWM (2006) Managing our radioactive waste safely: CoRWM's recommendations to government. Committee on Radioactive Waste Management (CoRWM), London. http://corwm.decc.gov.uk/en/crwm/cms/about_us/our_history/our_history.aspx

DECC (2012) 2011 UK greenhouse gas emissions, provisional figures and 2010 UK greenhouse gas emissions, final figures by fuel type and end-user. Department of Energy and Climate Change, UK. www.decc.gov.uk/assets/decc/11/stats/climate-change/4817-2011-uk-greenhouse-gas-emissions-provisional-figur.pdf

Defra & NDA (2007) The 2007 UK radioactive waste inventory: main report. Defra/RAS/08.002, NDA/RWMD/004

Dones R, Bauer C, Doka G (2009) Kerenergie. In: Dones R et al (ed) Sachbilanzen von Energiesystemen: Grundlagen fur den okologischen Vergleich von energiesystemen un den einbezug von energiesystemen in okobilanzen fur die Schweiz. Final report Ecoinvent no 6-VII, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dubendorf, Switzerland

Ecoinvent (2011) Ecoinvent v2.1 database. Swiss Centre for Life Cycle Inventories, Dübendorf

Entec (2010) LLW transport hubs assessment; draft report. Low level waste repository Limited, UK. www.llwrsite.com/UserFiles/File/OperationalStrategy/LLWTransportHubsStudy-March2010.pdf

European Commission (2010) Proposal for a council directive on the management of spent fuel and radioactive waste. EC, Brussels

Fthenakis VM, Kim HC (2007) Greenhouse gas emissions from solar electric and nuclear power: a life cycle study. Energ Policy 35:2549–2557

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, Koning (2001) A life cycle assessment: An operational guide to the ISO standards; Part 2a. CML, Leiden. http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html

Hall A (2010) Fierce battles as nuclear 'train of death' held up in Germany. The Telegraph, London

Hawken P, Lovins AB, Lovins LH (1999) Natural capitalism: the next industrial revolution. Earthscan, London

Hilton (undated). Practical steps to waste minimization. Envirowise, UK. http://envirowise.wrap.org.uk/media/attachments/197736/Practical-Steps-to-Waste-Minimisation.pdf

IAEA (2001) Methods for the minimisation of radioactive wastes from decontamination and decommissioning of nuclear facilities. Technical Report Series No. 401, IAEA, Vienna

IAEA (2006) Retrieval of fluidizable radioactive wastes from storage facilities. IAEA-TECDOC-1518, IAEA, Vienna

IAEA (2007) Retrieval and conditioning of solid radioactive waste from old facilities. Technical report series no. 456. IAEA, Vienna

ISO (2006a) ISO 14040-environmental management—life cycle assessment—principles and framework. ISO, Geneva

ISO (2006b) ISO 14044-environmental management—life cycle assessment—requirements and guidelines. ISO, Geneva

Jazayeri S, Kralovic P, Honarvar A, Naini A, Rozhon J, Shabaneh R and Walden T (2008) Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation in Ontario. Canadian Energy Research Institute. Calgary

Jensen SE, Nonbøl E (1999) Description of the Magnox type of gas cooled reactor (MAGNOX). Risø National Laboratory, Roskilde. www.nks.org/scripts/getdocument.php?file=111010111119675

Lenzen M (2008) Life cycle energy and greenhouse gas emissions of nuclear energy: a review. Energy Convers Manag 49:2178–2199

LLWR Repository and NDA (2012) Site specific baseline for low level waste repository, near Drigg. LLW Repository Ltd and NDA. www.llwrsite.com/UserFiles/File/Site_Specific_Baseline_2012.pdf

Madog-Jones H (2006) Decommissioning a Magnox power station. Neutron Users Club. www.npl.co.uk/upload/pdf/20051006_nuc_jones_1.pdf

Magnox Electric (2005) Discharges and monitoring of the environment in the UK. Monitoring our environment—annual report 2005

Magnox North (2009a) Clear Site; newsletter for Trawsfynydd site. http://magnoxnorthsites.com/UserFiles/File/MGNX013%20Clearsite-June_Final%20for%20web.pdf

Magnox North (2009b) ILW store accepts first package. Clear Site; newsletter for Trawsfynydd site. http://magnoxnorthsites.com/UserFiles/File/MGNX015_Clearsite_October_FINAL_lr.pdf

Magnox North (2010a) Residual resin retrieval trials underway. Clear Site; newsletter for Trawsfynydd site. http://magnoxnorthsites.com/UserFiles/File/MGNX013%20Clearsite-June_Final%20for%20web.pdf

Magnox North (2010b) Pond scabbling project achieves further milestones. Clear Site; newsletter for Trawsfynydd site

Magnox North (2010c) First trials planned for legacy oils. Clear Site; newsletter for Trawsfynydd Site

Mouchel (2010) Sustainability report 2010. www.mouchelreports.com

NAO (2008) Nuclear Decommissioning Authority: Taking forward decommissioning. Report by the Comptroller and Auditor General, National Audit Office. London, The Stationery Office. 53pp

NDA (2006) Trawsfynydd site summary: lifetime plan. Nuclear Decommissioning Authority, Cumbria

NDA (2007) Trawsfynnydd (NDA) Waste stream data sheet. www.nda.gov.uk/ukinventory/documents/Waste_Stream_Data_Sheets/Site_WSDS/loader.cfm?csModule=security/getfile&PageID=894

NDA (2010a) Strategic environmental assessment: site specific baseline Trawsfynydd. Nuclear Decommissioning Authority, Cumbria

NDA (2010b) Strategic environmental assessment: site specific baseline low level waste repository. Nuclear Decommissioning Authority, Cumbria

NDA (2010c) Strategic environmental assessment: site specific baseline Hunterston A. Nuclear Decommissioning Authority, Cumbria

NDA (2010d) Strategic environmental assessment: site specific baseline Hinkley Point. Nuclear Decommissioning Authority, Cumbria

NDA (2010e) Strategic environmental assessment: site specific baseline Bradwell. Nuclear Decommissioning Authority, Cumbria

NDA (2010f) Radioactive waste inventory main report. Nuclear Decommissioning Authority, Cumbria

NEA (1999) Decontamination techniques used in decommissioning activities. A report by the NEA task group on decontamination. Nuclear Energy Agency, OECD, Paris

Nirex (2003) Generic repository studies: generic repository design. Volume 1—overview of reference case design, descriptions of variant case and upper bound design. Report N/077, Nirex Limited, Didcot

OGC (2009) The State of the Estate in 2009: a report on the efficiency and sustainability of the government estate. Office of Government Commerce

PACE (2000) Measuring waste: advice for managers on the government estate. Information Note 1700. London, Property Advisors to the Civil Estate. http://webarchive.nationalarchives.gov.uk/20110822131357/http://www.ogc.gov.uk/documents/InformationNote1700.pdf

Parsons S (2007) Handling legacy waste streams at Trawsfynydd. Radwaste Solutions. Am Nucl Soc 14(4):22–29

PE International (2011) Life cycle assessment software (GaBi) v. 4.4. PE International, Leinfelden-Echterdingen

Resource NSW (2002) Waste reduction in office buildings: a guide for tenants. Paramatta, New South Wales

Simons A, Bauer C (2012) Life cycle assessment of the European pressurized reactor and the influence of different fuel cycle strategies. J Power Energy 226(3):427–444

Sovacool BK (2008) Valuing the greenhouse gas emissions from nuclear power: a critical survey. Energ Policy 36:2940–2953

UK Government (2006) Climate change and sustainable energy act 2006. HMSO, London

van Leeuwen JWS, Smith P (2005) Nuclear power: the energy balance. www.stormsmith.nl

Vattenfall AB (2010a) Certified environmental product declaration EPD of electricity from Ringhals Nuclear Power Plant. Vattenfall AB, Stockholm. http://gryphon.environdec.com/data/files/6/7315/epd26.pdf

Vattenfall AB (2010b) Certified environmental product declaration EPD of electricity from Forsmark Nuclear Power Plant. Vattenfall AB, Stockholm. http://gryphon.environdec.com/data/files/6/7310/epd21.pdf

Versemann R (2008) Decommissioning nuclear plants: experiences in Germany. Proc ICE Energy 161:101–113

von Lensa W, Bradbury D, Cardinal G, Eccles H, Fachinger J, Grambow B, Grave MJ, Marsden BJ & Pina G (2008) CARBOWASTE: New EURATOM Project on 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste'. Proceedings of the 4th International Topical Meeting on High-Temperature Reactor Technology HTR2008, Washington D.C., USA

Voorspools KR, Brouwers EA, D'haeseleer WD (2000) Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: results for the Low Countries. Appl Energy 67:307–330

Wall S, Shaw I (2002) Retrieval of intermediate level waste at Trawsfynydd nuclear power station. Proceedings WM'02 Conference, February 24–28, 2002, Tucson

Waste online (2004) Waste at work information sheet. http://dl.dropbox.com/u/21130258/resources/InformationSheets/WasteAtWork.htm

Weisser D (2007) A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 32:1543–1559

White SW, Kulcinski GL (2000) Birth to death analysis of the energy payback ratio and $CO_2$ gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. Fusion Eng Des 48:473–481