



Carbon footprint of the nuclear fuel cycle

Briefing note

A study for
British Energy
undertaken by



March 2006

Executive Summary

Carbon footprint of the nuclear fuel cycle

- AEA Technology Environment, on behalf of British Energy, have carried out a complete life cycle assessment for electricity supplied by Torness nuclear power station. A key area of interest in this study is the CO₂ emissions associated with mining and enrichment of uranium since these aspects have historically been an issue of contention with such analyses.
- This briefing note describes in detail the calculations used to determine the CO₂ emissions associated with the mining and milling, and enrichment stages of the Torness fuel cycle. It shows the mining and milling emissions to be 1.85gCO₂/kWh and enrichment emissions to be 0.43 gCO₂/kWh. When added to the remaining parts of Torness's fuel cycle, the life cycle emissions are 5.05g/kWh.
- The dominant contribution for mining and milling comes from the Olympic Dam facility. This is primarily because the ore grade at Olympic Dam is the lowest of the facilities assessed, therefore a greater amount of energy is required to obtain the required quantity of uranium.
- The grade of ore at Olympic Dam has been calculated to be 0.028%, which is a factor of ten lower than the average grade of ore from the world's ten largest mines (0.21%). If this low grade ore were used to provide *all* of the uranium for a future power station then, based on the analysis for Olympic Dam, the emissions associated with mining and milling would be double that calculated for Torness, about 3.65gCO₂/kWh.
- If the emissions associated with the remaining parts of the fuel cycle for a future nuclear station were the same as assessed for Torness, then the total life cycle emissions for a future station with *all* its uranium supplied by Olympic Dam would be 6.85gCO₂/kWh.
- These estimates are valid when applied to a new programme of nuclear build. All of the third generation nuclear reactor models currently marketed offer higher burn-up and reduced uranium requirements than the current fleet of nuclear reactors in the UK. On this basis, the carbon footprint of the Torness station represents an upper estimate of the likely impacts from generation of new nuclear plant.

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- Compared to the current and probable reserves of uranium, Olympic Dam represents a low grade ore. All things being equal, the carbon footprint of the Olympic Dam facility is therefore likely to represent a high end estimate of the energy use and CO₂ emissions from the mining and milling of uranium associated with generation from new nuclear facilities.
 - Gas centrifuge represents a more energy efficient enrichment process than gas diffusion, and all future planned enrichment capacity is based upon this technology. On this basis, the energy use associated with the Gronau plant that was analysed as part of the Torness EPD represents a reasonable basis for assessing the impacts of enrichment for new nuclear generation.

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Introduction

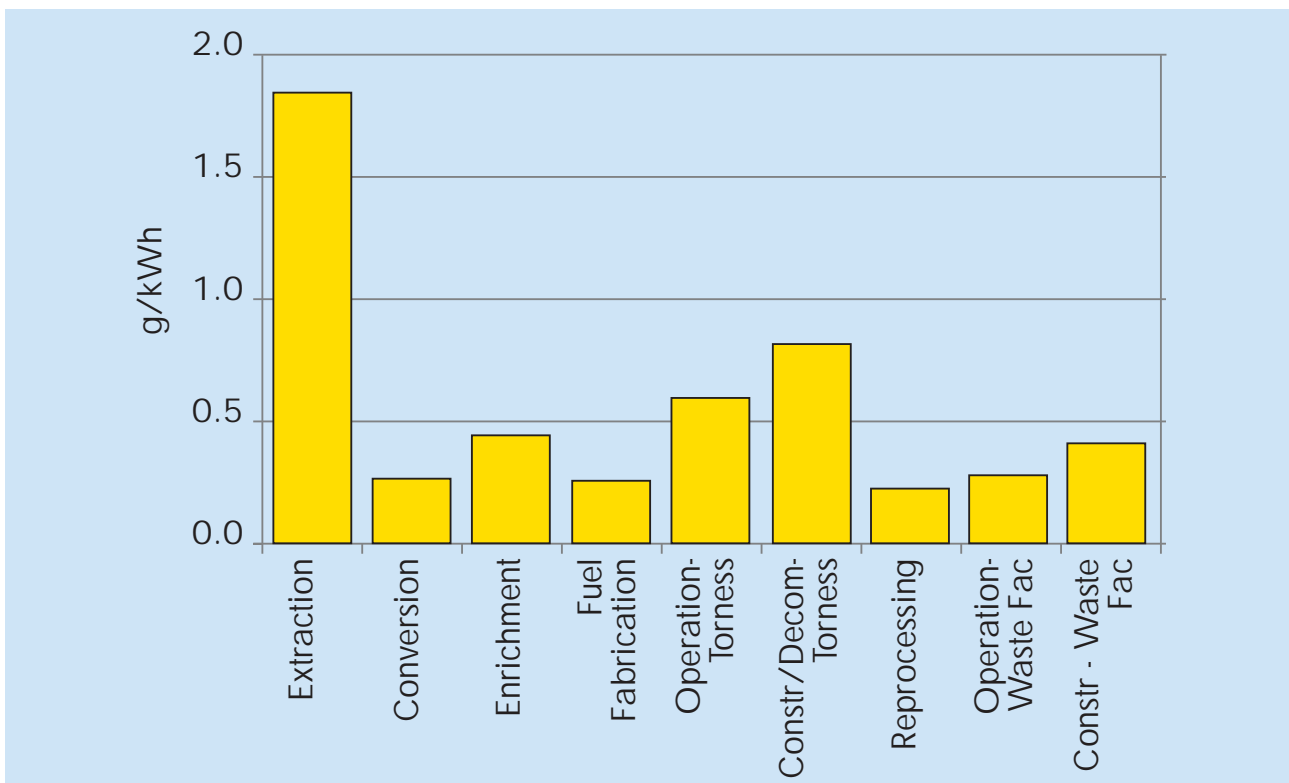
Carbon footprint of the nuclear fuel cycle

The Environmental Product Declaration (EPD) for electricity generated from Torness nuclear power station describes the CO₂ emissions (and other environmental impacts) associated with each stage of the nuclear fuel cycle. Of those, the uranium extraction (mining and milling) stage makes the single largest contribution.

For each of the stages in the Torness fuel cycle, the CO₂ emissions are shown in the chart below. The values have been normalised, in accordance with the EPD guidelines¹, to show the relative emissions per kWh electricity generated by Torness.

Uranium is supplied to Torness from various mines. The analysis presented in the Torness EPD is based upon the emissions from three of the world's largest mining facilities. The site that makes the greatest contribution to carbon footprint of Torness is the Olympic Dam mining facility in Australia. Since emissions associated with

Figure 1. Carbon dioxide emissions (g) per kWh of electricity generated by Torness power station during 2002



¹Product Specific Requirements (PSR) for preparing an environmental product declaration (EPD) for Electricity and District Heat Generation. PSR 2004:2* GEDnet (2004)

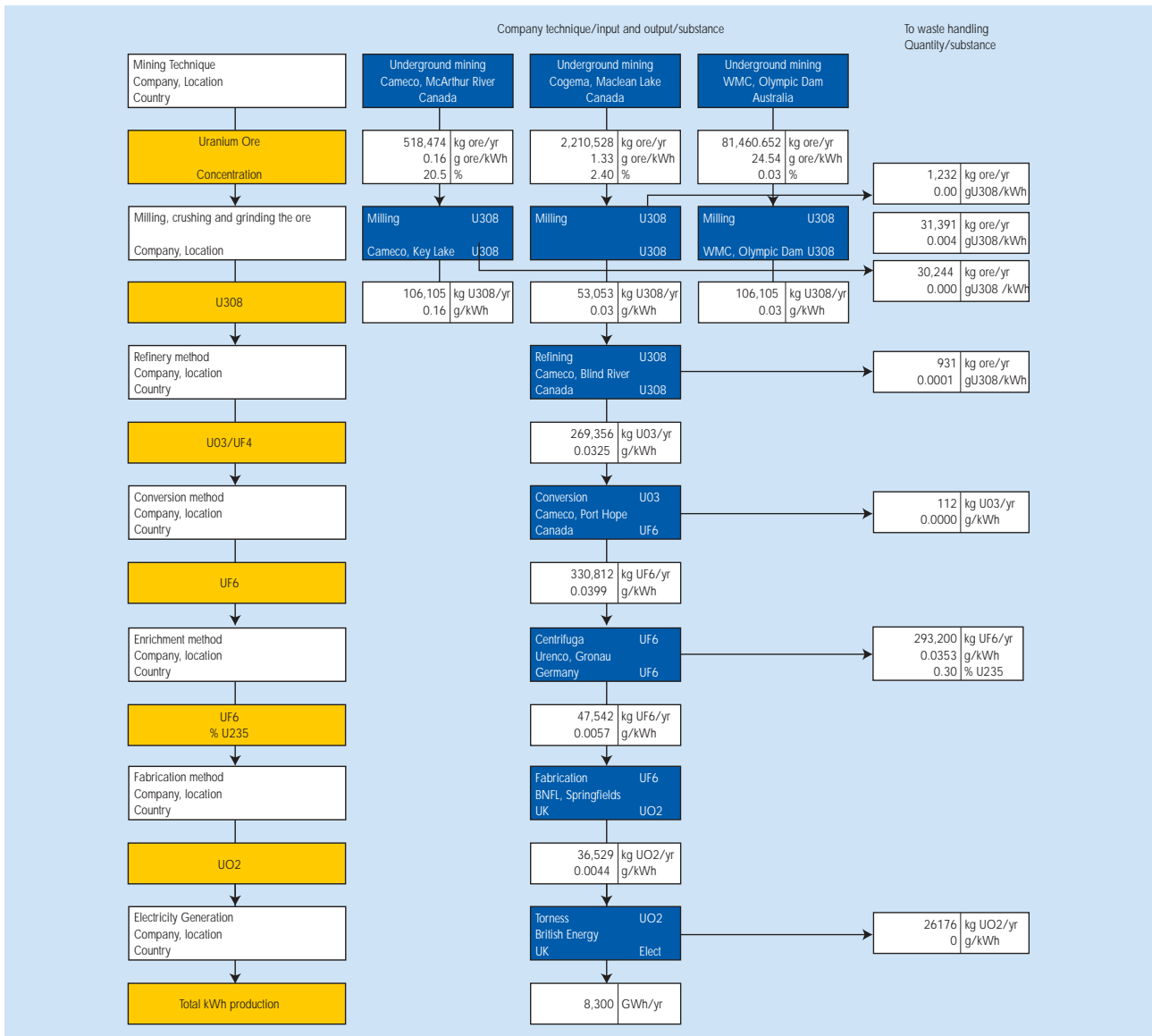
Olympic Dam are often cited in other studies it is useful to set out the detailed calculations that have been used in the development of the Torness EPD. CO₂ emissions have been calculated for each of the main source categories: electricity use, fuel use and transport. Similar calculations were carried out for the other mining facilities, and for other stages of the fuel cycle.

Whilst the enrichment stage represents less than 15% of the carbon footprint for Torness, other studies have found that the CO₂ emissions from uranium enrichment are more significant. This largely relates the choice of enrichment process (diffusion vs centrifuge) and the prevailing energy mix. For transparency, and to aid comparison with alternative estimates, the calculations used to analyse the carbon footprint for the enrichment stage of the Torness fuel cycle are also provide below.

The uranium balance for Torness

Carbon footprint of the nuclear fuel cycle

The uranium balance effectively describes the amount of uranium required during the operation of Torness. Uranium, in its various forms, is traced through the supply chain to determine the amount of uranium oxide that is required from the Olympic Dam facility, and the amount of enriched UF₆ required from the facility at Gronau. The uranium balance that has been assumed in the Torness fuel cycle is described in the figure below. This is followed by a description of the underlying calculations.



The reference year for the EPD is 2002 (although annual differences are very small). The data stated here was supplied by the organisations running the relevant facilities.

2.1 Rate of U_3O_8 consumption

Electricity Generation During the reference year Torness generated 8,300 GWh electricity, equal to 8.3×10^9 kWh.

The fuel used to generate this level of output was equivalent to 32,200 kgU (3.22×10^7 gU). This is equal to a fuel burn up of 28 GWd/tU, assuming a 37% conversion efficiency.

Fuel fabrication occurs at the Springfields site, where enriched uranium is converted into uranium dioxide powder and pressed into small pellets. These pellets are the inserted into fuel rods, which make up the fuel elements that are used in the nuclear reactor.

By scaling molecular masses the 3.22×10^7 gU used by Torness during the reference year, is equivalent to 3.65×10^7 gUO₂.

Enrichment is assumed to occur at Urenco's gas centrifuge enrichment facility at Gronau. During the enrichment stage gaseous uranium hexafluoride is enriched, to enhance the U-235 isotope content in the fuel. Torness requires the uranium fuel to be enriched to about 3% U-235 (natural uranium is 0.7% U-235).

By a further scaling of molecular masses, the quantity of enriched UF₆ required to produce the 3.65×10^7 gUO₂ consumed by Torness during the reference year is 4.75×10^7 g UF₆. The amount of natural UF₆ required in order to produce the enriched uranium varies according to initial concentration of UF₆ input and the required concentration of UF₆ output.

On the basis of Torness fuel requirements, and the throughput of enriched uranium at Gronau during the reference year, we estimated the output from the plant of 5.03×10^8 g enriched UF₆ from 3.5×10^9 g natural UF₆ input. To produce Torness's 4.75×10^7 g enriched UF₆ therefore requires:

$$3.5 \times 10^9 / 5.03 \times 10^8 \times 4.75 \times 10^7 = 3.31 \times 10^8 \text{ g UF}_6.$$

Conversion is assumed to occur at Cameco's Port Hope facility. During the reference year, the plant converted 1.15×10^{10} gUO₃ into 1.42×10^{10} gUF₆. Therefore to produce Torness's 3.31×10^8 gUF₆ requires:

$$1.15 \times 10^{10} / 1.42 \times 10^{10} \times 3.31 \times 10^8 = 2.69 \times 10^8 \text{ gUO}_3.$$

Refinement is assumed to occur at Cameco's Blind River facility. During the reference

year, the plant required $1.34 \times 10^{10} \text{gU}_3\text{O}_8$ to produce $1.37 \times 10^{10} \text{gUO}_3$. Therefore to produce Torness's $2.69 \times 10^8 \text{gUO}_3$ requires:

$$1.34 \times 10^{10} / 1.37 \times 10^{10} \times 2.69 \times 10^8 = 2.65 \times 10^8 \text{g U}_3\text{O}_8.$$

The rate of U_3O_8 consumption is therefore:

$$2.65 \times 10^8 / (8.3 \times 10^9) = \mathbf{0.032 \text{gU}_3\text{O}_8/\text{kWh}}.$$

Carbon Footprint for Olympic Dam

Carbon footprint of the nuclear fuel cycle



Olympic Dam is a multi-mineral ore body. It is the world's fourth-largest remaining copper deposit and the largest uranium deposit. It also contains significant quantities of gold and silver.

The analysis reported in the Torness EPD was based upon data reported by then owner WMC resources, for the reference year 2002³. The data has been independently audited by PriceWaterhouseCoopers as part of WMC verification procedures. The key data for Olympic Dam, as used in the Torness EPD, are shown in the table below. For comparison, data from 2003 and 2004 have also been included.

Table 1. Olympic Dam environmental data

Environmental Data Table	2002	2003	2004
Ore treated (million tonnes) ¹	8.875	8.387	8.887
Energy Usage (terajoules)	4,881	4,667	5,477
Electricity	2,746	2,685	3,066
Diesel	685	768	839
LPG	802	693	846
Coke	234	195	300
Other fuels	414	326	426
Products			
Gold (ounces)	64,293	86,116	88,633
Silver (ounces)	643,935	601,395	861,628
Copper (tonnes)	178,120	160,079	224,731
Uranium Oxide (tonnes)	2,890	3,203	4,404
Energy use (MJ/tonne ore treated)	616	677	582

3.1 Emissions from electricity use

Emissions from electricity use were not reported directly in the Olympic Dam site report. The total amount of electricity used at the site during the year was 2,746TJ. The CO₂ emissions from electricity use were calculated on the basis of the local generation mix for South Australia, using emission factors from the Simapro5.1 LCA database. This is equivalent to 846g CO₂/kWh electricity used. For the reference year, the total CO₂ emissions were estimated to be 6.45x10¹¹g.

A key assumption in the carbon footprint for uranium mining is the proportion of the

³ Olympic Dam Operations - Business Site Data report 2002

total emissions at the Olympic Dam site that are associated with the uranium fuel cycle. It is not appropriate, and not consistent with the ISO14041 series of standards, to allocate all of the carbon dioxide emissions to the uranium mined, since Copper, Silver and Gold are also mined at the site. WMC estimate that 75% of the resources are associated with copper extraction. In the Torness EPD, we conservatively assumed that the remaining 25% of resources were used to mine uranium.

The total CO₂ emissions associated with electricity use for extraction of the uranium at the site is therefore:

$$6.45 \times 10^{11} \text{ gCO}_2 \times 0.25 = 1.61 \times 10^{11} \text{ gCO}_2.$$

The total quantity of U₃O₈ mined and milled at Olympic Dam during the year was 2.89x10⁹g.

On this basis, the relative CO₂ emissions associated with electricity use for extraction of the uranium at the site is therefore:

$$1.61 \times 10^{11} / 2.89 \times 10^9 = 55.8 \text{ gCO}_2/\text{gU}_3\text{O}_8.$$

In the uranium balance for Torness, it was assumed the Olympic Dam provided 40% of Torness's uranium requirement. Therefore, the life cycle emissions due to electricity use for mining are:

$$0.032 \text{ gU}_3\text{O}_8/\text{kWh} \times 55.8 \text{ gCO}_2/\text{gU}_3\text{O}_8 \times 0.4 = 0.71 \text{ gCO}_2/\text{kWh}.$$

3.2 Emissions from on-site fossil fuel use

The emissions from fossil fuel combustion at the site have been determined from the quantities for fuel consumed multiplied by the relevant emission factors. Emissions factors have been taken from the Australian Department for Environment and Heritage⁴. The table below shows site level emissions:

⁴ http://www.greenhouse.gov.au/challenge/tools/workbook/factorsmethod_section2.html

Table 2. CO₂ emissions from fossil fuel use at Olympic Dam

Fuel	Quantity consumed	Emission factor (kgCO ₂ /GJ)	CO ₂ emissions (gCO ₂)
Diesel fuel	685	7.77x10 ⁷	5.32x10 ¹⁰
Coke	234	1.31x10 ⁸	3.07x10 ¹⁰
Liquified petroleum gas	802	6.71x10 ⁷	5.38x10 ¹⁰
Other fuels	414	7.74x10 ⁷	3.20x10 ¹⁰
Total			1.70x10¹¹

Dividing this by the total quantity of U₃O₈ mined during the year and applying the allocation factor of 25% for the uranium contribution gives a relative emission factor from fuel combustion at the site of:

$$1.70 \times 10^{11} \times 0.25 / 2.89 \times 10^9 = \mathbf{14.7 \text{ gCO}_2/\text{gU}_3\text{O}_8}.$$

Allowing for Olympic Dam contributing 40% of Torness's uranium, the life cycle emissions due to fuel use for mining are therefore:

$$0.032 \text{ gU}_3\text{O}_8/\text{kWh} \times 14.7 \text{ gCO}_2/\text{gU}_3\text{O}_8 \times 0.4 = \mathbf{0.19 \text{ gCO}_2/\text{kWh}}.$$

Emissions from materials transport

The CO₂ emissions from the off-site transport of material to the site⁵, and transport of materials on-site⁶, are calculated by deriving the total tonne-km of materials transported and multiplying by a specific emission factor for HGV transport. Transport distances have been approximated based upon available evidence. Materials are grouped into 3 categories: fuel and explosives, ore transported on site, and raw materials transported to site. Quantities are summarised below:

Table 3. Material transport at Olympic Dam

Material	Quantity (t)	Distance travelled	t-km
Fuel and explosives	4.365x10 ⁴	1000	4.37x10 ⁷
Ore	8.875x10 ⁶	2.5	2.22x10 ⁷
Raw materials	1.382x10 ⁶	2000	2.76x10 ⁹
Total			2.89x10⁹

⁵ Transport of U₃O₈ from the site is accounted for in the next stage (conversion) of the fuel cycle

⁶ We have assumed that the diesel use on site is not used as a transport fuel, so a separate calculation of on-site transport impacts has been undertaken

The total load travelled is multiplied by an emission factor of $180\text{gCO}_2/\text{t}\cdot\text{km}^7$ to give site emissions due to transport of:

$$2.89 \times 10^8 \times 1.8 \times 10^2 = 5.04 \times 10^{11} \text{gCO}_2.$$

Dividing this by the total quantity of U_3O_8 mined during the year and applying the factor of 25% for the uranium contribution gives a concentration for emissions due to transport at the site of:

$$5.04 \times 10^{11} \times 0.25 / 2.89 \times 10^9 = \mathbf{43.9\text{gCO}_2/\text{gU}_3\text{O}_8}.$$

Allowing for Olympic Dam contributing 40% of Torness's uranium, the life cycle emissions due to transport for mining are therefore:

$$0.032\text{gU}_3\text{O}_8/\text{kWh} \times 43.9\text{gCO}_2/\text{gU}_3\text{O}_8 \times 0.4 = \mathbf{0.56\text{g/kWh}}.$$

Summary of emissions from other mining facilities

The calculations above show how the emissions due to mining and milling operations at Olympic Dam in Australia contribute to Torness's life cycle impacts (it is assumed that Olympic Dam provides 40% of the uranium for Torness). They are summarised below along with the contributions from McClean Lake (assumed to supply 20%) and McArthur River (assumed to supply 40%). Ore from McArthur River is milled at Key Lake, shown separately in the table (note the figures are subject to rounding).

Table 4. CO₂ emissions from mining facilities

Site	gCO ₂ /kWh			
	Electricity	Fuel	Transport	Total
Olympic Dam	0.71	0.19	0.56	1.46
McClean Lake	0.06	0.06	0.01	0.14
McArthur River	0.07	0.03	0.00	0.10
Key Lake	0.07	0.05	0.04	0.15
Total				1.71

The carbon footprint of Olympic Dam, per quantity of uranium supplied, is higher than for the other facilities, since the uranium grade at Olympic Dam is lower. If

⁷ Emission factor is based upon average emissions per tonne-km from HGV transport in the UK in 2002, based upon data reported in the UK National Atmospheric Emissions Inventory

Olympic Dam were used to provide all of the uranium for a future power station then, based on the analysis for Olympic Dam, the emissions associated with mining and milling would be 3.65gCO₂/kWh.

If the emissions associated with the remaining parts of the fuel cycle for a future nuclear station were the same as assessed for Torness, then the total life cycle emissions for a future station with all its uranium supplied by Olympic Dam would be 6.85gCO₂/kWh.

Carbon footprint of uranium enrichment



Carbon footprint of the nuclear fuel cycle

Previous life cycle studies of nuclear power have identified the uranium enrichment stage as an important stage in the carbon footprint, since it is associated with a potentially large energy demand. There are two enrichment processes in large-scale commercial use; gaseous diffusion and gas centrifuge. Gaseous diffusion consumes about 40 times more energy than the gas centrifuge method⁸.

The reference facility that has been analysed as part of the Torness fuel cycle is the Gronau site in Germany, owned by Urenco Group. The Gronau facility employs a gas centrifuge enrichment technology and is considered representative of the enrichment stage of British Energy's supply chain. The analysis has largely been based upon data reported in the 2002 Environmental report for the Gronau site⁹.

The materials balance for the enrichment stage is more complicated than some of the other stages in the fuel cycle, as the resource requirements will vary according to the required U-235 concentration of enriched uranium. This is defined in terms of the separative work (i.e. the amount of effort required for enriching uranium), and reflects the required concentration of enriched uranium, the initial U-235 concentration of uranium being enriched, and the uranium concentration of the tails. For the purposes of the Torness analysis, the carbon footprint for enrichment has been derived based upon the throughput of uranium at Gronau in the reference year, and the estimated requirements from Torness¹⁰.

In the reference year, the Gronau site produced an estimated 5.03×10^8 g enriched UF_6 . As stated above, Torness required 4.75×10^7 g enriched UF_6 during the year, therefore the proportion of resource use associated with Torness was estimated to be:

$$4.75 \times 10^7 / 5.03 \times 10^8 = 9.45\%$$

4.1 Emissions from on-site energy use

The Gronau site uses natural gas for space heating and diesel for transport, and also as a standby fuel. The site consumed approximately 4.73×10^5 m³ natural gas and 3.06×10^4 litres of diesel fuel, during the reference year. On this basis the CO₂ emissions from on-site energy use were reported as 1.11×10^9 g.

⁸ Comparison of energy systems using life cycle assessments. World Energy Council July 2004

⁹ Urananreicherungsanlage gronau. Umwelterklärung 2002. Urenco Deutschland

¹⁰ For AGRs the uranium dioxide fuel is enriched to about 3% U-235 (natural uranium is 0.7% U-235)

4.2 Emissions from electricity use

Emissions from electricity use were not reported directly in the Gronau site report. The total amount of electricity used at the site during the year was 52.82GWh. The CO₂ emissions from electricity use were calculated on the basis of the local generation mix for Germany, using emission factors from the Simapro5.1 LCA database. This is equivalent to 683g CO₂/kWh electricity used. For the reference year, the total CO₂ emissions were estimated to be 3.61x10¹⁰g.

4.3 Emissions from off-site transport

Emissions from off-site transport have been estimated on the basis of transport requirements associated with the Torness fuel cycle. Transport distances were estimated based upon data provided by British Energy's uranium procurement team. The analysis assumed that all of the UF₆ inputs were transported from the Port Hope conversion facility in Canada.

The emissions due to transport are derived from site transport quantities of tonne-km by HGV and tonne-km by ship, as described in the table below.

Table 5. Transport emissions associated with the enrichment stage

Mode	t-km	Emission factor (gCO ₂ /t-km)	CO ₂ emissions (gCO ₂)
HGV	1.03x10 ⁶	179.6	1.86x10 ⁸
Ship	1.98x10 ⁷	31.0	6.14x10 ⁸
Total			8.0x10⁸

For the reference year, the total CO₂ emissions were estimated to be 8.00x10⁸gCO₂.

4.4 Total emissions from the enrichment stage

Since the requirements of Torness in the reference year represent 9.45% of the total output from the Gronau site, the CO₂ emissions associated with uranium enrichment, that can be allocated to the Torness fuel cycle can be summarised as:

Table 6. Total emissions from the enrichment stage

	Site	Torness allocation
Energy use	1.11x10 ⁹ gCO ₂	1.05x10 ⁸ gCO ₂
Electricity use	3.61x10 ¹⁰ gCO ₂	3.41x10 ⁹ gCO ₂
Transport use	8.00x10 ⁸ gCO ₂	7.56x10 ⁷ gCO ₂
Total	3.80x10¹⁰ gCO₂	3.59x10⁹ gCO₂

In the reference year Torness generated 8.3TWh, therefore the rate of emissions due to enrichment was:

$$3.59 \times 10^9 \text{ gCO}_2 / 8.3 \times 10^9 = \mathbf{0.43 \text{ gCO}_2/\text{kWh.}}$$

¹⁰ For AGRs the uranium dioxide fuel is enriched to about 3% U-235 (natural uranium is 0.7% U-235)

Applicability of the results of the Torness EPD to a programme of new nuclear build

Carbon footprint of the nuclear fuel cycle

The analysis presented above has been based upon data for the reference year 2002 and is valid for describing the current, and short-term future impacts of nuclear generation.

This section provides a brief discussion of the applicability of the above analysis for describing the carbon footprint for new build nuclear capacity. It is not the intention to make detailed forecasts of the future supply and demand for uranium, but simply to indicate the potential influence on future developments on the carbon footprint i.e. if emissions are anticipated to be greater or lesser than current estimates.

In assessing the future carbon footprint the review will focus on three components:

- Uranium demand per GWh electricity output
- Supply and concentration of uranium resources
- Enrichment of uranium

5.1 Uranium demand per GWh electrical output

If the new nuclear plant were significantly more or less efficient than Torness, then all things being equal, the carbon footprint of the nuclear fuel cycle would need to be adjusted proportionately.

The thermal energy produced in the nuclear power plant from the uranium in the fuel typically ranges from 40 and 43.4 GWd/t U¹¹ for pressurized water reactors (PWR), and 33 and 40 GWd/t U for boiling water reactors (BWR)¹². As described above the uranium demand for Torness was approximately 32.2 tonnes U to generate 8.3×10^9 kWh electricity. Assuming the efficiency of converting thermal energy into net electricity is approximately 37%, this is equivalent to a uranium burn up of 28 GWd/t U.

Efficiency of new nuclear stations

Any new build new nuclear generation capacity is likely to adopt third generation advanced thermal reactors, of which there are at least 13 different models currently being marketed.

According to the World Nuclear Association, third generation reactors all share the following characteristics:

¹¹ GWd stands for Gigawatt-days, 1 GWd is equal to 24 million kilowatt-hours

¹² WISE. Mass balance calculator. <http://www.wise-uranium.org/nfccc.html>

- a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time,
- a simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets,
- higher availability and longer operating life - typically 60 years,
- reduced possibility of core melt accidents,
- minimal effect on the environment,
- higher burn-up to reduce fuel use and the amount of waste,
- burnable absorbers (“poisons”) to extend fuel life.

As an example, the first unit of the Framatome ANP PWR is about to be built at Olkiluoto in Finland, with a second unit to follow in Flamanville, France. The manufacturers claim the reactor has a fuel burn-up of 65 GWd/t and the highest thermal efficiency of any light water reactor, at 36%.

Another major large (1500 MWe) advanced PWR design is being developed by four utilities with Westinghouse and Mitsubishi in Japan with a fuel efficiency of over 55 GWd/t burn-up.

In Russia, the VVER-1500 V-448 model is being developed by Gidropress, and two units each are planned as replacement plants for Leningrad and Kursk. The plant will have a fuel efficiency of 50-60 MWd/t burn-up and enhanced safety.

However, one potential factor that might counter these efficiencies is that some of the advanced reactors may require a higher U-235 concentration - so require additional enrichment effort to achieve the output. However, depending on the enrichment technology employed, this is unlikely to offset the savings associated with the improvements in reactor design.

On this basis the uranium resources required (and the associated carbon footprint) is likely to be lower, all things being equal, than the current Torness lifecycle assessment.

5.2 Supply and concentration of uranium resources

The table below describes the largest 10 uranium mines in the world, in terms of the total uranium production. This includes an estimate of the ore grade, where data has been published. Together the output from these mines represents almost 70% of global production.

Table 7. Uranium production at the 10 largest uranium mines (2004)

Mine	Country	Main owner	Type	Production (tu)	% of world	Ore Grade
McArthur River	Canada	Cameco	underground	7200	18%	20.90%
Ranger	Australia	ERA (Rio Tinto 68%)	open pit	4356	12%	0.24%
Olympic Dam	Australia	WMC	by-product/ underground	3706	9%	0.05%
Rossing	Namibia	Rio Tinto (69%)	open pit	3038	8%	0.30%
McClellan Lake	Canada	Cogema	open pit	2310	6%	1.40%
Rabbit Lake	Canada	Cameco	underground	2087	5%	1.20%
Akouta	Niger	Cogema/ Onarem	underground	2005	5%	0.38%
Arlit	Niger	Cogema/ Onarem	open pit	1277	3%	0.30%
Beverley	Australia	Heathgate	ISL	920	2%	-
Vaal River	South Africa	Anglogold	by-product underground	756	2%	-
Total				27,654	69%	0.21%

Source: UIC¹³

Olympic Dam is the third largest mining facility in terms of annual production output. However, the grade of the ore mined (0.03 - 0.05%) is lower than for all other mines¹⁴. This compares to an average grade of ore across the top ten mines of 0.21%.

Looking further into the future, current estimates of uranium ore reserves suggest that Australia has most at 30%, with Kazakhstan (17%) second, followed by Canada (12%).

¹³ <http://www.uic.com.au/njp41.htm>

¹⁴ In the analysis presented for the Olympic Dam site previously the grade of ore was estimated at 0.028% based upon the reported output of U₃O₈ per tonne of ore mined. The actual grade of ore fluctuates across the reserve between c. 0.03% and 0.05% which explains the variation in reported ore concentration in this section

Table 8. Known Recoverable Resources of Uranium

	Tonnes U	Percentage of world
Australia	1,074,000	30%
Kazakhstan	622,000	17%
Canada	439,000	12%
South Africa	298,000	8%
Namibia	213,000	6%
Brazil	143,000	4%
Russian Fed.	158,000	4%
USA	102,000	3%
Uzbekistan	93,000	3%
World total	3,537,000	

Source: WNA (2005)¹⁵

In terms of the grade of ore associated with estimated recoverable resources, Australia publishes extensive information on its reserves, as does Canada. A summary of the key resources are provided in the tables below.

Table 9. In situ resources available in operating and prospective Australian uranium mines

Deposit	Grade U ₃ O ₈	Contained U ₃ O ₈	Category
Olympic Dam	0.05%	392,000 t	Proved & Probable Reserves
	0.04%	1,500,000 t	Resources
Ranger	0.24%	43,900 t	Proved & Probable Reserves
Jabiluka	0.51%	71,000 t	Proved & Probable Reserves
Beverley	0.18%	21,000 t	Resources
Koongarra	0.80%	14,540 t	Proved & Probable Reserves
Kintyre	0.2-0.4%	35,000 t	Reserves & resources
Valhalla	0.14%	41,000 t	Resources
Yeelirrie	0.15%	52,000 t	Indicated Resources

Source: WNA¹⁶

¹⁵ <http://www.world-nuclear.org/info/inf75.htm>

¹⁶ <http://www.world-nuclear.org/education/ozuran.htm>

Table 10. Uranium resource in Canada

Mine	tonnes U	tonnes U3O8	Average ore grade	Category
Key Lake	250	300	0.53%	proven reserves
Rabbit Lake	4,070	4,8000	1.20%	proven reserves
	2,400	2,800	1.62%	probable reserves
Cluff Lake	1,800	2,130	2.50%	Reserves
McClellan Lake: McClellan	4,900	5,850	2.10%	Reserves
McArthur River	129,000	152,000	26.56%	proven reserves
	33,000	39,000	19.06%	probable reserves
	6,700	7,900	9.42%	measured + indicated resources
	41,000	48,000	9.51%	inferred resources
Cigar Lake	87,000	102,860	20.67%	proven reserves
	2,000	2,400	4.41%	probable reserves
	45,500	53,600	16.92%	inferred resources
Midwest	16,000	18,900	5.47%	proven & probable reserves
Dawn Lake	4,900	5,800	1.69%	indicated resources

Source: UIC (2006)¹⁷

The major emerging country, Kazakhstan, has less published info. However, the Tselinny area has uranium assets including 'several underground mines with estimated reserves of 75 million tonnes of ore average grade 0.12%'¹⁸.

On the basis of this simple comparison of the uranium content of the ore mined at Olympic Dam, with that of the current known and probably recorded reserves, it is clear that the Olympic Dam represents an extremely low grade ore. This suggests that the carbon footprint for Olympic Dam provides a high estimate of the likely impact of uranium mining for new nuclear build programme¹⁹.

¹⁷ <http://www.uic.com.au/nip03.htm>

¹⁸ <http://www.wise-uranium.org/upasi.html>

¹⁹ We recognise that this analysis is based upon a simple comparison of known reserves, and as such does not take into account any long term projections of supply and demand. Such analysis is beyond the scope of this report. The WNA position paper on this issue states "Current estimates of all expected uranium resources (including those not yet economic or properly quantified) represent 200 years' supply at today's rate of usage"

5.3 Enrichment facilities

The table overleaf describes the available global enrichment capacity at 2004. As described above, the carbon footprint of uranium enrichment is strongly related to the enrichment method selected, and the prevailing energy mix. Gaseous diffusion plants typically consume 40 times more energy per unit of output than centrifuge plants.

At present the gaseous diffusion process accounts for about 40% of world enrichment capacity, with the remainder gas centrifuge. However, though they have proved durable and reliable, most gaseous diffusion plants are now nearing the end of their design life and the focus is on centrifuge enrichment technology which seems likely to replace them²⁰.

- COGEMA (Eurodif) plans to replace the Georges-Besse gaseous diffusion enrichment plant with ultracentrifugation enrichment technology. Urenco and COGEMA signed a Memorandum of Understanding on 7 August 2002 to cooperate in the field of ultracentrifugation technology for uranium enrichment. The MOU covers design and construction of centrifugation facilities and equipment as well as research and development into uranium enrichment by centrifugation as it relates to the fabrication of nuclear fuel.
- In the USA, development has begun on a National Enrichment Facility, to be located in the state New Mexico. The facility will use URENCO's gas centrifuge technology and has a planned capacity of 3million SWU per year.
- No plans were identified for any new enrichment plant employing the gas diffusion approach.

On this basis it is reasonable to suggest that the energy use of the gas centrifuge plant at Gronau, is representative of the likely requirements for new nuclear build. The carbon footprint will of course vary according to the technology mix supplying electricity to the enrichment site. However, in all cases the centrifuge plant will require much less energy than the comparable gas diffusion technology.

²⁰ WNA. Uranium Enrichment June 2003

Table 11. Global enrichment facilities

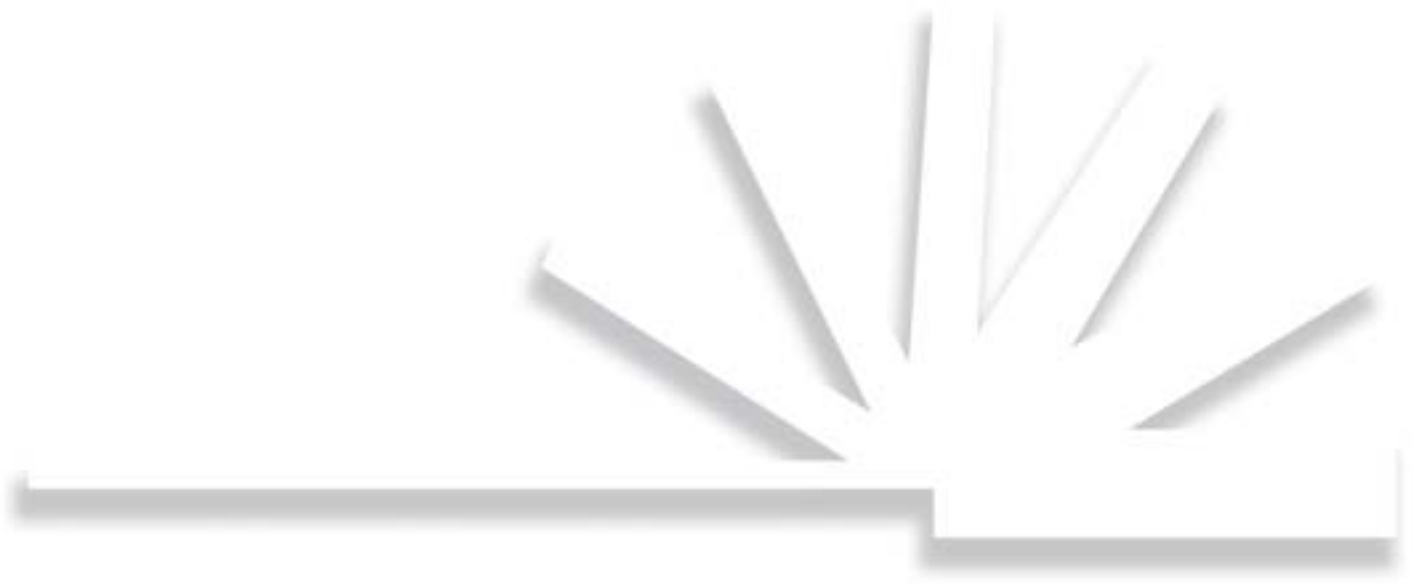
Country	Owner/Controller	Plant Name/ Location	Capacity [1000 SWU]
Gaseous Diffusion Plants			
China	CNNC	Lanzhou	900
France	EURODIF	Tricastin	10,800
	U.S. Corp. Enrichment	Paducah, Kentucky	11,300
		Portsmouth, Ohio (closed May 11,2001)	
<i>Subtotal</i>			<i>23,000</i>
Centrifuge Plants			
		Hanzhong	500
China	CNNC	Lanzhou	500
Germany	Urenco Deutschland GmbH	Gronau	1,462
India	DAE Nuclear Fuel Complex	Rattehalli, Karnataka	4.5
	JNC	Ningyo Toge	200
Japan	Japan Nuclear Fuel Limited (JNFL)	Rokkasho-mura	1,050
Netherlands	Urenco Nederland BV	Almelo	1,950
Pakistan	Pakistan Atomic Energy Commision (PAEC)	Kahuta	5
Russia		Urals Electorchemical Integrated Enterprise (UEIE) Novouralsk (formerly Sverdlovsk-44 near, Ekaterinburg)	7,000
		Siberian Chemical Combine (SKhK) Seversk (formerly Tomsk-7)	4,000
		Electrochemical Plant (ECP) Zelenogorsk (formerly Krasnoyark-45)	3,000
		Angarsk Electrolytic Chemical Combine (AEKhK) Angarsk	1,000
United Kingdom	Urenco (Capenhurst) Ltd	Capenhurst	2,438
<i>Subtotal</i>			<i>23,109</i>
<i>Total</i>			<i>53,510</i>

Source: WISE²¹²¹ <http://www.wise-uranium.org/efac.html#ENR>

Key conclusions

Carbon footprint of the nuclear fuel cycle

- This briefing note describes in detail the calculations used to determine the CO₂ emissions associated with the mining and milling, and enrichment stages of the Torness fuel cycle. It shows the mining and milling emissions to be 1.85gCO₂/kWh and enrichment emissions to be 0.43 gCO₂/kWh. When added to the remaining parts of Torness's fuel cycle, the life cycle emissions are 5.05g/kWh.
- The grade of ore at Olympic Dam has been calculated to be 0.028%, which is a factor of ten lower than the average grade of ore from the world's ten largest mines (0.21%). If this low grade ore were used to provide all of the uranium for a future power station then, based on the analysis for Olympic Dam, the emissions associated with mining and milling would be double that calculated for Torness, about 3.65gCO₂/kWh.
- If the emissions associated with the remaining parts of the fuel cycle for a future nuclear station were the same as assessed for Torness, then the total life cycle emissions for a future station with all its uranium supplied by Olympic Dam would be 6.85gCO₂/kWh.
- These estimates are valid when applied to a new programme of nuclear build. All of the third generation nuclear reactor models currently marketed offer higher burn-up and reduced uranium requirements than the current fleet of nuclear reactors in the UK. On this basis, the carbon footprint of the Torness station represents an upper estimate of the likely impacts from generation of new nuclear plant.
- Compared to the current and probable reserves of uranium, Olympic Dam represents a low grade ore. All things being equal, the carbon footprint of the Olympic Dam facility is therefore likely to represent a high end estimate of the energy use and CO₂ emissions from the mining and milling of uranium associated with generation from new nuclear facilities.
- Gas centrifuge represents a more energy efficient enrichment process than gas diffusion, and all future planned enrichment capacity is based upon this technology. On this basis, the energy use associated with the Gronau plant that was analysed as part of the Torness EPD represents a reasonable basis for assessing the impacts of enrichment for new nuclear generation.



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