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Life cycle energy and greenhouse gas emissions of nuclear energy: A review

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Abstract

The increased urgency of dealing with mitigation of the looming climate change has sparked renewed interest in the nuclear energy option. There exists a substantial stream of research on the amount of embodied energy and greenhouse gas emissions associated with nuclear generated electricity. While conventional fossil fuelled power plants cause emissions almost exclusively from the plant site, the majority of greenhouse gas emissions in the nuclear fuel cycle are caused in processing stages upstream and downstream from the plant. This paper distils the findings from a comprehensive literature review of energy and greenhouse gas emissions in the nuclear fuel cycle and determines some of the causes for the widely varying results.

The most popular reactor types, LWR and HWR, need between 0.1 and 0.3 kWh_{th}, and on average about 0.2 kWh_{th} for every kWh of electricity generated. These energy intensities translate into greenhouse gas intensities for LWR and HWR of between 10 and 130 g CO_2-e/kWh_{el}, with an average of 65 g CO_2-e/kWh_{el}.

While these greenhouse gases are expectedly lower than those of fossil technologies (typically 600–1200 g CO_2-e/kWh_{el}), they are higher than reported figures for wind turbines and hydroelectricity (around 15–25 g CO_2-e/kWh_{el}) and in the order of, or slightly lower than, solar photovoltaic or solar thermal power (around 90 g CO_2-e/kWh_{el}).

Keywords: Nuclear energy; Fuel cycle; Embodied energy; Greenhouse gas emissions; Life cycle assessment

1. Introduction

Despite its heat and electricity generating stages not causing any greenhouse gas emissions, nuclear energy is not a zero emissions energy source. Its extensive system of upstream supply stages requires energy inputs throughout, and given that in practice, a substantial part of these energy inputs are provided by fossil fuelled sources, nuclear energy indirectly involves the emission of greenhouse gases.

With climate change being increasingly viewed as one of the most pressing global problems, nuclear power has found its way back onto policy roundtables and into the media [1]. But, just how much CO_2 nuclear plants will be able to avoid depends, amongst other aspects, on the indirect emissions associated with the nuclear fuel cycle. This topic has been the subject of controversial debates,[1] and as a result, as part of his Uranium Mining, Processing and Nuclear Energy Review (UMPNER), the Australian Prime Minister called for an independent assessment of this question, the results of which were revealed to the public in December 2006.

This paper distils the findings from this, probably, most comprehensive review to date by summarising the energy and greenhouse gas life cycle analyses of the nuclear fuel cycle and by determining some of the causes for the widely varying results of previous studies. The following sections take the reader on a journey through the nuclear fuel cycle, with the goal of stating overall *energy* and *greenhouse gas*

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[1] See the exchanges between Mortimer [2,3] and opponents [4,5], and between Storm van Leeuwen and Smith [6–8] and opponents [9–12].

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intensities, that is, the ratio of the primary energy consumed, or greenhouse gases emitted during all stages of the nuclear fuel cycle, per unit of output of electrical energy over the lifetime of the power plant.[2] A few definitions are necessary upfront:

The *load factor* or *capacity factor* λ of an energy supply system is defined as the equivalent percentage of time over one year during which the system supplies electricity at 100% load, that is, supplies electricity at its nominal power rating P. For example, a 1000 MW power plant running constantly at 800 MW power output has a load factor of 80%. Equally, a 1000 MW power plant running for 292 days a year at 1000 MW has a load factor of 80%.

The energy intensity η of an energy supply system of power rating P and load factor λ, is defined as the ratio of the total (gross) energy requirement E for construction, operation, and decommissioning and the electricity output of the plant over its lifetime T:

$$\eta = \frac{E}{P \times 8760\ \mathrm{h\ y^{-1}} \times \lambda \times T}. \tag{1}$$

In calculating E, it is (a) convention to a exclude the energy from human labour, energy in the ground (minerals), energy in the sun and hydrostatic potential and (b) not to discount future against present energy requirements [13,14]. This review follows these conventions.

Similarly, the greenhouse gas intensity γ of an energy supply system of power rating P and load factor λ, is defined as the ratio of the total greenhouse gas emissions G for construction, operation and decommissioning and the electricity output of the plant over its lifetime T:

$$\gamma = \frac{G}{P \times 8760\ \mathrm{h\ y^{-1}} \times \lambda \times T}. \tag{2}$$

It is obvious that an increase in the assumed lifetime and load factor of an energy supply system causes a decrease of its energy and greenhouse gas intensities because the lifetime electrical output increases. This influence can be eliminated by normalising the modelled energy and greenhouse gas intensities to a constant load factor of L and a constant lifetime of Y years according to

$$\begin{aligned} \eta_{\mathrm{norm}} &= \eta \frac{\lambda}{L}\frac{T}{Y} = \frac{E}{P \times 8760\ \mathrm{h\ y^{-1}} \times L \times Y}, \\ \gamma_{\mathrm{norm}} &= \gamma \frac{\lambda}{L}\frac{T}{Y} = \frac{G}{P \times 8760\ \mathrm{h\ y^{-1}} \times L \times Y}. \end{aligned} \tag{3}$$

The inverse of the energy intensity is often called the *energy ratio* R. Calling $E_{\mathrm{out}} = P \times 8760\ \mathrm{h\ y^{-1}} \times \lambda \times T$ the lifetime electricity output of a system, the energy ratio is

$$R = \frac{E_{\mathrm{out}}}{E}. \tag{4}$$

This ratio describes the amount of electricity delivered per unit of fossil energy expended on it throughout the economy [13, Eq. 6.7]. In computing the total energy requirement E, all its constituents must be of the same energy quality (the "valuation problem", see Refs. [14–16], especially Ref. [17, p. 5–9] for the case of nuclear energy).

Energy intensity η and energy ratio R are related to the *energy payback time*. This is the time t that it takes the energy supply system to generate an amount of electricity $\frac{tE_{\mathrm{out}}}{T}$ that, had it been generated conventionally, for example fossil fuelled, would have had a primary energy embodiment $\frac{1}{R_{\mathrm{fossil}}}\frac{tE_{\mathrm{out}}}{T}$ equal to the system's energy requirement E.

$$t_{\mathrm{payback}} = \eta_1 \times T \times R_{\mathrm{fossil}} = \frac{R_{\mathrm{fossil}}}{R} T. \tag{5}$$

The energy payback time can be normalised just as the energy intensity. Note that the definition of an energy payback time implicitly assumes an initial energy sink associated with the construction of the energy supply system, followed by a continuous net energy source. This definition is less useful for technologies that are characterised with large energy sinks during stages towards the end of their lifetime [14]. Nuclear facilities, for example, require lengthy periods for dismantling and clean up.

2. Literature review

2.1. Uranium mining

One tonne of rock and soil contains on average 1–5 g of uranium, and 3–20 g of thorium. Concentrations in sediments can reach magnitudes of about 1 kg of uranium per tonne. One tonne of sea water contains about 3 mg of uranium. Amongst the two uranium isotopes, only $^{235}_{92}\mathrm{U}$ is fissile. Since the half life of $^{235}_{92}\mathrm{U}$ is about 1 billion years, which is smaller than that of $^{238}_{92}\mathrm{U}$ at 4.5 billion years, the concentration of $^{235}_{92}\mathrm{U}$ in natural uranium has decreased steadily. While, at the time of the consolidation of the earth, the concentration of $^{235}_{92}\mathrm{U}$ in natural uranium was about 30%, it is only 0.7% today. Of the naturally occurring isotopes, only $^{235}_{92}\mathrm{U}$ has a large enough cross section for fission, and this only applies to thermal neutrons. Nevertheless, $^{238}_{92}\mathrm{U}$ and $^{232}_{90}\mathrm{Th}$ are of interest because they can be used for breeding $^{239}_{94}\mathrm{Pu}$, $^{241}_{94}\mathrm{Pu}$ and $^{233}_{92}\mathrm{U}$, which, in turn, are fissile [18].

Amongst the naturally occurring fissile isotopes, only uranium is mined for nuclear fuel purposes. Uranium is extracted from ores using either open pit (30%), or underground excavation (38%), or *in situ* leaching (21%), or as a by product in other mining (11%) [19,20]. Amongst these techniques, open pit excavation involves the largest quantities of materials to be removed and in situ leaching the smallest [21]. In situ leaching avoids having to mill the uranium ore. Techniques to extract uranium from sea water are under investigation [22].

[2] Throughout this review, two energy units will be used: J (Joules) and Wh (Watt-hours; 1 Wh = 3600 J). These units refer to thermal energy, unless specifically marked with a subscript 'el'. $\mathrm{J_{th}}$, $\mathrm{J_{el}}$, $\mathrm{Wh_{th}}$ and $\mathrm{Wh_{el}}$ will be used interchangeably, especially where one form of energy dominates. For the use of energy ratios, $\mathrm{Wh_{th}/Wh_{el}}$ will be used, either as GWh, MWh or kWh. Older units such as kcal and BTU were converted.

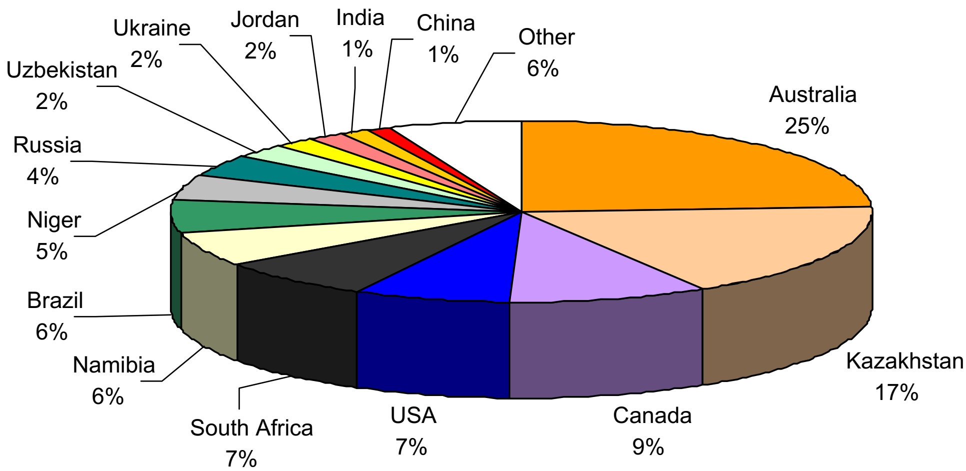

Fig. 1. Country shares of world uranium reserves [23].

Amongst about 4.7 million tonnes of known uranium reserves, Australia has the world's largest share (Fig. 1), as well as some of the world's largest uranium mines. However, Canada is today's largest exporter of uranium. Uranium consumption has been exceeding production since about 1985, which has been due to abundant stockpiles of fissile material keeping uranium prices at a low level (Figs. 2 and 3).

Excluding inferred resources, Australia has about just over 1 million tonnes of recoverable reserves of uranium [20,23,25]. Ore grades (% U_3O_8) vary significantly, but the average of ore grade is 0.045% [25] (Fig. 4).

For comparison, the situation in Canadian mines is markedly different: ore grades are more than an order of magnitude higher (the average grade is about 8%), but the overall amount of uranium is lower than that in Australia (Fig. 5).

When calculating the energy requirement and recovery rate for uranium mining, it is important to consider whether any other products are mined simultaneously. This is because the energy requirement must be apportioned (for example by mass) to both primary products and by products.[3] For example, in Australia's Olympic Dam mine, uranium is extracted as a by product of copper [27–29].

Detailed data on the energy requirements of uranium mining are available from an input output based hybrid life cycle assessment for the USA [17] (Table 1). They broadly agree with the Storm van Leeuwen and Smith [30] summary of 39 studies undertaken between 1968 and 2005, averaging 1.12 GJ *per tonne of ore* (× in Fig. 6).

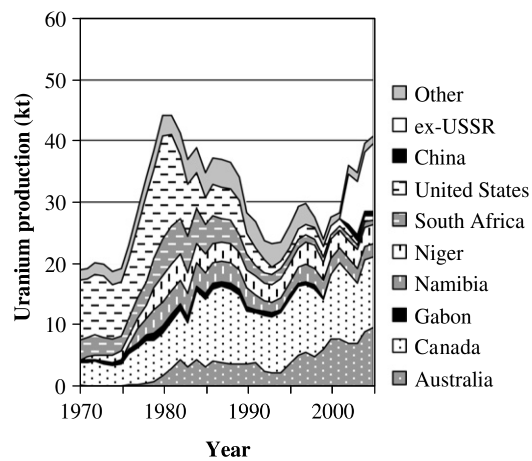

Fig. 2. World production of uranium (after [24]).

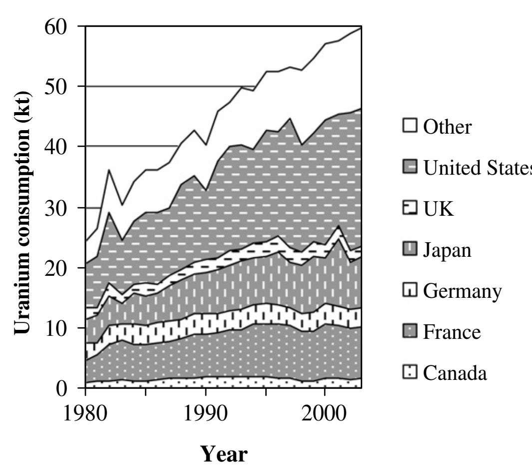

Fig. 3. World consumption of uranium (after [24]).

[3] BHP Billiton [27] states that "*It is correct to say, for Olympic Dam, that copper, gold, uranium and silver are extracted from one and the same rock body in a simultaneous operation. In the case of the Olympic Dam orebody, we can apportion the energy cost for mining the orebody amongst the four metals based on their relative mass contribution. Once the orebody reaches the surface, energy costs can also be apportioned for grinding. Once the ore then enters the processing circuit the calculation then becomes very process specific – i.e., at Olympic Dam a lot of the copper goes through flotation, smelting and refining, whereas uranium goes through none of these processes, so the flowsheet needs to be well understood in order to make a complex calculation.*"

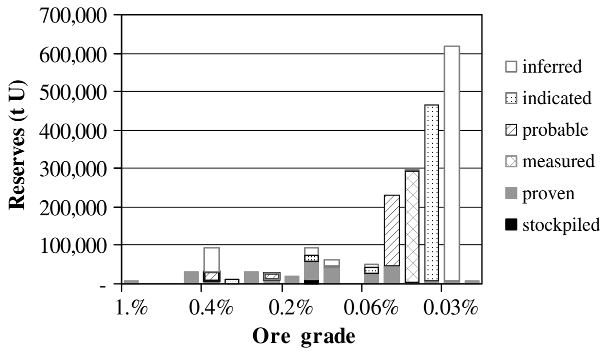

Fig. 4. Australian uranium reserves and resources [25,26].

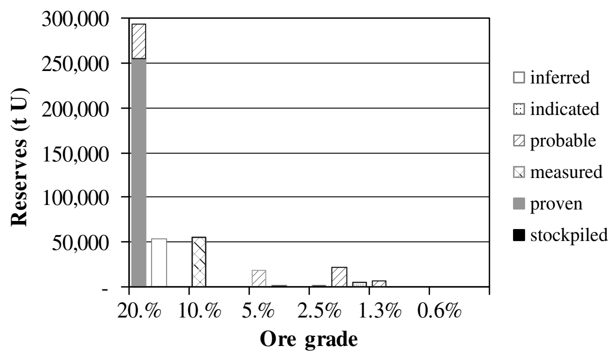

Fig. 5. Canadian uranium reserves and resources [20].

Table 1
Specific energy requirements for uranium mining [17,31]

Reference	Rock	GJ/t ore	GJ/t U @0.3%	GJ/t U @0.2%	GJ/t U @0.1%	GJ/t U @0.01%
Direct energy						
[17]	Ore	0.61	292	439	877	8774
[17]	Shale	0.10	47	70	141	1410
Indirect energy						
[17]	Ore	0.76	362	542	1085	10,847
[17]	Shale	0.30	143	214	428	4282
Total energy						
[31]	Ore	1.21	403	605	1210	12,100
[17]	Ore	1.37	654	981	1962	19,621
[17]	Shale	0.40	190	285	569	5692

The energy intensity *per unit of metal product* (Fig. 6), as well as the recoverable portion of uranium (Fig. 7) is dependent on the grade of the ore, that is, the concentration of the metal in the ore.

Fuel combustion during mining leads to greenhouse gas emissions, however, unlike in coal mines, direct methane emissions from uranium mines are found to be negligible [38].

2.2. Uranium milling

Following extraction from the ground, the raw ore is milled (crushed and ground), and uranium is chemically extracted by dissolving (using acid or alkaline solutions) and subsequent precipitation. Uranium milling is usually performed close to the mine site in order to avoid having to transport large amounts of ore. The output of a uranium mill is dry uranium ore concentrate ("yellowcake"), usually packed in steel drums, containing above 80% uranium [39].

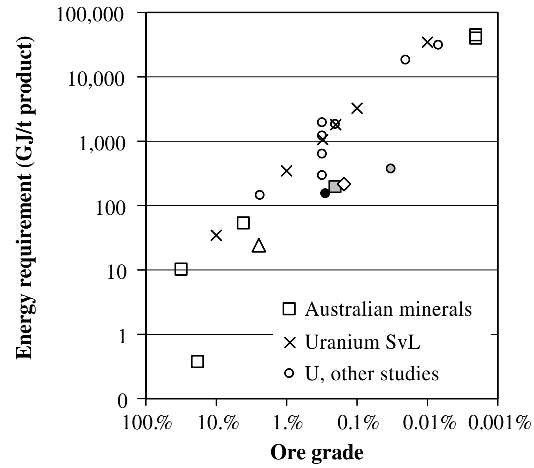

Fig. 6. Energy intensities for metal ore mining and milling (compiled from data in [9,24,28,31–37]). Australian minerals are uranium, iron ore, mineral sands, silver–lead–zinc ores, and gold. The outliers are the Rössing mine in Namibia (◯), the Ranger mine in the Northern Territory (□), and the Beverley mine in South Australia (◇). The triangle (△) represents Olympic Dam. In-situ leaching is shown to require less energy than conventional mining (●, [37]).

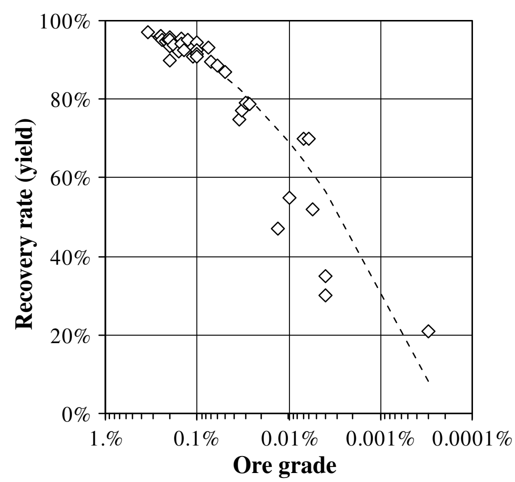

Fig. 7. Uranium recovery rate as a function of ore grade (% U_3O_8). The dashed line represents Storm van Leeuwen and Smith's regression [30]. The lower the ore grade, the less uranium is recoverable from the reserves.

Once again, detailed data on the energy requirements of uranium milling are available from an input output based hybrid life cycle assessment for the USA [17] (Table 2). Storm van Leeuwen and Smith [30] summarised studies undertaken between 1968 and 2005, averaging 1.66 GJ per tonne of ore.

2.3. Conversion to uranium hexafluoride (UF_6)

After milling or in situ leaching, the uranium is converted into gaseous UF_6 in order to enable enrichment, that is, the separation of the fissile ${}^{235}_{92}$U from the practically non-fissile

Table 2
Specific energy requirements for uranium milling [17,31]

Reference	Rock	GJ/t ore	GJ/t U @0.3%	GJ/t U @0.2%	GJ/t U @0.1%	GJ/t U @0.01%
Direct energy						
[17]	Ore	0.82	390	585	1169	11,695
[17]	Shale	0.69	327	491	981	9811
Indirect energy						
[17]	Ore	0.53	250	375	751	7509
[17]	Shale	0.39	186	279	559	5589
Total energy						
[31]	Ore	1.13	375	563	1125	11,250
[17]	Ore	1.34	640	960	1920	19,204
[17]	Shale	1.08	513	770	1540	15,400

${}^{238}_{92}U$. The conversion occurs by first purifying and reducing U_3O_8 to uranium dioxide UO_2 [40], which is then reacted with hydrogen fluoride (HF) to form uranium tetrafluoride (UF_4), which, in turn, is combined with gaseous fluorine to UF_6 in a fluidised bed reactor. The reaction of UO_2 with HF can occur either in a dry kiln, or by a wet process using aqueous HF [41]. The wet process uses significantly less energy [37]. The conversion into gaseous UF_6 is necessary no matter what enrichment method is employed.

Weis [37] states energy requirements for the wet process of only 7 MWh_{th}/tU. The Australian Coal Association's figures are 21 MWh_{el}/tU and 155 MWh_{th}/tU [42]. Rotty and co-workers state requirements of 14.6 MWh_{el} and 396 MWh_{th} [17, p. 63–64], with most of the energy needed in the form of natural gas. Their figure is also the highest in Storm van Leeuwen and Smith's literature review [30].

2.4. Enrichment

At its natural concentration of 0.7%, ${}^{235}_{92}U$ can be used as a reactor fuel only in particular reactor types (heavy water reactors (HWR) and high temperature reactors (HTR)). In order to be able to maintain a nuclear chain reaction in typical light water reactors, the concentration of ${}^{235}_{92}U$ in the uranium isotope mix has to be increased to about 3%. At present, there exist a range of enrichment methods using UF_6 as feed. Since uranium isotopes do not differ in their chemical behaviour, enrichment techniques exploit their mass difference as a means for separating them [43]. These methods are:

- Gaseous diffusion: The heavier ${}^{238}_{92}U$ isotope diffuses more slowly than the lighter ${}^{235}_{92}U$: $v_{\mathrm{diff}}({}^{235}_{92}UF_6)/v_{\mathrm{diff}}({}^{238}_{92}UF_6) = \sqrt{m({}^{238}_{92}UF_6)/m({}^{235}_{92}UF_6)}$, v diffusion velocity, m mass. Enrichment from 0.7% to 3% ${}^{235}_{92}U$ requires in the order of 1000 consecutive separation cascades. In 2002, 40% of all enrichment plants used gaseous diffusion (mostly France and USA). This percentage is decreasing in favour of the centrifuge method.
- Gas centrifuge: The partial pressure of two gases (contained as a gas mixture in a rotating cylinder) depends on their masses. Centrifugal forces cause a radial concentration gradient, with the heavier isotope concentrated outside and the lighter isotope concentrated inside. Enrichment from 0.7% to 3% ${}^{235}_{92}U$requires on the order of 10 consecutive separation cascades. In 2002, 60% of all enrichment plants used the centrifuge method (mostly Russia, Germany, UK, Netherlands, China and Japan).
- Electromagnetic isotope separation (EMIS): Uses the magnetic separation principle of a mass spectrometer, albeit at a larger scale. Used for building the Hiroshima bomb and in Iraq's nuclear program but now outdated.
- Aerodynamic (jet nozzle) method: Exploits the same physical principle as the gas centrifuge but creates a rotating gas mixture by injection into a circular jet. Demonstration plants built in Brazil and South Africa.
- Laser: The energy spectra and, therefore, the ionisation energies of different isotopes depend on their masses. Using mono-energetic laser beams, one isotope can be preferentially ionised, and filtered out using an electrostatic field.

At the end of this stage, the enriched UF_6 is converted into uranium oxide (UO_2).

The energy needed for enrichment is partly dependent on the incremental enrichment factor for one cascade, which, in turn, determines the number of cascades necessary to achieve enrichment to around 3%. Gaseous diffusion needs more cascades than the gas centrifuges and, additionally, requires the energy intensive compression of UF_6 at the entry point of each cascade (Table 3). Gas centrifuges only require electrical energy for rotation of the cylinders and some heat in order to maintain an axial convection of the UF_6. Atomic laser techniques require the normally metallic uranium to be evaporated (using considerable heat energy) and then transferred into a vacuum, so that the ions can be electrostatically filtered [43]. The laser technique is based on molecular rather than atomic laser separation. Instead of having to maintain uranium atoms in a hot gas, this technique uses the already gaseous UF_6, and preferentially excites UF_6 molecules.

Villani [49] summarises five enrichment technologies, distinguishing investment cost in the plants, operation (excluding electricity) and electricity inputs. Multiplied with the energy intensities given for the US [50] yields the results in Table 4.

The two tables above require an explanation of the unit SWU. Amounts of enriched uranium are usually expressed as *Separative Work Units* (for example tonne SWU).[4] There is a trade off between the amount of natural uranium feed and the number of SWUs needed to produce enriched uranium. For example: in order to produce 10 kg of

[4] A Separative Work Unit is defined as $SWU = P\ V(x_p) + TV(x_t) - FV(x_f)$, where the value function is $V(x)=(1-2x)\ln[(1-x)/x]$, P, T and $F = P + T$ are the masses, and x_p, x_t and $x_f = P/Fx_t + T/Fx_f$ are the assays (concentrations) of product, tails and feed, respectively [17, p. 65–6].

Table 3
Energy requirements for uranium enrichment (A: Aerodynamic method; C: Gas centrifuge; D: Gaseous diffusion; E: EMIS; L: laser)

Reference	Year	Type	kWh_{el}/kg SWU	Comments
[44]	1997	C	170	Converted using 3.5 SWU per kg 3%-U
[41]	2006	C	50	
[41]	2006	C	62.3	Urenco plant in the UK, figures includes "infrastructure and capital works"
[34]	1978	C	250	
[34]	1978	C	282	Including investment in the plant
[45]	1996	C	75	
[46]	2004	C	40	Urenco plants in Europe, TENEX plants in Russia
[44]	1997	D	2860	Converted using 3.5 SWU per kg 3%-U
cit. in [47]	1975	D	2330–2737	
cit. in [37]	1990	D	2100–3100	
[41]	2006	D	2500	
[31]	1975	D	2420	
[31]	1975	D	≈2520	Including capital
[17]	1975	D	2810	
[17]	1975	D	3050	Including plant construction, fossil fuels and process materials
[34]	1978	D	3080	
[45]	1996	D	2400	
[46]	2004	D	2400	Eurodif plant at Tricastin, France
[46]	2004	D	2600	USEC Paducah (USA)
[44]	1997	L	700	
[41]	2006	E	≈25,000	
[48]	1983	A	3000–3500	
[41]	2006	A	>3000	
[34]	1978	A	3080	

uranium at 4.5% ${}^{235}_{92}U$ concentration while allowing a tails assay of 0.3% requires 100 kg of natural uranium and 62 SWU. Asking for the tails to have only 0.2% assay limits the amount of natural uranium needed to 83 kg, but it also increases the separative work to 76 SWU. Hence, the optimal (tails assay) compromise between uranium feed and separative work depends on the price of natural uranium versus the cost of enrichment operating inputs. During times of cheap uranium, an enrichment plant operator will probably choose to allow a higher ${}^{235}_{92}U$tails assay and vice versa. In terms of the energy balance of the nuclear fuel cycle, this means that lower tails assays mean less energy is spent on mining, milling and conversion and more on enrichment and vice versa [17, p. 26–36 and 43].

2.5. Fuel fabrication

In the reactor, the fuel is contained within about 4 m long, hermetically welded tubes ("fuel rods"), about 100 of which at a time are combined into fuel bundles. The manufacture of fuel rods involves sintering and baking the enriched uranium oxide and pressing it into coin shaped ceramic pellets, which are stacked on top of each other and encased in the rods. The metal rods are made from zirconium alloys because these are characterised by low neutron absorption.

Some fuel rods contain a mixture of uranium oxide and plutonium oxide pellets with the plutonium recovered and re-processed from spent ${}^{235}_{92}U$ depleted fuel bundles. An assembly of such fuel rods is called a "mixed oxide" (MOX) fuel bundle [51]. In high temperature reactors (HTR), the uranium fuel exists in the form of small spheres encased in layers of pyrolytic carbon and silica carbide. These fuel particles are then embedded in graphite fuel bundles [44].

Storm van Leeuwen and Smith [30] list eleven studies on the energy requirements of fuel fabrication (Table 5). The Australian Coal Association [42] states 52.7 MWh_{el} and 32.7 MWh_{th}. The figure used in the World Nuclear Association report [9] is one of the highest in Storm van Leeuwen and Smith's list.

2.6. Reactor construction

In order to maintain a controlled nuclear chain reaction inside a reactor, it is necessary that of the 2–3 (fast) neutrons emitted from each fission event, on average of 1 (slow) neutron causes a new fission event. This requires fissile reactor fuel of sufficient concentration, a neutron moderator material to generate slow neutrons (water, heavy water, graphite, beryllium) and the near absence of neutron absorbing non-fissile materials, except for control rods (boron, cadmium).

Most commercial nuclear reactor types use enriched uranium as fuel, however, there are types that can use ${}^{235}_{92}U$at its natural concentration. The fission of uranium or plutonium results in a range of particles that are emitted into the reactor core at high velocities. These particles undergo multiple collisions with both fuel and moderator atoms, during which they lose their kinetic energy and slow down.[5] This energy loss manifests itself in heat, thus raising the temperature of the reactor core. In order to keep this temperature below the melting point of the core materials while at the same time transferring the heat (via a heat exchanger) to the electricity generating unit (steam turbine), a coolant has to be circulated through the core. In light and heavy water reactors (LWR, HWR), coolant and moderator are identical (water, H_2O, and heavy water, D_2O).[6] CO_2 and helium usually act as coolants in graphite moderated reactors. Thus, nuclear reactors are character-

[5] About 82% of the total kinetic energy of fission products is carried by the two nuclei resulting from the fission of the uranium or plutonium nucleus. Another 6% is carried by gamma particles, 5% by anti-neutrinos, and 3% each by electrons and neutrons. Except for the anti-neutrinos – which escape – most fission products (except those near the reactor wall) deposit their energy in the core.

[6] This feature brings about an intrinsic capacity for self-regulation: If the core temperature increases, the water density decreases, and with it decreases the ability to moderate, thus increasing neutron loss, and decreasing criticality.

Table 4
Energy requirements for uranium enrichment [49]

	Operation excl electricity (\$/SWU)	Construction (\$/SWU)	Electricity (kWh_{el}/SWU)	Energy in construction (kWh_{th}/SWU)	Energy in operation (kWh_{th}/SWU)	Total energy requirement (kWh_{el}/SWU)
Diffusion	7.5	52.5	2400	151.7	21.7	2458
Centrifuge	6.5	84.0	100	242.7	18.8	187
Jet nozzle	6.5	73.5	3000	212.4	18.8	3077
Laser	6.25	13.1	100	37.9	18.1	119
Chemical extraction	12.5	68.3	300	197.2	36.1	378

Table 5
Energy requirements for fuel fabrication

	Electrical energy (MWh_{el}/tU)	Thermal energy (GJ_{th}/tU)	Total energy requirement (GJ_{th}/tU)
Range	48–301	3–6170	635–7985
Average	145 ± 106	1403 ± 1966	2970 ± 2835

Figures were reconstructed from Ref. [30] by calculating the electrical energy e as $e = S/(1 + x)$, where x is the thermal to electrical energy ratio, and S is the specific energy given in Ref. [30], the thermal energy as $t = S - e$, and then, the total energy requirement as $T = 3e + t$.

ised by (a) their fuel, (b) their moderator and (c) their coolant [52]. Table 6 lists the most common types.

Apart from using up fuel, every reactor also creates fuel, through breeding $^{238}_{92}U$ and $^{232}_{90}Th$ into $^{239}_{94}Pu$, $^{241}_{94}Pu$ and $^{233}_{92}U$, which, in turn, are fissile. The conversion rate χ describes how many new fissile nuclei are bred for each fission event of the initial fissile fuel. Fast breeders have a conversion rate $\chi > 1$, meaning that they generate more fuel than they consume. Combined with the re-processing rate of spent fuel, the conversion rate of reactors has a significant influence on the energy balance of nuclear energy systems.[7]

Estimates of the energy requirement for the construction of a nuclear power plant vary widely, depending on the method employed for its calculation, and the type of reactor (Table 7).

First, it is interesting to see that employing the method of multiplying total cost with the national average energy intensity (AEI) yields an unusually high energy requirement. Second, advanced gas cooled reactors, heavy water reactors and fast breeders generally require more energy to build than high temperature gas cooled reactors and pressurised and boiling water reactors. This can be explained by the more complex design and additional components of the former reactor types, which involve, for example, the manufacturing of heavy water [64].

Multiplying the costs of the entire reactor with an economy wide average energy or greenhouse gas intensity ([32, p. 259]; [30, Chapter 3]) is not an appropriate method to assess the energy and greenhouse gas embodiments of a nuclear power plant because these intensities, calculated by dividing national energy consumption and greenhouse gas emissions by GDP, can only be applied to expenditures that are part of gross national expenditure (GNE). The costs of building a nuclear power plant are not part of GNE; they form part of intermediate demand [65]. Moreover, both plant construction and dismantling routinely involve large amounts of cost associated with leasing of land, court cases, approval procedures, licensing, delays, fees, taxes, insurance, interest and remote controlled dismantling [34,66–68], which, in a more detailed hybrid input output technique are not given high energy and greenhouse gas intensities. As a result, whereas Storm van Leeuwen and Smith (AEI) arrive at values around 25,000 GWh, Wagner ([34], hybrid I/O) concludes with 2160 GWh_{th} for a 1000 MW light water reactor.

2.7. Reactor operation

As with reactor construction, estimates of the energy requirement for the operation of a nuclear power plant vary widely (Table 8). Based on published information alone, it is difficult to establish conclusively any clear determinants for these figures.

For the operation of a LWR and a HWR, Rotty et al. [17] detail inputs of diesel, chemicals, hardware and maintenance of 8.5 GWh_{el} of electricity and 80 GWh_{th} of thermal energy annually. In addition, HWR reactors require on the order of 7 GWh_{el} of electricity and 40 GWh_{th} of thermal energy annually for their heavy water moderator ([17, p. 85], [64]). This input list probably omits a substantial amount of overhead costs, repair and replacement of components and changes to plants due to regulatory measures. Two studies apply average energy intensities to the entire financial operating budget of the nuclear power plant [30,69]. However, a closer examination of total operating data in Ref. [69] yields that about 40% of these costs are wages and pensions, a further 30% are insurance and administration and 15% each are technical services and materials. Excluding wages and pensions, average operating, maintenance and capital expenditures are about 120

[7] The conversion rate χ is related to the *burn-up* β through $\chi = \beta \times 24\ \mathrm{h/d}/(\rho_{iso}\eta_{235U}f) - 1$, where ρ_{iso} is the energy content of ^{235}U (24,500 $GWh_{th}/t^{235}U$), η_{235U} is the enrichment (%), and f is the fraction of ^{235}U burnt at re-loading (around $^2/_3$).

Table 6
Common reactor types and their characteristics [44,48]

Reactor type	Fuel (concentration)	Moderator	Coolant	Operating temperature (°C)	Conversion rate	Comments
Pressurised water (PWR)	UO_2 (3%)	H_2O	H_2O	320	0.55	Separate coolant and steam cycles; often used on military ships
Boiling water (BWR)	UO_2 (3%)	H_2O	H_2O	290	0.6	Identical coolant and steam cycles
Heavy water (HWR)	UO_2 (0.7%)	D_2O	D_2O	310	0.8	Needs high amount of moderator material. CANDU type, Canada
Gas-cooled graphite (GGR)	U (0.7%)	Graphite	CO_2	410	0.8	
Advanced gas-cooled graphite (AGR)	UO_2 (2.6%)	Graphite	CO_2	650	0.6	Magnox type, UK
High-temperature (HTR)	UO_2/ThO_2 (93%)	Graphite	Helium	>750	0.7	Can generate high-temperature process heat. Used to burn off stocks of weapon-grade fuel
Fast breeder (FBR)	UO_2/PuO_2 (18%)	–	Sodium (Na)	550	1.2	
Water–graphite (WGR)	UO_2 (1.8%)	Graphite	H_2O	280	0.6	RBMK type, Černobyl
Heat reactor (HR)	UO_2 (1.8–3%)	H_2O	H_2O	210	0.6	For district heating and water desalination. Large volume of coolant provides inherent safety

Table 7
Energy requirements for the construction of a 1000 MW nuclear power plant

	Energy requirement (GWh_{th}/GW_{el})			Number of studies		
	PA	I/O	AEI	PA	I/O	AEI
LWR		2412			2	
BWR		3613			2	
PWR	1177	3523	17,198	1	9	4
HTGR		3307			2	
HTR		3518			2	
FBR		5238			2	
HWR		5997			6	
AGR		6202			2	

AEI = Method of multiplying total cost with the national average energy intensity, I/O = Input output based hybrid analysis, PA = process analysis. After Refs. [17,30,31,34,42,47,48,53–62]. Further details in Ref. [63].

Table 8
Energy requirements (GWh_{th}/year) for the operation of a 1000 MW nuclear power plant [63]

	Energy requirement ($GWh_{th}/GW_{el}/y$)
Range	38–889
Average	255 ± 227

1990 US\$/kW_{el}/y [69], which agrees with a figure of 100 M\$/GW_{el}/y quoted by Storm van Leeuwen and Smith [30]. Converting the cost breakdown in Ref. [69] with energy intensities between 10 and 50 MJ/\$ yields an energy requirement of about 300 GWh_{th}/y for a 1000 MW reactor, which is close to the average in Table 8.

2.8. Decommissioning

At the end of its life, a typical nuclear reactor poses the task of disposing of about 10,000 tonnes of medium to high level radioactive waste, some 10,000 tonnes of low to medium level radioactive waste and some 100,000 tonnes of non-active materials [44,70]. Radioactive materials have to be disposed of just as tailings, tails, spent fuel and fission products, depending on their radioactivity levels. Most of the radioactivity (99%, [71]) is contained in the high level waste. Table 9 gives a comparative overview of radioactivity levels.

Heinloth [44] gives crude estimates for the cost of dismantling a nuclear reactor as typically in the order of 1/4 of the cost for its construction. A more detailed assessment is Komorowski and Meuresch's [72] account of cost for the decommissioning of reactors (both research and commercial types), waste repositories and re-processing plants. These authors state the example of the German Niederaichbach plant as the first completely disassembled nuclear reactor in Europe [67,73,74]. They note, however, that their cost figures may not be representative because the highly

Table 9
Comparative overview of radioactivity levels [44]

	Radioactivity (Bq/m^3)
Fuel during reactor operation	5×10^{17}
High-level waste	$>3.7 \times 10^{14}$ ($>10^4$ Ci/m^3)
Medium-level waste	$3.7–37 \times 10^{13}$ ($10^3–10^4$ Ci/m^3)
Plutonium	5×10^{13}
Low-level waste	$<3.7 \times 10^{13}$ ($<10^3$ Ci/m^3)
Uranium (natural)	5×10^8
People (natural)	10^5
Granite (natural)	10^5
Water (natural)	$10^2–10^4$
Air (natural)	$10–10^2$

Radioactivity is defined by the number of decay events per unit of time. Its measures are the Becquerel (Bq; 1 Bq = 1 decay per second) and the Curie (Ci; 1 Ci = 3.7×10^{10} Bq).

Table 10
Decommissioning cost for German nuclear installations (10^6 DM, after [72])

Plant	Construction cost (inflated)	Planned decommissioning cost	Idling cost since ceasing operation	Total decommissioning cost
Commercial HTR Hamm-Uentrop THTR-300	6997	642		642 (9%)
Commercial FBR Kalkar SNR-300	10,033	239	26	265 (3%)
Small reactor Niederaichbach	444	279	147	426 (96%)
Small reactor Karlstein	229	98	101	199 (87%)
Experimental reactor Karlsruhe	1019	529	86	615 (60%)
Multi-purpose reactor Karlsruhe	404	439	86	525 (130%)
Research reactor Karlsruhe	174	245	63	308 (177%)
Experimental reactor Jülich	219	358	147	505 (231%)
Re-processing plant Karlsruhe	458	3354	272	3626 (792%)
Repository shaft Asse	380	234	18	252 (66%)

variable durations and delays of the legal procedures preceding the decommissioning incurred variable idling costs (see also [74]), and the decommissioning of German nuclear installations in the 1990s generally occurred not because their end of life was reached but because of a change in the political consensus at the time.

The German data are highly variable but give an indication that large commercial reactors attract lower decommissioning cost (about 10% of construction cost) than small, experimental reactors (around 100%, compare also Ref. [75, p. 16–7]). The International Atomic Energy Association estimates decommissioning cost of commercial facilities to be in the order of 250–500 million US$ [68,75]. Even though the decommissioning of a single enrichment or conversion plant may cost more than that of a power plant, the latter dominate decommissioning cost for the whole fuel cycle [75, p. 24]. In their energy analysis, the World Nuclear Association [9] provides five figures for decommissioning of existing nuclear power plants, ranging between 4.3 PJ and 6.2 PJ.[8] Assuming energy requirements of 4100 GWhth $\approx$ 15 PJ, decommissioning represents about 35% of construction (see Table 10).

In contrast with these estimates, Storm van Leeuwen and Smith [30,32] argue for safeguarding periods ranging from decades to a century before the actual dismantling of the reactor. For the decommissioning stage, these authors distinguish two options. In the "environmentally responsible" option, which includes safeguarding, clean up, demolition, dismantling, packaging and permanent disposal, costs of 200% of the construction costs are incurred. In the "*après nous le déluge*" option, the plant is safeguarded but not disposed of at all, incurring 100% of construction costs. These costs are multiplied, as with construction and operation, with the national average energy intensity. The critique about the AEI method stated in Section 2.6 applies to this stage as well.

[8] Bruce A 5.2 PJ, Bruce B 4.3 PJ, Darlington 4.5 PJ, Pickering A 5.7 PJ, Pickering B 6.2 PJ [9].

2.9. Fuel re-processing

In typical light water reactors, fuel bundles are removed from operation once the concentration of neutron absorbing fission products is high enough to affect adversely the reactor's criticality. At this point, the concentration of $^{235}_{92}U$ has decreased to below 1%. Typically, a 1000 MW nuclear power plant produces about 25–30 tonnes of spent fuel per year [44], which can be either disposed of as waste, or re-processed. If re-processed, the spent fuel bundles are cut, and the fuel is dissolved and separated into its constituents, which are 95% $^{238}_{92}U$, 1% $^{235}_{92}U$, about 1–2% plutonium isotopes, 2–3% radioactive fission products (^{85}Kr, ^{129}I, $^{3}_{1}H$, etc.) and less than 0.1% trans-uranic elements. Uranium and plutonium are precipitated from the solution and fabricated into new fuel assemblies [44,48]. The separation of isotopes during re-processing is performed using the centrifuge method (see Section 2.4). Starting from spent fuel, $^{235}_{92}U$ has to be enriched to a higher degree, compared with conventional enrichment of natural uranium, because of the presence of $^{236}_{92}U$ impurities that act as a neutron absorber.

Re-processing reduces both the requirement for natural uranium and the volume of waste to be disposed. Rotty et al. [17] report values of about 30 GWh_{el} of electricity and 150 GWh_{th} of thermal energy annually for a 1000 MW light water reactor.

2.10. Nuclear waste storage

Spent fuel emits radiation principally from fission fragments (for example, krypton ^{85}Kr, iodine ^{129}I, and tritium $^{3}_{1}H$). This spent fuel is transferred into storage ponds and either re-processed or prepared for permanent disposal. Waste from spent fuels and re-processing is classified as high level radioactive (>10^4Ci m^{-3}). However, most of the fission fragments are short lived, so that before transferring this type of waste to central disposal facilities, they are, except for ^{85}Kr, encased in either glass (vitrified), concrete and/or metal and kept in ponds in the vicinity of the reactor for a time sufficient to allow their concentration (and radioactivity) to subside to less than 1% of its original magnitude [48,76].

Rotty et al. [17] state that most of the energy requirement in this stage is for process materials such as concrete for encasing and steel for storage canisters. However, the scope of their life cycle assessment and, in particular, whether it includes construction of the final repositories is unclear. They report values of about 167 MWh_{el} of electricity and 1800 MWh_{th} of thermal energy annually for storing the waste from a 1000 MW light water reactor. In Rotty's analysis, most of this energy is expended for ongoing operation rather than for construction of the disposal facilities.

Corresponding figures by the Australian Coal Association [42] are substantially higher at 1997 MWh_{el} of electricity and 14,733 MWh_{th} of thermal energy. This study only deals with the storage of high level active spent fuel, yielding specific energy requirements of about 80 MWh_{el}/t fuel and 600 MWh_{th}/t fuel. White and Kulcinski's [53] figure is comparable at 172 TJ_{th} per GWy and, if applied only to operational waste at the power plant, corresponds to about 400 MWh_{th} per tonne of radioactive material. The Australian Coal Association states storage to represent about 4% of a diffusion enriched nuclear cycle [42]. White and Kulcinski's figure is about 9% for a centrifuge enriched cycle [53].

By far the highest of all reported energy requirements for waste storage are calculated from cost data (151–1340 2000$/kg heavy metals) by Storm van Leeuwen and Smith [30]. Multiplying by the national average energy intensity yields 440 MWh_{el}/t fuel and 2200 MWh_{th}/t fuel. The critique about the AEI method stated in Section 2.6 applies here as well.

2.11. Nuclear waste disposal

In addition to decommissioning the plant, there are a number of stages in the nuclear fuel cycle that produce radioactive waste [40,75,77]. The first one is the mining and milling stage, where the remainder of the ore after extraction of uranium (the "tailings") have to be kept away from the environment. This is often done in specially engineered mined out pits [39,78,79]. Waste from mining and milling is classified as low level radioactive ($<10^3$ Ci m^{-3}).

The second stage to produce radioactive waste is enrichment. After concentration of $^{235}_{92}U$ from 0.7% to above 3% (typical for light water reactors), the depleted stream (the "tails") is discarded. Waste from enrichment contains less $^{235}_{92}U$than natural uranium. Small quantities of this waste are used for radiation shielding and for mixed oxide (MOX) fuel production [39].

The third stage is the operation of nuclear reactors, where structural components such as fuel rod tubes become contaminated. Typically, a 1000 MW nuclear power plant produces about 13 tonnes of contaminated structural material annually [44]. Waste from operation is classified as medium level radioactive (10^3–10^4Ci m^{-3}).

Fourth, spent fuel needs to be disposed after being stored in ponds in the vicinity of the reactor for a time sufficient to allow their concentration (and radioactivity) to subside.

Fifth, re-processing requires conversion and enrichment, which, in turn, leaves depleted uranium as a waste product. This can be stored either as UF_6, or as U_3O_8, with the HF being recycled [41].

Finally, at the end of the power plant's life, about 10,000 tonnes of medium to high level radioactive waste and some 10,000 tonnes of low to medium level radioactive waste have to be disposed of.

At present, low and medium level radioactive wastes are routinely disposed of in near surface strata such as abandoned mines. High level wastes are proposed to be disposed of in deep geological formations such as salt domes or granite bodies, which are required to exhibit a lack of contact with ground water, tectonic stability, sufficient heat conductivity and low permeability for radionuclides [77]. It is impossible to avoid completely the solution of radionuclides in circulating ground water because (a) every rock formation is, in principle, water permeable and (b) every container material is, in principle, water soluble or corrodible. However, it is also not necessary to absolutely hermetically seal radioactive wastes. Natural uranium and thorium is naturally dissolved into ground water at some small rate, and it is sufficient that the projected rate of release does not significantly exceed the natural rate [44].

The disposal stage is perhaps the most difficult to analyse of all stages because there are not many comprehensive studies on commercially operating nuclear waste facilities. The Swedish nuclear plant operator Vattenfall keeps low level waste inside the power plant, or buried at an on site facility. Intermediate level waste (such as contaminated reactor components) is transferred to a final repository (SFR Forsmark) consisting of vaults 50 m below the sea floor in 5 m deep water. The intermediate level waste deposited there requires on the order of 500 years to decay to background activity. High level waste (HLW) is kept for 30 years at Sweden's central interim storage facility for spent nuclear fuel (CLAB Oskarshamn), consisting of vaults located 25–30 m below ground. Spent fuel is stored there in deep pools of water in order to enable cooling to a temperature sufficiently low to enable final disposal. After 30 years, the waste is planned to be encapsulated in concrete or sealed in copper canisters and placed in a deep repository (at approximately 500 m depth). As of 2004, the location of this repository was not yet determined [40].

There are a number of studies that, in addition to storage, deal more comprehensively with waste management and include longer term disposal stages. These studies conclude that overall waste management is responsible for 5–9% [46], 14% [80] and 13% [81] of greenhouse gas emissions, respectively. The Environmental Product Declaration for Torness drew on input from a reference scenario for waste management [82]. Applying realistic energy intensities ([56,57,83–86], further details in Ref. [63]) to the data for this scenario yields energy embodiments of about 47 and 380 GWh_{th}, respectively (Table 11).

Including 3 MW of electricity input over 40 years [82, p. 10] yields the breakdown in Table 12.

By far the highest of all reported energy requirements for high level waste disposal are calculated from cost data (monetary values not stated) by Storm van Leeuwen and Smith [30]. Applying the national average energy intensity method yields 3500 MWh_{th} per tonne of HLW. As with waste storage, the critique about the AEI method stated in Section 2.6 applies to this stage as well.

Storm van Leeuwen and Smith [30] distinguish two kinds of intermediate and low level waste: operational wastes (conditioning and disposal) and enrichment tails of depleted uranium (re-conversion, conditioning and disposal). Depleted uranium forms the bulk of these ILW/LLW waste products, with an energy requirement of about 470 MWh_{th} per tonne. Most of this energy requirement is for re-conversion of the UF_6, and the per tonne coefficient is derived from data for conversion (see Section 2.3). In comparison, the Environmental Product Declaration for Torness [82] yields less than 100 MWh_{th} per tonne of general ILW/LLW waste (Table 12).

Table 11
Material and energy inputs into the construction of ILW/LLW and HLW waste repositories

ILW/LLW facility	'000 t	GWh	HLW facility	'000 t	GWh	MJ/kg
Reinforced steel				5.2	84.7	58.5
Stainless steel	0.5	16.6				111.6
Concrete	24.1	11.4		372.6	177.3	1.7
Copper				3.2	117.7	131.0
Cement	8.3	19.1				8.3
Totals	32.9	47.1		381.0	379.8	

Table 12
Total deposited waste mass, and energy requirements of ILW/LLW and HLW waste management

	High-level waste	Intermediate-level waste	Low-level waste
Mass (tonnes)	3192	10,138	32,923
Construction energy (GWh_{th})	380	47	
Electricity (GWh_{el})	1051	1051	
Total energy (GWh_{th})	3533	3201	
Construction energy per tonne (MWh_{th})	119	1	
Electricity per tonne (MWh_{el})	329	24	
Total energy per tonne (MWh_{th})	1107	74	

Finally, Storm van Leeuwen and Smith [30] quantify the energy requirements for restoring the mine site to "green fields" conditions, which primarily involves neutralising and immobilising the mine tailings. Immobilisation is assumed to be achieved by sandwiching the mine tailings between bentonite layers. The authors note that this process is based on their own hypothetical model, and that, in reality, mine tailings are not treated in this manner. They state specific energy requirements of 1.25 MWh_{th} per tonne of tailings.

2.12. Transport

There is a large body of literature on energy and greenhouse gas intensities of transport modes [87–98], reported as either monetary intensities (MJ and kg CO_2-e per unit of transport revenue/cost in$), or as physical intensities (MJ and kg CO_2-e per unit of transport task in net tonne kilometres, ntkm). Lenzen [99] presents a comparison between energy intensities obtained from input output analysis and process analysis of the Australian freight system.

2.13. Summary: energy and greenhouse gas intensities

In this work I have reviewed a large number of studies on the energy balance and greenhouse gas emissions associated with the nuclear fuel cycle or components thereof. A sizeable portion of these proved rather inaccessible for further analysis because

- some older reports are out of print and unavailable in electronic format,
- some reports are written in Japanese (I could evaluate only English and German reports) and
- many reports do not reveal critical details and assumptions.

Amongst those reports not evaluated for lack of detail is a 2006 Japanese study by Tokimatsu et al. [100] evaluating the CO_2 consequences of the Japanese economy under various nuclear scenarios, ranging from complete phase out to scenarios involving new generation fast breeder reactors. Similarly, the 2006 evaluation by Fthenakis et al. [101] for the entire US power system appears very thorough but does not reveal a lot of detail, thus warranting further investigation of the data sources. Finally, many of the older studies [34,57,60–62,102] focus on the dynamic transition of the energy supply system of a whole economy. Such analyses, involving a mix of power supply options, are more realistic and informative than a static life cycle assessment, but because of a lack of comparability, these are not reported here.

The most detailed of all studies reviewed are probably the early study of US reactor types by Rotty et al. [17], Storm van Leeuwen and Smith's general analysis [30] and the Environmental Product Declaration by Sweden's

Vattenfall [40,80]. Rotty et al.'s study is detailed in listing all energy requirements, and in that, it includes auxiliary services and upstream energy through input output analysis. Storm van Leeuwen and Smith's analysis covers all stages of the nuclear fuel cycle, however, it has been the subject of considerable controversy [9–12]. Vattenfall's study contains a detailed life cycle material inventory and transport tasks, however, it omits the energy and greenhouse gas impacts of many upstream contributions as well as auxiliary services such as insurance etc.[9]

As can be expected from the preceding review of fuel cycle stages, the results of energy intensities vary considerably amongst studies. Greenhouse gas intensities vary even more because of the additional influence of the fuel mix, or greenhouse gas intensity of the background economy. This is amply demonstrated in Fthenakis' study of the US [101], Andseta et al.'s comparative study of Canada [64], Lewin's assessment of nuclear plants in the German grid [104] and the report by Dones et al. on European countries [46,105,106].

Table 13 summarises all studies examined in this review. The most important plant parameters are given, such as technology vintage (year), assumed lifetime and load factor, uranium concentrations in ores, fuel and enrichment tails and the conversion rate of the whole fuel cycle. The column 'Stages covered' uses acronyms for the fuel cycle stages covered in this Section (see table caption), followed by bracketed numbers representing the percentage of the respective stage's requirement in the entire energy or greenhouse gas balance (compare with an overview by van der Vate [107]). All available information was extracted from the literature.

3. Meta-analysis

Section 2 has clearly demonstrated the large range of estimates of energy in the nuclear fuel cycle. Clearly, there exist considerable variability, which could, on one hand, be caused by real differences in energy and greenhouse gas characteristics of different technology choices and countries and, on the other hand, be the result of methodological aberrations, such as systematic errors or deliberate scope settings. As a first approach to analysing this variability, I apply multiple regression in order to elucidate factors influencing energy and greenhouse gas intensities of nuclear power. This regression is followed by a more detailed sensitivity analysis aiming at estimating the importance of a number of design parameters.

[9] Vattenfall's EPD document [80, p. 12] states systematic underestimations to be less than 7.5%. Given the substantial omissions of upstream energy and greenhouse gas requirements as well as service inputs, the truncation error is probably higher than 20% (compare [103]).

3.1. Multiple regression

Table 14 identifies seven main influences on energy intensity estimates, which are subjected to multiple regression.[10] The explained variable is the normalised energy intensity (in GWh_{th}/GWh_{el}, see Eq. (3)).

The multiple regression of data in Table 13 ($R^2 = 0.912$) yields good agreement with expected trends (Table 15).[11]

The energy intensity of nuclear power, normalised to a 35 year lifetime at 80% load, can be explained by

$$\begin{aligned}\eta_{\text{norm}} = & -0.025 \times ore + 0.079 \times enrich + 0.174 \times tails \\ & - 0.049 \times conv - 0.00009 \times year \\ & + 0.062 \times meth + 0.099 \times scope. \end{aligned} \tag{6}$$

The m values in Table 15 correspond to the coefficients in the regression equations; the Δm values are their standard errors. The t values in Table 15 are the results of a t-test (test for significance) for each variable. The most significant variable is the enrichment method, with centrifuges yielding a lower energy intensity than diffusion plants. The influence of the ore grade is significantly negative, i.e. richer ores mean lower energy intensity. The third significant variable is the method employed: PA yields low, I/O intermediate, and AEI high energy intensities. Increasing the scope naturally always increases the energy intensity, which is reflected in a positive coefficient. Also clearly, recent technologies are slightly more energy efficient than older ones. The choice of enrichment assay also has a strong and significant influence. As explained in Section 2.4, the choice of tails assay represents a compromise between the (monetary and energy) cost of uranium feed and separative work, but in general, higher tails assays improve the energy balance. A high conversion rate means that a high percentage of fission products (for example, plutonium) are used as reactor fuel, either through higher burn up or through re-processing, and this appears to improve the energy intensity.

Thus, using the multiple regression formula, an ideal life cycle assessment (i.e. full scope, modern reactors, specified ore and enrichment conditions) can be simulated from incomplete and variable literature data. For example, a modern ($year = 2006$) PWR in once through mode ($conv = 0.55$), supplied with uranium from typical Australian ore ($ore = 0.15$ %), enriched using 70% centrifuges ($enrich = 1.3$) with $tails = 0.25$% tails assay, assessed using an input output based hybrid analysis ($meth = 2$) covering the full nuclear fuel cycle ($scope = 1$) results in a regressed energy intensity of $\eta_{\text{norm}} = 0.124$.

With regard to the greenhouse gas intensity, it is not possible to regress the figures in Table 13 because they depend on additional parameters such as the greenhouse

[10] Compare a regression of wind energy studies in [119].

[11] Missing values in Table 13 were replaced with averages over all studies.

Table 13a
Results of energy studies of nuclear power systems

Reference	Year of study	Reactor type	Power rating (MW_{el})	Life time (y)	Load factor (%)	Ore grade (‰)	Enrichment technology	% tails	% ^{235}U in fuel	Conversion rate	Energy intensity $1/R_1 \left(\frac{kWh_{th}}{kWh_{el}}\right)$	Analysis type	Stages covered (% of life cycle)	Remarks
[31]	1973	HWR	1000	25	60	3.1	Df		2.1		0.22	I/O	M(2)L(2)V(2)**E(69)** F(1)C(16)O(10)	SGHWR [108]
[31]	1974	HTR	1000	25	60	3.1	Df		6.5		0.31	I/O	M(1)L(1)V(1)**E(85)**F(0)C(11)O(0)	TNPG design
[61]	1975	FBR	1000	25	100	–	–	–	18.0	1.0	0.04	I/O	M(0)L(0)V(0)EFOR(11)**C(89)**	Data in [57]
[31]	1975	HWR	1000	25	60	3.1	–		0.72		0.07	I/O	M(6)L(6)V(6)E(0)F(12)**C(52)**O(18)	Pickering CANDU
[31]	1975	AGR	1000	25	60	3.1	–	–	0.72		0.11	I/O	M(10)L(11)V(10)E(0)F(20)**C(49)**O(0)	Oldbury A Magnox
[17]	1975	HWR	1000	30	75	1.76	–	–	0.72		0.12	I/O	M(4)L(4)V(0)E(0)F(29)**CO(60)**R(3)SW(0)T(1)	CANDU
[17]	1975	PWR	1000	30	75	1.76	Df	0.3	3.2		0.17	I/O	M(2)L(3)V(5)**E(63)**F(5)CO(21)R(0)SW(0)T(0)	Pu rec.
[17]	1975	HTR	1000	30	75	1.76	Df	0.3	93.2	0.66	0.18	I/O	M(2)L(2)V(4)**E(70)**F(2)CO(20)R(0)SW(0)T(0)	^{233}U rec.
[17]	1975	BWR	1000	30	75	1.76	Df	0.3	2.73		0.20	I/O	M(3)L(3)V(6)**E(66)**F(4)CO(17)R(0)SW(0)T(0)	No rec.
[31]	1975	PWR	1000	25	60	3.1	Df		2.7		0.20	I/O	M(2)L(2)V(2)**E(79)**F(1)C(15)O(0)	Shearon Harris
[17]	1975	PWR	1000	30	75	1.76	Df	0.3	3.2		0.22	I/O	M(3)L(3)V(6)**E(68)**F(3)CO(16)R(0)SW(0)T(0)	No rec.
[31]	1975	PWR	1000	25	60	3.1	Df		2.6		0.22	I/O	M(2)L(2)V(2)**E(81)**F(1)C(14)O(0)	Maine Yankee
[17]	1975	PWR	1000	30	75	1.76	Df	0.2	3.2		0.25	I/O	M(2)L(2)V(4)**E(74)**F(3)CO(14)R(0)SW(0)T(0)	No rec.
[31]	1975	PWR	1000	25	60	3.1	Df		3.35		0.26	I/O	M(1)L(2)V(1)**E(83)**F(0)C(12)O(0)	Jos M. Farley
[31]	1975	AGR	1000	25	60	3.1	Df		2.45		0.27	I/O	M(2)L(2)V(2)**E(80)**F(1)C(15)O(0)	Hunterston B
[17]	1975	HTR	1000	30	75	0.06	Df	0.3	93.2	0.66	0.29	I/O	M(10)**L(33)**V(2)E(42)F(1)CO(12)R(0)SW(0)T(0)	^{233}U rec.
[17]	1975	PWR	1000	30	75	0.06	Df	0.3	3.2		0.32	I/O	M(12)**L(39)**V(3)E(33)F(3)CO(11)R(0)SW(0)T(0)	Pu rec.
[31]	1975	PWR	1000	25	60	3.1	Df		3.3		0.37	I/O	M(1)L(2)V(2)**E(87)**F(0)C(8)O(0)	Haddam Neck
[17]	1975	PWR	1000	30	75	0.06	Df	0.3	3.2		0.46	I/O	M(13)**L(43)**V(3)E(32)F(2)CO(8)R(0)SW(0)T(0)	No rec.
[60]	1976	HWR	1000	25	60	3.0	Df	0.25	2.1		0.24	I/O	M(2)L(2)V(2)**E(69)**F(1)C(21)O(3)	CANDU
[60]	1976	HWR	1000	25	60	0.07	Df	0.25	2.1		0.28	I/O	M(9)**L(39)**V(1)E(29)F(0)C(18)O(3)	CANDU
[34]	1978	FBR	1300	25	79.9	–	–	–			0.019	I/O	FO(19)**C(81)**	
[34]	1978	LWR	1300	25	79.9	2	Ce				0.04	I/O	**MLVEFO(71)**C(29)	
[34]	1978	HTR	1300	25	79.9	2	Ce				0.04	I/O	**MLVEFO(66)**C(34)	
[34]	1978	HTR	1300	25	79.9	0.2	Ce				0.13	I/O	**MLVEFO(89)**C(11)	
[34]	1978	LWR	1300	25	79.9	0.2	Ce				0.16	I/O	**MLVEFO(92)**C(8)	
[34]	1978	LWR	1300	25	79.9	2	Df				0.18	I/O	**MLVEFO(93)**C(7)	
[34]	1978	HTR	1300	25	79.9	2	Df				0.21	I/O	**MLVEFO(93)**C(7)	

[34]	1978	LWR	1300	25	79.9	0.2	Df				0.29	I/O	**MLVEFO(96)**C(4)	
[34]	1978	HTR	1300	25	79.9	0.2	Df				0.30	I/O	**MLVEFO(95)**C(5)	
[48]	1983	PWR	1000	25	75	≈3	Ce		3.0	0.55	0.11	AEI	MLV(12)EF(7)**C(68)**O(11)S(1)W(1)	Biblis A[c]
[62]	1988		1000	30	50						0.85[d]	AEI	MLVEF(12)**C(67)**OT(18)DSW(3)	
[56]	1992	PWR	1000	30	75		Df				0.19	I/O	M(3)L(3)V(7)**E(66)**F(3)C(8)O(9)R(0)S(0)T(0)	
[109]	1996	FBR	1000	30	75	–	–	–			0.009	I/O		
[110]	1999	BWR	1000	30	75		Ce			30[b]	0.036	I/O	ML(1)V(10)E(22)F(2)**O(33)**R(22)D(0)SW(10)	Pu recycle
[110]	1999	BWR	1000	30	75		Df			30[b]	0.10	I/O	ML(1)V(4)**E(81)**F(1)O(11)D(0)SW(2)	
[83]	2000	PWR	1000	40	86.8						0.006	PA	COD(100)	Doel 3/4
[83]	2000	PWR	1000	40	86.8						0.018	I/O	COD(100)	Doel 3/4
[53]	2000	PWR	1000	40	75		Ce		3.0		0.06	I/O	M(5)**LVEF(63)**C(10)O(12)D(1)SW(9)T(0)	
[42]	2001	PWR	1000	30	80	0.2	Df		3.2		0.14	PA	**MLE(86)**V(6)C(4)S(4)	U from Ranger mine, US grid
[46]	2004	PWR	1000	40	81.4	2.0	Df	0.26	3.8	42.8[b]	0.03	PA		MOX fuel
[46]	2004	BWR	1000	40	81.4	2.0	76% Ce	0.26	4.0	48[b]	0.045	PA		MOX fuel
[30]	2005	PWR	1000	24	82	1.5	70% Ce	0.2	4.2	46[b]	0.66[a]	AEI	ML(3)V(2)E(13)F(1)**C(24)**O(15)**D(24)**S(9)W(11)	
[30]	2005	PWR	1000	24	82	0.1	70% Ce	0.2	4.2	46[b]	1.63[a]	AEI	ML(22)V(1)E(5)F(0)C(10)O(6)D(10)S(4)**W(44)**	
[47]	1975	BWR	1000	30	80		Df		2.6	27[b]	0.063	I/O	M(0)L(2)**E(62)**F(0)C(36)R(0)	
[47]	1975	PWR	1000	30	80		Df		3.0	33[b]	0.064	I/O	M(0)L(2)**E(64)**F(0)C(33)R(0)	
[111]	2000	PWR	1000	30	75		Df				0.064		M(0)L(6)V(3)**E(71)**F(1)C(8)O(12) T(0)	
[102]	1977	PWR	1000	30	75	1.5	Df	0.3			0.2	I/O		U + Pu recycling
[9]	1976	LWR	1000	40	80	2.34	Df	0.25	2.3	45[b]	0.171	I/O	ML(1)V(5)**E(72)**F(3)CO(14)D(3)ST(1)	Ore from Ranger
[9]	1976	LWR	1000	40	80	2.34	Ce	0.25	2.3	45[b]	0.052	I/O	ML(3)V(18)E(6)F(11)**CO(47)**D(12)ST(3)	Ore from Ranger
[9]	1976	LWR	1000	40	80	0.1	Df	0.25	2.3	45[b]	0.206	I/O	ML(18)V(4)**E(60)**F(3)CO(12)D(3)ST(1)	
[9]	1976	LWR	1000	40	80	0.1	Ce	0.25	2.3	45[b]	0.087	I/O	ML(42)V(11)E(4)F(7)**CO(28)**D(7)ST(2)	

Notes: AEI = Method of multiplying total cost with the national average energy intensity, C = Construction, Ce = Centrifuge, D = Decommissioning, Df = Gaseous diffusion, E = Enrichment, F = Fuel fabrication, I/O = Input output based hybrid analysis, L = Milling, M = Mining, O = Operation, PA = Process analysis, R = Re-processing, rec. = recycling, S = Waste storage, T = Transport, V = Conversion, W = Waste disposal.

[a] Own calculations.

[b] Burn-up (GWd tU^{-1}) not conversion rate.

[c] Total cost DM 7.4bn @ 9 MJ/DM.

[d] Total cost$ 17bn @ 22 MJ/$.

Table 13b
Results of greenhouse gas emissions studies of nuclear power systems

Reference	Year of study	Reactor type	Power rating (MW_{el})	Life time (y)	Load factor (%)	Ore grade (‰)	Enrichment technology	% tails	% ^{235}U in fuel	burn-up (GWd/kgU)	GHG intensity ($\frac{g\ CO_2-eq.}{kWh_{el}}$)	Analysis type	Stages covered (% of life cycle)	Remarks
[56]	1992	PWR	1000	30			Df				34	I/O	M(4)L(4)V(7)**E**(**57**)F(4)C(12)O(11)R(0)S(0)T(0)	
[104]	1993	LWR	1300	20	77.6	20	Ce			33	5	I/O		100% nuclear grid "case 1"
[104]	1993	LWR	1300	20	77.6	20	Ce			45	21	I/O		average German grid
[104]	1993	LWR	1300	20	77.6	20	Ce			33	28	I/O		average German grid
[104]	1993	LWR	1300	20	77.6	20	Df			33	84	I/O		average German grid
[106]	1994	LWR	1000				10% Ce			40	6.5	PA	**ML**(**21**)V(17)E(11)F(0)C(17)O(11)R(17)D(2)SW(1)T(2)	UCPTE grid
[112]	1994	PWR	1100				Ce				7.9	I/O	**MLVEF**(**66**)C(22)OT(9)DSW(3)	
[113]	1994	LWR	1300	30	68.5						18.63	I/O	ML(35)V(15)E(5)F(1)**C**(**44**)	
[112]	1994	PWR	1100				Df				25.7	I/O	**MLVEF**(**90**)C(7)OT(3)DSW(1)	
[114]	1995	LWR	1000	40	70		10% Ce			40	8.88	PA	M(4)L(16)V(16)E(11)F(1)**CO(34)**R(13)S(0)W(3)	Swiss grid
[114]	1995	LWR	1000	40	70		Ce			40	8.92		M(4)L(16)V(16)E(12)F(1)**CO**(**34**)R(13)S(0)W(3)	Swiss grid
[114]	1995	BWR	1000	30	75		Ce			30	8.93		ML(3)V(12)E(22)F(1)**CO(50)**S(3)W(9)	Japanese grid
[114]	1995	BWR	1000	30	75		Ce			30	10.18		ML(2)V(9)E(15)F(1)**CO(44)**R(16)W(13)	Japanese grid
[114]	1995	BWR	1000	30	75		Df			30	19.41		ML(1)V(5)**E**(**55**)F(1)CO(23)R(8)W(7)	Japanese grid
[114]	1995	BWR	1000	30	75		Df			30	20.93		ML(1)V(5)**E**(**67**)F(1)CO(21)S(1)W(4)	Japanese grid
[45]	1996	PWR	600	60	87		Ce	0.28	3.7	40	6.0	PA		AP600[a]
[45]	1996	BWR	1300	60	87		Ce	0.28	3.7	45	6.0	PA		ABWR[a]
[109]	1996	FBR	1000	30	75	–	Ce				7.8	I/O		
[109]	1996	BWR	1000	30	75		Ce			30	10.4	I/O		Pu recycle
[109]	1996	BWR	1000	30	75		Df			30	21.1	I/O		
[64]	1998	HWR	600/900				–	–	–		3.2	PA	ML(9)V(2)F(0)**C**(**69**)O(0)D(19)T(0)	CANDU in actual Canadian grid
[64]	1998	HWR	600/900				–	–	–		15.41	PA	ML(3)V(1)F(1)**C(77)**O(15)D(4)T(0)	CANDU in hypothetical fossil grid
[83]	2000	PWR	1000	40	86.8						1.8	PA	COD(100)	Doel 3/4
[83]	2000	PWR	1000	40	86.8						4.0	I/O	COD(100)	Doel 3/4
[115]	2000	BWR	1000	30	70		Ce			30	11	I/O		Pu recycle

[53]	2000	PWR	1000	40	75		Ce		3.0		15	PA	M(3)**LVEF(59)**C(13)O(15)D(0)SW(9)T(1)	
[115]	2000	BWR	1000	30	70		mix			30	21.6	I/O		Pu recycle
[115]	2000	PWR	1000	30	70		mix			30	24.7	I/O		Pu recycle
[115]	2000	BWR	1000	30	70		mix			30	26.4	I/O		no Pu recycle
[115]	2000	PWR	1000	30	70		mix			30	31.4	I/O		no Pu recycle
[115]	2000	BWR	1000	30	70		Df			30	37	I/O		Pu recycle
[42]	2001	PWR	1000	30	80	0.2	Df		3.2		40.3	PA	**MLE(83)**V(7)C(7)S(2)	U from Ranger mine, US grid
[46]	2004	PWR	1000	40	81.4	2.0	Df	0.26	3.8	42.8	5.95	PA	M(9)L(20)V(23)E(9)F(2)**CO(23)**R(5)S(5)W(4)	MOX fuel, French grid
[46]	2004	BWR	1000	40	81.4	2.0	76% Ce	0.26	4.0	48	10.7	PA	M(4)L(9)V(10)**E(60)**F(1)CO(8)R(2)S(3)W(2)	MOX fuel, German grid
[80]	2005	BWR	1030	40	85	0.44	80% Ce	0.28	3.1		3.27	PA	**ML(35)**V(7)E(15)F(5)CD(17)O(6)SW(14)	MLVEF only direct effects
[81]	2005	AGR	625	40	75.8		Ce				5.05	PA	**ML(36)**V(6)E(9)F(5)CD(16)O(12)R(4)SW(13)	Torness
[116,117]	2005	BWR	1000	30	70		Df		3.4	40	24	I/O	ML(5)V(1)**E(62)**F(3)C(12)O(13)S(3)D(2)T(0)	
[30]	2005	PWR	1000	24	82	1.5	70% Ce	0.2	4.2	46	212[a]	AEI	ML(3)V(2)E(13)F(1)**C(24)**O(15)**D(24)**S(9)W(11)	
[30]	2005	PWR	1000	24	82	0.1	70% Ce	0.2	4.2	46	527[a]	AEI	ML(22)V(1)E(5)F(0)C(10)O(6)D(10)S(4)**W(44)**	
[101,118]	2006	LWR	1000	40	85	127	mix[c]	0.25	3.8	42	17	mix	ML(0)V(0)**E(72)**F(0)CD(6)O(16)S(1)W(5)	Canadian ore
[101,118]	2006	LWR	1000	40	85	0.5	mix[c]	0.25	3.8	42	54	mix	ML(9)V(2)**E(39)**F(1)CD(21)O(21)S(2)W(5)	CO_2-intensive grid, Australian ore

Notes: AEI = Method of multiplying total cost with the national average energy intensity, C = Construction, Ce = Centrifuge, D = Decommissioning, Df=Gaseous diffusion, E = Enrichment, F = Fuel fabrication, I/O = Input output based hybrid analysis, L = Milling, M = Mining, O = Operation, PA = Process analysis, R = Re-processing, rec. = recycling, S = Waste storage, T = Transport, V = Conversion, W = Waste disposal.

[a] Own calculations.

[b] Ore from Australia, Canada and US.

[c] 34% Df, 30% Ce, and 36% dilution of high grade weapon material.

Table 14
Main factors influencing the energy balance of nuclear power

Influence	Variable	Definition	Expected effect on energy ratio
Ore grade	*ore*	‰	Negative
Enrichment method	*enrich*	No enrichment = 0, centrifuge = 1, diffusion = 2, mix = 1.5	Positive
Tails assay	*tails*	%	Indeterminate
Conversion rate[a]	*conv*	As in Table 13	Negative
Vintage year	*year*	As in Table 13	Negative
Assessment method	*meth*	PA = 1, I/O = 2, AEI = 3	Positive
Assessment scope	*scope*	Percentage of stages covered; MLVEFCORDSWT = 1	Positive

[a] The conversion rate χ is related to the *burn-up* β through $\chi = \beta \times 24\ \mathrm{h/d}/(\rho_{iso}\ \eta_{235U} f) - 1$, where ρ_{iso} is the energy content of ^{235}U (24,500 $GWh_{th}/t^{235}U$), η_{235U} is the enrichment (%), and f is the fraction of ^{235}U burnt at re-loading (around 2/3).

gas intensity of the background economy.[12] These parameters were not given in any of the studies.

3.2. Sensitivity analysis

While the multiple regression in the previous chapter combines a large amount of information from many studies, it is not based on physical or engineering principles. Lenzen et al. [63, p. 99ff] present a detailed technical sensitivity analysis of the energy and greenhouse gas intensities of LWR and HWR. They assume a hypothetical nuclear industry in Australia meeting a power demand of 3370 MW_{el}, or 25,000 $GWh_{el}\ y^{-1}$ electricity output. Their life cycle assessment takes into account all stages in Section 2, including losses during milling, conversion, fabrication, heat loss in the reactor and electricity losses during distribution, but they ignore mine clean up.[13]

Table 16 contains a summary for parameters for the "LWR baseline" case in Ref. [63]. These parameters represent conservative estimates: For example,

- most economies have lower carbon coefficients than a pure black coal economy,
- reactor lifetimes are longer than 35 years when extended [69],
- thermal efficiencies of modern steam turbines can be well above 30%,
- burn ups can be stretched beyond 55 MWd_{th}/kgU,[14]

Table 15
Results from a multiple regression of energy intensities and system parameters, excluding outliers [30,62]

	scope	*ore*	*conv*	*tails*	*enrich*	*year*	*meth*
m	0.099	−0.025	−0.049	0.174	0.079	−0.00009	0.062
Δm	0.038	0.006	0.066	0.072	0.013	0.00003	0.020
t	**2.58**	**3.90**	*0.75*	2.42	**6.19**	**2.66**	**3.15**

Table 16
Parameters for the LWR baseline case

Variable	Unit	Baseline
Economy wide GHG intensity, thermal, black coal economy	kg_{CO2}-e/kWh	0.31
Economy wide GHG intensity, electrical, black coal economy	kg/kWh	1.0
Nominal power	MW	1300
Load factor		85% [123]
Lifetime	years	35
Distribution losses		5%
Thermal efficiency		30%
Heat loss factor		2%
Energy content of fissile isotopes	GWh_{th}/t heavy metals	24,500
Burn up	MWd_{th}/kgU	45
Fabrication loss		1%
Enrichment		3.5%
Enrichment method	30% Diffusion, 70% Centrifuge	
Tails assay		0.25%
Conversion loss		0.5%
Milling loss		0.5%
Recovery rate	Function of ore grade	93.1%
Ore grade		0.15%

[12] Economy-specific greenhouse gas intensities are caused by specific energy requirements for the manufacture of components for energy supply systems. The manufacture of a 500 kW German designed wind turbine in Brazil, for example, requires almost twice as much primary energy as its manufacture in Germany. This increase results mainly from different energy contents of steel, which are in turn due to differences in the steel production route and scrap utilisation between the two countries [120]. Nevertheless, German and Brazilian production are about equal in terms of CO_2, because 95% of Brazilian electricity is generated by hydroelectric plants. Similarly, a Danish on-shore farm of six 95 kW wind turbines manufactured from steel containing 88% scrap and 12% mined ore, and from copper containing 80% scrap and 20% mined ore, yielded an extraordinarily low energy intensity of only 0.014 kWh_{in}/kWh_{el} [121]. These figures demonstrate that energy intensities of energy supply systems can vary considerably with the country of manufacture.

[13] Lenzen et al. [63] chose not to apply the figures stated by Storm van Leeuwen and Smith [30] for storage, disposal, and for returning the mine site to "green fields" condition, because the procedure suggested by these authors differs from most of the descriptions in the open literature, and is not practised by the industry in Australia [78,79,122]. Lenzen et al. [63] assume current industry practices, so that the energy requirements for the treatment of mine tailings are included in the energy figures for mining.

[14] Long-term objectives for breeder fuel cycles are 150–200 MWd_{th}/kg [71].

Table 17
Sensitivity scenarios for the LWR

Scenario	Load factor (%)	Lifetime	Distribution loss (%)	Burn-up	Enrichment mix	Enrichment (%)	Tails assay (%)	Ore grade (%)	Economy-wide GHG intensity
Baseline	85	35	5	45	0.7	3.50	0.25	0.15	0.324
1980s USA	75								
1990s Japan	80								
Near-full load	90								
Early decommissioning		25							
Life extension		45							
Industry customer			2.5						
Customer mix			7.5						
Household customer			10.0						
Frequent re-load				35					
Infrequent re-load				55					
100% diffusion enrichment					0				
100% centrifuge enrichment					1				
Low-level enrichment						3			
High-level enrichment						4			
Expensive uranium							0.20		
Cheap uranium							0.30		
Canadian ore								2	
Low-grade shale								0.01	
Brown coal economy									0.342
Natural gas economy									0.184
90% renewable/nuclear economy									0.054
Best case	90	45	2.5	55	1	3	0.30	2	0.054
Worst case	75	25	10	35	0	4	0.20	0.01	0.342

- future enrichment will only use centrifuges, and
- uranium bearing ores are often mined for other metals as well.

The results of the sensitivity analysis (Table 17) confirm the results of the multiple regression in Section 3.1. For light water reactors, energy intensities are around 0.18 kWh_{th}/kWh_{el}, while greenhouse gas intensities are around 60 g CO_2-e/kWh_{el}. Energy payback times are around $6\frac{1}{2}$ years (Table 18). Both energy and greenhouse gas intensities show substantial scatter when parameters are varied. The ore grade and enrichment method are the most important influencing parameters. Moreover, the greenhouse gas intensity is significantly influenced by the greenhouse gas intensity of the background economy. The greenhouse gas intensities for the best case scenario agree with those obtained for the low carbon economies, Switzerland [46] and Japan [110,115].

For the case of the heavy water reactor (see Ref. [63]), energy intensities are around 0.20 kWh_{th}/kWh_{el}, while greenhouse gas intensities are around 65 g CO_2-e/kWh_{el}. Energy payback times are around 7 years. Once again, both energy and greenhouse gas intensities show substantial scatter when parameters are varied. Enrichment does not play a role since the HWR is fuelled with natural uranium. The ore grade is the most important influencing parameter.

4. Conclusions

The increased urgency of dealing with mitigation of the looming climate change has sparked renewed interest in the nuclear energy option. In addition to the traditional areas of debate, such as reactor and processing plant safety and secure long-term storage of radioactive waste, a substantial stream of research has dedicated resources to establishing the amount of greenhouse gas emissions associated with nuclear generated electricity in comparison with fossil fuelled and renewable sources. While fossil fuelled power causes most emissions on the power plant site, the majority of greenhouse gas emissions in the nuclear fuel cycle are caused in processing stages upstream and downstream from the plant.

The most popular reactor types, LWR and HWR, need between 0.1 and 0.3 kWh_{th}, and on average about 0.2 kWh_{th}, for every kWh of electricity generated. Depending on a number of factors such as the greenhouse gas intensity of the background economy and the grade of uranium ore mined, these energy intensities translate into greenhouse gas intensities for the LWR and HWR of between 10 and 130 g CO_2-e/kWh_{el}, with an average of 65 g CO_2-e/kWh_{el}.

While these greenhouse gas emissions are expectedly lower than those of fossil technologies (typically 600–1200 g CO_2-e/kWh_{el}), they are higher than reported figures

Table 18
Results and sensitivity analysis for the LWR

Variable	Unit	Scenario	Variation	Energy intensity (kWh_{th}/kWh_{el})	(Sensitivity)	GHG intensity (g CO_2-e/kWh_{el})	(Sensitivity)	Energy payback time (years)
		Baseline		0.178		57.8		6.3
Load factor	%	1980s USA	75%	0.187	(5%)	60.6	(5%)	6.6
		1990s Japan	80%	0.182	(2%)	59.1	(2%)	6.4
		Near-full load	90%	0.175	−(2%)	56.6	−(2%)	6.1
Lifetime	years	Early decommissioning	25	0.191	(7%)	62.0	(7%)	6.7
		Life extension	45	0.171	−(4%)	55.4	−(4%)	6.0
Distribution loss	%	Industry customer	2.5%	0.174	−(2%)	56.4	−(2%)	6.1
		Customer mix	7.5%	0.183	(3%)	59.2	(3%)	6.4
		Household customer	10.0%	0.188	(5%)	60.8	(5%)	6.6
Burn-up	$GW_{th}d$/tU	Frequent re-load	35	0.208	(16%)	67.2	(16%)	7.3
		Infrequent re-load	55	0.160	−(10%)	51.8	−(10%)	5.6
Enrichment method		100% Denrichment	0	0.252	(41%)	81.5	(41%)	8.8
		100% Centrifuge enrichment	1	0.147	−(18%)	47.6	−(18%)	5.2
Enrichment	%	Low-level enrichment	3%	0.162	−(9%)	52.3	−(9%)	5.7
		High-level enrichment	4%	0.195	(10%)	63.3	(10%)	6.9
Tails assay	%	Expensive uranium	0.2%	0.181	(2%)	58.7	(2%)	6.4
		Cheap uranium	0.3%	0.178	(0%)	57.6	(0%)	6.2
Ore grade	%	Canadian ore	2.5%	0.168	−(6%)	54.3	−(6%)	5.9
		Low-grade shale	0.01%	0.402	(125%)	130.2	(125%)	14.1
GHG intensity of economy	kg CO_2-e/kWh_{th}	Brown coal economy	0.342	0.178	(0%)	61.0	(6%)	6.3
		Natural gas economy	0.184	0.178	(0%)	32.7	−(43%)	6.3
		90% Renewable/ nuclear economy	0.054	0.178	(0%)	9.6	−(83%)	6.3
		Best case		0.106	−(41%)	5.7	−(90%)	3.7
		Worst case		0.726	(307%)	248.4	(330%)	25.5

for wind turbines and hydroelectricity (around 15–25 g CO_2-e/kWh_{el}, [63,119]) and in the order of, or slightly lower than solar photovoltaic or solar thermal power (around 90 g CO_2-e/kWh_{el}, [63,124]).

References

[1] Pasztor J. What role can nuclear power play in mitigating global warming? Energy Policy 1991;19:98–109.
[2] Mortimer N. Nuclear power and carbon dioxide – the fallacy of the nuclear industry's new propaganda. The Ecologist 1991;21(3): 129–32.
[3] Mortimer N. Nuclear power and global warming. Energy Policy 1991;19(1):76–8.
[4] Donaldson DM, Betteridge GE. Forum – nuclear power and global warming. Energy Policy 1991;19(813–814):76–8.
[5] Uranium Institute. Greenhouse gas emissions from the nuclear fuel cycle. <http://www.world-nuclear.org/co2&nfc.htm>, 2006.
[6] Storm van Leeuwen JW, Smith P. Rebuttal of critique of the analysis presented on this website. <http://www.stormsmith.nl/report20050803/Rebuttal_WNA.pdf>, Chaam, Netherlands, 2006.
[7] Storm van Leeuwen JW. Rebuttal. <http://www.nuclearinfo.net/Nuclearpower/SSRebuttal>, Chaam, Netherlands, 2006.
[8] Storm van Leeuwen JW. Rebuttal Storm2. <http://www.nuclearinfo.net/Nuclearpower/SSSRebuttal>, Chaam, Netherlands, 2006.
[9] World Nuclear Association. Energy analysis of power systems. Information Paper 11. <http://www.world-nuclear.org/info/inf11.htm>, London, UK: World Nuclear Association, 2006.
[10] School of Physics University of Melbourne. Energy lifecycle of nuclear power. <http://www.nuclearinfo.net/Nuclearpower/WebHomeEnergyLifecycleOfNuclear_Power>, Melbourne, Australia: School of Physics, University of Melbourne, 2006.
[11] Sevior M, Flitney A. Response by Sevior and Flitney in blue. <http://www.nuclearinfo.net/Nuclearpower/SSRebuttalResp>, Melbourne, Australia: School of Physics, University of Melbourne, 2006.
[12] Sevior M. Response from Martin Sevior to rebuttal 2 from Jan Willem Storm van Leeuwen. <http://www.nuclearinfo.net/Nuclearpower/SeviorSLSRebutall>, Melbourne, Australia: School of Physics, University of Melbourne, 2006.
[13] Perry AM, Devine WD, Reister DB. The energy cost of energy – guidelines for net energy analysis of energy supply systems. Report No. ORAU/IEA(R)-77-14. Oak Ridge, TN, USA: Institute for Energy Analysis, Oak Ridge Associated Universities, 1977.
[14] Herendeen RA. Net energy considerations. In: West RE, Kreith F, editors. Economic analysis of solar thermal energy systems. Cambridge, MA, USA: The MIT Press; 1988. p. 255–73.

[15] Leach G. Net energy analysis – is it any use? Energy Policy 1975;3(4):332–44.

[16] Huettner DA. Net energy analysis: an economic assessment. Science 1976;192(4235):101–4.

[17] Rotty RM, Perry AM, Reister DB. Net energy from nuclear power. IEA Report IEA-75-3. Oak Ridge, TN, USA: Institute for Energy Analysis, Oak Ridge Associated Universities, 1975.

[18] Martinez-Val JM, Piera M. Nuclear fission sustainability with hybrid nuclear cycles. Energy Convers. Manage. 2007;48(5): 1480–90.

[19] Uranium Information Centre. World uranium mining. Nuclear issues briefing paper 41. <http://www.uic.com.au/nip41.htm>, Melbourne, Australia: Uranium Information Centre, 2006.

[20] World Nuclear Association. Uranium mining in Australia and Canada. Education paper. <http://www.world-nuclear.org/education/mining.htm>, London, UK: World Nuclear Association, 2006.

[21] World Nuclear Association. In situ leach (ISL) mining of uranium. Information paper 03. <http://www.world-nuclear.org/info/inf27.htm>, London, UK: World Nuclear Association, 2003.

[22] Sugo T, Seguchi T, Shimizu T, Uotani M, Kashima R. Evaluation of cost of seawater uranium recovery and technical problems towards implementation (reprinted from Nihon Genshiryoku Gakkaishi 43(10), 2001). In: Andryushin I, Safronov S, Yudin Y, editors, Nuclear technologies and non-proliferation policies. Sarov, Nizhny Novgorod, Russia: Analytical Center for Non-Proliferation, 2004: Issue 13, Annex 8.

[23] World Nuclear Association. Supply of uranium. Information paper 75. <http://www.world-nuclear.org/info/inf75.htm>, London, UK: World Nuclear Association, 2006.

[24] Australian Bureau of Agricultural and Resource Economics. Australian commodity statistics. ABARE project 1059. Canberra, Australia: Australian Government, 2004.

[25] WISE Uranium Project. Uranium mine ownership – Australia. <http://www.wise-uranium.org/uoaus.html>, Amsterdam, Netherlands: World Information Service on Energy, 2006.

[26] Uranium Information Centre. Australia's uranium deposits and prospective mines. <http://www.uic.com/pmine.htm>, Melbourne, Australia: Uranium Information Centre, 2006.

[27] BHP Billiton. Personal communication, 20 October, 2006.

[28] WMC Sustainability Site. Olympic dam operations environmental data. <http://hsecreport.bhpbilliton.com/wmc/2004/performance/odo/data/index.htm>, BHP Billiton, 2004.

[29] Uranium Information Centre. Australia's uranium mines. <http://www.uic.com/emine.htm>, Melbourne, Australia: Uranium Information Centre, 2006.

[30] Storm van Leeuwen JW, Smith P. Nuclear power – the energy balance. <http://www.stormsmith.nl/>, Chaam, Netherlands, 2005.

[31] Chapman PF. Energy analysis of nuclear power stations. Energy Policy 1974;3(4):285–99.

[32] Storm van Leeuwen JW. Nuclear uncertainties – energy loans for fission power. Energy Policy 1985;13:253–66.

[33] Australian Bureau of Agricultural and Resource Economics. Energy update. 2006.

[34] Wagner H-J. The energy cost of building and operating selected energy supply system technologies. Angewandte Systemanalyse Nr. 10, Jül-1561. Jülich, Germany: Kernforschungsanlage Jülich GmbH, 1978.

[35] Rössing Uranium Limited. Rössing working for Namibia. Report to Stakeholders. Swakopmund, Namibia: Rössing Uranium Limited, 2004.

[36] Energy Resources of Australia Ltd. Social and environment report. <http://www.energyres.com.au/corporate/era-se-03.pdf>, Darwin, NT, Australia: Energy Resources of Australia Ltd, 2003.

[37] Weis M, Kienle F, Hortmann W. Atomic energy and CO_2: energy expense and CO_2-emissions in fuel extraction. Elektrizitätswirtschaft 1990;89(1/2):28–31.

[38] Taylor M. Greenhouse gas emissions from the nuclear fuel cycle Comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases, IAEA Advisory Group meeting/Workshop. Beijing, China: International Atomic Energy Agency; 1994. p. 133–7.

[39] World Nuclear Association. The nuclear fuel cycle. Information paper 03. <http://www.world-nuclear.org/info/inf03.htm>, London, UK: World Nuclear Association, 2005.

[40] Vattenfall. The nuclear fuel cycle. Reference to Vattenfall generation's certified product declarations S-P-00021 and S-P-00026. Stockholm, Sweden: Vattenfall AB Generation Nordic Countries, 2004.

[41] World Nuclear Association. Uranium enrichment. Information paper 28. <http://www.world-nuclear.org/info/inf28.htm>, London, UK: World Nuclear Association, 2006.

[42] Australian Coal Association. Electricity from a nuclear power station. Case study B16. Canberra, Australia: Australian Coal Association, 2001.

[43] Huber V. Uranium enrichment. <http://www.urananreicherung.de>, Gronau and Jülich, Germany: URENCO Deutschland GmbH, 2006.

[44] Heinloth K. The energy question. Braunschweig. Germany: Vieweg; 1997.

[45] Dones R, Gantner U, Hirschberg S, Doka G, Knoepfel I. Environmental inventories for future electricity supply systems for Switzerland. PSI Bericht Nr. 96-07. Villingen, Switzerland: Paul Scherrer Institut, 1996.

[46] Dones R, Bauer C, Bolliger R, Burger B, Heck T, Röder A, Emmenegger MF, Frischknecht R, Jungbluth N. Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. Data v1.1. Dübendorf, Switzerland: PSI and ESU-services, 2004.

[47] Rombourg CT, Koen BV. Total energy investment in nuclear power plants. Nucl. Technol. 1975;26:5–11.

[48] Heinloth K. Energy. Stuttgart, Germany: B.G. Teubner, 1983.

[49] Villani S. Progress in uranium enrichment. Naturwissenschaften 1984;71(3):115–23.

[50] Penner PS, Herendeen RA, Milke T. New hybrid 1971 energy intensities available. Energy 1979;4:469–73.

[51] World Nuclear Association. Mixed oxide fuel (MOX). Information paper 29. <http://www.world-nuclear.org/info/inf29.htm>, London, UK: World Nuclear Association, 2006.

[52] World Nuclear Association. Nuclear power reactors. Information paper 32. <http://www.world-nuclear.org/info/inf32.htm>, London, UK: World Nuclear Association, 2005.

[53] White SW, Kulcinski GL. Birth to death analysis of the energy payback ratio and CO2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. Fusion Eng Des 2000;48(248):473–81.

[54] Charpentier J-P. Concerning the necessary energy to make a nuclear reactor. Rev Energie 1975;26:892ff.

[55] Kolb G, Niehaus F, Rath-Nagel S, Voss A. The energy cost for building and operating nuclear power plants. Angewandte Systemanalyse Nr. 10, Jül-1230. Jülich, Germany: Kernforschungsanlage Jülich GmbH, 1975.

[56] Yasukawa S, Tadokoro Y, Kajiyama T. Life cycle CO_2 emission from nuclear power reactor and fuel cycle system Expert workshop on life-cycle analysis of energy systems methods and experience. Paris, France: Organisation for Economic Co-operation and Development, International Energy Agency; 1992. p. 151–60.

[57] Walford FJ, Atherton RS, Hill KM. Energy costs of input to nuclear power. Energy Policy 1976;4(2):166–70.

[58] Moraw G, Szeless A. Energy expense for building and operating power works. Elektrotech Masch 1976;93(7):301–3.

[59] Hohenwarter DJ, Heindler M. Net power and output of the German LWR nuclear power system. Energy 1988;13(3):287–300.

[60] Chapman PF. Methods of energy analysis. In: Blair IM, Jones BD, Van Horn AJ, editors. Aspects of energy conversion. Oxford, UK: Pergamon Press; 1976. p. 739–58.

[61] Hill KM, Walford FJ. Energy analysis of a power generating system. Energy Policy 1975;3(4):306–17.
[62] Tyner G, Costanza R, Fowler RG. The net-energy yield of nuclear power. Energy 1988;13(1):73–81.
[63] Lenzen M, Dey C, Hardy C, Bilek M. Life-cycle energy balance and greenhouse gas emissions of nuclear energy in Australia. Report to the Prime Minister's Uranium Mining, Processing and nuclear energy review (UMPNER). <http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf>, Sydney, Australia: ISA, University of Sydney, 2006.
[64] Andseta S, Thompson MJ, Jarrell JP, Pendergast DR. CANDU reactors and greenhouse gas emissions. 19th Annual Conference, Canadian Nuclear Society. Toronto, Canada: Canadian Nuclear Society; 1998.
[65] Lenzen M. Double-counting in frameworks applying life-cycle thinking. J Indu Ecol, 2008, in press.
[66] Junker WH. The nonproliferation program of the UKAEA. ATW 1995;40(4):236–8.
[67] Schwald P, Obst J, Orwantschke D, Valencia L. Dismantling and removal of Niederaichbach. ATW 1995;40(4):242–6.
[68] Technical Group on Decommissioning. Financial aspects of decommissioning. IAEA-TECDOC-1476. Vienna, Austria: International Atomic Energy Agency, 2005.
[69] Hewlett JG. The operating costs and longevity of nuclear power plants. Energy Policy 1992;20(7):608–22.
[70] Thierfeldt S. Release limit for remainder materials. ATW 1995;40(4):257–61.
[71] International Atomic Energy Agency. Nuclear power: an overview in the context of alleviating greenhouse gas emissions. Supporting document to the second assessment report of the intergovernmental panel on climate change, IAEA-TECDOC-793. Vienna, Austria: International Atomic Energy Agency, 1995.
[72] Komorowski K, Meuresch S. Immobilization and back building of core technical units. ATW 1995;40(4):231–5.
[73] Rüdinger V. Removal of nuclear power plant Niederaichbach. ATW 1991;36(12):561–4.
[74] Liebholz W-M. Green meadow. ATW 1995;40(8/9):517.
[75] International Atomic Energy Agency. Status of the decommissioning of nuclear facilities around the World. STI/PUB/ 1201. Vienna, Austria: International Atomic Energy Agency, 2004.
[76] International Atomic Energy Agency. Technical, economic and institutional aspects of regional spent fuel storage facilities. IAEA-TECDOC -1482. Vienna, Austria: International Atomic Energy Agency, 2005.
[77] World Nuclear Association. Waste management in the nuclear fuel cycle. Information paper 04. <http://www.world-nuclear.org/info/inf04.htm>, London, UK: World Nuclear Association, 2006.
[78] Uranium Information Centre. Environmental rehabilitation of the Mary Kathleen uranium mine. Mines paper # 6. Melbourne, Australia: Uranium Information Centre, 1996.
[79] Uranium Information Centre. Environmental management and rehabilitation of the Nabarlek uranium mine. Mines paper # 5. Melbourne, Australia: Uranium Information Centre, 1999.
[80] Vattenfall. Certified environmental product declaration of electricity from Forsmark Kraftgrupp AB (FKA). EPD S-P-00021. Stockholm, Sweden: Vattenfall AB Generation Nordic Countries, 2005.
[81] AEA Technology. Environmental product declaration of electricity from Torness nuclear power station. London, UK: British Energy, 2005.
[82] United Kingdom Nirex Limited. Nirex inputs to environmental product declaration for Torness power station. Technical Note 484461. Harwell, UK: United Kingdom Nirex Limited, 2005.
[83] Voorspools KR, Brouwers EA, D'haeseleer WD. Energy content and indirect greenhouse gas emissions embedded in 'emission-free' plants: results from the Low Countries. Appl Energy 2000;67:307–30.
[84] van de Vate JF. Full-energy-chain analysis of greenhouse gas emissions from different energy sources Comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases. IAEA Advisory Group meeting/Workshop. Beijing, China: International Atomic Energy Agency; 1994. p. 11–7.
[85] Lenzen M, Dey CJ. Truncation error in embodied energy analyses of basic iron and steel products. Energy 2000;25:577–85.
[86] Lenzen M, Treloar G. Energy embodied in buildings: wood versus concrete. Energy Policy 2002;30(3):249–55.
[87] Lenzen M, Dey C, Hamilton C. Climate change. In: Hensher DA, Button KJ, editors. Handbook of transport and the environment. Amsterdam, Netherlands: Elsevier B.V.; 2003. p. 37–60.
[88] Delucchi MA. A revised model of emissions of greenhouse gases from the use of transportation fuels and electricity. Report No. UCD-ITS-RR-97-22. Davis, CA, USA: Institute of Transportation Studies, University of California, 1997.
[89] DeLuchi MA, Johnston RA, Sperling D. Transportation fuels and the greenhouse effect. Transport Res Record 1988;1175:33–44.
[90] DeLuchi MA. Greenhouse-gas emissions from the use of new fuels for transportation and electricity. Transport Res A 1993;27(3):187–91.
[91] Delucchi M. Emissions of criteria pollutants, toxic air pollutants, and greenhouse gases, from the use of alternative transportation modes and fuels. Report No. UCD-ITS-RR-96-12. Davis, CA, USA: Institute of Transportation Studies, University of California, 1996.
[92] Eriksson E, Blinge M, Lövgren G. Life cycle assessment of the road transport sector. Sci Total Environ 1996;189/190:69–76.
[93] Hannon B, Herendeen R, Puleo F, Sebald A. Energy, employment and dollar impacts of alternative transportation options. In: Williams RH, editor. The energy conservation papers. Cambridge, MA, USA: Ballinger Publishing Company; 1975. p. 105–30.
[94] Rose AB. Energy intensity and related parameters of selected transportation modes: freight movements. Report No. ORNL-5554. Oak Ridge, TN, USA: Oak Ridge National Laboratory, 1979.
[95] Schipper L, Scholl L, Price L. Energy use and carbon emissions from freight in 10 industrialised countries: an analysis of trends from 1973 to 1992. Transport Res D 1997;2(1):57–76.
[96] Schipper L, Peake S, Marie C. Carbon-dioxide emissions from travel and freight in IEA countries: past and future. Plan Transport Res Comput 1997;413:493–518. PTRC Publications.
[97] Schipper L, Marie-Lilliu C, Gorham R. Flexing the link between transport and greenhouse gas emissions. Paris, France: International Energy Agency; 2000.
[98] Marheineke T, Friedrich R, Krewitt W. Application of a hybrid-approach to the life cycle inventory analysis of a freight transport task. In: Society of Automotive Engineers, editor. SAE 1998 Transactions – Journal of Passenger Cars. Warrendale, PA, USA: Society of Automotive Engineers (SAE), 1999.
[99] Lenzen M. Total energy and greenhouse gas requirements for Australian transport. Transport Res Part D 1999;4:265–90.
[100] Tokimatsu K, Kosugi T, Asami T, Williams E, Kaya Y. Evaluation of lifecycle CO2 emissions from the Japanese electric power sector in the 21st century under various nuclear scenarios. Energy Policy 2006;34:833–52.
[101] Fthenakis VM, Kim HC. Greenhouse-gas emissions from solar electric and nuclear power: A life-cycle study. Energy Policy 2007;35(4):2549–57.
[102] Moraw G, Schneeberger M, Szeless A. Energy investment in nuclear and solar power plants. Nucl Technol 1977;33:174–83.
[103] Lenzen M. Errors in conventional and input–output-based life-cycle inventories. J Ind Ecol 2001;4(4):127–48.
[104] Lewin B. CO_2-emission of power plants before and after inventory energy chain. VDI Berichte 1993;1093:115–30.
[105] Dones R, Heck T, Hirschberg S. Greenhouse gas emissions from energy systems, comparison and overview. Encyclopedia of energy. Amsterdam, Netherlands: Elsevier; 2004.
[106] Dones R, Hirschberg S, Knoepfel I. Greenhouse gas emission inventory based on full energy chain analysis. Comparison of energy sources in terms of their full-energy-chain emission factors of

greenhouse gases. IAEA Advisory Group meeting/Workshop. Beijing, China: Internation Atomic Energy Agency; 1994. p. 95–114.
[107] van de Vate JF. Overview of existing studies on full-energy-chain (FENCH) emissions of greenhouse gases. Comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases. IAEA Advisory Group meeting/Workshop. Beijing, China: International Atomic Energy Agency; 1994. p. 77–84.
[108] Moore J. The SGHWR. Atom 1973;195:7.
[109] Uchiyama Y. Life cycle analysis of electricity generation and supply systems. Electricity, health and the environment: comparative assessment in support of decision making. Vienna, Austria: International Atomic Energy Agency; 1995. p. 279–91.
[110] Uchiyama Y. Life cycle assessment of electricity generating systems. Tsukuba, Japan: University of Tsukuba; 1999.
[111] Rashad SM, Hammad FH. Nuclear power and the environment: comparative assessment of environmental and health impacts of electricity-generating systems. Appl Energy 2000;65:211–29.
[112] Yasukawa S, Tadokoro Y, Sato O, Yamaguchi M. Integration of indirect CO_2 emissions from the full energy chain. In: Planning and economic studies section, editor. Comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases, IAEA Advisory Group meeting/Workshop. Beijing, China: International Atomic Energy Agency, 1994, p. 139–50.
[113] Friedrich R, Marheineke T. Life cycle analysis of electricity systems: methods and results. Comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases. IAEA Advisory Group meeting/Workshop. Beijing, China: International Atomic Energy Agency; 1994. p. 67–75.
[114] van de Vate JF. Full-energy-chain analysis of greenhouse gas emissions: a comparison between nuclear power, hydropower, solar power and wind power. Int J Risk Assess Manage 2002;3(1):59–74.
[115] Hondo H, Uchiyama Y, Moriizumi Y. Evaluation of power generation technologies based on life cycle CO_2 emissions – re-estimation using the latest data and effects of the difference of conditions. CRIEPI Report No. 99009. Tokyo, Japan: Central Research Institute of the Electricity Producing Industry, 2000.
[116] Hondo H. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 2005;30:2042–56.
[117] Hondo H. Personal communication 13 October, 2006.
[118] Fthenakis VM. Personal communication 6 October, 2006.
[119] Lenzen M, Munksgaard J. Energy and CO_2 analyses of wind turbines – review and applications. Renew Energy 2001;26(3):339–62.
[120] Lenzen M, Wachsmann U. Wind energy converters in Brazil and Germany: an example for geographical variability in LCA. Appl Energy 2004;77:119–30.
[121] Grum-Schwensen E. Calculation of the energy consumed by the manufacturing and erection of a modern wind generator installation. In: International Atomic Energy Agency, editor. Assessment of greenhouse gas emissions from the full energy chain of solar and wind power and other energy sources, Working material. Vienna, Austria: IAEA, 1996.
[122] Uranium Information Centre. Former Australian uranium mines. <http://www.uic.com/fmine.htm>, Melbourne, Australia: Uranium Information Centre, 2006.
[123] Blake EM. U.S. capacity factors: leveled off at last. Nucl News 2006;49(6):26–31.
[124] Lenzen M. Greenhouse gas analysis of solar–thermal electricity generation. Sol Energy 1999;65(6):353–68.