

Valuing the greenhouse gas emissions from nuclear power: A critical survey

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ABSTRACT

This article screens 103 lifecycle studies of greenhouse gas-equivalent emissions for nuclear power plants to identify a subset of the most current, original, and transparent studies.

It begins by briefly detailing the separate components of the nuclear fuel cycle before explaining the methodology of the survey and exploring the variance of lifecycle estimates. It calculates that while the range of emissions for nuclear energy over the lifetime of a plant, reported from qualified studies examined, is from 1.4 g of carbon dioxide equivalent per kWh ($\text{g CO}_2\text{e/kWh}$) to 288 $\text{g CO}_2\text{e/kWh}$, the mean value is 66 $\text{g CO}_2\text{e/kWh}$. The article then explains some of the factors responsible for the disparity in lifecycle estimates, in particular identifying errors in both the lowest estimates (not comprehensive) and the highest estimates (failure to consider co-products). It should be noted that nuclear power is not directly emitting greenhouse gas emissions, but rather that lifecycle emissions occur through plant construction, operation, uranium mining and milling, and plant decommissioning.

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1. Introduction

The nuclear era began with a whimper, not a bang, on December 7, 1942. Amidst the polished wooden floors of a war-appropriated squash court at the University of Chicago, Enrico Fermi inserted about 50 ton of uranium oxide into 400 carefully constructed graphite blocks. A small puff of heat exhibited the first self-sustaining nuclear reaction, many bottles of Chianti were consumed, and nuclear energy was born (Metzger, 1984).

Since then, Americans have dreamed of exotic nuclear possibilities. Early advocates promised a future of electricity too cheap to meter, an age of peace and plenty without high prices and shortages where atomic energy provided the power needed to desalinate water for the thirsty, irrigate deserts for the hungry, and fuel interstellar travel deep into outer space. Other exciting opportunities included atomic golf balls that could always be found and a nuclear powered airplane, which the US Federal Government spent \$1.5 billion researching between 1946 and 1961 (Munson, 2005; Winkler, 2001; Duncan, 1978).

While nuclear technologies did not fulfill these dreams, nuclear power has still emerged to become a significant source of electricity. In 2005, 435 nuclear plants supplied 16% of the world's power, constituting 368 GW of installed capacity generating 2768 TWh of electricity (International Energy Agency, 2007). In the US alone, which has 29.2% of the world's reactors, nuclear facilities accounted

for 19% of national electricity generation. In France, 79% of electricity comes from nuclear sources, and nuclear energy contributes to more than 20% of national power production in Germany, Japan, South Korea, Sweden, Ukraine, and the United Kingdom.

Advocates of nuclear power have recently framed it as an important part of any solution aimed at fighting climate change and reducing greenhouse gas emissions. The Nuclear Energy Institute (2007) tells us, "it is important to build emission-free sources of energy like nuclear" and that nuclear power is a "carbon-free electricity source" (1998). Patrick Moore, co-founder of Greenpeace, has publicly stated that "nuclear energy is the only non-greenhouse gas emitting energy source that can effectively replace fossil fuels and satisfy global demand" (Environmental News Service, 2005). The nuclear power company Areva (2007) claims that "one coal power station of 1 GWe emits about 6 million tons of CO_2 per year while nuclear is quite CO_2 free".

Opponents of nuclear power have responded in kind. In their calculation, ISA (2006) argues that nuclear plants are poor substitutes to other less greenhouse gas intensive generators. They estimate that wind turbines have one-third the carbon-equivalent emissions of nuclear power over their lifecycle and hydroelectric one-fourth the equivalent emissions. The Oxford Research Group projects that if the percentage of world nuclear capacity remains what it is today, by 2050 nuclear power would generate as much carbon dioxide per kWh as comparable gas-fired power stations as the grade of available uranium ore decreases (Barnaby and Kemp, 2007a,b).

Which side is right? Analogous to the critical surveys of negative externalities associated with electricity production

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conducted by Sundqvist and Soderholm (2002) and Sundqvist (2004), this article screens 103 lifecycle studies of greenhouse gas-equivalent emissions for nuclear power plants to identify a subset of the most current, original, and transparent studies. It begins by briefly detailing the separate components of the nuclear fuel cycle before explaining the methodology of the survey and exploring the variance of lifecycle estimates. It calculates that while the range of emissions for nuclear energy over the lifetime of a plant reported from qualified studies examined is from 1.4 g of carbon dioxide equivalent per kWh ($\text{g CO}_2\text{e/kWh}$) to 288 $\text{g CO}_2\text{e/kWh}$, the mean value is 66 $\text{g CO}_2\text{e/kWh}$. The article then explains some of the factors responsible for the disparity in lifecycle estimates, in particular identifying errors in both the lowest estimates (not comprehensive) and the highest estimates (failure to consider co-products). It should be noted that nuclear power is not directly emitting greenhouse gas emissions, but rather that the lifecycle involves emissions occurring elsewhere and indirectly attributable to nuclear plant construction, operation, uranium mining and milling, and plant decommissioning.

2. The nuclear power lifecycle

Engineers generally classify the nuclear fuel cycle into two types: “once-through” and “closed.” Conventional reactors operate on a “once-through” mode that discharges spent fuel directly into disposal. Reactors with reprocessing in a “closed” fuel cycle separate waste products from unused fissionable material so that it can be recycled as fuel. Reactors operating on closed cycles extend fuel supplies and have clear advantages in terms of storage of waste disposal, but have disadvantages in terms of cost, short-term reprocessing issues, proliferation risk, and fuel cycle safety (Beckjord et al., 2003).

Despite these differences, both once-through and closed nuclear fuel cycles involve at least five interconnected stages that constitute a nuclear lifecycle: the “frontend” of the cycle where uranium fuel is mined, milled, converted, enriched, and fabricated; the construction of the plant itself; the operation and maintenance of the facility; the “backend” of the cycle where spent fuel is conditioned, (re)processed, and stored; and a final stage where plants are decommissioned and abandoned mines returned to their original state. Figs. 1 and 2 provide a brief depiction of the once-through and closed nuclear fuel cycle.

2.1. The frontend of the nuclear lifecycle

The nuclear fuel cycle is long and complex. The primary fuel for nuclear power plants, uranium, is widely distributed in the earth's crust and the ocean in minute quantities, with the exception of concentrations rich enough to constitute ore. Uranium is mined both at the surface and underground, and after extracted it is crushed, ground into a fine slurry, and leached in sulfuric acid. Uranium is then recovered from solution and concentrated into solid uranium oxide, often called “yellow cake,” before it is converted into hexafluoride and heated. Then, hexafluoride vapor is loaded into cylinders where it is cooled and condensed into a solid before undergoing enrichment through gaseous diffusion or gas centrifuge.

2.1.1. Uranium mining

Starting at the mine, rich ores embody concentrations of uranium oxide as high as 10%, but 0.2% or less is usual, and most uranium producers will consider mining ores with concentrations higher than 0.0004%. A majority of the usable “soft” ore found in sandstone has a concentration between 0.2% and 0.01%, and

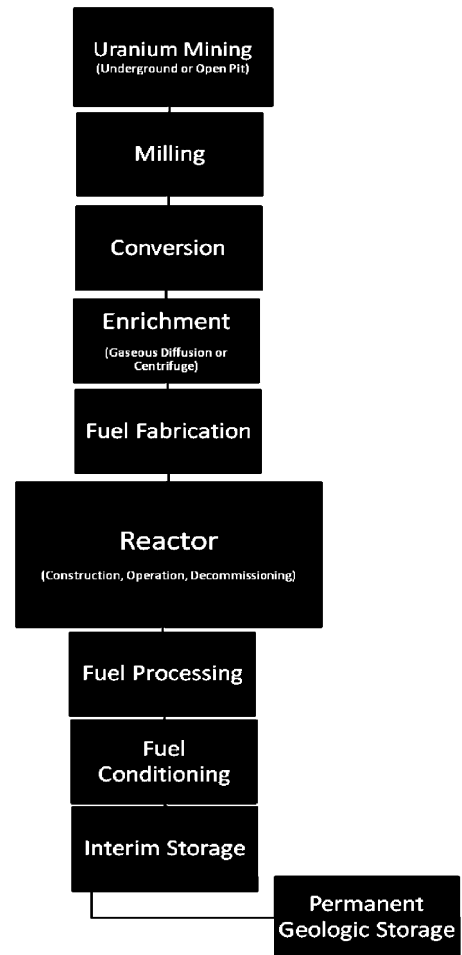


Fig. 1. The “once-through” nuclear fuel cycle.

“hard” ore found in granite has a lower uranium content, usually about 0.02% or less. Uranium mines are typically opencast pits, up to 250 m deep, or underground. A third extraction technique involves subjecting natural uranium to *in situ* leaching where hundreds of tons of sulfuric acid, nitric acid, and ammonia are injected into the strata and then pumped up again after 3–25 years, yielding uranium from treated rocks.

2.1.2. Uranium milling

Mined uranium must undergo a series of metallurgical processes to crush, screen, and wash the ore, letting the heavy uranium settle as the lighter debris is funneled away. The next step is the mill, often situated near the mine, where acid or alkali baths leach the uranium out of the processed ore, producing a bright yellow powder, called “yellowcake,” that is about 75% uranium oxide (whose chemical form is U_3O_8). In the cases where ores have a concentration of 0.1%, the milling must grind 1000 ton of rock to extract 1 ton of yellowcake. Both the oxide and the tailings (the 999 ton of remaining rock) remain radioactive, requiring treatment. Acids must be neutralized with limestone, and made insoluble with phosphates (Fleming, 2007; Heaberlin, 2003).

2.1.3. Uranium conversion and enrichment

Next comes conversion and enrichment, where a series of chemical processes are conducted to remove remaining impurities. Natural uranium contains about 0.7% uranium-235; the rest is mainly uranium-234 or uranium-238. In order to bring the

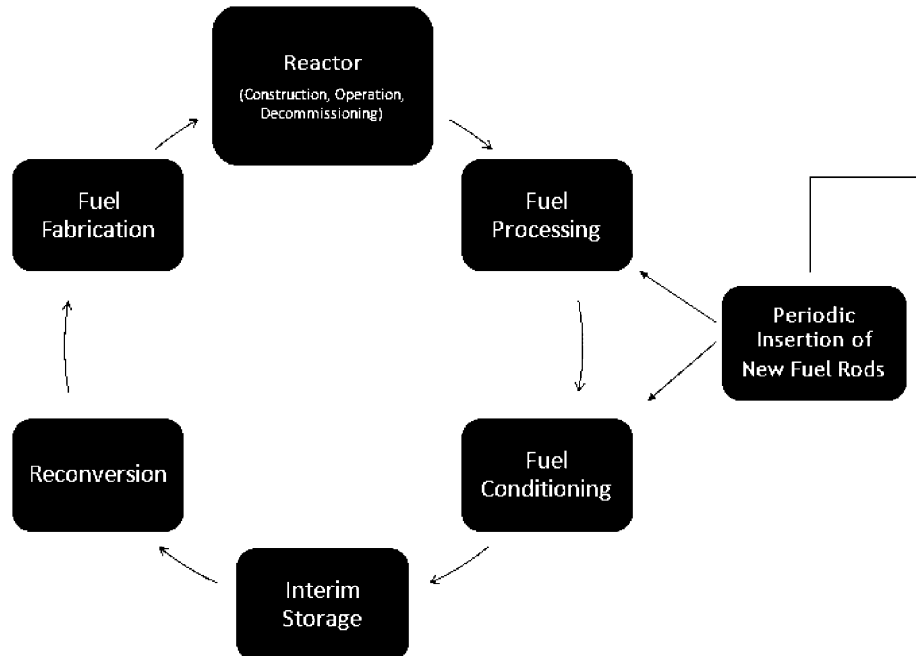


Fig. 2. The “closed” nuclear fuel cycle.

concentration of uranium-235 up to at least 3.5% for typical commercial light water reactors and about 4–5% for other modern reactors, the oxide must be enriched, and the process begins by converting uranium to uranium hexafluoride, UF_6 , or “hex.” Then, it is enriched, and the two dominant commercial enrichment methods are gaseous diffusion and centrifuge.

Gaseous diffusion, developed during the Second World War as part of the Manhattan Project, accounts for about 45% of world enrichment capacity. The diffusion process funnels hex through a series of porous membranes or diaphragms. The lighter uranium-235 molecules move faster than the uranium-238 molecules and have a slightly better chance of passing through the pores in the membrane. The process is repeated many times in a series of diffusion stages called a cascade, with the enriched UF_6 withdrawn from one end of the cascade and the depleted UF_6 removed at the other end. The gas must be processed through some 1400 stages before it is properly enriched (Uranium Information Centre, 2007).

The gas centrifuge process, first demonstrated in the 1940s, feeds hex into a series of vacuum tubes, and accounts for about 45% of world enrichment capacity. When the rotors are spun rapidly, the heavier molecules with uranium-238 increase in concentration towards the outer edge of the cylinders, with a corresponding increase in uranium-235 concentration near the center. To separate the two isotopes, centrifuges rotate at very high speeds, with spinning cylinders moving at roughly one million times the acceleration of gravity (Uranium Information Centre, 2007).

In United States, the gaseous diffusion plant at Paducah, Kentucky, primarily does enrichment while Europe and Russia utilize mostly centrifuge methods (Fthenakis and Kim, 2007). The remaining percentage (~10%) of nuclear fuel comes from the recycling of nuclear weapons.

After enrichment, about 85% of the oxide comes out as waste in the form of depleted hex, known as “enrichment tails,” which must be stored. Each year, for instance, France creates 16,000 ton of enrichment tails that are then exported to Russia or added to the existing 200,000 ton of depleted uranium within the country.

The 15% that emerges as enriched uranium is converted into ceramic pellets of uranium dioxide, UO_2 , packed in zirconium alloy tubes, and bundled together to form fuel rod assemblies for reactors.

To supply enough enriched fuel for a standard 1000MW reactor for 1 year, about 200 ton of natural uranium has to be processed (Fleming, 2007). Moreover, uranium must be transported from the mine to processing and enrichment facilities. Andseta et al. (1998) found that in Canada, the uranium needed to create fuel rods has traveled more than 4000 km before the process is complete. The IEA (2002) reports that in Europe most uranium is transported 150–805 km by railway, 1250 km by boat, or 378 km by truck.

2.2. Construction

The construction phase of the nuclear lifecycle involves the fabrication, transportation, and use of materials to build generators, turbines, cooling towers, control rooms, and other infrastructure. A typical nuclear plant usually contains some 50 miles of piping welded 25 thousand times, and 900 miles of electrical cables. Thousands of electric motors, conduits, batteries, relays, switches, operating boards, transformers, condensers, and fuses are needed for the system to operate. Cooling systems necessitate valves, seals, drains, vents, gauges, fittings, nuts, and bolts. Structural supports, firewalls, radiation shields, spent fuel storage facilities, and emergency backup generators must remain in excellent condition. Temperatures, pressures, power levels, radiation levels, flow rates, cooling water chemistry, and equipment performance must all be constantly monitored. While his estimate is from an older 1000MW Pressurized Water Reactor, White (1995) calculates that the typical nuclear plant needs 170,000 ton of concrete, 32,000 ton of steel, 1363 ton of copper, and a total of 205,464 ton of other materials. Many of these are carbon intense; 1 ton of aluminum has the carbon equivalent of more than 10,000 ton of CO_2 ; 1 ton of lithium, 44,000 ton; one ton of silver, 913,000 ton (White, 1995).

2.3. Operation

The operation phase of the lifecycle encompasses the energy needed to manage the cooling and fuel cycles of the plant, as well as the energy needed for its maintenance and the fuels used for backup generators. Indirect energy use includes the provision of power during reactor outages, repairs, and shutdowns.

The heart of the operating nuclear facility is the reactor, which generates electricity through the fission, or splitting, of uranium and plutonium isotopes. In a nuclear reactor, the fission process does not take place one atom at a time. Uranium has the rare and productive property that when it is struck by a neutron, it splits into two and produces more neutrons. If one uranium-235 atom collides with an atom of uranium-238, one of the other isotopes of uranium, it may stay there and induce a couple of decay cycles to produce plutonium-239. Plutonium-239, sharing the same property of uranium-235, splits when struck by neutrons to act as additional fuel. The process can be controlled by a moderator consisting of water or graphite to speed the reaction up, and neutron-absorbing control rods to slow it down (Fleming, 2007; Beckjord et al., 2003). Most nuclear reactors around the world have a present lifetime of 30–40 years, but produce electricity at full power for no more than 24 years (Fleming, 2007).

2.4. The backend of the nuclear lifecycle

The backend phase involves fuel processing, interim storage, and permanent sequestration of waste. Spent fuel must be conditioned for reactors operating on a once-through fuel cycle, and reprocessed for those employing a closed fuel cycle. Eventually, radioactive impurities such as barium and krypton, along with transuranic elements such as americium and neptunium, clog the uranium fueling a nuclear reaction. After a few years, fuel elements must be removed, and fresh fuel rods inserted. The half-life of uranium-238, one of the largest components of spent fuel, is about the same as the age of the earth: 4.5 billion years.

Spent fuel must then be stored at individual reactor sites in large pools of water for at least 10 years, after which they are located in large concrete casks that provide air-cooling, shielding, and physical protection. While there are many different cask types, those in the US typically hold 20–24 Pressurized Water Reactor fuel assemblies, sealed in a helium atmosphere inside the cask to prevent corrosion. Decay heat is transferred by helium from the fuel to fins on the outside of the storage cask for cooling.

The final stage of the backend of the cycle involves the sequestration of nuclear waste. Permanent geological repositories must provide protection against every plausible scenario in which radionuclides might reach the biosphere or expose humans to dangerous levels of radiation. These risks include groundwater seeping into the repository, corrosion of waste containers, leaching of radionuclides, and migration of contaminated groundwater towards areas where it might be used as drinking water or for agriculture.

2.5. Decommissioning

The last stage of the nuclear lifecycle involves the decommissioning and dismantling of the reactor, as well as reclamation of the uranium mine site. After a cooling off period that may last as long as 50–100 years, reactors must be dismantled and cut into small pieces to be packed in containers for final disposal. Proops et al. (1996) expect nuclear plants to have an operating lifetime of 40 years, but expect decommissioning to be longer, taking at least 60 years. While it will vary along with technique and reactor type,

the total energy required for decommissioning can be as much as 50% more than the energy needed for original construction (Fleming, 2007). At the uranium mine, the overburden of rock covering the area must be replaced and replanted with indigenous vegetation, and radioactive tailings must be treated and contained.

3. Review of nuclear lifecycle studies

To assess the total carbon dioxide-equivalent emissions over the course of the nuclear lifecycle, this study began by reviewing 103 studies estimating greenhouse gas emissions for nuclear plants. These 103 studies were narrowed according to a three-phase selection process.

First, given that the availability of high-quality uranium ore changes with time, and that mining, milling, enrichment, construction, and reactor technologies change over the decades, the study excluded surveys more than 10 years old (i.e., published before 1997). Admittedly, excluding studies more than a decade old is no guarantee that the data utilized by newer studies is in fact new. One analysis from Dones et al. (2004c), for instance, relied on references from the 1980s for the modeling of uranium mining; data from 1983 for modeling uranium tailing ponds; 1996 data for uranium conversion; and 2000 data for uranium enrichment. Still, excluding studies more than 10 years old is an attempt to hedge against the use of outdated data, and to ensure that recent changes in technology and policy are included in lifecycle estimates. Table 1 lists all 40 studies excluded by their date.

Second, the study excluded analyses that were not in the public domain, cost money to access, or were not published in English. Table 2 details the nine studies excluded for lack of accessibility.

Third, 35 studies were excluded based on their methodology. These studies were most frequently discounted because they either relied on “unpublished data” or utilized “secondary sources.” Those relying on “unpublished data” contained proprietary information, referenced data not published along with the study, did not explain their methodology, were not transparent about their data sources, or did not detail greenhouse gas emission estimates for separate parts of the nuclear fuel cycle in gCO₂e/kWh. Those utilizing “secondary sources” merely quoted other previously published reports and did not provide any new calculations or synthetic analysis on their own. Table 3 depicts the 35 studies excluded by methodology.

Excluding detailed studies that rely on unpublished or non-transparent data does run the risk of including less detailed (and less rigorous) studies relying on published and open data. Simply placing a study in the public domain does not necessarily make it “good.” However, the author believes that this risk is more than offset by the positive benefits of transparency and accountability. Transparency enhances validity and accuracy; public knowledge is less prone to errors, and more subject to the process of debate and dialogue that improves the quality of information. “Transparency,” says Ann Florini, an expert on governance, “is the most effective error correction system humanity has yet devised” (Florini, 2005, p. 16). Furthermore, transparency is essential to promoting social accountability. Society simply cannot make informed decisions about nuclear power without public discussion; for these reasons, the author believes that only results in the public domain should be included.

The remaining 19 studies met all criteria: they were published in the past 10 years, accessible to the public, transparent about their methodology, and provided clear estimates of equivalent greenhouse gas emissions according to the separate parts of the nuclear fuel cycle. These studies were “weighed” equally; that is,

they were not adjusted in particular for their methodology, time of release within the past 10 years, or how rigorously they were peer reviewed or cited in the literature. Table 4 documents the results of these 19 studies.

Statistical analysis of these 19 studies reveals a range of greenhouse gas emissions over the course of the nuclear lifecycle at the extremely low end of 1.4 gCO₂e/kWh and the extremely high end of 288 gCO₂e/kWh. Accounting for the mean values of emissions associated with each part of the nuclear lifecycle, the mean value reported for the average nuclear power plant is 66 gCO₂e/kWh. Tables 5 and 6 and Figs. 2 and 3 provide the complete breakdown of this estimate. As Fig. 3 depicts, the frontend component of the nuclear cycle is responsible for 38% of

equivalent emissions; decommissioning 18%; operation 17%; backend 15%; and construction 12% (Fig. 4).

4. Assessing the disparity in lifecycle estimates

What accounts for such a wide disparity among lifecycle estimates of greenhouse gas emissions associated with the nuclear fuel cycle? Studies primarily differ in terms of their scope; assumptions regarding the quality of uranium ore; assumptions regarding type of mining; assumptions concerning method of enrichment; whether they assessed emissions for a single reactor or for a fleet of reactors; whether they measured historical or marginal/future emissions; assumptions regarding reactor type, site selection, and operational lifetime; and type of lifecycle analysis.

4.1. Scope

Some studies included just one or two parts of the nuclear fuel cycle, whereas others provided explicit details for even subcomponents of the fuel cycle. Vorspools et al. (2000), for example, analyzed just the emissions associated with construction and decommissioning for reactors across the world, whereas ExternE (1998) assessed the carbon equivalent for the construction of the Sizewell B nuclear reactor in the United Kingdom. Their estimates are near the low end of the spectrum, at between 3 and 11.5 gCO₂e/kWh. In contrast, Storm van Leeuwen et al. (2007) looked at every single subcomponent of the fuel cycle, and produced estimates near the high end of the spectrum at 112–166 gCO₂e/kWh. Table 7 provides a breakdown of their estimate, which the authors emphasize is highly dependent on the quality of uranium ore being used to fuel nuclear plants. It has been included here for two reasons: to give readers a sense for how detailed lifecycle assessments can be, and because this study refers back to some of the numbers presented in this table when making comparisons below.

Storm van Leeuwen and Smith's estimate has not been universally accepted. Dones (2007) points out that while Storm van Leeuwen and Smith's analysis is transparent enough that it can be critiqued—something positive—he believes that their estimate is too high. His own survey of lifecycle studies found a range of 2–230 gCO₂e/kWh, but that the range of 2–77 gCO₂e/kWh was most common, with only 3 studies giving average estimates above 40 gCO₂e/kWh. Dones also argues that Storm van Leeuwen and Smith's treatment of greenhouse gases associated with the natural gas supply chain are inconsistent, that they rely on outdated references for some of their estimates, and that some of their cost conversion estimates are too generic. Dones argues that they pay no consideration to the coproduction of minerals, a common practice where economically viable mining and milling of low-grade uranium take place with other activities, meaning

Table 1
Lifecycle studies excluded by date

Study	Location	Estimate (gCO ₂ e/kWh)
Arron et al. (1991)	Canada	–
Bodansky (1992)	World	5.7–17
Bowers et al. (1987)	–	–
Bude (1985)	–	–
Chapman et al. (1974)	–	–
Chapman (1975)	–	–
CRIEPI (1995)	Japan	22
DeLucchi (1993)	United States	40–69
Dones (1995)	World	–
Dones and Frischknecht (1996)	World	–
Dones et al. (1994)	World	–
El-Bassioni (1980)	–	–
ERDA (1976)	United States	–
ExternE (1995)	Europe	–
Held (1977)	–	20
Hohenwarter and Heindler (1988)	Germany	–
IAEA (1996a)	World	–
IAEA (1996b)	World	–
IEA (1994)	World	30–60
Kivisto (1995)	Finland	17–59
Mortimer (1989)	United Kingdom	–
Mortimer (1991a)	World	47–54
Mortimer (1991b)	World	47–54
Perry (1977)	United States	–
Proops et al. (1996)	United Kingdom	2.83
Raeder (1977)	–	–
Rombough and Koen (1975)	–	–
Rose et al. (1983)	United States	–
Sandgren and Sorteberg (1994)	Norway	–
Science Concepts (1990)	United States	30
Spreng (1988)	–	–
Taylor (1996)	World	19.7
Tsoufanidis (1980)	United States	–
Tunbrant et al. (1996)	Sweden	–
Uchiyama (1994)	Japan	10.5–47
Uchiyama (1996)	–	–
Yasukawa et al. (1992)	Japan	–
Yoshioka et al. (1994)	Japan	–
White (1995)	United States	34.1–37.7
Whittle and Cameron (1977)	United States	–

Table 2
Lifecycle studies excluded by accessibility

Study	Location	Estimate (gCO ₂ e/kWh)	Reason excluded
ANRE (1999)	Japan	–	In Japanese
Dones et al. (2003a, b)	USA	~5	Only available toecoinvent subscribers
Dones et al. (2004c)	Switzerland	5–12	Only available toecoinvent subscribers
Dones (2003)	Europe	–	In German
Frischknecht (1995)	Germany	–	In German
Izuno et al. (2001)	Japan	–	In Japanese
Lewin (1993)	Germany	–	In German
Nuclear Energy Agency (2007)	World	–	Only available for purchase
Weis et al. (1990)	Germany	–	In German

Table 3
Lifecycle studies excluded by methodology^a

Study	Location	Estimate (g CO ₂ e/ kWh)	Reason excluded
Australia Coal Association (2001)	Australia	30–40	Relies on unpublished data
Barnaby and Kemp (2007a)	OECD Countries	11–130	Relies on secondary sources
Commonwealth of Australia (2006)	Australia, France, Germany, Japan, Sweden, Finland, United States	5–60	Relies on secondary sources
Delucchi (2003)	United States	26	Relies on unpublished data
Denholm and Kulcinski (2004)	World	10–100	Relies on secondary sources
Dones et al. (2004a)	World	~5–80	Relies on secondary sources
Echavarri (2007)	World	2.6–5.5	Relies on secondary sources
Fleming (2007)	World	88–134	Relies on secondary sources
Fritsche (1997)	Germany	34	Relies on unpublished GEMIS data
Fthenakis and Alsema (2006)	Europe	20–40	Relies on secondary sources
Gagnon et al. (2002)	World	15	Relies on unpublished data
Heede (2005)	United States	2.5–5.7	Relies on secondary sources
Koch (2000)	World	2–59	Relies on unpublished data
Krewitt et al. (1998)	Europe	19.7	Relies on unpublished data
Kulcinski (2002)	World	15	Relies on secondary sources
Lee et al. (2000)	South Korea	2.77	Relies on unpublished data
Lee et al. (2004)	South Korea	0.198–2.77	Relies on unpublished data
Meier (2002)	United States	17	Relies on secondary sources
Meier and Kulcinski (2002)	United States	15	Relies on secondary sources
Meier et al. (2005)	United States	17	Relies on secondary sources
Ontario Power Authority (2005)	Canada	5–12	Relies on unpublished data
Pembina Institute (2007)	Canada	10–120	Relies on secondary sources
Ruether et al. (2004)	United States	3	Relies on secondary sources
Spadaro et al. (2000)	World	2.5–5.7	Relies on unpublished data
Sustainable Development Commission (2006)	World	2–20	Relies on secondary sources
Tahara et al. (1997)	Japan	1.8	Relies on secondary sources
Tokimatsu et al. (2000)	Japan	20.9	Does not separate fuel cycle estimates for fission reactors
UKPOST (2006)	United Kingdom	~5	Relies on secondary sources and unpublished data
Utgikar and Thiesen (2006)	World	2–59	Relies on secondary sources
Van De Vate (1997)	World	9	Relies on unpublished FENCH data
Van De Vate (2003)	World	8.9	Relies on unpublished FENCH data
Vattenfall (1997)	Sweden	3.3	Relies on published utility data
World Energy Council (2004)	Australia, Germany, Sweden, Switzerland, and United Kingdom	3–40	Relies on unpublished data
Weisser (2007)	World	2.8–24	Relies on secondary sources
World Nuclear Association (2006)	Japan, Sweden, Finland	6–26	Relies on secondary sources

^a The phrase “relies on unpublished data” means that studies contained proprietary information, referenced data not published along with the study, did not explain their methodology, were not transparent about their data sources, or did not detail greenhouse gas emission estimates for separate parts of the nuclear fuel cycle in g CO₂e/kWh. The phrase “relies on secondary sources” means that studies merely quoted other previously published reports and did not provide any new calculations or synthetic analysis on their own.

energy expenditures allocated to uranium mining by Storm van Leeuwen and Smith may be high. As a result, Dones concludes that Storm van Leeuwen and Smith may overestimate the energy expenditures, and thus greenhouse gas emissions, associated with nuclear power.

4.2. Quality of uranium ore

Studies varied in their assumptions regarding the quality of uranium ore used in the nuclear fuel cycle. Low-grade uranium ores contain less than 0.01% yellowcake, and is at least ten times less concentrated than high-grade ores, meaning it takes 10 ton of ore to produce 1 kg of yellowcake. Put another way, if uranium ore grade declines by a factor of ten, then energy inputs to mining and milling must increase by at least a factor of ten (Diesendorf and Christoff, 2006). Storm van Leeuwen et al. (2007) point out that this can greatly skew estimates, as uranium of 10% U₃O₈ has emissions for mining and milling at just 0.04 g CO₂/kWh, whereas uranium at 0.013% grade has associated emissions more than 1500 times greater at 67 g CO₂/kWh. The same trend is true for the emissions associated with uranium mine land reclamation. With

uranium of 10% grade, emissions for reclamation are just 0.07 g CO₂e/kWh, but at 0.013%, they are 122 g CO₂/kWh.

4.3. Open-pit or underground uranium mining

The type of uranium mining will also reflect different CO₂e emissions. Open-pit mining often produces more gaseous radon and methane emissions than underground mines, and Andseta et al. (1998) note that mining techniques will release varying amounts of CO₂ based on the explosives and solvents they use to purify concentrate. They also point out that the carbon content associated with acid leaching used to extract uranium can vary, as well as the emissions associated with the use of lime to neutralize the resulting leached tailings. The emissions associated with uranium mining depend greatly on the local energy source for the mines. Andseta et al. (1998) note that in Canada, uranium extracted from mines closer to industrial centers relies on more efficient, centrally generated power. In contrast, remote mines there have relied on less efficient diesel generators that consumed 45,000 ton of fossil fuel per year/mine, releasing up to 138,000 ton of carbon dioxide every year (Andseta et al., 1998).

Table 4
Overview of detailed nuclear lifecycle studies^a

Study	Location	Assumptions	Fuel cycle	Individual estimate (g CO ₂ e/kWh)	Total estimate (g CO ₂ e/kWh)
Andseta et al. (1998)	Canada	CANDU heavy water reactor, 40-year lifecycle, high-quality natural uranium ore, enriched and charged with fossil fuel generators	Frontend Construction Operation Backend Decommissioning	0.68 2.22 11.9 – 0.61	15.41
Barnaby and Kemp (2007b)	United Kingdom	35-year lifecycle, average load factor of 85%, uranium ore grade of 0.15%	Frontend Construction Operation Backend Decommissioning	56 11.5 – – 16.5–54.5	84–122
Dones et al. (2005)	Switzerland	100-year lifecycle, <i>Gosgen</i> pressurized water reactor and <i>Liebstadt</i> boiling water reactor	Frontend Construction Operation Backend Decommissioning	3.5–10.2 1.1–1.3 – 0.4–0.5 –	5–12
Dones et al. (2003a, b)	Switzerland, France, and Germany	40-year lifecycle, existing boiling water reactors and pressurized water reactors using UCTE nuclear fuel chains	Frontend Construction Operation Backend Decommissioning	6–12 1.0–1.3 – 0.6 and 1.0 –	7.6–14.3
Dones et al. (2004b)	China	20-year lifecycle, once-through nuclear cycle using centrifuge technology	Frontend Construction Operation Backend Decommissioning	7.4–77.4 1.0–1.4 – 0.6–1.2 –	9–80
ExternE (1998)	United Kingdom	Analysis of emissions for construction of <i>Sizewell B</i> pressurized water reactor in the United Kingdom	Frontend Construction Operation Backend Decommissioning	– 11.5 – – –	11.5
Fritsche and Lim (2006) ^b	Germany	Analysis of emissions for a typical 1250 MW German reactor	Frontend Construction Operation Backend Decommissioning	20 11 – 33 –	64
Fthenakis and Kim (2007)	United States, Europe, and Japan	40-year lifecycle, 85% capacity factor, mix of diffusion and centrifuge enrichment	Frontend Construction Operation Backend Decommissioning	12–21.7 0.5–17.7 0.1–10.8 2.1–3.5 1.3	16–55
Hondo (2005)	Japan	Analysis of base-case emissions for operating Japanese nuclear reactors	Frontend Construction Operation Backend Decommissioning	17 2.8 3.2 0.8 0.4	24.2
IEA (2002) ^c	Sweden and Japan	40-year lifecycle for Swedish <i>Forsmark 3</i> boiling water reactor and 30 year lifecycle for Japanese boiling water reactor, advanced BWR, and fast breeder reactor	Frontend Construction Operation Backend Decommissioning	1.19–8.52 0.27–4.83 – 1.19–8.52 0.17	2.82–22
ISA (2006) ^d	Australia	Analysis of emissions for existing Australian light water reactors with uranium ore of 0.15% grade	Frontend Construction Operation Backend Decommissioning	4.5–58.5 1.1–13.5 2.6–34.5 1.7–22.2 0.1–1.3	10–130
ISA (2006) ^d	Australia	Analysis of emissions for existing Australian heavy water reactors with uranium ore of 0.15% grade	Frontend Construction Operation Backend Decommissioning	4.5–54 1.1–12.5 2.6–31.8 1.7–20.5 0.1–1.2	10–120

Table 4 (continued)

Study	Location	Assumptions	Fuel cycle	Individual estimate (g CO ₂ e/kWh)	Total estimate (g CO ₂ e/kWh)
Rashad and Hammad (2000)	Egypt	30 year lifecycle for a pressurized water reactor operating at 75% capacity	Frontend	23.5	26.4
			Construction	2.0	
			Operation	0.4	
			Backend	0.5	
			Decommissioning	–	
Storm van Leeuwen et al. (2005)	World	Analysis of emissions for existing nuclear reactors	Frontend	36	84–122
			Construction	12–35	
			Operation	–	
			Backend	17	
			Decommissioning	23–46	
Storm van Leeuwen (2006)	World	Analysis of emissions for existing nuclear reactors	Frontend	39	92–141
			Construction	13–36	
			Operation	–	
			Backend	17	
			Decommissioning	23–49	
Storm van Leeuwen et al. (2007)	World	Analysis of emissions for existing nuclear reactors assuming 0.06% uranium ore, 70% centrifuge and 30% diffusion enrichment, and inclusion of interim and permanent storage and mine land reclamation	Frontend	16.26–28.27	112.47–165.72
			Construction	16.8–23.2	
			Operation	24.4	
			Backend	15.51–40.75	
			Decommissioning	39.5–49.1	
Tokimatsu et al. (2006) ^e	Japan	60-year lifecycle, light water reactor reference case, emissions for 1960–2000	Frontend	5.9–118	10–200
			Construction	1.3–26	
			Operation	2.0–40	
			Backend	0.7–14	
			Decommissioning	0.1–2	
Vorspools et al. (2000)	World	Analysis of emissions for construction and decommissioning of existing reactors	Frontend	–	3
			Construction	~2	
			Operation	–	
			Backend	–	
			Decommissioning	~1	
White and Kulcinski (2000)	United States	40-year lifecycle of 1000 MW pressurized water reactor operating at 75% capacity factor	Frontend	9.5	15
			Construction	1.9	
			Operation	2.2	
			Backend	1.4	
			Decommissioning	0.01	

^a Frontend includes mining and milling, conversion, enrichment, fuel fabrication, and transportation. Construction includes all materials and energy inputs for building the facility. Operation includes energy needed for maintenance, cooling and fuel cycles, backup generators, and during outages and shutdowns. Backend includes fuel processing, conditioning, reprocessing, interim and permanent storage. Plant decommissioning includes deconstruction of facility and land reclamation.

^b Study mentions a total of 31 g kWh for ore extraction, enrichment, and construction, and another 33 g kWh of other greenhouse gases other than carbon.

^c The IEA study combined upstream and downstream emissions in their estimate. They have been divided equally over the upstream and downstream phases.

^d Numbers derived from 10 to 130/120 estimate and then apportioned according to percentages given in Figs. 5.11 and 5.22.

^e Numbers derived from 10 to 200 g/kWh estimate and apportioned according to percentages provided in Fig. 3(c).

Table 5

Summary statistics of qualified studies reporting projected greenhouse gas emissions for nuclear power plants^a

(g CO ₂ e/kWh)	Frontend	Construction	Operation	Backend	Decommissioning	Total
Min	0.58	0.27	0.1	0.4	0.01	1.36
Max	118	35	40	40.75	54.5	288.25
Mean	25.09	8.20	11.58	9.2	12.01	66.08
N	17	19	9	15	13	

^a Frontend includes mining and milling, conversion, enrichment, fuel fabrication, and transportation. Construction includes all materials and energy inputs for building the facility. Operation includes energy needed for maintenance, cooling and fuel cycles, backup generators, and during outages and shutdowns. Backend includes fuel processing, conditioning, reprocessing, interim and permanent storage. Plant decommissioning includes deconstruction of facility and land reclamation.

4.4. Gaseous diffusion or centrifuge enrichment

Another significant variation concerns the type of uranium enrichment. Dones et al. (2005) note that gaseous diffusion is much

more energy-intensive, and therefore has higher associated carbon dioxide emissions. Gaseous diffusion requires 2400–2600 kWh per separative work unit (a function measuring the amount of uranium processed proportioned to energy expended for enrichment),

Table 6
Mean statistics of qualified studies reporting lifecycle equivalent greenhouse gas emissions for nuclear plants

Study	Frontend	Construction	Operation	Backend	Decommissioning
Andseta et al. (1998)	0.68	2.22	11.9	–	0.61
Barnaby and Kemp (2007b)	56	11.5	–	–	35.5
Dones et al. (2005)	6.85	1.2	–	0.45	–
Dones et al. (2003a,b)	9	1.15	–	0.8	–
Dones et al. (2004b)	42.4	1.2	–	0.9	–
ExternE (1998)	–	11.5	–	–	–
Fritsche and Lim (2006)	20	11	–	33	–
Fthenakis and Kim (2007)	16.85	9.1	5.41	2.8	1.3
Hondo (2005)	17	2.8	3.2	0.8	0.4
IEA (2002)	4.86	2.55	–	4.86	0.17
ISA (2006)	31.5	7.3	18.55	11.95	0.7
ISA (2006)	29.25	6.8	17.2	11.1	0.65
Rashad and Hammad (2000)	23.5	2	0.4	0.5	–
Storm van Leeuwen et al. (2005)	36	23.5	–	17	34.5
Storm van Leeuwen and Willem (2006)	39	24.5	–	17	36
Storm van Leeuwen et al. (2007)	22.27	20	24.4	28.13	44.3
Tokimatsu et al. (2006)	61.95	13.65	21	7.35	1.05
Vorspools et al. (2000)	–	2	–	–	1
White and Kulcinski (2000)	9.5	1.9	2.2	1.4	0.01
Mean	25.09	8.2	11.58	9.2	12.01

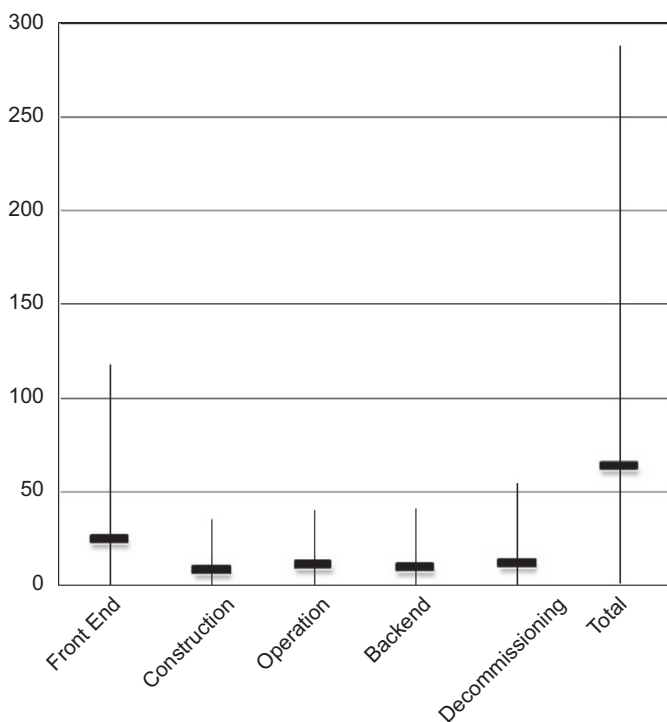


Fig. 3. Range and mean emissions reported from qualified studies for the nuclear fuel cycle (g CO₂e/kWh)

compared to just 40 kWh per SWU for centrifuge techniques. The energy requirements for these two processes are so vastly different because gaseous diffusion is a much older technology, necessitating extensive electrical and cooling systems that are not found in centrifuge facilities.

Emissions will further vary on the local power sources at the enrichment facilities. Dones et al. (2004a–c) calculate 9 g CO₂e/kWh for Chinese centrifuge enrichment relying on a mix of renewable and centralized power sources, but up to 80 g CO₂e/kWh if gaseous diffusion is powered completely by fossil fuels.

4.5. Individual or aggregate estimates

Some studies look at just specific reactors, while others assess emissions based on industry, national, and global averages. These obviously produce divergent estimates. Dones et al. (2005) look at just two actual reactors in Switzerland, the *Gosgen* pressurized water reactor and *Liebstadt* boiling water reactor and calculate emissions at 5–12 g CO₂e/kWh, whereas other studies look at global reactor performance and reach estimates more than 10 times greater.

4.6. Historical or marginal/future emissions

Yet another difference concerns whether researchers assessed historic, future, or prototypical emissions. Studies assessing historic emissions looked only at emissions related to real plants operating in the past; studies looking at future average emissions looked at how existing plants would perform in the years to come; studies analyzing prototypical emissions looked at how advanced plants yet to be built would perform in the future. Tokimatsu et al. (2006), for instance, found historical emissions for light water reactors in Japan from 1960 to 2000 to be rather high at between 10 and 200 g CO₂e/kWh. Others, such as Dones et al. (2005), looked at future emissions for the next 100 years using more advanced pressurized water reactors and boiling water reactors. Still other studies made different assumptions about future reactors, namely fast-breeder reactors using plutonium and thorium, and other Generation IV nuclear technology expected to be much more efficient if they ever reach commercial production.

4.7. Reactor type

Studies varied extensively in the types of reactors they analyzed. More than 30 commercial reactor designs exist today, and each differs in its fuel cycle, output, and cooling system. The most common are the world's 263 pressurized water reactors, used in France, Japan, Russia and the US, which rely on enriched uranium oxide as a fuel with water as coolant. Boiling water reactors are second most common, with 92 in operation throughout the US, Japan, and Sweden,

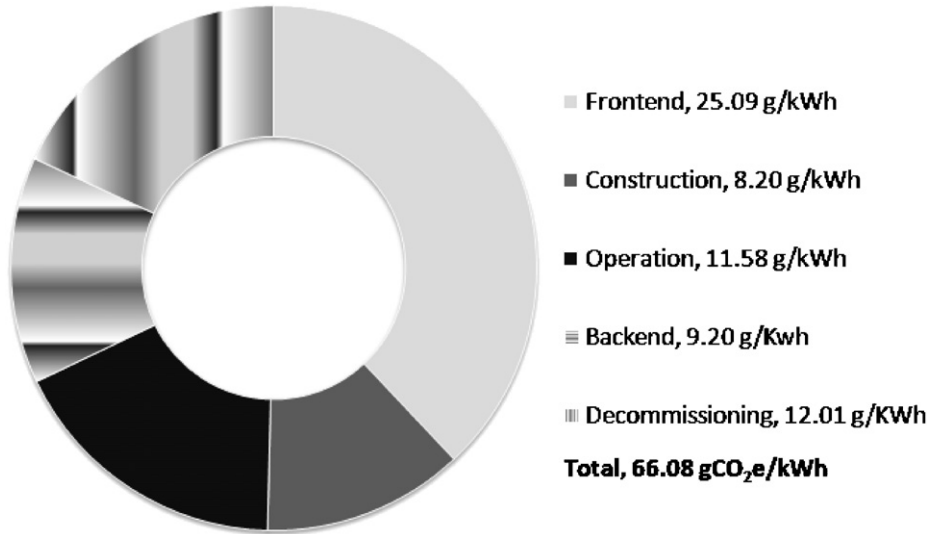


Fig. 4. Mean emissions reported from qualified studies for the nuclear fuel cycle (gCO₂e/kWh).

Table 7
Emissions for the nuclear fuel cycle from storm van Leeuwen and Smith (2007), in gCO₂/kWh

Nuclear process	Estimate (g CO ₂ /kWh)
<i>Frontend (total)</i>	16.26–28.27
Uranium mining and milling (soft and hard ores) (uranium grade of 0.06%)	10.43
Refining of yellow cake and conversion to UF ₆	2.42–7.49
Uranium enrichment (70% UC, 30% diff)	2.83–8.03
Fuel fabrication	0.58–2.32
<i>Construction (total)</i>	16.8–23.2
<i>Reactor operation and maintenance (total)</i>	24.4
<i>Backend (total)</i>	15.51–40.75
Depleted uranium reconversion	2.10–6.24
Packaging depleted uranium	0.12–0.37
Packaging enrichment waste	0.16–0.46
Packaging operational waste	1.93–3.91
Packaging decommissioned waste	2.25–3.11
Sequestration of depleted uranium	0.12–0.35
Sequestration of enrichment waste	0.16–0.44
Sequestration of operational waste	1.84–3.73
Sequestration of enrichment waste	1.98–2.74
Interim storage at reactor	0.58–2.32
Spent fuel conditioning for final disposal	0.35–1.40
Construction, storage, and closure of permanent geologic repository	3.92–15.68
<i>Decommissioning (total)</i>	39.5–49.1
Decommissioning and dismantling	25.2–34.8
Land Reclamation of uranium mine (uranium grade of 0.06%)	14.3
Total	112.47–165.72

which also rely on enriched uranium oxide with water as a coolant. Then come pressurized heavy water reactors, of which there are 38 in Canada, that use natural uranium oxide with heavy water as a coolant. Next comes 26 gas-cooled reactors, used predominately in the United Kingdom, which rely on natural uranium and carbon dioxide as a coolant. Russia also operates 17 light water graphite reactors that use enriched uranium oxide with water as a coolant but graphite as a moderator. A handful of experimental reactors, including fast-breeder reactors (cooled by liquid sodium) and pebble bed modular reactors (which can operate at full load while being refueled), still in the prototype stages, make up the rest of the world total (Beckjord et al. 2003).

To give an idea about how much reactor design can influence lifecycle emissions, Boczar et al. (1998) comment that CANDU reactors are the most neutron efficient commercial reactors, achieving their efficiency through the use of heavy water for both coolant and moderator, and reliance on low-neutron-absorbing materials in the reactor core. CANDU reactors thus have the ability to utilize low-grade nuclear fuels and refuel while still producing power, minimizing equivalent carbon dioxide emissions. This could be why Andseta et al. (1998) conclude that CANDU reactors have relatively low emissions (~15 g CO₂e/kWh) compared to the average emissions from qualified studies as described by this work (~66 g CO₂e/kWh). Others, such as Storm van Leeuwen et al. (2007), contest these numbers and argue that the production of heavy water associated with CANDU reactors is very energy-intensive and can produce emissions more than a factor of one greater than the projection made by Andseta et al.

4.8. Site selection

Estimates vary significantly based on the specific reactor site analyzed. The Sustainable Development Commission (2006) argues that location influences reactor performance (and consequential carbon-equivalent emissions). Some of the ways that location may influence lifetime emissions include differences in:

- construction techniques, including available materials, component manufacturing, and skilled labor;
- local energy mix at that point of construction;
- travel distance for materials and fuel cycle components;
- associated carbon footprint with the transmission and distribution (T&D) network needed to connect to the facility;
- cooling fuel cycle based on availability of water and local hydrology;
- environmental controls based on local permitting and siting requirements.

Each of these can substantially affect the energy intensity and efficiency of the nuclear fuel cycle.

Consider two extremes from Table 4. In Canada, the greenhouse gas-equivalent emissions associated with the CANDU lifecycle are estimated at about 15 g CO₂e/kWh. CANDU reactors tend to be built with skilled labor and advanced construction

techniques, and they utilize uranium that is produced domestically and relatively close to reactor sites, enriched with cleaner technologies in a regulatory environment with rigorous environmental controls. By contrast, the greenhouse-gas-equivalent emissions associated with the Chinese nuclear lifecycle can be as high as 80 gCO₂e/kWh. This could be because Chinese reactors tend to be built using more labor-intensive construction techniques, must import uranium thousands of miles from Australia, and enrich fuel primarily with coal-fired power plants that have comparatively less stringent environmental and air-quality controls.

4.9. Operational lifetime

How long the plants at those sites are operated and their capacity factor influences the estimates of their carbon dioxide-equivalent intensity. Storm van Leeuwen et al. (2007) note that a 30-year operating lifetime of a nuclear plant with a load factor of 82% tends to produce 23.2 gCO₂/kWh for construction. Switch the load factor to 85% and the lifetime to 40 years, and the emissions drop about 25% to 16.8 gCO₂/kWh. The same is true for decommissioning. A plant operating for 30 years at 82% capacity factor produces 34.8 gCO₂/kWh for decommissioning, but drop 28% to 25.2 gCO₂/kWh if the capacity factor improves to 85% and the plant is operated for 40 years.

Most of the qualified studies referenced above assume lifetime nuclear capacity factors that do not seem to match actual performance. Almost all of the qualified studies reported capacity factors of 85–98%, where actual operating performance has been less. While the nuclear industry in the US has boasted recent capacity factors in the 90% range, average load factors over the entire life of the plants is very different: 66.3% for plants in the UK (Association of Electricity Producers, 2007) and 81% for the world average (May, 2002).

4.10. Type of lifecycle analysis

The type of lifecycle analysis can also skew estimates. Projections can be “top-down,” meaning they start with overall estimates of a pollutant, assign percentages to a certain activity (such as “cement manufacturing” or “coal transportation”), and derive estimates of pollution from particular plants and industries. Or they can be “bottom-up,” meaning that they start with a particular component of the nuclear lifecycle, calculate emissions for it, and move along the cycle, aggregating them. Similarly, lifecycle studies can be “process-based” or rely on economic “input–output analysis.” “Process-based” studies focus on the amount of pollutant released—in this case, carbon dioxide or its equivalent—per product unit. For example, if the amount of hypothesized carbon dioxide associated with every kWh of electricity generation for a region was 10g, and the cement needed for a nuclear reactor took 10 kWh to manufacture, a process analysis would conclude that the cement was responsible for 100g of CO₂. “Input–output” analysis looks at industry relations within the economy to depict how the output of one industry goes to another, where it serves as an input, and attempts to model carbon dioxide emissions as a matrix of interactions representing economic activity.

Storm van Leeuwen et al. (2007), for example, rely heavily on calculating average energy intensity for various parts of the nuclear fuel cycle and aggregate those numbers into a final estimate. Dones et al. (2004a–c) uses process analysis to describe the full lifecycle of specific industries associated with the nuclear fuel cycle, such as material and chemical manufacturing, energy conversion, electricity transmission, and waste management. The

ISA (2006) uses a hybrid lifecycle assessment that combines process analysis with input and output methodologies. These different approaches produce understandably different results.

5. Conclusion

The first conclusion is that the mean value of emissions over the course of the lifetime of a nuclear reactor (reported from qualified studies) is 66 gCO₂e/kWh, due to reliance on existing fossil-fuel infrastructure for plant construction, decommissioning, and fuel processing along with the energy intensity of uranium mining and enrichment. Thus, nuclear energy is in no way “carbon free” or “emissions free,” even though it is much better (from purely a carbon-equivalent emissions standpoint) than coal, oil, and natural gas electricity generators, but worse than renewable and small scale distributed generators (see Table 8). For example, Gagnon et al. (2002) found that coal, oil, diesel, and natural gas generators emitted between 443 and 1050 gCO₂e/kWh, far more than the 66 gCO₂e/kWh attributed to the nuclear lifecycle. However, Pehnt (2006) conducted lifecycle analyses for 15 separate distributed generation and renewable energy technologies and found that all but one, solar photovoltaics (PV), emitted much less gCO₂e/kWh than the mean reported for nuclear plants. In an analysis using updated data on solar PV, Fthenakis et al. (2008) found that current estimates on the greenhouse gas emissions for typical solar PV systems range from 29 to 35 gCO₂e/kWh (based on insolation of 1700 kWh/m²/yr and a performance ratio of 0.8).

The second (and perhaps more obvious) conclusion is that lifecycle studies of greenhouse gas emissions associated with the nuclear fuel cycle need to become more accurate, transparent, accountable, and comprehensive. Thirty-nine percent of lifecycle studies reviewed were more than 10 years old. Nine percent, while cited in the literature, were inaccessible. Thirty-four percent did not explain their research methodology, relied completely on

Table 8
Lifecycle estimates for electricity generators^a

Technology	Capacity/configuration/fuel	Estimate (gCO ₂ e/kWh)
Wind	2.5 MW, offshore	9
Hydroelectric	3.1 MW, reservoir	10
Wind	1.5 MW, onshore	10
Biogas	Anaerobic digestion	11
Hydroelectric	300 kW, run-of-river	13
Solar thermal	80 MW, parabolic trough	13
Biomass	Forest wood Co-combustion with hard coal	14
Biomass	Forest wood steam turbine	22
Biomass	Short rotation forestry Co-combustion with hard coal	23
Biomass	FOREST WOOD reciprocating engine	27
Biomass	Waste wood steam turbine	31
Solar PV	Polycrystalline silicone	32
Biomass	Short rotation forestry steam turbine	35
Geothermal	80 MW, hot dry rock	38
Biomass	Short rotation forestry reciprocating engine	41
Nuclear	Various reactor types	66
Natural gas	Various combined cycle turbines	443
Fuel cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1050

^a Wind, hydroelectric, biogas, solar thermal, biomass, and geothermal, estimates taken from Pehnt (2006). Diesel, heavy oil, coal with scrubbing, coal without scrubbing, natural gas, and fuel cell estimates taken and Gagnon et al. (2002). Solar PV estimates taken from Fthenakis et al. (2008). Nuclear is taken from this study. Estimates have been rounded to the nearest whole number.

secondary sources, or were not explicit about the distribution of carbon-equivalent emissions over the different stages of the nuclear fuel cycle. All in all, this meant that 81% of studies had methodological shortcomings that justified excluding them from the assessment conducted here. No identifiable industry standard provides guidance for utilities and companies operating nuclear facilities concerning how to report their carbon-equivalent emissions. Regulators, utilities, and operators should consider developing formal standardization and reporting criteria for the greenhouse gas emissions associated with nuclear lifecycles similar to those that provide general guidance for environmental management and lifecycle assessment, such as ISO 14040 and 14044, but adapted exclusively to the nuclear industry.

Of the remaining 19% of studies that were relatively up to date, accessible, and methodologically explicit, they varied greatly in their comprehensiveness, some counting just construction and decommissioning as part of the fuel cycle, and others including mining, milling, enrichment, conversion, construction, operation, processing, waste storage, and decommissioning. Adding even more variation, studies differed in whether they assessed future emissions for a few individual reactors or past emissions for the global nuclear fleet; assumed existing technologies or those under development; and presumed whether the electricity needed for mining and enrichment came from fossil fuels, other nuclear plants, renewable energy technologies, or a combination thereof.

Furthermore, the specific reactors studied differ greatly themselves. Some utilize relatively high-quality uranium ore located close to the reactor site; others require the importation of low-quality ore from thousands of kilometers away. A nuclear plant in Canada may receive its fuel from open-pit uranium mines enriched at a gaseous diffusion facility, whereas a reactor in Egypt may receive its fuel from an underground mine enriched through centrifuge. A nuclear facility in France may operate with a load factor of 83% for 40 years on a closed fuel cycle relying on reprocessed fuel, whereas a light water reactor in the United States may operate with a load factor of 81% for 25 years on a once-through fuel cycle that generates significant amounts of spent nuclear fuel.

Rather than detail the complexity and variation inherent in the greenhouse gas emissions associated with the nuclear lifecycle, most studies obscure it; especially those motivated on both sides of the nuclear debate attempting to make nuclear energy look cleaner or dirtier than it really is.

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