Life Cycle Greenhouse Gas Emissions of Nuclear Electricity Generation

Systematic Review and Harmonization

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Summary

A systematic review and harmonization of life cycle assessment (LCA) literature of nuclear electricity generation technologies was performed to determine causes of and, where possible, reduce variability in estimates of life cycle greenhouse gas (GHG) emissions to clarify the state of knowledge and inform decision making. LCA literature indicates that life cycle GHG emissions from nuclear power are a fraction of traditional fossil sources, but the conditions and assumptions under which nuclear power are deployed can have a significant impact on the magnitude of life cycle GHG emissions relative to renewable technologies.

Screening 274 references yielded 27 that reported 99 independent estimates of life cycle GHG emissions from light water reactors (LWRs). The published median, interquartile range (IQR), and range for the pool of LWR life cycle GHG emission estimates were 13, 23, and 220 grams of carbon dioxide equivalent per kilowatt-hour (g CO_2-eq/kWh), respectively. After harmonizing methods to use consistent gross system boundaries and values for several important system parameters, the same statistics were 12, 17, and 110 g CO_2-eq/kWh, respectively. Harmonization (especially of performance characteristics) clarifies the estimation of central tendency and variability.

To explain the remaining variability, several additional, highly influential consequential factors were examined using other methods. These factors included the primary source energy mix, uranium ore grade, and the selected LCA method. For example, a scenario analysis of future global nuclear development examined the effects of a decreasing global uranium market-average ore grade on life cycle GHG emissions. Depending on conditions, median life cycle GHG emissions could be 9 to 110 g CO_2-eq/kWh by 2050.

Introduction

Background

Nuclear power is an often highlighted option for capacity increases because of the need for a low greenhouse gas (GHG)-emitting, reliable base-load electricity generation technology (Nuclear Energy Institute 2012). Uranium ore goes through an extensive extraction and conversion process that requires significant energy inputs that can generate significant indirect GHG emissions attributable to nuclear power. Nuclear power's GHG emission reduction potential compared to the current fossil fuel-based power system depends on evaluating these indirect emissions, typically through the use of life cycle assessments (LCAs). Methodological and contextual inconsistency between the many published nuclear power LCAs has resulted in widely ranging results, making

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direct comparison difficult and thwarting a clear, collective understanding.

Past literature has devoted some effort to assessing, reducing, and explaining the uncertainty and variability in selected published estimates of life cycle GHG emissions from nuclear power. Fthenakis and Kim (2007) explored some significant causes of life cycle GHG emissions variability by creating several future nuclear power scenarios for the United States from a small sample of prior LCAs. They concluded that GHG emission estimate variation could be largely explained by LCA method choice and contextual factors. LCA methods included the process chain analysis (PCA), economic input/output (EIO), or average economic intensity (AEI), which is a highly aggregated version of EIO. Contextual factors included the uranium enrichment method and primary source energy mix. Primary source energy mix refers to the combination of different primary energy sources (coal, natural gas, oil, hydropower, wind, solar, nuclear, etc.) that supply energy to an economy. The energy mix is a proxy for exact knowledge of the GHG emissions profile of the primary energy sources, which contributes to embodied GHG emissions of economic products. The economic products of importance in the context of nuclear power are primarily enriched uranium.

Two other related meta-analyses (Lenzen 2008; Lenzen et al. 2006) reviewed studies of energy use throughout the nuclear life cycle to construct a series of scenario-based estimates for Australia using regression analysis. These studies included a literature pool not limited to LCAs. Potentially important regression variables were similar to Fthenakis and Kim (2007), but also included system boundaries, uranium ore grade, and conversion rates.

Sovacool (2008) assessed a more comprehensive collection of LCA literature (103 references), utilizing 19 studies to calculate an arithmetic mean and range for life cycle GHG emissions from nuclear power.

Finally, Beerten and colleagues (2009) mostly qualitatively analyzed a small subset of three studies representing extreme life cycle GHG emission estimates. In the course of recalculating the results of past studies, Beerten and colleagues (2009) explored differences in methods and assumptions and critiqued flaws in each. Conclusions about significant sources of life cycle GHG emission variability largely overlapped with the above-described meta-analyses.

Purpose/Goal

The objectives of the present meta-analysis include identifying, explaining, and, where possible, reducing variability—through a meta-analytical process called "harmonization"—in estimates of life cycle GHG emissions for nuclear power. The purpose of this analysis and its umbrella project, the LCA Harmonization Project,[1] which examines other electricity generation technologies such as coal and natural gas, is to inform decision making and future analyses that rely on such estimates. (Articles from the LCA Harmonization Project appearing in this special issue on meta-analysis of LCAs perform similar analysis on crystalline silicon photovoltaic [Hsu et al. 2012], thin film photovoltaic [Kim et al. 2012], coal [Whitaker et al. 2012], concentrating solar power [Burkhardt et al. 2012], and wind [Dolan and Heath 2012].) Some contextual and/or consequential factors effecting life cycle GHG emission variability, previously identified in LCAs as significant, would be difficult to address through harmonization. For these, other methods are used to explain and/or reduce potential life cycle GHG emission variability.

Harmonization Methods

Life Cycle Phase Definitions and Conceptual Process Description

Figure 1 illustrates the life cycle of electricity generated from nuclear power, as defined in this study. The dotted box indicates the system boundary achieved through harmonization. We grouped life cycle phases into three aggregate categories:

- **Upstream processes**: Upstream processes occur once prior to operational processes, and include facility construction and supply of materials.
- **Operational processes**: Operational processes result in GHGs emitted on a continual basis per unit of electricity generated. They include uranium mining, milling, conversion, enrichment, fuel rod fabrication, transportation, facility operation and to maintenance, and reprocessing. Uranium mine rehabilitation is also included as an operational phase process because the need for mine rehabilitation is modulated by how much uranium is demanded for electricity generation.
- **Downstream processes**: Downstream processes occur once after a facility's operational processes cease, and include facility decommissioning; nonradioactive waste disposal/recycling; and temporary, long-term, and permanent radioactive waste storage after electricity generation and facility lifetime.

Operational processes could have been further subdivided into processes related directly to facility operations and to uranium processing. However, facility operations were typically negligible or aggregated with other operational processes. Temporary storage was grouped with downstream processes for two reasons. Temporary storage GHG emissions were usually aggregated with long-term storage and were generally associated with nonoperational processes despite temporary storage typically located on-site and occurring during the period of facility operation. Resource prospecting was rarely discussed in the literature and not evaluated here. In the supporting information available on the Journal's Web site, a section entitled *Life Cycle Phase Definitions and Conceptual Process Description* contains a more detailed description and discussion of the nuclear life cycle and collected LCA literature.

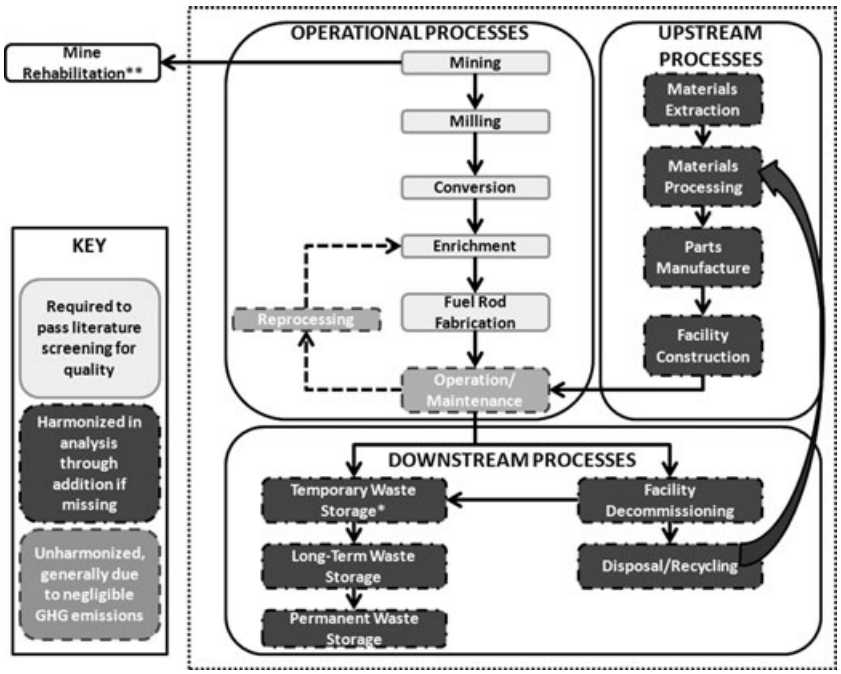

Figure 1 Life cycle assessment (LCA) harmonization system boundaries (dotted line box) for nuclear power electricity generation. Elements outside the system boundary are harmonized by subtraction. Arrows typically indicate transportation and remain unharmonized due to negligible greenhouse gas (GHG) emissions. *Applies only to highly radioactive wastes. **Occurs once, but its impact on electricity generation is modulated by fuel demand.

Literature Collection and Screening Approach

A comprehensive search of the English-language literature resulted in 274 references pertaining to life cycle environmental impacts of nuclear electricity generation. A single article often reported multiple estimates of life cycle GHG emissions, which we call "scenarios." Consistent with the established screening methodology for the LCA Harmonization Project, scenarios were processed through two rounds of review to determine whether to include them in this meta-analysis. Although an entire reference wasn't necessarily eliminated if only one of its scenarios was screened out, most screening criteria applied to the reference as a whole. Therefore the results of screening are reported at the level of the reference.

Primary Screening

The first screen, used as a coarse indicator of quality, removed papers that did not evaluate electricity as the product; were abstracts, posters, PowerPoint presentations, conference papers less than five double-spaced pages, and trade journal articles less than three double-spaced pages; or were published prior to 1980. Articles that were not LCAs—defined as having evaluated at least two life cycle phases—also did not meet our criteria. Of the 274 references collected, 199 met these criteria.

Secondary Screening

A second, more rigorous, quality screen established a minimum standard for inclusion in the final pool of literature. Article criteria included requirements of quality LCA and GHG accounting methods, completeness of reporting methods and results, and that the evaluated technology or design was of modern relevance (i.e., operating currently or could begin construction today). Sixty-six papers passed these quality and relevance criteria.

To satisfy the quality LCA and GHG methods criterion, a study needed to evaluate uranium mining/milling, conversion, enrichment, and fuel fabrication as a part of the LCA. Studies that used AEI methods were excluded. The AEI method has been identified as producing inaccurately high outlier estimates, as well as other critiques, even relative to studies using more common EIO methods (Beerten et al. 2009; Fthenakis and Kim 2007; Lenzen 2008; Lenzen et al. 2006). We decided not to require that GHGs more than carbon dioxide (CO_2) (i.e., nitrous oxide [N_2O] and methane [CH_4]) be evaluated because (1) studies that accounted for more GHGs did not systematically estimate higher GHG emissions than those that accounted for fewer, (2) negligible N_2O emissions were only once reported in any nuclear power LCA that would otherwise pass the second screen, and (3) the highest estimated contribution of CH_4 to life cycle GHG emissions was 0.5 grams carbon dioxide equivalent per kilowatt-hour (g CO_2-eq/kWh), which is a negligible contribution (Dones et al. 1996).[2]

Only GHG emission estimates that were reported numerically (and not just graphically) and provided sufficient detail on the analyzed system to evaluate the reasonableness of the data were included for harmonization. Duplicate estimates from one study quoting another or from the same author group publishing the same estimate multiple times were not included. Estimates

reported in another functional unit (e.g., avoided GHG emissions) that could not be converted to grams carbon dioxide equivalent per kilowatt-hour were not retained for analysis. No exogenous assumptions were employed in such conversions or in any other stage of this research. Of the 66 references that passed the screening process, 34 contained original GHG emissions estimates convertible to the necessary functional unit for the following nuclear technologies:

- light water reactor (LWR), including (27 references)
  - —pressurized water reactor (PWR) (15 references)
  - —boiling water reactor (BWR) (7 references)
- advanced gas-cooled reactor (AGR) (3 references)
- heavy water reactor (HWR) (4 references)
- fast breeder reactor (FBR) (3 references)

Twenty-three references disaggregated GHG emissions by life cycle phase, the results of which are summarized in the supporting information section *Published Results* on the Web.

Previously published LCAs focused on LWRs more than all other nuclear power technologies combined. Given the LWR focus of the literature and of the current nuclear industry (U.S. and global), this article focuses on presenting and discussing the results for LWR technologies. Harmonization was carried out for the other technologies, and is reported in the supporting information on the Web, as more specifically noted below.

LWRs have two subclassifications: boiling water reactors (BWRs) and pressurized water reactors (PWRs). Some studies only addressed specific subtechnologies, while others, because of their similarities, addressed the broader LWR category. Our study reports results for LWRs, BWRs, and PWRs, but discussion will focus almost exclusively on the broader LWR category. Only small differences in life cycle GHG emission results were found when comparing similar life cycle PWR and BWR systems that employed similar performance characteristics such as lifetime, thermal efficiency, and capacity factor (see the *Harmonized Results* section of the supporting information on the Web).

Results are based on 27 references reporting 99 LWR life cycle GHG emissions estimates. Of these LWR papers, 16 disaggregated life cycle GHG emissions by life cycle phase for a total of 24 estimates. Fifteen estimates from seven references evaluated unspecified mixes of BWRs and PWRs. These are included only in the broad LWR grouping of the *Results and Discussion* section of this article.

Harmonization Approach

Level of Harmonization

For the LCA Harmonization Project as a whole, two levels of harmonization were devised. The more resource-intensive level was envisioned as a process similar to that employed by Farrell and colleagues (2006) to harmonize the results of LCAs of ethanol. In that process, a subset of the available literature estimates of life cycle GHG emissions was carefully disaggregated. This process produced a detailed meta-model based on factors such as adjusted parameter estimates, realigned system boundaries within each life cycle phase, and a review of all data sources. A less intensive approach is more appropriate for the harmonization of a larger set of literature estimates of life cycle GHG emissions at a more gross level. The less-intensive approach was chosen as the appropriate level of harmonization for nuclear power LCAs. The decision-making process for the level of harmonization is discussed in the *Level of Harmonization* section of the supporting information on the Web.

In keeping with the less-intensive harmonization approach, estimates were not audited for accuracy; published GHG emission estimates were taken at face value and converted to consistent units prior to being harmonized. Additionally, no exogenous assumptions were employed; if a reference did not report the information required for harmonization or conversion to the common functional unit, no assumptions were made. The selection of the light harmonization process precluded full analytical harmonization of several more complex factors identified as potentially important determinants of nuclear power life cycle GHG emissions. Specifically, future uranium ore grade, primary source energy mix, LCA method, and uranium enrichment method were commonly identified important factors in previous meta-analyses of nuclear power LCAs. Collected life cycle GHG emissions data were qualitatively categorized to examine the effects of the latter three factors (see the *Other Qualitative Categorization Steps* section of this article). Published estimates of uranium ore grade were examined as a continuous variable. However, uranium ore grade was uncommonly reported and often did not vary significantly from study to study. Strong conclusions about the impact of uranium ore grade on life cycle GHG emissions based on the LCA literature alone were difficult to make. In the literature, the impacts of uranium ore grade on life cycle GHG emissions are generally mentioned in the context of potential future conditions. We likewise examine the impact of variations in ore grade on life cycle GHG emissions of nuclear power in a series of projections exploring the potential boundaries of its impact (see the *Future Uranium Ore Grade Scenario Projections* section of this article and the supporting information on the Web).

Statistical Assessment

Statistical assessments of the central tendency and variability of published and harmonized datasets are used to characterize the LCA studies passing the quality and relevance criteria. Central tendency is reported using both medians and arithmetic means (hereafter referred to as the "mean") of the datasets. Variability of the datasets also is described using multiple parameters, including the standard deviation (SD), the range (maximum value minus minimum value), and the interquartile range (IQR) (75th percentile value minus the 25th percentile value). The present discussion focuses on median and IQR, as these are more robust measures of dataset central tendency and spread than are the mean, SD, or range, because the median and IQR are not as heavily influenced by dataset outliers. However, the range is still discussed because in some cases harmonization only had significant effects on estimates

on the outer boundaries of the distribution. For each harmonization step, changes in central tendency and variability are compared with published estimates to describe the impact of the harmonization step.

These statistics are meant to summarize the current state of LCA literature of nuclear power technologies. Although the number of studies and estimates from those studies is reasonably large and we selected for only high-quality studies, the available studies might not cover all possible cases of manufacture, deployment, or use. Thus the range exhibited in this article may not represent the true minimum, maximum, or central tendency for nuclear power life cycle GHG emissions or the current state of the technology as deployed or anticipated. In addition, the literature passing screens may not necessarily include all relevant contributions with regard to the depth and breadth across the supply chain. For example, the difference in results generated using process chain compared to hybrid economic input-output methods indicates that system boundary truncations can have significant impacts (Suh et al. 2004). In this respect, the upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end.

The distribution of our results also cannot be considered a distribution of likelihood for actual life cycle GHG emissions for current or future applications of the technology. The precision and range of results is improved with the large sample size evaluated here, but sample limitations impact the accuracy of the results compared to the "true" life cycle GHG emissions range and central tendency of nuclear power under all potential conditions.

Finally, the impact of harmonizing a particular parameter on reducing variability is an indicator of the influence that parameter exerts on life cycle GHG emissions for nuclear electricity generation, but is not a formal sensitivity analysis.

Description of Analyzed Studies

Table 1 summarizes selected quantitative and qualitative descriptors of the evaluated technology and study characteristics. Data are drawn from the 27 LWR nuclear LCAs passing screens. Where not explicitly reported in the references, attempts were made to retrieve this information via personal communication with corresponding authors, but with limited success. Table S1 in the supporting information on the Web reports corresponding results for non-LWRs. Quantitative and qualitative descriptors (and acronyms) that appear in these tables are described below.

- **Technology type (Tech. type):** Nuclear power technology classification of light water reactor (LWR), boiling water reactor (BWR), pressurized water reactor (PWR), advanced gas-cooled reactor (AGR), heavy water reactor (HWR), and fast breeder reactor (FBR).
- **Thermal efficiency (TF)**: Net electricity generated divided by energy content of fuel input multiplied by 100 (%). LWR thermal efficiencies range from 30% to 36% in the literature passing screens. Generally BWRs have lower thermal efficiency than PWRs (Dones et al. 2007a).
- **Capacity (CP):** Electricity generating capacity of the power plant (in megawatts [MW]). In some cases the literature was unclear whether net or gross capacity was reported.
- **Operating lifetime (L):** Analysis lifetime for the LCA or facility (years). LWR operating lifetimes range from 25 to 60 years in the literature passing screens.
- **Capacity factor (CF):** The ratio of actual net electricity generation to maximum electricity generation of the facility (capacity multiplied by 8,760 hours/year) multiplied by 100 (%). LWR capacity factors range from 65% to 93% in the literature passing screens.
- **Missing life cycle phase (MLCF)**: Missing life cycle phases to be harmonized include nuclear waste management (W), facility construction (C), and facility decommissioning (D) (see the *Life Cycle Phase Definitions and Conceptual Process Description* section of this article and the supporting information on the Web).
- **Uranium mining method**: The mixture of open pit (OP), underground (U), uranium obtained as a by-product (U-BP), or in situ leaching (ISL) methods used to mine uranium, reported as a percentage of the total mass excavated (%). If the percentage is unspecified, the precise mixture was unspecified.
- **Uranium ore grade (UOG)**: Assumed average mined uranium ore grade. LWR uranium ore grade ranges from 0.01% to 12.7% in the literature passing screens.
- **Enrichment method (EM)**: The process assumed for uranium enrichment: gaseous diffusion (Diff.) or centrifuge (Cent.) methods, or mixtures primarily of centrifuge (M-Cent.) diffusion (M-Diff.), or an equal mixture (Cent.-Diff.).
- **Reprocessing (R)**: Is nuclear waste reprocessing included in the LCA (yes/no)?
- **Temporal vintage (Temp. vint.):** Describes the analyzed scenario as primarily a case study of an existing technology (CS), a hypothetical study of existing technologies (H), or a study of proposed future technologies (P).
- **LCA method (Mthd.)**: Characterization of whether the LCA mostly used process chain analysis (PCA) or a mix of PCA and economic input-output (EIO) economic input-output (EIO) methods (hybrid).
- **Data type:** Describes the data used in analyzed scenarios as primarily empirical (E) or theoretical (T).
- **Study location:** Identifies the location of the study by country or region (e.g., Union for the Coordination of Transmission of Electricity [UCTE] for Europe).
- **Primary source energy mix classification (PSEM)**: Classifies the GHG emissions intensity (low, medium, or high) of the background primary source energy mix based on either reported characteristics or by using location as a proxy. For comparison, "high," "medium," and "low"

Table 1 Select scenario attributes of light water reactor (LWR) life cycle assessment (LCA) studies that passed quality and relevance screens and contained original estimates. Abbreviations used are listed and described in the *Description of Analyzed Studies* section earlier in this article

Author(s)	*Year*	*Tech. type*	*TF (%)*	*CP (MW)*	*L (years)*	*CF (%)*	*MLCF*	*Uranium mining method*	*UOG (%)*	*EM*	*R*	*Temp. vint.*	*Mthd.*	*Data type*	*Other*	*Study location*	*PSEM*
AXPO Nuclear Energy	2008	PWR	—	730	50	93%	—	ISL	—	Cent.	Yes	CS	PCA	E	—	Switzerland	Low
Beerten et al.	2009	PWR	33%	1000	40	85%	W	38% U/62% OP	0.20%	Cent.-Diff.	No	H	PCA	E	—	Belgium	Low
Beerten et al.	2009	PWR	30%	1000	35	85%	—	40% U/60% OP	0.15%	M-Cent.	No	P	Hybrid	T	Coal Elec.	Australia	High
Beerten et al.	2009	PWR	30%	1000	35	85%	—	40% U/60% OP	0.15%	M-Cent.	No	P	Hybrid	T	N/Oil	Australia	Low
Beerten et al.	2009	PWR	30%	1000	35	85%	—	40% U/60% OP	0.15%	M-Cent.	No	P	Hybrid	T	EU/Oil	Australia	High
Beerten et al.	2009	PWR	30%	1000	35	85%	—	40% U/60% OP	0.15%	M-Cent.	No	P	Hybrid	T	EU/NG	Australia	Medium
Dones et al.	1996	LWR	—	1000	40	70%	D	U/OP	—	M-Diff.	Yes	CS	PCA	E	—	Switzerland	Low
Dones et al.	1996	LWR	—	1000	40	70%	D	U/OP	—	M-Diff.	Yes	CS	PCA	E	—	UCTE	Low
Dones et al.	1996	LWR	—	1000	40	70%	D	U/OP	—	M-Diff.	Yes	CS	PCA	E	—	UCTE	Medium
Dones et al.	1996	LWR	—	1000	40	70%	D	U/OP	—	Cent.	Yes	CS	PCA	E	—	UCTE	Medium
Dones et al.	2004	PWR	31%	1000	30	—	D	U/OP/ISL	—	Cent.	No	P	PCA	T	—	China	Low
Dones et al.	2005	LWR	33%	1000	40	80%	—	U/OP	—	M-Cent.	Yes	CS	PCA	E	—	UCTE	Low
Dones et al.	2005	PWR	32%	1000	40	89%	—	U/OP	—	Cent.	Yes	CS	PCA	E	—	Switzerland	Low
Dones et al.	2007a	BWR	32%	1000	40	89%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	Switzerland	Low
Dones et al.	2007a	BWR	33%	1000	40	85%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	Germany	Low
Dones et al.	2007a	BWR	33%	1000	40	80%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	UCTE	Low
Dones et al.	2007a	LWR	32%	1000	40	89%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	Switzerland	Low
Dones et al.	2007a	LWR	33%	1000	40	85%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	Germany	Low
Dones et al.	2007a	LWR	33%	1000	40	80%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	UCTE	Low
Dones et al.	2007a	PWR	32%	1000	40	89%	—	60% U/40% OP	—	Cent.	Yes	CS	PCA	E	—	Switzerland	Low
Dones et al.	2007a	PWR	32%	1000	40	89%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	Switzerland	Low
Dones et al.	2007a	PWR	33%	1000	40	85%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	Germany	Low
Dones et al.	2007a	PWR	33%	1000	40	72%	—	60% U/40% OP	—	Diff.	Yes	CS	PCA	E	—	France	Low
Dones et al.	2007a	PWR	33%	1000	40	80%	—	60% U/40% OP	—	M-Diff.	Yes	CS	PCA	E	—	UCTE	Low
Dones et al.	2007b	LWR	32%	1000	40	89%	—	U/OP	—	M-Cent.	No	H	PCA	E	—	US	Medium
Frischknecht	1998	PWR	31%	3000	30	85%	W, C, D	—	—	Cent.	Yes	H	PCA	E	—	France	Low
Fthenakis and Kim	2007	LWR	—	1100	40	85%	—	—	12.70%	Diff.	No	H	PCA	T	Worst	US	Medium
Fthenakis and Kim	2007	LWR	—	1100	40	85%	—	—	0.20%	Diff.	No	H	Hybrid	T	AVG	US	Medium
Fthenakis and Kim	2007	LWR	—	1100	40	85%	—	—	—	Diff.	No	H	Hybrid	T	Best	US	High
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	Cent.	No	H	Hybrid	E	—	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	Diff.	No	H	Hybrid	E	—	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	No	H	Hybrid	E	50 SD1	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	No	H	Hybrid	E	200 SD1	Japan	Medium

(Continued)

Table I *Continued*

Author(s)	*Year*	*Tech. type*	*TF (%)*	*CP (MW)*	*L (years)*	*CF (%)*	*MLCF*	*Uranium mining method*	*UOG (%)*	*EM*	*R*	*Temp. vint.*	*Mthd.*	*Data type*	*Other*	*Study location*	*PSEM*
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	No	H	Hybrid	E	200 SD2	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	Yes	H	Hybrid	E	50 SD1	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	No	H	Hybrid	E	50 SD2	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	Cent.	Yes	P	Hybrid	E	—	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	Diff.	Yes	P	Hybrid	E	—	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	Yes	P	Hybrid	E	50 SD2	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	Yes	P	Hybrid	E	200 SD1	Japan	Medium
Hondo	2005	BWR	32%	1000	30	70%	—	—	—	M-Diff.	Yes	P	Hybrid	E	200 SD2	Japan	Medium
Kivisto	1995	PWR	—	—	—	80%	W, D	—	—	Diff.	No	H	Hybrid	T	—	Finland	Medium
Kivisto	1995	PWR	—	—	—	80%	W, D	—	—	Cent.	No	H	Hybrid	T	—	Finland	Medium
Krewitt et al.	1997	PWR	—	1375	40	89%	C, D	OP	0.84%	Diff.	Yes	CS	Hybrid	E	—	Germany	Medium
Lecointe et al.	2007	PWR	34%	1000	40	80%	—	U/OP	1.00%	Diff.	Yes	H	PCA	E	—	EU	Low
Lecointe et al.	2007	PWR	34%	1000	60	86%	—	U/OP	1.00%	Diff.	Yes	P	PCA	T	BAU	EU	Low
Lecointe et al.	2007	PWR	34%	1000	60	86%	—	U/OP	1.00%	Diff.	Yes	P	PCA	T	Pessimistic	EU	Low
Lecointe et al.	2007	PWR	34%	1000	60	86%	—	U/OP	1.00%	Diff.	Yes	P	PCA	T	Realistic	EU	Low
Lecointe et al.	2007	PWR	34%	1000	60	86%	—	U/OP	1.00%	Diff.	Yes	P	PCA	T	Optimistic	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	86%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	BAU	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	86%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	Pessimistic	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	86%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	Realistic	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	86%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	Optimistic	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	86%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	BAU	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	90%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	Pessimistic	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	90%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	Realistic	EU	Low
Lecointe et al.	2007	PWR	36%	1590	60	90%	—	U/OP	1.00%	Cent.	Yes	P	PCA	T	Optimistic	EU	Low
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	75%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	80%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	25	90%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	25	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	45	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	Freq. R	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	Infreq. R	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	Diff.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	LLE	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	HLE	Australia	High

(Continued)

Table 1 *Continued*

Author(s)	*Year*	*Tech. type*	*TF (%)*	*CP (MW)*	*L (years)*	*CF (%)*	*MLCF*	*Uranium mining method*	*UOG (%)*	*EM*	*R*	*Temp. vint.*	*Mthd.*	*Data type*	*Other*	*Study location*	*PSEM*
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	EUO	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	CUO	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	2.00%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.01%	M-Cent.	—	P	Hybrid	T	—	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	Coal Elec.	Australia	High
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	NG Elec.	Australia	Medium
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	0.15%	M-Cent.	—	P	Hybrid	T	90% RE	Australia	Low
Lenzen et al.	2006	PWR	30%	1000	30	85%	—	40% U/60% OP	2.00%	Cent.	—	P	Hybrid	T	Best Case	Australia	Low
Lenzen et al.	2006	PWR	30%	1000	25	75%	—	40% U/60% OP	0.01%	Diff.	—	P	Hybrid	T	Worst Case	Australia	High
Meridian Corporation	1989	BWR	—	1000	30	70%	W, D	—	0.17%	Diff.	No	H	PCA	T	—	US	Medium
Rashad and Hammad	2000	PWR	—	1000	30	75%	D	Global AVG	0.20%	Diff.	No	H	PCA	E	—	—	Medium
San Martin	1989	BWR	—	1000	30	70%	W, D	—	0.17%	Diff.	No	H	PCA	T	—	US	Medium
Tokimatsu et al.	2006	LWR	—	1000	60	90%	—	—	—	Cent.	No	CS	PCA	E	—	Japan	Medium
Tokimatsu et al.	2006	LWR	—	1000	60	90%	—	—	—	M-Diff.	Yes	P	PCA	T	—	Japan	Medium
Uchiyama	1996a	BWR	32%	1000	30	75%	—	—	—	Cent.	Yes	H	Hybrid	T	—	Japan	Medium
Uchiyama	1996b	BWR	33%	1000	30	75%	—	—	—	Diff.	No	H	Hybrid	T	Base Case	Japan	Medium
Uchiyama	1996b	BWR	36%	1000	30	75%	—	—	—	Diff.	No	H	Hybrid	T	—	Japan	Medium
Uchiyama	1996b	BWR	30%	1000	30	75%	—	—	—	Diff.	No	H	Hybrid	T	—	Japan	Medium
Uchiyama	1996b	BWR	33%	1000	30	65%	—	—	—	Diff.	No	H	Hybrid	T	—	Japan	Medium
Uchiyama	1996b	BWR	33%	1000	30	75%	—	—	—	Diff.	Yes	H	Hybrid	T	PR	Japan	Medium
Uchiyama	1996b	BWR	33%	1000	30	75%	—	—	—	Cent.	Yes	H	Hybrid	T	—	Japan	Medium
Vattenfall	2007a	LWR	34%	3671	50	88%	—	46% U/54% OP	—	Cent.	No	CS	PCA	E	—	Sweden	Low
Vattenfall	2007b	BWR	34%	3158	50	90%	—	37% U/42% OP/21% ISL	—	Cent.	No	CS	PCA	E	—	Sweden	Low
Voorspools et al.	2000	PWR	33%	1000	40	85%	W	38% U/62% OP	0.20%	Cent.-Diff.	No	H	PCA	E	C EIO	Belgium	Low
Voorspools et al.	2000	PWR	33%	1000	40	85%	W	38% U/62% OP	0.20%	Cent.-Diff.	No	H	PCA	E	C PCA	Belgium	Low
White and Kulcinski	1999	PWR	33%	1000	40	75%	—	—	—	Cent.	No	H	Hybrid	T	—	US	Medium
Wibberley	2001	PWR	—	1000	30	80%	D	OP	0.20%	Diff.	No	H	PCA	T	—	US	Medium
Yasukawa et al.	1992	PWR	33%	1000	30	75%	D	—	—	Diff.	Yes	H	Hybrid	T	—	Japan	Medium
Yasukawa et al.	1996	PWR	—	1100	—	—	D	—	—	Diff.	No	H	Hybrid	T	—	Japan	Medium
Yasukawa et al.	1996	PWR	—	1100	—	—	D	—	—	Cent.	No	H	Hybrid	T	—	Japan	Medium

Notes: Tech. type = technology type; TF (%) = thermal efficiency, as a percentage; CP (MW) = capacity, in megawatts; L (years) = lifetime, in years; CF (%) = capacity factor, as percentage; MLCF = missing life cycle phase(s); UOG = uranium ore grade; EM = enrichment method; R = reprocessing; Temp. vint. = temporal vintage; Mthd. = LCA method; PSEM = primary source energy mix classification.

correspond closely to a mostly coal-based system, mostly natural gas, and a high renewable/nuclear-dependent energy system, respectively.

- **Other scenario characteristics (Other)**: If the above characteristics do not distinguish a particular study scenario compared to others reported in the same reference, other descriptors and their acronyms are included here.
  - —200-year or 50-year waste storage (by two methods—200 SD 1, 200 SD 2, 50 SD 1, 50 SD 2) (see the *Analyzed Study Description* section in the supporting information on the Web for more details).
  - —Construction phase calculated using EIO or PCA (C EIO and C PCA).
  - —The primary source energy mix is Canadian electricity mix, fossil electricity mix, coal, natural gas, or renewable energy (CEM, FEM, Coal Elec., NG Elec., and RE).
  - —Cheap and expensive uranium ore scenarios where more or less uranium waste is allowed to be generated (CUO and EUO).
  - —Frequent and infrequent uranium reload (Freq. R and Infreq. R).
  - —Low- and high-level enrichment (LLE and HLE).
  - —Includes plutonium recycling (PR).
  - —Reactor like the "international thermonuclear experimental reactor" (ITER) reference power reactor.
  - —Reverse shear (RS) operating mode reactor.
  - —High life cycle GHG emissions nuclear (i.e., Storm van Leeuwen 2007) and oil primary source energy (N/Oil).
  - —European mix and natural gas primary source energy (EU/NG).
  - —Business as usual scenario (BAU).
  - —European mix and oil primary source energy (EU/Oil).

See the *Description of Analyzed Studies* section of the supporting information on the Web for further description of the analyzed studies.

Key Harmonization Parameters

Published estimates of GHG emissions were harmonized in three ways: (1) adjustment to the latest Intergovernmental Panel on Climate Change (IPCC) 100-year global warming potentials (GWPs) when masses of individual GHGs were reported (IPCC 2007), (2) proportional adjustment to consistent estimates for several influential performance characteristics (capacity factor 92%, operational lifetime 40 years, and thermal efficiency 33%), and (3) alignment to common, gross system boundaries, as defined in figure 1, by adding missing life cycle phases that were found to significantly contribute to total life cycle GHG emissions by Beerten and colleagues (2009). Performance characteristics were selected based on average U.S. nuclear power operating conditions in 2009 from the Energy Information Administration (EIA) (2011), but were not meant to represent the "true" parameters.

Other Qualitative Categorization Steps

LCA scope and methods, uranium enrichment method, uranium ore grade, nuclear reactor operating lifetime, and primary source energy mix have been previously identified as important contributors to variability in nuclear life cycle GHG emissions (Beerten et al. 2009; Fthenakis and Kim 2007; Lenzen 2008; Lenzen et al. 2006). The harmonization process addressed some of these sources of variability. To consider the other potential sources of variability that could not be harmonized using the approaches employed here, the published life cycle GHG emissions estimates were categorized to qualitatively compare the distributions of estimates. Groups investigated include

- **LCA method**: PCA and hybrid (of PCA and EIO);
- **uranium enrichment method**: primarily gaseous diffusion or centrifuge; and
- **source energy mix**: low, medium, and high GHG emissions intensity profiles.

When the source energy mix (principally regarding electricity generation) was not explicitly reported, enrichment facility location was used as a proxy. The GHG emissions intensity of primary energy is important for nuclear power because nuclear power life cycle GHG emissions are heavily influenced by energy used in mining and enrichment. The enrichment facility location was selected as the proxy indicator because uranium enrichment usually uses more primary energy than any other single process in the nuclear life cycle (Beerten et al. 2009).

Life cycle GHG emissions by uranium enrichment method were investigated, but alone it was found to be a weak explanatory variable in the *Examination of Remaining Elements of Variability* section of this article. Our analysis focuses on its interaction with the primary source energy mix.

The influence of uranium ore grade on life cycle GHG emissions was investigated as a continuous variable. Data from the ten references that reported ore grade were subdivided by the primary source energy mix classifications. The characteristics of energy consumed in uranium recovery are the primary determinant of the uranium recovery's life cycle GHG emissions.

Results and Discussion

Published Results

Figure 2 and table 2 summarize the central tendency and variability of published estimates of life cycle GHG emissions passing screens for quality and relevance from LWR technologies. Table S2 in the supporting information on the Web contains corresponding results for non-LWR technologies. Approximately 70% of the studies passing our screens and containing life cycle GHG emissions in a usable functional unit examined PWRs and 30% examine BWRs, which reflects the proportions of each technology deployed internationally (IAEA 2009).

LWR life cycle GHG emissions variability as represented by IQR and range was 23 and 220 g CO_2-eq/kWh, respectively. The median LWR estimate was at the lower end of the

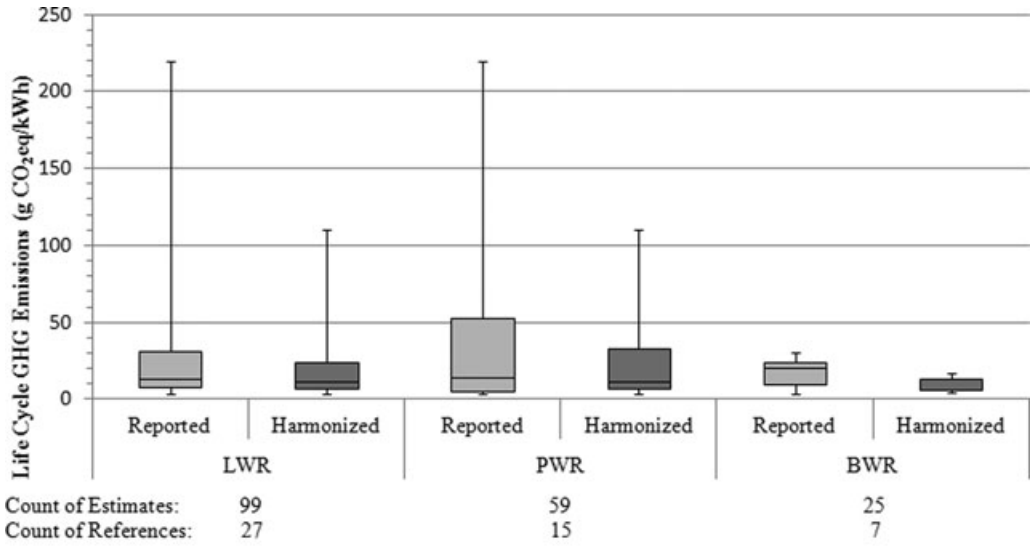

Figure 2 Published and harmonized life cycle greenhouse gas (GHG) emission distribution plots. Whiskers represent minimums and maximums. Boxes represent 25th percentile, median estimate, and 75th percentile. LWR = light water reactor; PWR = pressurized water reactor; BWR = boiling water reactor; g CO_2eq/kWh = grams carbon dioxide equivalent per kilowatt-hour.

distribution at 13 g CO_2-eq/kWh. Most variability in LWR life cycle GHG emissions stems from estimates categorized as PWRs (i.e., IQR of 47 versus 14 and range of 220 versus 26 for PWR compared to BWR, respectively). The median PWR estimate was 14 g CO_2-eq/kWh while the median BWR estimate was 21 g CO_2-eq/kWh. After harmonization, the difference between these life cycle GHG emissions is less than they initially appear here (see the *Harmonized Results* section below).

Table S3 in the supporting information on the Web summarizes the central tendency and variability in published estimates of life cycle GHG emissions for all nuclear power technologies disaggregated by broad life cycle phase.[3] For LWRs, operational processes contribute the majority of life cycle GHG emissions (78%). Life cycle GHG emissions for upstream processes and downstream processes make up 14% and 8% of published estimates of total life cycle GHG emissions, respectively.

Harmonized Results

Figure 3 displays the results of each harmonization step applied independently (frames b–h) and then all cumulatively (frame i). A reduction in variability is indicated by a flatter harmonized data series (white points) relative to the published data series (solid points). Table S4 in the supporting information on the Web reports the results displayed in figure 3 numerically. Figure S1 in the supporting information on the Web illustrates figure 3 as successive (cumulative) harmonization steps.

Harmonization of GWPs had little to no effect on variability (frame b in figure 3). Harmonization of the selected performance characteristics (frames c–e) led to the greatest reduction in life cycle GHG emission variability and therefore contributed to most of the change between published and harmonized data series (frame i). Most LWR LCA studies tended to define broad and consistent system boundaries even if the estimates of GHG emissions from each phase differed. Therefore the reduction in variability from the steps aligning the system boundary is not significant (frames f–h).

Overall, harmonization decreased the range and IQR for LWRs. The LWR range decreased by a much greater percentage (50%) than the IQR (26%), indicating the selected harmonized factors had a relatively larger influence on outer values. Harmonization decreased the median estimate for all LWR technology categories so that the medians of BWRs, PWRs, and all LWRs are similar, at approximately 12 g CO_2-eq/kWh.

After harmonization based on operational performance characteristics, remaining variation in life cycle GHG emissions appears to mostly arise from differences in methods, datasets, and alternative life cycle assumptions and parameters in non-operational portions of the life cycle. Some of these differences that appear across several papers are discussed in subsequent sections, but many estimates outside the 25th and 75th percentile are potentially explained by paper-specific factors that could not be altered. For example, the maximum estimate is a scenario from Lenzen and colleagues (2006) (and Lenzen (2008)) that is the result of the convergence of several "worst case" factors effecting life cycle GHG emissions and therefore should not be generalized.

Examination of Remaining Elements of Variability[4]

Figure 4 (frames a and b) show harmonized life cycle GHG emission qualitative data categorization and distribution plots. Table S5 in the supporting information on the Web supplements figure 4 with numerical results. Results support the

Table 2 Central tendency and variability statistics for published life cycle greenhouse gas (GHG) emissions and for light water reactor (LWR) harmonization steps applied independently and then cumulatively by all

	As published life cycle GHG ($g CO_2$-eq/kWh)	*Harmonized by capacity factor ($g CO_2$-eq/kWh)*	*Harmonized by lifetime ($g CO_2$-eq/kWh)*	*Harmonized by thermal efficiency ($g CO_2$-eq/kWh)*	*Added nuclear waste handling ($g CO_2$-eq/kWh)*	*Added facility construction ($g CO_2$-eq/kWh)*	*Added facility decommissioning ($g CO_2$-eq/kWh)*	*Harmonized by All ($g CO_2$-eq/kWh)*
LWR								
Mean	25	22	20	24	25	25	25	18
SD	29	25	20	28	29	29	29	17
Minimum	3.1	3.1	3.8	3.1	3.1	3.1	3.1	3.7
25th quartile	7.7	6.6	7.6	7.7	7.7	7.7	7.7	6.8
Median	13	12	15	13	13	13	13	12
75th quartile	31	27	26	30	31	31	31	24
Maximum	220	180	140	210	220	220	220	110
Interquartile range (75th–25th)	23	20	18	22	23	23	23	17
Range (maximum–minimum)	220	180	140	210	220	220	220	110
Change in mean (%)	—	−12%	−23%	−5%	0%	0%	0%	−28%
Change in SD (%)	—	−14%	−36%	−5%	0%	0%	0%	−41%
Change in median (%)	—	−8%	17%	0%	0%	0%	0%	−8%
Change in interquartile range (%)	—	−13%	−25%	−6%	0%	0%	0%	−26%
Change in range (%)	—	−18%	−44%	−7%	0%	0%	0%	−50%
Count of estimates*	—	61	91	60	8	2	16	99
Count of references*	—	21	25	13	6	2	11	27
PWR								
Mean	30	27	24	29	30	30	30	22
SD	35	30	24	34	35	35	35	20
Minimum	3.1	3.1	3.8	3.1	3.1	3.1	3.1	3.7
25th quartile	5.6	5.1	7.0	5.6	5.6	5.6	5.6	6.9
Median	14	13	14	14	14	14	14	12
75th quartile	53	47	37	50	53	53	53	33
Maximum	220	180	140	210	220	220	220	110
Interquartile range (75th–25th)	47	42	30	44	47	47	47	26
Range (maximum–minimum)	220	180	140	210	220	220	220	110
Change in mean (%)	—	−10%	−22%	−4%	0%	0%	0%	−27%
Change in SD (%)	—	−14%	−37%	−4%	0%	0%	0%	−43%
Change in median (%)	—	−7%	0%	0%	0%	0%	0%	−14%

(Continued)

Table 2 *Continued*

	As published life cycle GHG ($g CO_2$-eq/kWh)	*Harmonized by capacity factor ($g CO_2$-eq/kWh)*	*Harmonized by lifetime ($g CO_2$-eq/kWh)*	*Harmonized by thermal efficiency ($g CO_2$-eq/kWh)*	*Added nuclear waste handling ($g CO_2$-eq/kWh)*	*Added facility construction ($g CO_2$-eq/kWh)*	*Added facility decommissioning ($g CO_2$-eq/kWh)*	*Harmonized by All ($g CO_2$-eq/kWh)*
Change in interquartile range (%)	—	−11%	−40%	−10%	0%	0%	0%	−45%
Change in range (%)	—	−18%	−44%	−7%	0%	0%	0%	−50%
Count of estimates*	—	30	52	50	6	2	9	60
Count of references*	—	11	13	10	4	2	7	15
BWR								
Mean	18	14	14	18	18	18	18	11
SD	7.6	5.6	5.4	7.6	7.6	7.6	7.6	3.8
Minimum	3.7	3.6	4.6	3.8	3.7	3.7	3.7	4.6
25th quartile	10	8.4	7.7	10	10	10	10	6.2
Median	21	17	16	21	21	21	21	13
75th quartile	24	18	18	24	24	24	24	13
Maximum	30	23	23	30	30	30	30	17
Interquartile range (75th–25th)	14	9.6	10	14	14	14	14	6.8
Range (maximum–minimum)	26	19	18	26	26	26	26	12
Change in mean (%)	—	−22%	−29%	0%	0%	0%	0%	−39%
Change in SD (%)	—	−26%	−39%	0%	0%	0%	0%	−50%
Change in median (%)	—	−19%	−29%	0%	0%	0%	0%	−38%
Change in interquartile range (%)	—	−31%	−42%	0%	0%	0%	0%	−51%
Change in range (%)	—	−27%	−42%	0%	0%	0%	0%	−54%
Count of estimates*	—	23	25	9	2	0	2	25
Count of references*	—	7	7	3	2	0	2	7

Notes: $g CO_2$-eq/kWh = grams carbon dioxide equivalent per kilowatt-hour; SD = standard deviation; PWR = pressurized water reactor; BWR = boiling water reactor; LWR = light water reactor. *On which a given harmonization step was applied.

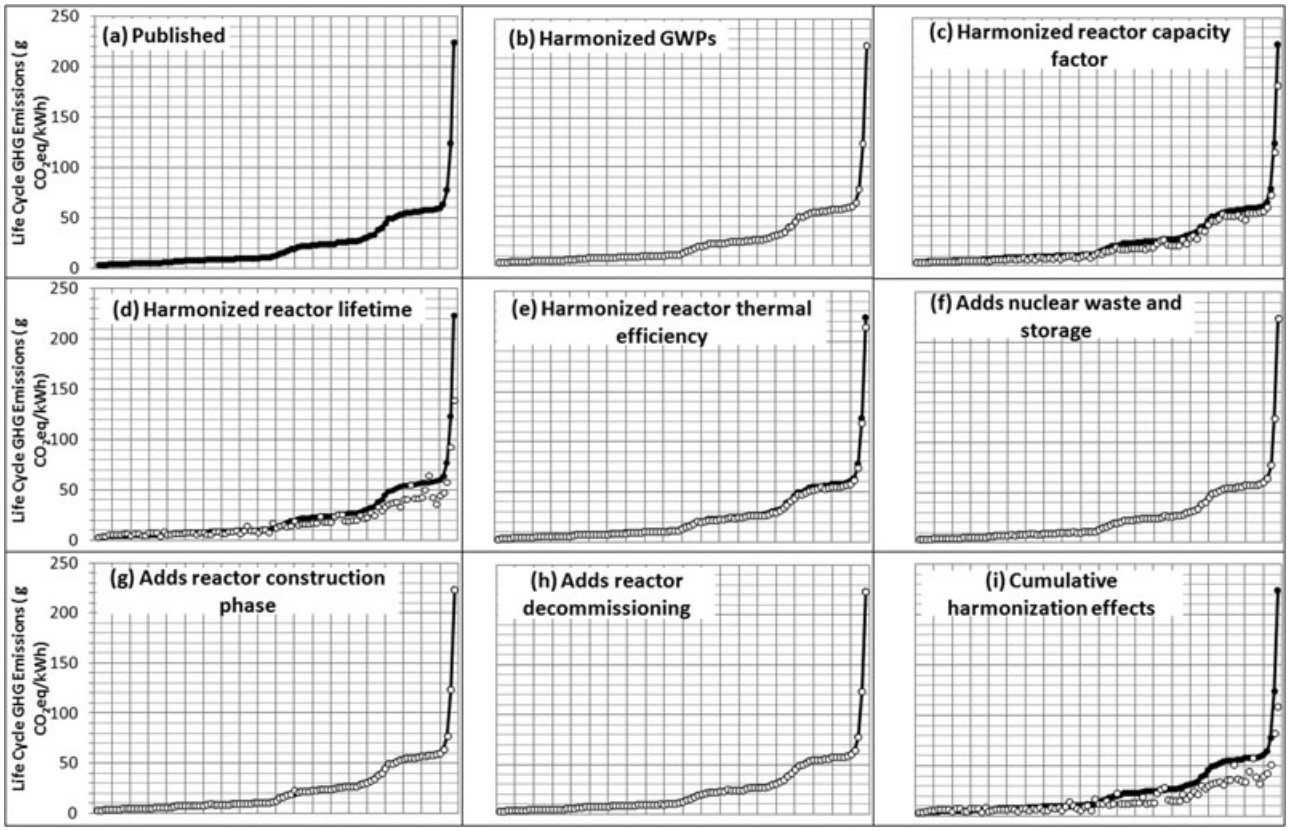

Figure 3 Ordinal scale ranking from lowest to highest of published life cycle greenhouse gas (GHG) emissions (g CO_2-eq/kWh) compared to published results independently harmonized in stages and then cumulatively by all factors. Frame (a) reports only published data. Published estimates are shown as solid points and harmonized estimates are shown as white points. GWPs = global warming potentials.

conclusions of previous meta-analyses about the influence of the choice of LCA method on life cycle GHG emissions. (See the *Upstream Processes* section of the supporting information on the Web for more details.) The median estimate using PCA methods was about one-third (7.2 g CO_2-eq/kWh) of those using hybrid methods (22 g CO_2-eq/kWh). While variability among studies using the PCA method is relatively small (IQR and range of 2.6 and 23 g CO_2-eq/kWh, respectively), the hybrid method category had a much larger IQR and range (IQR and range of 21 and 110 g CO_2-eq/kWh). Much of the remaining variability can probably be traced to other unharmonized factors (e.g., primary source energy mix), but also different balances of PCA and EIO methods used in hybrid LCAs.

Frame (b) of figure 4 illustrates estimates grouped by low, medium, and high GHG emission intensity of the primary source energy mix, subdivided by enrichment method. Results seem to indicate that a significant portion of unharmonized variability in life cycle GHG emissions could be explained by different assumptions about the primary source energy mix and the uranium enrichment method (which is a high-energy consumption process). There are six modestly distinct data categories, although the 25th and 75th percentiles of some groupings display some overlap. With the exception of the "high carbon-diffusion" group,[5] each category displays lower variability (IQRs of 1.7 to 7 g CO_2-eq/kWh) than when grouped by technology (IQRs from 6.8 to 26 g CO_2-eq/kWh). The reduction in variability and the distinctiveness of these groupings occurs despite several mitigating factors such as unharmonized LCA methods (i.e., hybrid versus PCA) and the somewhat subjective nature of our categorization approach.

A small trend of increasing life cycle GHG emissions associated with decreasing ore grade is barely visible in frame (c) in figure 4. Many LCAs study potential and future nuclear power development scenarios, but ore grade is often not dynamically examined or even directly reported. The lack of a larger and more diverse pool of life cycle GHG emissions estimates where ore grade is quantitatively reported prevents more robust conclusions than vaguely confirming the uranium ore grade and life cycle GHG emission relationship discussed in past meta-analyses. Therefore a scenario analysis is employed in the *Future Uranium Ore Grade Scenario Projections* section of this article.

Comparison to Previously Published Results

Four high-quality, detailed meta-analyses of nuclear power life cycle GHG emissions have been published—all within the

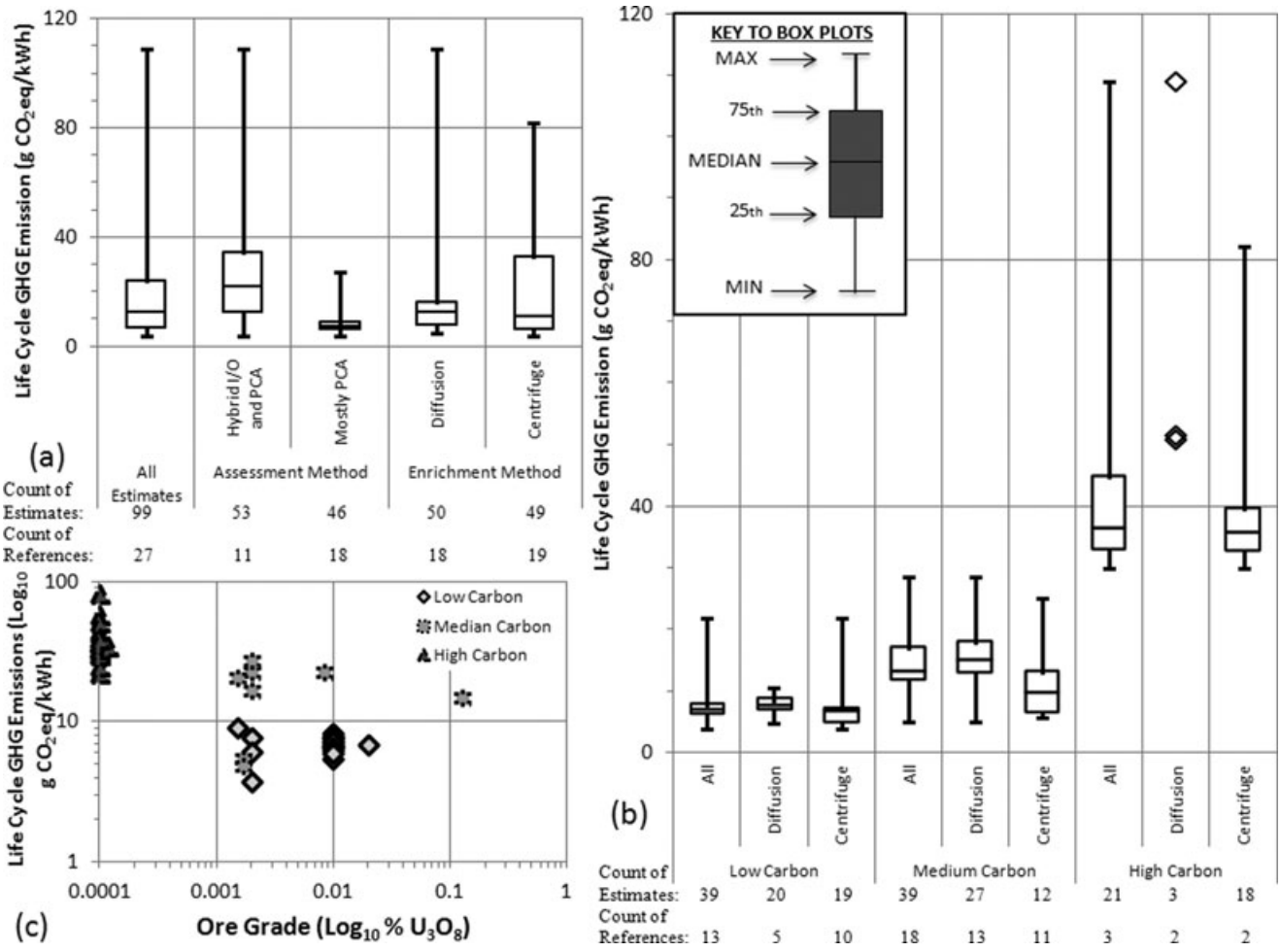

Figure 4 Qualitative characteristic groupings of life cycle greenhouse gas (GHG) emissions. Scatter plot of uranium ore grades by the $\log_{10}$ of g CO_2-eq/kWh. Points represent single estimates. Frame (a) groups life cycle GHG emissions by primary life cycle assessment (LCA) analysis method and enrichment method. Frame (b) groups life cycle GHG emissions by GHG emission intensity profile and then is divided into a further subgrouping by enrichment method. Frame (c) is a scatter plot of $\log_{10}$ g CO_2-eq/kWh versus ore grade of various primary source energy mix GHG emissions intensity profiles. PCA = process chain analysis.

last five years. The meta-analysis by Lenzen (2008) is not directly comparable to our results as it involves the creation of a regression equation that is used to analyze an original case study. The results of two other studies (Beerten and colleagues 2009; Fthenakis and Kim 2007) are not entirely comparable with this article's results. Fthenakis and Kim produced U.S.-based LWR life cycle GHG emissions estimates for a best, worst, and average case scenario based on seven previous LCAs. Despite differences in methods, this article's and Fthenakis and Kim's (2007) results correspond under similar scenarios. Beerten and colleagues (2009) did not create composite life cycle GHG emissions estimates. Instead, they recalculated and analyzed the results of previous studies by Lenzen (2008), Storm van Leeuwen (2007), and Voorspool and colleagues (2000).

One comparable previous meta-analysis by Sovacool (2008) reviewed a large LCA pool (103 references) before analyzing estimates from 19 LCAs that passed his quality screening process. Sovacool's 19 studies mostly overlap with literature passing our screens. Major differences between this study and Sovacool's are our more comprehensive literature search, his more restrictive publication date requirement, and our employment of a more restrictive LCA method requirement (i.e., AEI method LCAs were removed). Sovacool's analysis of collected life cycle GHG emissions data was also more limited and did not differentiate between nuclear power technologies. Sovacool (2008) reports that average life cycle GHG emissions from nuclear power are 66 g CO_2-eq/kWh with a range of 1 to 288 g CO_2-eq/kWh. Differences in results are almost exclusively attributable to our exclusion of estimates using AEI methods and the selection of median as the measure of central tendency.

LCAs of two other nuclear power technologies exist for comparison to LWRs. HWRs and gas-cooled reactors (GCRs) are studied (four and three studies, respectively) but are less frequently deployed than LWRs. Results from table S2 in the supporting information on the Web appear to indicate that

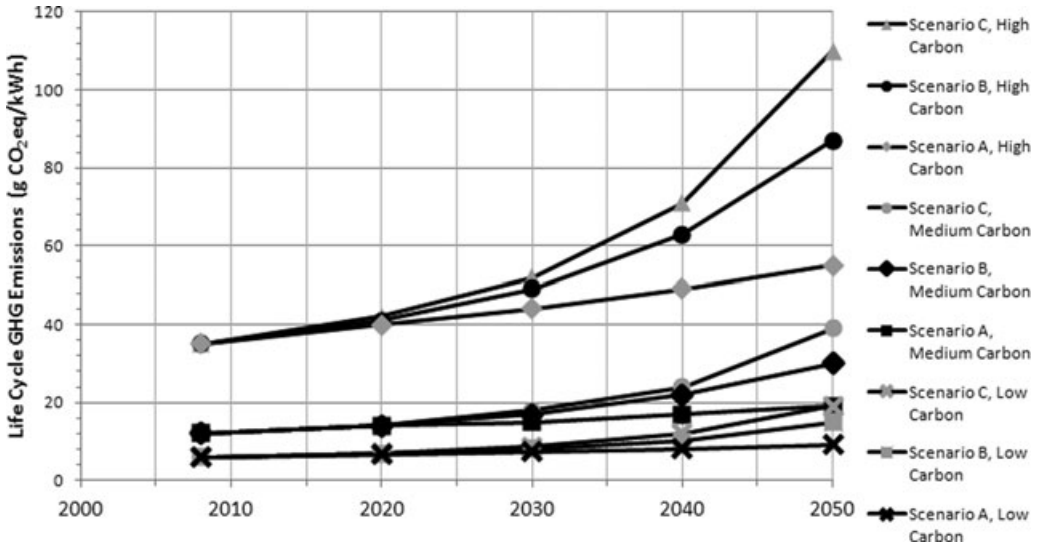

Figure 5 Life cycle greenhouse gas (GHG) emissions over time for three alternative uranium ore grade quality scenarios (as determined by uranium consumption levels) categorized by three primary source energy mix GHG emission intensity levels.

GCRs and HWRs produce lower and higher life cycle GHG emissions relative to LWRs, respectively. A likely source of the apparent differences is the combination of a small data pool and systematic differences in key attributes of the GCR and HWR estimates compared to those in the LWR literature. For example, most GCR and HWR estimates modeled low and high GHG emissions intensity profile primary source energy mixes, respectively. Results reported in table S2 in the supporting information on the Web for LWRs categorized by GHG emissions intensity profile indicate that it is possible that life cycle GHG emissions for HWRs and GCRs would be similar to LWRs if similar nuclear performance characteristics are assumed.

Future Uranium Ore Grade Scenario Projections

Many factors that influence nuclear life cycle GHG emissions are expected to improve over time, lowering GHG emissions. For example, the increased use of multipurpose mines reduces the energy required to extract uranium, and the gradual switch to centrifuge uranium enrichment reduces the energy required for this process compared to diffusion enrichment. On the other hand, if the global uranium market-average ore grade decreases over time, life cycle GHG emissions could increase for the average nuclear power plant due to higher energy demand for uranium recovery. Emissions from mining and milling can contribute to a significant portion of life cycle GHG emissions; for example, Dones and colleagues (2007a) estimate approximately 30%. Uranium is a nonrenewable resource and global rates of recovery are highest for the higher-quality ore grades, even though the majority of global recoverable resource consists of lower ore grades (ABARE 2004, IAEA 2008). The potential impact of decreasing uranium ore grades creates a major difference between nuclear and renewable technologies for future GHG mitigation potential[6] (Storm van Leeuwen 2007). Here we use a scenario analysis framework similar to Storm van Leeuwen's (2007), but without the influence of the AEI method, with more recent data, and with a more global focus. The present analysis is intended to explore the boundary of the potential impact of decreasing ore grade on life cycle GHG emissions.

Three alternative nuclear development scenarios from 2010 to 2050 were considered. Scenario A assumes that the amount of electricity generated by nuclear facilities remains constant. Scenario B maintains nuclear's share of total global electricity generation. An increasing share scenario, scenario C, assumes a 4% annual growth rate for nuclear power (Beckjord et al. 2003), which leads to an increasing share of global electricity generation. These scenarios assume no technological improvement in the life cycle of nuclear power. See the *Future Uranium Ore Grade Scenario Projections and Examination of Remaining Elements of Variability* section of the supporting information on the Web for details on scenario construction and calculation of the relationship between consumption and ore grade from Lenzen (2010).

Global uranium market-average ore grade and associated life cycle GHG emissions for future nuclear power development scenarios are shown in figure 5, categorized by GHG emissions intensity profile of the source energy mix. The maximum possible global ore grade is projected to decrease from 2008 to 2050 in all three scenarios as existing inferred resources are consumed. From 2008 to 2050, the life cycle GHG emissions in scenarios A, B, and C grew by about 55%, 145%, and 220%, respectively. Real-world conditions similar to scenario A are unlikely to lead to a large increase in life cycle GHG emissions from nuclear power given conservative scenario assumptions about technological and resource progression over time. In the constant share scenario (scenario B) and the increasing share scenario (scenario C), large increases in life cycle GHG emissions represent

a larger risk of increased future life cycle GHG emissions, presuming no actions (e.g., direct policy changes and investment) occur to offset changes in market ore grades. By 2050 the results of scenario C (i.e., about 110 g CO_2-eq/kWh) are comparable to ore grade sensitivity analysis by Lenzen (2008) and Lenzen and colleagues (2006) of about 120 g CO_2-eq/kWh. Nuclear power life cycle GHG emissions are only a fraction of those from traditional fossil sources like coal (with a median harmonized life cycle GHG emission estimate of 1,001 g CO_2-eq/kWh (Whitaker et al. 2012). Though uncertain, it is possible that nuclear power will emit more GHGs in the future. Therefore nuclear power may be considered to involve an added level of risk for delivering GHG emissions mitigation relative to other technologies.

Unaccounted for in the simple set of scenarios developed for this analysis are several possibilities for mitigating decreases in uranium market ore grades. Most commonly assumed and discussed in the literature is that market forces resulting from increases in uranium prices (resulting, in turn, from higher extraction costs) for low-quality ores will lead to increased uranium exploration and discovery of resources. However, even if exploration increases, there are no guarantees that new resources will be of high enough ore grade quality and quantity to prevent decreases in global uranium market ore grade. Other steps, such as investment to increase the efficiency of practices (e.g., multiple-use mines) and advance the current state of the technology (e.g., greater use of reprocessing), may be needed instead of or in addition to reliance on market forces.

Alternatively, the deployment of nuclear power technologies that consume little to no uranium ore would reduce the chances of large uranium market ore grade decreases. Theoretical FBRs have been evaluated in the LCA literature. The limited literature that evaluates this potential future technology reports median life cycle GHG emissions (table S2 in the supporting information on the Web) similar to or lower than LWRs and purports to consume little or no uranium ore.

Limitations of the Analysis

The broad goal of the current phase of the LCA Harmonization Project is to clarify estimates of life cycle GHG emissions to better inform decision making and future analyses where such estimates would be useful. However, to provide a more comprehensive perspective of the environmental and social impacts of power generating technologies, other parameters, such as human health impacts, water consumption, and jobs created, should also be assessed.

The harmonization process decreased the variability and increased the precision of previously published estimates by systematically aligning common system parameters across studies to a consistent set of values. However, improved precision does not imply improved accuracy. There are many potential consequential effects of deployment of nuclear power not typically considered in the majority of attributional nuclear LCAs, and these effects could increase or decrease previously published estimates of life cycle GHG emissions. Another issue is truncation error that is often inherent in process-based LCAs, which form the majority of LCAs (but not estimates) considered in this article. In this respect, the middle to upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end. Potential sources of truncation error or unaccounted consequential impacts such as the GHG intensity of the background economy and future uranium mining emissions due to increased consumption are examined in this and the following section (i.e., *Future Uranium Ore Grade Scenario Projections and Examinations of Remaining Elements of Variability*) while others such as mine rehabilitation and prospecting have been noted as being absent in the existing literature in the *Life Cycle Phase Definitions and Conceptual Process Description* section of this article.

This study's meta-analysis and harmonization has been limited in other ways. Two common reasons inconsistencies in the collected studies' methods were not harmonized are (1) their influence on life cycle GHG emissions was deemed small, or (2) the necessary information was not reported. For example, harmonization was not attempted on uranium ore transportation because it was often shown to be negligible in LCA literature (e.g., Beerten et al. 2009). Reprocessing and operations-related GHG emissions were rarely separately reported and also cannot be divorced from the multiple life cycle phases that its use influences. Therefore simplifying assumptions narrowed our analysis to a specific technology and a limited set of consistently reported factors.

Variations in nuclear waste reprocessing methods, enrichment systems, and nuclear facility performance characteristics are almost the only major system conditions consistently and explicitly studied in LCA scenario analyses. Several nuclear power performance characteristics noted for their potential significance in past LCAs are often not investigated or described:

- Mining methods are reported in less than 50% of LCAs passing our screens, and some techniques are rarely investigated.
- Uranium ore grade was reported in slightly less than 50% of LCAs collected and was rarely varied under alternative future scenarios.
- Decommissioning was not usually described in detail; when described, most seem to closely resemble only "immediate dismantling," not full decommissioning (see the *Downstream Processes* section of the supporting information on the Web).
- Mine rehabilitation, which may be associated with a significant portion of GHG emissions (Beerten et al. 2009), was rarely discussed and never evaluated in any LCAs passing screens.
- The primary source energy mix was infrequently studied or reported.
- LCA methods are typically not reported with enough detail to examine the effect that the method selection has on individual life cycle stages or to assess the balance of methods in hybrid LCA analyses.

Harmonization of identified, but unharmonized dimensions would require contacting study authors to acquire the following detailed datasets and method descriptions:

- raw GHG emissions from each process source;
- GHG emissions reported per life cycle phase, and clear definition of phases;
- identification of the LCA methods employed in each life cycle phase and in the collection of substitute process or economic data;
- proportion of assumed energy sources; and
- additional study parameters such as mining methods and uranium ore grade.

This type of "full" harmonization would require work similar to Farrell and colleagues (2006) and Plevin (2009). These studies carefully researched a subset of the available literature's estimates of life cycle GHG emissions for ethanol to produce a detailed meta-model based on adjusted parameter estimates, realigned life cycle system boundaries within each life cycle phase, and review of all the study's data sources. However, with the exception of harmonizing dimensions already qualitatively assessed in this article, it isn't clear that additional harmonization of other factors would reduce the variability of life cycle GHG emissions for nuclear power in a manner that would change the overall conclusions reached here.

Another potential limitation to our results is that the studies passing our screens do not represent a statistically independent sample. Clustering of published results owing to the use of similar methods could exist along at least one of three dimensions: multiple estimates reported in the same reference, multiple estimates from the same or similar author groups publishing serially, and multiple references citing the same sources of input data. We assert based on the analysis discussed in the *Limitations of the Analysis* section of the supporting information on the Web that any correction of potential bias by the above-described sources is not likely to change the median or IQR of life cycle GHG emissions in a conclusion-relevant manner.

Several other statistical and methods limitations were previously outlined in the *Statistical Assessment* section of this article.

Recommendations for Future Work

Based on our review of the collected LCA literature, nearly a dozen recommendations were developed for planning, conducting, and documenting future nuclear LCA work. These recommendations highlight some general deficiencies and gaps in the current literature that should be addressed in future LCAs and LCA research on nuclear power:

- Follow established minimum guidelines, such as the International Standards Organization (ISO) 14040 series, for conducting LCA (ISO 2006a, 2006b).
- Clearly report the assumed technological vintage (e.g., third-generation PWR).
- State assumptions about whether the technology assessed is a case study, projection, or theoretical system.
- Identify the characteristics of the primary source energy mix.
- Better evaluate existing reactor operations to identify unrealistic performance characteristics. Literature variation seems larger than reported practice (IAEA 2009).
- Include and provide more detailed assumptions for theoretical life cycle phases such as decommissioning, nuclear waste storage, operations, and mine rehabilitation.
- Identify mining methods used for uranium ore recovery.
- Specify or at least justify using the generalized LWR category instead of more specific BWR to PWR categories.
- Provide more detailed reporting on the influence of reprocessing on life cycle impacts.
- Focus, as needed, on data refinement for significant life cycle GHG emission contributors (e.g., uranium enrichment).
- Develop standardized language and boundaries for nuclear life cycle phase descriptions.
- Identify assumed ore grades and address ore grade changes in projection analyses.

In most instances another LWR LCA study of GHG emissions is probably not necessary given the relatively low variability in estimates of life cycle GHG emissions after conducting the harmonization process used in this article and the explanatory power of other factors examined (i.e., LCA methods, primary source energy mix, and enrichment methods). However, there are three potentially useful spheres of additional research that would benefit the nuclear power LCA field: (1) examining understudied nuclear power technologies or, perhaps preferably, future proposed nuclear technologies; (2) analyzing future nuclear power deployment more dynamically;[7] and (3) examining under what circumstances or conditions PCA or EIO LCA methods are more or less appropriate for analyzing a particular life cycle phase.

Most existing nuclear power LCAs have focused on a narrow set of technologies. Newer third- and fourth-generation technology designs exist or have been proposed but have not been extensively evaluated. Even though unavailable data may limit such research on newer technologies, also missing is an analysis of future deployment of current technologies. Future conditions from some aspects of the nuclear fuel cycle have been well researched (e.g., enrichment and reprocessing), but many others (e.g., primary source energy mix) have not.

The association of life cycle GHG emissions results and LCA methods seems to indicate the need for a more complex and nuanced approach to conducting a nuclear power LCA. Most LCAs will continue to use hybrid methodologies because of limitations in data and of the PCA and EIO methods individually. Therefore guidelines could assist in determining under which conditions the LCA method is more or less appropriate for a given life cycle phase. The development and use of guidelines could reduce variability among future LCAs and lead to better approximations of the "true" life cycle GHG emissions

of nuclear power. A more detailed analysis of the relationship between LCA methods and LCA results would inform this process, allow higher-quality assessments of previous work, and have broader applicability to the LCA field.

Conclusions

Harmonization was successful in reducing the variability and clarifying the central tendency of existing literature. The published median, IQR, and range for the pool of LWR life cycle GHG emissions estimates were 13, 23, and 220 g CO_2-eq/kWh, respectively, and 12, 17, and 110 g CO_2-eq/kWh, respectively, after harmonization. The IQR was reduced by 26% and the range was reduced by 50% through harmonization. Assuming consistent performance characteristics, the median life cycle GHG emissions of LWR subtechnologies were nearly identical after harmonization.

This study ultimately concludes that given the large number of previously published life cycle GHG emissions estimates of nuclear power systems, their relatively narrow distribution postharmonization, and assuming deployment under relatively similar conditions examined in literature passing screens, it is unlikely that new process-based LCAs of LWRs would fall outside the range of, and will probably be similar in central tendency to, existing literature. The collective LCA literature indicates that life cycle GHG emissions from nuclear power are only a fraction of traditional fossil sources (e.g., Whitaker et al. 2012) and comparable to renewable technologies (e.g., Dolan and Heath 2012). Evidence is limited on whether similar conclusions apply consistently to other common technologies (i.e., HWRs and GCRs).

However, the conditions and assumptions under which nuclear power is deployed can have a significant impact on the magnitude of life cycle GHG emissions, and several related contextual and consequential issues remain unexamined in much of the existing literature. While small relative to coal, the difference between nuclear power life cycle GHG emissions constructed in an electric system dominated by nuclear (or renewables) and a system dominated by coal can be fairly large (in the range of 4 to 22 g CO_2-eq/kWh compared to 30 to 110 g CO_2-eq/kWh, respectively). A large portion of the variation in existing evaluations appears to be explainable by four main factors, only one of which was harmonized (i.e., nuclear facility performance characteristics). The three significant unharmonized factors were (1) the type of primary source energy mix; (2) the demand for electricity, which is largely dependent on the uranium enrichment method; and (3) the LCA method. The impacts of uranium ore grade on life cycle GHG emissions, as examined in this study, have largely been unaddressed in the literature, even in projection-based LCAs. There could be significant effects on the future GHG emissions mitigation potential of nuclear power as uranium ore grade is significantly reduced through increased consumption. Additional consequential LCAs would enhance our understanding of the true life cycle GHG emissions of nuclear power and may change the comparison to renewable technologies. However, additional consequential LCAs are unlikely to fundamentally change the comparison of nuclear power to fossil fuel-based electricity generation sources.

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Notes

1. Additional data and results of the project are available at http://openei.org/apps/LCA.
2. One gram (g) = 10^{-3} kilograms (kg, SI) $\approx$ 0.035 ounces (oz); one kilowatt-hour (kWh) $\approx 3.6 \times 10^6$ joules (J, SI) $\approx 3.412 \times 10^3$ British Thermal Units (BTU); CO_2-eq: Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference.
3. No disaggregated life cycle GHG emissions for fast breed reactor (FBR) were found in the literature.
4. All results in this section refer to analysis of harmonized estimates.
5. Although neither high GHG emission intensity profile grouping can be considered very robust, as only two references are used, this particular grouping's variability is greatly affected by the low number of estimates (three), one of which is a worst-case scenario with three times the emissions of the average case from the same study.
6. Arguably a similar but less extreme dynamic relationship between ore grades and fossil energy consumption could apply to rare earth materials used in some renewable technologies.
7. While projections of advanced forms of the LWRs have been examined, there has been very relatively little exploration of alternative deployment conditions, such as background energy or uranium ore grade.

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Supporting Information

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