Greenhouse Gas Emissions from Nuclear Power in 2030:
Examining Emissions Estimates and Projected Growth

By Simon Tudiver

I. Introduction

The specter of global climate change and the attendant push to reduce carbon dioxide (CO_2) emissions has large implications for electricity production around the world. About two-thirds of global electrical production comes from burning fossil fuels, which releases more than a quarter of the world's anthropogenic CO_2.[1,2] In contrast, the 439 nuclear reactors in operation (with a total capacity of 372 GW) produce a substantially smaller portion of total power and emissions. In 2006, nuclear reactors supplied 14.8 percent of global electricity, and 6.2 percent of total primary energy.[1] Despite ongoing safety concerns, recent reports in the popular media suggest that nuclear power may be enjoying something of a renaissance because of its relatively light carbon footprint.[3,4] There are forty-two new nuclear reactors currently under construction, and most energy experts predict a future increase in nuclear capacity as long as governments choose policies intent on mitigating anthropogenic emissions of carbon dioxide.[5,8] The International Atomic Energy Agency claims that nuclear power is clean because it "emits almost no greenhouse gases."[6] It is true that harnessing energy from nuclear chain reactions does not directly emit greenhouse gases—but there are indirect emissions from other stages of the nuclear lifecycle, although the exact quantity of these emissions is uncertain.

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The goal of this paper is to provide a clear picture and estimate of nuclear power's potential to offset CO_2 emission from energy production given current projections of nuclear growth. I do this by first reviewing and critiquing estimates of lifecycle CO_2 emissions from nuclear power production, paying close attention to data sources and the relative contribution of different lifecycle stages. I then review projections of nuclear capacity and production in 2030. Finally, I compare these data with emissions from fossil fuel and renewable energy production.

II. The Nuclear Lifecycle

Nuclear power has a long and complex lifecycle, with CO_2 emissions spread unevenly throughout. The basic stages are: plant construction, fuel extraction and processing, operation, spent fuel storage, and decommissioning. It can also be useful to think about the fuel cycle separately. This can be divided into the frontend, which includes mining, milling, converting and enriching uranium to make fuel, and the backend, which includes temporary and long-term storage of spent fuel, as well as fuel reprocessing for reuse in a small subset of reactors.

NUCLEAR REACTORS ARE SOME OF THE MOST COMPLEX INDUSTRIAL FACILITIES BUILT BY HUMANS, AND THEY USE HUGE QUANTITIES OF MATERIALS, MANY OF WHICH ARE ENERGY AND EMISSIONS-INTENSIVE.

Mining and milling uranium is a labor-intensive process. Uranium is found throughout the globe, but there are few sites with high enough concentrations to make mining worthwhile. Even in these sites, concentrations are relatively low. (Ores can be found with as much as 10 percent uranium oxide, but it is not uncommon to mine ores with concentrations of 0.02 percent or lower.[9]) Deposits are also categorized as either soft or hard; the former tend to be found in higher concentrations than the latter, and are also less energy-intensive to extract.[10] Once mined, the ore is ground up and processed using chemicals. (In some cases, uranium is processed in situ by leaching chemicals like sulfuric acid directly into the earth and then mining afterward.) The world's largest producers of uranium are Canada (23 percent of global production), Australia (21 percent), and Kazakhstan (16 percent).[11] The variation in uranium quality means that energy use—and thus emissions—can vary considerably depending on the source of the ore being used.

Uranium conversion and enrichment come next. Impurities are removed chemically (conversion) before boosting the concentration of the uranium-235 isotope (enrichment). The two main methods of enrichment are gaseous diffusion and centrifuge. Diffusion is most common in the United States and parts of Europe, and the process consumes fifty times the energy of a centrifuge.[12] About 40 percent of the world's enriched uranium currently comes from diffusion, but that figure is expected to drop as diffusion facilities reach the end of their lifespan and are replaced with centrifuges.

Another large source of emissions is power plant construction. Nuclear reactors are some of the most complex industrial facilities built by humans, and they use huge quantities of materials, many of which are energy and emissions-intensive.

Spent fuel storage is a complex and still uncertain link in the nuclear chain. Currently, most nuclear waste is stored in temporary cooling facilities, either at the site of power production or at a central facility. Long-term waste storage remains a contentious political issue in this country, despite the commissioning of a deep geological repository at Yucca Mountain, Nevada.[13] The uncertainty surrounding long-term storage means its energetic costs remain unknown.

Decommissioning nuclear facilities after their productive lives is a much bigger undertaking than shutting down other types of power plants. Numerous high and low-level radioactive wastes must be contained, in addition to dismantling the reactor and other facilities. The full extent of this enterprise is not currently known, as no nuclear facility has ever been fully decommissioned and dismantled. Thus, this stage of the lifecycle is also riddled with uncertainties as to the energy required (and thus the emissions released) for full decommissioning.

III. Estimates of lifecycle emissions

Quantifying emissions from a process as complex as the nuclear power lifecycle is no simple task. Add to that the many political and economic interests surrounding this controversial power source, and one begins to understand why there is such disparity between emissions estimates. I have drawn data from a range of sources below to sample this vast literature.

The Intergovernmental Panel on Climate Change cites a figure of "below 40 gCO_2-eq/kWh" in its fourth assessment report.[8] This figure is taken from a report by the World Energy Council, which presents lifecycle emissions values for five nuclear power facilities.14 The WEC estimates range from a low of 3 gCO_2eq/kWh (data from the Swedish nuclear power operator Vattenfall) to a high of 40 gCO_2eq/kWh (data from the Australian Coal Association Research Program). Intermediate figures come from ExternE—the European Externalities of Energy project (data at least ten years old). (The IPCC report does mention one other estimate in passing, that of Storm van Leeuwen and Smith, who provide "much higher figures."[8,10] The report does not formally include those figures, and fails to explain why.) There are two main problems with the IPCC data: (1) some of the sources noted above may not be impartial, and may have vested interests in reporting low or high figures and (2) the mid-range data is old enough to question its applicability.

In a report comparing different electricity generating options, the International Energy Agency uses emissions data from two sources.[15] One is the same Swedish nuclear power operator cited by the IPCC, which reports emissions of 2.82 gCO_2e/kWh; the other is a study of three Japanese nuclear facilities, which reports emissions between 7.8 and 20.9 gCO_2e/kWh. The low value in the latter study is for a fast-breeder reactor, which remains an experimental reactor type (i.e. there are no commercial-scale reactors currently operating). The Japanese data is also more than ten years old.

Sovacool reviews 103 lifecycle studies of GHG emissions from nuclear power.[9] Only nineteen of the studies make it through his inclusion criteria; he excludes old and unreliable data, and draws emissions estimates from the remaining pool. (He does not explain how he compiled the original list of 103.) Sovacool finds a large range of estimates in the literature: from 1.4 gCO_2e/kWh to 288 gCO_2e/kWh for the complete nuclear lifecycle. He breaks down the estimates by lifecycle stage and calculates the mean value from the means of each stage of that lifecycle. The result is a mean of 66 gCO_2e/kWh. Sovacool suggests a number of explanations for the significant differences between estimates, including the scope of each assessment as well as assumptions about the quality of the uranium ore, the method of mining and the type of reactor.

	Min	Max	Mean	*N*
Frontend	0.58	118	25.09	17
Construction	0.27	35	8.2	19
Operation	0.1	40	11.58	9
Backend	0.4	40.75	9.2	15
Decommissioning	0.01	54.5	12.01	13
Total	1.36	288.25	66.08	

Table I: Carbon dioxide emissions from different stages of the nuclear power lifecycle, measured in gCO_2e/kWh. *Data from Sovacool.*[9]

Table I summarizes Sovacool's results, broken down by lifecycle stage. The data show that the early stages of the cycle—i.e. frontend and construction—contribute about half of the mean lifecycle emissions (and more than half for minimum and maximum estimates).

IV. Sources of Uncertainty

Storm van Leeuwen and Smith find that nuclear lifecycle emissions depend so heavily on the quality and concentration of the uranium ore used that, under certain conditions, the nuclear lifecycle could emit more GHGs than a natural gas-fired plant.[10,16] Storm van Leeuwen calculates the threshold at uranium concentrations of about 0.01 percent (i.e. 100 grams of uranium for every ton of rock). At this point, "the nuclear system in effect becomes a complex and expensive gas burner."[16] The future availability of uranium in high quality deposits thus may be crucial for maintaining the efficiency of the nuclear lifecycle.

Storm van Leeuwen also argues that since no commercial nuclear facility has ever completed a full lifecycle, uncertainties are greatest in the backend and decommissioning stages.[16] In his calculations, Storm van Leeuwen assumes that more energy is needed to dismantle a nuclear plant than was used to build it in the first place. Most other estimates do not make this same assumption—but this is a matter of uncertainty and disagreement rather than correct or incorrect assumptions.

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V. Expanding Nuclear Capacity

According to the IAEA, the world currently has just over 372 GW of installed nuclear capacity in 439 reactors.[5] The vast majority of those plants came online prior to 1990 (the only countries with significant new starts since then are China, South Korea and Japan).[17] Assessing how this picture will change over the next 25-30 years is a complex task, and it depends on the evolution of global and regional economic growth, energy demand, and policy decisions.

	Current ('05/'06/'07)		Projected (2030)		Growth		Capacity Factor		
	Capacity (GW)	Production (TWh)	Capacity (GW)	Production (TWh)	Capacity	Production	Current	Projected	Change
IEA-Reference	369	2793	416	3304	13%	18%	86%	91%	5%
IEA-Alternative	369	2793	519	4119	41%	47%	86%	91%	5%
EIA	374	2600	498	3800	33%	46%	79%	87%	10%
IAEA-Low	372	2608	473	3522	27%	35%	80%	85%	6%
IAEA-High	372	2608	748	5551	101%	113%	80%	85%	6%

Table II: Projected increases in nuclear capacity to 2030. Capacity factor measures the portion of time the facilities are producing power. (Underlined figures are my calculations.[18]) *Data from IEA, EIA, and IAEA.*[1,7,19,20]

Table II shows projections for how nuclear capacity could grow between now and 2030. Each organization uses different types of models and makes different assumptions about how that growth will occur. Note that all projections assume that efficiency increases in the future (i.e. the capacity factor is higher in 2030). This may have indirect implications for emissions estimates, since greater efficiency implies fewer fixed emissions (e.g. construction, dismantling), although no fewer variable emissions (from fuel extraction and processing). I will return to these figures later when calculating future emissions.

The IEA proposes two main scenarios for future growth of energy supply, both of which are based on extensive economic modeling of future trends. In the Reference Scenario, GDP growth slows over the next thirty years, dampening growth in energy demand. While the economy continues to become more energy-efficient, the scenario assumes no major policies aimed at accelerating that efficiency. In this scenario, the portion of power coming from nuclear energy decreases over time, with few new reactors coming online and a number of existing ones shutting down. Regionally, nuclear power grows in China, India, Russia, Japan, and South Korea, but declines in Europe. Contrasted with this picture is the IEA's Alternative Policy Scenario, which assumes that countries "adopt all of the policies they are currently considering related to energy security and energy-related CO_2 emissions."[7] In this scenario, nuclear production is 25 percent higher than the reference case, with two-thirds of that increase coming from OECD countries.

INVESTING IN NEW PLANTS HAS BECOME MORE ATTRACTIVE FOR A NUMBER OF REASONS, INCLUDING THE IMPROVED PERFORMANCE OF EXISTING REACTORS, HIGH FOSSIL FUEL PRICES, AND APPARENTLY CHEAPER NEW PLANT DESIGNS.

The IAEA also proposes two scenarios for future growth. Its explanation of the assumptions underlying these scenarios suggests a more simplistic model than described above. The low estimate includes "only firm plans" of governments and utilities to build or refurbish power plants, while the high estimate adds additional capacity "suggested by the long term plans of governments or utilities."[6] The IAEA has increased its projections significantly over the past couple of years, and the low and high projections are both considerably more optimistic than those of the IEA.[6,20] It is likely that all of these projections will change over time, but in which direction, and by how much, is impossible to say.

VI. Construction Timelines and Costs

The IAEA reports median construction times for all nuclear power producing countries since 1976.[17] According to this data, median construction time peaked in the late nineties at around twelve years. The same data suggests that median construction time has been falling since then—but there have also been much fewer plants built in recent years, thereby decreasing the sample size. Only reporting the median also obscures the significant variation in construction times, and may underestimate how long it actually takes to build a nuclear plant. (The counterargument would be that reporting averages and/or maxima skews the data—that those cases are outliers rather than integral to understanding construction trends.) Nuclear projects are notorious for costing more money and taking more time to build than anticipated.[21]

The cost of nuclear power production remains uncertain and contentious. Joskow argues that investing in new plants has become more attractive for a number of reasons, including the improved performance of existing reactors, high fossil fuel prices, and apparently cheaper new plant designs.[22] (Joskow does admit that the timeline and cost data he uses from the nuclear industry should be viewed with "skepticism" because of the industry's "poor record" of accurately predicting cost.) Joskow calculates that nuclear power could compete with natural gas as a source of electricity if fossil fuel prices rise and if carbon is taxed in some way. These estimates also assume faster and cheaper construction of nuclear power plants than has ever been realized in the past.

	Sovacool (2008)		Hondo (2005)		IEA (2002)		
Technology	Capacity/type	Emission	Capacity/type	Emission	Capacity/type	Emission	Average
Wind	1.5 MW, onshore	10	300 kW	29	Swedish	2	
					Japanese	35	19
Hydroelectric	300 kW, run-of-river	13	10 MW	11	Swedish	1	
					Japanese	18	11
Solar Thermal	80 MW, parabolic trough	13					13
Solar PV	Polycrystalline silicone	32	3 kW, Polycrystalline silicone	53			43
Geothermal	80 MW, hot dry rock	38	55 MW, Double Flash	15			27
Nuclear	Various reactor types	66	1000 MW, BWR*	24	Japanese boiling water reactor	21	37
Natural gas	Various combined cycle turbines	443	1000 MW, Combined Cycle	518	Combined cycle	568	
			1000 MW, LNG-fired	608	LNG (non-combined cycle)	651	558
Fuel cell	Hydrogen from gas reforming	664					664
Diesel	Various	778					778
Heavy oil	Various	778	1000 MW, with SCR & FGD†	742			760
Coal	Various with scrubbing	960	1000 MW, with SCR & FGD†		Coal gasification, combined cycle	860	
	Various without scrubbing	1050		975	Coal energy content < 23.8 MJ/kg	1340	1037

*Boiling Water Reactor (light water); †Selective Catalytic Reduction and Flue Gas Desulphurization

Table III: Emissions estimates for different types of renewable and fossil fuel power generation measured in gCO_2e/kWh. *Data from Sovacool, Hondo, and IEA.*[9,15,23]

VII. Avoided Emissions

In order to compare emissions from nuclear power with those of other energy sources, we first need emission estimates from those other sources. The table below compiles three sets of estimates. Each set comes from a study that drew data from a wide range of literature.

Using the average values from Table III combined with projections reported in Table II, we can now calculate the potential emissions offset (or added) by nuclear power in 2030.[24] Table IV (overleaf) uses the predicted increases in nuclear production for 2030 (in TWh) to calculate hypothetical emissions for other power sources were they to replace the added nuclear capacity. For instance, if the IAEA's high projection turned out to be correct, nuclear power would produce an additional 194 MT of CO_2-equivalent emissions in 2030. If that power came from coal instead, more than 3,000 MT of GHGs would be emitted. Even using Sovacool's high estimate of nuclear emissions (848 MT), all fossil fuels remain quite a bit dirtier. But the data also show that nuclear emissions remain significantly higher than renewable sources of power, even if only the pre-operation emissions are considered (i.e. frontend and construction).

VIII. Is Nuclear Power the Answer?

From the perspective of greenhouse gas emissions, this paper suggests that nuclear power may indeed be an attractive alternative to fossil fuel-burning power production—but not as attractive as renewable sources, such as wind, solar and hydro. However, this conclusion about nuclear power should be qualified by the significant uncertainties surrounding the nuclear lifecycle. These include the quality of future uranium ore, the energetic costs of decommissioning and long-term waste disposal, government policy decisions, and reactor efficiencies, among other factors. And of course, beyond issues of greenhouse gas emissions lurk a host of negative environmental impacts of producing nuclear power, from radioactive pollution and the challenges of long-term waste storage to the potential for nuclear accidents and the proliferation of nuclear weapons. Whatever GHG case there is to be made at the political level ought not to consider these emissions in isolation as I have done in this paper, but ought to take a holistic view of nuclear power, with a central place for uncertainty. ■

		Added Emissions in 2030 (in MT)				
		(IEA)	(IAEA)	(EIA)	(IEA)	(IAEA)
Technology	gCO_2e/kWh	511	914	1200	1326	2943
Wind	19	10	17	23	25	56
Hydroelectric	11	5	10	13	14	31
Solar Thermal	13	7	12	16	17	38
Solar PV	43	22	39	51	56	125
Geothermal	27	14	24	32	35	78
Natural gas	558	285	510	669	740	1641
Fuel cell	664	340	607	797	880	1954
Diesel	778	398	711	934	1032	2290
Heavy oil	760	389	695	912	1008	2237
Coal	1037	530	948	1244	1375	3052
Nuclear Total	66	34	60	79	88	194
Frontend	25	13	23	30	33	74
Construction	8	4	7	10	11	24
Operation	12	6	11	14	15	34
Backend	9	5	8	11	12	27
Decommissioning	12	6	11	14	16	35
Nuclear high	288	147	263	346	382	848
Vs. Renewables		22	40	53	58	129
Vs. Fossil Fuels		-355	-634	-832	-919	-2040

Table IV: Possible emissions of various energy sources in 2030 if they were to replace projected growth in nuclear power. Production data taken from Table II ([projected production]-[current production]). The bottom two rows compare nuclear emissions to those of renewables (wind, hydro, solar, geothermal) and fossil fuels (natural gas, fuel cells, diesel, oil, coal). Positive values indicate a relative increase; negative values indicate reductions.

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Appendix

	New Capacity		Shut-downs	
Year	Country	MW	Country	MW
2008	China	4000		
	S. Korea	2300		
	Russia	2170		
2007	China	2610		
	S. Korea	1920		
	France	1600		
	Japan	1325		
	Romania	655		
	India	202		
	Russia	60		
2006	China	2610	UK	870
	S. Korea	960	Bulgaria	816
	Russia	750	Slovakia	408
	India	490	Spain	142
2005	Japan	2371	Sweden	600
	Finland	1600	Germany	340
	China	1000		
	S. Korea	960		
	India	490		
	Pakistan	300		
2004	Japan	2191	Lithuania	1185
	Ukraine	1900	UK	200
	Russia	950		
	China	610		
	India	470		

Appendix Table A1: New nuclear capacity by country. Includes construction starts and units coming online. *Data from IAEA.*[5]

	1976 - 1980		1981 - 1985		1986 - 1990		1991 - 1995		1996 - 2000		2001 - 2005		2006		2007		
Country	#	Months	#	Months	#	Months	#	Months	#	Months	#	Months	#	Mths	#	Mths	
ARGENTINA			1	109													
ARMENIA	2	73															
BELGIUM			4	88													
BRAZIL			1	132					1	296							
BULGARIA	1	87	1	104	1	89	1	113									
CANADA	4	89	7	98	5	101	2	97									
CHINA							3	73			6	88	1	88	1	88	
CZECH REP.			1	74	3	93			1	167	1	191					
FINLAND	4	63															
FRANCE	13	66	24	88	15	66	3	93	4	124							
GERMANY	9	88	7	100	6	103											
HUNGARY			2	112	2	90											
INDIA	1	152	2	154	1	152	3	120	4	122	1	84	1	74	1	82	
ITALY	1	101															
JAPAN	11	61	10	46	8	49	10	46	3	42	4	47					
KOREA REP.	1	59	4	65	4	62	2	61	5	56	4	54					
LITHUANIA			1	88	1	116											
MEXICO					1	151	1	210									
PAKISTAN									1	83							
ROMANIA									1	169					1	290	
RUSSIAN FED.	6	74	9	73	4	72	1	110			2	233					
SLOVAKIA	2	89	2	99					2	187							
SLOVENIA			1	88													
SOUTH AFRICA			2	102													
SPAIN			5	112	2	96											
SWEDEN	3	65	4	74													
SWITZERLAND	1	63	1	125													
UK	4	105	6	185	4	98	1	88									
UKRAINE	3	89	7	84	6	57	1	113			2	227					
USA	18	95	25	115	22	144	1	221	1	278							
TOTAL, MEDIAN	86	74	131	99	86	95	29	104	23	146	20	84	2	77	3	88	87.5
AVERAGE		82		98		97		111		152		125		77		144	111

Appendix Table A2: Number of new reactors connected to the grid by year and median construction time. *Data from IAEA.*[17]

Abbreviations

EIA	Energy Information Administration (U.S. Department of Energy)
gCO_2e/kWh	Grams of carbon dioxide-equivalent per kilowatt-hour
GHG	Greenhouse gas
GW	Gigawatt
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MT	Megatons
OECD	Organization for Economic Cooperation and Development
TWh	Terawatt-hour (109 kilowatt-hours)
WEC	World Energy Council
WNA	World Nuclear Association

NOTES

[1] International Energy Agency, Key World Energy Statistics 2008, (Paris: IEA, 2008).
[2] Intergovernmental Panel on Climate Change, Climate Change 2007: Synthesis Report, (Geneva, 2007).
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[11] World Nuclear Association, "World Uranium Mining," http://www.world-nuclear.org/info/inf23.htm (accessed November 28, 2008).
[12] World Nuclear Association, "Uranium Enrichment," http://www.world-nuclear.org/info/inf28.html (accessed December 15, 2008).
[13] Even Yucca Mountain may not hold all of the U.S. waste. The U.S. Energy Secretary submitted a report to the President late last year warning that the country may need a second repository unless Yucca Mountain regulations are changed to allow more high-level wastes.
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[17] International Atomic Energy Agency, Nuclear Power Reactors in the World, in Reference Data Series No. 2(Vienna: IAEA, 2008b).
[18] Current IEA production was calculated from reported data on the nuclear portion of total primary energy, which was then multiplied by IEA's assumed 33% thermal efficiency of nuclear production. Growth was calculated as ([projected]-[current])/[current]. Capacity factor was calculated as number of production hours divided by number of hours in a year: ([production]/[capacity]*1000)/(365*24).
[19] Energy Information Administration, International Energy Outlook, (Washington, D.C.: EIA, 2008).
[20] International Atomic Energy Agency, Energy, Electricity and Nuclear Power Estimates for the Period up to 2030, in Reference Data Series No. 1(Vienna: IAEA, 2008c).
[21] See, for instance, the case of Diablo Canyon in California, which ran $4 billion over budget and took ten years longer to build than expected. Demoro, H. W., "PUC Staff Says PG&E Should Pay for Diablo," San Francisco Chronicle (San Francisco: May 15, 1987): 1.
[22] Joskow, P.L., The Future of Nuclear Power in the United States: Economic and Regulatory Challenges, (Boston: MIT Center for Energy and Environmental Policy Research, 2006).
[23] Hondo, H., "Life cycle GHG emission analysis of power generation systems: Japanese case." Energy 30 (2005): 2042-2056.
[24] For nuclear power, in Table 4, I have not used the averages from Table 3, but Sovacool's mean figure of 66 gCO2e/kWh (as well as his high estimate of 288). The reason for this is discussed earlier in the paper.