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Greenhouse Gas Emission of European Pressurized Reactor (EPR) Nuclear Power Plant Technology: A Life Cycle Approach

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Abstract: Nuclear electricity generation technologies are considered to be important clean alternative energy sources as they do not directly generate carbon dioxide during the generation process. The environmental analysis over greenhouse gas emissions from European Pressurized Reactor (EPR) nuclear power plant, one type of pressurized water reactor (PWR), was studied by considering the entire life-cycle of the energy production. It was found that 1.98 g CO_2eq/kWh was emitted. The other air emissions, energy consumption, the amount of waste produced and their radioactivity were also estimated.

Key words: Nuclear energy; Fuel cycle; Life cycle assessment; EPR.

1. Introduction

Currently, electricity production in the world relies heavily on fossil fuels. According to the awareness of global environmental problems, the production of electricity from the burning of these fuels including coal and natural gas generally generates high amount of greenhouse gas (GHG) emissions and other pollutants. It has been known that replacing fossil combustion with nuclear power would dramatically reduce future GHG emissions. Nevertheless, although nuclear power plants do not emit GHG when generating electricity, nuclear energy would not be considered as a zero emissions energy source as it generally pollutes when its entire life cycle is accounted. This study applied a process life cycle assessment (LCA) method for studying hidden emissions (mainly GHG emissions) of European Pressurized Reactor (EPR) nuclear power on the basis of Thailand for about the next 10 years and also investigated the energy consumption as well as waste produce throughout its life cycle. The study is divided into four sections regarding the life cycle study method. The first section is goal definition and scope, while the second one considers the life cycle inventory (LCI). The third section is the life cycle impact assessment (LCIA) and the last consideration is the life cycle interpretation. It is noted that the goal of LCA is to evaluate resources and energy requirement as well as pollutants and wastes emitted throughout the life cycle of EPR nuclear power plant on the basis of Thailand, which have 1.63 GW capacities [1], 94% availability factor [2], 37% efficiency [3] and 70 GWd/tU burn-up rate [2]. The scope of LCA in this research was on facility related to nuclear fuel cycle. There are five main areas in the nuclear fuel cycle: Front-End (mining, milling, refinery, conversion, enrichment, fuel fabrication), Operation, Back-End (interim storage, waste conditioning, and waste disposal), Construction and Decommissioning. Importantly, the transportation was also included in the calculation.

2. Experimental

Figure 1 shows the facilities that have been assumed and included in the inventory analysis of LCA based on facilities owned by Areva Corporation (an important vendor of EPR technology).

2.1 Mining and Milling

McArthur River mine is the world's largest high-grade uranium mine operated by Cameco corporation (Areva share 30%). It is located in Saskatchewan, Canada. Average ore grade is 12.75%U_3O_8. This mine is underground pit type. Ore milled at Key Lake (Areva share 16%) operation, 80-kilometres southwest by road. Key Lake produces yellowcake (U_3O_8) [4]. Parametric data were obtained from the WISE uranium project website [5] and the IAEA website [6].

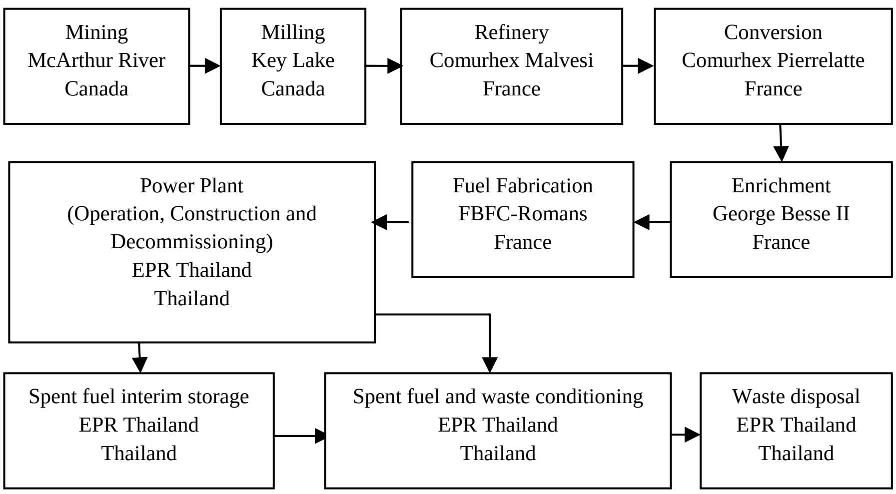

Figure 1. EPR Thailand Nuclear fuel cycle (once-through).

Table 1. Distances for transportation [17].

Kilometers		Substance	Route Segment
80	Truck	Uranium ore slurry	McArthur River to Key Lake
4380	Truck	Yellow cake	Key Lake to Point Tupper
6049	Ship	Yellow cake	Point Tupper to Fos
213	Truck	Yellow cake	Fos to Malvesi
234	Truck	UF_4	Malvesi to Tricastin(Pierrellatte)
0	-	UF_6 natural	Tricastin(Pierrellatte) to Tricastin(Eurodif)
20.4	Truck	UF_6 enriched	Tricastin(Eurodif) to Romans
235	Truck	UO_2 pellets	Romans to Marseilles
13560	Ship	UO_2 pellets, Heavy components	Marseilles to Bangkok
494	Truck	Heavy components	Saint Marcel to Marseille
1016	Truck	Heavy components	Jeumont to Marseille

2.2 Refinery, Conversion, Enrichment and Fuel fabrication

All the above facilities are located in France and all operated by Areva Company. Comurhex Malvesi refinery plant is in Narbonne region [7], where the first stage of conversion of uranium-bearing concentrate (yellow cake) from milling site to produce UF_4 is carried out. The second stage of conversion is in Comurhex Pierrelattle conversion plant (located on the Tricastin industrial site) [8], transforming UF_4 into UF_6 (uranium hexa-fluoride). The objective of this conversion is to give the uranium chemical form that is adapted to enrichment at George Besse II enrichment plant [9]. The next stage of the fuel cycle is at FBFC fuel fabrication plant at Romans [10]. FBFC converts UF_6 into UO_2 fuel pellets for use as fuel in the EPR nuclear power plant. All parametric data can be obtained from Areva's website.

2.3 Operation (EPR Power Plant)

By making the assumption that the power plant is constructed in Thailand, the amount of spent fuel can be obtained from the calculation and other information including emissions and waste were obtained from UK-EPR website [11-12].

2.4 Interim spent fuel storage, Spent fuel and waste conditioning, Waste disposal

These stages were assumed to include only once-through of fuel life cycle and on-site interim spent fuel storage (at EPR until the end of power plant). There is no specific data for these stages, therefore, emissions can be calculated from other research done on that have PWR emissions [13-14]. It is noted that all of these stages were assumed to proceed in Thailand without consideration of transportation.

2.5 Construction

Heavy components for construction need to be imported from Areva at France, nevertheless, others simple materials such as concrete, steel or copper were assumed to supply from Thailand. The amount of raw materials needed for construction was obtained from UK-EPR's website [15] and the time for construction was estimated to be about 5 years.

2.6 Decommissioning

There are 3 stages in the decommissioning of a power plant; (1) removal of spent fuel, (2) decontamination and dismantling, and (3) demolition. After demolition, the land is returned to a condition where no radioactive hazard remains (further surveillance, inspection, or tests are not required). All of these stages need 12 years for completing. Waste produce can be found from UK-EPR website [16], while emissions that produce can be found from other research related with PWR reactor [13-14].

2.7 Transportation

GHG emissions from transporting of uranium, materials, waste and heavy components were obtained from Google's website and Portworld's website. Heavy components include reactor pressure vessel, steam generators, reactor coolant pumps, and pressurizer [2]. Table 1 shows the distances for trans ortation between each location.

3. Results and Discussion

3.1 Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) involves data collection and calculation. The uranium flow balance for 1 kWh of electricity generated from EPR was created to quantify environmental impacts, material consumption, energy consumption and waste products of different processes. Table 2 shows all parameters used in material balance calculations.

Table 2. Process parameters [6,18].

Process	Parameters	Amount	Unit
Mining	-Waste/Ore Ratio -Ore Grade -Diesel consumption* -Electricity consumption*	27 12.75 57.7 70.6	 $\%U_3O_8$ MJ/t Ore kWh/t Ore
Milling	-Extraction Losses -Diesel consumption* -Electricity consumption*	1.6 483 18.6	% MJ/t Ore kWh/t Ore
Refinery	-Losses	1	%
Conversion	-Losses	1	%
Enrichment	-Product Assay -Tails Assay - Specific Electricity Consumption	4.3 0.3 48	%U-235 %U-235 kWh/SWU
Fuel Fabrication	-Losses	1	%
Power Plant	-Fuel Burn up -Efficiency -Capacity factor -Net capacity	70 37 94 1.63	GWd/tU % % GWy

*Diesel consumption and electricity consumption in mining and milling are based on the figures from WISE uranium project [5] for underground mine and mill in U.S. since no data is available for mine in Canada.

Table 3 shows the input data from different processes. These data were taken from the press of each plant [7-10,19]. Only electricity consumption and SWU in enrichment plant was calculated. As for the back-end and decommissioning, there is no specific data related to an EPR reactor; hence, the data for the emissions emit from these processes were taken from other PWR type power plants [13-14]. According to the emissions and waste data, they come from both calculation and press released [11,20] and the results as shown in groups of wastes and emissions are given in Table 4.

Table 3. Input data collections.

Process	Input (consumption)		
Mining (underground)	-Diesel -Electricity	57.7 70.6	MJ/t ore kWh/t ore
Milling	-Diesel -Electricity -Sulfuric acid -Ammonia	483 18.6 1,880 57.7	MJ/t ore kWh/t ore t kg/ton ore kg/ton ore
Refinery	-Heavy fuel type2 -Heavy domestic oil -Electricity -Nitric acid -Ammonia -Hydrofluoric acid -Water	9,970 601 1,850 593 260 70.5 90.8	MJ/ton$U_{n3}O_8$ MJ/ton $U_{n3}O_8$ kWh/ton$U_{n3}O_8$ kg/ton $U_{n3}O_8$ kg/ton $U_{n3}O_8$ kg/ton $U_{n3}O_8$ m^3/ton $U_{n3}O_8$
Conversion	-Fossil fuel -Electricity -Hydrofluoric acid -Water	7,250 5,360 227 0.132	MJ/tonU_nF_4 kWh/ton U_nF_4 kg/ton U_nF_4 m^3/ton U_nF_4
Enrichment (diffusion)	-Electricity -SWU (separative work unit) -Natural gas -Production of thermal energy -Water	48 128,000 5.23 0.549 0.0016	kWh/ SWU SWU MJ/ SWU MJ/ SWU m^3/SWU
Fuel Fabrication	-Electricity -Natural gas -Water	39,500 49,400 95	kWh/tonU_eF_6 MJ/ton U_eF_6 m^3/ton U_eF_6
Operation (60 years)	-Diesel -Electricity -Water -Water for cooling -Chemicals	242,000 N/A 12,100 85,700,000 N/A	MJ/ton U_eO_2 kWh/ton U_eO_2 m^3/ton U_eO_2 m^3/ton U_eO_2 kg/ton U_eO_2
Interim spent fuel storage	-Diesel -Electricity -Borate water	N/A N/A 1,56	MJ/ton SF* kWh/ton SF m^3/ton SF
Spent fuel and waste conditioning	-Diesel -Electricity -Package materials	N/A N/A N/A	MJ/ton SF kWh/ton SF kg/ton SF
Waste disposal	-Diesel -Electricity	N/A N/A	MJ/ton SF kWh/ton SF
Construction (5 years)	-Concrete -Steel (for reinforce concrete) -Steel (for components and pipes) -Copper -Aluminium -Fresh water -Heavy components (import from Vendor)	720,000 46,000 5,000 330 140 1,100,000 3,29	t/plant t/plant t/plant t t m^3/plant t/plant
Decommissioning (12 years)	-Electricity -Fossil fuel	N/A N/A	kWh/plant MJ/plant

N/A; not applicable
SF; Spent fuel

Table 4. Air emissions and waste data collection (include transportation).

Process			Unit	Waste		Unit
Mining	**CO_2	84.1	kg/ton ore	Waste rock	27	ton/ton ore
	NO_x	0.770	kg/ton ore			
	PM	0.282	kg/ton ore			
Milling	**CO_2	763	kg/ton ore	Mill tailings	875	kg/ton ore
	CO	0.288	kg/ton ore			
	Ammonia	0.869	kg/ton ore			
	NO_x	1.11	kg/ton ore			
	PM	3.03	kg/ton ore			
	SO_2	1.52	kg/ton ore			
	VOCs	7.68	kg/ton ore			
Refinery	**CO_2	3,840	kg/ton $U_{n3}O_8$	Solid waste	570	kg/ton $U_{n3}O_8$
	NOx	10.3	kg/ton $U_{n3}O_8$	Liquid waste	3.50	m^3/ton $U_{n3}O_8$
	PM	0.439	kg/ton $U_{n3}O_8$			
	Fluoride	0.012	kg/ton $U_{n3}O_8$			
Conversion	**CO_2	1,170	kg/ton U_nF_4	Solid waste	845	kg/ton U_nF_4
	Tritium	$1.41x10^7$	Bq/ton U_nF_4	Liquid waste	0.660	m^3/ton U_nF_4
	C-14	$1.44x10^5$	Bq/ton U_nF_4			
	Fluoride	0.048	kg/ton U_nF_4			
Enrichment	**CO_2	0.724	kg/SWU	UF_6 depleted	2.21	kg/SWU
	Chlorine	$1.96x10^{-4}$	kg/SWU	Water discharge	0.495	m^3/SWU
	Fluorine	$8.10x10^{-5}$	kg/SWU			
	Radioactive	7.870	Bq/SWU			
Fuel Fabrication	**CO_2	43,000	kg/ton U_eF_6	Solid waste	4,840	kg/ton U_eF_6
				Liquid waste	21.0	m^3/ton U_eF_6
Power plant	**CO_2	20,600	kg/ton U_eO_2	Spent fuel	1,000	kg/ton U_eO_2
	CO	0.0269	kg/ton U_eO_2	Radioactive solid waste	3.37	m^3/ton U_eO_2
	SO_2	33.7	kg/ton U_eO_2	Conventional solid waste	23,300	kg/ton U_eO_2
	NO_2	354	kg/ton U_eO_2			
	Formaldehyde	0.0285	kg/ton U_eO_2			
	Ammonia	38.0	kg/ton U_eO_2			
	Tritium	$3.18x10^{12}$	Bq/ton U_eO_2			
	C-14	$4.05x10^{10}$	Bq/ton U_eO_2			
	Iodine	$1.84x10^7$	Bq/ton U_eO_2			
	Noble gas	$9.17x10^{11}$	Bq/ton U_eO_2			
	F|P/AP*	$1.43x10^7$	Bq/ton U_eO_2			
Back-end	**CO_2	0.42	g/kWh			
Construction	**CO_2	$5.09x10^8$	kg/plant	Solid waste	N/A	kg/plant
	CO	N/A	kg/plant			
	PM	N/A	kg/plant			
	HC	N/A	kg/plant			
	NO_x	N/A	kg/plant			
Decommissioning	**CO_2	0.616	g/kWh	*VLLW,LLW,ILW	$1.34x10^7$	kg/plant

*FP/AP: Other fission or activation product emitting beta or gamma radiation
PM: also include PM-10 and PM-2.5
VLLW: very low level waste, LLW: low level waste, ILW: intermediate level waste
**These are LCA based greenhouse gas emission

Energy consumption for each stage calculated only front-end, others use value from WNA (world nuclear association) [21]. PWR type nuclear power plant are presented in Table 5.

Table 5. Energy consumption (thermal).

Front-end	847	TJ/year
Operation	27.5	TJ/year
Back-end	108	TJ/year
Construction	34.2	TJ/year
Decommissioning	68.3	TJ/year

3.2 Life cycle impact assessment (LCIA)

By considering the GHG emissions (CO_2) basis on 1 KWh of electricty generated from the EPR 1.63 GWy capacities, 94% availability factor, 37% efficiency and 70 GWd/tU burn-up rate and 60 years operation, Table 6 shows the GHG emissions from each technical stage. It was found that EPR nuclear power plant emits about 1.98 gCO_2/kWh and GHG from transportation is about 0.02 gCO_2/kWh (1.01%).

Figure 2 shows GHG emissions of each stage including transportation in front-end and construction. Comparing GHG emissions from this calculation with other research, WNA reported the value of 17 gCO_2/kWh for the first enrichment plant in France. The difference in values reported could be due to the presence of on-site nuclear reactors for supply electricity of the technology considered here, which results in the low CO_2 emission at the front-end part.

Figure 3 shows the GHG emission from each stage that separates transportation from front-end and construction. It was found that CO_2 from transportation share is about 1.01%. In Figure 4, the thermal energy consumption for proceeding is presented. The energy consumption is 1,085 PJ/year (thermal).

According to "Life cycle energy and greenhouse gas emissions of nuclear energy: a review [13]", the information in the present work are in good agreement with that reported from the review. The GHG emissions from calculation value as presented in Table 6 is comparable with GHG emissions from other generation of nuclear reactors with slightly less than those of other previous nuclear reactors (3.24–54 gCO_2/kWh); this could be due to the reduction of uranium requirement for the newly developed third generation technology which offers a higher burn-up rate. The major contributions of GHG emissions are from the back-end processes, decommissioning, and construction since these technologies are typically old processes and would be replaced with more efficient technologies. The mining contributed very low GHG emissions because McArthur River mine represented a relatively high grade ore (10.81%U). The enrichment stage generated the least GHG emissions. This is much lower than the reported values from other studies largely because the electricity supplied to the enrichment plant come from nuclear.

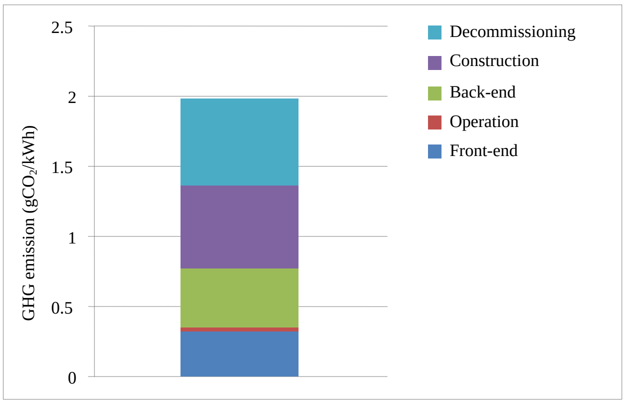

Figure 2. GHG emission include transportation in gCO_2/kWh.

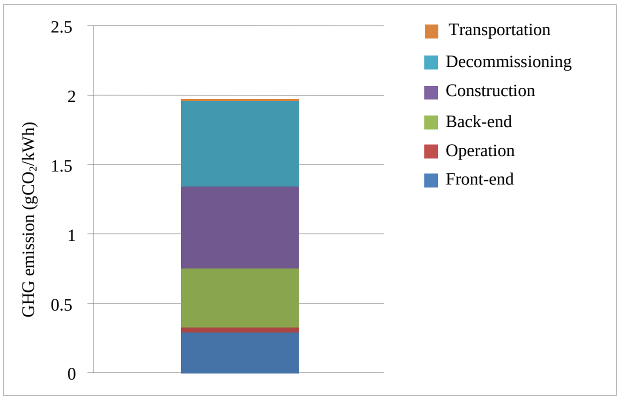

Figure 3. GHG emissions include transportation in gCO_2/kWh.

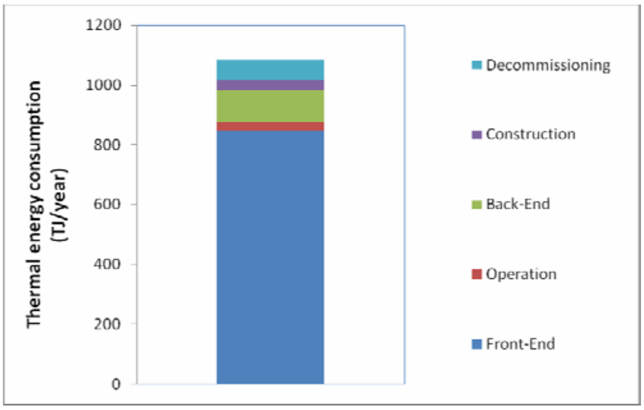

Figure 4. Energy consumption in TJ/year.

Table 6. GHG emissions from each stage.

	Include transportation (gCO_2/kWh)	Exclude transportation (gCO_2/kWh)
Front-end	0.317	0.299
Operation	0.035	0.035
Back-end	0.420	0.420
Construction	0.595	0.593
Decommissioning	0.616	0.616
Total	1.98	1.96

4. Conclusions

The GHG emissions, amount of waste, air emissions and energy consumption for EPR nuclear power plant were studied by LCA. It was found that the GHG emissions are 1.98 gCO_2eq/kWh, while the energy consumption throughout its lifecycle is 1,085 PJ/year. It is noted that nuclear power plant emits less GHG emissions but it also produces other air emissions, solid waste, liquid waste and dangerous waste such as radioactive waste, which must be taken into consideration.

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