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Change impact analysis on the life cycle carbon emissions of energy systems – The nuclear example

Victor Nian

Energy Studies Institute, National University of Singapore, Singapore

HIGHLIGHTS

- This paper evaluates the life cycle carbon emission of nuclear power in a scenario based approach.
- It quantifies the impacts to the LCA results from the change in design parameters.
- The methodology can give indications towards preferred or favorable designs.
- The findings contribute to the life cycle inventories of energy systems.

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ABSTRACT

The life cycle carbon emission factor (measured by t-CO_2/GW h) of nuclear power is much lower than those of fossil fueled power generation technologies. However, the fact of nuclear energy being a low carbon power source comes with many assumptions. These assumptions range from system and process definitions, to input–output definitions, to system boundary and cut-off criteria selections, and life cycle inventory dataset. However, there is a somewhat neglected but critical aspect – the design aspect. This refers to the impacts on the life cycle carbon emissions from the change in design parameters related to nuclear power. The design parameters identified in this paper include: (1) the uranium ore grade, (2) the critical process technologies, represented by the average initial enrichment concentration of ^{235}U in the reactor fuel, and (3) the size of the nuclear power reactor (measured by the generating capacity). If not properly tested, assumptions in the design aspect can lead to an erroneous estimation on the life cycle carbon emission factor of nuclear power. In this paper, a methodology is developed using the Process Chain Analysis (PCA) approach to quantify the impacts of the changes in the selected design parameters on the life cycle carbon emission factor of nuclear power. The concept of doing so broadens the scope of PCAs on energy systems from “one-off” calculation to analysis towards favorable/preferred designs. The findings from the analyses can serve as addition to the life cycle inventory database for nuclear power as well as provide indications for the sustainability of nuclear energy systems.

1. Introduction

Nuclear power, despite being blamed for the recent incidents, is an effective means of decarbonizing the electricity sector [1]. The business-as-usual (BAU) projections by the U.S. Energy Information Administration (EIA) [2] indicates that world carbon emissions in 2040 will be around 42% higher than in 2013. According to the Intergovernmental Panel on Climate Change (IPCC) [3], these carbon emissions will likely result in the atmospheric CO2 concentration reaching the alarming levels by 2040. In a most recent life cycle analysis (LCA), Nian and others [4] reported that the life cycle carbon emission factor of nuclear power is about 23 t-CO_2/GW h. Benchmarking the life cycle emission factors reported by Hondo [5] and the IPCC [6], nuclear power was more competitive against all other power generation technologies except hydropower, which tend to be particularly dependent on geographical locations (Fig. 1).

Thus, one may argue that a major way to combat these BAU dire predictions is by substantially increasing the deployment of nuclear power. However, the most recent Fukushima incident put a speed bump for the much expected “nuclear renaissance”. According to Nian and Chou [7], a number of countries, such as Germany and Switzerland decided to completely phase out nuclear after decades of commitment. Nevertheless, many other countries in the developing world remained interested in nuclear. In Asia, China was leading the construction of new nuclear power reactors. Among the member states of the Association of South East Asian

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E-mail address: nian@nus.edu.sg

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Nomenclature

Abbreviations

BAU	Business-as-usual
EIA	Energy Information Administration
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IOA	Input–Output Analysis
IPCC	Intergovernmental Panel on Climate Change
IR	inferred resources
ISL	in-situ leaching
LCA	life cycle analysis
LCI	life cycle inventory
IPCC	Intergovernmental Panel on Climate Change
LWR	light water reactor
NEA	Nuclear Energy Agency
PCA	Process Chain Analysis
SMR	Small Modular Reactor

Symbols

C	carbon emissions
C_E	carbon emissions due to energy input
C_{Ext}	extrinsic emission of process input
$C_{E,n}$	carbon emissions from the *n*th process due to energy input
C_{Fuel}	carbon emissions from fuel
C_{Int}	intrinsic emission of process input
C_{NE}	carbon emissions due to non-energy input
$C_{\mathrm{NE},n}$	carbon emissions from the *n*th process due to non-energy input
C_{sys}	total carbon emission of the LCA Main System
c	carbon intensity or emission factor
$c_{e,i}$	carbon intensity of energy input by type
$c_{e,i}$	carbon intensity of non-energy input by type
$c_{E,n}$	carbon intensity of energy input
$\mathrm{C}_{\mathrm{Fuel}}$	carbon emission from the conversion of fuel in the power plant
c_{sys}	carbon emissions factor of the LCA Main System
E_i	energy input to each process of the LCA Main System
E_n	energy input to support the process activities
E_{out}	life cycle energy output from a system
e	energy intensity
e_i	energy intensity by type
e_n	energy intensity of product p_n
NE_{in}	non-energy input to power generation
NE_n	non-energy input to the *n*th process
NE_i	non-energy input to each process of the LCA Main System
ne	intensity of non-energy input
ne_i	intensity of non-energy input by type
ne_n	intensity of non-energy input required to produce p_n
P_n	the *n*th process of the LCA Main System
P_e	generating capacity of the plant
p_n	product of the *n*th process of the LCA Main System
p_{n-1}	product of upstream process P_{n-1}
GW D	Gigawatt day
GW h	Gigawatt hour
kg	kilogram
TW h	Terawatt hour

Nations (ASEAN), Vietnam planned to start constructing two reactors in 2020. Thailand was also expected to embrace nuclear power in the country's energy mix by 2040 [8]. Based on the information from [7,9], the change in the share of nuclear power in the electricity fuel mix can only be detected in very few countries despite the sharply polarized opinions towards nuclear. Globally, nuclear supplied 18.4% of the total electricity in 2012, which was only a marginal reduction from 2011 at 19%.

There are two types of natural resources, Uranium and Thorium, suitable for fission power generation. They are neither abundant nor very rare metals in the earth crust: their abundance is comparable to that of Tin, Tungsten or Molybdenum, of the order of 3 gram per metric ton for uranium, and 7 for thorium. As of today, commercial nuclear power plants are fueled primarily by uranium. Unlike other natural resources such as coal and natural gas, uranium cannot be directly "burned" to produce electricity. It requires a series of transformations for producing the final usable fuel form.

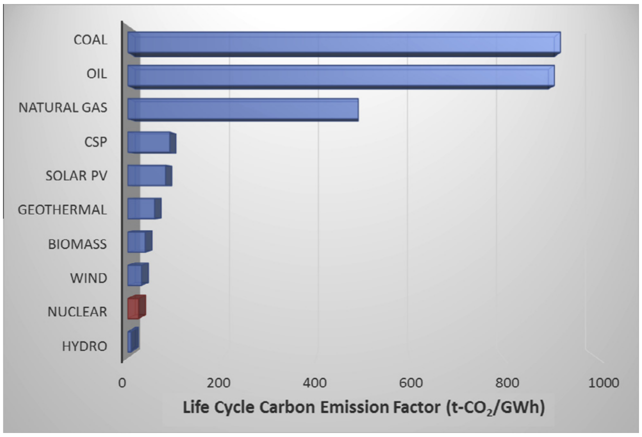

Fig. 1. Benchmarking life cycle carbon emission factors.

Nuclear fission is an extremely potent source of energy with a very high energy density when measured in the amount of energy produced per unit mass of fuel. Compared to chemical reactions such as combustion of fossil fuels, fission requires much less fuel material to produce an equivalent amount of energy. The energy released from 1 kilogram (kg) of uranium in a typical light water reactor (LWR) is equivalent to that released by burning about 45,000 kg of wood, 22,000 kg of coal, 15,000 kg of oil, or 14,000 kg of liquefied natural gas. Despite the low fuel material requirement, changes in the design parameters related to the uranium supply chain can have significant impacts on the life cycle carbon emission factor of nuclear power.

This is especially true for the mining and milling process. The quantities of uranium ore to be mined and milled depend primarily on the average grade of the uranium ore. Typically, the uranium ore grade ranges from 15% to 0.1%. Thus, the quantities of uranium ore can range from 6.7 to 1000 metric ton to produce one metric ton of "yellow cake" (U_3O_8 as the main content). With the depletion of the higher grade uranium ore, the nuclear industry may move towards harvesting the lower grade ones. Based on the case study results from [4], there were uncertainties with the life cycle carbon emission factor of nuclear power under the influence of the decreasing uranium ore. Another source of uncertainty came from the average initial ^{235}U enrichment concentration. Since all of the commercial LWRs are fueled by enriched uranium, it is important to quantify the impact on the life cycle carbon emission factor from the changes in the enrichment concentration.