Energy Proceedings
Vol 31, 2023
ISSN 2004-2965

Life cycle assessment (LCA) of electricity generation technologies in China: Overview, comparability and limitations

Yinchen Liu[1, 2], Xiaoyu Yan [1, 2*]

1 Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9FE, UK

2 College of Engineering, Mathematics and Physical Sciences, University of Exeter, Cornwall TR10 9FE, UK

ABSTRACT

Electricity sector is a main contributor of greenhouse gas (GHG), NO_x, SO_2 and $PM_{2.5}$ and related environmental impact in China. This research conducted a critical review of 36 studies containing 51 cases involving 10 electricity generation technologies in China to analyze the ranges of emission data for GHG, NO_x, SO_2 and $PM_{2.5}$, summarize the current LCA methodologies and the key indicators like impact categories and temporal scale. The results showed it's incomplete to measure the environmental performance of an electricity generation technology solely based on GHG emission. Emissions data were set and evaluated at different life cycle stages for different electricity generation technologies. Emissions from fuel combustion contributed the majority of the life cycle emissions for fossil fuel power, up to 90% for GHG, 70% for SO_2, similarly, biomass fuel provision accounted the largest share of emissions for biomass technologies, up to 85% for GHG. Emission and environmental impacts from plant infrastructure contributed the largest share for renewable energies. And the emission of end-of-life treatment from renewable energies can offset considerable life cycle emissions. The results from this review provided a concrete and balanced basis for further LCA modelling in the China's whole electricity sector.

Keywords: electricity sector, LCA, renewable energy, energy systems for power generation.

1. INTRODUCTION

In developing countries like China and India, majority electricity supply depend on fossil fuel. In the last two decades, China experienced slow energy transition path, where the fossil fuel electricity share dropped from 82.12% in 2000 to 67.95% in 2019 [1] and coal power's proportion dropped from 78.21% to 64.61%. China's electricity sector has contributed considerable CO_2 emission in the last 2 decades too, increased from 45% (1427 Mt) to 53% (4896 Mt) of total CO_2 emission. Electricity sector has become the largest contributor of carbon dioxide or GHG, where coal power's share soar from 1365.5 Mt to 4726.6 Mt [1]. Moreover, SO_2 and $PM_{2.5/10}$ are also concerning in China. Many studies have noticed the country suffered a lot of haze fog and acid rain, to which electricity generation is one of the largest contributors (Chen et al., 2011)[2,3] and causes lots of environmental problems.

In this regard, the environmental impacts associated with different energy technologies are increasingly becoming an important part of supporting policy making. Carbon footprint, other greenhouse gas accounting methods and life cycle assessment (LCA) are usually used to evaluate environmental performance [4–6]. LCA is an environmental method which provides accounting for and assessing the environmental aspects and potential impacts related to products, services, or processes [7,8]. ISO 14040 and ISO 14044 defined the standard 4 steps approach, which are: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA) and (4) interpretation.

There are a significant number of LCA studies focused on China's electricity generation technologies in the past decade, most of these are case studies which focus on China's one or multiple electricity technologies. Majority of them analyzed emission inventory, especially carbon footprint which is the most common indicator [9–13]. While less studies applied LCIA [3,14–17] to analyze a wide range of environmental impacts about China's electricity sector. Various methods exist in current LCA practice in China, but the importance of method choices, emission types, and contributions of different life cycle stages has not been rigorously assessed in the context of power generation. A systematic review of the results of method selection and technical performance is required to establish a concrete and balanced basis for further LCA modelling in the China's electricity sector.

This study conducts the first in-depth review of LCA studies on 10 different electricity generation technologies in China to (i) summarize current LCA methodologies and (ii) systematically evaluate and compare their emission inventory, environmental impacts and the determining factors.

2. METHODOLOGY

2.1 Research scope

The selected electricity generation technologies are: coal, natural gas, oil, hydro, wind, solar, biomass, geothermal, tidal and wave and nuclear. Overall, two approaches are used in current LCA practices: process chain analysis (PCA) and input–output analysis (IOA), which the process chain analysis is widely applied in China. Emission factors, like GHG, SO_2, NO_x and $PM_{2.5}$, environmental impact categories, like global warming potential (GWP) and acidification potential (AP), and other indicators like temporal, special scale are also analyzed additionally.

2.2 Literature screening

The collected literature are searched via Google Scholar, Science Direct, Springer and ACS, where Google Scholar was chosen as the major search database, by applying the terms like “life cycle assessment” or LCA, electricity, China; “life cycle assessment” or LCA, energy, China; “life cycle assessment” or LCA, tidal power, China; “life cycle assessment” or LCA, wave power, China, 116 studies were found out. LCA studies were included based on a range of criteria: (1) the included studies should consider more than 2 kinds of emission inventory or 3 environmental impact categories; (2) the selected studies should be published after 2010 to ensure the data availability; (3) the considered studies should contain a functional unit clearly related to electricity generation like 1 kWh or 1 MWh. 56 studies were finally screened out by applying these criteria.

2.3 Results

This study collected 51 cases from 39 studies in China, from 2009-2021. 25 of them conducted life cycle impact assessment, which only 6 of them identified 18 impact categories, 26 cases conducted emission inventory analysis, which majority studies analyzed GHG and SO_2, while 6 cases considered emission inventory and impact assessment simultaneously. In this study, 3 LCA methods can be identified, which are process-based LCA, Economic IO-LCA and hybrid LCA, where most of the collected studies applied process-based LCA, the hybrid and economic IO LCA can be identified in 4 and 3 studies respectively. Professional LCA software are widely applied in those studies which conducted LCIA, including Simapro, Gabi, also professional LCA database can be located as well, like Ecoinvent which is the most popular database and CLCD, a China’s localized dataset.

Table 1. Overview of the technologies considered, spatial and temporal scale and LCA methodologies.

Study	*Technology type*	*Spatial scale*	*Temporal scale*	*LCA methodology*
[18]	Coal	Plant scale	2009	LCIA, ReCiPe, 18 categories
[19]	Coal	Plant scale	2009	LCIA, CML 2001, 8 impact categories
[20]	Coal	Plant scale	2010	Emission inventory and LCIA, CML 2001, 5 impact categories
[16]	Coal	Plant scale	2015	Emission inventory, CO_2, SO_2, NO_x
[17]	Coal	Plant scale	2009	Emission inventory CO_2, SO_2, NO_x and $PM_{2.5}$
[2]	Coal	Plant scale	2013-2017	Emission inventory, CO_2, SO_2, NO_x and $PM_{2.5}$
[21]	Coal	Plant scale	2010-2014	LCIA, mid-point impacts, 8 impact categories
[22]	Coal	Plant scale	2016	LCIA, CML 2001, 5 impact categories
[15]	Coal	Plant scale	2019	Hybrid-LCA, emission inventory, economic analysis
[23]	Natural gas	Plant scale	2016	LCIA, 5 impact categories
[24]	Natural gas	Plant scale	2020	Emission inventory, GHG
[25]	Natural gas	Plant scale	2020	Emission inventory, GHG
[26]	Natural gas	Provincial scale	2015	Emission inventory, CO_2, SO_2, NO_x
[27]	Natural gas	Plant scale	2017	LCIA, CML 2001, GHG
[28]	Oil	National scale	2010	Tsinghua-CA3EM, Emission inventory, CO_2; CH_4 and N_2O
[27]	Oil	Plant scale	2017	LCIA, CML 2001, GHG
[29]	Wind	Provincial scale	2013	Emission inventory and LCIA, 2 impact categories, EP, GWP
[30]	Wind	Plant scale	2016	Economic input-output LCA, emission inventory, CO_2, SO_2, NO_x and $PM_{2.5}$
[16]	Wind	Plant scale	2015	Emission inventory, CO_2, SO_2, NO_x and $PM_{2.5}$
[31]	Wind	Plant scale	2017	LCIA, CML2001, 11 impact categories
[12]	wind	Plant scale	2018	LCIA, CML 2001, 5 impact categories
[32]	Wind	Plant scale	2012	Emission inventory, CO_2, CO, SO_2, NO_x and PM and energy consumption
[17]	Wind	Plant scale	2010	Emission inventory, CO_2, SO_2, NO_x and $PM_{2.5}$
[26]	Wind	Provincial scale	2015	Emission inventory, CO_2, SO_2, NO_x
[26]	Solar	Provincial scale	2015	Emission inventory, CO_2, SO_2, NO_x
[33]	Solar	Plant scale	2014	Gabi4, LCIA, 6 impact categories
[34]	Solar (ms-Si)	National scale	2013	Hybrid LCA, emission inventory, CO_2, CH_4, SO_2, N_2O and NO_x

[35]	Solar	Plant scale	2010	Emission inventory, GHG, SO_2, NO_x and TSP
[36]	Solar	Plant scale	2019	Simapro 8.3 and Ecoinvent 2.0, LCIA, Eco-Indicator 99, 18 impact categories
[37]	Solar	National Scale	2010	LCIA, Receipt, 16 impact categories
[38]	Solar	Provincial scale	2017	Emission inventory, GHG and energy payback time
[39]	Wave	Plant scale	2017	LCIA, ReCiPe, 18 impact categories, energy payback time
[40]	Geothermal	Plant scale	2019	LCIA, CML 2002, 3 impact categories, CLCD database
[41]	Hydro	Plant scale	2016	Economic IO-LCA, CLCD database, emission inventory, GHG
[42]	Hydro	Plant scale	2018	Emission inventory, GHG; LCIA, GHG
[43]	Hydro	Plant Scale	2014	Economic IO-LCA, emission inventory, CO_2
[44]	Hydro	Plant scale	2014	Gabi6, Ecoinvent 2.2, LCIA, CML2001, 6 impact categories
[12]	Hydro	Plant scale	2018	LCIA, CML 2001, 5 impact categories
[26]	Hydro	Provincial scale	2015	Emission inventory, CO_2, SO_2, NO_x
[45]	Biomass	Plant scale	2012	Emission inventory, CO_2 CO CH_4 N_2O NO_x Dust SO_2, LCIA, 5 impact categories
[46]	Biomass	Plant scale	2014	Hybrid LCA, emission inventory, GHG; economic analyse
[47]	Biomass	Plant scale	2015	LCIA, ReCiPe method, 18 impact categories
[15]	Biomass	Plant scale	2019	Hybrid-LCA, emission inventory, economic analysis
[26]	Biomass	Provincial scale	2013	Emission inventory, CO_2, SO_2, NO_x
[48]	Biomass	Plant scale	2018	LCIA, 7 impact categories; emission inventory, CO_2 CO CH_4 N_2O NO_x Dust SO_2
[49]	Biomass	Plant scale	2019	Emission inventory, CO_2 CO CH_4 N_2O NO_x SO_2, HC, PM_{10}; LCIA, 5 impact categories
[28]	Nuclear	Plant scale	2010	GREET, emission inventory, GHG
[24]	Nuclear	Plant scale	2020	Emission inventory, GHG, SO_2, NO_x and $PM_{2.5}$
[12]	Nuclear	Plant scale	2018	LCIA, CML 2001, 5 impact categories
[26]	Nuclear	Provincial scale	2015	Emission inventory, CO_2, SO_2, NO_x
[50]	Nuclear	National scale	2017	LCIA, Eco-indicator 99 3 impact categories, Simapro

2.3.1 LCA of fossil fuel power

Sixteen cases about coal, natural gas and oil power were screened according to the criteria, where only one reported the emission factors on national scale another one on provincial scale, fourteen reported the emission factors on plant scale. Four type of coal power technology were considered: Subcritical, Supercritical, Ultra-supercritical and Integrated coal gasification combined cycle (IGCC). This distinction was made because of the prominent performance variation, it can be noticed in emission factors and system efficiencies. Six studies conducted environmental impact assessment (4 for coal power, 1 for natural gas, 1 for oil power), only one study considered the whole 18 impact categories. GWP, AP, EP were widely reported, where most of their contributions can be referred to plant operation. While ten studies reported the emission inventory, apart from GHG, emission data for SO_2, NO_x and PM were identified in 10, 9 and 5 studies, respectively, similar to environmental impacts, most of the emissions were related to plant operation, the emission factor of CO_2 is in the range of 410-1317 gCO_2 -eq/kWh at the plant level, 380-1000 gCO_2 -eq/kWh for provincial scale (natural gas power only), 1181.61 gCO_2 -eq/kWh for national scale (oil power only). For SO_2, NO_x and $PM_{2.5}$, only plant scale data can be identified, which are 0.097-7.6 gSO_2/kWh, 0.388-8.05 gNO_X/kWh and 0.16-2.2 $gPM_{2.5}$/kWh, respectively.

Coal power has the largest reported emission factor of CO_2 in fossil fuel power, while the natural gas reported the smallest CO_2 emission. For emission factors of SO_2, NO_x and PM, distinct difference can't be identified among fossil fuel powers. All studies on fossil fuel power found the plant operation is the largest contributor to the 4 emissions, ranging from 88% [51] to 95% [23]. Apart from plant operation, majority studies agreed the fossil fuel mining and processing is the second largest contributor of GHG, due to the methane emissions during mining and processing. Followed by fossil fuel transportation, including bulk and pipeline transportation, which contributed 1%-3% of greenhouse gas, especially the methane, but some studies believed it's the largest source of PM [21], contributing 92% of dust emission. Emissions from plant construction and infrastructure were reported as negligible in all studies.

2.3.2 LCA of renewable energies

30 cases of renewable energies are selected, including 8 of wind, 7 of solar, 1 study of wave and geothermal, 6 of hydro and 7 of biomass, see table 1.

2.3.2.1 LCA of wind power

For wind power studies, 2 of them reported the provincial scale results, while the rest of the studies reported the plant scale results. 3 studies conducted LCIA, 5 studies reported emission inventory, which [30] applied EIO-LCA to calculate emission inventory. No study analyzed the whole 18 impact categories, but GWP and AP can be identified individually, where the nacelle (30%-50%), tower (41%-45%) and rotor (19%) were reported as major contributors of GWP. All of eight studies reported GHG and SO_2 emission, emission factors of NO_x and PM_{10} were reported in 6 and 4 studies respectively, with specifying the contributions throughout the life cycle for four emissions. The emission factor of GHG was reported in the range of 7.7-31.36 g CO_2/kWh for plant scale, 3-41 gCO_2/kWh for provincial scale, with high variation. Most of the reviewed studies believe the production stage was the largest contributor of CO_2 [16,17], ranging from 65% to 90%, followed by the transportation and construction, which ranked second and third in life cycle CO_2 emission of wind turbine. Majority studies agreed the recycling can offset considerable amount of emissions, up to 20% [3,11,52]. Operation and maintenance was reported as the smallest contributor for 4 reviewed emissions.

2.3.2.2 LCA of solar power

For solar power, 3 studies applied environmental impact assessment, 4 studies conducted emission inventory analysis. Only one study analyzed full impact categories, all collected studies agreed the production stage is the largest contributor to all environmental impacts, while the electricity consumption is the largest contributor for GWP and Terrestrial Acidification. The emission factor of GHG showed high variation (up to one order of magnitude), from 5.6 to 207 g CO_2 -eq/kWh for national scale; from 29.2 to 64.5 g CO_2 -eq/kWh for plant level, much higher than results reported by previous review study (13–130 g CO_2 -eq/kWh), all studies agreed the mass use of high fossil fuel based electricity in cell manufacturing, including different type of silicon manufacturing and processing, aggravated the GHG emission, up to 36 % [36]. Cell manufacturing contributed up to 88% of CO_2 emission in total [35,53,54]. A similar occurrence can be explained for NO_x and SO_2 emissions as well, such as the reported emission factor of SO_2 and NO_x were 0.12-0.7 g SO_2/kWh and 0.15-0.4 gNO_x/kWh (plant scale only), respectively, mainly from electricity consumption in cell manufacturing as well. For materials' attribution, silicon is another major source of CO_2 in cell manufacturing, apart from electricity, account about 35% of CO_2 emission [33,36,54], glass [37] and aluminum [55] ranked third and fourth in materials related emissions.

2.3.2.3 *LCA of geothermal, wave and hydro power*

One study about wave and geothermal power and six studies about hydro power were screened. The geothermal and wave studies identified the environmental impact contributions in plant scale, which the wave convertor and geothermal generator had the largest share in GWP and AP, while the contribution of maintenance and operation are negligible [39,40]. Three hydro power studies reported the results of environmental impacts, which the concrete and steel in reservoir construction were largest contributor in all reported impact categories. All studies reported the emission factor of GHG (plant scale only), which were in the range of 89 gCO_2/kWh (wave), 3.88-80.49 gCO_2/kWh (geothermal) and 6.2-195 gCO_2/kWh (hydro), respectively.

6 studies of hydro power, including one small hydro project, four middle and large size hydro project, conducted emission inventory analyzes, three study identified the SO_2 emission. Majority studies agreed operation & Maintenance of reservoir was the major contributor of GHG, whereas [12,24,44] believed the material production was the largest contributor of GHG, while [41] believed the river sediment emission from retirement stage was the largest GHG emission source. All study about middle and large size system reported methane emissions from the anaerobic decomposition of flooded organic matter, which account less than 10% of general GHG emission [56], while [42] believe the reservoir inundation contribute more than 80% of GHG emission in operation & maintenance stage. The reservoir emissions depend on the local climate, water depth, type and amount of flooded vegetation and soil type [57].

2.3.2.4 LCA of biomass power

Five studies, including 4 studies with LCIA and 1 emission inventory analysis, were reviewed, see table 1. Similar to fossil fuel power, the plant operation is the largest contributor of emission inventory and environmental impacts, followed by the biomass fuel provision, the biofuel transportation shared the smallest contribution. All studies reported the emission factor of GHG, while 5 studies addressed the emission factors of SO_2 and NO_x, two studies reported emission of $PM_{2.5}$.

Depends on different type of biomass fuel, the emission factor of GHG varied intensively: 42-191 gCO_2 -eq/kWh for straw based direct combustion, 493.2 gCO_2 -eq/kWh for gasification. Likewise, the emission factors of SO_2 and NO_x varied several orders of magnitude: from 0.03 to 9.16 g SO_2/kWh and from 0.08 to 3.53 g NO_x/kWh. For GHG emission, the share of plant operation varied from 41% [58] to 85% [15], while the share of agricultural plantation varied from 23% [59] to 46% [58], ranked the second. But [49] reported the agricultural plantation phase was the largest contributor of CO_2, up to 89%, due to the large application of chemical fertilizer.

2.3.3 LCA of nuclear power

Five studies were considered in this review, 3 of them reported emission inventory, including GHG, and two studies identified contributions from individual life cycle stages, see table 1. Emissions of SO_2, NO_x and $PM_{2.5}$ were reported in 3, 2 and 1 studies, respectively. Only one study identified the contributions from the whole life cycle.

The results showed that GHG emission factors varied smoothly, compared with other electricity generation technologies, ranging from 10.8 to 23.4 g CO_2/kWh in plant scale, the national scale value had differences of up to one order of magnitude to provincial scale, from 3-35 to 6.36 g CO_2/kWh. The result is in the range of previous review which included 10 studies (3.1–35 g CO_2 -eq/kWh) [60]. Due to lacking of individual assessment about nuclear power plant in China, it’s difficult to explain the reason of such variation. Fuel excavation and disposal are the largest contributor of GHG and GWP [12,24,61], followed by plant operation, [28] and [61] reported the fuel excavation and processing account 60% and 80% of the CO_2 emission, respectively. The emission factor of SO_2 and NO_x were in the range of 0.003-0.015 g SO_2/kWh and 0.01-0.05 g NO_x/kWh, respectively. Only [12] reported the infrastructure related emissions and environmental impacts were negligible.

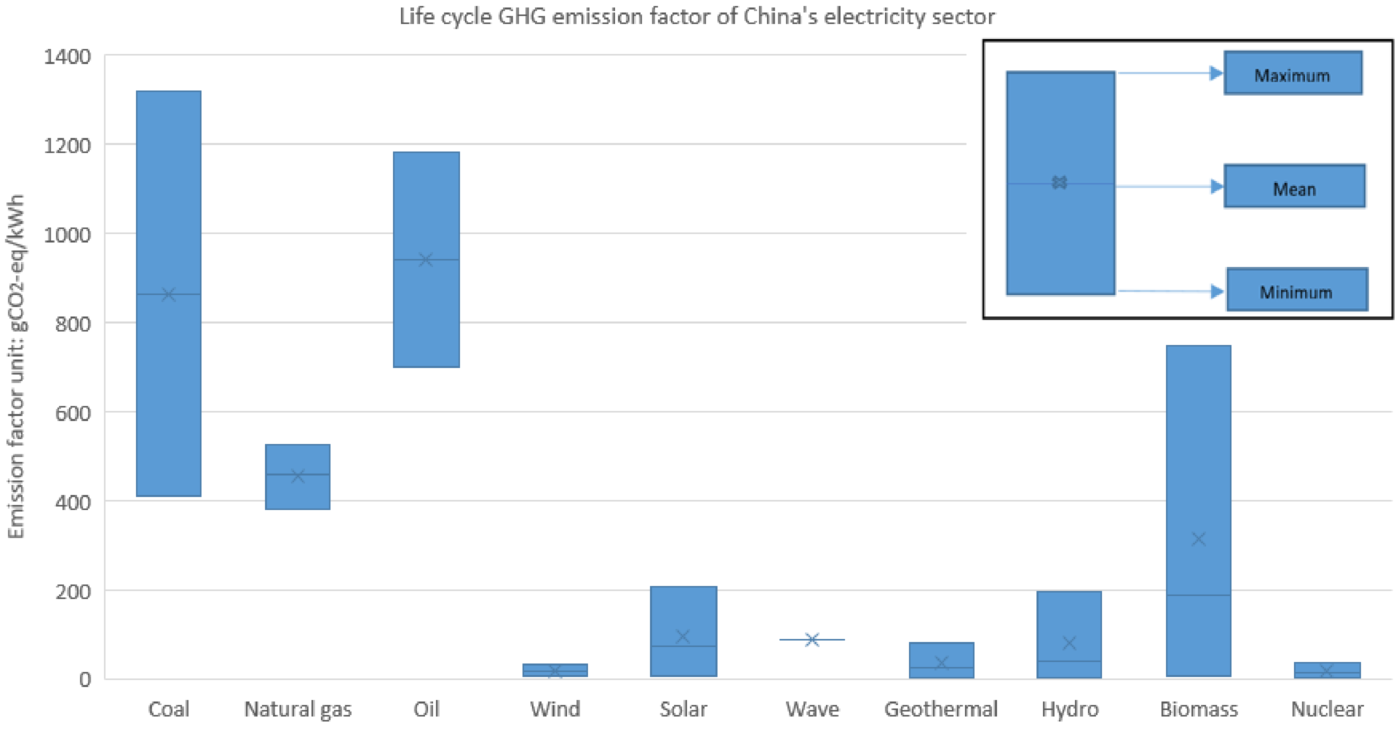

Figure 1. GHG emission factor of the reviewed China’s electricity sector

2.4 Discussion

Of the 54 studies reviewed, GHG emission is the fundamental research indicator in all studies, only 16 studies fully reviewed 4 emissions: GHG, SO_2, NO_x and $PM_{2.5}$. Although GHG emission is a primary indicator of the environmental performance regarding global warming, other environmental impacts should also be studied, for example, the figure 1 showed the oil, natural gas and coal power have similar emission factor of GHG (380-1000 gCO_2-eq/kWh for natural gas, 700-1020 gCO_2-eq/kWh for coal and 800-1000 gCO_2-eq/kWh for oil), while the gas power showed modestly better environmental performance than oil and coal power in GHG emission, with 20% lower emission intensity in GHG than oil and coal power, but they had similar emission factors of SO_2 and NO_x, see figure 1. Likewise, biomass and solar power had similar GHG emission (8.5-178–190 gCO_2-eq/kWh and 5.6–207 gCO_2-eq/kWh, respectively), but biomass power reported much larger emissions of SO_2 and NO_x (0.2–2.1 gSO_2/kWh and 0.18-2.9 gNO_x/kWh) than solar power (0.12–0.427 gSO_2/kWh and 0.15-0.4 gNO_x/kWh), therefore, only focusing on GWP or GHG emission is incomplete and misleading. Biomass power and solar power had relatively higher emissions environmental impacts than wind, hydro and nuclear power which had the smallest emission factors in all reviewed technologies.

Compared with fossil fuel energy, renewable energy technologies have significantly lower GHG emission, see figure 1. The difference in their emissions is mainly due to specific material consumption in individual life cycle stages. Majority life cycle stages and materials of fossil fuel and renewable energy technologies are different and independent, therefore, it's difficult to conduct comparisons between individual life cycle stage and material. Fossil fuel energy studies mainly address emissions from fossil fuel cycle, because its emission are mainly from fossil fuel combustion, while in addition to explain emissions from individual life cycle stage, renewable energy studies also emphasis on reporting emissions from material consumption of plants. Noticeably, considerable renewable energy studies reported the emissions from end-of-life treatment, which can offset large part of life cycle emissions [17,50], while end-of-life emissions are ignored in majority fossil fuel studies.

2.5 Conclusions

This article reviewed 56 recent LCA studies directly related to the life cycle GHG emissions from a range of fossil fuel and renewable electricity generation technologies and provides assessment of contributions from individual life cycle stages. The review has shown that the lowest GHG emissions were associated with nuclear power (mean life cycle GHG emissions could be 3 to 35 gCO_2-eq/kWh). Noticeably, different biofuel based biomass power can lead to high variation emission intensity (97.2–750 gCO_2-eq/kWh for hybrid fuel; 14.4–178 gCO_2-eq/kWh for straw based fuel, respectively). While, the coal power reported the highest emission intensity of GHG, averagely 500% higher than nuclear power. The review further demonstrates the variability of existing LCA GHG emission estimates for electricity generation from both renewable and fossil fuel power. While some of these differences may reflect actual differences in GHG emissions, others may largely be due to assumptions and other modelling choices. This offers areas for improvement and opportunities for standardization. The results of this review can provide suitable baseline estimates for China's emissions from power generation sector based on one year or two, as well as the future projects in developing renewable energy technologies for electricity generation.

REFERENCE

[1] China - Countries & Regions. IEA n.d. https://www.iea.org/countries/china (accessed August 20, 2021).

[2] Man Y, Han Y, Hu Y, Yang S, Yang S. Synthetic natural gas as an alternative to coal for power generation in China: Life cycle analysis of haze pollution, greenhouse gas emission, and resource consumption. Journal of Cleaner Production 2018;172:2503–12. https://doi.org/10.1016/j.jclepro.2017.11.160.

[3] Yang J, Chang Y, Zhang L, Hao Y, Yan Q, Wang C. The life-cycle energy and environmental emissions of a typical offshore wind farm in China. Journal of Cleaner Production 2018;180:316–24. https://doi.org/10.1016/j.jclepro.2018.01.082.

[4] Asdrubali F, Baldinelli G, D'Alessandro F, Scrucca F. Life cycle assessment of electricity production from renewable energies: Review and results harmonization. Renewable and Sustainable Energy Reviews 2015;42:1113–22. https://doi.org/10.1016/j.rser.2014.10.082.

[5] Contributing to local policy making on GHG emission reduction through inventorying and attribution: A case study of Shenyang, China - ScienceDirect n.d. https://www.sciencedirect.com/science/article/pii/S0301421511005192 (accessed August 20, 2021).

[6] Vázquez-Rowe I, Marvuglia A, Rege S, Benetto E. Applying consequential LCA to support energy policy: Land use change effects of bioenergy production. Science of The Total Environment 2014;472:78–89. https://doi.org/10.1016/j.scitotenv.2013.10.097.

[7] Davidsson S, Höök M, Wall G. A review of life cycle assessments on wind energy systems. Int J Life Cycle Assess 2012;17:729–42. https://doi.org/10.1007/s11367-012-0397-8.

[8] Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel H-J. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. Int J Life Cycle Assessment 2006;11:80–5. https://doi.org/10.1065/lca2006.02.002.

[9] Ji S, Chen B. Carbon footprint accounting of a typical wind farm in China. Applied Energy 2016;180:416–23. https://doi.org/10.1016/j.apenergy.2016.07.114.

[10] Li J, Li S, Wu F. Research on carbon emission reduction benefit of wind power project based on life cycle assessment theory. Renewable Energy 2020;155:456–68. https://doi.org/10.1016/j.renene.2020.03.133.

[11] Li Q, Duan H, Xie M, Kang P, Ma Y, Zhong R, et al. Life cycle assessment and life cycle cost analysis of a 40 MW wind farm with consideration of the infrastructure. Renewable and Sustainable Energy Reviews 2021;138:110499. https://doi.org/10.1016/j.rser.2020.110499.

[12] Wang L, Wang Y, Du H, Zuo J, Yi Man Li R, Zhou Z, et al. A comparative life-cycle assessment of hydro-, nuclear and wind power: A China study. Applied Energy 2019;249:37–45. https://doi.org/10.1016/j.apenergy.2019.04.099.

[13] Wang S, Wang S, Liu J. Life-cycle green-house gas emissions of onshore and offshore wind turbines. Journal of Cleaner Production 2019;210:804–10. https://doi.org/10.1016/j.jclepro.2018.11.031.

[14] Feng K, Hubacek K, Siu YL, Li X. The energy and water nexus in Chinese electricity production: A hybrid life

cycle analysis. Renewable and Sustainable Energy Reviews 2014;39:342–55. https://doi.org/10.1016/j.rser.2014.07.080.

[15] Wang C, Zhang L, Zhou P, Chang Y, Zhou D, Pang M, et al. Assessing the environmental externalities for biomass- and coal-fired electricity generation in China: A supply chain perspective. Journal of Environmental Management 2019;246:758–67. https://doi.org/10.1016/j.jenvman.2019.06.047.

[16] Xue B, Ma Z, Geng Y, Heck P, Ren W, Tobias M, et al. A life cycle co-benefits assessment of wind power in China. Renewable and Sustainable Energy Reviews 2015;41:338–46. https://doi.org/10.1016/j.rser.2014.08.056.

[17] Zhao X, Liu S, Yan F, Yuan Z, Liu Z. Energy conservation, environmental and economic value of the wind power priority dispatch in China. Renewable Energy 2017;111:666–75. https://doi.org/10.1016/j.renene.2017.03.032.

[18] Cui X, Hong J, Gao M. Environmental impact assessment of three coal-based electricity generation scenarios in China. Energy 2012;45:952–9. https://doi.org/10.1016/j.energy.2012.06.063.

[19] Liang X, Wang Z, Zhou Z, Huang Z, Zhou J, Cen K. Up-to-date life cycle assessment and comparison study of clean coal power generation technologies in China. Journal of Cleaner Production 2013;39:24–31. https://doi.org/10.1016/j.jclepro.2012.08.003.

[20] Wang C, Mu D. An LCA study of an electricity coal supply chain. JIEM 2014;10:311–35. https://doi.org/10.3926/jiem.1053.

[21] Wang J, Wang R, Zhu Y, Li J. Life cycle assessment and environmental cost accounting of coal-fired power generation in China. Energy Policy 2018;115:374–84. https://doi.org/10.1016/j.enpol.2018.01.040.

[22] Ghadimi P, Wang C, Azadnia AH, Lim MK, Sutherland JW. Life cycle-based environmental performance indicator for the coal-to-energy supply chain: A Chinese case application. Resources, Conservation and Recycling 2019;147:28–38. https://doi.org/10.1016/j.resconrec.2019.04.021.

[23] Yin L, Liao Y, Liu G, Liu Z, Yu Z, Guo S, et al. Comparative analysis of gas and coal-fired power generation in ultra-low emission condition using life cycle assessment (LCA). IOP Conf Ser: Mater Sci Eng 2017;199:012054. https://doi.org/10.1088/1757-899X/199/1/012054.

[24] WANG Yanzhe ZS, WANG Yanzhe ZS. Comprehensive assessment of the environmental impact of China’s nuclear and other power generation technologies. Journal of Tsinghua University(Science and Technology) 2021;61:377–84. https://doi.org/10.16511/j.cnki.qhdxxb.2021.25.006.

[25] Nie Y, Zhang S, Liu RE, Roda-Stuart DJ, Ravikumar AP, Bradley A, et al. Greenhouse-gas emissions of Canadian liquefied natural gas for use in China: Comparison and synthesis of three independent life cycle assessments. Journal of Cleaner Production 2020;258:120701. https://doi.org/10.1016/j.jclepro.2020.120701.

[26] Wang M, Yao M, Wang S, Qian H, Zhang P, Wang Y, et al. Study of the emissions and spatial distributions of various power-generation technologies in China. Journal of Environmental Management 2021;278:111401. https://doi.org/10.1016/j.jenvman.2020.111401.

[27] Song Q, Wang Z, Li J, Duan H, Yu D, Liu G. Comparative life cycle GHG emissions from local electricity generation using heavy oil, natural gas, and MSW incineration in Macau. Renewable and Sustainable Energy Reviews 2018;81:2450–9. https://doi.org/10.1016/j.rser.2017.06.051.

[28] Ou X, Xiaoyu Y, Zhang X. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. Applied Energy 2011;88:289–97. https://doi.org/10.1016/j.apenergy.2010.05.010.

[29] Ding N, Liu J, Yang J, Yang D. Comparative life cycle assessment of regional electricity supplies in China. Resources, Conservation and Recycling 2017;119:47–59. https://doi.org/10.1016/j.resconrec.2016.07.010.

[30] Yang J, Chang Y, Zhang L, Hao Y, Yan Q, Wang C. The life-cycle energy and environmental emissions of a typical offshore wind farm in China. Journal of Cleaner Production 2018;180:316–24. https://doi.org/10.1016/j.jclepro.2018.01.082.

[31] Xu L, Pang M, Zhang L, Poganietz W-R, Marathe SD. Life cycle assessment of onshore wind power systems in China. Resources, Conservation and Recycling 2018;132:361–8. https://doi.org/10.1016/j.resconrec.2017.06.014.

[32] Li H, Jiang H-D, Dong K-Y, Wei Y-M, Liao H. A comparative analysis of the life cycle environmental emissions from wind and coal power: Evidence from China. Journal of Cleaner Production 2020;248:119192. https://doi.org/10.1016/j.jclepro.2019.119192.

[33] Fu Y, Liu X, Yuan Z. Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. Journal of Cleaner Production 2015;86:180–90. https://doi.org/10.1016/j.jclepro.2014.07.057.

[34] Yao Y, Chang Y, Masanet E. A hybrid life-cycle inventory for multi-crystalline silicon PV module manufacturing in China. Environ Res Lett 2014;9:114001. https://doi.org/10.1088/1748-9326/9/11/114001.

[35] Zhang D, Tang S, Lin B, Liu Z, Zhang X, Zhang D. Co-benefit of polycrystalline large-scale photovoltaic power in China. Energy 2012;41:436–42. https://doi.org/10.1016/j.energy.2012.02.056.

[36] Jia X, Lv F, Li P, Wang W. Life-cycle assessment of p-type multi-Si back surface field (BSF) solar module in China of 2019. Solar Energy 2020;196:207–16. https://doi.org/10.1016/j.solener.2019.12.018.

[37] Chen W, Hong J, Yuan X, Liu J. Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China. Journal of Cleaner Production 2016;112:1025–32. https://doi.org/10.1016/j.jclepro.2015.08.024.

[38] Wang C, Cheng X, Shuai C, Huang F, Zhang P, Zhou M, et al. Evaluation of energy and environmental performances of Solar Photovoltaic-based Targeted Poverty Alleviation Plants in China. Energy for Sustainable Development 2020;56:73–87. https://doi.org/10.1016/j.esd.2020.04.003.

[39] Zhai Q, Zhu L, Lu S. Life Cycle Assessment of a Buoy-Rope-Drum Wave Energy Converter. Energies 2018;11:2432. https://doi.org/10.3390/en11092432.

[40] Wang Y, Du Y, Wang J, Zhao J, Deng S, Yin H. Comparative life cycle assessment of geothermal power

generation systems in China. Resources, Conservation and Recycling 2020;155:104670. https://doi.org/10.1016/j.resconrec.2019.104670.

[41] Li Z, Du H, Xiao Y, Guo J. Carbon footprints of two large hydro-projects in China: Life-cycle assessment according to ISO/TS 14067. Renewable Energy 2017;114:534–46. https://doi.org/10.1016/j.renene.2017.07.073.

[42] Li X, Gui F, Li Q. Can Hydropower Still Be Considered a Clean Energy Source? Compelling Evidence from a Middle-Sized Hydropower Station in China. Sustainability 2019;11:4261. https://doi.org/10.3390/su11164261.

[43] Zhang J, Xu L. Embodied carbon budget accounting system for calculating carbon footprint of large hydropower project. Journal of Cleaner Production 2015;96:444–51. https://doi.org/10.1016/j.jclepro.2013.10.060.

[44] Pang M, Zhang L, Wang C, Liu G. Environmental life cycle assessment of a small hydropower plant in China. Int J Life Cycle Assess 2015;20:796–806. https://doi.org/10.1007/s11367-015-0878-7.

[45] Song J, Yang W, Yabar H, Higano Y. Quantitative Estimation of Biomass Energy and Evaluation of Biomass Utilization - A Case Study of Jilin Province, China. JSD 2013;6:p137. https://doi.org/10.5539/jsd.v6n6p137.

[46] Wang C, Zhang L, Chang Y, Pang M. Biomass direct-fired power generation system in China: An integrated energy, GHG emissions, and economic evaluation for Salix. Energy Policy 2015;84:155–65. https://doi.org/10.1016/j.enpol.2015.04.025.

[47] Xu C, Hong J, Chen J, Han X, Lin C, Li X. Is biomass energy really clean? An environmental life-cycle perspective on biomass-based electricity generation in China. Journal of Cleaner Production 2016;133:767–76. https://doi.org/10.1016/j.jclepro.2016.05.181.

[48] Gao C, Na H, Song K, Dyer N, Tian F, Xu Q, et al. Environmental impact analysis of power generation from biomass and wind farms in different locations. Renewable and Sustainable Energy Reviews 2019;102:307–17. https://doi.org/10.1016/j.rser.2018.12.018.

[49] Wang Z, Wang Z, Xu G, Ren J, Wang H, Li J. Sustainability assessment of straw direct combustion power generation in China: From the environmental and economic perspectives of straw substitute to coal. Journal of Cleaner Production 2020;273:122890. https://doi.org/10.1016/j.jclepro.2020.122890.

[50] Ding N, Pan J, Liu J, Yang J. An optimization method for energy structures based on life cycle assessment and its application to the power grid in China. Journal of Environmental Management 2019;238:18–24. https://doi.org/10.1016/j.jenvman.2019.02.072.

[51] Wang N, Ren Y, Zhu T, Meng F, Wen Z, Liu G. Life cycle carbon emission modelling of coal-fired power: Chinese case. Energy 2018;162:841–52. https://doi.org/10.1016/j.energy.2018.08.054.

[52] Xu L, Pang M, Zhang L, Poganietz W-R, Marathe SD. Life cycle assessment of onshore wind power systems in China. Resources, Conservation and Recycling 2018;132:361–8. https://doi.org/10.1016/j.resconrec.2017.06.014.

[53] Huang B, Zhao J, Chai J, Xue B, Zhao F, Wang X. Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. Solar Energy 2017;143:132–41. https://doi.org/10.1016/j.solener.2016.12.038.

[54] Hou G, Sun H, Jiang Z, Pan Z, Wang Y, Zhang X, et al. Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. Applied Energy 2016;164:882–90. https://doi.org/10.1016/j.apenergy.2015.11.023.

[55] Hong J, Chen W, Qi C, Ye L, Xu C. Life cycle assessment of multicrystalline silicon photovoltaic cell production in China. Solar Energy 2016;133:283–93. https://doi.org/10.1016/j.solener.2016.04.013.

[56] Li Z, Du H, Xu H, Xiao Y, Lu L, Guo J, et al. The carbon footprint of large- and mid-scale hydropower in China: Synthesis from five China's largest hydro-project. Journal of Environmental Management 2019;250:109363. https://doi.org/10.1016/j.jenvman.2019.109363.

[57] Jiang T, Shen Z, Liu Y, Hou Y. Carbon Footprint Assessment of Four Normal Size Hydropower Stations in China. Sustainability 2018;10:2018. https://doi.org/10.3390/su10062018.

[58] Wang C, Chang Y, Zhang L, Chen Y, Pang M. Quantifying uncertainties in greenhouse gas accounting of biomass power generation in China. Energy 2018;158:121–7. https://doi.org/10.1016/j.energy.2018.06.008.

[59] Gao C, Zhu S, An N, Na H, You H, Gao C. Comprehensive comparison of multiple renewable power generation methods: A combination analysis of life cycle assessment and ecological footprint. Renewable and Sustainable Energy Reviews 2021;147:111255. https://doi.org/10.1016/j.rser.2021.111255.

[60] Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renewable and Sustainable Energy Reviews 2013;28:555–65. https://doi.org/10.1016/j.rser.2013.08.013.

[61] Jiang ZiYing, Pan ZiQiang, Xing Jiang, Yu Fan. Greenhouse gas emissions from nuclear power chain life cycle in China. China Environmental Science 2015;35:3502–10.