Applied Energy 249 (2019) 37–45

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A comparative life-cycle assessment of hydro-, nuclear and wind power: A China study

Like Wang[a], Yuan Wang[a], Huibin Du[b,*], Jian Zuo[c], Rita Yi Man Li[d], Zhihua Zhou[a], Fenfen Bi[a], McSimon P. Garvlehn[a]

[a] School of Environmental Science and Engineering, Tianjin University, Tianjin, China
[b] College of Management and Economics, Tianjin University, Tianjin, China
[c] School of Architecture & Built Environment, The University of Adelaide, SA 5005, Australia
[d] Department of Economics and Finance/Sustainable Real Estate Research Center, Hong Kong Shue Yan University, Hong Kong, China

HIGHLIGHTS

- A life-cycle comparison of three clean energy technologies is conducted.
- The evaluation covers not only the GHG emissions but also other impact categories.
- An example is provided to showcase the proposed evaluation method.

ARTICLE INFO

Keywords:
Environmental impact
Life cycle assessment
Nuclear
Wind
Hydro
China study

ABSTRACT

Energy sector is one of biggest contributors to the Greenhouse Gas (GHG) emissions. As a result, it has attracted considerable attention to reduce the GHG emissions of electricity production. Hydro-electric, nuclear and wind power are the top three clean energy in China. In this study, the environmental impacts of these three technologies are analyzed, assessed and compared via a life-cycle assessment approach. The entire life cycle, including the manufacturing, construction, operation and decommissioning stages is examined. Apart from global warming potential (GWP100) caused by GHG emissions, the environmental impacts assessed in this study also included acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP) and human toxicity potential (HTP). The results show that wind power technology has the most significant environmental impacts amongst these three clean energies, followed by nuclear power and hydropower. For example, in terms of global warming potential, wind power produces 28.6 ± 3.2 g CO_2-eq/kWh of GWP100 throughout its life cycle, which is higher than that of nuclear power (12.4 ± 1.5 g CO_2-eq/kWh) and hydropower (3.5 ± 0.4 g CO_2-eq/kWh). In addition, this study revealed that the the manufacturing stage is the largest contributor of environmental impacts for wind and hydropower. By contrast, the decommissioning stage is most significant for nuclear power in terms of environmental impacts. The comparative life cycle assessment method proposed in this study provides useful tool for the future environmental assessment of electricity production technologies. Findings of this study provide useful inputs for the sustainable transformation of the energy sector.

1. Introduction

Urban energy system play a crucial role in the development and maintenance of low-carbon cities. Electricity generation has been an essential element of the urban energy system of the past century [1]. At present, the Chinese power sector still largely depends on thermal power, which accounted for 70.9% of the total electricity production in China in 2017 [2]. Air pollution derived from thermal power plants has presented significant challenges in most Chinese cities. Similarly, water pollution and soil degradation have drawn wide concern from the general public. Renewable energy sources can reduce the dependence on fossil fuels and meet the growing energy demand, without increasing greenhouse gas (GHG) emissions or polluting the local environment [3]. Hydro-electric and land-based wind power plant capacities in China were ranked the first over the world in 2015 [4]. Non-thermal power accounted for 29.1% of electricity production in 2017. Hydropower,

* Corresponding author.
E-mail address: duhuibin@tju.edu.cn (H. Du).

https://doi.org/10.1016/j.apenergy.2019.04.099
Received 15 October 2018; Received in revised form 18 March 2019; Accepted 16 April 2019
Available online 28 April 2019

nuclear power, and wind power are the top three non-thermal energy sources, which accounted for 62.8%, 15.4% and 13.8% of non-thermal energy production respectively [2]. As stipulated in the "13th Five-Year Plan for Comprehensive Energy Conservation and Emission Reduction" [5], the proportion of energy produced by clean sources is projected to reach 68% by 2030 [6]. In addition, one the main focuses is the expansion of wind power. Therefore, we have chosen hydropower, nuclear power and wind power as the research objects since these are mature technologies which have been applied widely in the power sector in China.

Life Cycle Assessment (LCA) is a useful technique that is often employed to quantitatively assess the environmental impact of products, processes or technologies across the various different stages of their life cycles [7]. In general, the life cycle of a product or technology refers to the entire period from cradle to grave, which covers the manufacturing, usage, maintenance and final disposal stages. Thus, it is more appropriate to evaluate the overall environmental impacts from a life-cycle perspective. Compared to thermal power, alternatives such as nuclear, wind and hydropower produce substantially lower environmental pollution [8]. These three forms of power generation have significantly fewer direct impacts on the environment during their operational stages, as compared to thermal power plants. However, their potential for producing indirect environmental impacts indirectly should not be overlooked from a life-cycle perspective.

The aim of this study is to quantitatively compare the potential life-cycle environmental impacts of these three power generation methods. Consequently, the main pollutants contributing to those environmental impacts can be identified. Findings of this study offer useful information for policymakers, academics, and organizations related to clean energy sources.

2. Literature review

(1). Research object

A number of LCA studies have been undertaken on hydropower, nuclear power and wind power respectively. In term of wind power, some studies have focused on geographical and scale-related variability. For example, the energy production and CO_2 emissions associated with two specific wind turbines manufactured in different places were compared from a life-cycle assessment perspective [9]. The LCA of the onshore and offshore forms of wind energy production have also been compared [10]. Tremeac employed the LCA method to compare the generation of energy from wind power at different scales [11]. The overall carbon footprint of a typical wind farm in China was estimated using LCA and input–output analysis (IOA) [12]. In addition, some studies have examined emissions from a hybrid energy system (thermal and wind power) from a life-cycle assessment perspective [14–16]. As for nuclear power, Lenzen has reviewed the existing studies related to associated energy production and GHG emissions [17]. More specific case studies have been conducted in recent years. For example, Nian employed a bottom-up approach to obtain a carbon emission factor of 22.80 t-CO_2/GWh for nuclear power [18]. They further studied the impacts on life cycle carbon emissions and consequently various design parameters [19]. Seier and Zimmermann examined the environmental impacts dervived from the decommissioning of nuclear power plants [20]. Hydropower is more complex due to its diversity. For example, a Brazilian case study related to hydropower showed that the most important characteristic of hydropower plants is their large scale, e.g. a consequence of local topography and rich hydraulic resources [21]. The carbon footprints of two large hydropower projects in China were evaluated from a life cycle perspective [22]. LCA has also been applied to small community-scale hydropower systems located in rural areas [23]. The GHG emissions and the energy production of three run-of-river small hydropower projects were examined in India by using the economic input-output (EIO) technique [24].

(2). Environmental impacts

Existing studies concerning the environmental impacts of clean energy power generation can be generally classified into two groups. The first group of studies played focuses on GHG or CO_2 emissions [12,18,22,25]. These studies mainly employed the emission coefficient to calculate the greenhouse gas emissions over the whole life cycle. The second group of studies employed a more comprehensive approach to assess environmental impacts, including impacts on air quality, water and the biosphere generally [8,20,23]. In general, this kind of comprehensive environmental impact assessment is too complex to undertake unless advanced techniques (such as the database and assessment method provided by life cycle software, e.g. Gabi and SimaPro) are used. There are less number of studies on comprehensive environmental impacts than those on greenhouse gases due to its complexity and uncertainty. However, the value is limited if only GHG or CO_2 emissions were evaluated.

(3). Uncertainty

The environmental impact varied significantly as reported in previous studies. For example, the GHG emissions of nuclear power plants with a lifespan of 60 years range from 9.1 to 29 g CO_2-eq/kWh in Asian case studies [26,27,28], whereas ranging from 6 to 12 g CO_2-eq/kWh in European case studies [29,30]. The range of the GHG emissions of hydropower and wind power installations was 2.2–74.8 g CO_2-eq/kWh with a lifespan of 70 years, and 6–44.0 g CO_2-eq/kWh with a lifespan of 20 years, respectively [31]. A wide variety of factors may result in the inconsistency in these results, such as boundary conditions, installed capacity, annual electricity production, lifespan and location. Any change in these factors inevitably leads to variations. Martínez assessed the degree of uncertainty in the LCA for wind plants which is a result of parameter selections [13].

Therefore, an appropriate comparison between different electricity production technologies should be conducted following the same analytical structure, the same background data and methods for all case studies. Some studies have attempted to compare different kinds of energy production systems [8,31,32]. However, it is difficult to compare LCA results across different cases based on diverse hypotheses and methods. In this study, the life-cycle assessments of hydro-, nuclear and wind power technologies were undertaken using the same background database and methods for each type of energy production. The evaluation covers not only the GHG emissions but also other impact categories such as Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Eutrophication Potential (EP) and Human Toxicity Potential (HTP).

Majority of the comparisons amongst electricity generation technologies in existing studies involve hydropower, nuclear power and wind power [8,25,31,32]. To our best knowledge, there are very few studies which have compared hydropower, nuclear power and wind power in the same analytical structure. For instance, Siddiqui compared the life cycle environmental impacts of these three different forms of energy production in Canada [33]. However, that study only considered the impacts of CO_2, SO_2, NO_x and particulate matter on the atmosphere. There is generally lack of studies that are based on Chinese case studies.

3. Data and methods

3.1. System boundaries

The system boundaries of hydro-, nuclear, and wind power technologies are shown in Fig. 1A-C respectively. To ensure the comparison is conducted within the same analytical structure, the life-cycle stages are common to all three technologies, i.e. manufacturing, construction, operation, and decommissioning. The manufacturing phase includes the production of equipment and materials from raw materials. In terms of

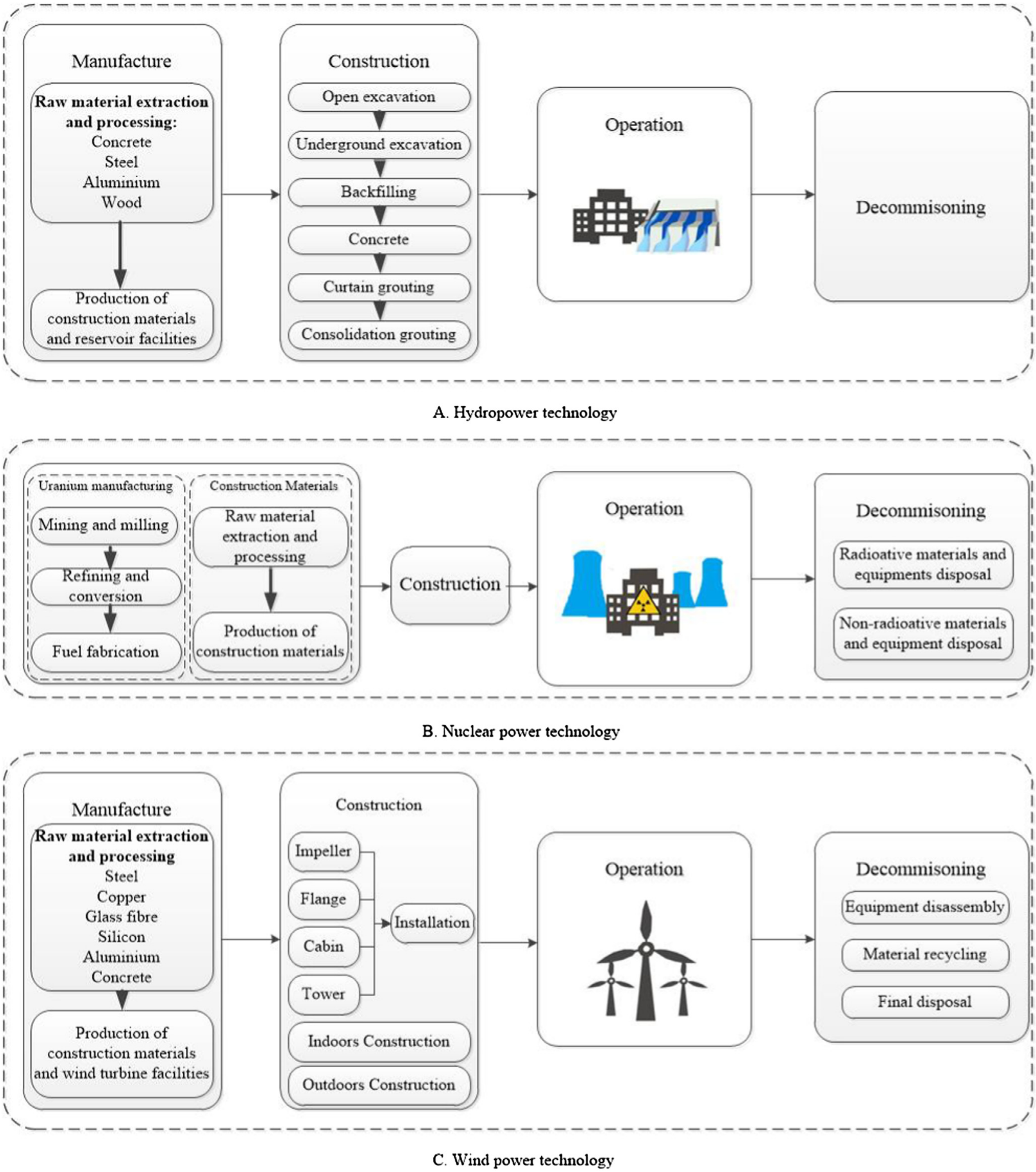

Fig. 1. System boundary and life-cycle stages.

nuclear power technology, the production of uranium is considered, including the processes of mining and milling, refining and conversion, and fuel fabrication. Transportation, construction and installation are considered in relation to the construction stage. The operational stage is relatively simple. The decommissioning stage includes the disposal of the equipment and construction materials.

3.2. Case selection and LCA input inventory analysis

LCA results vary according to assumptions and inventory data inputs. With a consideration of practical applications of three technologies in China and the data accessibility, three typical projects were selected in this study. These three projects provide the inventory data for LCA evaluation. 1 kWh of electricity generation was chosen as the functional unit.

Table 1
Summary of unit input material and fuel of hydropower project.

	Manufacturing	Construction	Operation	Decommissioning
Steel (g/kWh)	7.85E-01	–	–	–
Cement (g/kWh)	2.67E + 00	–	–	–
Aluminum (g/kWh)	4.55E-02	–	–	–
Wood (m^3/kWh)	5.60E-04	–	–	–
Diesel (g/kWh)	–	1.69E-02	–	–

Note: the listed data have been normalization by life-time electricity production from the reference [36].

3.2.1. Hydropower

Most hydropower stations in China are located along the upper streams of the Yangtze, Yellow and Pearl Rivers [34]. Pumped storage and conventional stations are the main types used in China [35]. One conventional hydropower station located on the main stream of the Qingjiang River (the upper section of the Yangtze River) was selected as the case study. The total installed capacity of this hydropower station is 252 MW, and it is designed to produce an average annual power generation of 897 GWh [36]. This hydropower station is a medium-sized project with an engineering grade of III. Its life span is assumed as 50 years [37].

In the inventory analysis of this hydropower project, the inputs of materials and fuels are mainly associated with the manufacturing stage and construction stage of the hydro reservoir facilities (see Table 1). In the manufacturing stage, the production of cement and steel for the hydropower station made considerable contributions to the pollution load. During the construction stage, a number of activities consume diesel, such as open excavation, underground excavation, backfilling, curtain grouting and consolidation grouting by mechanical facilities. During the operation of conventional hydropower stations, the electricity consumed is supplied by the facilities themselves. Therefore, almost no pollutants are generated during the operation. Although there is no material input during the operational stage, some GHG emissions are produced as a result of organic carbon escaping reservoirs [38,39]. Due to limitations of data accessibility, an assumption was made that the environmental impact during the decommissioning stage is 10% of that during the manufacturing phase [40].

3.2.2. Nuclear power

Most nuclear power plants in China are distributed around the eastern coastal areas. On the one hand, nuclear power plants are built near areas with a strong demand for electricity in a bid to reduce the power loss derived from the long-distance transmission of electricity. On the other hand, sufficient cooling water is needed since a large amount of energy is emitted in the form of heat as a by-product of nuclear power generation. In this study, the selected nuclear project is located in Dapeng Peninsula, Shenzhen. The average installed capacity of each reactor is 984 MW. This project is the longest-running commercial nuclear power plant in China. The life span of nuclear power plants, globally, is estimated to be 60 years in service [26]. Therefore, the life span of this project was assumed to be 60 years.

The manufacturing stage of this nuclear power project was divided this into two components: nuclear fuel supply and the production of the construction materials (see Fig. 1). Similarly, the supply of nuclear fuel was further divided into three processes. The processes during the mining and milling stage include: conventional mining, in-situ leaching, surface heap leaching, and in-situ blasting leaching. Based on the survey conducted in a previous study [42], main materials and the energy consumed during this stage are summarised in Table 2. In the refining and conversion process, uranium conversion consists of refining UO_2 in order to produce UF_4 and UF_6. Lastly, processes involved in the fuel manufacturing and production stage include: (1) producing pure uranium dioxide (UO_2) from UF_6 or UO_3; (2) producing high-density, accurately shaped ceramic UO_2 pellets; (3) the manufacturing of the metal framework for the fuel assembly (mainly from zirconium alloy); (4) the loading of the fuel pellets into the fuel rods; and (5) the sealing of these into the rods and the assembling of the rods into the final fuel assembly structure [43]. In addition, the production of construction materials mainly involves conventional materials such as steel, concrete and so on.

At the construction stage, electricity is consumed. Due to the limited data available, only electricity, in terms of energy use, is considered in this stage. Energy use in the operational stage takes a different form from that in hydropower plants as the electricity is purchased from external sources (and this can be assumed to be based on fossil fuel combustion). This externally-sourced energy is used to ensure the safe operation of nuclear power plants. In the decommissioning stage, the decommissioning of the nuclear plants and disposal of nuclear fuel are included. Waste treatment is comparatively complex because of the need to limit damage to the environment caused by radiation. In China, uranium enrichment diffusion is undertaken via processing facilities, chemical facilities, and auxiliary processing facilities. The data concerning materials usage related to the disposal of high-level radioactive waste and intermediate or low-level radioactive waste are retrieved from [20]. The landfill disposal scenario provided in SimaPro is used to analyze the disposal of non-radioactive substance.

3.2.3. Wind power

In China, wind farms are mainly distributed within coastal and northwestern areas, such as Inner Mongolia and the northern Gansu province. In these northwestern areas, the effective wind energy density is greater than or equal to 200 W/m^2, and the period of time with the wind speed of greater than or equal to 3 m/s is over 5000 h every year [44]. Despite abundant wind resources in coastal areas, offshore wind power in China are constrained by geological conditions and costs. By contrast, the land-based wind power has the cost advantage. With a consideration of aforementioned geological, economic and technical conditions, one wind power project located in Inner Mongolia was selected in this study. In line with to the analysis of the life time of wind turbines found in [31], the lifetime of wind power plants was assumed to be 20 years. The total installed capacity of this plant is 49.5 MW (each wind turbine rated at 1.5 MW), and the annual amount of electricity production is 102.6 GW [45].

The inventory data for the wind power project are shown in Table 3. At the manufacturing stage, copper, steel, iron, aluminum and concrete were used to manufacture the tower, impeller, flange, cabin and base. The construction stage covers the wind turbine installation and transportation where diesel fuel was consumed. During the operational stage, the main consumption of materials were from wastage and replenishment. However, it proved difficult to collect data on the consumption of materials during the operational stage. Based on the related previous studies [46], the material and energy consumption at this is 15% of the initial consumption (i.e., the consumption during the manufacturing stage). Compared with other electricity generation technologies, the wind power has better recyclability. The processes involved in the final stage include: equipment disassembly, material recycling and final disposal. However, there is no accurate information related to disassembly. Therefore, it is assumed that the emissions produced at this stage are 10% of those produced at the manufacturing stage [47], and material recycling was not taken into consideration.

3.3. Environmental impact categories

The CML 2001 method [48] provided by the SimaPro LCA software was employed in this study in order to assess the potential environmental effects of the three electricity generation technologies. This method was developed by the Institute of Environmental Sciences, Leiden University. The CML 2001 impact assessment methodology covers various impact categories and characterization methods. The

Table 2
Summary of unit input material and fuel of nuclear power technology.

	Manufacture				Construction	Operation	Decommissioning
	Mining and milling	Refining conversion	Fuel fabrication	Construction material			
Concrete(g/kWh)	4.22E-02	1.13E + 00	–	2.60E-01			5.92E-01
Steel(g/kWh)	4.91E-03	5.32E-02	2.63E-03	1.23E-01			7.68E-03
Aluminum(g/kWh)	2.23E-04	1.09E-05	–	–			3.29E-05
Coal(g/kWh)	1.16E-01	–	–	–			–
Copper(g/kWh)	–	8.83E-03	–	3.72E-04			9.73E-05
Zircon(g/kWh)	–	–	1.70E-03				–
Electricity(kWh /kWh)	1.97E-03	3.38E-04	2.19E-04		8.47E-06	2.11E-03	6.15E-03

Note: the listed data were from [20,41,42], and based on the GHG emission factor presented, the usage of unit g CO_2-eq/kWh was translated into that of g/kWh for input materials and fuel (excluding the unit of electricity).

Table 3
Summary of unit input of materials and fuel related to wind power technology.

	Manufacture	Construction	Operation	Decommissioning
Steel(g/kWh)	6.35E + 00	–	6.87E-04	–
Glass fibre(g/kWh)	3.22E-01	–	3.57E-04	–
Copper(g/kWh)	1.53E-01	–	4.46E-06	–
Silicon(g/kWh)	2.89E-03	–	4.34E-07	–
Concrete(g/kWh)	4.82E + 00	–	7.24E-04	–
Aluminium(g/kWh)	1.94E-01	–	–	–
Fuel oil(g/kWh)	–	7.29E-01	1.09E-01	–

Note: the listed data have been normalized by the total electricity production obtained from [45].

impacts examined are not only those which may affect the atmosphere but also those which may affect bodies of water and the biosphere. In this study, five kinds of impacts, i.e., Global Warming Potential (GWP100), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Eutrophication Potential (EP) and Human Toxicity Potential (HTP) were chosen to assess the potential environmental effects (Table 4). Moreover, in this study, we only considered the environmental impacts of conventional emissions whereas the impacts of unconventional pollution leakages were not taken into consideration.

4. Results

4.1. The contributions of various life-cycle stages

As shown in Fig. 2, the manufacturing stage was the largest contributor to the potential environmental impacts of wind power and hydropower, making contributions of between 50% and 75% in each impact category. This is because of the significant usage of energy and materials that are required in manufacturing of various facilities. However, the construction and operational stages showed relatively less impacts on the environment. Hence, in order to reduce the potential environmental impact of wind power and hydropower, it is essential to focus on reducing the emissions that are derived from constructing the facilities. Most wind power and hydropower plants are made of steel and concrete. Therefore, it is a most effective approach to reduce the emissions derived from the manufacturing and use of steel and concrete. As a result, the life-cycle environmental impact of the electricity generation from wind power and hydropower can be reduced.

As for nuclear power, the manufacturing stage consists of mining and milling, refining and conversion, fuel fabrication, and construction materials. Therefore, it is worth noting that the contributions of the manufacturing stage across all different kinds of environmental impacts account for a high, but variable proportion of the environmental impact of nuclear power, ranging from 30% to 60% (Fig. 2B). Moreover, the nuclear fuel supply processes (including mining and milling, refining and conversion, and fuel fabrication) accounted for 25%-50% of those impacts. By contrast, the production of construction materials contributed to a lesser environmental impact. In addition, the decommissioning and operational stages contributed to considerable environmental impacts. The operational phase made a contribution of 10%-20% in each impact category due to the usage of electricity generated from fossil fuels. The decommissioning stage has a larger impact than the operational phase due to the large quantity of electricity for the process involved in the disposal of radioactive materials. Special attention should be paid to the nuclear fuel supply processes and the decommissioning stages in order to reduce the life-cycle environmental impacts of nuclear power projects.

4.2. Comparisons of environmental impacts

The most significant pollutants across the various impact categories are shown in Fig. 3A-J. In general, the top three pollutants accounted for around 80% of the total pollutants. Therefore, it can be concluded that the main pollutants are emitted into the air and, to a lesser extent, into water.

(1). Global warming potential (GWP)

The main contributing emissions to GWP are carbon dioxide (CO_2), followed by methane (CH_4) and dinitrogen monoxide (N_2O). It is worth noting that the CO_2 emissions are mostly produced at the manufacturing stage in wind power. However, the decommissioning stage is the largest source of CO_2 emissions for nuclear power (Fig. 3A). wind power has the highest GWP100 of 28.3 g CO_2-eq/kWh, followed by nuclear power technology with a GWP100 of 12.4 g CO_2-eq/kWh. Hydropower technology has the lowest impact in this regard, i.e. 3.84 g CO_2-eq/kWh (Fig. 3F).

Table 4
Environmental impact categories addressed in this study.

Life cycle impact assessment indicators	Unit/kWh	Short form	Description
Global warming potential (time horizon 100 years)	g CO_2-eq	GWP100	Emissions inducing climate change
Acidification potential	g SO_2-eq	AP	Emissions causing acidification of the environment
Eutrophication potential	g PO_4^{3-}-eq	EP	Pollutants increasing environmental nutrient level
Photochemical ozone creation potential	g C_2H_4-eq	POCP	Emissions causing thinning of the stratospheric ozone
Human toxicity potential	g 1,4-DB-eq	HTP	Toxic substances leading to adverse human impacts

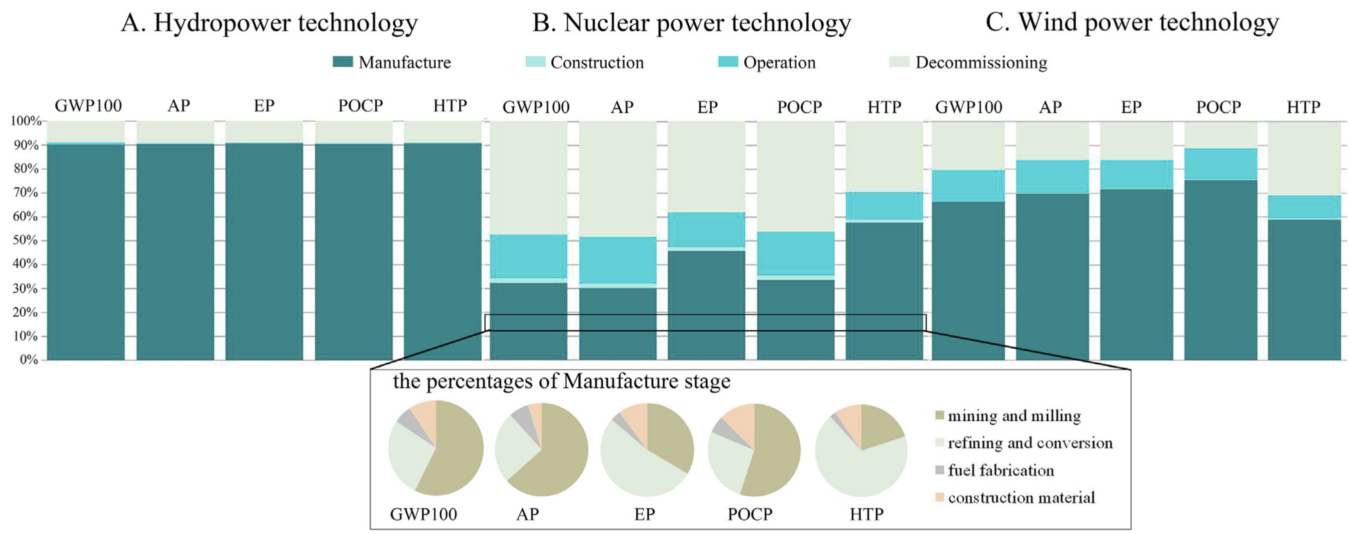

Fig. 2. Percentage contributions of life-cycle stages to environmental impacts.

(2). Acidification potential (AP)

It can be observed from Fig. 3B that the largest amount of SO_2 were emitted during the manufacturing stage for wind and hydro- power projects. By contrast, both the manufacturing stage and the decommissioning stage contribute a great deal of SO_2 emissions for nuclear power plants. The contributions of NO_X and NH_3 are smaller than those from SO_2, across all three power generation technologies. The SO_2 emissions from wind power are the highest among the three power generation technologies. Wind power has the highest AP impact of 0.202 g SO_2-eq/kWh, followed by nuclear power with 0.115 g SO_2-eq/kWh. Hydro reservoir facilities have the lowest life-cycle acidification potential impact on the environment with a value of 0.0162 g SO_2-eq/kWh due to their lower SO_2 emissions.

(3). Eutrophication potential (EP)

Phosphorus discharged into water is the main cause of EP, followed by nitrogen pollutants. The manufacturing of facilities was the major contributor to phosphorus (see Fig. 3C). On the other hand, the decommissioning stage was the major contributor to EP for nuclear power projects, via nitrate pollutants. The third most significant pollutant in terms of EP is COD. The biggest contributor to COD is hydropower rather than wind power. A comparison on EP is shown in Fig. 3H. Wind power is found to have the highest EP impact of 94.5 mg PO_4^{3-}-eq/kWh, followed by nuclear power (12.8 mg PO_4^{3-}-eq/kWh) and hydropower (4.66 mg PO_4^{3-}-eq/kWh).

(4). Photochemical ozone creation potential (POCP)

Fig. 3D and I show the comparison results of POCP. Carbon monoxide (CO) is the most significant pollutant in this impact category, followed by sulfur dioxide (SO_2) and Benzene (C_6H_6) (Fig. 3D). Wind power is the most significant contributor to this impact category with 16.6 mg C_2H_4-eq/kWh. This is because to it has the highest CO emissions to the atmosphere at the manufacturing stage. Nuclear power has a life-cycle POCP of 4.61 mg C_2H_4-eq/kWh. Unlike wind power, the POCP impact of nuclear power can mainly be attributed to the emissions of SO_2 derived from its manufacturing stage. In line with its other impacts, hydropower's POCP is the least significant (1.62 mg C_2H_4-eq/kWh), owing to the fact that it has the lowest CO and SO_2 emissions per kWh.

(5). Human toxicity potential (HTP)

The main contributing factors to the HTP are the Selenium at the manufacturing stage of all three electricity generation technologies. Selenium causes an HTP impact via the medium of water. Major quantities of Benzene and Chromium VI are released from the manufacturing stage of wind power and hydropower and the decommissioning stage of nuclear power. As a result, a HTP impact is generated via the medium of air. The comparisons show that (see Fig. 3E and J) wind power has the highest HTP (31.5 g 1,4-DB-eq/kWh), due to its emission of the highest level of pollutants (Selenium, Benzene and Chromium VI) during the manufacturing of the wind turbine. Nuclear power has the second highest HTP (3.65 g 1,4-DB-eq/kWh) and Hydropower has the lowest HTP (1.63 g 1,4-DB-eq/kWh).

In summary, more attention should be paid to the manufacturing stage as it is responsible for the most significant amount of pollutant emissions, followed by the decommissioning stage. From a life cycle perspective, wind power has the most significant environmental impact, followed by nuclear power. The environmental impacts of hydropower are the least significant of all three electricity generation technologies. The manufacturing stage of wind power and hydropower is the largest contributor to pollutants. However, in terms of nuclear power, the environmental impacts of the decommissioning and operational stages are more significant.

5. Discussion

5.1. Uncertainly analysis with a focus on the environmental impacts

A Monte Carlo analysis was conducted via the SimaPro software in order to examine the uncertainty (Fig. 4). With a confidence interval of 95%, the HTP and EP of hydropower technology have higher environmental impacts than other impact categories. The HTP has the highest uncertainty level (-44.39% ~ +44.39%), followed by the EP (−38.52% ~ +38.52%). For nuclear power plants, the EP and HTP have comparatively high environmental impacts. Of these, the EP has the maximum uncertainty level (−36.29% ~ +36.29%), followed by that of the HTP (−30.56% ~ +30.56%). In addition, the HTP of wind power technology has the maximum uncertainty (−37.31% ~ +37.31%). Therefore, among five environmental impact categories, the assessment of HTP has the highest uncertainty.

5.2. Sensitivity analysis on recycling rate

Recycling is not taken into consideration in the above LCA analysis. Because wind power's manufacturing stage has the greatest

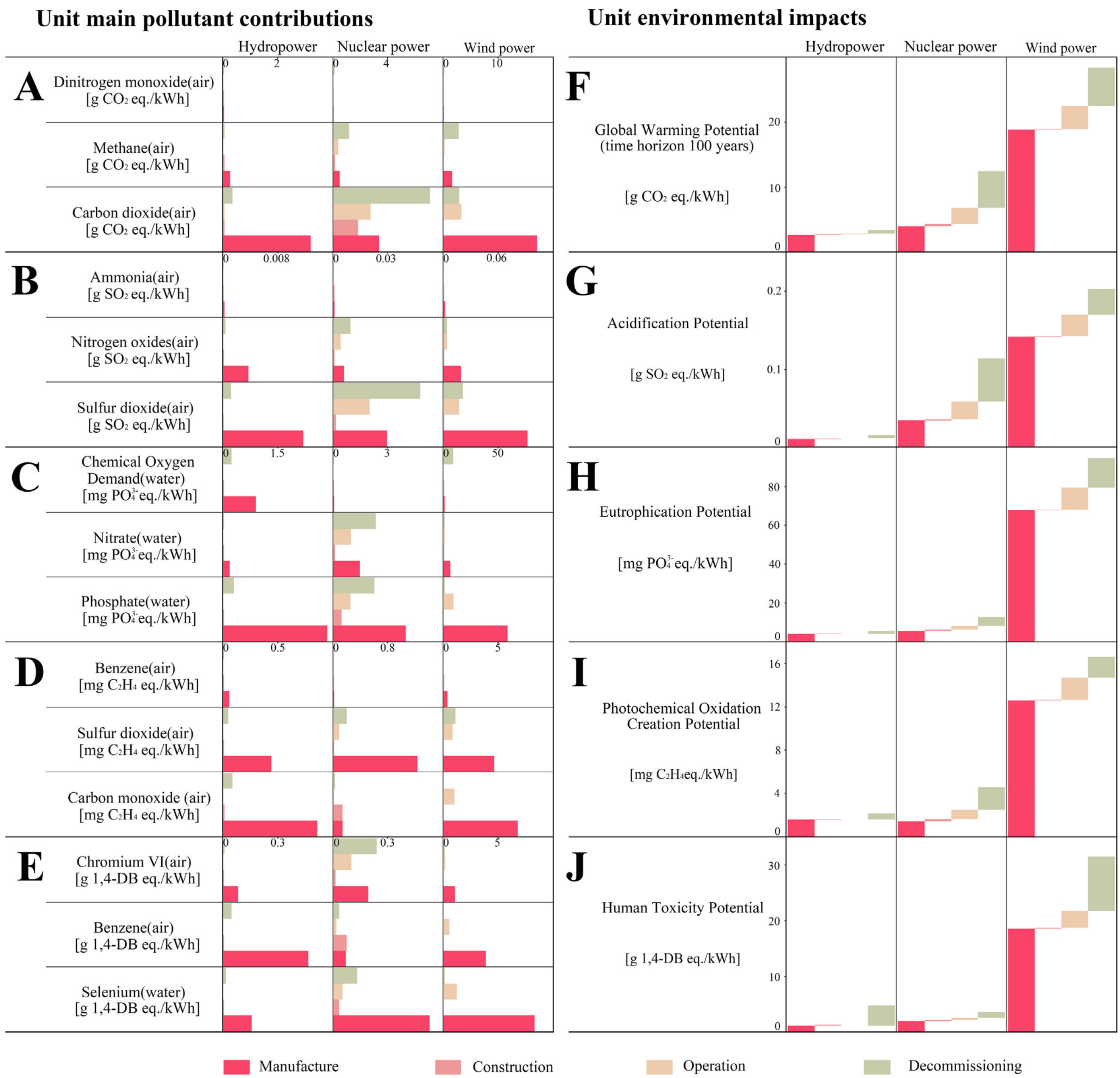

Fig. 3. Unit environmental impacts and main pollutant contributions of the three power generation technologies. (A-E) main pollutant contributions; (F-G) environmental impacts.

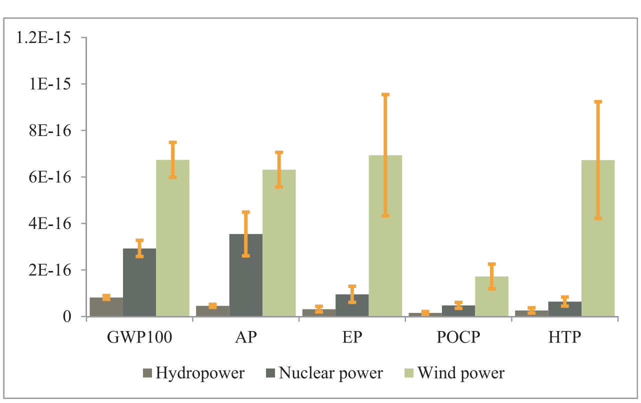

Fig. 4. Uncertainly analysis for environmental impacts by normalization for the three electricity technologies.

Table 5
Sensitivity analysis of recycling rate on the life-cycle environmental impacts of wind power.

Rate(%)	GWP100(g CO_2-eq/kWh)	AP (g SO_2-eq/kWh)	EP(g PO_4^{3-}-eq/kWh)	POCP(g C_2H_4-eq/kWh)	HTP (g DCB-eq/kWh)
0	28.56	0.20	0.094	0.016	38.41
20	18.27	0.15	0.064	0.011	29.81
40	16.24	0.13	0.053	0.010	24.28
60	13.17	0.11	0.040	0.0079	18.18
80	10.09	0.086	0.027	0.0056	12.09

environmental impact, wind power was taken as an example in order to analyze the impact of recycling rates. The recycling rate of the copper used in wind turbines in developed countries is generally around 90% [49]. The average recovery rate of scrap steel in China is about 85%

[50]. Other materials (such as concrete, waste resin and blades) are generally landfilled [51]. Blades, nacelles and towers made of steel can be considered for recycling, and the foundation can remain in-situ when the turbines are decommissioned. The results of sensitivity analysis are shown in Table 5. For instance, at a recycling rate of 80%, the GWP impact is as low as 10.09 g-CO_2 eq/kWh. This corresponds to a 65.27% decrease as compared to the impacts with a 0% recycling rate. Similarly, the AP, EP, POCP and HTP decrease significantly. Therefore, the recycling rate is a sensitive parameter that significantly affects the results of LCA evaluations.

There are other factors that may affect the results of final evaluation. For example, variations in energy use over time can influence the life cycle impact assessment models and results. Annual average electricity production mixes and hourly electricity production mixes provide different starting points for impact assessment. The use of averages may lead to the underestimation of some potential environmental impacts. However, these data are the best data that could be collected from the case studies. It is worth undertaking further research once more accurate inventory data become available.

6. Conclusions and policy implications

6.1. Conclusions

The life-cycle environmental impacts of these clean energy sources, i.e. hydropower, nuclear power and wind power are calculated, analyzed and compared. The significance of five environmental impact categories were calculated using the SimaPro software. The results show that wind power has the highest environmental impact, followed by nuclear power and hydropower. The impacts of wind power were: GWP100 of 28.6 ± 3.2 g-CO_2 eq/kWh, AP of 0.2 ± 0.02 g SO_2-eq/kWh, EP of 0.09 ± 0.04 g PO_4^{3-}-eq/kWh, POCP of 0.02 ± 0.05 g C_2H_4-eq/kWh, and HTP of 38.5 ± 14.3 g 1,4-DB-eq/kWh. The impacts of nuclear power were: GWP100 of 12.4 ± 1.5 g-CO_2 eq/kWh, AP of 0.1 ± 0.03 g SO_2-eq/kWh, EP of 0.01 ± 0.04 g PO_4^{3-}-eq/kWh, POCP of 0.004 ± 0.001 g C_2H_4-eq/kWh, and HTP of 3.6 ± 1.1 g 1,4-DB-eq/kWh. The impacts of hydropower were: GWP100 of 3.4 ± 0.3 g-CO_2 eq/kWh, AP of 0.01 ± 0.02 g SO_2-eq/kWh, EP of 0.004 ± 0.001 g PO_4^{3-}-eq/kWh, POCP of 0.001 ± 0.0005 g C_2H_4-eq/kWh, and HTP of 1.5 ± 0.6 g 1,4-DB-eq/kWh. This is mainly due to the fact that the manufacturing stage of wind power and hydropower requires higher inputs of materials and energy. On the contrary, , the decommissioning stage plays a more important role in terms of environmental impact in nuclear power.

6.2. Policy implications

The decarbonization of electricity production will not only mitigate impacts of climate change but will also present an opportunity to reduce other forms of pollution. According to the national plan [6], the development of hydropower will be slowed down in China since 2030. The risks associated with the nuclear energy present a significant challenge for its development in the future. By contrast, wind power is expected to become the main clean energy technology because of its significant social and environmental benefits. China's wind power installations are expected to reach a capacity of 400–600 MW by 2050, and wind power will become the third largest power generation source following thermal power and hydropower [52]. However, according to findings of this research, the government should pay attention to the environmental impacts at the manufacturing stage of wind power. The pollution intensities of the Chinese raw-material industries (such as the cement and steel), remain higher than those of developed countries. Therefore, green manufacturing technology should be promoted in order to reduce the potential environmental impacts and the manufacturing stages deserves closer attention especially their input materials. Meanwhile, results of the environmental impact assessments are very sensitive to recycling rates. Thus, technological innovations on recycling should be encouraged so that environmental impacts can be reduced.

Acknowledgements

This research has been supported by the National Key Research and Development Program of China [Grants #2018YFC0213600]; National Natural Science Foundation of China (Grants no. 41871211, no. 71834004, no. 7167030761 and no. 41571522) and Tianjin Municipal Science and Technology Commission (Contract No. 17JCZDJC39800).

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