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Life Cycle Cost of Electricity Production: A Comparative Study of Coal-Fired, Biomass, and Wind Power in China

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Abstract: Economic cost is decisive for the development of different power generation. Life cycle cost (LCC) is a useful tool in calculating the cost at all life stages of electricity generation. This study improves the levelized cost of electricity (LCOE) model as the LCC calculation methods from three aspects, including considering the quantification of external cost, expanding the compositions of internal cost, and discounting power generation. The improved LCOE model is applied to three representative kinds of power generation, namely, coal-fired, biomass, and wind power in China, in the base year 2015. The external cost is quantified based on the ReCiPe model and an economic value conversion factor system. Results show that the internal cost of coal-fired, biomass, and wind power are 0.049, 0.098, and 0.081 USD/kWh, separately. With the quantification of external cost, the LCCs of the three are 0.275, 0.249, and 0.081 USD/kWh, respectively. Sensitivity analysis is conducted on the discount rate and five cost factors, namely, the capital cost, raw material cost, operational and maintenance cost (O&M cost), other annual costs, and external costs. The results provide a quantitative reference for decision makings of electricity production and consumption.

Keywords: electricity production; life cycle cost; external cost; sustainable energy



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1. Introduction

Economic progress has been stimulated the demand for electricity production in recent years. However, the resource and environmental problems caused by fossil fuels have accelerated the development of renewable energy [1]. In the context of global energy transition and emission reduction, renewable energy has exhibited a clear upward trend [2], see Figure 1. The costs of electricity generation directly affect the decision of stakeholders. Thus, the quantification of electricity generation cost has become a popular research topic.

Life cycle cost (LCC) is an effective method to quantify electricity generation costs. Soni et al. concluded that LCC was an economic method to calculate the entire cost of a product, process, or activity discounted during the life cycle [3]. LCC was originally used to calculate the operational and maintenance cost of public procurement in the 20th century [4]. Since the 1980s, LCC has been applied in the field of construction and environmental protection [5–7]. In recent years, LCC has been applied in the energy and environment field [8,9]. Current research studies have found that high investment cost has become the main limitation of renewable energy development. However, because of the low environmental impact of renewable energy, it can present economic benefits when considering external costs in long-term projects [10]. LCC accounting system will help stakeholders recognize the competitiveness of renewable energy, compared to fossil fuels. LCC is used to assess the economics of a product by calculating its internal cost of basic

process and external cost. Internal cost refers to the cost incurred in each life cycle stage, including capital cost, raw material cost, management cost, labor cost, etc. [11]. External cost is used to quantify the cost related to environmental damage [12,13].

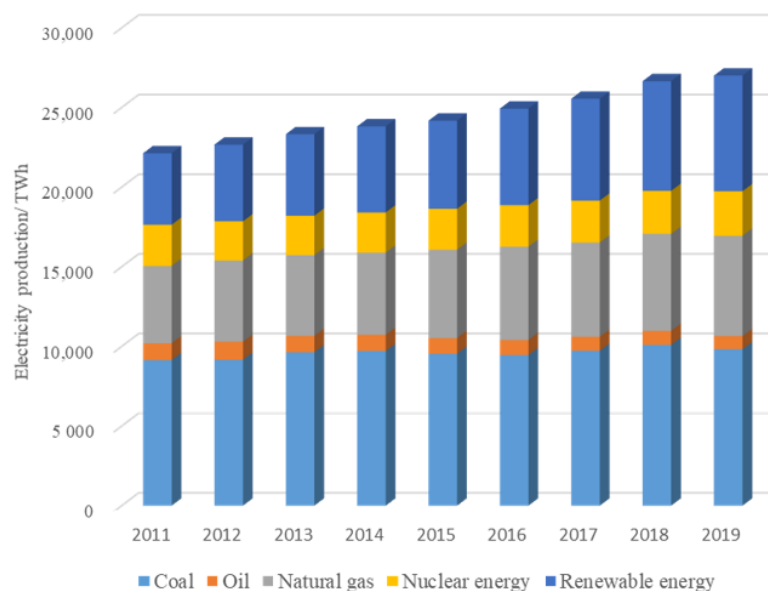


Figure 1. Global electricity generation by fuel.

The lifetime of power generation equipment is about 20–40 years, which could be regarded as a long project. When calculating the LCC of each power generation project, it is necessary to convert the annual cash flow occurring during the lifetime of equipment into present value resulting from the time value of money. Table 1 shows an overview of LCC calculation methods and the external cost quantification model. The calculation methods of LCC include the net present value (NPV), the internal rate of return (IRR), and the levelized cost of energy (LCOE) [14–16]. The NPV can be used in a single case or cases of consistent scales for comparison. For incompatible scales, the NPV cannot achieve the comparison among different cases. The key point of IRR is to determine the internal rate of return, which is the discount rate when the NPV of the case is equal to zero. The LCOE method establishes a link between the generation cost and the power generation. It is defined as the ratio of the generation cost to the power generation, which is only used to evaluate the cost of different power generation when producing 1 kWh electricity. It would help stakeholders decide among a series of power generation methods [17,18]. These three kinds of LCC calculation methods are aimed at distinguished application scopes, objectives, and goals, but all of them take the time value of money into consideration, which is reasonable.

Table 1. An overview of LCC calculation methods and external cost quantification model.

Country	LCC Calculation Methods	External Cost Quantification Model	Source
G20		LIME ₃	[19]
Morocco	LCOE		[20]
Australia	NPV		[21]
China	LCOE		[22]
China		GHG, PM _{2.5} , SO ₂ , NO _x	[23]
Germany	NPV		[24]
China	LCOE		[25]
USA	LCOE	GHG, SO ₂ , NO _x , PM ₁₀ , PM _{2.5}	[26]
Alberta	NPV	Carbon tax	[27]
Canada	NPV and IRR		[15]

Table 1. Cont.

Country	LCC Calculation Methods	External Cost Quantification Model	Source
Scotland	NPV		[28]
Greece	LCOE	ExternE methodology, Impact pathway approach	[29]
Lithuania		ExternE methodology, Impact pathway approach	[30]
China	NPV		[14]
Canada	NPV		[31]
Greece		ExternE methodology	[12]
Greece	LCOE	Carbon trade	[32]
Bosnia and Herzegovina		ExternE methodology	[33]
Singapore	NPV		[34]
USA	LCOE	Air pollution, Resource depletion, Distribution, Securing resources and use impacts	[16]
Singapore	NPV		[35]

As we cannot obtain external cost analogous to internal cost, the marginal damage cost of each impact category is used to calculate external costs. Marginal damage cost data are usually obtained based on the willingness to pay (WTP) theory or other national policies, such as tax credits, pollution charges, or carbon taxes [19,36–38]. The WTP method is that people are willing to pay a certain amount of money to avoid (or exchange) a certain change [39]. In some European countries, the calculation of external cost is based on another scientific method that is the “impact pathway” method. The damage cost data used in this method are collected by the “New Energy Externalities Developments for Sustainability” project, and the data related to atmospheric emission factors are taken from the life cycle assessment (LCA) database [12,24,29,33].

Combined with the LCA method, external costs can be quantified according to the monetization result of the environmental impact categories. The ReCiPe model that breaks the regional limitations of the traditional LCA model is widely applied, which includes 18 midpoint environmental impact categories [40–42]. Cui et al. calculated the external cost of ultra-low emission treatment technology for sintering flue gas and established the currency factors of different midpoint impact categories [43]. Karkour et al. applied the LIME₃ model, which contained the weighting factors of G20 countries, the complete impact categories, and the WTP for each endpoint environmental impact of damages [19,44]. The methods of external cost calculation show a trend of diversification [30]. However, factors such as discount rate, environmental impact category model, and regional differences have a great effect on LCC [45–47].

Based on three representative enterprises of coal-fired, biomass, and wind power generation in Shandong Province, this study aims to analyze the internal costs and external costs caused by pollutant emissions following the improved LCOE method from the framework of the life cycle. Furthermore, the environmental impacts caused by pollutant emissions are quantified with the ReCiPe model, and then the LCC of the three cases can be compared. The research results can provide data support for the government to formulate relevant policies such as on-grid electricity prices and financial subsidies.

2. Materials and Methods

2.1. The Improvement of the LCOE Model

LCOE is a common method of cost accounting in the electricity generation field but lacks an integrated form. It is defined as the ratio of the present value of cost and power generation. Roth and Ambs hold that the initial capital, O&M cost, fuel cost, and external cost associated with air pollutants, resources, and land use should be considered, but the discount of annual power generation was not included [16]. It has no practical significance to discount the power generation, which is actually the discount of power generation income.

This study improves the LCOE method from three perspectives:

- Considering the quantification of external cost: in this paper, integration of LCA and LCC is conducted to establish a corresponding calculation model. In the framework of LCA, the objective, scope, system boundary, function unit and inventory data of LCC should be consistent with LCA. The external cost is quantified based on the ReCiPe model in the SimaPro database. As a multiparametric method, ReCiPe provides an integrated vision that takes various environmental aspects into account when calculating the impacts [48].
- Expanding the compositions of internal cost: internal costs consist of capital cost, raw material cost, O&M cost, other annual costs. The compositions of capital cost are comprehensive including power plant construction cost, equipment installation cost, equipment and tool purchase cost, other engineering and construction costs, basic reserve cost, reserve fund for price variation, and interest expenses during the construction period. Additionally, the compositions of other annual costs consist of salary and welfare funds, insurance, sales tax, and some daily tariff.
- Discounting power generation: when choosing one year as the base year, the cost factors and power generation of the selected case should be converted to present value to obtain the cost of producing 1 kWh electricity. However, that is not to say the power generation also has time value analogous to the time value of money. The discount of power generation is regarded as the discount of income during each period.

The improved LCOE model is shown in Equation (1).

$$LCOE = \frac{I_0 + \sum_{t=1}^N (F_t + O\&M_t + R_t) \cdot (1+r)^{-t} + \sum_{t=1}^N E_{xt}}{\sum_{t=1}^N (E_t \cdot (1+r)^{-t})} \quad (1)$$

where I_0 represents capital cost, F_t represents raw material cost, $O\&M_t$ represents O&M cost, R_t represents other annual costs, E_{xt} represents external cost, E_t represents annual power generation, N represents the equipment lifetime, and r represents the discount rate.

2.2. Quantification Model of External Cost

An integrated economic value conversion factor system for 18 environmental impact categories in the ReCiPe midpoint (H) model is established by the regulation of pollutant discharge fee, the environmental tax, and WTP theory.

• Climate Change

A national carbon emission trading system is being established in China [49]. According to China's prospective carbon emissions from 2000 to 2030, the economic value conversion factor of climate change is 0.03 USD per kg C eq [50].

• Terrestrial Acidification

The characteristic substance of terrestrial acidification is SO_2 . The Tax Law of Environmental Protection stipulates that the tax per pollution equivalent of air pollutants is USD 0.17–1.74, and the average SO_2 emission fee is USD 0.96 per eq [51]. The equivalent standard of SO_2 emission is 0.95 kg, and the corresponding tax is USD 1.01 per kg SO_2 . The economic value conversion factor of this environmental impact category is USD 1.01 per kg SO_2 eq.

• Freshwater and Marine Eutrophication

Phosphorus and nitrogen are the characteristic substances that lead to freshwater and marine eutrophication, respectively. According to the Tax Law of Environmental Protection, the tax per pollution equivalent of water pollutants is USD 0.20–2.03, and the average value is 1.12 per equivalent USD [51]. The equivalent standards of phosphorus and nitrogen are 0.25 and 0.8 kg, separately. The economic value conversion factors of the two environmental impact categories above are USD 4.48 per kg P eq and 1.40 USD per kg N eq.

• Terrestrial, Freshwater, and Marine Ecotoxicity

The characteristic substance of these three environmental impact categories is p-dichlorobenzene. The national average p-dichlorobenzene tax is 0.22 USD/eq, and the pollutant equivalent value is 0.02 kg [52,53]. The economic value conversion factor is USD 11.24 per kg 1,4-DBC eq.

- Agricultural Land Occupation and Natural Land Transformation

The Tax Law of Cultivated Land Occupation sets the average tax per m² of cultivated land in Shandong Province at USD 3.26 [54]. Thus, the economic value conversion factor of these two environmental impact categories is 3.26 USD/m².

- Urban Land Occupation

According to the *Tax Law of Urban Land Use*, the tax of urban land use in Shandong Province is USD 0.22–4.35 per m² [55]. The average urban land use tax is 2.28 USD/m², which is set as the economic value conversion factor of urban land occupation.

- Water Depletion

According to the Administrative Measures for the Collection and Use of Water Resources Fees in Shandong Province, the tax standard of surface water is not less than 0.06 USD/m³ [56]. The economic value conversion factor of water resources consumption is 0.06 USD per m³.

- Metal Depletion

The tax rate of iron ore with 66% iron substance is 3% [57,58]. The price of iron ore is 105.85 USD/t, and the economic value conversion factor of metal resource consumption is USD 0.0048 per kg Fe eq.

- Fossil Depletion

Petroleum is the characteristic substance of this environmental impact category. The average price of petroleum is 0.34 USD/kg [59]. The tax rate of petroleum ranges from 6% to 10% [60]. The average tax rate of 8% is selected, which determines that the economic value conversion factor of fossil energy is 0.027 USD/kg oil eq.

- Ozone Depletion, Photochemical Oxidant Formation, Particulate Matter Formation, Human Toxicity, and Ionizing Radiation

The five environmental impact categories above are attributed to human health in the endpoint environmental impact category model. The total annual medical and health expenditure in China was USD 893.43 billion in 2018 [61]. The mortality and disease burden in China was 95,968,218 DALY [62]. DALY is a measurement unit that is used to indicate the total years of healthy life lost from the impact to death. The economic value conversion factor of human health is USD 9309.70 per DALY by dividing the above two items.

Thus, the external LCC can be calculated through Equation (2) as follows:

$$E_{xt} = \sum c_j \cdot e_k \quad (2)$$

where c_j represents the economic value conversion factor of the j environmental impact category, the unit of c_j is USD, and e_k represents the characteristic value of the k environmental impact category.

2.3. Case Study

Three representative power plants in Shandong Province are selected as cases, including coal-fired, biomass, and wind power. Coal-fired power plants use coal as fuel and generate electricity through steam-driven generators. Biomass power plants generate steam from the direct combustion of straw and branches and then generate electricity. Wind power plants generate electricity directly through wind turbines. The three power plants went into operation in 2015; thus, this year is selected as the base year. The discount rate of internal cost is 8% and the design lifetime of equipment and facilities is 20 years.

The average annual salary of local workers is USD 8028. The coal-fired power plant is equipped with four units that are two 330 MW subcritical pulverized coal boilers and two 670 MW supercritical pulverized coal boilers. The biomass power plant has a 35 MW steam turbine generator unit, and the wind farm possesses 88 wind turbine generator units, with 850 kW for each unit.

Table 2 shows the installed capacity, electricity generation, and cost-related information of three power plants.

Table 2. Information of the three power plants in the base year of 2015.

Items	Coal-Fired Power	Biomass Power	Wind Power
Installed capacity (MW)	2000	35	75
Electricity generation (kWh/a)	9.97×10^9	2.72×10^8	6.74×10^7
Capital cost (million USD)	1239	33.3	52.3
Raw material cost (million USD/a)	339.4	15.98	/
O&M cost (million USD/a)	4.96	1.96	/
Other annual cost (million USD/a)	12.4	3.94	0.14
Number of employees	1541	102	17

In this study, the system boundary is “cradle to gate.” The functional unit is “the generation of 1 kWh electricity.” The production of electricity and the acquisition of raw materials are considered, but the use of generated electricity and the disposal of the power plant are not included in the system boundary.

3. Results

3.1. Internal Cost Accounting

The life cycle inventories of coal-fired and biomass power plants are shown in Tables 3 and 4. According to Equation (1), the internal costs of coal-fired, biomass, and wind power are 0.053, 0.093, 0.081 USD/kWh, respectively.

Table 3. Life cycle inventory of coal-fired power plant.

Material	Input/Output	Unit	Overall Consumption	Consumption per kWh	Unit Price (USD)	Annual Total Cost (USD)
Coal	Input	t	4,048,033	4.0602×10^{-4}	80.274	324,965,721.5
Diesel	Input	t	761	7.6329×10^{-8}	963.329	733,093.5714
Water	Input	m ³	16,404,421	1.6454×10^{-3}	0.161	2,633,809.807
Electricity	Input	10 ⁴ kWh	65,322.24	6.5519×10^{-2}	0.064	4195.1217
Limestone	Input	t	229,539	2.3023×10^{-5}	11.239	2,579,752.424
Liquid ammonia	Input	t	5727	5.7442×10^{-7}	353.221	2,022,895.126
V-W-TiO ₂	Input	m ³	3219	3.2287×10^{-7}	1894.548	6,098,548.584
Hydrochloric acid	Input	t	1998	2.0040×10^{-7}	91.516	182,849.528
NaOH	Input	t	1833	1.8385×10^{-7}	112.388	206,007.9635
Particulate matter	Output	t	176.68	1.7721×10^{-8}		
SO ₂	Output	t	1088.305	1.0916×10^{-7}		
NO _x	Output	t	1480.495	1.4850×10^{-7}		
Mercury and its compounds	Output	kg	23	2.3069×10^{-9}		
Waste water	Output	m ³	2,589,573	2.5974×10^{-4}		
COD	Output	t	134.40	1.3480×10^{-8}		
Ammonia nitrogen	Output	t	11.70	1.1735×10^{-9}		
Electricity	Output	kWh	9.97×10^9			

Table 4. Life cycle inventory of biomass power plant.

Material	Input/Output	Unit	Overall Consumption	Consumption per kWh	Unit Price (USD)	Annual Total Cost (USD)
Straw	Input	t	163,900	6.0257×10^{-4}	48.166	7,894,407
Branch	Input	t	42,600	1.5662×10^{-4}	48.166	2,051,872
Electricity	Input	kWh	2.7216×10^7	0.10006	0.064	1,741,824
Coal	Input	t	50,159.48	1.8441×10^{-4}	80.277	4,026,653
Limestone	Input	t	19,352	7.1147×10^{-5}	11.239	217,497.1
Intermediate water	Input	t	830,000	3.0515×10^{-3}	0.048	39,840
Tap water	Input	t	3600	1.3235×10^{-5}	0.369	1328.4
Particulate matter	Output	t	17.54	6.4485×10^{-8}		
SO ₂	Output	t	59.4	2.1838×10^{-7}		
NO _x	Output	t	119.3	4.3860×10^{-7}		
NH ₃	Output	t	0.8	2.9412×10^{-9}		
Electricity	Output	kWh	2.74×10^8			

3.2. External Cost Accounting

Given the environmentally friendly and pollution-free characteristics of wind power, its external cost is considered zero. For coal-fired and biomass power, the result of impact assessment characterization is shown in Table 5. It shows that 18 environmental impact categories of the ReCiPe model varied for coal-fired and biomass power. The influence of climate change has the largest value for coal-fired and biomass power, compared with other environmental impact categories, which is 0.4679 and 0.2972 kg CO₂ eq, respectively, followed by fossil depletion, which is 0.027 and 0.1336 kg oil eq, respectively.

Table 5. Life cycle inventory assessment midpoint results of coal-fired and biomass power plant.

Impact Category	Unit	Economic Value Conversion Factor (USD)	Coal-Fired Power Generation		Biomass Power Generation	
			Total (/kWh)	External Cost (USD/kWh)	Total (/kWh)	External Cost (USD/kWh)
Climate change	kg CO ₂ eq	0.03	0.4679	0.0140	0.2972	8.9150×10^{-3}
Terrestrial acidification	kg SO ₂ eq	1.01	2.5551×10^{-3}	2.5807×10^{-3}	1.6670×10^{-3}	1.6840×10^{-3}
Freshwater eutrophication	kg P eq	4.48	1.9601×10^{-4}	8.7810×10^{-4}	9.6800×10^{-5}	4.3400×10^{-4}
Marine eutrophication	kg N eq	1.40	1.1717×10^{-4}	1.6404×10^{-4}	3.8600×10^{-5}	5.4000×10^{-5}
Terrestrial ecotoxicity	kg 1,4-DB eq	11.24	4.1252×10^{-6}	4.6370×10^{-5}	5.0200×10^{-6}	5.6400×10^{-5}
Freshwater ecotoxicity	kg 1,4-DB eq	11.24	3.5302×10^{-3}	0.0397	1.8690×10^{-3}	0.0210
Marine ecotoxicity	kg 1,4-DB eq	11.24	3.3678×10^{-3}	0.0379	1.7870×10^{-3}	0.0201
Agricultural land occupation	m ² a	0.163	0.0236	3.8514×10^{-3}	0.0928	0.0151
Urban land occupation	m ² a	0.114	0.0107	1.2146×10^{-3}	0.0067	7.6700×10^{-4}
Natural land transformation	m ²	3.26	4.8533×10^{-5}	1.5822×10^{-4}	3.4500×10^{-5}	1.1200×10^{-4}
Water depletion	m ³	0.06	2.3629×10^{-3}	1.4177×10^{-4}	3.3670×10^{-3}	2.0200×10^{-4}
Metal depletion	kg Fe eq	0.0048	5.9180×10^{-3}	2.8406×10^{-5}	3.4420×10^{-3}	1.6500×10^{-5}
Fossil depletion	kg oil eq	0.027	0.2535	6.8435×10^{-3}	0.1336	3.6070×10^{-3}
Ozone depletion	DALY	9309.70	8.3400×10^{-12}	7.7643×10^{-8}	1.1600×10^{-11}	1.0800×10^{-7}
Photochemical oxidant formation	DALY	9309.70	3.6000×10^{-11}	3.3515×10^{-7}	2.4100×10^{-11}	2.2400×10^{-7}
Particulate matter formation	DALY	9309.70	2.8000×10^{-7}	2.6067×10^{-3}	1.7900×10^{-7}	1.6660×10^{-3}
Human toxicity	DALY	9309.70	1.0800×10^{-7}	1.0054×10^{-3}	4.6600×10^{-8}	4.3400×10^{-4}
Ionising radiation	DALY	9309.70	-1.0000×10^{-11}	-9.3097×10^{-8}	3.4500×10^{-11}	3.2100×10^{-7}
Total				0.111		0.074

The external cost of coal-fired power in the base year is 0.111 USD/kWh. According to Equation (1), the external cost of coal-fired power is 0.226 USD/kWh if the time value of electricity generation is considered in the following 20 years, which accounts for 82% of the LCC. It is necessary to further analyze the contribution degree of each midpoint environmental impact category. Figure 2a indicates that the external cost of coal-fired power is mainly concentrated on four environmental impact categories, i.e., freshwater ecotoxicity, marine ecotoxicity, climate change, and fossil depletion, which account for 36%, 34%, 13%, and 6%, respectively. For biomass power, the external cost is 0.151 USD/kWh, accounting for 62% of the LCC, which is lower than that of coal-fired power. As shown in Figure 2b, the external cost of coal-fired power is also mainly concentrated on four environmental impact categories, i.e., freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, and climate change, which account for 28%, 27%, 20%, and 12%, respectively.

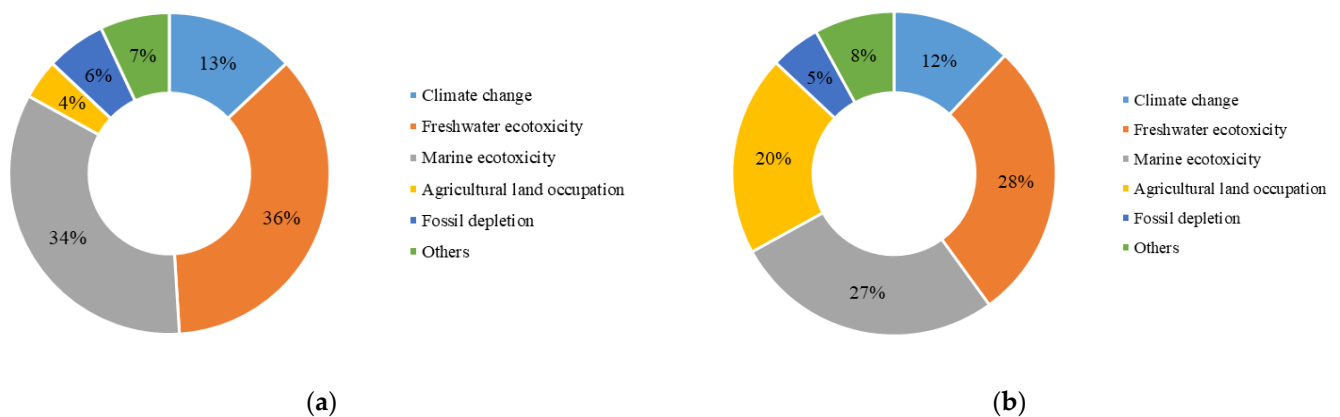


Figure 2. The breakdown of external cost for coal-fired power and biomass power: (a) coal-fired power; (b) biomass power.

3.3. Life Cycle Cost

As shown in Figure 3, without the consideration of external cost, the electricity generation that has the minimal internal cost is coal-fired power, which is 0.049 USD/kWh. The internal cost of wind power is higher than coal-fired power, which is 0.081 USD/kWh. The electricity generation that has the maximal internal cost is biomass power, which is 0.098 USD/kWh. Compared with biomass and wind power, coal-fired power lacks competitiveness in internal cost resulting from the limitation of installed capacity. With the consideration of external cost, the life cycle cost of producing 1 kWh electricity for coal-fired power and biomass power is increased to USD 0.275 and USD 0.249, respectively. The life cycle cost of wind power remains unchanged at 0.081 USD/kWh.

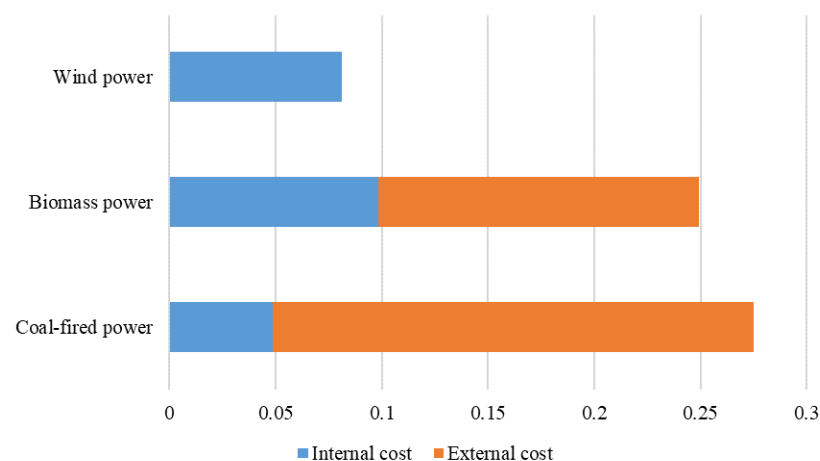


Figure 3. The internal cost and external cost of coal-fired, biomass, and wind power.

Figure 4 shows that the cost compositions with maximal percentage for both coal-fired and biomass power are external cost, which accounts for 82.25% and 60.53%, respectively. The cost compositions with the second-largest percentage for both coal-fired and biomass power are raw material cost, which accounts for 12.38% and 23.59%, respectively. In the cost factors of wind power, the proportion of capital cost takes the first place by 97.44%, followed by other annual costs, which account for only 2.56%.

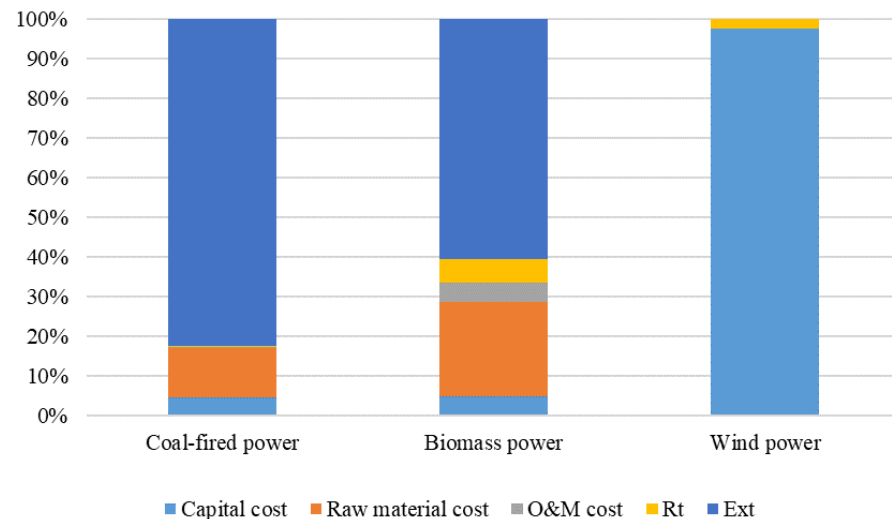


Figure 4. The LCC compositions of coal-fired, biomass, and wind power.

4. Discussion

4.1. Comparisons of Life Cycle Cost

According to LCC results, the internal cost compositions with maximal percentages for coal-fired and wind power are raw material costs. For wind power, capital cost occupies the largest proportion of internal cost compositions. The external cost of coal-fired, biomass power is 0.226 and 0.151 USD/kWh. Wind power has no external cost. Compared with internal cost, the external cost of coal-fired power has a significant influence on its LCC. Therefore, efforts should be placed on reducing the environmental impact and external cost of coal-fired power. Increasing thermal efficiency and reducing coal consumption is an effective way. According to the life cycle inventory assessment midpoint results of coal-fired power and biomass power, the external cost resulted from freshwater ecotoxicity, marine ecotoxicity, and climate change of coal-fired power is higher than that of biomass power. However, the external cost resulting from freshwater eutrophication and water depletion of coal-fired power is lower than that of biomass power. Apart from the above impact category, for biomass power, the external cost caused by agricultural land occupation is higher than coal-fired power. The high cost of raw materials collection and storage has significant impacts on the external cost of biomass power.

The LCC of coal-fired power is higher than biomass power and wind power when taking external cost into consideration. Similar conclusions have been obtained in previous studies. Wang et al. compared the LCC of biomass and coal-fired power generation of different installed capacities [23]. The internal cost of wood-based biomass was higher than others without external cost. When taking external cost into consideration, the LCC of wood-based biomass was lower than any other unit. Roth et al. concluded the combined cycle plants had the lowest LCC without external cost [16]. When external cost was considered, landfill gas recovery had the lowest LCC. This shows that whether external costs are considered or not determines the LCC and its ranking of different electricity generation methods.

4.2. Sensitivity Analysis

4.2.1. Sensitivity Analysis of Cost Factors

Figure 5 shows the sensitivity analysis of coal-fired, biomass, and wind power in cost factors. A 10% variation for five cost factors causes different changes of LCC on three kinds of power generation. For coal-fired power, the changes are 1.27×10^{-3} , 3.56×10^{-3} , 8.85×10^{-5} , 1.26×10^{-4} , and 2.27×10^{-2} USD/kWh for capital cost, raw material cost, O&M cost, other annual costs, and external cost, respectively. It is observed that external cost exerts the largest impact on the LCC of coal-fired power, followed by raw material cost. For biomass power, the changes are 1.25×10^{-3} , 1.17×10^{-2} , 1.26×10^{-3} , 1.45×10^{-3} , and 1.51×10^{-2} USD/kWh for capital cost, raw material cost, O&M cost, other annual costs, and external cost, respectively. Therefore, the priority should be assigned to reduce external cost and raw material cost of coal-fired and biomass power. For wind power, the changes are 7.9×10^{-3} and 2.08×10^{-4} USD/kWh for capital cost and other annual costs, respectively. The capital cost of wind power is the major contributor to its LCC. With the emerging advances in wind energy technology, the capital cost has been reduced, and wind energy has become one of the most prospective and cost-competitive renewable energy.

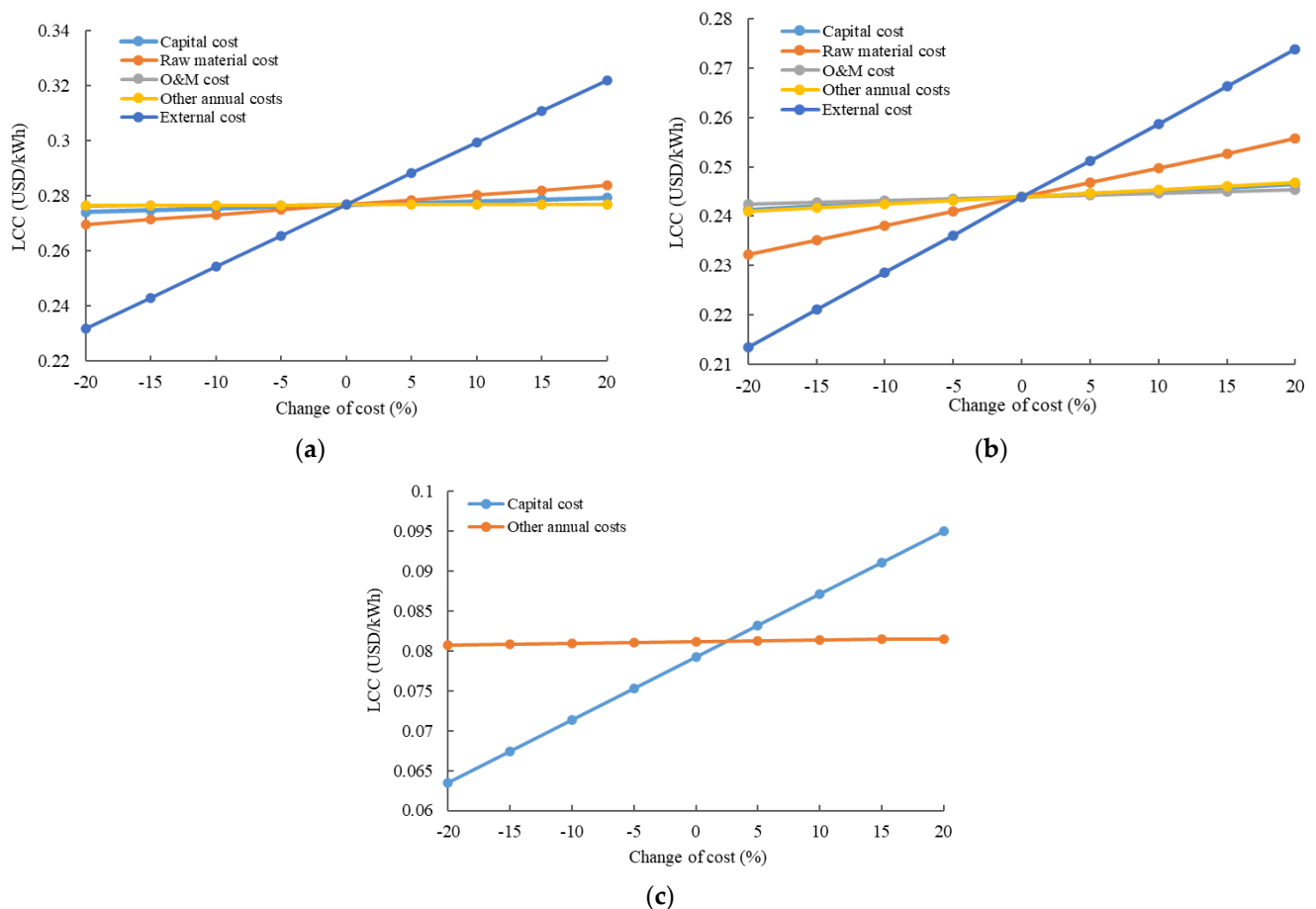


Figure 5. Sensitivity analysis of coal-fired, biomass, and wind power in cost factors: (a) coal-fired power; (b) biomass power; (c) wind power.

4.2.2. Sensitivity Analysis of Discount Rate

The sensitivity analysis of coal-fired, biomass, and wind power in terms of the discount rate is shown in Figure 6. With the discount rate increasing to 10%, the life cycle cost of producing electricity is 0.314, 0.269, and 0.093 USD/kWh for coal-fired, biomass, and wind power, separately. Coal-fired power is more sensitive to the variation of a discount rate than biomass and wind power due to a large proportion of the annual raw material

cost, O&M cost, and other annual costs. Furthermore, the distance between coal-fired power and biomass power increases with the increase of discount rate. The change of LCC resulting from the discount rate highlights the competitiveness of biomass power from the perspective of time value.

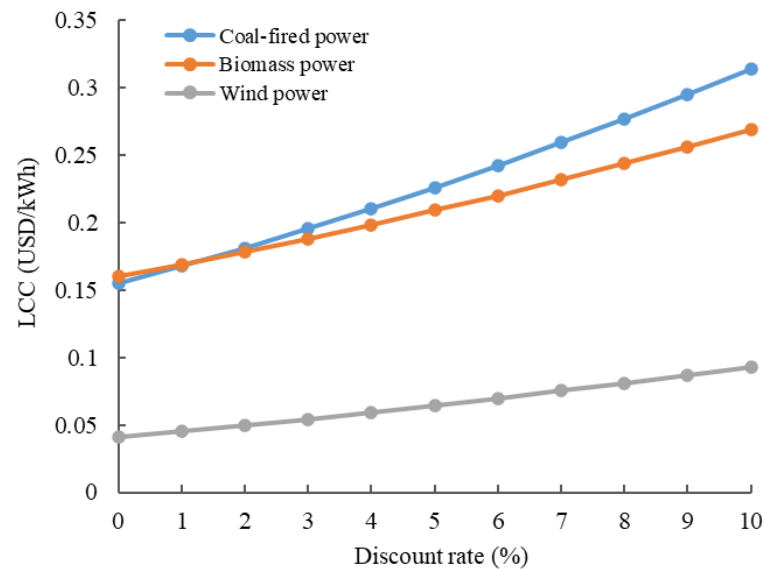


Figure 6. Sensitivity analysis of coal-fired, biomass, and wind power in terms of the discount rate.

4.3. Policy Implications

The LCC results of three cases show that coal-fired power has the maximal cost with the quantification of external cost. Although its initial capital cost takes a minor proportion of LCC, the sustainable development of coal-fired power is still facing a great challenge due to massive coal consumption, severe environmental pollution, and huge annual expenses. The coal-fired power industry should actively explore clean and efficient power generation technologies, to reduce pollutant emissions. Coal processing, coal conversion, waste energy utilization, and flue gas purification will play important roles to decrease the LCC of coal-fired power.

Compared with coal-fired power, the internal cost of biomass power is higher without the consideration of external cost. However, biomass power can be regarded as an environmentally friendly project, compared with the direct burning of biomass, which has resulted in serious air pollution in autumn and winter in some countries such as India and China. From the perspective of cost compositions, the key factors constraining its development are raw material costs. The insufficient supply of straw resources also affects biomass power development. It is suggested to establish a payment mechanism and improve the subsidies for biomass resource collection based on the local development level of biomass power. These measures can further strengthen the competitiveness of biomass power by reducing production costs caused by raw material collection and transportation under the continuous and sufficient supply of biomass resources.

Wind power has the minimal LCC among the three kinds of electricity generation. In the cost factors of wind power, the proportion of capital cost takes the first place, which accounts for 97.44% of LCC. The capital cost is recognized as the key factor that restricted the development of wind power. Different from coal-fired power and biomass power, small and medium-sized wind power projects are suitable for distributed development and utilization, particularly for the inland areas. The decentralized wind power can effectively reduce initial capital cost [63]. Coastal regions with abundant offshore wind resources are encouraged to develop offshore wind power so as to reduce the occupation of land resources and initial cost in the meanwhile.

5. Conclusions

The LCOE method is improved from three perspectives, namely, considering the quantification of external cost, expanding the compositions of internal cost, and discounting power generation. The LCCs of coal-fired, biomass, and wind power are evaluated with the improved LCOE model. External cost is quantified by environmental impact categories of the ReCiPe model and the economic value conversion factor of each environmental impact category, which is obtained from the calculation of WTP, environmental taxes, and sewage charges. The result shows that the internal costs of coal-fired, biomass, and wind power are 0.049, 0.098, and 0.081 USD/kWh, respectively. The LCC of coal-fired, biomass, and wind power are 0.275 and 0.249 USD/kWh with the quantification of external cost. The LCC of wind power remains 0.081 USD/kWh. Therefore, the internal cost of coal-fired power is lower than that of biomass and wind power without external cost. When taking external cost into consideration, the LCC of coal-fired power is higher than that of others. External cost both occupies the highest proportion in the LCC of coal-fired and biomass power, which accounts for 82.25% and 60.53%, respectively. In the LCC of wind power, the proportion of capital cost takes first place, by 97.44%.

According to the sensitivity analysis of the three cases in cost factors, the changes of external cost and raw material cost have a great impact on the LCC for coal-fired power and biomass power. When external cost is reduced by 10%, the costs of coal-fired and biomass power decrease by 8.26% and 6.06%, separately. When raw material cost is reduced by 10%, the costs of coal-fired power and biomass power decrease by 1.29% and 4.70%, separately. A variation of discount rate has a more distinct impact for coal-fired power than biomass and wind power resulted from high annual cost.

Combined with the internal cost and external cost calculation of coal-fired, biomass, and wind power, this study reveals that biomass and wind power are more economical and environmentally friendly than coal-fired power. The government should further take effective policy measures to increase the proportion of electricity generated by biomass and wind in total electricity generation.

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