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Mini review

Electricity generation comparison of food waste-based bioenergy with wind and solar powers: A mini review

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ABSTRACT

The food waste treatment-based anaerobic digestion has been proven to play a primary role in electricity industry with high potentially economic benefits, which could reduce electricity prices in comparison with other renewable energy resources such as wind and solar power. The levelized costs of electricity were reported to be 65, 190, 130 and 204 US$ MWh^{-1} for food waste treatment in anaerobic landfill, anaerobic digestion biogas, solar power, and wind power, respectively. As examples, the approaches of food waste treatment via anaerobic digestion to provide a partial energy supply for many countries in future were estimated as 42.9 TWh yr^{-1} in China (sharing 0.87% of total electricity generation), 7.04 TWh yr^{-1} in Japan (0.64% of total electricity generation) and 13.3 TWh yr^{-1} in the US (0.31% of total electricity generation). Electricity generation by treating food waste is promised to play an important role in renewable energy management. Comparing with wind and solar powers, converting food waste to bioenergy provides the lowest investment costs (500 US$ kW^{-1}) and low operation cost (0.1 US$ kWh^{-1}). With some limits in geography and season of other renewable powers, using food waste for electricity generation is supposedly to be a suitable solution for balancing energy demand in many countries.

1. Introduction

In recent years, the escalating increase in energy consumption due to rapid industrial development has threatened the environmental balance. The generation of organic wastes, especially, food waste (FW) also results in environmental pollution problems if not well managed. The FW contains many biodegradable organic components and could be anaerobically digested to produce biogas as a green bioenergy [1]. Moreover, the approach of the FW as a source of bioenergy feedstock is expected to solve some issues of waste treatment and green energy generation and also overcome the controversy on using crops for fuel/energy.

Treating FW via anaerobic processes could greatly maximize the efficiency of hydrogen and methane production for potential energy use [2]. This energy conversion might offer a stable electricity source for many countries. Some previous studies have demonstrated that FW could also be treated by a two-step of dark- and photo-fermentation for bio-hydrogen production or three-stage fermentation for bio-hydrogen and bio-methane [3]. At present, anaerobic digestion (AD) is the most commercial method for FW treatment and biogas recovery (mostly bio-methane generation). AD could give the highest energy benefits, and is the most suitable method for the commercialization of FW treatment, in which the electricity generation of one-phase and two-phase anaerobic digestion is about 220 and 404 kWh t^{-1} FW, respectively [1].

AD is considered as a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. The process involves three phases of conversion including hydrolysis, acidogenesis, and methanogenesis. Four main groups of bacteria involved each phase include i) Hydrolytic bacteria, ii) Acetogenic bacteria, iii) Acetoclastic methanogens, and iv) Hydrogenotrophic methanogens. The two-phase process for methane is usually a sequential process (more complex than methane production, one-phase) [4]. AD process mostly generates methane content up to 75% of total biogas [5]. For one- or two-

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Nomenclature

AD	anaerobic digestion
FW	food waste
kWh	kilowatt-hour
LCOE	Levelized cost of electricity
MWh	megawatt-hour
REN21	renewable energy policy network for the 21st century
SP	solar power
TWh	tegawatt-hour
US$	United States Dollar
WP	wind power

phase process for methane production composing of methanogenic bacteria, together with halophilic and thermo-acidophilic bacteria, makes up a group of micro-organisms called Archaebacteria. The methane content in a single process step can be up to 85–90% prior to the gas cleaning step.

At batch scale, the one-phase system with organic loading rate about 24 m^3 t^{-1} FW and pH control at 7 could produce a stable methane yield at about 364 ± 7 mL CH_4 g^{-1} VS [6]. There are some other studies of AD process for hydrogen and methane productions as below:

– Two-phase thermophilic AD process: operation temperature is at 55 °C with pH control at 5.2 ± 0.2 (First phase) and 8.1 ± 0.1 (Second phase). Biogas yield is about 690 L kg^{-1} total volatile solids $(TVS)_{added}$ (7% H_2, 58% CH_4 and 35% CO_2) [7].
– Dark fermentation coupled with AD process: operation temperature is at 55 °C with pH control at 5.7 ± 0.3 (First phase) and 8.4 ± 0.2 (Second phase). The hydrogen yield is up to 66.7 L kg^{-1} TVS_{added} and CH_4 yield 720 L kg^{-1} TVS_{added} (CH_4 58%, H_2 6.9%, CO_2 36%) [8].
– The two-phase hydrogen/methane fermenting reactor has controlled temperature around 33 ± 4 °C, pH 5.3 ± 0.2 (First phase) and 36 ± 4, pH 7.4 ± 0.3 (Second phase). Total biogas is up to 2446 Nm^3 d^{-1} (with H_2 yield around 1223 Nm^3 d^{-1}) [9].

The system of one-phase fermentation for methane has been developed at full scale plant, which was reported to generate about 383 kWh t^{-1} of FW [10]. While it is revealed that two-phase process for hydrogen and methane produces a total electricity of 780 kWh t^{-1} of FW [11,12].

Treating FW to produce biogas and then to generate electricity exposes that FW is becoming a prospective electricity supplement source among various renewable energy suppliers. However, the competition of this electricity with other main renewable energy sources of wind and solar is not reported in any studies or researches. Therefore, this mini-review aims to obtain a comparison between FW-based bioenergy via one-phase and two-phase AD in commercial scale plants with wind power (WP) and solar power (SW) in terms of economic and energy benefit evaluations.

2. Overview of food waste to bioenergy via anaerobic digestion

AD is a popular method for treating organic wastes [13]. There are formulae developed by Gary and Jenkins as a technical guideline of AD process for FW that has been adopted by many FW to biogas via AD studies [14]. Theoretically, one tonne of FW could potentially produce 247 m^3 methane and generate approximately 90 GJ of heat or 847 kWh electricity [15]. This review used these values to compute the maximum energy potential of treating FW-based theoretical AD process.

FW treatment-based AD technology has been widely practiced around the world. There are 1455 AD facilities in the US and 124 AD plants in Europe [16]. At present, the largest capacity is at Cedar Grove in Everett in the US at 280,000 t FW yr^{-1} [17]. For larger scales, such as commercial FW treatment facilities in Canada and the US, energy output of FW treatment-based AD technology was found to be as high as 220 kWh t^{-1} FW [16]. This review uses this energy output value to compute energy potential from FW treatment via one-phase AD process, the results are presented in Table 1.

The results of pilot-scale plant operating with two continuous stirred tank reactors (0.2 m^3 for first phase [dark-fermentation for hydrogen) and 0.76 m^3 for second phase (AD for methane)] showed that hydrogen production was about 66.7 L kg^{-1} TVS_{added} with the final biogas amount 0.72 m^3 kg^{-1} TVS_{added} [8]. It illustrates that dark-fermentation coupling with AD enhances biogas yield. The maximum electricity generation in the entire process was about 404 kWh t^{-1} FW [8]. This value is used to compute the energy potential of FW treatment via two-phase AD process. In fact, in a comparison between one-phase with two-phase of AD, the potential electricity of two-phase AD could have been expected to exhibit higher energy yield than that of one-phase AD system [18].

There are thousands of large-scale FW treatment plants in France, Italy, Germany, Denmark, UK, Sweden, US, Canada and Southeast Asian countries [4,17]. For power generation purposes, many organic waste-AD plants are connected to the current grid of nationwide energy supplies in Germany, Switzerland, Netherlands, UK and Sweden [4,17]. As of now, German AD based FW treatment AD has reached 2 Mt of FW per year, which accounts for 16.3% of their annual FW generation. The Netherlands have disposed their FW by about 0.8 Mt yr^{-1} with the average capacity per AD facility being 54 kt yr^{-1} [4,17]. The UK has reached 500 kt of FW treatment by AD (3% of total FW) for an average capacity of 35 kt FW yr^{-1} per plant.

Table 1 presents the energy benefits in comparison with WP and SP in Australia, US, Germany, China and Japan. China has the highest population and also contributes the highest amount of FW in the world [1]. It is estimated that China with 195 Mt of FW generation annually could mean producing approximately 42.9 TWh yr^{-1} of electricity via one-phase AD process (sharing 0.76% total electricity generation) and 78.8 TWh yr^{-1} of electricity via two-phase AD process (sharing 1.39% total electricity generation) [12]. This could be an impressive share in the total renewable power generation of China in comparison with WP and SP generation. Meanwhile, the US is the world leader of bio-power generation, but they use biomass from forest such as fast-growing trees, crop residues (wheat straw, barley straw, and sugarcane wastes) and animal dung, while the FW is not commonly used in commercial energy production [19]. It is estimated that the FW of the US could produce about 13.4 TWh yr^{-1} (sharing 0.31% total electricity generation) via one-phase AD and 24.6 TWh yr^{-1} (sharing 0.57% total electricity generation) via two-phase AD processes, respectively [12].

Among the European countries, Germany has the highest chance of expanding AD technology to treat FW since they could convert 2.7 TWh yr^{-1} (sharing 0.44% of total national electricity generation) via one-phase AD process and 4.96 TWh yr^{-1} (sharing 0.81% total electricity generation) via two-phase AD process. It could highlight the steadily increasing role in biological treatment for FW in Europe, whereas Germany targets using natural gas, which has been set to reach 6% of total gas consumption by 2020, and 10% by 2030 [20].

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Table 1
Energy benefits comparison between wind power, solar power and FW treatment via anaerobic digestion processes.

Country[a]	Total amount of food waste (wet weight) (Mt yr^{-1})	Electricity generation by (TWh yr^{-1}) (%)		Energy potential of FW treatment via AD (TWh yr^{-1}) (%)		National energy generation[b] (TWh yr^{-1})
		Wind power	Solar power	One-phase AD	Two-phase AD	
Australia	2.26 [15]	12 [21] (6%)	3.5 [22] (1.48%)	0.5 (0.20%)	0.9 (0.37%)	244.5
China	195 [36]	140 [19] (2.84%)	8.7 [26] (0.176%)	42.9 (0.76%)	78.8 (1.39%)	5650
Germany	12.26 [37,38]	53.4 [24] (8.65%)	29.7 [25] (5.3%)	2.7 (0.44%)	4.95 (0.81%)	614
Japan	32 [39]	4 [24] (0.36%)	13.6 [27] (1.4%)	7.0 (0.66%)	12.9 (1.22%)	1061
United States	60.85 [40]	167.7 [23] (4.1%)	9.3 [23] (0.2%)	13.4 (0.31%)	24.6 (0.57%)	4297

[a] GDP per capita by country, World Bank data, 2014–2015.
[b] National Energy Generation in 2014–2015 from BP Statistical Review of World Energy.

3. Energy - economic efficiency evaluation between FW-based bioenergy and other renewable energy sources (WP and SP)

3.1. Data collection

The data for FW generation of five countries were collected from published documents and other sources, and the electricity estimation converting from FW of each country is shown in Table 1. Besides, data for electricity generation and capital costs of SP, WP and FW treatment-based bioenergy were collected from official reports as shown in Tables 1 and 2.

3.2. Energy evaluation

In this section, the potential electricity generation from FW would be compared with WP and SP. The overall benefits from three renewable energy sources were documented and analyzed using data from five countries, including Australia, US, Germany, China and Japan [19]. According to Renewable Energy Policy Network for the 21st Century (REN21), these five countries are the top countries in using renewable energy. In recent decades, these countries put more efforts in exploiting green energy from various renewable sources, such as wind, solar, geothermal and biomass [19].

In Australia, WP is the main energy source (6% vs. SP 1.48% of the total electricity generation [21,22]). The United States is currently exploiting around 167.7 TWh yr^{-1} from WP (sharing 4.1% of national output of electricity) and 9.3 TWh yr^{-1} from SP (sharing 0.2% of the total national electricity generation) [23], and currently ranks first with its capacity in bio-power generation. Germany is consuming 53.4 TWh yr^{-1} (8.65% of total electricity consumption) from wind energy and 29.7 TWh yr^{-1} (5.3% of total electricity consumption) from solar energy [24,25]. Up to the end of 2014, it is estimated that China has obtained 140.1 TWh yr^{-1} from WP (2.84% of total national energy) [19] and 8.7 TWh yr^{-1} from SP (0.17% of total national energy) [26]. Thus, China ranks first in its installed WP capacity, and China is also the world leader in solar investment with investing US $31.2 billion every year [19]. Japan uses WP producing 4 TWh yr^{-1} (sharing 0.36% of total electricity generation) and SP producing 13.6 TWh yr^{-1} (sharing 1.4% of total electricity generation) [24,27].

In practice, AD for treating FW could generate electricity as an ideal renewable energy source, and is also a suitable solution for environmental protection. Based on our previous study [12,28], the potential of electricity generation from the FW in China could feasibly provide 78.8 TWh yr^{-1}, sharing 1.39% of total electricity generation. Australia should obtain energy from FW via AD to provide 0.913 TWh yr^{-1}, composing 0.37% of total national energy. Germany, Japan and US could expect such a significant energy provision by treating FW, which were calculated as 5.0 TWh yr^{-1} for Germany (0.81% of total electricity generation), 12.9 TWh yr^{-1} for Japan (1.22% of total electricity generation), and 24.6 TWh yr^{-1} for the US (0.57% of total electricity generation). Table 1 is an energy

Table 2
The comparison of capital costs and economic benefits between wind power, solar power and FW treatment via anaerobic digestion in some studied cases.

Country	Economic factors	Electricity generation by wind power[a]	Electricity generation by solar power[b]	Energy potential of FW treatment via AD[c]
Australia	Capital costs (Million US$)	10,000	3600	700
	Operation and maintenance cost (Million US$)	324	36	52
	Economic benefit (Million US$ yr^{-1})	3240	945	247
The United States	Capital costs (Million US$)	125,000	16,500	18,800
	Operation and maintenance cost (Million US$)	4530	165	1400
	Economic benefit (Million US$ yr^{-1})	21,630	1071	3170
Germany	Capital costs (Million US$)	64,500	17,200	3790
	Operation and maintenance cost (Million US$)	1440	172	282
	Economic benefit (Million US$ yr^{-1})	19,810	11,020	1840
China	Capital costs (Million US$)	75,600	31,200	60,255
	Operation and maintenance cost (Million US$)	3780	310	4485
	Economic benefit (Million US$ yr^{-1})	11,210	700	6300
Japan	Capital costs (Million US$)	7610	15,700	9890
	Operation and maintenance cost (Million US$)	150	160	740
	Economic benefit (Million US$ yr^{-1})	1040	3540	3360

Economic benefits of AD technology are calculated based on energy potential of FW via AD multiply with current electricity costs of each country, including Australia 0.27 US$ kWh^{-1}; United States 0.129 US$ kWh^{-1}; Germany 0.371 US$ kWh^{-1}; China 0.08 US$ kWh^{-1}; and Japan 0.27 US$ kWh^{-1}.
[a] Capital costs and economic benefits of wind power-based countries are documented from Refs. [19,22,24,41].
[b] Capital costs and economic benefits of solar power-based countries are documented from Refs. [27,30,42].
[c] Capital costs and operation & maintenance costs are referred from commercial FW treatment-based AD facility in Vancouver landfill (capacity 108,600 tonne FW yr^{-1}) and Cedar Grove AD's system in Everett Washington (capacity 280,000 t FW yr^{-1}) [33].

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benefit comparison between three renewable energy sources (WP, SP, and FW treatment via AD) in five countries. It is demonstrated that energy from FW is expected to be a commercial source of electricity.

3.3. Economic evaluation

The cost analyses of potential energy from three kinds of renewable energy were made to illustrate the economic benefits of three electricity generation technologies including FW treatment via AD process versus WP and SP, which could be a valuable source of data for many countries to consider.

Table 2 shows the comparison of capital cost between WP, SP, and bioenergy from FW via AD of five-case studied countries. The US has the highest investment in WP with a total of 125,000 million US$, corresponding to 21,630 million US$ in electricity benefit [24]. Followed by China, with 75,600 million US$, which annually provides up to 11,208 million US$ in selling electricity [29]. Germany is currently being the third largest wind farm in the world with a total of 64,798 million US$ [19]. The current electricity cost in Germany of one kWh electricity is about 0.371 US$, economic benefit from selling electricity will be around 19,800 million US$. Meanwhile, the total investment costs of WP in Australia and Japan are reported about 10,000 and 7610 million US$, respectively, which annually provide around 3240 and 1040 million US$ in electricity benefit, respectively.

In these countries, SP receives less investment than WP. Currently, the total investment on SP in Australia, US, Germany, China, and Japan are 3,600, 16,500, 17,200, 31,200, and 15,700 million US$, respectively [30]. China is the largest investment but Germany earns the biggest benefits from SP; total of 696 million US$ of annual benefit outcome from using SP in China in comparison with those of 11,020 million US$ in Germany. The reason could be explained by geographical effect and solar panel technology which differentiates Germany from other countries [19].

Using FW to generate electricity, in comparison with WP and SP, could give an optimal solution to handle impact categories by geography and season. In terms of investment, AD requires installation cost of about US$ 319 t^{-1} FW, and annual operation and maintenance costs of about US$ 23 t^{-1} FW [16]. Table 2 also provides the capital costs, operation and maintenance cost, and economic benefit of electricity generation of FW treatment via AD process. The results show that the abundant FW in five countries could supposedly generate an amount of electricity equivalent to the outcome economic benefits as: China, 6300 million US$ (with current electricity costs around 0.08 US$ kWh^{-1}); Japan, 3360 million US$ (0.27 US$ kWh^{-1}); the US, 3170 million US$ (0.129 US$ kWh^{-1}); Germany, 1840 million US$ (0.371 US$ kWh^{-1}); and Australia, 699 million US$ (0.27 US$ kWh^{-1}). Consequently, this illustrates that the payback period of total capital investment could be shortened between 2 and 10 yr. Meanwhile, those of WP and SP are 3–7 and 2–45 yr, respectively.

According to another analysis from REN21 (2014), the average capital costs of wind-offshore (US$ 4500–5500 kW^{-1}) power is the highest in comparison with SP (utility-scale: US$ 1200–1950 kW^{-1}), wind-onshore power (US$ 1500–1950 kW^{-1}) and typical bio-power from AD (landfill) (US$ 1900–2200 kW^{-1}) [19]. They also used the levelized cost of electricity (LCOE) to express the economic value comparison between different electricity generation sources. LCOE is often cited as “a convenient summary measure of the overall competitiveness of different generating technologies. It represents the per kWh cost (US$ kWh^{-1}) of building and operating a generating plant over an assumed financial life and duty cycle [31]. According to the US Energy Information Administration [23], the average LCOE were: wind-offshore US$ 204 MWh^{-1}, wind-onshore power US$ 80 MWh^{-1} and SP (utility-scale) US$ 130 MWh^{-1} [31]. Up to the present, the LCOE of FW treatment-based AD has not yet been documented due to its rare facilities, but it could be estimated based on real AD case studies. AD for organic waste treatment in landfill could be referred for LCOE of FW treatment-based AD, which is estimated to be around US$ 40–65 MWh^{-1}, while AD facilities for biogas have LCOE of about US$ 40–190 MW h^{-1} [19]. Fig. 1 presents the LCOE of these different renewable sources. Generally, LCOE of FW treatment-based AD is less expensive in comparison with WP and SP. Besides, the capacity factor and conversion efficiency of AD is higher than those of WP and SP (with 90% of FW treatment-based AD, in comparison with 25% of SP and 40% of WP) [19].

The cost-benefit analysis of WP, SP and FW treatment via AD is shown in Fig. 2. Economic benefits is defined as “benefit quantifiable in terms of money, such as revenue, net cash flow and net income” [24], while capital costs is “the one-time costs associated with a project, including the price of purchased assets, such as land, equipment, or other supplies, and the cost of going into debt or issuing stock in order to fund the project. Calculating alternate capital costs allow a business to decide which funding models will provide the best net return on investments” [32]. A comparison between capital costs and economic benefits with other renewable powers indicates that energy potential from FW via AD could bring lucrative revenues (economic benefits), as calculated, for Australia (US$ 247 million yr^{-1}), Germany (US$ 1837 million yr^{-1}), the US (US$ 3171 million yr^{-1}), Japan (US$ 3361 million yr^{-1}), and China (US$ 6302 million yr^{-1}) [28]. The results illustrated that Japan should consider to use FW treatment-based AD instead of SP mainly because of the same economic benefit with cheaper investment half of the total capital cost of SP investment. Especially, China should consider developing FW treatment-based AD to replace their current tremendous investments in SP, since the potential electricity generation from treating FW of China could generate 9 times more energy than SP while only doubling the capital costs [28].

Due to the limitations of SP in the winter time or the dependence of WP because of geography, bioenergy extracted from the FW via AD could be ideal for many countries to sustain their increasing energy demand. Some advantages and disadvantages

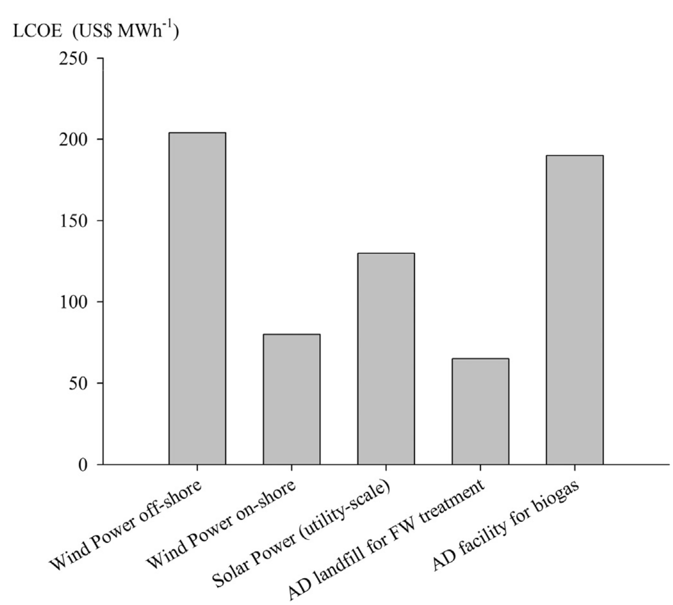

Fig. 1. Levelized cost of energy of different renewable sources [19].

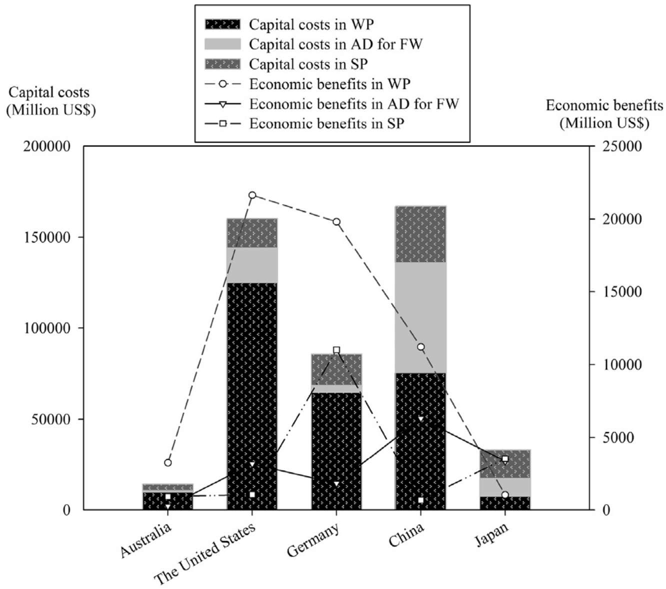

Fig. 2. Cost - benefit analysis of wind power (WP), solar power (SP) and bioenergy from food waste via anaerobic digestion.

between these renewable energy sources are identified and summarized in Table 3. FW treatment via AD offers the lowest investment costs (500 US$ kW^{-1}) and operation cost (0.1 US$ kWh^{-1}) [33], which is lower than those of WP (4500–5500 US$ kW^{-1}) and SP (1200–1950 US$ kW^{-1}) [19]. That is a suitable method to provide electricity for centralized cities and also has high conversion efficiency [19]. Capacity factor of power from AD technology is higher than that of WP and SP since its operation is independent in terms of local geography and seasons. Additionally, the co-digestion of FW with other organic feedstocks not only improves the maximum acceptable organic loading rates, but also enriches bio-energy yield in AD process [34].

3.4. *Prospects and future directions of FW conversion to bioenergy*

The above mentioned results illustrate that AD is a reliable way for bio-energy recovery from FW. For long-term development prospects, there are some issues that should be elucidated to motivate the commercial use of FW conversion to bioenergy [1]. Firstly, two-phase AD should be improved, and higher hydrogen and methane contents in the produced biogas will facilitate its co-use with natural gas. Furthermore, the biogas-based energy systems (natural gas grid and electricity grid) in some countries should be developed and broadly established to utilize bioenergy from FW. Secondly, an integrated collection grid of co-feedstocks, such as agricultural residues, cattle manure, slaughter waste, and sewage sludge, should be established to co-digest FW with other organic forms of feedstock to enhance quantity and quality of by-products. Lastly, the completed FW management system should be established by the governments to centralize FW for large scale AD plants. Currently, there are some countries in their new regulation to encourage people to collect their FW, such as Chinese government enacting regulation to require citizens to collect FW or not they will have to pay US$ 12 per tonne of disposal FW [35]. Taiwan has a similar regulation to enforce small restaurants, companies, schools and families to collect FW for recycling activities or being fired around US$ 150 per each law breaking case [1], and some countries as Australia, US, Canada, Japan, South Korea have banned landfilling FW, and set the way forward towards "zero waste", in which AD has been identified to be prior technology for treating and converting FW to biogas [28]. Generally, FW conversion to bioenergy is not only offering such a chance for future energy generation in comparison with other renewable energy sources, but also overcoming FW management for many countries. The critical results convinced that commercially treating FW via AD could provide an electricity amount of 220 kWh t^{-1} FW for one-phase AD and 404 kWh t^{-1} FW for two-phase AD. The potential electricity generation from the FW in China, Germany, Japan and US could feasibly provide 78.8, 5.0 (0.81% of total electricity generation), 12.9 (1.22% of total electricity generation), and 24.6 TWh yr^{-1} (0.57% of total electricity generation), respectively.

4. Conclusions

The electricity conversion potential of FW via one-phase and two-phase AD was reviewed to emphasize potential and economic value of FW-based bioenergy. The energy and economic benefits between WP, SP and FW via AD were compared. In comparison with WP and SP, the utilization of electricity generation from FW-based bioenergy could reduce the energy costs such as LCOE of food waste treatment in AD landfill (US$ 65 MWh^{-1}) and AD facilities (US$ 190 MWh^{-1}), which are lower than those of SW (US$ 130 MWh^{-1}) and WP off-shore (US$ 204 MWh^{-1}). This electricity evaluation from different renewable sources, presented here, reveals that the efforts to promote the FW-based bioenergy have not only achieved the best solution for tackling FW management issue but also help some countries reduce their electricity production costs.

Table 3
Advantages and disadvantages of three renewable sources.

Renewable sources	Advantage	Disadvantage
Bioenergy from FW treatment via AD	– Stable feedstock and could be co-digested with other organic feedstocks, such as sewage sludge, agricultural waste, cattle manure [34] – Independence from geography and season – Lowest investment costs (500 US$ kW^{-1}) and low operation cost (0.1 US$ kWh^{-1}) [33] – Suitable for centralized areas – High conversion efficiency and capacity factor	– Un-sorted FW could affect efficiency of operation process – Some countries have not yet connected bioenergy and biogas from AD facilities or landfills with national grid
Wind power	– Low operation costs – National grid had connected to wind energy for years	– Highest investment costs (4500–5500 US$ kW^{-1}) and maintenance costs (27 US$ kWh^{-1}) [19] – Output energy efficiencies depend on geography – Low conversion efficiency and capacity factor
Solar power	– Low operation and maintenance costs (0.2 US$ kWh^{-1}) [43] – Suitable for decentralized areas	– Production efficiencies depend on geography and season – Need large space in setting up utility-scale systems – High investment costs (1200–1950 US$ kW^{-1}) [19] – Low conversion efficiency and capacity factor

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