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Promoting the Circular Economy via Waste-to-Power (WTP) in Taiwan

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Abstract: The waste management sector significantly contributes to emissions of ambient air pollutants and greenhouse gases, especially in sanitary landfills. In this regard, Taiwan is moving toward a circular economy society via resource recycling and waste-to-power (WTP) in the waste management. In the past decade, the recycling rate of general waste (including recyclable waste, kitchen waste, and bulk waste) increased from 40.97% in 2008 to 60.22% in 2017. On the other hand, 24 large-scale waste incineration plants gained about 2.5 TW-h of net electricity generation, based on 6.25 million metric tons of waste incinerated in 2017. The objectives of this paper are to update the status of waste generation and its WTP in Taiwan. Based on these updated data, the preliminary benefit analysis of WTP showed annual benefits of equivalent electricity charge of around \$US 3.3×10^8 (using the feed-in-tariff rate 3.8945 NTD\$/kW-h; 1 \$US $\approx$ 30 NTD\$) and equivalent CO_2 mitigation of about 1.4 million metric tons (using the electricity emissions factor 0.55 kg CO_2 equivalent/kW-h). In order to gain environmental, energy, and economic benefits, the regulatory and technological measures for promoting WTP are briefly summarized to create another low-carbon society in Taiwan.

Keywords: municipal solid waste; waste-to-power; feed-in-tariff; benefit analysis; regulatory promotion

1. Introduction

Taiwan, a high population density (i.e., about 650 people per km^2) island with a tropical/subtropical climate, is located in East Asia. More importantly, it is a country with a lack of natural resources. For example, its dependence on imported energy ranged from 97% to 98% in the past two decades. In 2017, the primary energy supply in Taiwan amounted totally to 146.6 million kiloliters of oil equivalent (KLOEs), showing a slight decrease of 0.03% in 2016 [1]. The energy supply can be divided into two categories. One belongs to indigenous energy, which contributed 3.0 million KLOEs or 2.02%. Another is the imported energy, which occupied 97.98%, or 143.6 million KLOEs. By classifying them with energy forms, their contributions were given as follows [1]: Coal (30.17%), oil (48.45%), natural gas (15.15%), hydro power (0.36%), solar photovoltaic (PV) and wind power (0.22%), solar thermal heat (0.08%), biomass and waste-to-power (WTP) (1.15%), and nuclear power (4.43%). According to the definition of renewable energy, the share of renewable energy (including hydro power, solar photovoltaic and wind power, solar thermal heat, and WTP) was only 1.81%, based on the total energy supply (i.e., 146.6 million KLOEs). Over the past two decades (1997–2017), the Taiwan government adopted several regulatory, financial, and subsidiary measures to promote renewable energy development and also to mitigate greenhouse gas (GHG) emissions [2]. The renewable energy supply increased from 1.0 million KLOEs in 1997 to 3.0 million KLOEs in 2017, showing an average annual growth rate of around 5.5%.

Biomass has been considered as a carbon-neutral fuel because the carbon dioxide (CO_2) emitted when it is burned is equal to that absorbed during growing through the photosynthesis route. As mentioned above, the largest proportion of renewable energy in Taiwan is biomass energy, which refers to the energy generated by direct use or treatment of domestic general waste (i.e., municipal solid waste or MSW) and general industrial waste (i.e., industrial non-hazardous waste), according to the definition of the "Renewable Energy Development Act" passed in 2009 and recently revised in 2019. In Taiwan, the combustible proportions in the MSW and general industrial waste were almost all burned at special WTE plants that use the released heat to make steam for further generating electricity via the combined heat and power (CHP) or cogeneration system. More significantly, the benefits of a CHP system can be connected with the higher energy efficiency and lower air pollutants emissions, thus reducing the GHG and toxic air (i.e., SOx, NOx, and Hg) emissions as compared to the burning of fossil fuels (e.g., coal) in separate electricity and heat production plants [3,4].

Since 2010, the feed-in tariffs (FIT) have been announced by the Ministry of Economic Affairs (MOEA) to promote power generation from renewable resources in Taiwan, under the authorization of the Renewable Energy Development Act. As shown in Figure 1, the FIT rates of WTP indicated an upward trend. For instance, the FIT rates of WTP in 2010 and 2018 were 2.0615 and 3.8945 NTD$/kW-h ($US 1 ≈ 30 NTD$), respectively. In Taiwan, these WTP plants are currently dependent on the 24 large-scale MSW incinerators in operation. More importantly, these 24 incineration plants gained 3.13 TW-h of electricity generation based on 6.25 million metric tons of waste incinerated in 2017 [1]. Among this figure, 2500 GW-h was purchased by the Taiwan Power Company (one of the state-owned enterprises in Taiwan), which gained a percentage of power sold with 78.3% and a revenue of power sold of NT$4.33 billion [5]. In other words, these incineration plants in Taiwan not only provided the facilities for treating MSW and industrial general (non-hazardous) waste in a standards-meeting way, but also created added economic and environmental values.

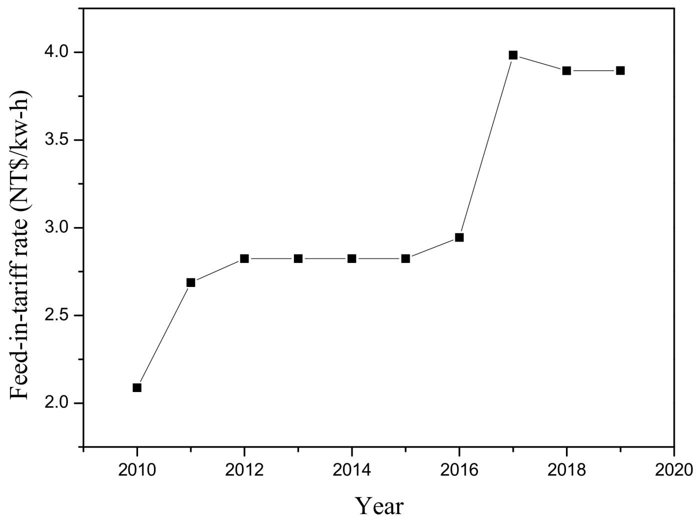

Figure 1. Feed-in-tariff rates of waste-to-power in Taiwan since 2010.

In recent years, the concept of a circular economy has become a prevailing way, which aims at reducing the negative impacts of the linear economy, building long-term resilience, generating business and economic opportunities, and also providing environmental and societal benefits by efficient energy use and renewable energy production [6–9]. Based on the concept, WTP can be said to be another option for turning waste into renewable energy in the modern circular economy society because this waste management can be used an indicator of the positive effect, with regard to one of GHG mitigation approaches [10–12]. More significantly, to date, there are scarcely case reports that address the benefit analysis of energy production, economic gain, and environmental sustainability from WTP in the literature [13]. Therefore, the objectives of this paper are to update the status of waste generation and WTP in Taiwan. Using the updated data on WTP and local default values, the preliminary analysis of WTP is addressed in the paper to verify its benefits of equivalent GHG reduction and economic values from electricity generation. Finally, the regulatory and technological measures for upgrading WTP are briefly summarized to create another circular economy in Taiwan.

2. Statistical Data and Methods

The main aim of this work was to analyze the benefits of carbon reduction and economic gain from WTE plants. According to the methodology developed by the Intergovernmental Panel on Climate Change (IPCC), the Tier 2 method was adopted in this work, which was based on the activities (national statistics) and country-specific emission factors. In order to update the status of WTP and further analyze its carbon reduction benefits in Taiwan, the statistical data and methods adopted by this work are briefly summarized below.

- Activities of Waste Management and Energy Sectors

The updated data on the statistics and status of waste management and energy sectors in Taiwan were obtained from the official statistical databanks [1,5], which were compiled by the Environmental Protection Administration (EPA) and the Ministry of Economic Affairs (MOEA).

- Preliminary Benefit Analysis of Waste-to-Power

In this work, the author analyzed the preliminary GHG mitigation benefits of WTP in Taiwan, which were based on the activity data and the GHG mitigation/emission factors. These carbon disclosure data were revealed by the IPCC [14] and the Taiwan Power Company (one of the state-owned companies).

- Regulatory and Technological Measures for Upgrading Waste-to-Energy

The information about the regulatory and technological measures of upgrading WTP was accessed on the official websites, including the EPA and the MOEA.

3. Results and Discussion

3.1. Status of Waste Management Sector in Taiwan

3.1.1. Statistics of Waste Generation and Treatment in Taiwan

General Waste

According to the definition by the Waste Management Act in Taiwan, waste is divided into general waste and industrial waste. The former includes bulk waste, recyclable waste, food (kitchen) waste, hazardous waste, and general garbage (i.e., general waste other than bulk waste, recyclable waste, kitchen waste, and hazardous waste). The latter can be grouped into industrial general (non-hazardous) waste and industrial hazardous waste, which are produced from industrial activities. Figure 2 shows the figures regarding the Taiwan's waste generation and its treatment patterns in 2016 [5]. Table 1 further lists the statistics of general waste generation by type over the past decade (2008–2017) [5]. By contrast, Table 2 summarizes the statistics of general waste treatment methods by percentage in the same period [5]. Based on the data in Tables 1 and 2, the important features are given below:

1. The recycling rate of general waste (including recyclable waste, kitchen waste, and bulk waste) increased from 40.97% in 2008 to 60.22% in 2017. The increase of the resource recycling rate indicated that the progress is approaching a zero-waste society because the Four-in-One Resource Recycling Program has been successful since 1997 [15].
2. The average amount of MSW generated showed a V-type trend during the years of 2010–2017. This variation should be correlated with economic growth. For instance, the economic growth during 2015–2017 indicated an increased trend from 0.8% in 2015 to 2.8% in 2017, coupled with increased MSW. More significantly, the total amount of MSW incinerated presented a decreasing trend in the past decade because more MSW was recycled. On average, MSW generated per capita per day in Taiwan was about 0.9 kg/capita-day.

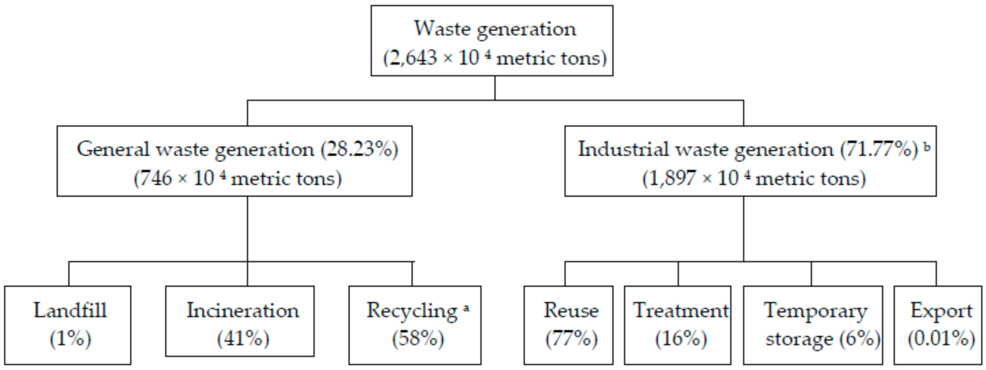

Figure 2. Statistics of Taiwan's waste generation and its treatment patterns in 2016. [a] Including recyclable waste, food waste, and part of bulk waste. [b] Including manufacturing sector (87.93%), construction sector (8.68%), agriculture sector (0.86%), medical sector (0.54%), transportation sector (0.22%), education sector (0.03%), defense sector (0.01%), and other sectors (1.73%).

Table 1. Statistics of general waste generation by type over the past decade in Taiwan [a].

Year	Total (Metric tons)	Amount Generated Per Capita Per Day (kg/capita-day)	Type of General Waste (Metric Tons)			
			Garbage	Bulk Waste	Recyclable Waste	Food Waste
2008	7,537,374	0.896	4,255.396	163,224	2,427,526	691,194
2009	7,746,019	0.920	4,141,167	147,790	2,735,591	721,472
2010	7,957,601	0.942	3,993,155	159,665	3,035,617	769,164
2011	7,554,589	0.892	3,550,342	140,832	3,052,215	811,199
2012	7,403,948	0.869	3,332,125	136,248	3,101,035	834,541
2013	7,332,694	0.861	3,253,304	130,770	3,153,406	795,213
2014	7,369,439	0.863	3,218,030	120,476	3,310,560	720,373
2015	7,229,290	0.844	3,153,771	146,196	3,319,617	609,706
2016	7,461,342	0.867	3,045,299	149,201	3,690,910	575,932
2017	7,870,896	0.915	3,044,948	141,519	4,133,098	551,332

[a] Source [5].

Table 2. Statistics of general waste generation by percentage over the past decade in Taiwan [a].

Year	Treatment Method by Percentage (%)		
	Recycling [b]	Incineration	Sanitary Landfill
2008	41.97	54.90	3.13
2009	45.48	52.13	2.40
2010	48.82	48.90	2.28
2011	52.20	45.91	1.88
2012	54.36	44.26	1.38
2013	54.99	43.76	1.25
2014	55.59	43.28	1.13
2015	55.23	43.50	1.27
2016	58.00	40.95	1.04
2017	60.22	38.93	0.89

[a] Source [5], [b] It includes the recycling of bulk waste, recyclable waste and food waste.

Industrial Waste

With the rapid economic growth in the past decades, industrial waste has resulted in serious environmental threats due to its complexity and toxicity. In 2000, the EPA formulated the "National Industrial Waste Management Program" and established the "Industrial Waste Control Center", as well as a reporting and tracking system that controlled the complete life-cycle of industrial wastes from cradle (generation) to grave (final disposal). Subsequently, the central competent authorities (e.g., MOEA) were required to announce the reuse categories and management methods of industrial waste under the authorization of Article 39 of the Act. According to the definition of the Act, the "reuse" refers to the use of industrial waste as raw material, materials, fuel, land reclamation fill, or other acts of use recognized by the central competent authority via self-use, sale, transfer, or commissioning, and in compliance with the relevant regulations. Currently, the main categories of combustible waste in the industrial sector of Taiwan, which have been blanketed into the lists of industrial waste reuse, included pulp sludge, scrap wood, sugarcane bagasse, textile sludge, spent lubricating oil, spent solvent, and scrap rubber. These industrial wastes were reused as auxiliary fuels in the utilities (e.g., boiler, rotary kiln, heater, and incinerator). On the other hand, the EPA also conducted industrial waste reuse and recycling assessments to raise the percentage of recyclable wastes through the promotions of cradle-to-cradle, product carbon footprint, and corporate carbon emission disclosure. Therefore, the reuse and recycling rate of industrial waste reached 77% in 2016, based on the total generation amount of around 19.0 million metric tons in Taiwan (Figure 2). In order to achieve the goal of zero industrial waste, its reuse, by recycling organic wastes for renewable resources (e.g., fertilizer, cultivation media, and energy) and turning inorganic wastes into public construction materials, can be increased to 85% in 2020. Complying with the goal, its generation amount can be additionally reduced by 10% in 2020, as expected by the EPA.

3.1.2. Status of Waste-to-Power in Taiwan

The energy recovery from MSW and agricultural and industrial wastes has received much attention since the 1990s. This energy use was mainly motivated by the advances in CHP technologies, soaring oil prices, the urban waste management crisis, and global warming issues [16–18]. Currently, the MSW generation in Taiwan was about 7.5 million metric tons, which was treated by recycling and incineration at around 60% and 40% respectively. As mentioned above, the Four-in-One Resource Recycling Plan was successfully implemented over the past two decades (1998–2017), resulting in a decreasing trend in the incinerated amount of MSW (Table 2). In order to meet the total design capacity of 24 large scale incineration plants (i.e., 24,650 metric tons/day) with a total installed capacity of 622.5 MW, these WTP facilities were permitted to treat industrial general waste with MSW under the EPA, jointly coordinated with local governments since the early 2000. Based on the national statistics surveyed by the EPA [5], Table 3 lists the facts about the operation of these 24 WTP plants in the past decade, giving the following notable features:

1. The electricity production efficiencies, in terms of power generation per ton of incinerated MSW, indicated an upward trend, having the average 502 kW-h/ton in the last 5 years (2013–2017) compared to 483 kW-h/ton for another five years (2008–2012). The increase was likely due to the efforts in upgrading the energy recovery system (e.g., the decrease in excess air supplied and pipe renewal in the economizer and boiler) in recent years.
2. The amount of industrial general waste received by MSW incineration plants indicated a stable trend in recent years (2011–2016), with an average of 2.25 million metric tons per year. A special case appeared in 2017, which could be associated with the abrupt increase in MSW due to more natural disasters (e.g., earthquake, typhoon) in the current year.

Table 3. Operation performances of large-scale incineration plants over the past decade in Taiwan [a].

Year	Amount of Waste Received (ton/year)			Amount of Waste Incinerated [b] (ton/year)	Amount of Power Generated (10^3 kW-h)	Percentage of Power Sold (10^3 kW-h)	Income of Power Sold (10^3 NT$) [c]	Performance of Power Generated	
	Total	General Waste	Industrial General Waste					kW-h/ton [d]	kW-h/h [e]
2017	6,251,196	5,088,471	1,162,725	6,266,855	3,187,516	78.32%	4,333,656	508.6	7,059
2016	6,441,999	4,271,179	2,170,820	6,392,159	3,245,229	78.21%	4,623,852	507.7	7,164
2015	6,622,071	4,329,863	2,292,208	6,534,388	3,217,212	78.14%	5,385,105	492.4	7,017
2014	6,420,400	4,192,142	2,228,258	6,294,479	3,187,484	77.84%	5,269,972	506.4	7,141
2013	6,471,766	4,214,871	2,256,895	6,349,913	3,131,460	77.05%	5,055,048	493.2	7,045
2012	6,506,906	4,204,289	2,302,617	6,404,987	3,056,476	76.79%	4,550,039	477.2	6,865
2011	6,507,763	4,234,971	2,272,792	6,355,422	3,076,345	76.87%	4,510,608	484.1	6,944
2010	6,406,781	4,441,197	1,965,584	6,235,390	3,026,003	76.82%	4,311,719	485.3	6,940
2009	6,286,601	4,559,218	1,727,383	6,092,929	2,924,934	76.13%	4,053,509	480.1	6,816
2008	6,184,083	4,535,133	1,648,950	6,110,838	2,967,218	76.54%	3,437,853	485.6	7,070

[a] Source [5], [b] Based on 24 large-scale incineration plants with total design capacity of 24,650 tons/day, [c] Currency exchange rate: 1US$ ≈ 30 NT$, [d] Based on total amount of waste incinerated, [e] Based on total time of boiler operated.

3.2. Preliminary Benefit Analysis of Waste-to-Power in Taiwan

In Taiwan, the WTP has been identified as a valuable energy source because it supplies about 1.3% of total electricity demand. In this work, a simple method (Tier 2 method) was used to estimate the equivalent CO_2 emissions mitigation from the WTP systems for electricity generation [14], which was based on the net quantities of electricity generated and the average default emission factor (DEF). Using the data on the amount of power sold in 2017 (i.e., 2.5×10^9 kW-h), the FIT rate $US 0.13 per kW-h (Figure 1), and the average default value 0.55 kg CO_2/kW-h (Note: This value, announced by the MOEA, is for the average Taiwan electricity production, from mixing all energy sources.), the equivalent electricity charge, and equivalent mitigation of CO_2 (Gg) from the WTP systems for electricity generation were thus estimated, as given below:

- Equivalent electricity charge: 2.5×10^9 kW-h × $US 0.13 kW-h^{-1} ≈ $US 3.3×10^8.
- Equivalent CO_2 mitigation: 2.5×10^9 kW-h × 0.55 kg CO_2·kW-h^{-1} × 10^{-6} Gg·kg^{-1} ≈ 1.4×10^3 Gg CO_2.

3.3. Regulatory and Technological Measures for Upgrading Waste-to-Energy in Taiwan

3.3.1. Upgrading of Recovery of Waste Heat from Large-scale Incinerators

As mentioned above, there are 24 large-scale MSW incineration plants under commercial operation in Taiwan, which annually treat a total of over 6.0 million metric tons of general waste and industrial general (non-hazardous) waste. In addition, these WTP plants produced about 3200 GW-h of electricity, of which 2500 GW-h or 78.3% was sold to the Taiwan Power Company (one of the state-owned enterprises in Taiwan) in 2017. However, the energy efficiencies of MSW incineration plants, on average, were only about 16.2% in recent years (2008–2012) [19]. As a consequence, the EPA is currently executing a demonstration plan, aiming at a 30% increase in the overall energy efficiency, which combines the district heating and cooling (DHC) system with waste heat from all MSW incineration plants. In the DHC system [20], a heat source (hot water) from a MSW incineration plant is used to supply heat to nearby homes and enterprises (heat users) via district water pipes, which are very well insulated to avoid heat loss during pipeline transportation. By contrast, the district cooling systems can use waste heat from combined heat and power (CHP) units or excess heat from MSW incineration plants to run absorption refrigerators for cooling during the summer time, greatly reducing electricity usage. On the other hand, the energy efficiencies of MSW incineration plants were also enhanced by upgrading the operation stability (e.g., automatic combustion control by fuzzy logic) and increasing the power generation performance (e.g., reducing excess air supply to reasonable level, about 1.4).

3.3.2. Energy Use of Waste Cooking Oils and Other Biodegradable or Combustible Recyclables

In recent years, there has been much concern in Taiwan about how to dispose of waste cooking (edible) oil. Currently, the annual amount of waste cooking oil recycled is about 25, 000 metric tons. Thus, the EPA has decided to list waste cooking oil as one of "general waste items that should be recycled" (i.e., mandatory recyclables) in 2014. This used oil can be transformed into a variety of products, including biodiesel, soaps, and stearic acids. For example, waste cooking oil has been reused for biodiesel (fatty acid methyl ester) production in Taiwan, which has been demonstrated, in the garbage cars and public buses, to mitigate the GHG emissions and improve the urban air quality [21]. On 3 November 2017, the EPA further announced the reuse types (e.g., renewable biomass energy like WTP and biogas-to-power) of four general wastes, which include kitchen waste, night soil, waste lubricating oil, and waste cooking oil [22].

3.3.3. Build-up of Bioenergy Plants Using Food Waste

Expectedly starting its commercial operation by August 2018, Taiwan's first food waste-to-bioenergy plant held a groundbreaking ceremony on 24 October 2017. By using the concepts of circular economy, the plant will utilize biogas produced from food waste (or kitchen waste) via the anaerobic digestion (AD) process to generate electricity [23]. In addition, the system also produces plenty of solid digestate, which can be reused as an organic fertilizer [24]. The central ministry (EPA) was planning to subsidize local governments to build three food waste-to-power plants, with a total investment of NT$1.8 billion (about $US 60 million), in the next five years. According to the projection by the EPA, annual food waste processing can be increased to 180,000 metric tons, accompanying the electricity generation of 32.92 million kW-h. More significantly, the three plants will generate benefits as follows: A total revenue of more than NT$131.92 million from selling electricity and CO_2 emission reduction by 17,400 metric tons.

3.3.4. Promotion of Biogas-to-Power in the Livestock Industry

Anaerobic digestion (AD) is a demonstrated valorization technology for converting organic components into a methane-rich biogas [23,25], which is first treated by a hydrogen sulfide (H_2S) removal system when reusing it as a gaseous fuel, for the generation of electric power and heat. In Taiwan, the central ministries, including the MOEA, the EPA, and the Council of Agriculture (COA), have given a financial support to large-scale pig farms to establish the biogas-to power system. For example, the MOEA announced the "Directions for Subsidizing of the Promotion of Biogas Generation Program" since 2013, which has further cooperated with local governments on subsidizing the fee for the biogas-to-power system, up to 50% of the total installation fee and/or NT$45,000 per kW-h. This biogas-to-power system installation fee includes the expenditures for the biogas purification system, the power generator, and related engineering items (e.g., pipework and foundation). On the other hand, the FIT rate of biogas-to-power adopting the AD processes in 2018 was as high as 5.0161 NTD $/kW-h ($US 1 ≈ 30 NTD$) [26].

3.3.5. Promotion of Biomass (Lignocellulosic) Waste Reuse in the Industrial Utilities

The reuse of energy from lignocellulosic waste as an available biomass energy in boilers has also received much attention in recent years, because biomass is a CO_2-neutral energy source [27]. This transition was mainly driven by the advances in WTP technologies and the global warming issue. Under the authorization and promotion of the relevant regulations in Taiwan, biomass residues, such as woody and agricultural by-products (e.g., sugarcane bagasse), are increasingly being reused as auxiliary solid fuels in industrial utilities (e.g., boilers, heaters, and furnaces) for the purpose of steam production. However, there are concerns about the levels of particulate matters in the flue gas and the contents of toxic components (e.g., arsenic, chromium, copper, lead) present in the bottom ash during the combustion of woody waste and wood-derived products because they may be impregnated with lead-containing paints, chromated copper arsenate (CCA), and copper-based preservatives [28,29].

4. Conclusions and Prospects

The concept of a circular economy is a new business model which is aimed at increasing resource efficiency and reducing environmental impact, at all scales and every stage of the product and its service lifecycle. In Taiwan, the dependence on imported energy was over 95%. In 2017, indigenous energy supply only contributed about 2%, which was mostly from the WTP. Currently, the majority of WTP facilities are 24 large-scale MSW incineration plants, which annually treat a total of over 6.0 million metric tons of general waste and industrial general (non-hazardous) waste, producing about 3200 GW-h of electricity. Based on the data on the amount of power sold in 2017 (i.e., 2.5×10^9 kW-h), the FIT rate of $US 0.13 per kW-h and the average default value 0.55 kg CO_2/kW-h, the annual benefits of equivalent electricity charge are around $US 3.3×10^8 and an equivalent CO_2 mitigation of about 1.4 million metric tons. Under the frameworks of the Energy Management Law and the Renewable Energy Development Act, some regulatory and technological measures for upgrading the energy efficiencies of WTP facilities are in progress. These include waste heat recovery from MSW incineration plants by the district heating and cooling (DHC) system, energy reuse of waste cooking oils and other biodegradable or combustible recyclables as biogas (or bio-to-power) by anaerobic digestion (AD), or auxiliary solid fuels by the co-firing processes in industrial utilities (e.g., boilers, heaters, and furnaces). In order to establish a low-carbon, sustainable, stable, high-quality, and economically efficient energy system, the Taiwan government has launched the share of renewable energy in total electricity generation to 20% by 2025. Regarding the biomass energy development, the goals, in terms of installed capacity (or electricity generation), are aimed at increasing from 727 MW (or 3.5 TW-h) in 2016 to 813 MW (or 5.9 TW-h) in 2025. Expectably, the WTP system will be a win-win option for the waste management sector to gain the benefits for the environment, energy, and the economy, gradually achieving the goals of total resource recycling and zero-waste disposal.

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