energies

Editorial

Waste-to-Energy: A Midas Touch for Turning Waste into Energy

Long Zhang [1], Wuliyasu Bai [2] and Jingzheng Ren [3,*]

[1] School of Business, Xinyang Normal University, Xinyang 464000, China
[2] School of Economics and Management, China University of Geosciences, Wuhan 430078, China
[3] Department of Industrial and Systems, The Hong Kong Polytechnic University, Hong Kong, China
* Correspondence: jingzheng.jz.ren@polyu.edu.hk

Presently, the rapid urbanization and industrialization have generated a great amount of waste around the world, which has led to increasing environmental pollution and greenhouse gas (GHG) emissions. With the prevalence of Sustainable Development Goals (SDGs), proper waste management and treatment have attracted the attention of scholars, experts, and decision makers. The world has generated more than 2 billion tonnes of municipal solid waste (MSW) annually, and this number is expected to reach 3.4 by 2050 [1]. At the country level, United States has generated the most MSW of 258 million tonnes in 2017, followed by China and India with a MSW generation of 220 and 168 million tonnes, respectively, and they will still be the top three MSW generators by 2050 with 543 million tonnes generated by India, 360 million tonnes by United States, and 336 million tonnes by China [1]. At the average level, about 0.74 kg per capita of MSW is generated every day around the world. However, this number varies greatly among different countries within the range of 0.11 to 4.54 kg per capita per day due to the great divergence in income levels and urbanization rates [1]. According to the data from Statista, the daily MSW generation per capita in United States was 2.58 kg in 2018, leading global daily MSW generation per capita, whereas only 1.02 and 0.34 kg per capita of MSW have been generated every day in China and India, respectively, far less than that of the United States. However, the total quantity of waste generated in low-income countries is expected to grow by more than three times by 2050 [1].

To achieve SDGs, reducing pollutant emissions and improving waste treatment efficiency are required. However, due to the insufficiency of efficient waste management capacities, open dumping of MSW is the most prevalent practice in most developing countries and underdeveloped areas. Traditionally, the popular ways for waste treatment include landfilling and incineration [2]. A regular and perfect landfilling system usually consists of bottom liner, topsoil cover, gas and leachate collection and treatment systems, and works based on a series of biological processes where organic matter is digested and decomposed into biogas by micro-organisms in the absence of oxygen. Landfilling is the most preferred MSW disposal method in developed countries [3]. However, most landfilling sites in developing countries do not have complete sanitary facilities, and most wastes are directly dumped and buried, which leads to the emission of GHGs contributing to global warming, leachate containing organic matters, and toxic heavy metals that pollute the soil, surface, and groundwater, as well as various hazardous materials that can generate negative effects on the environment and human health [3]. Even with a complete landfilling system to control the emissions of harmful gases and pollutants, the landfilling system still lacks the capacity of completely eliminating the threat to the environment. Incineration has been widely used for MSW disposal due to its benefits in the reduction in massive waste and even energy recovery [2]. Compared with landfilling, incineration has the advantages of low cost, reduction in waste volume, avoids occupying a large amount of land, and even generating heat and electricity [2]. Therefore, it has been widely adopted for MSW disposal in many developing countries and even in some highly dense, developed countries. In addition, the incinerated ashes from MSW incineration can be used to replenish soil

Citation: Zhang, L.; Bai, W.; Ren, J. Waste-to-Energy: A Midas Touch for Turning Waste into Energy. *Energies* **2023**, *16*, 2238. https://doi.org/10.3390/en16052238

Received: 19 September 2022
Accepted: 28 September 2022
Published: 25 February 2023

fertility; the pathogens and perishable organics that generate harmful gases contained in MSW are completely eliminated under high temperature conditions during the process of incineration. However, the ash generated from MSW incineration contains a lot of toxic heavy metal materials and substances, which can be released to the atmosphere, and further leads to environment pollutions [4].

Therefore, it is important to find innovative MSW treatment and management countermeasures and technologies to reduce pollution and even turn waste into value-added products. Waste-to-energy (WTE) treatment is an effective way to improve waste management efficiency and achieve waste valorization by optimizing energy, material, and capital from lifecycle perspectives. By adopting WTE recycling processes including pyrolysis, liquefaction, gasification, and anaerobic digestion, various green energy products can be produced from MSW, such as bio-oil, producer gas, synthesis gas, methane, hydrogen, and biochar [5,6]. As such, recovering energy from various wastes can greatly improve overall energy efficiency, and reduce GHG emissions and the final wastes to landfills.

To implement WTE, the Bio-Circular-Green (BCG) economy model has been introduced, and it aimed at turning various resources and waste steams into value-added products, such as food, feed, bio-based products, and bioenergy [7], which is in line with the UN SDGs. By stressing the development of bioeconomy, circular economy, and green economy at the same time, the BCG model can drive sustainable development [7].

Presently, various emerging technologies are available for implementing WTE, including biological treatment technologies, thermal treatment technologies, and biorefineries.

Biological treatment technologies can digest and composite the MSW with or without the presence of oxygen, which generates two different biological processes: aerobic digestion (in the presence of oxygen) and anaerobic digestion (in the absence of oxygen) [8]. The aerobic process can composite the biodegradable waste in MSW into heat, water, and CO_2 and other inorganic substance; whereas, the anaerobic process produces a mixture of gases, mainly methane and carbon dioxide, which is also known as biogas [8]. In fact, with a complete energy recovery system, landfilling gas, or biogas generated in landfilling sites, can also be recovered for WTE [9].

Thermal treatment technologies that have been widely adopted in WTE include incineration, gasification, and pyrolysis [10]. The incineration process can dispose MSW with high efficiency by using an incinerator that works at an adequate temperature [11]. By connecting with a cogeneration system, the superheated steam produced in the incineration process can be used to produce electricity and heat [11,12]. However, a main concern about this process is about the emission of GHGs and heavy metals. The gasification process can transform the organic compounds in MSW into value-added by-products, mainly syngas, also including some liquid fuels and chemical feedstock, under specific conditions of temperature, moisture, and oxygen. Biogas can be further used for energy production [13,14]. Pyrolysis is the process of thermal decomposition of organic materials in the absence of oxygen, which requires separation of glass, metals, and inert materials from the MSW [15]. The final by-products of pyrolysis include syngas, bio-oil, and solid residuals, which can be further utilized in bioenergy production [8]. In addition, some other thermal treatment processes, such as torrefaction and plasma technology, can also be used for WTE [13].

Just like a traditional refinery producing multiple fuels and products from fossil fuels, the waste refinery, or biorefinery, is a system that integrated the conversion of biomass from MSW into biofuels, power, heat, bio-fertilizers, and other value-added chemicals [8]. With such a biorefinery system, the produced liquid and gaseous biofuels can be used for generating heat, electricity, and transport fuels. The organic residuals can even be used for producing biogas, and the inorganic fraction can be used to produce solid recovered fuel for syngas production [16].

Apparently, there is an urgent need for efficient MSW management and the implementation of WTE to treat the increasing MSW generation and reduce GHG emissions around the world. The academia has also made intensive investigations on the application of different WTE technologies in disposing various waste and compared their efficiency and sustainability performance. However, some research gaps still need to be filled: (i) the geographical, temporal, and technological scope has been ignored in the selection of WTE technologies and facility sites; (ii) the chemical composition and lower heating value of the waste should be considered, as they can make a great difference in determining the life cycle sustainability performance of WTE projects; (iii) the uncertain aspects of the WTE projects need to be discussed and properly addressed; (iv) a lot of studies have failed to consider the environmental impacts from capital goods, which should be specified in the assessment of WTE technologies; (v) the environmental impacts should not only associate with the GHG emissions, and the toxic emissions and resource depletion should also be taken into consideration.

The critical issues that need to be addressed in waste management are reducing waste and improving energy recovery efficiency, which calls for WTE technologies selection, system optimization, energy recovery, and energy substitution integration. In addition, the energy recovery and GHGs emissions reduction performance should also be assessed. Thus, we launched this Special Issue aiming to: (i) investigate advanced technologies implementation, systemic solutions, and data-driven optimization of the waste management and energy problems encountered in cities; (ii) identify the post-pandemic opportunities and roles for WTE systems, such as sustainable consumption, business models, and social impacts; (iii) promote eco-industrial development, waste recycling, landfill, and final disposal reduction, achieving the zero-waste city target from a circular economy perspective; (iv) assess advanced waste management systems from a life cycle perspective, including technology assessment, environmental impact evaluation, social benefits analysis, etc.

By launching this Special Issue, we have several academic articles submitted and published, which has great significance for achieving WTE and a low carbon city.

Industrial waste has been massively generated in industrial production, and most of them are harmful to environment. Wastewaters generated in crude oil extraction contain organic compounds and high salinity. Although these wastewaters are usually reinjected into the extraction well with suitable treatment, they are still a great threat to environmental safety. By adopting an advanced WTE technology, reverse electrodialysis, green electricity can be generated from these wastewaters [17]. Site selection for deploying waste-treatment facilities has always been a critical problem in the practice of waste management. For instance, the highly alkaline and fine particle size of red mud emitted from the alumina industry can bring increased risk of dam failure. So, the proper treatment and alternative utilization of red mud are necessary. With the application of PROMETHEE, Hendrik et al. (2022) addressed the suitable location of optimal red mud pilot plant sites by considering various criteria and alternatives [18]. Agricultural waste is also a good alternative feedstock for implementing WTE with slow pyrolysis process. However, different by-product distribution can be achieved under different temperature conditions, and the carob waste has been proved to be a suitable feedstock for biochar production rather than energy recovery [19].

In order to achieve SDGs, the concepts of a low carbon city and zero waste community have been proposed and practiced. In fact, great potential for the GHGs inventory is contained at the community level, which is an important part in building zero-waste cities and improving waste-management efficiency. By taking the Honjo Waseda community in Japan as an example, first-hand field data on energy consumption and waste treatment sectors at the community level are calculated, and the highest GHG emitters of the waste sector are identified [20]. Moreover, three technological WTE scenarios are provided for the comparison of GHG emission reduction performance toward a zero-waste community, and the WTE system that integrates solid recovered fuel and bio-gasification has shown the highest energy recovery performance, and this system can achieve better GHG emission reduction performance as a heat supply than for electricity generation [20]. The environmental problems, including GHG emissions and atmosphere pollution, are mainly induced by excessive urban energy consumption, and the corresponding measures are usually taken from the aspects of energy saving, demand optimization, and environment protection. However, the synergistic effects of these measures are critical for achieving sustainable urban development. By Taking Guangzhou City of China as an example, Xie et al., (2022) investigated the synergic effect of different categories of measures, and found that measures of energy saving and demand optimization have the best synergistic effect on energy saving and emission reduction, measures of demand-optimization and energy-saving have the best synergistic effect on cost saving and CO_2 emission reduction, and the environmental-protection measures have remarkable synergistic effects in reducing the cost of health loss and labor loss [21].

To achieve WTEs and build zero-waste cities, both technological development and application, financial incentives, and policy regulations are required.

Technologically, carbon-neutral processes and zero-waste technologies can play an important role. Since GHG emissions are mainly caused by fossil energy consumption, various renewable energy technologies can have great potential in achieving energy substitution and reduction in waste emissions, especially that energy storage technologies can reduce the volatility and mismatch between energy supply and demand. Carbon sink technologies are also important means for achieving carbon neutralization. For instance, the solid residual byproduct of thermal treatment technologies for WTE is biochar, which is an important form of carbon sink. The CO_2 capture, utilization, and storage (CCUS) technologies are a necessity for GHG emission reduction, and this technology can be combined with the WTE technologies to better deal with the issues in waste treatment, energy recovery, and GHG emissions. To improve the efficiency of WTE and GHG emissions, different carbon-neutral processes and WTE technologies can be integrated and combined to achieve zero-waste cities and society.

Although various carbon-neutral processes and zero-waste technologies are available for implementing WTE and circular economy, government policies and regulations, as well as financial incentives, are still needed for the deployment of WTE facilities and the establishment and operation of supply chain networks, especially in developing countries. As such, a complete policy and regulation framework needs to be established to guide the planning, construction, and operation of the WTE projects. Since financial difficulty and technology privatization are the main obstacles for WTE application in developing countries, an international cooperation framework should be established to facilitate the financial investment and technology transfer from developed countries to developing ones, which needs to be discussed and established.

WTE is the ideal solution for achieving low carbon development and zero-waste cities, but great challenges are also there to address. Only if we cooperate regionally, nationally, and globally, is there the chance to achieve the global scale of GHG emission reduction, and the improvement in quality of life and environment health.

Author Contributions: Conceptualization, J.R.; writing—original draft preparation, L.Z., W.B. and J.R.; writing—review and editing, L.Z., W.B. and J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Philosophy and Social Science Planning Program in Henan Province, China (2020CJJ094), the Key R&D and Promotion Project (Soft Science Research) in Henan Province, China (222400410122), the Nanhu Scholars Program for Young Scholars of XYNU, China, and the grant from Research Institute for Advanced Manufacturing (RIAM), The Hong Kong Polytechnic University (PolyU) (Project No. 1-CD4J, Project ID: P0041367).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kaza, S.; Yao, L.C.; Bhada-Tata, P.; Van Woerden, F. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development*; World Bank: Washington, DC, USA, 2018. Available online: https://openknowledge.worldbank.org/handle/10986/30317 (accessed on 7 September 2022).
2. Di Giacomo, G.; Romano, P. Evolution and Prospects in Managing Sewage Sludge Resulting from Municipal Wastewater Purification. *Energies* **2022**, *15*, 5633. [CrossRef]
3. Guo, H.; Xu, H.; Liu, J.; Nie, X.; Li, X.; Shu, T.; Bai, B.; Ma, X.; Yao, Y. Greenhouse Gas Emissions in the Process of Landfill Disposal in China. *Energies* **2022**, *15*, 6711. [CrossRef]
4. Bogacka, M.; Poranek, N.; Łaźniewska-Piekarczyk, B.; Pikoń, K. Removal of Pollutants from Secondary Waste from an Incineration Plant: The Review of Methods. *Energies* **2020**, *13*, 6322. [CrossRef]
5. Frantzi, D.; Zabaniotou, A. Waste-Based Intermediate Bioenergy Carriers: Syngas Production via Coupling Slow Pyrolysis with Gasification under a Circular Economy Model. *Energies* **2021**, *14*, 7366. [CrossRef]
6. Mata-Lima, H.; Silva, D.W.; Nardi, D.C.; Klering, S.A.; de Oliveira, T.C.F.; Morgado-Dias, F. Waste-to-Energy: An Opportunity to Increase Renewable Energy Share and Reduce Ecological Footprint in Small Island Developing States (SIDS). *Energies* **2021**, *14*, 7586. [CrossRef]
7. Usapein, P.; Tuntiwiwattanapun, N.; Polburee, P.; Veerakul, P.; Seekao, C.; Chavalparit, O. Transition Pathway Palm Oil Research Framework Toward a Bio-Circular-Green Economy Model Using SWOT Analysis: A Case Study of Thailand. *Front. Environ. Sci.* **2022**, *10*, 877329. [CrossRef]
8. Zaccariello, L.; Mastellone, M.L.; D'Amelia, L.I.; Catauro, M.; Morrone, B. Assessment of Integration between Lactic Acid, Biogas and Hydrochar Production in OFMSW Plants. *Energies* **2020**, *13*, 6593. [CrossRef]
9. Gaze, B.; Knutel, B.; Zając, K.; Jajczyk, M.; Bukowski, P. Comparison of Selected Technologies to Improve the Quality of Exhaust Gases from Landfill Gas Combustion. *Energies* **2022**, *15*, 778. [CrossRef]
10. Eriksson, O. Energy and Waste Management. *Energies* **2017**, *10*, 1072. [CrossRef]
11. Pavlas, M.; Dvořáček, J.; Pitschke, T.; Peche, R. Biowaste Treatment and Waste-To-Energy—Environmental Benefits. *Energies* **2020**, *13*, 1994. [CrossRef]
12. Eriksson, O.; Finnveden, G. Energy Recovery from Waste Incineration—The Importance of Technology Data and System Boundaries on CO2 Emissions. *Energies* **2017**, *10*, 539. [CrossRef]
13. Rasheed, T.; Anwar, M.T.; Ahmad, N.; Sher, F.; Khan, S.U.D.; Ahmad, A.; Khan, R.; Wazeer, I. Valorisation and emerging perspective of biomass based waste-to-energy technologies and their socio-environmental impact: A review. *J. Environ. Manag.* **2021**, *287*, 112257. [CrossRef] [PubMed]
14. Pavičić, J.; Novak Mavar, K.; Brkić, V.; Simon, K. Biogas and Biomethane Production and Usage: Technology Development, Advantages and Challenges in Europe. *Energies* **2022**, *15*, 2940. [CrossRef]
15. Qureshi, M.S.; Oasmaa, A.; Pihkola, H.; Deviatkin, I.; Tenhunen, A.; Mannila, J.; Minkkinen, H.; Pohjakallio, M.; Laine-Ylijoki, J. Pyrolysis of plastic waste: Opportunities and challenges. *J. Anal. Appl. Pyrolysis* **2020**, *152*, 104804. [CrossRef]
16. Aracil, C.; Haro, P.; Giuntoli, J.; Ollero, P. Proving the climate benefit in the production of biofuels from municipal solid waste refuse in Europe. *J. Clean. Prod.* **2017**, *142*, 2887–2900. [CrossRef]
17. Cosenza, A.; Campisi, G.; Giacalone, F.; Randazzo, S.; Cipollina, A.; Tamburini, A.; Micale, G. Power Production from Produced Waters via Reverse Electrodialysis: A Preliminary Assessment. *Energies* **2022**, *15*, 4177. [CrossRef]
18. Hendrik; Yuan, Y.; Fauzi, A.; Widiatmaka; Suryaningtyas, D.T.; Firdiyono, F.; Yao, Y. Determination of the Red Mud Industrial Cluster Sites in Indonesia Based on Sustainability Aspect and Waste Management Analysis through PROMETHEE. *Energies* **2022**, *15*, 5435. [CrossRef]
19. Maniscalco, M.; Infurna, G.; Caputo, G.; Botta, L.; Dintcheva, N.T. Slow Pyrolysis as a Method for Biochar Production from Carob Waste: Process Investigation and Products' Characterization. *Energies* **2021**, *14*, 8457. [CrossRef]
20. Zhao, R.; Sun, L.; Zou, X.; Dou, Y. Greenhouse Gas Emissions Analysis Working toward Zero-Waste and Its Indication to Low Carbon City Development. *Energies* **2021**, *14*, 6644. [CrossRef]
21. Xie, Y.; Wang, P.; Dou, Y.; Yang, L.; Ren, S.; Zhao, D. Assessment on the Cost Synergies and Impacts among Measures on Energy Conservation, Decarbonization, and Air Pollutant Reductions Using an MCEE Model: A Case of Guangzhou, China. *Energies* **2022**, *15*, 1258. [CrossRef]