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Life cycle sustainability assessment of waste-to-electricity plants for 2030 power generation development scenarios in western Lombok, Indonesia under multi-criteria decision-making approach

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ABSTRACT

Globally, the dual challenges of power shortages and waste management underscore the critical need for innovative and sustainable energy solutions. Addressing these issues is essential for achieving environmental sustainability, economic development, and social well-being. This paper proposes an integrated life cycle sustainability assessment (LCSA) of waste-to-electricity (WtE) technologies for the future energy mix in Western Lombok, Indonesia which strongly faces power shortage and waste management challenges. The proposed LCSA assesses three WtE technologies, including gasification, incineration, and landfill gas (LFG) with 5 environmental, 3 social, and 4 economic indicators to estimate the final sustainability score under a multi-criteria decision-making framework. Also, a comparative analysis from the LCSA perspective for different WtE technologies, along with coal, and diesel power plants is conducted as a decision support tool in the 2030 power capacity development scenarios. To indicate the effectiveness and flexibility of the proposed model, the robust decision-making analysis using different important weights on sustainability aspects is investigated. Results show LFG is the most sustainable technology among all options scoring around 0.78. However, coal with a levelized cost of 0.42 $/MWh, and diesel with a payback period of 1.75 years are much more economical options for western Lombok. Sensitivity analysis proves that electricity price is a key parameter strongly affecting the final sustainability score. If supportive policies are adopted associated with electricity produced from WtE, this technology can experience a 16.2 % increase, making it an economic option for Lombok in the future.

Nomenclature

t	Lifetime period (yr.)
D	Discount rate.
I	Total number of decision aspects
TC_a^{cap}	Total capital cost of technology a ($)
C_a^{cap}	Investment cost of technology a ($/kW)
P_a	Installed capacity of technology a (kW)
T_a^{anu}	Total annual cost of technology a ($/yr.)
$TC_a^{cap,anu}$	Total annual capital cost of technology a ($/yr.)

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C_a^{fixed}	Fixed annual cost of technology a ($/yr.)
$C_a^{O\&M}$	Variable operation and maintenance cost of technology a ($/yr.)
C_a^{fuel}	Fuel cost of technology a ($/yr.)
Revenue_a	The annual revenue of the energy sold to the grid ($/yr.)
$LOCE_a$	Levelized cost ($/kWh)
E_a^{anu}	The annual energy generation by technology a (kWh/yr.)
Cal	Calorific or heat value (GJ/ton)
W	Mass of solid waste (ton)
η	Energy efficiency
Co	The conversion factor for GJ to MWh equal to 3.6
$V(a)$	The score of sustainability
w_i	The importance weight of the aspect
$V_i(a)$	The technology sustainability score for aspect i

Table 1
Studies on LCSA of power generation technologies in different countries.

Ref.	Goal& Scope	Country	Technology	WtE Technology	Number of considered indicators
[6]	LCSA on interconnected Electricity generation systems	Greek	Coal, Natural Gas, Hydropower, Wind, Photovoltaic, Biomass	Incineration	Environmental: 6 Economic: 2 Social: 6
[7]	LCSA for electricity generation technology	Brazil	Coal, Oil, Natural Gas, Nuclear, Hydropower, Wind, Geothermal, Photovoltaic, Biomass, Biogas, Ocean	No	Environmental: 15 Economic: 6 Social: 3
[8]	LCSA on waste-to-electricity technologies	Nigeria	Waste, Diesel, Electricity Import	Incineration, Gasification, LFG, Anaerobic Digestion	Environmental: 6 Economic: 3 Social: 2
[9]	LCA on Waste-to-Electricity technology	Denmark	Waste-to-Electricity	Incineration	Environmental: 8 Economic: 0 Social: 0
[10]	LCA on Waste-to-Electricity technology	Finland	Waste-to-Electricity	Incineration	Environmental: 22 Economic: 1 Social: 0
[11]	Techno-economic analysis of Waste-to-Heat, Waste-to-Electricity	Canada	Biomass, CHP, Waste-to-Electricity	Gasification	Environmental: 1 Economic: 1 Social: 0
[12]	LCA on Waste-to-Electricity	Macau	Waste-to-Electricity	Incineration	Environmental: 7 Economic: 0 Social: 0
[13]	LSCA on Waste-to-Electricity technologies	Bangladesh	Waste-to-Electricity	Pyrolysis, Incineration, Gasification, Anaerobic digestion	Environmental: 15 Economic: 7 Social: 7
[14]	LCSA on electricity production technologies	Pakistan	Hydropower, run-of-river, thermal, Gas, Coal, Nuclear, Wind, Electricity Import	No	Environmental: 11 Economic: 3 Social: 5
[15]	LCSA on electricity production options	Turkey	Coal, Natural Gas, Hydropower, Offshore wind, Geothermal, Run-of-River	No	Environmental: 11 Economic: 3 Social: 5
[16]	LCSA on renewable/non-renewable electricity production	Portugal	Coal, Natural Gas, Hydropower, Wind, Photovoltaic	No	Environmental: 11 Economic: 2 Social: 3
[17]	LCSA on electricity production projects	Spain	Coal, Gas, Oil, PV, Wind, CHP, Nuclear, Waste, Hydropower, Biomass, Biogas	Incineration	Environmental: 6 Economic: 1 Social: 1
[18]	LCSA on electricity generation technologies	Bangladesh	Natural gas, Coal, Oil, Photovoltaic, Hydropower	No	Environmental: 11 Economic: 3 Social: 4
[19]	LCA and LCC on electricity production technology	China	Thermal, Nuclear, Wind, Hydropower, Photovoltaic, Biomass	No	Environmental: 6 Economic: 3 Social: 0
[20]	LCA on electricity generation technologies	Indonesia	Coal, Geothermal, Hydropower, Natural Gas, CHP, Diesel	No	Environmental: 7 Economic: 0 Social: 0
[21]	LCA on the renewable electricity generation	Indonesia	Wind, Photovoltaic, Hydropower	No	Environmental: 8 Economic: 0 Social: 0

1. Introduction

Rapid population growth coupled with urbanization, especially in developing countries, doubles the need for sustainable resources to face the energy shortage crisis. Since waste generation is intrinsically tied to gross domestic product and development, many fast-growing economies are struggling under the burden of rapid waste growth. It is anticipated that the production of global municipal solid waste will increase from 2.3 billion tons in 2023 to 3.8 billion tons by 2050 [1]. Meanwhile, global energy consumption has been rising steadily, driven by economic growth and industrialization, particularly in developing countries [2]. Hence, the need for a proper waste management system (WMS) is essential. Meanwhile, the electricity industry is crucial for the sustainable development of all countries due to its impacts on several social, economic, and environmental concerns. Promising progress in WMS technologies such as incineration, landfill gas (LFG), and gasification, in recent years, has made this challenge a suitable opportunity for sustainable electricity supply from solid waste named waste-to-electricity (WtE) process [3].

Sustainable development in electricity generation, as well as waste management, involves balancing social, economic, and environmental issues. Hence, the life-cycle sustainability assessment (LCSA) is quite appropriate for analyzing the impacts of electricity production from solid waste [4,5]. Aggregating multiple social, economic, and environmental indicators under the LCSA can be a powerful decision-supporting tool to assess all advantages, and disadvantages of WtE from different stakeholders' points of view compared with other power generation technologies. LCSA is an integrated concept that includes multiple factors from social life cycle assessment (s-LCA), economic life cycle costing (LCC), and environmental life cycle assessment (e-LCA) aspects to back up governmental decisions on expanding electrical power capacity.

As given in Table 1, the sustainability assessment issues on power generation technologies have been addressed for different countries. The research differed in terms of the sustainability indicators, power generation technologies taken into consideration, as well as the assessment methodology. As can be seen, e-LCA is widely used for impact assessment. Some studies developed eco-environmental analysis on power generation technologies. Given the intricacy of many current approaches and the lack of standard procedures, as well as the lack of access to social databases, s-LCA is addressed rarely. Although various aspects of sustainability have been investigated for different technologies, in the case of WtE, these studies are mostly limited to examining environmental indicators, and within the scope of established works, economic and social aspects have been less investigated. At the same time, due to its social effects such as local employment, as well as economic issues, it should be examined under the LCSA. It should be noted that the studies conducted on LCSA are also different in terms of methodology and analysis of the final solution of sustainability. Commonly, sustainable technology is scored separately without integrating the three aspects (e-LCA, s-LCA, and LCC), and multi-criteria decision-making (MCDM) methods are less used due to their complexity.

Lombok is an Indonesian island in the south with a population of 3.7 million and an area of 4725 km^2 that is not connected to the upstream power grid [22]. This causes the price of electricity to double of average tariff in the price of electricity in Indonesia, reaching 13 ¢/kWh. Fig. 1 shows the geography of Lombok Island [23]. Mataram City on the western side of Lombok with several paddy fields and industrial factories has the highest population density. Western Lombok's WMS is already insufficient with a share of unmanaged

Fig. 1. Lombok Island geographic location.

waste of 59–69 % which is dominated by landfilling.

National and local estimations show that households and industry sections in western Lombok generated 116225 tons in 2022 [22, 24]. Fig. 2 indicates the composition of waste in this area. Assuming a calorific value of 9 GJ/ton, with an annually 100,000-ton waste generation per year, the power generation potential is 20–30 MW. A 25 MW WtE plant is assessed in this study to burn 100000 tons of waste.

Considering the aforementioned descriptions, waste policies and regulations, as well as the appropriate potential for WtE in Western Lombok are two main motivations to find long-term sustainable solutions for waste management, capturing all social, economic, and environmental aspects.

Although the LCSA for WtE technology has not been investigated in the scope of Indonesia, limited studies have been conducted in other countries. A comprehensive LCSA of the Greek interconnected electrical network is carried out by Ref. [6]. The results of this study indicated that hydropower and wind power generation are the most environmentally friendly technologies. Meanwhile, when considering social effects first, solar energy appears to be the most sustainable option. In Nigeria, prospective research on WtE generation based on LCSA was created [8]. In this paper, four WtE technologies, including incineration, landfill, gasification, and anaerobic digestion are evaluated and compared to diesel power generation, and electricity import. The LCSA on co-firing with coal power generation using three types of biomass technologies, including waste forest wood, miscanthus, and willow was studied by Ref. [25] in the UK. Results showed that biomass is attractive from an environmental perspective, but currently, it is less economically. A prospective LCC for Nigerian solid waste-based power generation was created by Ref. [26]. This paper compared WtE technologies, including incineration, gasification, landfill, and anaerobic digestion from economic indicators perspectives. Overall results of all scenarios showed that incineration is the most sustainable economic option based on its positive LCC, lowest payback, lowest levelized cost, and highest internal rate of return. The LCC analysis as a cost management approach in the case of WtE technology was implemented in China [27]. The sensitivity analysis of results demonstrated that annual operation hours, electricity price, and efficiency significantly affect the total cost of the project. Author of [28], used an LCSA technique to evaluate the effects of electricity from various resources, including coal, peat, lignite, diesel, natural gas, hydropower, wind, solar, biomass, and municipal waste incineration on the environment, resource scarcity, and human health. Results revealed diesel was the most detrimental to resource scarcity, hydropower was detrimental to ecosystems, and lignite was most detrimental to human health. An analysis of Spain's electrical system's sustainability was presented in Ref. [17]. The research considers four different predictions for 2030 and 2050 in addition to covering historical inventories of installed capacity, electricity production, and technology mix from 1990. The findings indicate that the most ambitious projections for the share of renewable energy sources offer the greatest benefits in terms of cost savings, job creation, and environmental impact.

The impact assessment of WtE technology is completely dependent on local conditions, and if they are not properly accounted for in the assessment, contradictory results will be provided. For example, authors of [9] indicated that a large difference can be seen in WtE technology performance between northern and southern Europe regarding recovery efficiencies, flue gas cleaning technologies, and residue management. A multi-objective optimization approach, considering economic and environmental goals for WtE power plant operation was developed by Ref. [10]. This study integrated the LCA model into the optimization framework and showed the incineration technology can be optimized economically and environmentally by changing its performance setup. A comprehensive techno-economic model for WtE technologies, including biomass, solid waste, and waste heat in Canada was presented by Ref. [11]. The LCA of WtE development in Macau, focusing on Incineration technology is investigated by Ref. [12]. This paper proposed potential patterns to improve the incineration performance from environmental impacts. To this end, source separation, and integrated WMS are considered as the much better action. In Ref. [13], a multi-criteria analysis LCSA on WtE generation, including Pyrolysis, Incineration, Gasification, and Anaerobic digestion was studied. This research supports the future policy for sustainable solid waste management. In Ref. [29], the LCSA of different electricity scenarios for the UK, extending to 2070 was investigated. The findings indicated that even if future cost reductions for developing technologies are projected, decarbonization is likely to result in greater electricity costs. On the other hand, vulnerability to fluctuating fuel costs is reduced by two-thirds across all low-carbon technology scenarios.

LCSA and its corresponding aspects have been extended as a decision tool in power capacity development in several countries. Authors of [16], presented an LCSA of electricity production technologies in Portugal, including gas, hydropower (small and large scale), wind, solar, and coal. Small hydropower plant is the system that is most ecologically and socioeconomically sustainable according to the LCSA results. The e-LCA and LCC are integrated to analyze the electricity production in Liaoning province [19]. As a main strategy for capacity development in Liaoning, wind power, and nuclear should be investigated more and more, and vice versa the share of thermal power in total installed capacity must be reduced. A novel quantitative LCSA framework for integrated energy systems was investigated by Ref. [30]. Five potential energy development scenarios incorporating a combined heat and power system and solar technologies with various penetration levels are examined in this paper. The integrated LCSA based on the novel optimization framework for renewable power production in Iranian energy system was investigated by Ref. [31]. The findings indicated that

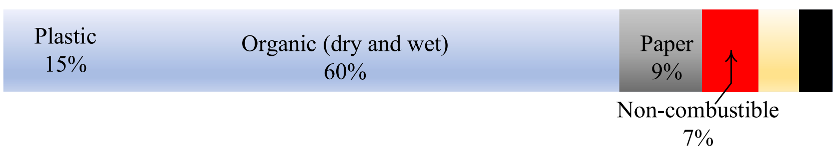

Fig. 2. Composition of waste in Western Lombok.

the main factor influencing sustainable expansion is the wider use of wind, and solar thermal technologies, respectively. The sustainability assessment on power cogeneration from sugarcane bagasse in Jamaica was studied by Ref. [32]. The findings showed that using bagasse for cogeneration to generate power is an acceptable alternative that adds value to the economy, environment, and society. The sustainability assessment of electricity production technologies in Egypt is developed by Ref. [33]. The findings demonstrated a perfect agreement between the stakeholders' technology rankings and the sustainable scenario, which places natural gas at the highest rank, and nuclear and coal at the lowest ranking.

In the case of Indonesia, LCSA and e-LCA are integrated with some power capacity development strategies. To evaluate the net-zero scenario in Indonesia by 2060, a comparative e-LCA is investigated in energy production options, including considering coal, geothermal, gas, CHP, and HSD by Ref. [20] for an interconnected Jamali network. Results indicated that the role of coal power plants should be greatly reduced due to significant impacts on environmental and human health. In Ref. [21], LCA is implemented on a mini-hydro power plant in the Karai River. Results indicated that the mini-hydro technology is a much-sustainable option for capacity development. The electricity production from biomass [34], and combined cycle power plant [35] are evaluated under the e-LCA in Indonesia. In these studies, e-LCA is considered as a decision tool that can be used by the Indonesian government for better energy strategy. The community microgrid concept is developed for the eco-environmental analysis of Lombok Island [36]. This paper just provided a daily operation of Lombok's grid under the multi-objective optimization without considering sustainability assessment. In Ref. [37], a multi-dimensional rapid appraisal technique is developed for evaluating the sustainability of energy plantation forests in Lombok Island. This paper only focused on plantation forests with limited sustainability indicators, ignoring other types of energy generation technologies.

The LCSA value comprises the summation of values of e-LCA, s-LCA, and LCC to show how three life cycle approaches—environmental, social, and economic—are combined [38]. Usually, the findings of the life cycle are analyzed independently, and a comparison conclusion about the sustainability border. However, under MCDM approaches all three life cycle aspects are combined into a single life cycle score for sustainability. Although decision-making and stakeholders' targets during the life chain can be well addressed under multi-criteria approaches, these methods have rarely been considered in the field of power capacity development. To optimize future energy mixes in Pakistan, authors in Ref. [14] proposed policy recommendations and an implementation framework for the power industry using an integrated LCSA methodology. According to the results, oil has the greatest negative social and economic effects in Pakistan, whereas hydropower plants are the most environmentally friendly and sustainable alternative. An integrated LCSA of electricity generation options, considering coal, gas, wind, geothermal, and hydropower plants in Turkey was developed by Ref. [15]. Turkey's most sustainable energy alternative is hydropower, where wind and geothermal come next. Gas power has the lowest capital costs, but it also has the worst levelized costs, depletes the ozone layer, and creates the least number of direct jobs. An Integrated LCSA on power generation development strategies in Bangladesh was studied by Ref. [18]. Results show that among renewable options, PV is much more sustainable, while gas has a higher score than fossil fuels. A hesitant Preference Ranking Organization Method (PROA) is integrated with s-LCA to evaluate the social impacts of small hydropower plants in China [39]. This research offers a novel viewpoint for evaluating the social sustainability of small hydropower technology and helps to make more logical and fact-based decisions. In Ref. [40], the MCDM approach was developed to prioritize of energy system in the UK. In this research, coal, gas, nuclear, and offshore wind power are evaluated and ranked from a sustainability indicators point of view.

The literature review shows that WMS in developing countries should be seriously investigated. The high energy rate and calorific value of municipal and industrial wastes reveal the importance of integrating WtE technology in generation development plans, although this has been limited. In the case of Indonesia, even though waste management is considered a national challenge, no impact assessment study has been done on WtE technology. On the other hand, despite conducting various studies on LCSA in the capacity development plans on renewable and non-renewable resources, the failure to provide an integrated approach for ranking and the final solution of sustainability leads to reduce the efficiency of LCSA. Most of the conducted studies have investigated the final solution of sustainability separately and without considering the stakeholders' goals. Therefore, it is necessary to implement multi-criteria evaluation methods in examining the LCSA of electricity generation technologies, especially WtE with several social, economic, and environmental impacts.

To tackle above mentioned gaps, this paper provides an integrated LCSA on the WtE plant in Western Lombok under the MCDM approach. To this end, three options are evaluated and compared according to Lombok Energy Outlook 2030 [41], including:

- **Option 1**: Generation capacity development based on a 25 MW WtE plant in western Lombok. In this scenario, LCSA is developed for three WtE technologies, including gasification, incineration, and LFG.
- **Options 2**: Generation capacity development based on a 50 MW high-speed diesel (HSD) plant.
- **Option 3**: Option 2 is based on a 50 MW Coal power plant.

The sustainability of power generation based on WtE, HSD, and Coal, is assessed using 12 indicators. Under e-LCA, 5 indicators, including global Warming Potential (GWP), Acidification Potential (AP), Human Toxicity Potential (HTP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP) are analyzed, using the CML-IA baseline method. Capital cost, annual cost, and levelized cost, as well as payback period, are captured as costing indicators. A number of employments, and fatalities, as well as the local workforce (as the most important indicator for Lombok), are considered social indicators. Firstly, all analyses on e-LCA, LCC, and s-LCA for the three mentioned scenarios are investigated separately. Then, the MCDM approach is developed to aggregate all aspects and provide the final sustainability score. It should be noted that the sensitivity analysis is provided to indicate the importance of the conversion efficiency and electricity price in the final results. To reveal the effectiveness of the proposed method as flexible decision tool support, results are evaluated under the same and different importance weight coefficients. The main contributions of this study can be summarized as follows:

- ✓ Integrated LCSA on three WtE technologies, including incineration, LFG, and gasification in Western Lombok for the first time.
- ✓ Comparative LCSA for WtE, HSD, and coal power plants as decision tool support in generation capacity development scenarios.
- ✓ Developing MCDM to aggregate all aspects of sustainability and calculate the final results, considering all social, economic, and environmental indicators. As a flexible decision-making tool, different importance weight coefficients are considered to analyze the robustness of the results from stakeholders' points of view.
- ✓ Proposing sensitivity analysis on conversion efficiency of power generation technologies, as well as electricity price to assess its impacts on sustainability outputs.

The rest of this paper is organized as follows: Section 2 provides the methodology of LCSA on the scope of the study. In section 3 results obtained by the MCDM method are presented. Section 4 discusses on most important outputs, and also carries out the sensitivity analysis on conversion efficiency, and electricity price for all scenarios. Finally, section 5 concludes the paper.

2. Methodology

Based on ISO 14040/14044 standards the foundation of the proposed LCSA is depicted in Fig. 3 [42]. The goal and scope specification are the first step of the LCSA study. The main action of this step is to define the function unit, where 1 kWh of electricity is considered a function unit. Next, an inventory list is gathered that describes the interactions between the product's life cycle during contraction, transportation, and operation, with the outside world. The inventory data is allocated to environmental, economic, and social impact indicators in the ensuing impact assessment. In this step, all inputs, outputs, and materials per function unit are classified and characterized based on the considered indicators. Also, the normalization phase can be used as an optional phase for better analysis of results based on the standard normalization factor [43].

As mentioned before, 12 indicators are considered in the model. In the end, an interpretation phase incorporates the diverse metrics from each of the three sustainability aspects to facilitate decision-making based on MCDM. It should be noted that different importance weight coefficient analyses, as well as sensitivity analyses, are carried out to indicate the effectiveness of the proposed model.

2.1. Goal and scope

The goal of the proposed study is to analyze the LCSA of generation capacity development, focusing on WtE technologies in western Lombok. A 1 kWh electricity production from WtE, HSD, and coal plants is considered a function unit. The scope of this study includes the material preparation, transport and collection, construction, and plant operation phases which is depicted in Fig. 4. The daily municipal solid waste is considered as input material for WtE technologies. After collection and transportation, the construction, and operation processes to produce 1 kWh of electricity are evaluated under the integrated LCSA. This procedure is also established for coal and HSD. It should be mentioned that the stage of coal mining, which in turn increases the number of jobs, dangerous accidents, pollution, etc., is included in the calculation of the relevant indicators.

2.2. Sustainability indicators

The sustainability indicators related to environmental, economic, and social aspects for impact assessment of power generation

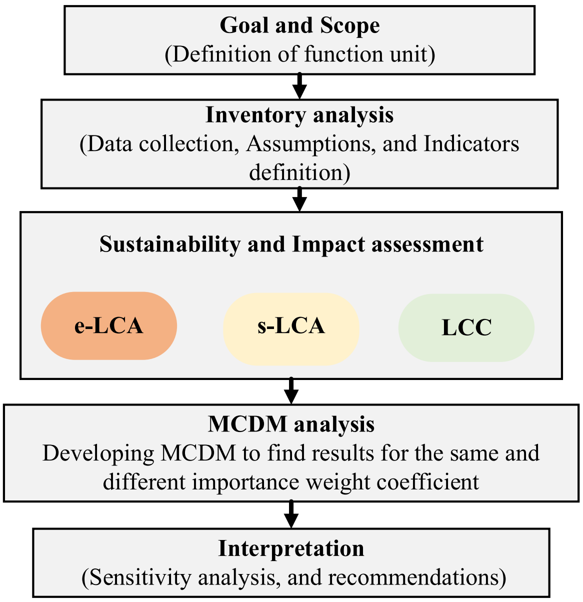

Fig. 3. Overview of the proposed methodology.

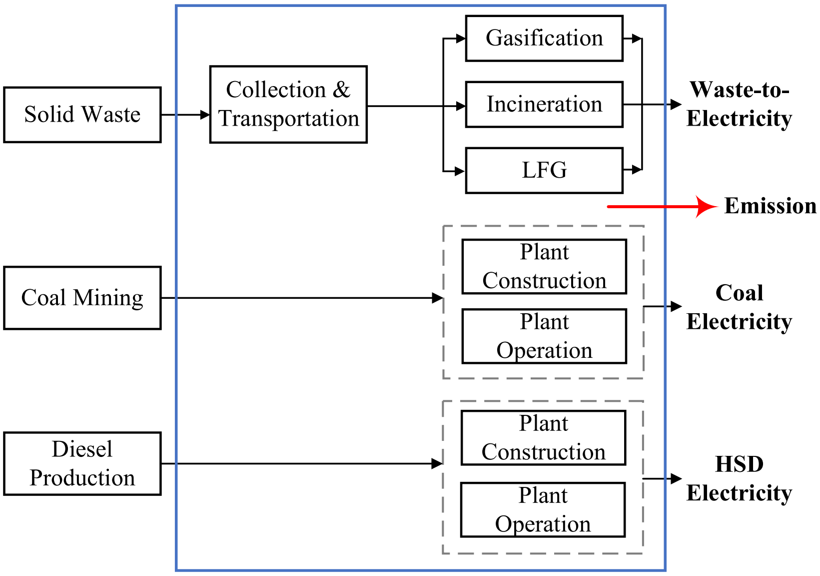

Fig. 4. Scope of the 1 kWh electricity generation by WtE, HSD, and coal plants.

through WtE, HSD, and coal plants are given in Table 2.

As mentioned in the introduction, 5 environmental indicators, including GWP, AP, HTP, EP, and POCP are considered. Details of e-LCA indicators are provided in Ref. [44]. The e-LCA indicators are classified and characterized in the life cycle impact assessment (LCIA) phase using the CML-IA baseline framework.

For s-LCA, the number of employments, number of fatalities as health and safety indicators, as well as local workforce are calculated per 1 kWh of electricity generation. Although there are some formulations for calculating social indicators like [8,15], it is a fact that the basis for calculating these indicators is field data and the use of information obtained from on-site interviews.

Economic indicators related to electricity production are more tangible than other aspects [45]. The total capital cost shows the total investment and construction cost which is formulated in (1).

$$TC_a^{cap} = C_a^{cap} \times P_a \tag{1}$$

Total annual cost represents the annual capital cost, fuel cost, annual operation & maintenance cost, etc. as Eq. (2) [45].

$$T_a^{anu} = TC_a^{cap,anu} + C_a^{fixed} + C_a^{O\&M} + C_a^{fuel} \tag{2}$$

Annual capital cost is calculated using Eq. (3):

$$TC_a^{cap,anu} = TC_a^{cap} \times f \tag{3}$$

Where f is the annual factor calculated based on Eq. (4).

Table 2
Description of environmental, social, and economic indicators.

No.	Indicator	Unit
Environmental Indicators		
1	GWP	kg CO2-eq/kWh
2	AP	kg mol H+/kWh
3	EP	mol N-eq/kWh
4	POCP	kg NMVOC-eq/kWh
5	HTP	CTUh/kWh
Social Indicator		
1	Number of accidents	Number of injuries/kWh
2	Number of jobs	Person-year/kWh
3	Local workforce	Person-year/kWh
Economic Indicators		
1	Total Capital Cost	$
2	Total Annualize cost	$/year
3	Levelized cost	$/kWh
4	Payback Period	Years/kWh

$$f = \frac{d \times (1+d)^t}{(1+d)^t - 1} \tag{4}$$

The levelized cost of electricity (LCOE) shows the unit of electricity cost as follows:

$$LOCE_a = \frac{T_a^{anu}}{E_a^{anu}} \tag{5}$$

The payback period is the most important indicator during energy planning strategy. Eq. (6) calculates the payback period.

$$\text{Payback}_a = \frac{TC_a^{cap}}{\text{Revenue}_a - C_a^{O\&M}} \tag{6}$$

It is assumed that operation & maintenance cost follows Eq. (7) [15]:

$$C_a^{O\&M} = 0.03 \times TC_a^{cap} + 0.005 \times E_a^{anu} \tag{7}$$

2.3. Sustainability assessment: capacity development scenarios, assumptions, and data collection

The entire installed capacity of Lombok Island, which primarily uses fossil fuels, reached 416 MW by the end of 2022 [41]. Table 3 shows the composition of installed capacity.

Considering that the peak load in Lombok is about 310 MW, generation expansion planning is one of the vital needs of this island [46]. Considering the potential of this western Lombok, the Indonesian Electricity Company, PLN NTB has several plans to solve the power shortage by 2030. However, to know which plan is more useful from a social, environmental, and economic point of view, a comprehensive LCSA model is required. To evaluate the sustainability of the power generation development strategy in western Lombok, three scenarios are assessed.

In the first scenario, three WtE technologies, including LFG, incineration, and gasification are evaluated and compared from economic, environmental, and social aspects. The following assumptions are considered for this scenario:

- Except non-combustible and rubber, other compositions of solid waste are used for gasification (88 % of total waste).
- Expect non-combustible, rubber, and textile, other compositions of solid waste are used for incineration (84 % of total waste).
- All composition of waste can be used for LFG.
- Power consumption during the burning of the WtE plant is provided by the Jeranjang coal power plant which is currently committed.
- Energy production by WtE is calculated using the following equation:

$$P = \frac{Cal \times W \times \eta}{Co} \tag{8}$$

The conversion factor for GJ to MWh equal to 3.6 [47].

- All solid waste collection and transportation are carried out using diesel-based vehicles which 9 litters per ton of waste is consumed during the transportation phase.
- Renewable electricity tariff is assigned to WtE power generation, which is double of average price.

Table 4 shows the main characteristics of three WtE technologies.

In two other scenarios, it is assumed that 50 MW power generation is provided by HSD and coal. The electricity tariff for these power plants is to be an average tariff in Indonesia. Also, fuel transportation is carried out using diesel-based vehicles as the first scenario.

A) Environmental Data

The inventory analysis of environmental data based on the goal and scope of the LCSA is provided in this subsection. It should be mentioned that the inventory data are collected from various sustainability studies, Indonesian government and industry reports, annual reports, extensive literature reviews, etc.

Table 5 shows the emission factor and emission composition during transportation.

The WtE plant is powered by the Jeranjang plant during start-up and first operation. So, the emission during power consumption that the Jeranjang power plant releases into the air should be captured in the e-LCA given in Table 6.

Table 3
The existing power plant in Lombok [41].

Type of power plant	Unit	Installed Capacity (MW)
Coal	5	140
Diesel	23	113
Natural Gas	13	127
PV	6	20.8
Hydro	10	16

Table 4
Technical characteristics of three WtE technologies [48].

Technology	Calorific (MJ/kg)	Electricity consumption (kWh/ton)	Energy production (kWh/ton)	Conversion efficiency (%)
Incineration	10	70	723	26
Gasification	8	339	512	23
LFG	12	14.3	1100	33

Table 5
Emission factor and emission pollution during the transportation phase [8].

Emission	Emission Factor (kg/liter)	Emission (kg/kWh)		
		Gasification	Incineration	LFT
CO_2	2.663	4.69E-02	3.32E-02	2.18E-02
CO	0.01195	2.10E-04	1.49E-04	9.78E-05
HC	0.00175	3.08E-05	2.18E-05	1.43E-05
NO_x	0.00236	4.16E-05	2.94E-05	1.93E-05
PM	0.00062	1.09E-05	7.73E-06	5.07E-06

Table 6
Emission pollution during start-up and operation per 1 kWh of electricity production [49].

	unit	Gasification	Incineration	LFG
PM 2.5	kg/kWh	3.87E-04	5.65E-05	7.58E-06
SO_2	kg/kWh	1.83E-02	2.67E-03	3.58E-04
NO_X	kg/kWh	3.19E-02	4.66E-03	6.25E-04

The inventory data of HSD and coal plants during the operation phase for 1 kWh production of electricity are given in Table 7. Also, the value of emission composition to air by three WtE technologies is given in Table 8. It should be noted that the emission value per function unit is calculated based on the Intergovernmental Panel on Climate Change (IPCC) [50].

B) Cost Data

To calculate LCC on proposed scenarios, cost inventory is constructed based on [49]. Table 9 shows the cost inventory list. Using (1)-(8), the annual cost, levelized cost, total energy production, etc. are determined based on the rated capacity. All details of calculations are available upon request.

C) Social Data

The lack of a comprehensive database on social parameters such as the number of fatalities, and job creation is one of the challenges of the social inventory. This paper has prepared an inventory based on the information available in Refs. [22,24], and annual reports in Indonesia, which can be seen in Table 10.

2.4. MCDM analysis

In order to determine the sustainability of a life cycle perspective, the relationship's sum sign denotes an integration of the three tools (e-LCA, LCC, and s-LCA) in the LCSA. This involves analyzing and identifying a product or process's performances from the perspectives of the environment, economy, and society. One of the biggest challenges of sustainability analysis is integrating its aspects so that all aspects can be seen and compared in the end. Considering the many advantages of multi-criteria analysis methods, in this section, the MCDM analysis is described. The overall sustainability score for each option is determined using this method:

Table 7
Composition of emission to air for HSD and coal plants [49,50].

Composition of emission to air	Value (kg/kWh)	
	HSD	Coal
HCF	4.05E-08	–
CH_4	5.62E-05	1.53E-05
CO_2	1.37E-02	9.45E-01
CO	3.71E-04	1.77E-04
NO_x	5.54E-04	2.90E-03
N_2O	3.98E-12	1.32E-05
SO_x	2.50E-05	1.67E-03
PM	5.54E-05	1.72E-04

Table 8
Composition of emission to air by WtE technologies [8,49].

Composition of emission to air	Value (kg/kWh)		
	Gasification	Incineration	LFG
CO_2 organic	1.15E-03	2.80E-03	1.62E-04
CO_2	5.68E-04	1.38E-03	–
CH_4	–	–	2.53E-05
NO_x	1.34E-03	2.33E-04	–
SO_x	8.95E-05	–	–
HCL	5.51E-05	–	–
Hg	1.19E-07	–	–
Ar	1.03E-07	–	–
Ni	6.89E-08	–	–
Cd	1.19E-08	–	–
VOC	1.89E-05	–	–
HF	5.85E-07		–
CO	–	5.82E-05	–
N_2O	–	2.33E-06	–
NH_3	–	4.65E-06	–
Non Methane (NMVOC)	–	5.82E-06	–

Table 9
Financial and cost inventory of several power generation technologies [49].

Financial data	HSD	Coal	Incineration	Gasification	LFG
Nominal Investment (M$/MW)	0.80	1.65	6.80	3.92	2.50
Fixed O&M (M$/MWe/year)	0.8	0.0453	0.24	0.47	0.13
Variable O&M ($/MWh)	6.4	0.13	24.10	3.00	13.50
Technical lifetime (yr.)	25	30	25	15	12

Table 10
Social inventory of several power generation technologies [22,24].

Technology	Number of employments (person*yr.)	Number of fatalities and accidents		
		Fall and car accident	Exposure	Electrified
Gasification	225	200	170	87
Incineration	180	200	105	65
LFG	150	200	85	40
HSD	350	112	750	350
Coal	2000	150	890	490

$$V(a) = \sum_{i=1}^{I} w_i V_i(a) \tag{8}$$

To calculate the ultimate sustainability score, the MCDM was completed in two stages. First, the scores for each sustainability component were derived using (8), taking into account the values of the respective sustainability indicators found in the sustainability assessment as well as their importance weights of relevance. The choice criterion in equation (8) then represents the sustainability indicators. In the second stage, the sustainability components function as the selection criteria. To estimate the final sustainability score of technology, equation (8) is applied, taking into account the important weights provided to each factor linked with the sustainability scores in the first stage.

The decision tree is provided as the first phase in the MCDM process. Aspects to be analyzed in the findings might be given equal or differing significant weights. The same weight is considered for each aspect $w_i = 1/3$. Because there are different numbers of indicators for each sustainability component and to avoid bias, the following weights have been assigned to the indicators:

- 5 environmental indicators: $w_i=1/5$,
- 3 social indicators: $w_i=1/3$,
- 4 economic indicators: $w_i=1/4$,

The importance of aspects may be different from several stakeholders' perspectives, e.g., the LCC aspect is more important than the e-LCA from the power plant owner's point of view, MCDM has the flexibility to analyze the final results by changing the importance coefficients. This is a very important feature in facilitating the decision-making process which is developed in the proposed model.

2.5. Data quality and uncertainty analysis

In this study, the accuracy and reliability of the LCSA results are contingent on the quality of the input data. This paper sources data from reputable databases and literature, ensuring comprehensive coverage of the environmental, social, and economic indicators. Despite these efforts, some uncertainties remain due to potential biases and assumptions inherent in the data collection process. To address these, this study employs sensitivity analysis to evaluate the impact of data variability on results, ensuring the robustness of the proposed method by changing the importance of weighting coefficients.

Fig. 5 shows the overview of the proposed methodology. After defining the goal and scope of the study on the considered scenarios on the generation capacity development, all social, environmental, and economic data are collected as inventory assessment. Then, all indicators for all aspects are defined. The CML-IA midpoint method on the environmental indicators is carried out [51], while the financial and social life cycle is developed to calculate all indicators, using IPPC and Equations. (1)–(7). In the next step, the MCDM approach based on Eq. (8) is developed to rank and determine the sustainability score for all scenarios. To show the robustness of extreme decision-making, different importance weights are associated with aspects to analyze the final results. Finally, the results are discussed and sensitivity analysis on the most important parameters like electricity price, and conversion efficiency are carried out to provide the complete decision toll package. Details are provided in the next.

3. Results and discussion

In this section, the results of e-LCA, s-LCA, and LCC are discussed, separately and sensitivity analysis on important parameters, like conversion efficiency, and electricity price are presented. Then, the sustainability assessment via the integrated MCDM method is

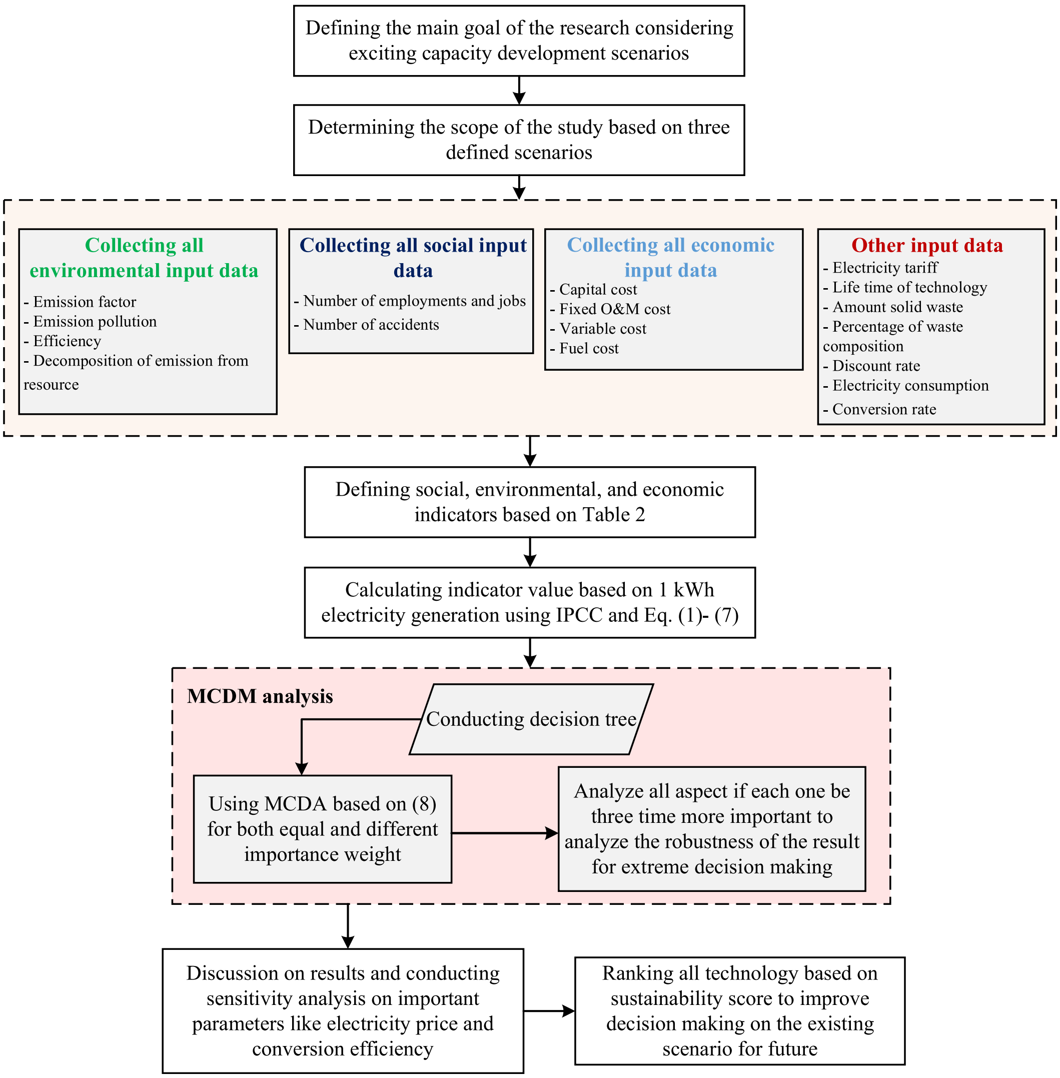

Fig. 5. Overview of the proposed methodology.

addressed. It should be noted that the decision tree and different importance weight coefficients for environmental, economic, and social aspects are investigated to indicate the effectiveness of the proposed model, as well as the robustness of decision tool support in generation capacity development strategies.

3.1. Results of e-LCA assessment

The e-LCA results are presented for WtE technologies, HSD, and coal for 5 environmental indicators as shown in Fig. 6.

From the GWP point of view, coal is the worst option as expected (0.945 kg CO_2/kWh). The main contribution of high GWP value of coal is CO_2 emission (98 %). Between WtE technologies, gasification generates 4.86 E−02 which makes it the worst WtE technology. The main component of emission released by gasification is HCF gas (3.14 E−05 kg CO_2/kWh). It should be noted that the main reason for GWP for WtE technologies is related to power consumption which is assumed to be provided by the Jeranjang power plant. If the WtE plant is committed after start-up and it is a self-supplied power plant, the environmental indicators decrease by 15 % on average.

Coal and HSD have the highest AP values, 4.75 E−03, and 2.05 E−03 kg mol H+/kWh, respectively. A noteworthy point is gasification's high AP value compared to other WtE technologies (1.47 E−03 kg mol H+/kWh). The main contribution to that is NO_x emissions (1.38 E−03 kg mol H+/kWh).

Considering NO_x as the main component in HTP characterization like AP, coal, HSD, and gasification have the highest value. It should be noted that volatile organic compound (VOC) is another composition of HTP by gasification that contributes to 1.89 E−05

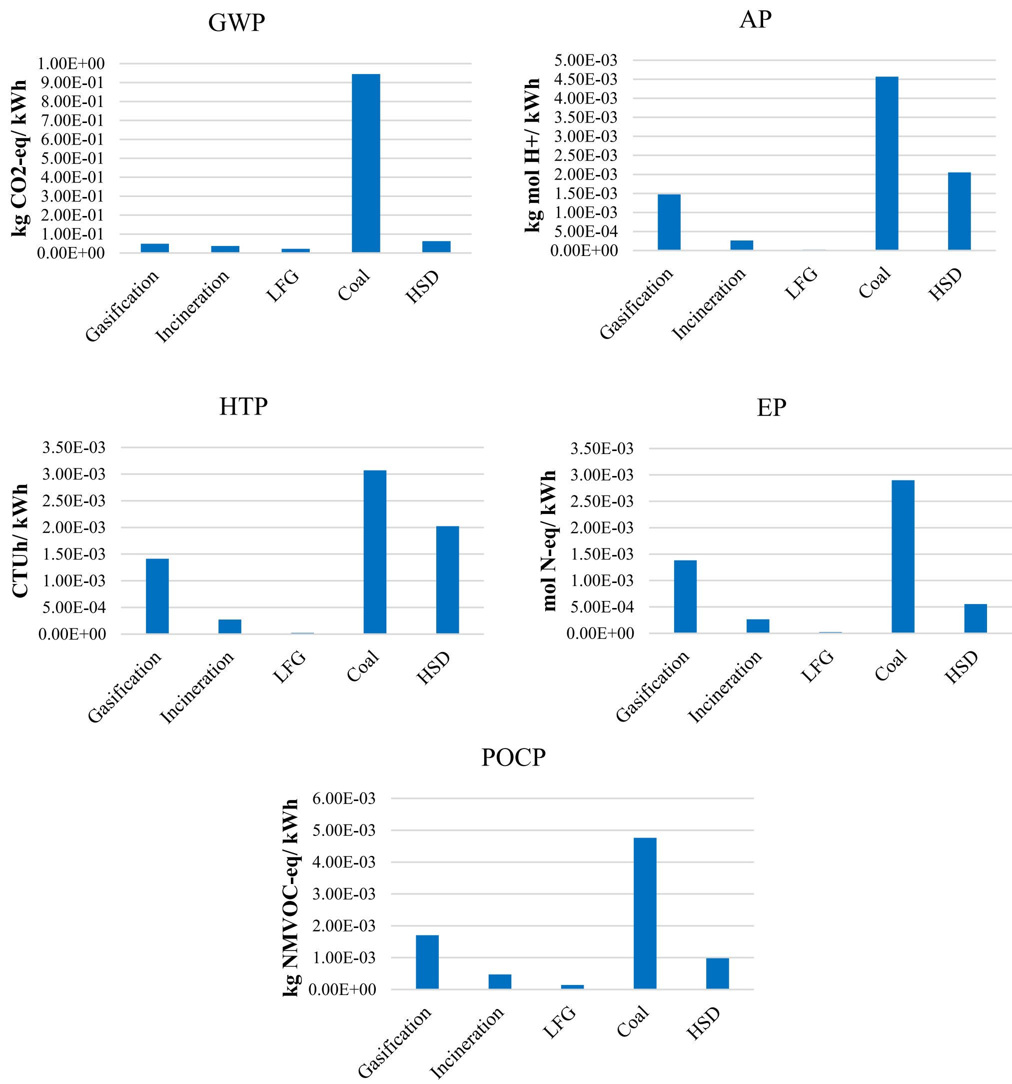

Fig. 6. e-LCA results on power generation technologies in western Lombok.

CTUh/kWh. This procedure is established to EP indicator as can be seen in Fig. 6.

In terms of POCP, while coal is the worst option, gasification has a greater value compared to HSD. The main reason is SO_x emissions by gasification (8.95 E−05 kg NMVOC-eq/kWh). A deeper look at Fig. 6 reveals that LFG, followed by incineration is the most environmentally friendly technology for western Lombok.

To indicate the impact of conversion efficiency on the e-LCA results by all technologies, the sensitivity analysis is carried out. To achieve this goal, the influence of efficiency deviation is investigated during the sensitivity analysis by ±20 % for GWP, AP, and POCP which is depicted in Fig. 7. As presented in Table 4, the conversion efficiency of gasification, incineration, and LFG are 23, 26, and 33 %. Fig. 6, (a) shows that with a +20 % increase in conversion efficiency of LFG, the GWP decreases with more slope compared to other technologies. It means that, if the efficiency of LFT technology increases to 39 %, the GWP emission decreases up to 19 %. In terms of AP, incineration technology is more sensitive to efficiency, and as can be seen, with increasing conversion efficiency, the AP decreases more steeply for incineration. Deviations in conversion efficiency do not cause significant changes in pollution (Fig. 6, c). This point is quite evident in the case of gasification.

3.1.1. Uncertainty analysis

To evaluate the uncertainty of energy efficiency in WtE technologies, a comprehensive uncertainty analysis was conducted. The analysis focused on the efficiency of three WtE technologies: Gasification, Incineration, and LFG. Efficiencies were modeled as normally distributed variables with specified means and standard deviations to reflect the variability in real-world operational conditions. Monte Carlo simulation (MCS) was employed to assess how these efficiency uncertainties impact key environmental metrics, including GWP, EP, HTP, AP, and POCP. By running 10,000 iterations, a distribution of possible outcomes for each metric was generated. This approach provides a robust statistical basis for evaluating the environmental impacts of each technology.

The MCS results included mean values, standard deviations, and 95 % confidence intervals for each environmental impact category. These statistical measures offer insights into the potential variability and associated risks. The 95 % confidence intervals, in

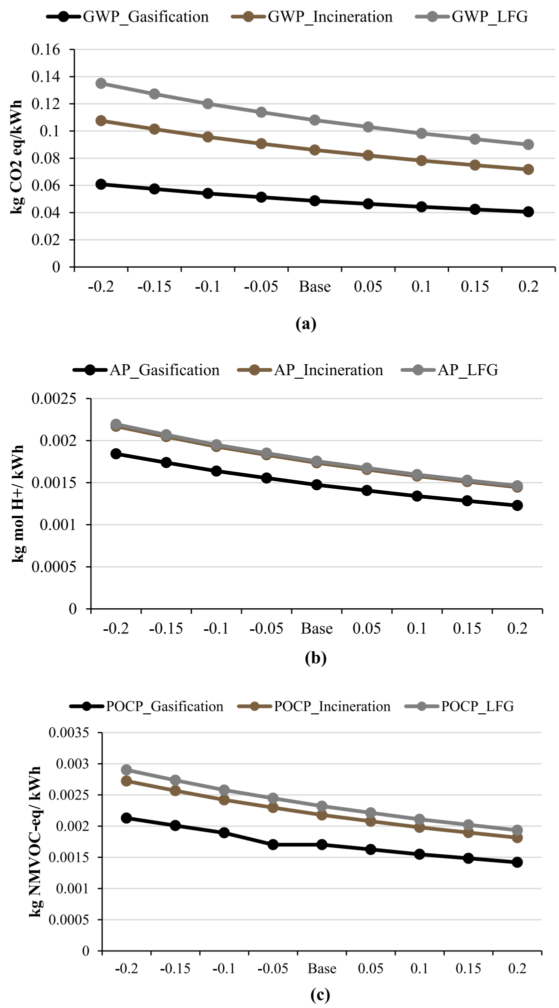

Fig. 7. Sensitivity analysis on conversion efficiency for (a) GWP, (b) AP, and (c) POCP.

particular, provide a range within which the true environmental impact is likely to fall, thereby quantifying the precision and reliability of the estimates.

For instance, the uncertainty analysis for GWP is given in Fig. 8. This analysis reveals the variability and uncertainty associated with each technology, highlighting the importance of considering both average performance and potential fluctuations in environmental impacts.

Additionally, it is important to recognize that there are different uncertainties in the input parameters beyond efficiency, such as operational conditions, and technology-specific factors. These uncertainties can also significantly influence the overall environmental performance of WtE technologies. Future studies incorporate these factors to provide a more comprehensive uncertainty analysis.

3.2. Results of s-LCA analysis

In this section, the results of s-LCA for all technologies are discussed. As mentioned, number of employments, the number of fatalities, and the local workforce are considered as social indicators. Fig. 9 shows the number of employments during the life cycle in the construction, transportation, and operation phases, as well as the percentage of the local workforce. It should be noted that the number of employments is calculated for a 25 MW WtE plant, 50 MW coal, and 50 MW diesel. As can be seen, a coal plant requires much more labor during its life cycle. However, the WtE plant creates more jobs in the transportation phase due to the need to collect municipal waste by local transport vehicles. On the other hand, due to the need for technicians and specialized forces for construction and operation, the coal power plant is not suitable for Lombok in terms of the local workforce. However, WtE power plants attract more local labor due to the simplicity of the technology, which can be suitable for Lombok's economy.

A number of large accidents and fatalities for all power plants are analyzed as shown in Fig. 10. As can be seen, WtE technologies lead to more accidents due to the need to collect and transport solid waste to landfills daily. However, these units are safe in the operation phase. Coal-fired power plant causes higher fatalities and accidents in the construction and operation phases.

3.3. Results of LCC analysis

Economic indicators including total capital cost, total annualized cost, levelized cost, and payback period are analyzed by LCC in this section. Fig. 11 shows the capital cost and total annual cost for all power generation technologies. According to Fig. 11, the incineration plant is much more expensive from investment cost which makes it an uneconomical option for western Lombok. However, the total annual cost of WtE technologies is more economical compared to HSD and coal plants based on LCC results. The cost analysis of HSD expresses the claim that the high cost of private sector units has led to the annual cost being higher than the investment cost.

Fig. 12 shows the composition of the total annual cost. As expected, the capital cost of WtE technologies is the greater contribution to the total annual cost. The fuel cost for these types of power plants is almost negligible. However, the variable O&M cost of gasification is much higher than incineration and LFG.

According to the levelized cost, the coal power plant is a much more economical option for Lombok. also, LFG is a suitable option among all WtE technologies (Fig. 13). The payback period is completely dependent on the electricity price. Based on electricity tariff in Indonesia, the price for all renewable energy is double of average price.

Fig. 13 indicates that the payback period of incineration is more than 7 years. The LFG is an attractive option due to less payback period (2 years). However, fossil fuels (HSD and coal) are still more beneficial in terms of economics and payback period for investors.

Fig. 13 reveals that there is no interdependency between levelized cost and payback period, and electricity price can change the final LCC results. Payback period indicator is affected by an electricity price variance of ±20 %.

Fig. 14 shows that the payback period of incineration drops steeply if the electricity price increases to 16.6 ¢/kWh. HSD has no

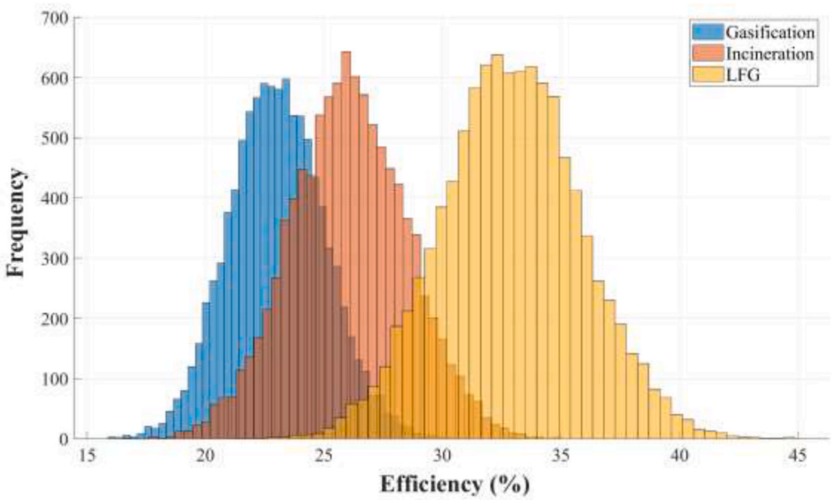

Fig. 8. Efficiency distributions for Gasification, Incineration, and LFG technologies, generated using MCS with 10,000 iterations.

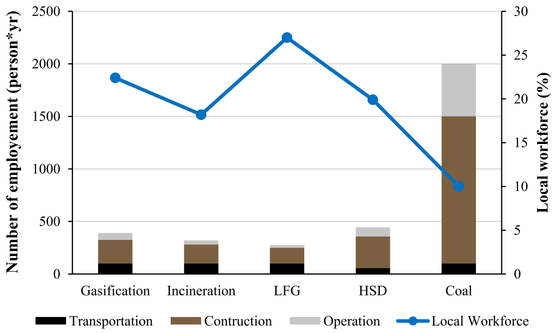

Fig. 9. Number of employments during life cycle, as well as local workforce.

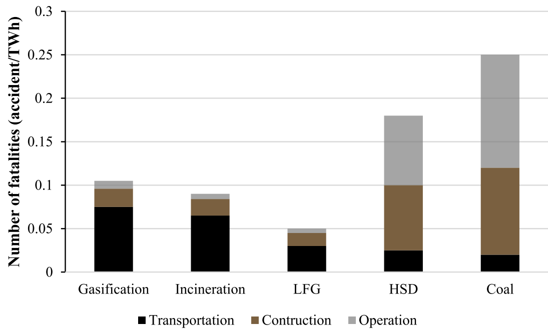

Fig. 10. Number of fatalities for all power generation technologies.

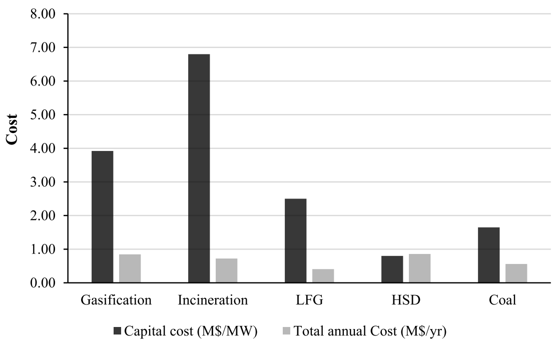

Fig. 11. Capital cost and total annualized cost for all power generation technologies.

tangible sensitivity to price; however, gasification and coal show the same response to price deviations. This result can lead Indonesia's energy decision-makers to allocate more subsidies to the price of electricity produced from renewable sources.

3.4. MCDM analysis on final sustainability result

Although in the previous sections, the most suitable technology for western Lombok was determined from the point of view of environmental, social, and economic aspects individually, however, combining all three aspects and choosing the most sustainable technology for the scope of the study in a way that integrates all the indicators, requires the development of a MCDM.

Fig. 15 shows the decision tree for 3 aspects (environmental, social, and economic), and corresponding indicators for five electricity generation technologies. As discussed in section 2.4, MCDM determines the final solution of sustainability by assigning importance coefficients to each aspect. According to the number of indicators (5 environmental, 4 economic, and 3 social indicators), the coefficients of each indicator always remain constant (see Section 2.4). However, to test the robustness of decision-making on electricity production technology, one can change the importance coefficients of three aspects and analyze the final results.

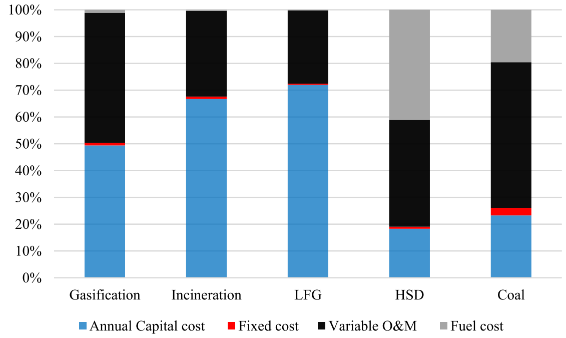

Fig. 12. Composition of total annualized cost for different electricity generation options.

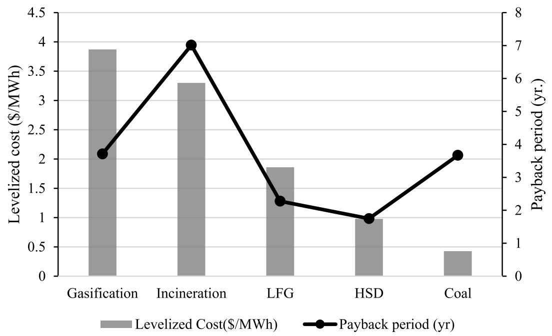

Fig. 13. Levelized cost and payback period indicator for electricity generation technologies.

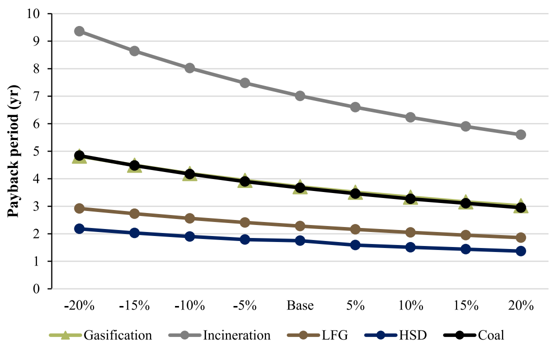

Fig. 14. Sensitivity analysis of electricity price on payback period indicator.

3.4.1. Same importance weight coefficients

The final sustainability score with the same importance weight (for each aspect $w_i = 1/3$) is given in Fig. 16. As shown in this figure, the LFG technology is the most sustainable technology for western Lombok, scoring around 0.78. After that, incineration with a score of 0.422 is the second-ranking. Coal is the least sustainable option with a score of 0.35. From an economic aspect, incineration technology is the least sustainable option. Meanwhile, HSD and coal technologies are more economical compared to other power plants, scoring 0.243, and 0.224 respectively. From a social aspect, all WtE technologies are much more sustainable; and among all of them, gasification with scoring around 0.275 is the first-ranking option.

It should be noted that the adoption of LFG technology faces several barriers, including initial capital costs, regulatory hurdles, and limited public awareness. To address these challenges, financial incentives such as grants, and low-interest loans could be offered to reduce capital costs. Streamlining regulatory processes and providing clear guidelines can facilitate smoother project implementation. Additionally, public education campaigns highlighting the benefits of LFG technology can enhance community support and acceptance.

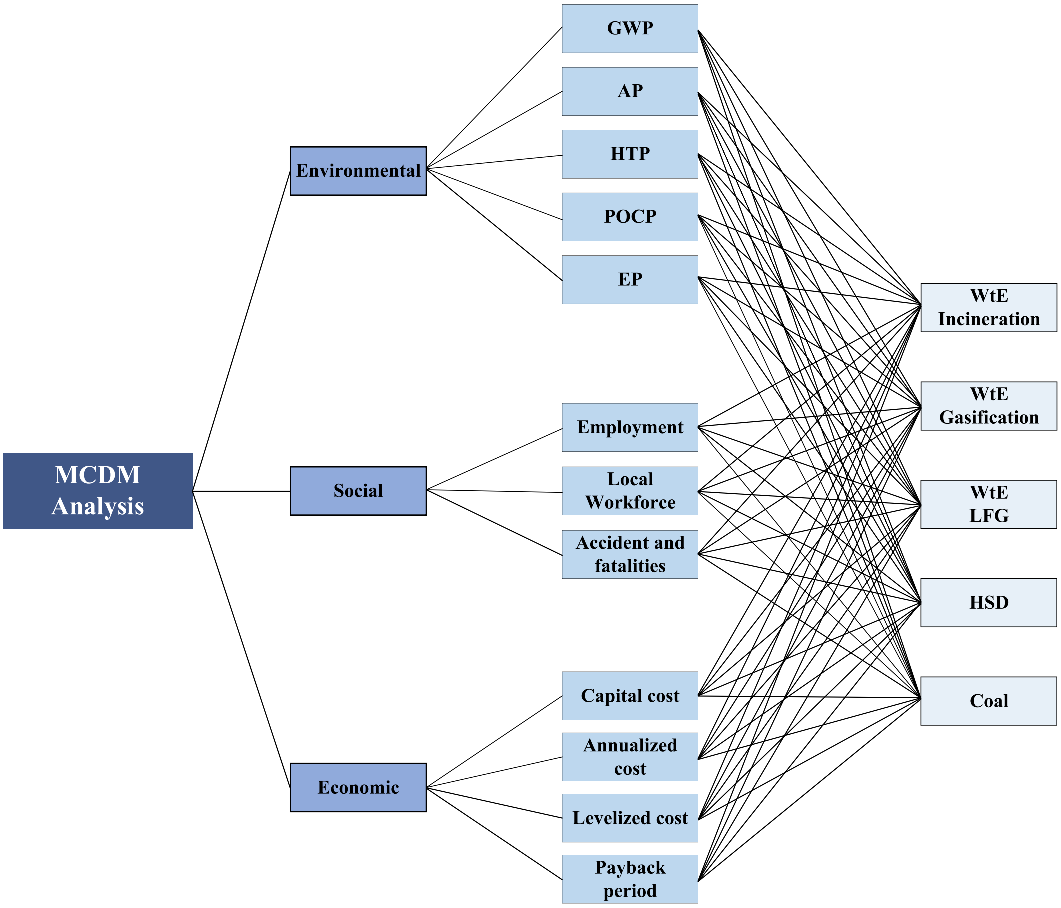

Fig. 15. Decision tree based on the MCDM analysis and midpoint indicator for final sustainability score.

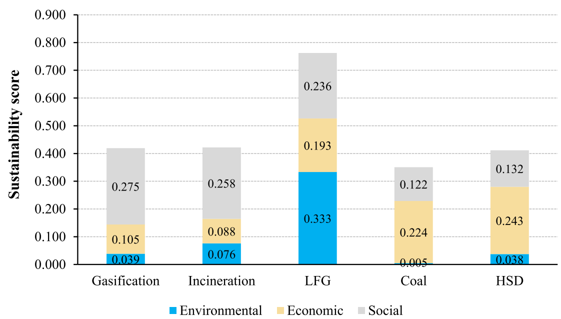

Fig. 16. Final sustainability score based on MCDM with the same importance weights.

3.4.2. Different importance weight coefficients

To determine how the technology ranking varies with varied sustainability preferences, each aspect has been suggested to be much more important than others. To this end, an importance weight of three times ($w_i = 0.6$) is assessed which shown in Fig. 17.

When e-LCA is three times more important than LCC, and s-LCA (Fig. 17, a), the technology ranking remains as Fig. 16, and LFG is the most sustainable technology. However, its score grows up to 12 %. The sustainability score of coal and HSD decreased by 29 %, and 38 %, respectively.

If s-LCA is three times more important (Fig. 17, b), WtE technologies have a much better foothold. The main reason is to create more jobs in the transportation of municipal waste to the plant. It should be mentioned that in this case, coal gets a score of 0.36, which is higher than the base case (Fig. 16). Gasification and incineration have the highest increase with 41 and 33 % respectively, and their ranking is higher than HSD.

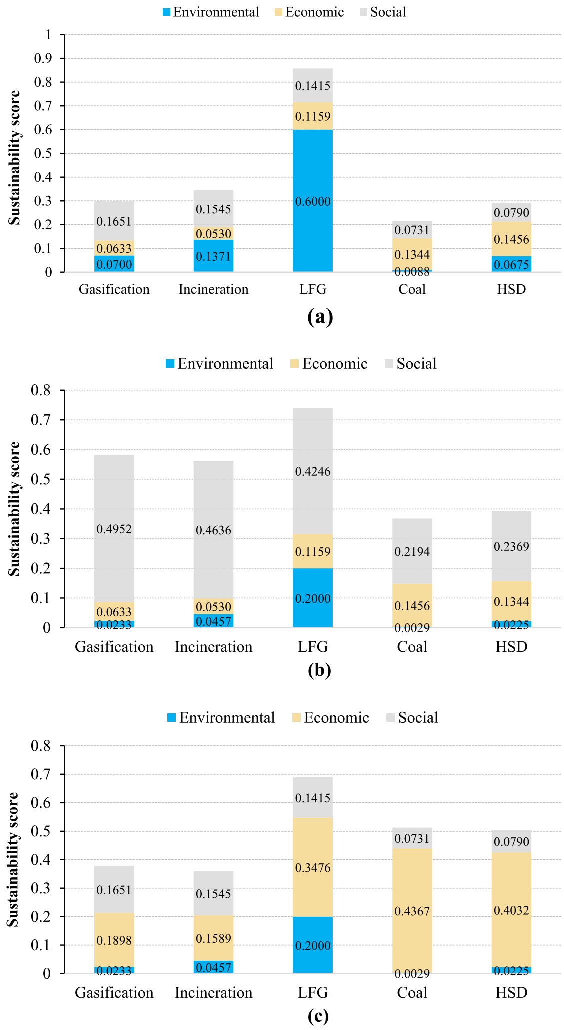

Fig. 17. Final sustainability score with different importance weights. (a) The e-LCA aspect is three times more important than the other two aspects, (b) the s-LCA aspect is three-time much important than the other two aspects, (c) the LCC aspect is three times more important than the other two aspects.

When LCC is three times more important than e-LCA, and s-LCA (Fig. 17, c), the ranking of technologies changes completely. As mentioned before, fossil fuels are more attractive from an economic point of view, and with the increase of the importance coefficient of LCC, coal, and HSD assign scores of 0.51 and 0.5, respectively, which is much higher than gasification and incineration.

The proposed results in Fig. 16 for all three cases showed that by changing the importance coefficients, LFG is still the most sustainable technology for western Lombok. The analysis of this paper shows that only when the importance weight of seven times ($w_i = 0.78$) is considered for LCC, the coal power plant has the highest ranking. These results show the flexibility of the proposed method to analyze the final sustainability score and make the decision-making process more effective.

While the results prove the significant role of the WtE application in terms of waste management and sustainability, still there are different challenges for WtE implementation. In the following, this paper discusses possible supportive policies and practical challenges in terms of WtE implementation.

3.5. Supportive policies and their potential impact on the feasibility of WtE

Implementing WtE technologies in Western Lombok requires supportive policies that facilitate investment, technology adoption, and public acceptance. Indonesia has policies promoting renewable energy, but specific incentives for WtE technologies are limited. To address this gap, a multifaceted policy framework is necessary to create a conducive environment for WtE projects as follows:

1. Feasible policy measures could include tax incentives for WtE projects, such as reduced corporate taxes and tax holidays for the initial years of operation. These incentives would make WtE investments more attractive to private investors and reduce the financial burden on project developers. Additionally, subsidies for initial capital investments can lower the entry barrier for new projects, ensuring that more players can participate in the development of WtE infrastructure.

2. Regulations mandating waste segregation at the source are critical for ensuring a consistent and high-quality feedstock for WtE plants. Such regulations can be supported by providing households and businesses with the necessary resources and education to implement effective waste segregation practices. The government can also introduce penalties for non-compliance to enforce these regulations more strictly.
3. Furthermore, feed-in tariffs specifically designed for electricity generated from WtE technologies can provide a stable revenue stream for WtE plant operators. Feed-in tariffs guarantee a fixed price for electricity fed into the grid, which can significantly improve the financial viability of WtE projects. This policy has been successfully implemented in various countries to promote renewable energy adoption and can be tailored to suit the local context in Western Lombok.
4. To enhance public acceptance, community engagement and education programs are essential. These programs should aim to raise awareness about the environmental and social benefits of WtE technologies, addressing common misconceptions and concerns. By involving local communities in the planning and decision-making process, project developers can build trust and gain public support. Educational campaigns can also highlight the potential economic benefits, such as job creation and local economic development, further strengthening community backing.

Moreover, aligning local policies with national and international environmental goals can attract funding and technical assistance from global organizations.

3.6. Practical challenges and solutions for WtE

Implementing WtE technologies in Western Lombok presents several practical challenges. Infrastructure development is crucial, including the establishment of waste collection systems, transportation networks, and WtE plant facilities. Effective waste collection systems ensure that sufficient and high-quality waste feedstock is available for energy generation. Developing transportation networks is equally important to facilitate the efficient movement of waste from various collection points to the WtE plants. Public acceptance is another critical factor, which can be fostered through awareness campaigns and community involvement in project planning. Ensuring that the local population understands the benefits and addresses any concerns they might have can lead to greater community support and cooperation. Additionally, there is a need for technical expertise, which could be addressed by training programs and partnerships with international experts. These programs can help build local capacity and ensure that the WtE plants are operated efficiently and effectively. By addressing these challenges, the successful implementation of WtE technologies can be achieved.

Moreover, securing financial investments and navigating regulatory landscapes pose additional challenges. Attracting investments requires a clear demonstration of the project's economic viability and long-term benefits. This can be achieved through comprehensive feasibility studies and presenting successful case studies from other regions. Regulatory hurdles, such as obtaining necessary permits and compliance with environmental standards, need to be managed proactively. Establishing a streamlined regulatory process can facilitate faster project implementation.

4. Conclusion

Lombok is one of the most populated southern islands of Indonesia which suffers from the lack of a waste management system and sufficient electricity capacity. This paper considered these two challenges as a suitable opportunity to examine the 2030 power generation development scenarios in Lombok, under the integrated life-cycle sustainability assessment, considering all economic, social, and economic aspects. A comparative analysis for incineration, gasification, landfill gas, diesel, and coal power plants was evaluated considering 12 sustainability indicators based on a flexible multi-criteria decision-making approach. Results showed LFG is the most sustainable technology for western Lombok among all options scoring around 0.78. Diesel has the highest economic ranking with a score of 0.243. Also, gasification technology has the highest social ranking with a score of 0.275. The proposed method as a flexible decision support framework analyzed the robustness of the results for extreme decision-making by changing the importance weights so that even if the economic aspect is 3 times more important than the other two aspects, LFG has the highest ranking. The analysis showed that if the economic aspect is considered extremely 7 times more important, then coal is the best option. The sensitivity analysis of this paper indicated that deviation in electricity prices in the future can change capacity development strategies in such a way that with a 20 % increase in electricity prices, incineration, and gasification options will have a higher ranking than fossil fuels for electricity generation.

Future works

This paper focuses on life cycle sustainability assessment under the multi-criteria decision-making approach while the aspect of temporal precision is not addressed. For future research, the authors recommend extending this work to incorporate dynamic life cycle assessment. This would involve integrating multiple temporal precisions to account for the time-dependent variations in power production models. Such an approach could provide a more accurate representation of the future energy mix, thereby enhancing the robustness and relevance of sustainability assessments.

Also, to meet the growing power demands of Western Lombok, scaling up WtE technologies is essential. This can be achieved through incremental expansion of existing plants, development of additional WtE facilities, and integration with other renewable energy sources. Projections indicate that future power demand will require a multi-faceted approach, where WtE technologies play a key role. Strategic planning and investment in scalable infrastructure will be critical to accommodate this growth. For example, modular WtE plants can be developed, allowing for phased expansion as demand increases. Additionally, integrating WtE technologies with smart grid systems can enhance the efficiency and reliability of the power supply.

CRediT authorship contribution statement

Mohammad Hemmati: Writing – original draft, Software, Resources, Methodology. **Navid Bayati:** Writing – review & editing, Validation, Supervision. **Thomas Ebel:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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