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Research paper

Techno-economic assessment of energy and environmental impact of waste-to-energy electricity generation

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ABSTRACT

This study explored cumulative 127.5MW waste to energy (WtE) potential in five populous cities of Pakistan based on local waste characterization profiles and global standards. The 50MW WtE plant in Lahore using National electricity regulator codes and practices resulted in an attractive Levelized cost of electricity (LCOE) of US¢ 7.86/kWh over 25 years with a $151.5 million investment cost. The net savings to Lahore Waste Management Company can be $103.4 and $137.7 million respectively with and without tipping fees on account of waste disposal cost, bricks revenue using bottom ash, and waste fee. The project developers can get net savings of $16.9 and $51.5 million respectively with and without tipping fees other than LCOE. Furthermore, the greenhouse gas emissions of 216.6 million tons of CO_{2eq} can be saved throughout plant life against 279 GWh/year energy generation, in terms of grid emission factor and current methane release into the atmosphere from the dumping site.

1. Introduction

Energy contributes a dynamic role in the social and economic growth of a nation and the energy demand has an ever-increasing trend globally (Asim et al., 2022a). Global renewable energy generation has experienced a rapid acceleration in the last two decades mainly because of a sharp decline in the associated capital and manufacturing costs, particularly for solar photovoltaic (PV) and wind power (Asim et al., 2022d; Rehman Tahir et al., 2018). Most nations of the world have set INDC targets for fast deployment of renewable energy generation in their future energy portfolios and are working towards the achievement of those green objectives (Asim et al., 2022c,b). Pakistan currently has only around 5.0% of its total energy attributed to renewable energy sources despite the huge potential for energy generation from solar, wind, biomass, and solid waste. The government of Pakistan has set targets to increase the renewable share of energy generation up to 20% by 2025 and to 30% by 2030 in the Alternative & Renewable Energy (ARE) Policy (AEDB Pakistan, 2019; Saleem et al., 2021).

Developing countries like Pakistan are also facing a worse challenge of ever-increasing municipal solid waste (MSW) which is dangerous for the environment and human health. Kaza et al. (2018) reported that the daily waste generation in Pakistan is about 0.43 kg/capita. However, this is more than 0.6 kg/capita/day in Lahore, the most populous city of Punjab province and 2nd most populous city in Pakistan. The MSW generation trend in Pakistan and other South Asian countries, is presented in Fig. 1. MSW generation mainly depends on the population growth rate, urbanization development, economic activities, and social behaviors or norms that an individual country may have Vergara and Tchobanoglous (2012). The percentage composition of MSW in South Asian countries is presented in Fig. 1 (Kaza et al., 2018).

The global MSW is around two billion tons for the year 2016 and is forecasted to be 2.59 and 3.4 billion tons for the years 2030 and 2050 respectively. The generation of MSW in South Asia is 334 million tons with an average rate of 0.52 kg/capita/day and this quantity would be double by the year 2050. Pakistan produces around 32 million tons of solid waste in a year with an average rate of 0.43 kg/capita/day. The urbanization rate in Pakistan is high along with the increased population growth rate results in a higher waste generation (Cudjoe and Acquah, 2021; Elagroudy et al., 2016; Ferdous et al., 2021). The trends and quantification of MSW are normally categorized in low, lower-middle, upper-middle-, and high-income areas. A detailed description of the solid waste composition in South Asia is shown in Fig. 2 based on the income level of countries.

Waste-to-Energy (WtE) is a popular solution of MSW management and has emerged as a successful technology in the last few

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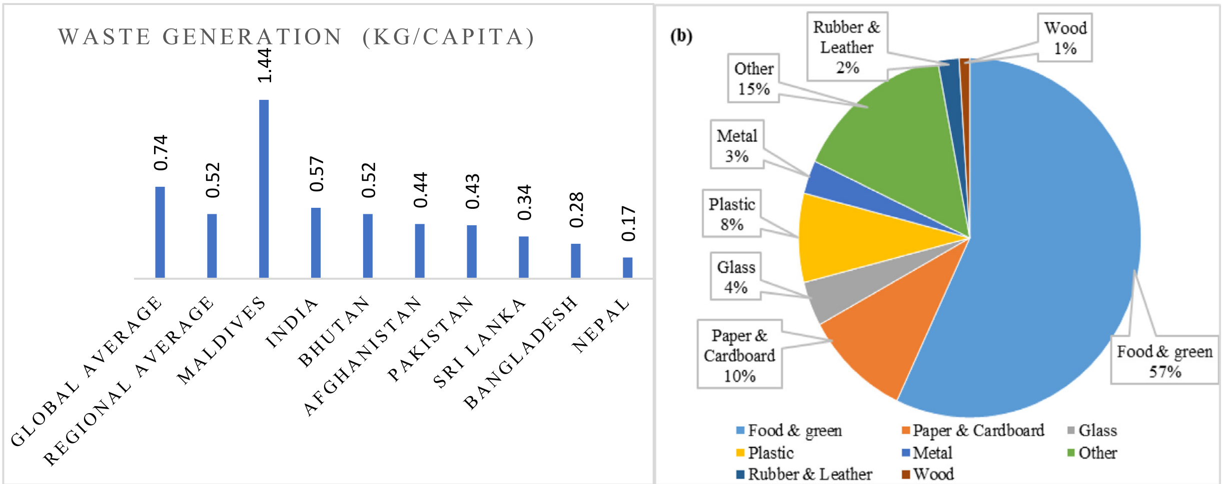

Fig. 1. Solid waste generation in South Asia; (a) country-wise generation, (b) waste composition (Kaza et al., 2018).

Nomenclature

WtE	Waste to Energy
NEPRA	National Electric Power Regulatory Authority
MW	Megawatt
GWh	Giga watt-hour
CO_2	Carbon dioxide
GHG	Green House Gas
kW	Kilo Watt
MJ	Mega Joule
USD	United States Dollar
LIBOR	London Inter-Bank Offered Rate
kg	Kilogram
WASA	Water and Sanitation Agency
DISCOs	Distribution Companies
AQI	Air Quality Index

years (Nandy et al., 2022). The overall hierarchy of solid waste integration systems comprises logical steps starting from waste avoidance and minimum waste generation, collection, storage (primary & secondary), transportation, processing, recovery, and finally disposal of solid waste through WtE technologies (Chen et al., 2022). The WtE conversion technologies include incineration or controlled landfilling and methane capturing for energy generation (Rehan et al., 2019).

The dumping of solid waste is becoming unsafe and unhealthy for the public and damaging our environment with air pollution and hazards in Pakistan. The large heaps of dumped solid waste without any scientific treatment such as landfills or waste treatment plants are creating innocuous upset and grief in society. Moreover, the rain and outset created leachate of solid waste penetrating land is a risk for potential drinking water for the associated periphery of dumping waste (Das et al., 2019). The land is reserved for two dumping sites in Lahore, one dumping site has already closed with around 13 million tons of MSW being dumped there, depicted in Fig. 3 (Lahore Waste Management Company, 2022). The only dumping site currently operational in Lahore is with only a small portion of the area reserved for landfill whereas most of the area is being used for open dumping as shown in Fig. 4 (Lahore Waste Management Company, 2022). Open dumping of solid waste causes several diseases due to emissions of methane, CO_2, and other greenhouse gases which are also damaging our environment (Ali Shah et al., 2021)

Landfills do not decrease the volume of waste and require more land whereas WtE can reduce the waste down to 25%–30% by weight and 10% by volume through incineration. The MSW is an alternate or renewable fuel that is being used globally for the generation of electricity, heat, and many other applications (Sohoo et al., 2021b). WtE technologies offer an option to solve not only the pressing waste disposal problems but several other challenges simultaneously, such as greenhouse gas emissions from inappropriate waste disposal, scarcities in power production, and inadequate space for dumping (Akmal and Jamil, 2021).

Different waste conversion technologies are used for different waste feedstock available and different conditions as shown in Fig. 5. Incineration or direct combustion of MSW is the most popular and successful in lower-middle-income countries in recent years.

The incineration-based mass burning of solid waste stands out as a prudent technology and is commercially more economical in comparison with other technologies such as methane capturing of a controlled sanitary landfill, and gasification.

WtE projects developed in region having similar MSW profiles like Pakistan, are successfully using mass burning of MSW through direct combustion with high standards of flue gas control systems (Xin-Gang et al., 2016; Dhar et al., 2017). The gasification and pyrolysis have higher upfront costs and limitations in upscaling plant sizes, requiring a higher calorific waste but are more environmentally friendly. The governments and administrations, instead of environmental waste disposal costs, offer subsidies in form of tipping/gate fees other than the energy generation price from solid waste (Ali Shah et al., 2021). Electricity generation from WtE plants can be transmitted to the national grid as another advantage in addition to reduced emissions and diseases. The residual ash can be used to build roads, buildings, ferrous metals, or bricks. A typical incineration-based WtE power plant including a waste handling system, an environment system comprising bag filters, and an energy generation system with a steam turbine and generator is depicted in Fig. 6 (Alam, 2019). The schematic also indicates the use of end products other than electricity available for the grid, such as space heating or cooling.

There are more than 1200 WtE incineration plants globally in more than 40 countries. China had around 300 operational incineration-based WtE plants with a power generation capacity of 6250 MW and a waste treatment capacity of 52.36 million tons (Cudjoe and Acquah, 2021; Cabré et al., 2018; Ding et al., 2021;

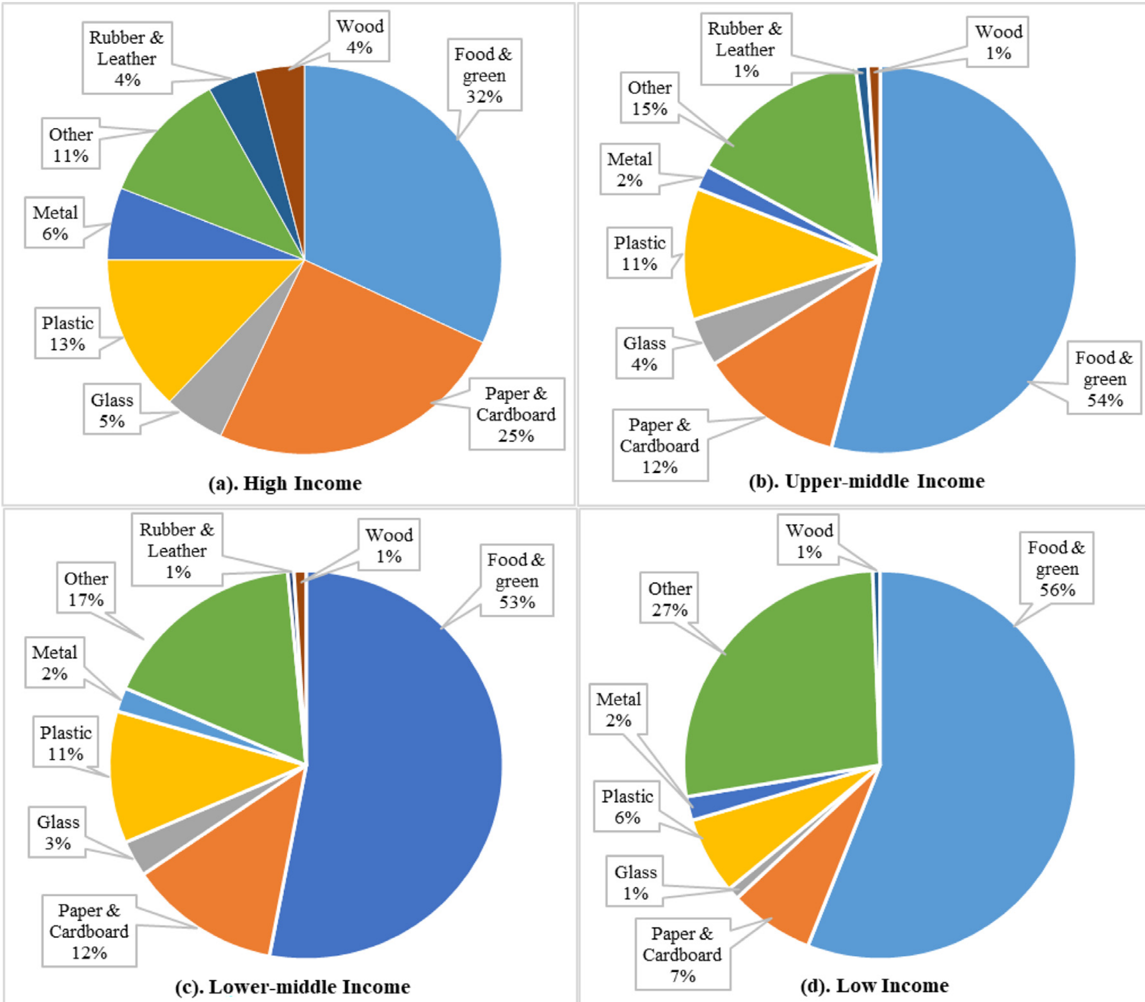

Fig. 2. Solid waste composition of South Asian countries based on income levels (Kaza et al., 2018).

Fig. 3. Mehmood Booti Dumping Site at Lahore.

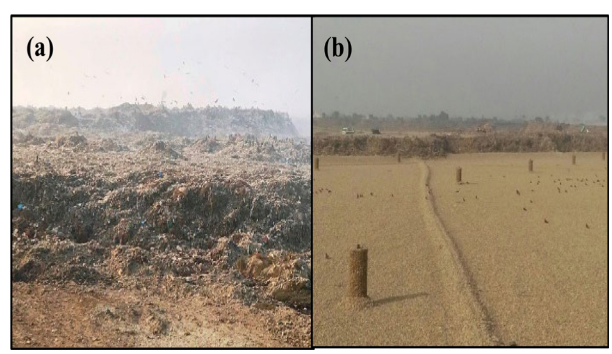

Fig. 4. Lakhodair dumping site (a) open dumping (b) landfill area.

Jin et al., 2021; Kosajan et al., 2021). The tipping payments from the local administrations fluctuated from 13.04 to 19.56 $/ton and were exempted from excise duty and value-added tax (VAT) (Manegdeg et al., 2021).

The techno-economic evaluation with waste disposal tipping/gate fee as well as without tipping fee, and energy cost evaluation in the form of Levelized tariff would help the policymakers, project developers, and power consumers to reach a decision. It would also help in attracting private investment for the development of WtE project(s) soon in Pakistan. Table 1 provides project Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) comparisons in China, Europe, and the United States of America for incineration and anaerobic digestion-based WtE projects (Kaza et al., 2018).

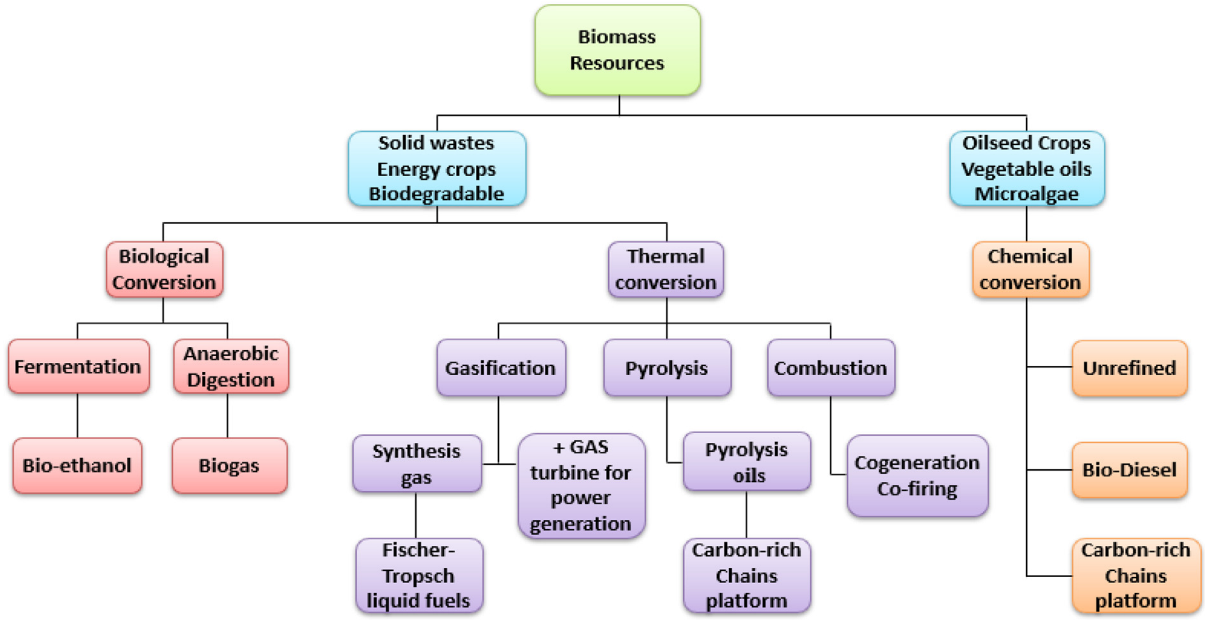

Fig. 5. Different waste conversion approaches for WtE systems (Zinoviev and Miertus, 2021).

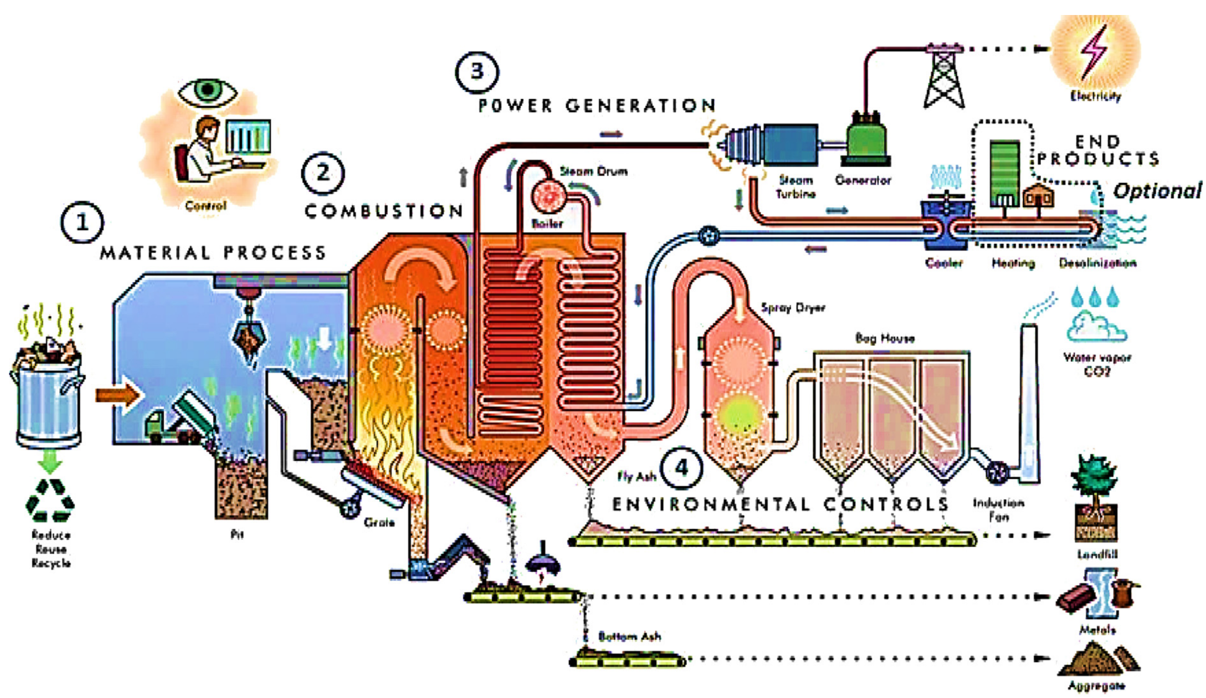

Fig. 6. Schematic diagram of a typical MSW incineration based WtE power plant.

This study aims to provide suggestive measures to policymakers, decision-makers, and project developers about WtE potential in five cities and a techno-economic assessment for Lahore for evaluating LCOE, potential environment savings, and other associated benefits based on prudent incineration-based technology. The study includes evaluating the size of the WtE plant, and its economic and environmental viability in Lahore. The estimated project sizes, based on waste generation rate, collection, and availability for Faisalabad, Gujranwala, Multan, and Rawalpindi are also evaluated. A Waste Characterization Study (WCS) of Lahore conducted by Lahore Waste Management Company (LWMC), analysis of technical input data from International Renewable Energy Agency (IRENA) along with operational WtE plant data, and the typical financial parameters of National Electric Power Regulatory Authority (NEPRA) of Pakistan is used. The last 10 years' consolidated data compiled globally for all renewable power projects including WtE is maintained and freely available from ARENA only. The mentioned data are used to prepare techno-economic financial model to assess the Levelized cost of energy for the grid. The environmental impact is assessed

Table 1
Comparison of expenditures of WtE in China, Europe & United States.

Countries	Incineration		Anaerobic digestion	
	CAPEX (USD/ton)	OPEX (USD/ton)	CAPEX (USD/ton)	OPEX (USD/ton)
China	190–400	12–22	325	25
Europe	600–1000	25–30	345–600	31–57
United States	600–830	44–55	220–660	22–55

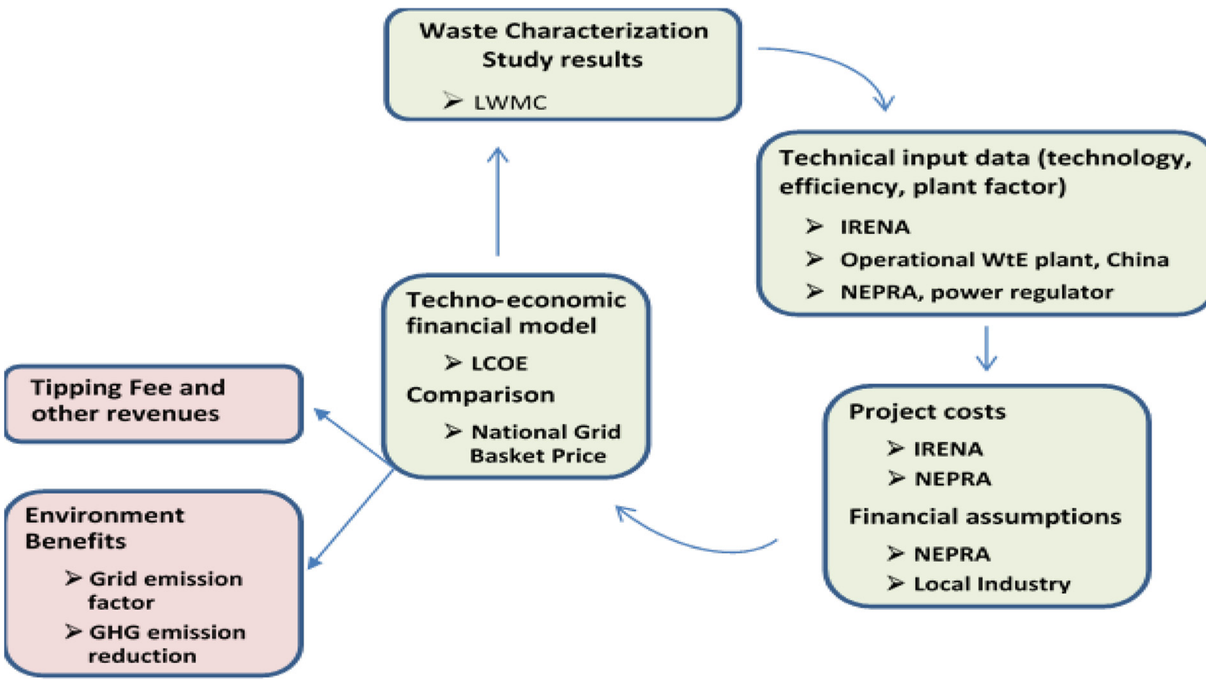

Fig. 7. The methodology adopted for current research work.

in terms of GHG emissions based on the guidelines from the Asian Development Bank (ADB) (World Bank Group, 2020).

2. Methodology

The focus of this research is to assess the potential of Waste to Energy (WtE) capacity or size based on the collection of available waste reached a dumping site in five populous cities of Pakistan. The quantity (available waste) and quality of MSW are key parameters for ascertaining the WtE potential in the above-mentioned cities as well as the techno-economic/environmental assessment and associated potential benefits one of the most populous city of Lahore. The quantity of MSW is linked with its availability via waste generation as per population of above cities and collection of MSW from Waste Management Companies.

The waste characterization study conducted by LWMC was based on random waste sampling in different seasons (winter, summer, rainy monsoon season, etc.) around the year (Ozcan et al., 2016). The locations in the data were selected based on the global methodology of low, lower-middle, upper-middle, and high-income areas where waste generation trends are different. The overall methodology and its components for this research work are shown in Fig. 7.

Data of lab results of WCS taken from LWMC which is a regular activity at their end. The prime focus is to assess the techno-economic/environment assessment of Lahore waste where environment urgency emerged due to the increased intensity of dumped waste of 24 million tons. Though, the WtE potential and project sizing for other cities are also estimated.

The plant efficiency and plant availability factors are other key factors to determining the plant capacity generally (in MWs). Plant efficiency relates to the overall efficiency in consideration of the conversion of heat value into electrical output.

The reference WtE plants established in China are considered in the research because of efficiency of incineration-based technology helps in assessing the potential capacity of WtE at Lahore, Faisalabad, Gujranwala, Multan, and Rawalpindi. The national electricity and power regulator also recommended such efficiency-based WtE plants in its Feed-in-tariff determination for MSW-based projects. Also, the waste characterization of Pakistan is similar to regional countries like China. Table 2 shows the waste supply, power generation capacity, and efficiency of the mentioned Chinese WtE plants.

The data presented in Table 2 is just a reference and comparison to show the bankability of the WtE project in Pakistan. The waste characterization study, waste calorific value, plant sizing, and all other economic parameters are standard in line with national and international practices. The economic model used is specifically suitable for local policies and practices.

Current practice for the collection of solid waste is considered for Lahore city as provided by LWMC. World Bank also endorses the collection of Lahore waste about 68%. Only 42% of collected waste in Lahore was assumed as available for the WtE plant at Lahore i.e., 2000 tons/day of MSW in the study. According to LWMC, 30%–40% of waste streams were either in use or in the planning of composting or supply to the industry where it was used as Refused Derived Fuel (RDF). Different scenarios were employed by assuming 2000 tons/day of MSW for determining the capacity of the Lahore WtE project by using different values of calorific value, efficiency, and plant factor. Table 3 presents the key input values that are employed in this study to determine

Table 2
Efficiency of WtE plants with power capacity in China (Xidong, 2022; Grantop, 2022; Everbright Environment, 2022).

Plant name	Waste supply (tons/day)	Power capacity (MW)	Efficiency (%)
Guangzhou Panyu	2000	40	22.3
Hebei Julu	2000	40	20.6
Wuxi Xidong	2000	40	21.9
Nanjing Tongjing	2000	40	21.3

Table 3
Waste generation in cities as per world bank & WMCs data.

City	Population in the 2017 Census (millions)	Average waste generation[a] (kg/day)	Waste generation[b] (kg/day)	Estimated waste generation (tons/day)	Waste collection[c] (tons/day)	Waste available for WtE plant (tons/day)
Lahore	11.12	4,781,600	7,005,600	7000	4760	2000
Faisalabad	3.23	1,388,900	1,615,000	1600	1088	1000
Gujranwala	2.80	1,204,000	1,204,000	1200	816	800
Multan	2.25	967,500	1,012,500	1000	680	700
Rawalpindi	2.09	898,700	877,800	875	595	600

[a]As per World Bank report.
[b]As per WMC & PEPA.
[c]Waste collection @68% as per World Bank report.

WtE potential and plant size in MW for the available MSW at Lahore, Faisalabad, Gujranwala, Multan, and Rawalpindi.

The following method is used to calculate size that covers data from five major steps;
Waste available = B = kg/year
CV = Calorific Value = D = MJ/kg
E = 1 kWh = 3.6 MJ
F1 = efficiency = %
G = Plant availability factor = hours
Project Plant Capacity (MW) = $(B \times D \times F1)/(E \times G)$ = MW

The trend for global weighted average capacity factors for biomass/WtE-based sources of power generation was considered for the assessment in this study from Ref. Grantop (2022). Plant efficiency and plant factor both are used to assess the potential capacity of the WtE power plant. The range of plant capacity factors was taken from the IRENA data bank. Regulator NEPRA indicated same in the proposed Feed-in-tariff for MSW-based power plants. IRENA Global Atlas also provided consolidated CAPEX data and the Levelized cost of electricity (LCOE) for biomass/WtE for the decade 2010–20 indicated in Ref. Everbright Environment (2022). The installation cost for bioenergy/WtE plants was in the range of 1269–3064 USD/kW. NEPRA allowed a project cost of 3.5 million USD/MW in its proposed upfront tariff determination for MSW-based power projects.

The economic assessment is based on the potential sector investment typically involved in Independent power producers (IPP) based development cycle where debt and equity along with other relevant financial assumptions are used. All financial assumptions used by NEPRA has considered and indicated in the assessment by using a model to determine LCOE. The aim is to provide suggestive measures to policymakers, decision-makers, and project developers about the commercial viability of the WtE potential project at Lahore. The CAPEX has assumed 3 million USD/MW into consideration of the IRENA Atlas dataset for incineration based WtE projects.

The other financial assumptions are used in this study based on bankable private investment parameters, industry norms, and the assumptions typically used by NEPRA for electricity generation tariff determination. The key financial assumptions were Equity, Debt, Return on Equity, Internal Rate of Return of the project, and foreign financing markup on LIBOR which revolved around CAPEX and OPEX. A 12-year private investment was assumed, 4.5% LIBOR as mark-up rate, 75%–25% debt–equity proportion, Engineering Procurement Construction (EPC) cost of 2.5 million USD/MW, 3 million USD/MW CAPEX, 5% of EPC as OPEX, 3-year construction period, 0.5% of EPC as insurance during construction. Those were the major input values used in the techno-economic financial model which was prepared to assess the LCOE of the WtE plant for Lahore for 25 years based on foreign investment of equity and debt and then a similar model was employed for the other four cities as well.

A scenario is built up with assumptions for the award of a tipping fee and without a tipping fee as an opportunity cost to the project developer by LWMC. The focus is to create scenarios of additional revenue streams of tipping fees and associated potential benefits other than grid tariff. The aim is to envisage the opening towards sustainability of LWMC by ways and means for a circular economy of waste. Similarly, potential savings are assessed for both LWMC and potential project developers over the plant life of 25 years. The scenario of sharing mechanism for both LWMC and the project developer is introduced.

The potential environmental benefits are assessed following Asian Development Bank (ADB) guidelines for estimated Green House Gas (GHG) emissions. The fossil fuel-based Grid Emission Factor and Savings of methane emission through the WtE plant are used to determine savings of ton CO_2 equivalent.

ADB guidelines estimated that when methane CH4 is released into the atmosphere, GHG emissions can be calculated with the following equation;
GHG emissions = M CH_4 × GWP CH_4
Where CH_4 = amount of CH_4 released into the atmosphere, tons of CH_4/year
GWP CH_4 = Global Warming Potential of CH_4, 25 tons of CO_2/ton of CH_4

3. Results and discussions

The results for the waste characterization for the five cities, the power capacity evaluation for WtE projects, the tariff evaluation for a 50 MW WtE project, other potential revenues from a WtE plant besides electricity generation, and the environmental impact of WtE projects development in Pakistan are presented. However, the detailed techno-economic assessment, environmental assessment, and associated potential benefits are calculated in detail for Lahore due to the following reasons:

There is an emergent environmental situation in Lahore in terms of the increased intensity of dumped waste. The emission of methane from dumped waste, which is 25 times more potent than CO_2, damages the city environment and Lahore's Air Quality Index (AQI) is ranging from 300–500 in the last few years. One

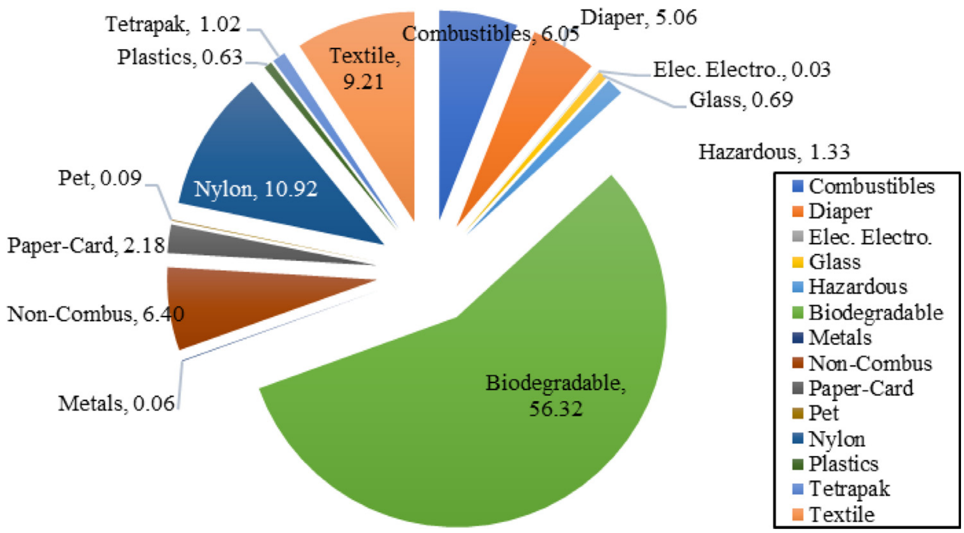

Fig. 8. Waste characterization of Lahore with weighted average values.

dumping site has already to its full capacity and closed with more than 13 million tons of MSW and the present operational landfill/dumping site has already dumped waste of 10 million tons. Waste available around 2000 tons/day; economies of scale for the WtE project and WCS results available for Lahore waste.

3.1. Waste characterization study

Accurate and verified waste characterization data is only available for Lahore both by a waste management company as well as the world bank. The accuracy of data is key for economic viability and project bankability. For other cities, it was just an estimate of potential plant size and it further needs thorough investigation from waste collection to waste characterization.

The data from the waste characterization study (WCS) conducted by LWMC as the fractional composition of MWS and weighted average values are indicated in Fig. 8. The results of WCS clearly showed that there was a high percentage of organic waste as learned in other low-income countries. Combustible fractions including PET, nylon, textile, and tetra pack were also relatively in a considerable amount despite the higher scavenging effect. The fraction of hazardous waste found in the mixed waste was very minimal. The composition of MSW is based on the average results of each economic category of people living in Lahore. The physical properties of solid waste from the Proximate Analysis (PA) are indicated in Table 3. Lab results of PA are presented on ARB—As the received basis, ADB—Air Determined basis/As the determined basis, and DB—Dry basis. The results show that the average Gross Calorific Value (GCV) for ARB is around 1711 kcal/kg, and this is the key value to be used in determining the plant size capacity. Moreover, around 25% of ash contents showed approximately 25 tons of bottom ash generation with the burning of 100 tons of solid waste (see Table 4).

3.2. WtE potential evaluation

The results from the waste characterization study for Lahore, the technical details of currently operational WtE plants, and the financial assumptions from NEPRA for tariff evaluation of WtE plants were used in this study to develop a financial model. The model was implemented on different scenarios with different input parameters and the WtE plant capacity was evaluated in each case. The waste availability for a WtE power project in Lahore was kept at 2000 tons/day as provided by the LWMC which is equivalent to 7.3 $\times$ 10^8 kg of waste available every year. The calorific value of the waste was kept as 1711 kcal/kg or 7.15 MJ/kg in one set of scenarios and 6.5 MJ/kg in the second set of scenarios. The plant efficiency was consecutively kept as 22%, 25%, and 28% in scenarios of both sets. The WtE plant was assumed to operate with a 75% availability factor i.e., for 6570 out of the 8760 h in a year. The WtE power plant capacity for the efficiencies of 22%, 25%, and 28% was evaluated to be 48.5 MW, 55 MW, and 61.8 MW respectively with the higher calorific value. The power capacity for the same efficiencies was 44 MW, 50 MW, and 56.2 MW respectively with the more conservative calorific value of 6.5 MJ/kg.

The data assumptions in the above scenarios are compared and the scenario with the conservative 6.5 MJ/kg waste calorific value and a moderate plant efficiency of 25% was used to determine the WtE plant capacity in Faisalabad, Gujranwala, Multan, and Rawalpindi. The assumptions from the WtE evaluation for Lahore were projected onto the WtE projects for other cities due to the lack of waste characterization data for those cities. The corresponding waste availability values of the four cities were used as provided by their respective WMCs and the plant availability was kept at 6570 h. The power capacity of a WtE plant at Faisalabad was calculated as 25 MW with 1000 tons/day waste availability, for Gujranwala the capacity was 20 MW with 800 tons/day waste available, for Multan the capacity was 17.5 MW with 700 tons/day waste available, and the capacity for WtE project at Rawalpindi was 15 MW with 600 tons/day waste availability.

3.3. Techno-economic assessment

The techno-economic tariff model used in this study is based on the NEPRA financial assumptions largely used in tariff determination for power generation projects for the sale of electricity to the national grid. The technical and financial assumptions are obtained from NEPRA tariff determinations for bagasse and MSW-based power generation projects and implemented for a 50 MW WtE power plant in Lahore based on 2000 tons/day of waste availability. The assumptions were in line with IRENA cost data series and industry norms for bioenergy and solid waste-based projects available for the national grid. Moreover, the financial model is based on private-sector foreign financing. The LCOE was determined by using CAPEX, working capital, plant factor,

Table 4
Waste characterization study lab results (PA).

Parameters	Basis	Waste classification				Average
		Low	Middle	High	Inst/Comm	
Total moisture (%)	ARB	37.47	57.34	39.33	40.35	43.62
	ADB	5.30	20.87	11.08	5.28	10.63
Volatile matter (%)	ARB	27.20	23.96	30.91	31.42	28.37
	ADB	42.12	44.59	45.31	49.74	45.44
	DB	44.49	56.85	50.96	52.48	51.20
GCV (kcal/kg)	ARB	1620.67	1499.67	1869.33	1855.67	**1711.33**
	ADB	2507.67	2747.67	2739.33	2924.67	2729.83
	DB	2650.33	3512.33	3081.67	3082.00	3081.58
Ash content (%)	ARB	32.09	15.26	27.58	23.84	24.69
	ADB	47.85	27.86	40.40	37.67	38.45
	DB	50.48	35.00	45.44	39.72	42.66
Fixed carbon (%)	ARB	3.23	3.44	2.17	4.40	3.31
	ADB	4.73	6.67	3.21	7.31	5.48
	DB	5.03	8.16	3.60	7.81	6.15

and OPEX including variable and fixed costs. Waste fuel cost was assumed zero. The assessed LCOE was compared with the average generation basket price of Pakistan. Table 5 lists the techno-economic model and associated assumptions.

3.4. Tariff for WtE plant

The Levelized tariff for the 50 MW WtE plant was evaluated corresponding to the total project cost of around USD 151.5 million with 25% equity and 75% debt, 15% return on equity and 4.5% mark-up rate, loan tenure of 12 years, and equity IRR of 12.17%. The outcomes of the financial model for the 50 MW WtE plant in Lahore are presented in Table 6. The tariff was evaluated as the sum of the variable and fixed costs for operation and maintenance, insurance, working capital, return on equity, principal, and markup rate in US¢ per kWh of energy generation. Table 7 presents the trend for the tariff value as well as for the constituting elements for the years 1, 2, 12, and 25. The Levelized tariff will be US¢ 8.9678/kWh from year 1 up until year 12. The principal and mark-up amounts will drop to zero after the loan tenure and will remain zero till the end of plant life at year 25. The levelized tariff after year 12 will be US¢ 4.5417/kWh. Overall, the levelized tariff for the 50 MW WtE plant with a 25-year operational life was evaluated to be US¢ 7.8641/kWh.

The data from the NEPRA State of Industry Report depicting all DISCOs data was taken and the LCOE of US¢ 7.8641/kWh was compared with the current average tariff of Pakistan to assess the commercial viability and to meet the requirement under ARE Policy 2019. The average tariff in Pakistan is around US¢ 12.13/kWh without taxes & duties. If on average, 20% transmission and distribution losses account for this uniform average tariff, then the average generation basket price becomes US¢ 9.73/kWh. This clearly shows that the LCOE of US¢ 7.8641/kWh for a 50 MW WtE plant at Lahore, based on foreign financing, is less than the average generation basket price and easily meets the requirements under ARE Policy for the development of the WtE project under new technology mode.

3.5. Other financial revenue streams

3.5.1. Waste handling cost

The NEPRA tariff determination for incineration-based power generation using MSW in the year 2018 mentioned that the handling cost of solid waste at a landfill/dumping site was about PKR 850/ton. Each ton of waste used in the WtE project would hence cause a handling cost of around USD 4.25 (USD 1 = around PKR 200). Waste disposal cost, as opportunity cost, because of the WtE power plant at Lahore was assessed for 2000 tons/day of waste availability. The annual waste usage based on 75% plant factor i.e., for 274 days is 548,000 tons and the waste handling cost at the dumping site including machinery, manpower, and operational cost make up the yearly savings of around USD 2.33 million. So, for a total plant life of 25 years, revenue in terms of waste handling cost can be USD 58.25 million. A tipping fee can be offered to the project developer by the Municipality/Waste Management Company through the above-mentioned savings. If USD 2.125/ton of waste as a tipping fee is offered to the project developer i.e., 50% of USD 2.33 million per annum for 25 years; the total saving in handling cost will be USD 29.125 million and the project remains economically feasible.

3.5.2. Bottom ash for bricks

The waste consumption in one year based on a 75% plant factor was 548,000 tons per annum. 25% of this value would produce 137,000 tons of bottom ash per annum. A recent study and market analysis revealed the feasibility of the production of bricks by using bottom ash with silica after separating slag from ash. Only 50% of the bottom ash is used to mix with cement as a stabilizer and water to prepare bricks after separating heavy metals. It is estimated in the paper that a ratio of 80% ash and 20% cement is employed. 1.8 kg of ash with 0.45 kg cement and 0.9 kg water is used to produce one brick (WASA, 2022). This shows that 38,055,555 bricks can be produced with the above-estimated values and around 342,500 bags of 50 kg cement would be utilized. The bricks cost is estimated on the market price of bricks at PKR 13/brick, cement cost at PKR 675 per 50 kg bag, and water use charges by WASA notified at PKR 134.27 per thousand gallons. Water consumption would be around 34,250,000 kg or 10, 282 gallons. Since the bottom ash produced from waste belongs to LWMC, therefore it was proposed that the cost on account of cement and water may be incurred by the project developer. Therefore, bricks revenue can be shared 50% each to LWMC and the project developer equivalent to PKR 118.233 million or USD 591,165 per annum and PKR 2.95 billion or USD 14.75 million for the 25 years of plant life.

3.5.3. Waste collection service

Keeping in view the collection of waste as a service and not as a facility, it is important to raise public awareness amongst the masses to pay for this service of waste collection. Further, to ensure the sustainability of WMC, minimum waste charges are necessary. Presently, residents pay waste charges in an unregularized way ranging from PKR 50 to 300. According to WASA (Gómez-Sanabria et al., 2022), 610,000 public water connections

Table 5
Techno-economic model with associated assumptions.

Financing terms			
	Basis of assumption	Unit	Amount
Loan term	NEPRA/IRENA	Years	12
Mark-up rate	NEPRA/IRENA	%	4.50
Working capital			
Working capital	IRENA (0.1% of EPC)	USD/year	125,000
Mark-up rate	NEPRA	%	4.35
Capital cost assumption			
Direct cost/EPC cost	IRENA (2.5 M USD/MW)	USD	125,000,000
Non-EPC cost/Indirect cost			–
Project development cost/Consulting fee	IRENA/NEPRA (7.5% of EPC)	USD	9,375,000
Customs and sales tax	NEPRA (5% of EPC)	USD	6,250,000
Pre-commissioning/Commissioning cost	NEPRA (1% of EPC)	USD	1,250,000
Insurance during construction	IRENA/NEPRA (0.5% of EPC)	USD	625,000
Financing charges	Industry norm	% of Debt	1.50
OPEX			
Insurance during operations	IRENA/NEPRA (0.5% of EPC)	USD/year	625,000
Fixed maintenance cost	IRENA/NEPRA (2% of EPC)	USD/year	2,500,000
Variable O & M			
Outsourcing auxiliary material	Industry norm (1.5% of EPC)	USD/year	1,875,000
Outsourcing fuel	–	–	–
Outsourcing electricity	Industry norm (0.75% of EPC)	USD/year	937,500
Labor cost	Industry norm (0.75% of EPC)	USD/year	937,500
Maintenance cost	IRENA/NEPRA (2% of EPC)	USD/year	2,500,000
Land acquisition fee	Public land	USD/year	–
Landfill of fly ash	–	USD/year	–
Landfill of slag	–	USD/year	–
Other costs	–	USD/year	–
Fixed maintenance cost	IRENA/NEPRA (2% of EPC cost)	USD/year	2,500,000
Sub total – Operation cost			6,250,000
Variable O & M	6,250,000–2,500,000		3,750,000
CAPEX			
Return on equity	RE policy 2006/19	%	15.00
Discount rate	Industry norm	%	10.00
Receivable/payables			
Cash reserve requirement		USD	1,000,000
Technical assumptions			
LHV		kJ/kg	6500
LHV		Btu/kg	6161
Efficiency		%	25.00
Heat rate		Btu/kWh	13,648
Waste consumption		Ton/year	547,500
Electricity output			
Plant life (1–25 years)		GWh/year	279.225

are serving around 6.1 million people in Lahore. It is proposed that a very minimum amount of PKR 50/month may be charged by WASA initially against the above public water connections for the waste collection service at Lahore. This amount may be transferred to LWMC as earnings equivalent to PKR 366 million or USD 1.83 million per annum and PKR 9.15 billion or USD 45.75 million throughout the plant life of 25 years. The overall summary of the revenue streams from a 50 MW WtE plant besides electricity generation and the beneficiary of revenue is presented in Table 8.

3.6. Environmental impact of WtE projects

According to the report of the Asian Development Bank (ADB), two factors can provide savings of tons CO_2 equivalent through. The first is the grid emission factor and the other is a reduction in methane emission through WtE plants. ADB estimated and consolidated grid emission factors for different countries including Pakistan. The 50 MW WtE project at Lahore, with a 75% plant factor, can produce 279,225 MWh in one year, so 139,891.72 tons of CO_2 equivalent can be saved. For the whole 25 years of plant life, around 3.5 million tons of CO_2 equivalent can be saved through the WtE plant based on 2000 tons/day at Lahore. As per the World Bank Atlas for CO_2 emissions for Pakistan (1960–2018), the most recent value of a ton of CO_2 equivalent is a dollar (World Bank Group, 2020), so the estimated savings for 25 years would be USD 3.5 million. Another environmental impact of the WtE plant would be a reduction in methane emissions into the atmosphere (Sohoo et al., 2021a). The ADB guidelines estimated that when methane is released into the atmosphere, the global warming potential is given as 25 times for a ton of methane relative to a ton of CO_2. The release of methane into the atmosphere at the dumping site at Lahore is estimated at 340,976 tons/year (Alam et al., 2022), which means that 8,524,400 tons of methane equivalent can be saved per annum with a WtE plant, and it can be translated to 213.11 million tons of CO_{2eq} savings. The total net CO_2eq by adding both (213.11 + 3.5) gives us a value of 216.6 million tons CO_2eq. In terms of monetary savings, a 50 MW WtE plant if achieved, can save USD 213.11 million over its life of 25 years through methane reduction.

Table 6
Financial model outcomes with the capacity of 50 MW WtE at Lahore.

Project development		
	Unit	Value
Construction period	Months	36
Operational period	Years	25
Technical details		
Gross capacity	MW	50.0
Auxiliary consumption	MW	7.5
Net capacity	MW	42.5
Capacity utilization factor		75.00%
Annual generation (Average)	GWh	279.225
Costs		
Direct cost/EPC cost	USD	125,000,000
Project development cost	USD	9,375,000
Insurance during construction	USD	625,000
Financing charges	USD	1,704,475
Customs and sales tax	USD	6,250,000
Commissioning cost	USD	1,250,000
Interest during construction	USD	7,304,410
Total	USD	151,508,885
Funds		
Equity (25%)	USD	37,877,221
Debt (75%)	USD	113,631,664
Summary		
Equity IRR	%	12.17%
Levelized cost of energy	¢/kWh	7.8641

4. Conclusion

Waste characterization data of Lahore indicates major biodegradable solid waste fractions comprising 56% by weight and the remaining belonged to combustible, textile, plastics, and paper. The waste management company at Lahore may have an available waste of 4760 tons/day with a waste collection rate of 68%; however, keeping in view the utilization of waste streams in waste management system as composting, RDF, only 42% of the waste was considered for WtE project at Lahore. The availability of waste, on the above collection rate, in Faisalabad would be around 1000 tons/day, 800 tons/day in Gujranwala, 700 tons/day in Multan, and 600 tons/day in Rawalpindi.

Proximate analysis, based on lab results, revealed that waste calorific value was around 7.11 MJ/kg of mixed solid waste, moisture contents 43%, and ash contents 25% on a received basis. However, keeping in view the annual seasonal variation in solid waste, a lesser calorific value was assumed as 6.5 MJ/kg.

WtE power plants have efficiency in the range of 22 to 28% and plant availability factor from 72 to 85%. After optimization, the WtE project size of 50 MW was determined for Lahore based on 2000 tons/day. Similarly, the city of Faisalabad can produce 25 MW based on 1000 tons/day, 20 MW in Gujranwala based on 800 tons/day, 17.5 MW in Multan, and 15 MW in Rawalpindi based on 700 and 600 tons/day respectively. The assessment of waste as a fuel revealed that the calorific value should not be less than 6 MJ/kg for the feasibility of incineration based MSW projects.

The considered project cost of USD 151.5 million (USD 3 million/MW) as foreign financing on LIBOR with debt 75%, equity 25% through private investment on 25 years of plant life. The LCOE calculated through the financial model is US¢ 7.8641/kWh with equity IRR of 12.17% and generation of 279.225 GWh supplied to the national grid on a 75% plant factor. The levelized tariff of 50 MW WtE is quite less than the current average generation basket price of US¢ 9.73/kWh which can easily meet the criteria of ARE Policy under new technology projects.

Net savings to LWMC without tipping fee to the project developer would be USD 118.75 million on account of waste disposal cost, bricks revenue by using bottom ash, and the waste fee charged for 25 years. The net savings to LWMC would be reduced to USD 89.65 million in case a tipping fee is provided to the project developer. Similarly, the project developer, other than getting LCOE, would be benefited from net savings of USD 43.9 million with a tipping fee from LWMC and getting revenue of bricks sale over the plant life. Without a tipping fee, net savings to the developer would be reduced to USD 14.75 million.

The environmental impact was translated through the Grid Emission Factor of savings of around 3.5 million tons of CO_2 equivalent for 279,225 MWh annual energy generation of the 50 MW WtE plant at Lahore with 25 years of plant life. The monetary savings can be achieved as USD 3.5 million considering the recent value of USD 1/tons of CO_2 equivalent in Pakistan. Further, 213.11 million tons of CO_2 equivalent can be saved on account of the reduction in the release of methane into the atmosphere at the dumping site in Lahore. This in terms of monetary savings, if achieved, can be USD 213.11 million over 25 years of plant life.

Table 7
Levelized tariff and constituting elements in US¢/kWh for the WtE plant.

Year	Variable O & M	Fixed O & M	Insurance	Working capital	Return on equity	Principal	Mark-up	Tariff
1	1.3430	0.8953	0.2238	0.0447	2.0347	2.6239	1.8021	8.9678
2	1.3430	0.8953	0.2238	0.0447	2.0347	2.7434	1.6827	8.9678
12	1.3430	0.8953	0.2238	0.0447	2.0347	4.2810	0.1450	8.9678
25	1.3430	0.8953	0.2238	0.0447	2.0347	–	–	4.5417

Table 8
Summarized net savings of LWMC and project developer.

Revenue streams	Beneficiary	Savings	
		Million USD per annum	Million USD (25 years)
Waste handling cost	LWMC (without tipping fee)	2.330	58.250
	Project developer (50% of the above cost as a tipping fee)	1.165	29.125
Bricks making thru bottom ash	LWMC (50% sharing)	0.591	14.750
	Project developer (50% sharing)	0.591	14.750
Fee charged against waste collection	LWMC	1.830	45.750
Net savings to LWMC (without tipping fee)		4.751	118.750
Net savings to LWMC (with tipping fee)		3.586	89.650
Project developer (without tipping fee)		0.591	14.750
Project developer (with tipping fee)		1.756	43.900

CRediT authorship contribution statement

Muhammad Asim: Conceptualization, Project administration. **Rohan Kumar:** Conceptualization, Supervision, Writing & review. **Ammara Kanwal:** Writing – original draft. **Amir Shahzad:** Methodology, Investigation. **Ashfaq Ahmad:** Writing – review & editing. **Muhammad Farooq:** Formal analysis.

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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