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RESEARCH ARTICLE

Material Flow-Based Assessment of Hybrid Waste-to-Energy and Solar Photovoltaic Systems for Supporting Electric Vehicle Charging Infrastructure in Bali, Indonesia

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ABSTRACT

Rapid tourism development and urban growth in Bali have increased municipal solid waste (MSW) generation while simultaneously raising the demand for sustainable energy infrastructure. Although waste-to-energy (WtE) and solar photovoltaic (PV) technologies have been widely studied, integrated assessments linking waste management, renewable energy generation, and electric vehicle charging infrastructure in tourism-intensive regions remain limited. This study evaluates the potential of a hybrid WtE–PV system to support *Stasiun Pengisian Kendaraan Listrik Umum* (SPKLU) at the Mengwi Type-A Terminal, Bali, using municipal waste supplied from *Tempat Pengolahan Sampah Terpadu* (TPST) Mengwitani. A material flow analysis (MFA) approach was employed to quantify waste availability and energy recovery potential. Electricity generation from waste incineration and solar PV systems was estimated using energy conversion models, while environmental performance was evaluated through landfill diversion and greenhouse gas (GHG) emission reduction indicators. The results show that TPST Mengwitani processes approximately 56.6 tons of MSW per day, with 72% of the waste stream suitable for thermal conversion. The WtE system can utilize 40.75 tons day^{-1} of combustible waste and generate approximately 15.4 MWh day^{-1} of electricity. An 800 m^2 PV installation contributes an additional 0.77 MWh day^{-1}, resulting in a total renewable electricity potential of 16.2 MWh day^{-1}. The hybrid system also reduces landfill dependency and contributes to GHG emission mitigation. This study demonstrates that integrating WtE and PV systems can support low-carbon transportation infrastructure while promoting resource recovery and circular urban energy management in tourism-oriented regions.

Introduction

Urbanisation, economic growth, and rising consumption are increasing municipal solid waste (MSW) generation worldwide. Global MSW generation is projected to exceed 3.4 billion tonnes annually by 2050 [1], while the economic burden of waste management is also expected to increase substantially [2–4]. Continued reliance on landfilling is associated with land requirements, leachate generation, and greenhouse gas (GHG) emissions [3]. These pressures have strengthened interest in resource-recovery strategies that can simultaneously reduce disposal requirements and recover energy from waste. Waste-to-energy (WtE) is one such strategy because it links waste treatment with energy recovery and can contribute to a more circular urban resource system [5]. These challenges are particularly relevant in Bali, Indonesia, where population growth and tourism activity increase both waste generation and energy demand. Badung Regency, one of Bali's principal tourism areas, generates more than 195,000 tonnes of waste annually, while a substantial proportion of the waste stream remains dependent on final disposal.

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The continued use of landfill-based management creates environmental pressures associated with land demand, leachate, GHG emissions, and potential risks to public health and ecosystems. Consequently, resource recovery and energy recovery strategies are increasingly relevant to the sustainable management of waste in tourism-intensive regions. Bali provides a distinctive setting for assessing integrated waste and energy systems because three conditions occur simultaneously. First, waste generation is strongly influenced by tourism activity and therefore may vary seasonally. Second, the island has limited land availability for continued expansion of final-disposal facilities. Third, tourism and transport infrastructure are increasing electricity demand while Bali has substantial solar-energy potential. The interaction among tourism-driven waste generation, renewable-energy availability, and transport-energy demand is therefore more complex than in conventional urban settings and warrants an integrated assessment. Municipal solid waste management remains a major environmental challenge in Indonesia, particularly in rapidly urbanising and tourism-dependent areas. National waste generation exceeds 38 million tonnes annually, with substantial regional differences in collection, treatment, and recovery capacity [6]. In Bali, the concentration of tourism-related activities further intensifies the waste-management challenge.

Conventional disposal pathways can require substantial land resources and may contribute to methane emissions and other environmental impacts. These conditions strengthen the case for strategies that recover material and energy value from waste before final disposal. Thermal conversion technologies, including WtE incineration, provide an option for recovering energy from non-recyclable waste fractions while reducing the mass requiring final disposal. Previous studies have demonstrated that WtE can contribute to waste-volume reduction, energy recovery, and diversification of local energy resources [6–8]. However, the integration of WtE with electric-vehicle (EV) charging infrastructure has received less attention than studies focused on waste treatment or electricity generation as separate systems. Recent research has increasingly examined the environmental and economic performance of MSW incineration and the integration of renewable-energy technologies. For example, integrated assessments have shown that the environmental performance of WtE depends not only on electricity recovery but also on processes such as flue-gas treatment, transportation, and the displacement of grid electricity.

Reviews of hybrid WtE systems further indicate that coupling waste conversion with photovoltaic (PV) and other renewable technologies can improve resource utilisation and reduce dependence on single energy sources [9,10]. Nevertheless, most studies continue to evaluate WtE, renewable generation, and transport-energy infrastructure as partially independent systems rather than as an integrated urban resource system. Indonesia is also accelerating the deployment of battery electric vehicles and public electric vehicle charging stations (*Stasiun Pengisian Kendaraan Listrik Umum*/SPKLU). The environmental benefit of EVs, however, depends partly on the electricity mix used for charging. Where grid electricity remains carbon intensive, coupling charging infrastructure with locally available renewable resources can further reduce the carbon intensity of electric mobility. In this context, locally generated electricity from WtE can complement solar PV generation. The proximity of *Tempat Pengolahan Sampah Terpadu* (TPST) Mengwitani to the Mengwi Type-A Terminal provides a relevant case for examining whether waste-derived and solar electricity can jointly support SPKLU operations.

Recent studies on renewable-powered EV charging have primarily considered PV generation, battery storage, grid interaction, and charging optimisation [10,11]. Such studies demonstrate the value of hybrid charging infrastructure for improving renewable-energy utilisation, grid resilience, and charging sustainability [11]. However, the potential integration of MSW-derived electricity with solar PV for EV charging in tourism-intensive regions remains insufficiently characterised. In particular, few studies have simultaneously linked local waste availability, energy recovery, EV charging demand, landfill diversion, and GHG mitigation within a single analytical framework. WtE systems nevertheless face uncertainties associated with waste quantity and composition, moisture content, calorific value, conversion efficiency, and seasonal variation. Solar PV can complement this variability by providing additional electricity during periods of solar availability. Bali receives relatively high solar irradiation, with an average daily value exceeding 5 kWh m^{-2} day^{-1} [12]. The combination of WtE and PV therefore offers a potentially complementary configuration for supporting EV charging. The principal research gap addressed in this study is the limited integration of MSW management, WtE conversion, solar PV generation, EV charging demand, and environmental indicators within a tourism-oriented urban context.

To address this gap, the study develops an integrated assessment framework for a tourism-intensive urban area in which MSW management, WtE conversion, solar PV generation, and public EV charging infrastructure are considered within a common system boundary. TPST Mengwitani and the Mengwi Type-A Terminal are used as a case study to quantify resource flows, renewable electricity generation, charging potential, landfill diversion, and GHG-emission reduction. Accordingly, this study evaluates the potential of integrating MSW incineration and solar PV to support the electricity demand of SPKLU at the Mengwi Type-A Terminal. The specific objectives are to: (i) quantify the combustible MSW fraction available for thermal conversion at TPST Mengwitani; (ii) estimate electricity generation from WtE and PV systems; (iii) assess the potential of the hybrid system to support EV charging; (iv) quantify landfill diversion and avoided GHG emissions; and (v) discuss the implications and limitations of the integrated system for sustainable urban resource and energy management in tourism-intensive regions. This study provides a site-specific assessment of the technical potential of integrating locally available waste and solar resources to support low-carbon transport infrastructure in Badung Regency, Bali. The assessment focuses on the potential of the proposed system under the adopted technical assumptions and available operational data.

Materials and Methods

Study Area and System Description

The study was conducted in Badung Regency, Bali Province, Indonesia, and focused on two connected locations: TPST Mengwitani, an integrated MSW processing facility, and the Mengwi Type-A Terminal, the proposed location for SPKLU. MSW generated from household, commercial, and tourism-related activities is processed at TPST Mengwitani, while the terminal represents the electricity-demand location. Their proximity provides a practical basis for assessing a locally integrated WtE and renewable-electricity supply system. The assessment covers MSW reception and sorting, thermal conversion of the combustible fraction, WtE electricity generation, solar PV generation at the terminal, electricity supply to SPKLU, landfill diversion, and avoided grid-electricity emissions. Infrastructure construction and equipment manufacturing were excluded because the analysis focuses on operational energy and environmental potential. An 800 m² PV installation was assumed based on conservatively estimated usable roof and open-space areas that would not interfere with terminal operations; this area is not intended to represent the maximum theoretical PV capacity. As illustrated in Figure 1, the proposed system links waste processing and WtE electricity generation at TPST Mengwitani with solar PV generation and SPKLU operations at the Mengwi Type-A Terminal. The combined energy pathway conceptually integrates locally available waste and solar resources, while landfill diversion and avoided grid-electricity use represent the principal environmental pathways assessed in this study.

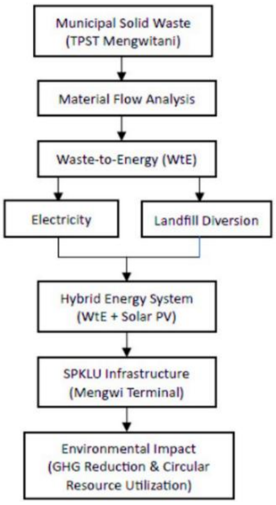


Figure 1. Conceptual framework of the integrated municipal solid waste management, WtE, PV, and SPKLU system in Badung Regency, Bali, Indonesia. The framework illustrates the flow of municipal solid waste from TPST Mengwitani through sorting and thermal conversion, the generation of electricity from WtE and solar PV at the Mengwi Type-A Terminal, and the supply of renewable electricity to SPKLU infrastructure. The framework highlights the integration of waste recovery and renewable energy generation with electric mobility, with the main intended outcomes being landfill diversion, greenhouse gas emission reduction, renewable electricity utilization, and improved circular resource utilization.

Data Sources

The analysis combines operational records, institutional reports, facility observations, and secondary data from peer-reviewed studies. Operational data on MSW generation and TPST Mengwitani performance were obtained from the Environmental Agency of Badung Regency. Facility observations were used to characterise the existing waste-processing conditions and to support interpretation of the operational data. These sources were used to establish the baseline waste flow entering the TPST Mengwitani system. Data on waste composition and calorific characteristics were obtained from the municipal-waste characterisation study by Qonitan et al. [13]. The study provides representative values for Indonesian municipal solid waste streams and was used to estimate the combustible fraction and energy recovery potential of the waste. Solar radiation and meteorological data for Bali Province were obtained from the study by Adiyasa et al. [12]. These records include monthly readings of solar irradiation and other climatic variables that may be used to estimate the output of photovoltaic power systems. In order to evaluate the solar energy potential in the specified region, it was decided that the selected dataset was appropriate.

To carry out the environmental impact assessment, internationally known emission variables were used. Waste management landfill methane emission estimates and grid electricity emission factors were derived from World Bank and UNEP reports, respectively [11]. With these emission data, we were able to estimate the greenhouse gas emissions caused by conventional power generation and waste disposal. The suggested hybrid WtE-PV system was evaluated at TPST Mengwitani based on its expected environmental benefits.

Model Assumptions and Parameter Selection

The energy recovery potential of the proposed hybrid system could only be approximated by considering a multitude of elements. Results from waste characterisation tests in Bali and operating data from TPST Mengwitani indicated that 72% of the garbage was combustible. According to these investigations, the bulk of the residual waste stream consisted of organic materials, polymers, and other flammable elements that might be transformed thermally [13,14]. When calculating the LHV (lower heating value) of MSW, a value of 6.2 MJ kg^{-3} was assumed. According to previous research on municipal trash in Indonesia, this number falls somewhere between 5.5 and 7.0 MJ kg^{-1}, which is the average calorific value of mixed rubbish under typical working conditions [13]. The performance range often observed for facilities that use steam turbine technology to incinerate municipal solid waste is as follows [7,15]. We expected the waste-to-energy system's electrical conversion efficiency to be 22%. The solar photovoltaic producing system made use of modules with an efficiency of 18%. This estimate agrees with previous studies on renewable energy in Indonesia [12,16]. This is reflective of the widely used monocrystalline solar modules in tropical regions and is commercially available. These features were selected to represent real-world operational conditions so that a careful evaluation of the system's performance could be given.

Sensitivity Analysis

To evaluate the robustness of the model, a sensitivity analysis was performed for the key parameters affecting electricity generation. Four parameters were considered: the combustible waste fraction, LHV, WtE electrical conversion efficiency, and PV module efficiency. Each parameter was varied independently by ±10% from its baseline value, while all other parameters were held constant. The selected variation was intended to represent a moderate range of uncertainty in the principal technical and feedstock characteristics without introducing operating conditions that would be inconsistent with the assumed system configuration. Variations in waste composition, calorific value, thermal conversion efficiency, and PV conversion efficiency can influence the estimated energy output; therefore, testing these parameters provides an indication of the sensitivity of the modelled electricity-generation potential to uncertainty in the principal input assumptions.

Table 1 summarizes the baseline values, sensitivity ranges, and the basis for selecting each parameter. The combustible waste fraction represents the proportion of the incoming MSW stream that is available for thermal conversion and therefore directly determines the quantity of feedstock available to the WtE system. The LHV represents the energy content of the combustible waste and determines the amount of thermal energy available for conversion. The WtE electrical efficiency describes the effectiveness of converting recovered thermal energy into electricity, whereas PV module efficiency determines the proportion of incident solar energy converted into electrical output. These parameters were selected because they represent the principal conversion and resource-availability factors governing the estimated electricity production of the integrated WtE–PV system. The ±10% sensitivity range was applied consistently to each parameter, as shown in Table 1.

Table 1. Parameters and assumptions used in the sensitivity analysis of the proposed hybrid WtE–PV system. The table presents the baseline values, ±10% sensitivity ranges, selection basis, and expected influence of the combustible waste fraction, LHV, WtE electrical conversion efficiency, and PV module efficiency on estimated electricity generation. The parameters represent the principal resource-availability and energy-conversion factors considered in evaluating the robustness of the model for the integrated WtE and solar PV system in Badung Regency, Bali, Indonesia.

No.	Parameter	Baseline value	Sensitivity range	Basis of selection	Expected influence on model
1	Combustible waste fraction	72%	64.8–79.2%	Operational data from TPST Mengwitani and waste characterization studies.	Determines the quantity of waste available for incineration and electricity generation.
2	Lower heating value (LHV)	6.2 MJ kg^{-1}	5.58–6.82 MJ kg^{-1}	Representative calorific value of Indonesian MSW	Directly affects thermal energy recovery.
3	WtE electrical efficiency	22%	19.8–24.2%	Typical steam-turbine WtE performance.	Determines conversion of thermal energy into electricity.
4	PV module efficiency	18%	16.2–19.8%	Commercial monocrystalline PV modules used in tropical regions.	Determines photovoltaic electricity generation.

This approach allows the relative influence of variations in waste availability, waste energy content, WtE conversion performance, and PV conversion performance to be examined under comparable conditions. The resulting changes in electricity-generation potential were then evaluated to identify which parameters exert the greatest influence on the model output. The sensitivity analysis therefore provides an assessment of model robustness and indicates the extent to which uncertainty in the principal technical and resource parameters may affect the estimated performance of the proposed hybrid system.

Material Flow Analysis (MFA)

The flow of MSW through the TPST Mengwitani processing system was measured using an MFA (material flow analysis) method, and the percentage of MSW that could be recovered for energy was estimated. Research on waste management often use MFA to monitor material flow through treatment processes and assess resource recovery possibilities [17]. Solid waste is a common occurrence at the TPST Mengwitani factory. Approximately 20,654 tonnes of solid garbage are received by the facility annually. That works up to 56.6 tonnes of MSW every day that they obtain. Sorting is done on the municipal solid garbage upon arrival. They go through the trash for recyclables including metal, glass, and building materials. Sorting the solid waste reveals that thermal processing can still make use of around 72% of it. Organic matter, leaf litter, and recyclable plastic make up the bulk of this solid waste component. Consequently, a mass balance technique was used to determine the quantity of garbage that might be incinerated, and the result is in accordance with equation 1.

$$M_{inc} = M_{total} \times \left(1 - f_{recyclable}\right) \tag{1}$$

The mass of MSW sent to the incineration process is represented by M_{inc}, the total MSW received by TPST is represented by M_{total}, and the fraction of recyclable or inert materials removed during sorting before thermal treatment is called $f_{recyclable}$. The mass-balance framework lays the groundwork for future estimates of energy production and allows for the determination of the effective feedstock available for WtE conversion. The MFA not only theoretically tracks the whole flow of MSW through the treatment system, but it also estimates the combustible waste portion. The incoming garbage is first sorting into four categories: recyclables, refuse-derived fuel (RDF) appropriate, flammable, and residual inert. The combustible portion is converted into usable power and other by-products, such as bottom ash, fly ash, and gaseous emissions, during thermal treatment. Bottom ash is assumed to represent the major solid residue remaining after combustion, whereas fly ash is collected through the air-pollution-control system. The gaseous emission stream consists primarily of carbon dioxide together with regulated pollutants such as nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), trace heavy metals, and dioxins/furans. Although the present study focuses on electricity generation potential and greenhouse gas reduction, these material and emission streams are included within the analytical system boundary to provide a complete representation of municipal solid waste conversion.

WtE Conversion Model

The potential energy recovery from municipal solid waste was estimated using a waste-to-energy conversion model based on the calorific value of the combustible waste fraction [18,19]. Thermal treatment through incineration turns the chemical energy in waste materials into heat. The system produces heat, which the steam turbine generator uses to generate electrical power. The waste stream heat energy was calculated through the Indonesian municipal waste heating value. Research from past studies shows that Indonesian municipal waste has an average lower heating value of 5.5 to 7.0 megajoules per kilogram [13]. This value depends on the waste composition and moisture content. In this study, we used a value of 6.2 joules per kilogram to estimate the calorific content of the combustible waste fraction. The total thermal energy generated from waste incineration is estimated using equation 2.

$$Q_{thermal} = M_{inc} \times LHV \tag{2}$$

Where Q_{th} is the thermal energy produced from waste combustion (MJ day^{-1}), M_{inc} represents the mass of waste sent to incineration (kg day^{-1}), and LHV denotes the lower heating value of municipal solid waste (MJ kg^{-1}). The electrical output from the waste-to-energy system was subsequently estimated by applying a net electrical conversion efficiency of 22%, which corresponds to typical performance ranges reported for modern municipal waste incineration facilities operating with steam turbine cycles [10,20]. The electricity generation potential is based on equation 3.

$$E_{WtE} = Q_{thermal} \times \eta_{WtE} \tag{3}$$

Where E_{WtE} represents the electrical energy produced by the waste-to-energy system (MJ day^{-1}), and η_{WtE} denotes the net electrical conversion efficiency of the incineration system. The thermal conversion process also produces combustion residues and flue gases. The air pollution control systems used by modern MSW incineration plants often include electrostatic precipitators, baghouse filters, dry or semi-dry scrubbers, and activated carbon injection to reduce emissions into the atmosphere. These systems are intended to trap particulate matter, neutralise acidic gases like SOx, lessen emissions of heavy metals, and absorb dioxins before to their discharge from stacks. Consequently, there are regulated residual streams that accompany the produced power and need to be appropriately managed during the plant's operation.

Solar Photovoltaic Energy Model

Solar radiation in Bali averages 5.34 kWh/m²/day, which was used to estimate the daily solar energy output at Mengwi Terminal. Photovoltaic is the term for the method by which a solar panel turns sunlight into energy. Cells constructed from materials like silicon undergo this process. The photovoltaic effect is what makes the solar cells function. During this process, an electric current is generated as electrons flow inside the cells due to the influence of sunlight [19]. Solar panels come in several varieties. One form of panel is the monocrystalline panel. They achieve a remarkable 15% efficiency. Panels are another kind. Compared to panels, they are less efficient but less expensive. Because of the irregularity in their crystal structure, this occurs. Such panels are used in the production of solar energy. Photovoltaic cells convert sunlight into usable energy. Crucial to this is the photovoltaic process.

Solar energy production becomes feasible with its help. This kind of energy is used by Mengwi Bay Terminal. Bali is where it uses radiation. On a daily basis, the radiation amounts to 5.34 kWh/m². Estimating energy production is made easier with this quantity. Powering it is solar panels. They turn sunlight into electricity. This electricity can be used at the Mengwi Terminal. It supports the terminal operations. Solar energy is helpful this way. It provides a source of electricity. Solar panels are an environmentally friendly renewable energy source that do not produce greenhouse gas emissions and utilize the abundant energy of the Mehedi et al. [16]. The electrical energy produced by the PV system is given by equation 4.

$$E_{PV} = A \times G \times \eta_{PV} \tag{4}$$

Where A represents the available area for PV module installation (m²), GGG denotes the average daily solar radiation (kWh m^{-2} day^{-1}), and η_{PV} is the conversion efficiency of the PV modules, which was assumed to be 18% based on the specifications of commercially available monocrystalline photovoltaic system.

Environmental Impact Assessment

The environmental performance of the proposed hybrid system was evaluated by estimating greenhouse gas emission reductions resulting from two main mechanisms: diversion of municipal waste from landfill disposal and displacement of electricity from the conventional power grid. The integration of waste-to-energy and solar photovoltaics can really help reduce emissions. This is a deal because it can help with climate benefits.

Less methane is produced into the atmosphere when garbage is not dumped in landfills. Decomposition of organic waste in landfills devoid of oxygen results in the production of methane. Solar photovoltaic integration and waste-to-energy technologies may assist with this. One harmful greenhouse gas is methane. It contributes far more to global warming than carbon dioxide. Reducing emissions, particularly methane, requires the integration of waste-to-energy and solar photovoltaic systems.

In addition to reducing GHG emissions, incineration of municipal solid waste may produce a number of controlled air pollutants, such as sulphur oxides (SOx), particulate matter (PM), dioxins/furans, trace metals, and nitrogen oxides (NOx). These pollutants need suitable emission-control devices as they are produced by the burning of diverse waste products. In order to meet environmental regulations, most modern waste-to-energy facilities use flue-gas treatment systems. These systems typically include dry or wet scrubbers to control sulphur oxides, baghouse filters to remove particulate matter, and activated carbon injection to adsorb dioxins and heavy metals. Although quantitative emission modelling of these pollutants is beyond the scope of the present study, their potential generation and control are recognized as essential components of sustainable WtE operation. The avoided landfill emissions are estimated using equation 5.

$$E_{landfill} = M_{(inc,year)} \times E_{landfill} \tag{5}$$

where $M_{(inc,year)}$ represents the annual mass of municipal solid waste diverted from landfill disposal (ton year^{-1}), and $EF_{landfill}$ denotes the methane emission factor associated with landfill disposal (tCO_2e ton^{-1} MSW), as reported in global waste management assessments published by UNEP and the World Bank [11].

In addition to landfill diversion, the renewable electricity produced by the hybrid system can offset electricity that would otherwise be generated from the national power grid, which in Indonesia is still largely dominated by fossil-fuel power plants. The avoided grid emissions are estimated using equation 6.

$$E_{grid} = E_{total} \times EF_{grid} \tag{6}$$

Where E_{total} represents the total electricity generated by the proposed hybrid WtE–PV system (kWh), and EF_{grid} denotes the grid emission factor, representing the average carbon intensity of electricity supplied by the Indonesian power grid (kg CO_2 kWh^{-1}). The total greenhouse gas emission reduction was calculated as the combined effect of landfill diversion and avoided grid electricity emissions based on equation 7.

$$E_{totalGHG} = E_{landfill} + E_{grid} \tag{7}$$

Solid residues generated during incineration consist primarily of bottom ash and fly ash. After proper quality evaluation, bottom ash—which often makes up the bulk of combustion residue—may be used as a building material or subjected to further treatment. Alternatively, fly ash necessitates regulated treatment and disposal in conformity with environmental standards due to its greater concentrations of heavy metals and other harmful components. By including these byproduct streams into the system boundaries, the suggested hybrid WtE-PV architecture takes into account both the environmental impacts of waste conversion and power production.

This way, we can see how the proposed system helps stop climate change by comparing energy generated from waste to energy generated by throwing waste into landfills and burning fossil fuels to generate electricity. We are looking at the proposed system. We want to know whether it is better for the climate than the old ways of throwing waste away and burning fossil fuels to generate electricity. The proposed system is being evaluated to determine whether it is a way to reduce the negative effects on the climate.

Performance Indicator for SPKLU

Public electric vehicle charging stations (SPKLU) is designed with facilities to provide charging power, allowing the owner to fill in repeatedly. This supports the government's efforts to accelerate the battery-based electric motor vehicle program. Charging technology at SPKLU is divided into four types: slow charging, medium charging, fast charging, and ultrafast charging [20]. The hybrid energy system was evaluated to determine whether it can support vehicle charging. This was done by using the amount of energy electric vehicles need, which is 25 kWh per electric vehicle. The hybrid energy system and electric vehicles were studied to determine whether the hybrid energy system can effectively support electric vehicle charging. The number of vehicles that can be served per day is estimated using equation 8 and E_{total} using equation 9.

$$N_{EV} = \frac{E_{total}}{E_{EV}} \tag{8}$$

where:

$$E_{total} = E_{electric,WtE} + E_{PV} \tag{9}$$

The MFA was applied to quantify the flow of municipal solid waste through TPST Mengwitani into energy output and residuals, using standard mass-balance methodologies [21]. The electrical output potential from WtE conversion was modelled by multiplying the thermal energy content of MSW by the net conversion efficiency, as commonly used in waste energy assessments, avoided grid emissions were calculated by applying grid emission factors to the electricity produced [15], and reduced methane emissions from avoided landfill disposal were estimated based on global landfill gas emission studies [22]. To clearly define the scope of these energy and environmental assessments, a system boundary was established to identify the operational processes, material flows, and environmental pathways included in the analysis. The adopted system boundary is illustrated in Figure 2.

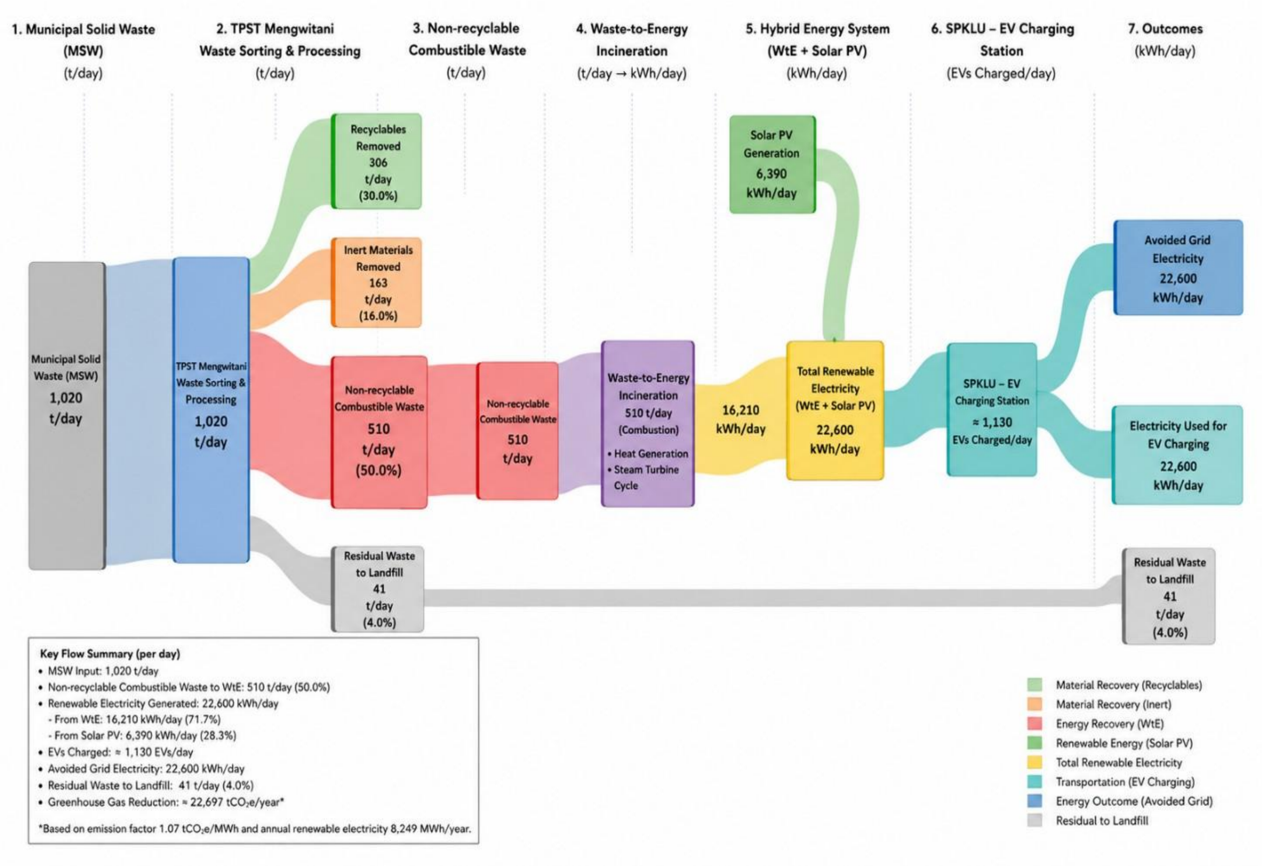


Figure 2. System boundary adopted for the assessment of municipal waste utilization, renewable energy generation, and SPKLU operation within the proposed hybrid WtE–PV system. The figure illustrates the main material and energy flows from municipal solid waste reception and sorting at TPST Mengwitani, through thermal conversion and electricity generation from WtE and solar PV, to electricity supply for SPKLU, while landfill diversion and avoided grid-electricity emissions are considered as the principal environmental benefits. Secondary outputs from thermal treatment, including recyclable materials, RDF fractions, bottom ash, fly ash, and regulated atmospheric emissions, are included within the system boundary, whereas infrastructure construction and equipment manufacturing are excluded because the assessment focuses on operational energy recovery and environmental potential [23].

Model Validation

Previous research on municipal solid waste incineration contrasted the computed power production potential with performance measures. We compared the predicted electrical yield per metric tonne of garbage with figures from WtE plants that use similar waste properties and conversion methods [10,20,24]. The purpose of the comparison was to check that the assumed values were technically reasonable and that the predicted energy production was within the range of values found in the literature. Direct operational calibration could not be done as the intended system has not been fully built yet. Consequently, published WtE performance statistics served as a standard for validation.

Preliminary Economic Assessment

The economic worth of the power produced by the proposed hybrid system was estimated via a preliminary economic evaluation. Profitability was estimated by multiplying the yearly power output from WtE and solar PV systems by the current power tariff. Do not take this as an exhaustive economic feasibility study; it only gives a ballpark figure for the worth of the power produced. Instead of providing a comprehensive financial feasibility analysis, this evaluation aimed to show how renewable power production may help the economy. Depreciation, financing arrangements, capital investment expenses, and maintenance costs were left out and should be included in future research based on equation 10.

$$R = E_{electric,WtE} \times E_{PV} \tag{10}$$

Where R represents the annual economic value of electricity generated by the proposed hybrid system (IDR year^{-1}), $E_{electric,WtE}$ denotes the annual electricity generation (kWh year^{-1}), and T_{PV} is the prevailing electricity tariff (IDR kWh^{-1}).

Results and Discussion

Results

Municipal Solid Waste Flow at TPST Mengwitani

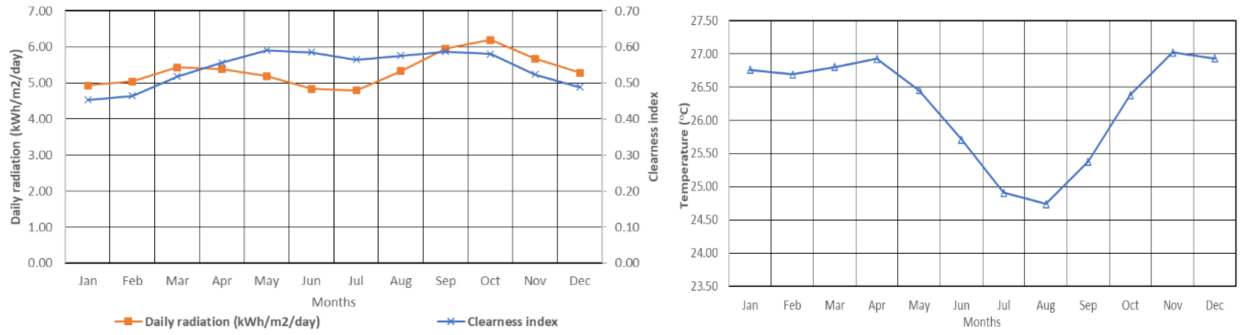
Operational records indicate that TPST Mengwitani receives approximately 20,654 tonnes of MSW annually, equivalent to 56.6 tonnes day^{-1}. After sorting, approximately 72% of the incoming stream is identified as suitable for thermal conversion. This corresponds to approximately 40.75 tonnes day^{-1} of combustible feedstock. The result indicates that the facility has a substantial locally available waste stream that could serve as the feedstock for a WtE system, although long-term operation would remain dependent on the consistency of waste quantity and composition. The estimated 40.75 tonnes day^{-1} of combustible waste represents the principal feedstock available for energy recovery. From an operational perspective, this quantity is sufficiently large to support a continuous WtE process in principle, but the actual operating capacity would depend on plant design, feedstock preparation, moisture content, downtime, and auxiliary energy requirements. The result should therefore be interpreted as a feedstock potential rather than as a demonstrated continuous plant throughput.

Energy Potential of Waste Incineration

Using the adopted LHV of 6.2 MJ kg^{-1} and the combustible feedstock identified by the MFA, the estimated thermal energy content of the daily waste stream is approximately 252.7 GJ day^{-1} [13]. Applying the assumed net electrical conversion efficiency of 22% yields an estimated WtE electricity output of approximately 15.44 MWh day^{-1}. This output represents the technical potential under the baseline assumptions and is consistent with the order of magnitude reported for MSW-to-electricity systems using comparable waste characteristics and conversion efficiencies [10,20,24]. The estimated 15.44 MWh day^{-1} of WtE electricity indicates that the waste stream is potentially a significant local energy resource. The magnitude of the result is primarily governed by the combustible fraction, LHV, and net electrical efficiency. Because these parameters are sensitive to waste composition and plant operation, the electricity estimate should be treated as a baseline potential rather than a guaranteed output. The WtE estimate demonstrates that a substantial fraction of the electricity demand associated with the proposed SPKLU could potentially be supplied by locally recovered waste energy. The significance of this result lies not only in electricity generation but also in the simultaneous diversion of combustible waste from landfill disposal. The result therefore links waste-management performance with transport-energy supply within a single system boundary.

Contribution of Solar Photovoltaic Energy

The PV contribution is approximately 5% of the total daily renewable electricity output. Its role is therefore complementary rather than dominant. Nevertheless, the temporal profile of PV generation is valuable because it provides additional daytime electricity and can reduce the extent to which SPKLU demand depends on the WtE source or the conventional grid. In a future operational configuration, the actual benefit would depend on charging demand profiles, power-control strategies, and any energy-storage system included in the design. The solar resource used in the PV assessment was characterized based on its seasonal variability, as illustrated in Figure 3.



(a) (b)

Figure 3. Seasonal variation in daily solar irradiation and clearness index used to estimate the electricity-generation potential of the proposed PV system at the Mengwi Type-A Terminal, Badung Regency, Bali, Indonesia. The figure presents the daily solar irradiation (kWh m^{-2}) and clearness index values used to characterize the available solar resource for the PV assessment. The adopted mean daily solar irradiation of 5.34 kWh m^{-2} day^{-1} provides the basis for estimating the contribution of an 800 m^2 PV installation to the proposed hybrid WtE–PV electricity supply system [12].

Hybrid Energy Supply for SPKLU

Combining the estimated WtE and PV outputs gives a total renewable electricity potential of approximately 16.21 MWh day^{-1}. The WtE component contributes about 15.44 MWh day^{-1}, while PV contributes approximately 0.77 MWh day^{-1}. The combined result indicates that the two sources are complementary and that PV increases the renewable electricity available for charging beyond the contribution of WtE alone.

Under the assumed charging demand of 25 kWh per vehicle, the daily renewable electricity potential is equivalent to approximately 648 full 25-kWh charging events per day. This value represents an energy-equivalent charging capacity and should not be interpreted as the actual number of vehicles that can be served operationally, because charging losses, charger availability, demand timing, vehicle state of charge, and concurrent charging constraints are not included in the model. The hybrid system therefore has a substantial theoretical capacity to support EV charging at the Mengwi Terminal. The result is more appropriately interpreted as an upper-bound energy-equivalent potential than as a forecast of actual SPKLU utilisation. In practice, the fraction of charging demand supplied by the hybrid system would depend on the temporal match between electricity generation and charging demand, the charging infrastructure, and the availability of grid backup or energy storage.

Landfill Reduction and Resource Efficiency

Reducing the quantity of garbage that enters ultimate disposal sites is achieved by diverting around 40.75 tonnes of municipal solid waste per day, or 14,874 tonnes per year, from landfill disposal. This garbage may be used as a source for WtE production instead of being thrown away in landfills. By reusing energy from materials that would otherwise be thrown away, the process of converting MSW into power enhances resource utilisation. As a result, the integrated waste management framework and the proposed WtE system are mutually supportive of landfill diversion and sustainable energy generation.

Greenhouse Gas Emission Reduction

The proposed hybrid WtE–PV system is estimated to provide an operational avoided-emission benefit of approximately 22,697 tCO_2e $year^{-1}$. This benefit is derived from two complementary mechanisms: diversion of combustible municipal solid waste from landfill disposal and displacement of grid electricity through locally generated electricity from WtE and solar PV. The landfill-diversion component represents the dominant contribution, accounting for approximately 17,849 tCO_2e $year^{-1}$, while avoided grid-electricity emissions contribute approximately 4,851 tCO_2e $year^{-1}$. The predominance of the landfill-diversion component indicates that the environmental value of the proposed system is strongly influenced by the quantity of combustible MSW redirected from landfill disposal. In contrast, the contribution from grid-electricity displacement reflects the additional climate benefit associated with supplying locally generated renewable electricity to the proposed SPKLU infrastructure. The relative contribution of these two mechanisms may vary under different waste compositions, electricity-generation conditions, and grid emission factors. The estimated avoided grid emissions are conditional on the adopted Indonesian grid-emission factor of 0.82 kg CO_2 kWh^{-1}. Consequently, changes in the electricity generation mix or the use of a location-specific and time-resolved grid-emission factor would directly affect the estimated grid-displacement benefit. The reported value should therefore be interpreted as an operational estimate under the assumptions adopted in the present assessment rather than as a directly measured emission reduction.

Overall, the results indicate that the hybrid configuration provides complementary environmental functions by diverting combustible MSW from landfill disposal while supplying locally generated electricity for electric vehicle charging. The WtE component provides the primary contribution to the estimated avoided emissions through landfill diversion, whereas the PV component enhances renewable electricity diversification and contributes to the displacement of grid electricity [23]. This interpretation is consistent with previous assessments showing that the environmental performance of WtE systems depends not only on energy recovery but also on the waste-management pathway and energy source displaced by the recovered electricity [11,24,25].

Summary of Key System Parameters and Results

Table 2 summarises the baseline parameters and principal outputs of the integrated WtE–PV system. The results indicate that the 72% combustible fraction is the dominant feedstock parameter, while the 22% WtE efficiency determines the conversion of waste energy into electricity. The 800 m^2 PV installation contributes approximately 0.77 MWh day^{-1}, increasing total renewable electricity availability to about 16.21 MWh day^{-1}. The system-level indicators therefore show simultaneous benefits in energy recovery and landfill diversion, with an estimated operational GHG reduction of approximately 22,697 tCO_2e $year^{-1}$.

Table 2. Key parameters and estimated performance of the integrated WtE–PV system for electricity supply to SPKLU at the Mengwi Type-A Terminal, Badung Regency, Bali. The table summarises the principal input parameters, including the combustible waste fraction, WtE conversion efficiency, and PV installation area, together with the estimated electricity generation, landfill diversion, and operational GHG emission reduction of the proposed system. Based on the assumptions adopted for MSW processed at TPST Mengwitani and an 800 m^2 PV installation at the Mengwi Type-A Terminal, the results indicate that the system combines waste-derived and solar electricity generation while providing potential benefits through landfill diversion and avoided grid-electricity emissions.

No.	Variable	Value
1	Municipal waste input	56.6-ton day^{-1}
2	Combustible waste fraction	72%
3	Waste for incineration	40.75-ton day^{-1}
4	Lower heating value (LHV)	6.2 MJ kg^{-1}
5	WtE conversion efficiency	22%
6	PV installation area	800 m^2
7	PV efficiency	18%
8	Electricity from WtE	15.44 MWh day^{-1}
9	Electricity from PV	768.96 kWh/day^{-1}
10	Total electricity generation	16.21 MWh/day^{-1}
11	Landfill diversion	40.75-ton day^{-1}
12	Annual GHG reduction	22,697 tCO_2 $year^{-1}$

As shown in Table 2, the estimated system performance is primarily influenced by the availability and energy characteristics of the combustible MSW fraction. The WtE component provides the main contribution to electricity generation and landfill diversion, whereas the PV system provides an additional renewable electricity source. The reported values represent estimated performance under the assumptions adopted in this study and should therefore be interpreted as technical potential rather than measured operational performance.

Comparative Scenario Analysis

The proposed hybrid system was evaluated against four alternative scenarios to assess its relative performance. The baseline scenario represents conventional landfill disposal without energy recovery, while the alternative configurations comprise PV-only, WtE-only, and the proposed hybrid WtE–PV system for supporting SPKLU operations. The scenarios were compared using three performance indicators: renewable electricity generation, landfill waste diversion, and GHG emission reduction. The comparative results for the four evaluated scenarios are summarized in Table 3.

Table 3. Comparison of alternative waste-to-energy and renewable electricity scenarios. The table compares four system configurations—baseline landfill disposal, PV-only, WtE-only, and the proposed hybrid WtE–PV system—based on renewable electricity generation, landfill waste diversion, and GHG emission reduction. The comparison illustrates the complementary benefits of integrating WtE and solar PV, with the hybrid configuration providing the most comprehensive combination of energy recovery, landfill diversion, and GHG emission mitigation among the evaluated scenarios.

No.	Scenario	Electricity generation	Landfill diversion	GHG reduction
1	Landfill only	0	0	0
2	PV only	PV output only	0	Low
3	WtE only	WtE output only	High	Moderate
4	WtE + PV	Highest	High	Highest

The comparison indicates that the hybrid WtE–PV configuration provides the most comprehensive environmental and energy benefits among the evaluated scenarios. The PV-only configuration contributes to renewable electricity generation but does not directly reduce the amount of MSW requiring landfill disposal. In contrast, the WtE-only configuration provides both energy recovery and substantial landfill diversion because the combustible waste fraction is redirected from disposal to thermal conversion. The hybrid configuration combines these complementary functions, increasing renewable electricity availability while maintaining the waste-diversion benefit of WtE and providing an additional contribution from solar PV.

These results indicate that the integration of WtE and PV can provide a more diversified energy supply for SPKLU than either technology considered independently. However, the comparison represents the technical and environmental potential under the assumptions adopted in this study and should not be interpreted as a comprehensive techno-economic or life-cycle assessment of the four scenarios.

Implications for Sustainable Urban Energy Systems

The proposed hybrid WtE–PV configuration illustrates how waste management, renewable electricity generation, and electric mobility can be integrated within a localized urban energy system. At the Mengwi Type-A Terminal, electricity generated from the proposed WtE pathway using combustible MSW from TPST Mengwitani can be complemented by solar PV generation to support SPKLU operations. This configuration provides a pathway for converting locally available waste and solar resources into electricity while simultaneously reducing dependence on conventional grid electricity and supporting the transition toward lower-carbon transportation systems. The integration is particularly relevant in tourism-intensive regions, where waste generation and transportation energy demand can increase concurrently [10]. The composition of the MSW processed at TPST Mengwitani further supports the potential for resource recovery.

The waste stream comprises food waste (16%), garden waste (34%), and plastics (28%), with the remaining fraction consisting of materials such as paper, metals, rubber, glass, and textiles [14]. The relatively substantial proportion of organic and combustible materials indicates that a portion of the residual waste stream may be suitable for thermal conversion following appropriate sorting and processing [19]. Previous research on waste management in Indonesia similarly indicates the importance of separating recoverable and combustible fractions to improve resource utilization and reduce the quantity of waste requiring final disposal [18,19]. Waste sorting is therefore a critical step in the proposed resource-recovery pathway. The separation of recyclable materials from the residual combustible fraction can improve the quality and consistency of the feedstock supplied to thermal conversion while retaining recyclable materials within higher-value recovery pathways. In this context, TPST Mengwitani can serve not only as a waste-processing facility but also as a potential node for circular resource management, in which selected waste fractions are recovered as material resources and combustible residues are considered for energy recovery.

This approach links waste diversion with local electricity generation rather than treating waste disposal and energy supply as separate urban services. The spatial relationship between TPST Mengwitani and the Mengwi Type-A Terminal provides an additional advantage for the proposed integrated system. As illustrated in Figure 4, the two locations form the principal physical components of the proposed WtE–PV energy pathway, with

TPST Mengwitani representing the waste-processing and WtE component and the Mengwi Terminal representing the electricity-demand and PV-generation location. Their proximity provides a practical basis for connecting locally generated electricity with the charging infrastructure while potentially limiting the distance over which electricity must be transferred. However, the actual transmission losses and infrastructure requirements would require detailed electrical-system assessment and are beyond the scope of the present study. The physical context of the proposed charging infrastructure at the Mengwi Type-A Terminal is shown in Figure 5.

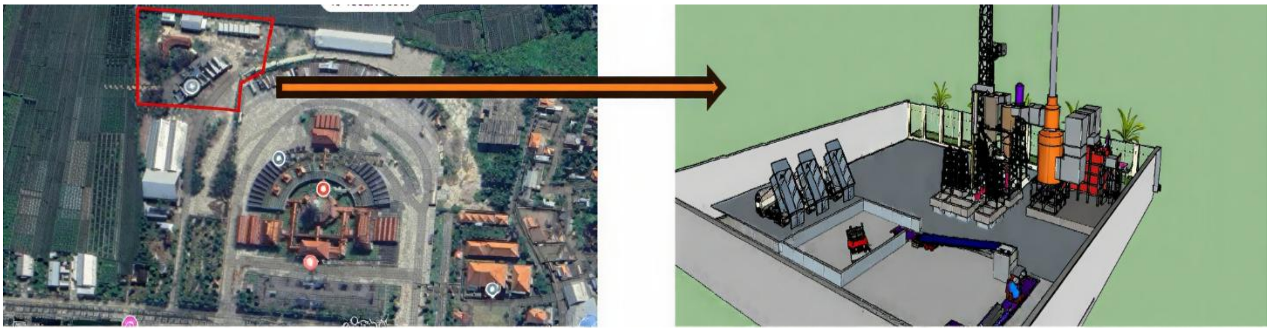


Figure 4. Spatial relationship between TPST Mengwitani and the Mengwi Type-A Terminal as the principal waste-processing and electricity-demand locations of the proposed hybrid WtE–PV system in Badung Regency, Bali, Indonesia. The figure illustrates the physical proximity of the integrated MSW processing facility and the terminal, providing the spatial basis for connecting waste-derived electricity and solar PV generation with SPKLU infrastructure. The configuration highlights the potential for localized integration of waste management, renewable electricity generation, and electric mobility within a tourism-intensive urban area.

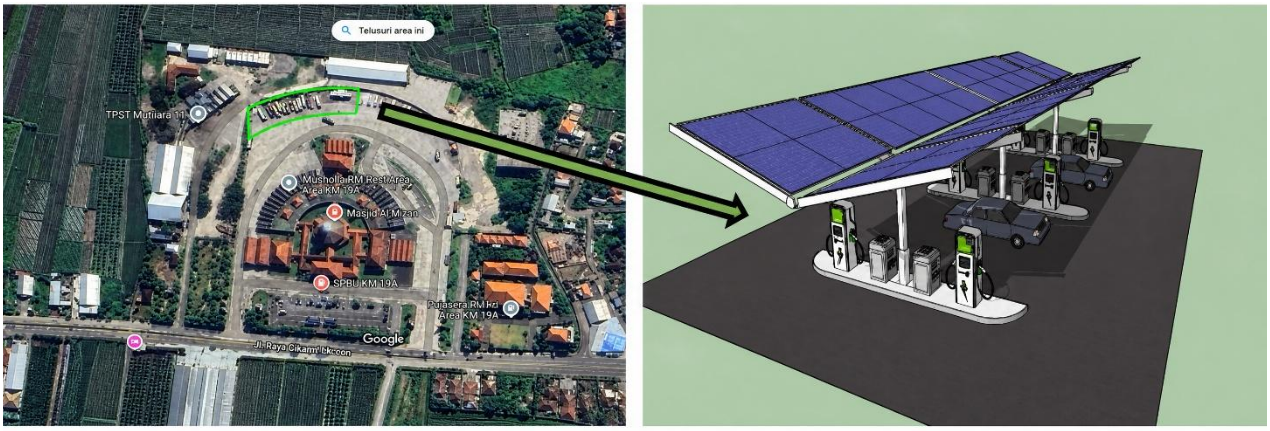


Figure 5. SPKLU installed at the Mengwi Type-A Terminal, Badung Regency, Bali, Indonesia. The figure provides the physical context for the proposed utilization of locally generated WtE and solar PV electricity to support electric vehicle charging operations at the terminal. The infrastructure illustrates the connection between renewable electricity generation and low-carbon electric mobility within the proposed localized urban energy system.

The integration of SPKLU with locally generated electricity creates a direct linkage between resource recovery, renewable electricity generation, and electric mobility. Rather than considering waste management, renewable energy, and transportation infrastructure as independent systems, the proposed configuration treats them as interconnected components of a localized circular urban energy system. From a sustainability perspective, the main implication is that the proposed system can simultaneously address three interconnected urban challenges: the management of combustible MSW, the provision of electricity for electric mobility, and the reduction of dependence on conventional electricity supply. The WtE component contributes primarily through waste diversion and energy recovery, whereas solar PV provides an additional renewable electricity source and increases the diversity of local energy supply [23]. This complementary role is consistent with the broader objective of integrating locally available resources into sustainable urban energy systems [10].

Nevertheless, the proposed configuration should be interpreted as a technical and environmental potential rather than as a demonstrated operational system. Its practical performance will depend on waste composition and availability, sorting effectiveness, thermal-conversion efficiency, PV performance, electricity-demand profiles, environmental controls, and the requirements for integrating the generated electricity with SPKLU infrastructure. Further techno-economic, life-cycle, and operational assessments are therefore required before the system can be considered for full-scale implementation.

Discussion

The results indicate that integrating WtE and solar PV generation can provide a complementary approach to supplying electricity for public electric vehicle charging infrastructure while improving the utilization of locally available resources. The principal contribution of the proposed configuration is not simply the additional electricity generated, but the coupling of two otherwise separate urban systems: municipal solid waste management and electricity supply for electric mobility. This integration is particularly relevant in Badung Regency, where tourism activity contributes to both waste generation and transportation-related electricity demand [26,27]. The estimated WtE contribution is strongly influenced by the characteristics of the residual waste stream. The relatively high combustible fraction identified at TPST Mengwitani provides a substantial feedstock base for thermal energy recovery.

Waste composition, lower heating value, moisture content, and conversion efficiency are recognized as key determinants of WtE performance, and variations in these parameters can substantially alter the resulting electricity yield. Previous studies similarly demonstrate that the environmental and energy performance of WtE systems is highly dependent on waste characteristics and the technology used for energy recovery [11]. The sensitivity analysis in the present study reinforces this interpretation by showing that changes in the principal feedstock and conversion parameters directly affect the estimated energy output. Therefore, improving waste sorting and maintaining a relatively stable combustible fraction may be more important for reliable energy recovery than increasing nominal conversion capacity alone.

The role of solar PV is complementary rather than substitutive. PV generation does not directly address the waste-disposal problem, but it provides an additional renewable electricity source that can diversify the energy supply to SPKLU. The hybrid configuration consequently reduces dependence on a single resource pathway: WtE is linked to waste availability and composition, whereas PV generation is primarily influenced by solar irradiation and conversion efficiency. Similar hybrid WtE–solar studies have identified the value of combining these resources to improve energy availability and broaden the range of recoverable urban resources. In the present case, this complementarity is particularly relevant because the waste-processing facility and the electricity-demand location are geographically connected, providing a practical basis for localized resource-to-energy integration [26].

The environmental interpretation requires greater caution. The estimated climate benefit is primarily associated with the avoided landfill pathway, with avoided grid electricity providing an additional contribution. This result is consistent with previous research showing that the comparison between WtE and landfilling depends strongly on the waste composition, landfill-gas management, energy recovery efficiency, and electricity source displaced. Accordingly, the estimated GHG benefit should not be interpreted as an intrinsic property of incineration. Rather, it represents the potential benefit under the specific waste characteristics, landfill emission factor, grid emission factor, and energy-conversion assumptions adopted in this study. Changes in these parameters could alter both the magnitude and relative contribution of the two emission-avoidance pathways [23,25].

The environmental implications of thermal conversion also extend beyond greenhouse gas emissions. Incineration can generate bottom ash, fly ash, and atmospheric emissions that require appropriate treatment and monitoring. Recent WtE literature emphasizes that energy recovery should be accompanied by effective emission-control systems and management of residual materials; otherwise, the environmental burden associated with thermal treatment may offset part of its benefits. Therefore, the proposed system should be understood as a potential resource-recovery pathway rather than as an unconditional replacement for waste prevention, reuse, recycling, or other higher-priority waste-management strategies. In particular, recyclable materials should remain within material-recovery pathways before the combustible residual fraction is considered for energy recovery [27].

From a circular-resource perspective, the proposed configuration provides a link between material recovery, energy recovery, and electric mobility. The contribution of the system therefore lies in converting selected residual waste and solar irradiation into an electricity service rather than treating waste management and transport-energy provision as independent activities. This interpretation is consistent with recent circular-economy research that positions WtE as one component of a broader resource-recovery system, while emphasizing the continued importance of material recycling and safe management of thermal-treatment residues. The proposed configuration may therefore be particularly relevant for tourism-intensive urban areas where waste management, energy demand, and transport infrastructure are spatially concentrated.

The spatial relationship between TPST Mengwitani and the Mengwi Type-A Terminal further strengthens the practical relevance of the proposed configuration. Locating resource recovery and electricity demand within the same local system can potentially reduce the complexity associated with long-distance energy transfer and facilitate direct coordination between waste processing, electricity generation, and charging demand [28,29]. However, the present study does not quantify electrical transmission losses, charging-load variability, grid constraints, or the temporal matching between electricity generation and charging demand. These factors are important because daily or seasonal differences between waste availability, solar generation, and EV charging demand may influence the actual utilization of the generated electricity. Several limitations should therefore be considered when interpreting the findings.

First, the assessment represents a modeled operational potential rather than measured performance from a fully operational integrated WtE–PV–SPKLU system. Direct operational calibration was not possible because the proposed configuration has not yet been implemented as a complete system. Second, several technical parameters, including waste calorific value, conversion efficiency, PV efficiency, and emission factors, are based on literature or adopted assumptions. Third, the environmental assessment focuses on landfill diversion and avoided grid emissions and does not constitute a full life-cycle assessment. Infrastructure construction, equipment manufacturing, transportation, detailed air-pollutant emissions, and residual-ash treatment are therefore outside the quantitative environmental assessment [30,31]. These limitations mean that the estimated values should be interpreted as indicative system potential rather than as definitive environmental performance [32,33].

Future research should extend the present assessment in three directions. First, operational validation should be conducted using measured waste composition, moisture content, calorific value, WtE output, PV generation, and SPKLU charging demand. Second, a dynamic assessment should examine seasonal and hourly interactions among waste availability, solar generation, and EV charging demand, including energy storage or grid interaction where appropriate [34,35]. Third, a comprehensive techno-economic and life-cycle assessment should be undertaken to evaluate capital and operating costs, residual management, air emissions, embodied impacts, and alternative waste-management pathways. Such analyses would provide a stronger basis for determining whether the proposed hybrid configuration is not only technically feasible but also environmentally and economically appropriate for implementation in Bali. Overall, the findings support the potential of integrating WtE and solar PV as a localized energy pathway for electric mobility in tourism-intensive regions [26]. The key implication is that the value of the proposed system arises from the integration of waste diversion, energy recovery, renewable electricity generation, and charging demand, rather than from any single technology considered independently. Further validation and system-level assessment are required before the concept can be translated into a full-scale operational strategy.

Conclusions

This study assessed the estimated potential of an integrated WtE and solar PV system to support SPKLU at the Mengwi Type-A Terminal using MSW processed at TPST Mengwitani. Based on the Material Flow Analysis and the technical assumptions adopted in this study, approximately 72% of the processed MSW, equivalent to 40.75 tonnes day^{-1}, was identified as potentially suitable for thermal conversion. The estimated WtE electricity generation was approximately 15.4 MWh day^{-1}, while the assumed 800 m^2 PV installation contributed approximately 0.77 MWh day^{-1}, resulting in an estimated combined electricity potential of approximately 16.2 MWh day^{-1}. The estimated environmental benefit was associated with two pathways: diversion of combustible waste from landfill disposal and displacement of grid electricity by locally generated electricity. The combined avoided greenhouse gas emissions were estimated at approximately 22,697 tCO_2e year^{-1} under the adopted landfill and grid-emission factors.

These values represent modelled technical and environmental potential rather than measured operational performance, as the proposed integrated WtE–PV–SPKLU system has not yet been implemented and directly calibrated as a complete operating system. The findings indicate that integrating WtE and PV can provide complementary sources of locally generated electricity while linking waste recovery with electric mobility.

However, the magnitude of the estimated benefits is sensitive to waste composition, calorific value, conversion efficiency, PV performance, and the emission factors used in the assessment. Therefore, the results should be interpreted within the assumptions and system boundary adopted in this study rather than as a definitive assessment of full-scale system performance. Further research should focus on operational validation using measured waste characteristics, WtE and PV electricity generation, and SPKLU charging demand. A subsequent techno-economic assessment and life-cycle assessment should also examine investment and operating costs, residual-ash management, air emissions, infrastructure impacts, and other life-cycle environmental burdens to determine the long-term feasibility and scalability of the proposed configuration.

Author Contributions

ADD: Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Writing – Original Draft; and **YMWIW:** Conceptualization, Validation, Supervision, Methodology, Writing – Review & Editing.

AI Writing Statement

During the preparation of this manuscript, the authors used Microsoft Copilot solely as a language-editing and writing-assistance tool to improve the clarity, grammar, and readability of the manuscript. Microsoft Copilot was not used for data analysis, interpretation of results, or the formulation of scientific conclusions. All AI-assisted text was critically reviewed, revised, and validated by the authors, who retain full responsibility for the content, accuracy, interpretation, and conclusions presented in the manuscript.

Conflicts of interest

There are no conflicts to declare.

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