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Techno-Economic and Environmental Assessment of Municipal Solid Waste Energetic Valorization

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Abstract: In 2019, Chile generated 20 million tons of waste, 79% of which was not properly disposed of, thereby providing an attractive opportunity for energy generation in advanced thermochemical conversion processes. This study presents a techno-economic and environmental assessment of the implementation of Waste-Integrated Gasifier-Gas Turbine Combined Cycle (WIG-GTCC) technology as an alternative for Municipal Solid Waste (MSW) treatment. The studied case assesses the conversion of 14.61 $t{\cdot}h^{-1}$ of MSW, which produces a combustible gas with a flow rate of 34.2 $t{\cdot}h^{-1}$ and LHV of 5900 $kJ{\cdot}kg^{-1}$, which, in turn, is used in a combined cycle to generate 19.58 MW of electrical power. The proposed economic assessment of the technology uses the energy generation processes as a reference, followed by a model for an overall economic evaluation. The results have shown that the profit could be up to USD 24.1 million, and the recovery of investment between 12 and 17 years would improve the environmental impacts of the current disposal technology. The WIG-GTCC has the most efficient conversion route, emitting 0.285 kg $CO_{2\ eq}$/kWh, which represents 48.21% of the potential yield of global warming over 100 years (GWP_{100}) of incineration and 58.51% of the GWP_{100} of the standard gasification method. The WIG-GTCC would enable the energetic valorization of MSW in Chile, eliminate problems associated with landfill disposal, and increase opportunities for decentralized electricity generation.

Keywords: gasification; municipal solid waste; cogeneration; energetic valorization; techno-economic assessment; environmental assessment

1. Introduction

The treatment and disposal of solid waste constitutes one of the biggest problems facing humankind. It is estimated that around 1.7 to 1.9 billion metric tons of Municipal Solid Waste (MSW) is generated each year [1,2]. The World Bank estimates that MSW generation reached approximately 1.3 billion tons per year across all cities in 2012, which is increasing by around 5~6% per year [3]. This figure is expected to increase to 2.2 billion tons annually by 2025 [4,5].

In modern society, many products are consumed and quickly discarded. A typical inhabitant of Western Europe is estimated to produce more than 450 kg of garbage annually [6]. In the South American region, Chile leads the relative waste production with an average of 456 kg produced per individual per year, ahead of countries such as Brazil, Uruguay, Panama, and Argentina, which have a per capita production of 383, 376, 343, and 341 kg, respectively [7]. In 2019, Chile's figures were alarming: 20 million tons of MSW were generated, and only 21% of it was valorized. A total of 9.8% was recycled, and 11.2% was used for thermal applications or as supplementary material in processes [8]. The government took measures in 2016 to mitigate this problem by approving the recycling promotion law, which required manufacturers to manage the waste derived from their products. However, recent reports indicate that the participation in recycling waste has not increased significantly between 2016 and 2019. In 2022, 77% of the 20 million tons of MSW generated in Chile is still disposed of in the 38 sanitary landfills around the country [8]. It is important to note that Chile joined the Organization for Economic Cooperation and Development (OECD), which requires the implementation of environmental legislation and the improvement of its institutional framework, as well as the improvement of waste management standards [9].

According to Siga [10], the MSW generation in the city of Concepcion in 2018 was estimated at 227 tons per day or 82,850 tons per year. However, this figure could exceed 95,964 tons, considering the increase in the city's population and the flow of people who are temporarily in the city.

The inappropriate disposal of MSW may generate extensive environmental impacts. Sanitary landfills require strict management systems to prevent local contamination and mitigate emissions from the decomposition of waste; however, even well-maintained sanitary landfills are still a source of environmental pollution. Landfills and incineration can dispose of this waste, but these methods lead to environmental pollution [11]. Currently, there are several conversion technologies that enable the energetic valorization of MSW while reducing the amount of waste that is sent to sanitary landfills; these can be mainly divided into thermochemical treatment technologies (incineration, pyrolysis, and gasification) and anaerobic digestion technologies. Among them, MSW valorization through pyrolysis has been implemented mainly on a pilot scale, aiming to produce bio-oil to provide a solution to the conventional fossil fuel deficiency, thereby reducing the environmental threats of overexploitation [12–15]. MSW's incineration (MSWI) for power generation has been widely used for its thermal valorization, as it reduces the MSW volume by 70–90% while producing electricity with an efficiency of usually 20~30%. When used for heating, this efficiency can be up to 80% [16,17].

Gasification is a globally recognized and commercially available process based on the thermochemical conversion of carbonaceous material into a combustible gas (producer or syngas) in sub-stoichiometric conditions with oxygen, air, and/or steam at temperatures above 700 °C [18–21]. The generated gas composition comprises a mixture of hydrogen (H_2), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), and traces of other hydrocarbons (C_xH_y). The process temperature, gasifying agent, feedstock properties, particle size, operating pressure, equivalence ratio, the addition of catalyst, and the gasifier type are usually the most important factors in determining gas composition [18–24]. The gas produced through gasification can be used to synthesize fuels such as methanol and hydrogen and is also used in electricity generation in combined cycle plants [19,20,25,26]. When the syngas produced is properly cleaned and/or cooled, it can be used as fuel for gas turbines and engines [27–30]. The generation of electricity from gasification has been used in various parts of the world to reduce greenhouse gas emissions and provide renewable electricity [28,31–34]. The process is highly efficient, achieving cold gas efficiencies of 60 to 70% and up to 99% carbon conversion. This process is a viable alternative for the energetic valorization of MSW [20,21].

Previous assessments have suggested that the Waste-Integrated Gasifier-Gas Turbine Combined Cycle (WIG-GTCC) could be a better alternative than MSWI [35] in terms of electricity generation efficiency, as this technology is a viable option for recovering part of the energy contained in the waste due to its technological maturity and logistics in small-to-medium scale processes [3,36,37].

A gasification plant with a combined cycle in which the recovered energy is used to generate electricity could be a technologically and economically viable alternative for treating MSW in Concepcion [3,38–42]. The present study focuses on the feasibility of implementing this technology using a modified updraft gasifier.

WIG-GTCC is an innovative technology [33,43–45] that is potentially competitive with MSWI in waste treatment because it raises the power generation capacity per unit of waste processed. Due to MSW's characteristics, i.e., inhomogeneity and high humidity content, updraft gasification technology is the most suitable reactor design for introducing WIG-GTCC in waste treatment.

Technical assessments concluded that introducing WIG-GTCC is technically viable [26–30] and the necessary economic assessments have been performed to evaluate the projected configurations' financial viability. In this background, the study's objective is to conduct an economic and environmental assessment of the WIG-GTCC's implementation for the treatment of MSW. This study focused on the percentage of waste that cannot be recycled or reused in order to arrive at a solution for managing it in the best possible way and prevent it from going to dumps or landfills, thus reducing its pollution potential.

2. Studied Case

This study evaluates the feasibility of implementing WIG-GTCC to valorize the MSW generated in the city of Concepcion. The system consists of a gasification plant with a combined cycle in which the recovered energy used to generate electricity is a technologically and economically viable alternative. In this context, the process selected for the analysis is gasification using a modified updraft gasifier [46].

The proposal consists of the partial oxidation of MSW, producing a combustible gas with a flow rate of 34.2 $t \cdot h^{-1}$ and an LHV of 5900 $kJ \cdot kg^{-1}$. To ensure the viability of using the producer gas in a combined cycle, the gas turbine's fuel requirements must be guaranteed in terms of tar and particle content [47]. The clean producer gas is then compressed before being used in a combined cycle to generate 19.58 MW of electrical power and 17.63 MW of useful heat with a combined heat and power (CHP) efficiency of 44.54%. Mass and energy balances (Table 1) were performed on each equipment involved in the process to determine the optimal operating parameters obtained by introducing WIG-GTCC technology. Figure 1 presents the simplified configuration of the WIG-GTCC system.

The gasification plant consists of an updraft gasifier, a cyclone, an air-gas exchanger, a Venturi scrubber, and a compressor. The MSW, with a moisture content of 40.8%, is fed into the mill to reduce its size, from which it enters the gasifier at a mass flow of 4.06 $kg \cdot s^{-1}$. The air entering the system is preheated in a heat exchanger, which recovers a fraction of the heat carried by the gas leaving the gasifier. Subsequently, the producer gas obtained enters a cleaning system based mainly on a Venturi scrubber, complemented with filters, which is similar to the cleaning system proposed by [48–51]. Before the gas enters the cleaning system, the particulate matter is removed in the cyclone, and the hot producer gas preheats the gasification air. Subsequently, the producer gas is cooled down through the Venturi scrubber by a pressurized spraying water jet, which also removes tars and inorganic impurities such as ammonia and alkali compounds. To complete the cleaning stage, a series of bag filters [52] eliminates the remaining contaminants formed when vapors are cooled below their dew point, ensuring an appropriate composition of the producer gas. A compressor is used to increase the pressure of the gas so that it can be used in the combustion chamber of the gas turbine to generate electricity through a combined cycle.

Table 1. Mass and energy balance.

Point	**1 (MSW)**	**2 (Ash)**	**3 (Air)**	**4 (Producer Gas)**	**5 (Volatile Ash)**	**6 (Air)**
Mass flow (kg·s^{-1})	4.06	0.406	5.85	9.5	0.032	5.85
Temperature K (°C)			473 (200)	823 (550)	823 (550)	288 (15)
Enthalpy (kJ·kg^{-1})		753.6		1764		
LHV (kJ·kg^{-1})	19713.8			5900		
Point	7 (Producer gas)	8 (Producer gas)	9 (Water)	10 (Producer gas)	11 (Water)	12 (Producer gas)
Mass flow (kg·s^{-1})	9.5	9.5	42.5	9.02	42	9.02
Temperature K (°C)	823 (550)	317 (44 °C)	308 K (35 °C)	314.6 (41.6)	288 (15)	642 (369)
Enthalpy (kJ·kg^{-1})	1064	412.1	146.1	408.9	62.6	789.66
LHV (kJ·kg^{-1})	5900	5900		5900		5900
Point	13 (Air)	14 (Air)	15 (Exhaust gases)	16 (Exhaust gases)	17 (Exhaust gases)	18 (Exhaust gases)
Mass flow (kg·s^{-1})	57.9	57.9	67	67	67	67
Temperature K (°C)	298 (15)	685 (412)	1396 (1123)	822 (559)	495 (222)	431 (158)
Pressure (kPa)	101.3	1520	1520	101.3	101.3	101.3
Point	20 (Subcooled liquid)	21 (Saturated liquid)	22 (Superheated steam)	23 (Superheated steam)	24 (Saturated liquid)	
Mass flow (kg·s^{-1})	7.15	7.15	7.15	7.15	7.15	
Pressure (MPa)	0.5	0.5	0.5	0.006	0.006	
Enthalpy (kJ·kg^{-1})	151.5	640.2	3188	2618	151.5	
Point	25 (Power of the gas turbine)	26 (Power of the steam turbine)	27 (Gross power)	Efficiencies	28 (Power consumed by the mill)	29 (Power consumed by gasification island)
Power (kW)	15,623.7	3953.2	19,576.9	$R_{gas\ cycle}$: 25.7% $R_{steam\ cycle}$: 21.7% $R_{combine\ cycle}$: 44.5%	276.4	1249.9

The gas obtained in the gasification plant feeds a gas turbine to drive a generator. The gas turbine's exhaust gases are used to produce steam in the heat recovery steam generator (HRSG). In addition, a heat exchanger is added to preheat the boiler's feed water. The determined electrical power generated by the gas cycle was 15.62 MW, with an efficiency [53,54] of 25.7%. With the energy recovered from the exhaust gases, it is possible to generate 25,740 kg·h^{-1} of steam, which generates an electrical power of 3.95 MW with an electrical efficiency of 21.7% for the steam cycle. The plant's auxiliary equipment consumes 8% of the energy produced in the combined cycle.

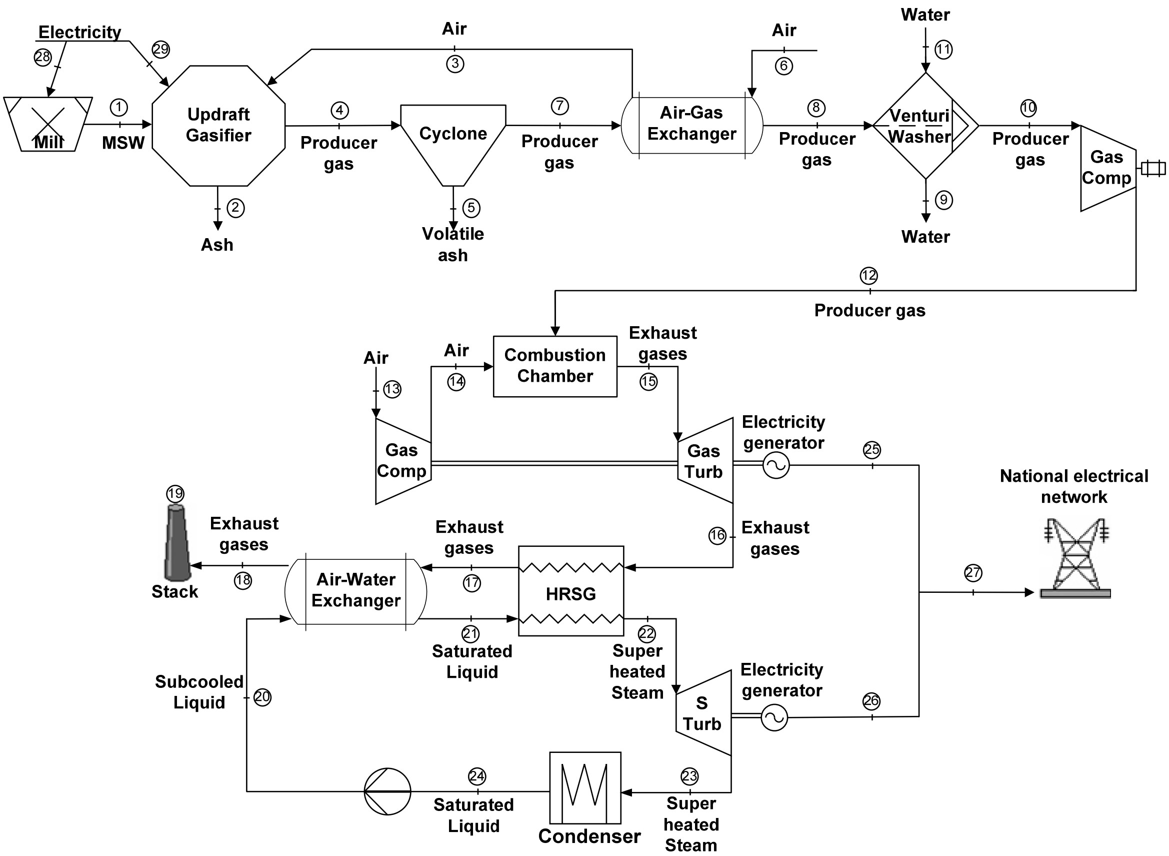

Figure 1. Simplified diagram of the WIG-GTCC system. Critical installation points of the plant were numbered and identified in Table 1.

3. Economic Appraisal Methodology for the WIG-GTCC's Incorporation into MSW Treatment

The methodology used for the economic analysis includes the most critical elements of the economic assessment methodology previously described by Antonio Caputo et al. [55]. The cost values obtained by Caputo et al. were converted to actual values for 2020 using the Chemical Engineering Plant Cost Index (CEPCI); the indexes 468.2 and 596.2 were used for 2005 and 2020, respectively [56]. The relationship shown in Equation (1) was used for the calculations

$$C_{2020} = C_{year\ ref}\left(\frac{CEPCI_{2020}}{CEPCI_{year\ ref}}\right) \tag{1}$$

where C (USD) is the equipment cost and CEPCI is the chemical plant's updated rate of costs according to CEPCI [56]. The methodology assesses the attractiveness of a project by analyzing the investment, operating costs, and revenues in order to determine the profitability of the proposal. In a cogeneration system, electricity is produced simultaneously in gas and steam turbines. The production costs were estimated for its implementation in Chile, using the municipality values of Concepción as a reference. The plant's income from electricity production and the expected annual revenues were estimated to define the feasibility of implementing the WIG-GTCC technology in the waste sector. This analysis is based on the comparison of three economic indicators: the payback period of the invested capital with the average lifetime of the technologies involved, the internal rate of return (IRR) with the interest rate set by the financial institution, and the net present value (NPV) as a critical indicator of the profitability of the proposal [29,55].

The economic assessment considers the total investment (TIC) and total operating cost (TOC), as well as the revenue (R) from the provision of services and the sale of electricity. The TIC (USD) considers the sum of the direct (DC) and indirect (IC) costs.

$$TIC = DC + IC \tag{2}$$

$$DC = PE + P + E + CW + DIC + AS + SIC \tag{3}$$

$$IC = EG + SU \tag{4}$$

where DC (USD·year^{-1}) includes the electricity costs (E), purchased equipment (PE), pipelines (P), auxiliary services (AS), direct installation (DIC), civil works costs (CW), and site preparation and instrumentation (SIC). At the same time, IC (USD·year^{-1}) considers commissioning (SU) and engineering (EG) costs. The pipeline, civil works, and electricity costs were calculated by interpolating commercial information from suppliers and contractors, updated to 2020, using Equation (1) [55,57].

The equipment costs are the basis for various approaches to estimating capital investment. Caputo et al. [55] proposed correlations obtained from the interpolation of experimental data from the literature, corresponding the following structure:

$$PE = \sum_{i=1}^{N} aS^{b} \tag{5}$$

where N is the number of types of equipment, assuming a total of 23 pieces of equipment (11 for power generation, 5 for the management and storage of MSW, and 7 for ash treatment); *a* and *b* are specific coefficients (coefficient *a* includes the cost update for the year 2020 through the ratio $CEPCI_{2020}/CEPCI_{year\ ref}$); and S is a parameter that characterizes each piece of equipment. In this technical proposal, S can be expressed as the net power W_{NE} (19.5769 MW), the power generated by the steam cycle W_{ST} (3.95 MW), the gas turbine power W_{GT} (15.6237 MW), the flow rate of MSW that feeds the gasifier $M_{G/CC}$ (8646 $kg_{dry\ basis}$·h^{-1}), and the HRSG vapor-produced flow, M_{HRSG} (25740 kg·h^{-1}), as appropriate.

The plant was assumed to process MSW from the city of Conception (76,771.2 t·year^{-1}) and also process waste from neighboring cities up to a maximum of 25,590.4 t·year^{-1}. The annual operating hours of the plant (OH) have been considered as 7008 h·year^{-1}; that is to say, the plant is kept in operation for 80% of the year, and the remaining time is spent mainly spent for maintenance. This maintenance is planned twice a year after or for every five months of continuous operation.

Table 2 shows the equipment cost correlations adopted for each piece of equipment, considering their specific design parameters.

Auxiliary equipment investment for waste storage handing and treatment of exhaust gases were directly correlated with W_{NE} (Table 2), updated for 2020, according to the CEPCI index [55,56].

The costs of civil works (CW), electricity (E), and pipelines (P) were estimated through relations with the W_{NE} and have been determined. The other parameters were determined as a percentage of the total cost of PE and derived from the literature: direct installation costs (DIC) were 30%, additional services costs (AS) accounted for 15%, and engineering costs (EG) constituted 12%. Site preparation, commissioning, and instrumentation were considered as 10% (Table 2), updated for 2020 [55].

Table 2. Correlations for equipment, components, and civil work costs.

Plant Section	Equipment Plant	PE Correlation (USD)
Power generation	Steam turbine	$806{,}054W_{ST}^{0.398}$
	Gasifier	$2037M_{G/CC}^{0.917}$
	Turbo-gas group	$4839W_{GT}^{0.754}$
	HRSG	$8328M_{HRSG}^{0.81}$
	Condenser	$506{,}808W_{ST}^{0.333}$
	Heat exchanger (cooling water)	$65{,}579W_{ST}^{0.5129}$
	Alternator	$176{,}109W_{ST}^{0.6107}$
	Fans	$44{,}951W_{ST}^{0.3139}$
	Condensate extraction pumps	$11{,}460W_{ST}^{0.4425}$
	Feed pumps	$44{,}569W_{ST}^{0.6107}$
	Pumps	$35{,}655W_{ST}^{0.5575}$
Waste storage-handing	Waste storage	$145{,}294W_{NE}^{0.5575}$
	Waste handling	$59{,}340W_{NE}^{0.9554}$
	Dryers and compressor	$14{,}517W_{NE}^{0.5575}$
	Emergency fuel (Diesel)	$46{,}097W_{NE}^{0.1989}$
	Heat-recovery dryer	$12{,}225M_{G/CC}^{0.65}$
Exhaust treatment	SO_x and NO_x removal equipment	$160{,}447W_{NE}^{0.5882}$
	Exhaust purification	$84{,}808W_{NE}^{0.7565}$
	Ashes storage	$112{,}440W_{NE}^{0.3139}$
	Ashes extraction	$119{,}062W_{NE}^{0.4425}$
	Fans	$36{,}292W_{NE}^{0.5575}$
	Fumes ductworks	$65{,}579W_{NE}^{0.5129}$
	Discharge stack	$36{,}292W_{NE}^{0.5575}$
Accessories	*Accessories installation*	*Cost correlation (USD)*
Piping	Firefighting tank	$109{,}129W_{NE}^{0.1040}$
	Firefighting components	$6749W_{NE}^{0.7565}$
	Firefighting system	$8404W_{NE}^{0.\ 7565}$
	Industrial water tank	$11{,}843W_{NE}^{0.\ 7565}$
	Tanks	$13{,}116W_{NE}^{0.\ 5129}$
	Heat exchanger	$43{,}550W_{NE}^{0.\ 5575}$
	Degasifier	$21{,}775W_{NE}^{0.\ 5575}$
	Low-pressure valves	$26{,}232W_{NE}^{0.5129}$
	High-pressure valves	$36{,}292W_{NE}^{0.\ 5575}$
	Control valves	$12{,}861W_{NE}^{0.\ 6756}$
	Valves	$36{,}292W_{NE}^{0.\ 5575}$
	Pipes	$53{,}864W_{NE}^{0.\ 885}$
	Pipe rack	$15{,}408W_{NE}^{0.\ 686}$
Electrical	Switches	$17{,}063W_{NE}^{0.\ 3672}$
	Electric protections	$56{,}920W_{NE}^{0.2266}$
	Transformer	$82{,}261W_{NE}^{0.4289}$
	Auxiliary transformer	$17{,}827W_{NE}^{0.4425}$
	Electrical equipment	$520{,}943W_{NE}^{0.6415}$
	Assembly	$237{,}996W_{NE}^{0.7137}$
Civil works	Buildings' yard guards	$89{,}264W_{NE}^{0.4425}$
	Conditioning plant and ventilation system	$29{,}797W_{NE}^{0.6328}$
	Civil works	$1{,}703{,}028W_{NE}^{0.3672}$
	Personnel of building yard	$170{,}252W_{NE}^{0.3672}$
	Buildings yard facilities	$16{,}936W_{NE}^{0.7565}$
	Wastewater treatment	$8786W_{NE}^{0.6107}$

Corresponding correlations were compared and validated with the costs calculated with the actual investments of plants with similar characteristics, and the adjustment results were satisfactory [29,58].

Equation (6) was used to determine the total operation cost (TOC), which was added to the ash transport costs (AT), operative labor costs (OL), ash removal costs (AR), insurance and general costs (IG), waste transport costs (WT), and maintenance costs (M).

$$TOC = OL + AT + AR + WT + M + IG \tag{6}$$

The maintenance, general costs, and insurance are equivalent to 1% and 1.5% of the TIC [55,59]. Table 3 shows the equations for each component's determination.

Table 3. Components of total operational costs.

Cost Component	Equation
Operative labor (USD·year^{-1})	$OL = C_p \times n$
Ash transport (USD·year^{-1})	$AT = C_{AT} \times M_A$
Ash removal (USD·year^{-1})	$AR = C_{AR} \times M_A$
Waste transport (USD·year^{-1})	$WT = V \times TP$
Maintenance (USD·year^{-1})	$M = 0.015 \times TIC$
Insurance and general (USD·year^{-1})	$IG = 0.01 \times TIC$

The OL has been determined according to the employed personnel (CP) remuneration, established at USD 8365.unit^{-1}·year^{-1} (equivalent to 500,000 CLP.unit^{-1}·mes^{-1}), and the number of employees that works annually (n) constituted three rotating shifts of eight hours each. Given the plant's size, implementing the WIG-GTCC requires 36 employees. The assumed specific cost of ash transport (CAT) for the AT was 62 USD·t^{-1}. The assumed ash-flow rate (M_A) was 10% of the total annual waste flow rate (M_W) [29,60,61]. The AR was calculated according to the ash removal rate (C_{AR}), which has been assumed to be 24 USD·t^{-1}. The WT has been assessed as the transport personnel costs (TP) and product of vehicle costs (V), calculated through Equations (7) and (8), respectively:

$$TP = C_{TP} \times n_T \tag{7}$$

$$V = d_T \times C_{VT} \tag{8}$$

$$d_T = \frac{4}{3}\left(\frac{M_W}{D_W \pi}\right)^{0.5} \times \left(\frac{M_W}{VC}\right) \tag{9}$$

where vehicle costs (V) have been expressed as the total annual distance traveled (d_T) by the specific cost of transporting vehicles (C_{VT}), reported as 1.14 USD.km^2 [55]. In addition, d_T depends on each vehicle's capacity (VC), which has been considered as 20 t·vehicle^{-1}, and the uniform distribution density of the available MSW (D_W) was considered to be 346.4 t·km^{-2}year^{-1} in the studied case (Equation (9)). In contrast, the commune of Concepción has a surface area of 221.6 km^2. Transportation personnel costs (TP) have been assumed as the transportation operations' employees rate (C_{TP}) of 21,080 USD·unit^{-1}year^{-1}, and the number of personnel in operations transport (n_T). Twenty-six haulers were considered sufficient for transporting the MSW to the plant.

The expected annual revenues (R) define the annual gains from installing a system that produces surplus electricity for commercial purposes and tax incentives to develop renewable energy from MSW. The R was determined by Equation (10).

$$R = (W_{ANE} \times OH \times EP) + (M_W \times F_R) \tag{10}$$

The R from the sale of electric power depends on the plant's net production of available power (W_{ANE}), assumed to be 92% of W_{NE}. The remaining 8% is used for the energy needs of the plant's equipment. It was considered that the current market price of electricity (EP) is 0.15 USD·kWh^{-1} [62]. This analysis considers government subsidies (F_R) with tariffs of 50 USD·t^{-1} of processed MSW, which have been implemented in different countries to encourage the development of renewable energy from MSW [10]. It was assumed that financial support from the Chilean government was essential for commercialization. Otherwise, the overall profit might not convince investors. The high initial investment costs of the WIG-GTCC plant still make this energy technology less competitive in Chile.

Finally, Equation (11) was used to calculate the net present value (NPV), where N is the useful plant life (20 years), F_k is the annual cash flow in the year *k*, and *i* is the discount rate. It also depends on taxes (T), the TOC, and financial charges (FC) (Equation (12)). A tax rate of 7% on revenue has been assumed [29], and the TIC will be amortized over the plants to evaluate FC. Interest rates of 4 to 8% were considered in borrowed capital.

$$NPV = \sum_{k=1}^{N} \frac{F_k}{(1+i)^k} - TIC \tag{11}$$

$$F_k = R - TOC - T - FC \tag{12}$$

To address the issue of energy and environmental security simultaneously, some countries have enacted laws that promote the use of MSW by providing various benefits in the form of tax incentives, i.e., exemption from VAT, income tax, tariff exemption, and the accelerated depreciation of assets, all to reduce the growth and development of renewable energies and the advancement in the production of fuels derived from MSW, making them increasingly attractive within the country [40,62].

4. Methodology for Determining the Impact Indicators for MSW's Gasification for Power Generation in Chile

Environmental life cycle assessment (ELCA) is a widely used technique for obtaining normalized indicators of the environmental impact of processes. Several studies have used ELCA with different methodologies [63–67]. Most of the ELCA studies of waste-to-energy focus on the direct incineration of the residues [67]. In the case of this work, the ELCA of WIG-GTCC's implementation was carried out considering the ISO 14,040 series standard. The specific procedure is detailed below.

4.1. Goal and Scope Definition

This study aims to compare the performance of the WIG-GTCC process with other waste-to-energy life cycle studies from the literature, both in terms of energy balance and environmental impact. For this work, the MSW is considered to be treated and transformed into refuse-derived fuel (RDF). The transformation process from MSW to RDF consists of drying, shredding, screening, manual separation, and magnetic and air separation of the MSW [40].

The functional reference unit is 1000 kg of MSW (1 ton), as delivered to the Concepcion municipal landfill. The limits include residue collection, transport to the processing plant, pre-treatment processes, the material recovered for recycling, and heat/power generation. The impact of electricity distribution was not considered. Figure 2 shows the system boundaries considered.

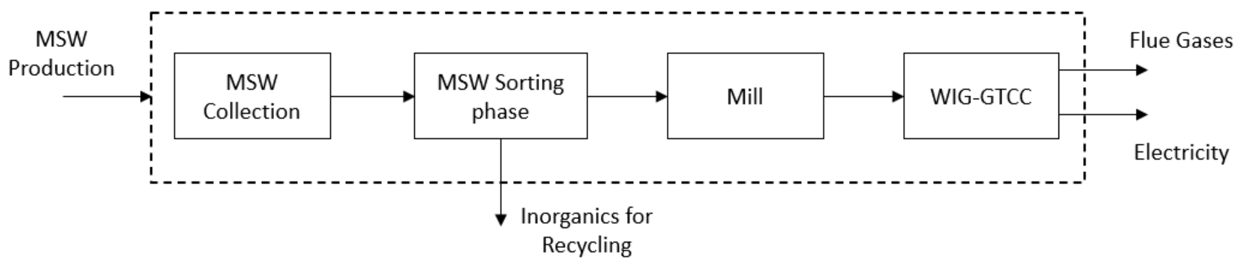

Figure 2. System Boundaries.

4.2. Life Cycle Inventory (LCI)

This study uses the Ecoinvent database in the OpenLCA software to access data related to the upstream process of MSW production in Chile and the construction of the necessary equipment in WIG-GTCC. González et al. [68] sampled the MSW generated in the bio-bio region in Chile and reported the average composition of MSW considered in the study; they collected and reported MSW's weight composition on a dry basis according to the national and international standards [69,70]. The composition reported was organic matter (54%), papers and cardboard (13%), plastic (10%), textiles and leather (2%), garden residues (2%), glasses (3%), metals (2%), and other inorganic residues (14%). Organic matter is formed mainly by food and wood waste with high moisture content.

4.3. Power Generation

It is considered that 1000 kg of MSW input into the WIG-GTCC generates 1339.42 kWh of valuable electric energy for the power grid with an estimated overall electrical efficiency of 24.5%. The conventional gasification power plant produces 644 kWh per 1000 kg of MSW, and the conventional incineration process produces 755 kWh per 1000 kg of MSW [68].

4.4. Emissions from the Syngas Combustion

The exhaust gas emissions from the process were assumed to come exclusively from syngas combustion in the gas turbine with 40% excess air. The estimated emissions of CO_2 come from the mass conservation of syngas combustion. Emissions of CO, NO_x, SO_2, and particulate matter of the WIG-GTCC were adopted from Tang et al. [71], which have specific emission values for the waste-to-energy gasification–combustion combined cycle. Ashes disposal and air pollution control (APC) residues were assumed according to the values reported by Dong et al. [65]. The solid residues from the WIG-GTCC were assumed to be disposed of in landfills. Dong et al. have also adopted energy consumption to transport and transform MSW to RDF and its emissions in the environment related to this process [65]. Table 4 indicates the values considered regarding MSW emissions.

Table 4. Input/output based on theoretical analysis and secondary data derived from Dong et al. [65] & Tang et al. [71].

Input	Unit	Value
MSW	kg	1000
Electricity	kWh	100
Diesel	L	7.7
Limestone	kg	4.3
Output		
Electricity	kWh	1035.28
Heat	MJ	0
Emissions		
CO_2, fossil	kg	331.4
CO	kg	0.2
SO_2	kg	0.1
NO_x	kg	0.1
HCl	kg	0
Dust	kg	0
Dioxins	kg I-TEQ	2.5×10^{-7}
Solid Residues		
Ashes	kg	120
APC residues	kg	20

4.5. Environmental Life Cycle Impact Assessment (ELCIA)

The CML baseline 2000 method has been employed to investigate and render the LCI data into categorized impacts. The method yields the Global Warming potential over

100 years (GWP_{100}), eutrophication potential (E_{Pot}), Human toxicity (HTP), and acidification potential (AP).

5. Results and Discussion

5.1. Economic Analysis of the WIG-GI TCC Incorporation in the MSW Treatment

The proposed economic analysis of the configuration was developed by applying the methodology described by Caputo et al. [55]. The results show that WIG-GTCC needs a capital investment of USD 111.8 million (USD 5712 kW^{-1} installed), which is consistent with the literature [58]. One year of operation will require USD 4.6 million, with an annual revenue of up to USD 24.1 million from the sale of electric energy and government subsidies, which the government of Chile has implemented to encourage the development of renewable energy from MSW. During the plants' operation, the highest expenses correspond to maintenance (36.5% of TOC), insurance, and general (24.3% of TOC). Another relevant expense was the transport of waste and ashes (~14% of TOC).

With the implementation of the WIG-GTCC, it is feasible to obtain an annual gross income sufficient to cover the plant's operating costs, taxes, and finance charges. Considering the collected taxes of USD 1.7 million per year and the annual loan amortization of USD 5.6 million, the project's economic performance makes implementing the WIG-GTCC configuration feasible. The cost of energy production through integrated gasification and combined cycle technology from MSW fuels derived was estimated at 0.04 USD.kWh^{-1}, which is consistent with other reports [40]. Figure 3 presents the expected annual revenues after applying the WIG-GTCC configuration to gasify the MSW generated in the city of Conception and its neighboring cities.

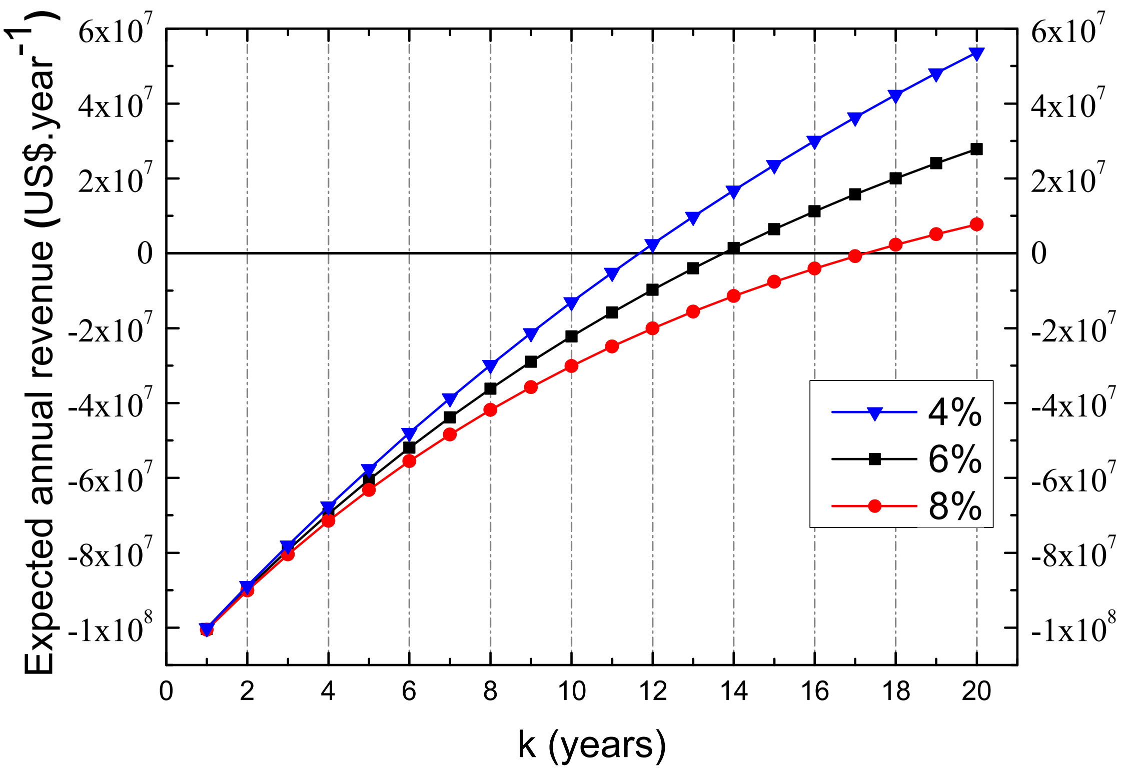

Figure 3. Annual revenue expected with WIG-GTCC for different annual interest rates.

In this case, economic viability was established for years 12, 14, and 17 at interest rates of 4, 6, and 8%, respectively. Therefore, considering that the IRR is 9%, the financial institution's interest rate should be less than 9%. Thus, the economic viability and profitability of the investment can be guaranteed during the plant's useful life. This proposal has an amortization of the investment in a reasonable period, considering the useful life of the involved technologies, as long as an interest rate lower than 9% is established. The NPV was always positive for interest rates of up to 8%, so the technical proposal is profitable and will generate million-dollar profits in 20 years of operation.

The assessment of the expected annual revenue behavior concluded that the implementation of MSW gasification as an alternative for final disposal is a viable option from an economic point of view and opens a new interface between the energy and waste sectors. This technology contributes to renewable energies and reduces environmental pollution, one of society's fundamental problems.

5.2. Results of the Environmental Impact Assessment

As the predominant technology used for waste management in the Chilean Bio-Bío Region, landfill disposal was the base scenario used for comparison in the impact assessment.

The impact indicators of the WIG-GTCC, gasification, and incineration numbers reflect a comparison between the technology assessed and the actual disposal technology. Negative values on the impact indicators imply an improvement in the ecological footprint. The impact indicators calculated for the WIG-GTCC system are exhibited in Table 5. The indicators for gasification and incineration are taken from González et al. [68] for comparison, which are consist of three main scenarios: landfill disposal (LD), gasification (GS), and incineration (INC).

Table 5. Impact indicators per ton and kWh of MSW disposed of/valorized.

Impact Category	Reference Unit	Landfilling [a]	WIG-GTCC	Gasification [a]	Incineration [a]
		Per ton			
AP	kg $SO_{2\ eq.}$	0.2	−1.7	−3.1	−2.9
GWP_{100}	kg $CO_{2\ eq.}$	516	−134	−135	−148
E_{POT}	kg $PO_{4\ eq.}$	0.1	0.1	0.2	0.9
HTP	kg 1.4 $DB_{eq.}$	16	−466	−661	−15
		Per kWh			
AP	kg $SO_{2\ eq.}$	-	−0.0013	−0.0045	−0.0036
GWP_{100}	kg $CO_{2\ eq.}$	-	0.2852	0.5916	0.4874
E_{POT}	kg $PO_{4\ eq.}$	-	0.0001	0.0005	0.0014
HTP	Kg 1.4 DB	-	−0.3359	−1.0016	0.0013

[a] Data derived from González et al. [68].

The indicators show that the environmental impact of landfills without energy recovery is related to global warming, mainly due to methane emissions during the decomposition process of MSW. The impact indicators of WIG-GTCC, gasification, and incineration corresponded to the results found by Tang et al. [71] for China using a different LCA approach.

The three thermochemical processes considered for comparison do not emit methane and convert the organic part of MSW into CO_2; this improves the GWP_{100} emitted by these cases. For the case of WIG-GTCC, this reduction is estimated to be 134 kg $CO_{2\ eq.}$/ton of MSW, which is around the same as conventional gasification.

Another evident contrast between the three thermochemical processes considered and landfill disposal is the human toxicity potential. Landfill disposal is associated with many adverse effects in the surrounding areas and can cause health problems in the nearby population [72]; this is drastically lower in the three analyzed thermochemical processes.

The acidification potential of the thermochemical process mentioned is also lower than ordinary landfill disposal because a portion of the acids formed during the decomposition of MSW is dissociated when heated at the high temperatures of these processes.

When comparing the pure gasification system analyzed by González et al. [68] and the WIG-GTCC configuration, it is possible to note that the results of GWP_{100} and EP are the same. This is expected since WIG-GTCC emissions are related to the syngas's combustion in the gas turbine combustor. Therefore, the difference in the impact of the WIG-GTCC and gasification is more related to differences in the infrastructure of the process than the actual emissions of syngas combustion. However, the emissions are similar in terms of magnitude. There is a difference between the human toxicity potential depicted by both systems, where the HTP of the WIG-GTCC is −466 kg/1.4 DB eq. and the HTP of the gasification is −661 kg/1.4 DB eq. This divergence can be explained by including the ash and APC residues management in the LCA analysis of WIG-GTCC, which assumed high emissions of pollutants and the consumption of fossil fuels for disposal.

The incineration system yields similar results as those observed in the WIG-GTCC for GWP_{100} and AP, while they vary considerably in human toxicity. The lower emissions of particulate matter can explain this. Dioxins and NO_x were emitted to the atmosphere by the combustion of syngas in the case of WIG-GTCC [73].

When comparing them in terms of energy produced for the thermochemical process, the WIG-GTCC stands out as the minor pollutant of the three in terms of GWP_{100} and E_{POT}. Table 5 also shows the same impact indicators for each analyzed technology when considering the energy produced.

The WIG-GTCC treatment, with the most efficient conversion, allows for the emission of 0.285 kg $CO_{2\ eq}$/kWh; this represents 48.21% of the yield of GWP_{100} of incineration and 58.51% of the GWP_{100} of the standard gasification treatment. The AP- and HTP-related economy of the WIG-GTCC is still higher than gasification and lower than incineration.

6. Conclusions

The proposal's economic evaluation verified the profitability of the project at interest rates below 9% and the investment recovery between 12 and 17 years. In terms of emissions per ton of MSW processed, the impact indicators of the WIG-GTCC found were similar to those of other researchers of thermochemical processes such as landfill disposal and incineration. Additionally, the ecological footprint of the WIG-GTCC system appears to be the best option in terms of the energy produced. The economic appraisal of the WIG-GTCC's implementation and its ecological footprint has proven the implementation viability of this technology in the Bio-Bio Region of Chile.

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Nomenclature

AP	Acidification potential (kg $SO_{2\ eq.}$)
APC	Air pollution control
AR	Ash removal cost (USD$·year^{-1})
AS	Costs of auxiliary services (USD$)
AT	Costs of ash transport (USD$·year^{-1})
C_{AR}	Ash removal cost (USD$·t^{-1})
C_{AT}	Ash transport cost (USD$·t^{-1})
C_p	The remuneration of the employed personnel (USD$·unit^{-1}year^{-1})
C_{TP}	Transportation operations personnel rate (USD$·unit^{-1}year^{-1})

C_{VT}	Vehicle transporting costs (USD$·km^{-1})
C_{2020}	Updated equipment costs to the year 2020 (USD$)
$C_{year\ ref}$	Equipment reference cost (USD$)
$CEPCI_{2020}$	Chemical Engineering Plant Cost Index of 2020
$CEPCI_{year\ ref}$	Cost Index of the reference year of the Chemical Engineering Plant
CW	Costs of the civil works (USD$)
DC	Direct costs (USD$)
DIC	Direct installation costs (USD$)
d_T	Total distance covered annually (km·year^{-1})
D_W	Uniform distribution density of MSW (t·km^{-2}year^{-1})
E	Electricity costs (USD$)
EG	Engineering costs (USD$)
EP	Current market electricity price (USD$·kWh^{-1})
E_{POT}	Eutrophication potential (kg of $PO_{4\ eq}$.)
FC	Financial charges (USD$)
F_k	Annual cash flow in the year k (USD$)
F_R	Government subsidies (USD$·t^{-1})
GS	Gasification
GWP_{100}	Global Warming Potential over 100 years (kg $CO_{2\ eq}$.)
HTP	Human toxicity
IC	Indirect costs (USD$)
IG	General and insurance costs (USD$·year^{-1})
INC	Incineration
IRR	Internal rate of return
k	Number of years
LCA	Life cycle assessment.
LCI	Life cycle inventory
$LCIA$	Life Cycle Impact Assessment
LD	Landfill disposal
M	Maintenance costs (USD$·year^{-1})
M_A	Ash flow rate (t·year^{-1})
$M_{G/CC}$	Flow rate of MSW feeding the reactor (kg·h^{-1})
M_{HRSG}	HRSG steam flow produced (kg·h^{-1})
MSW	Municipal solid waste
M_W	Waste flow rate (t·year^{-1})
NPV	Net present value (USD$)
n	Number of personnel that works annually (unit)
n_T	Number of employees in transport operations (unit)
OH	Plant´s annual operation hours (h·year^{-1})
OL	Operative labor costs (USD$·year^{-1})
P	Pipeline costs (USD$)
PE	Purchased equipment costs (USD$)
R	Revenue (USD$·year^{-1})
RDF	Refuse Derived Fuel
SIC	Site preparation and instrumentation costs (USD$)
SU	Start-up costs (USD$)
T	Taxes (USD$)
TIC	Total investment cost (USD$)
TOC	Total operation cost (USD$·year^{-1})
TP	Transportation personnel costs (USD$·year^{-1})
V	Vehicle costs (USD$·year^{-1})
VC	Each vehicle capacity (t·vehicle^{-1})
W_{ANE}	Plant's net production of electric power for sale (MW)
W_{GT}	Gas turbine Power (MW)
W_{NE}	Net power (MW)

W_{ST}	Power generated by Rankine cycle (MW)
WT	Waste transport costs (USD$\cdot$year^{-1})
Subscript	
G/CC	Dry MSW feeding the Gasifier
GT	Gas turbine
$HRSG$	Heat Recovery Steam Generator
ST	Steam turbine
Greek letters	
η_{ge}	Electricity generation efficiency (%)
η_{gl}	Global efficiencies (%)
η_{M}	Electric motor efficiency (%)
AP	Acidification potential (kg $SO_{2\ eq.}$)

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