Should the Chilean Government Encourage Waste-to-Energy Facilities for Municipal Solid Waste?

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EXECUTIVE SUMMARY

The term Waste-to-Energy (WTE) is used to refer to highly technical engineering processes that use municipal solid waste (MSW) as a fuel, to produce electricity and heat. These facilities are different and significantly more advanced as compared to the traditional incinerators that were used to incinerate household or medical waste without energy recovery and without advanced Air Pollution Control Systems, as is the case of the WTE plants.

At present time in Chile, a private waste management enterprise cannot afford to implement WTE in Santiago, for non-recyclable wastes unless the gate fee is increased from US $20/ton of MSW at landfills to US $45/ton at a WTE facility. However, the external environmental costs of landfilling are not factored in a fully private investment.

The first part of the study provides a summary of a pre-feasibility study on the development of a WTE plant with annual waste capacity of 330,000 tons per year and capital cost of US $615/annual ton of capacity; it was conducted by the Ministry of Energy and the Metropolitan Regional Government in 2018. Results showed that the gate fee would have to be US $43.6/ton (selling electricity only), which is 2.5 times higher than the average gate fee of US $17/ton of waste, paid on average by the municipalities in the Metropolitan Region. Considering a realistic scenario with an electricity price of < US $50/MWh by 2040, the gate fee to the WTE plant would have to be US $66.7/ton, as there would be less revenues from the sales of electricity. Therefore, the shortfall needed to be covered to advocate WTE deployments instead of landfilling is between $25/ton to US $50/ton of waste.

The second part of this study described the status of Chinese WTE market, in order to asses if lower investment costs from Chinese developers could decrease the gate fee in a WTE facility in Chile. Results showed that the capital cost for Chinese facilities is much lower than in other countries, with an average of US $250/ton of annual capacity. However, it is expected that in Chile, capital cost will not be as low, considering other factors that affect the capital required, such as permitting time, land, development and civil works, and social opposition; a reasonable estimate would be US $450/ton of annual capacity, less than the estimations provided by the Ministry of Energy and the Metropolitan Regional Government

The third part of the study briefly assessed the limits of recycling and the role of WTE in circular economy. Recycling does not compete with WTE. The Lock in effect and the 3-R Trade off mostly occurs in countries with high WTE capacity, but also were high recycling rates have been accomplished.

Recycling has many limitations that relate to the quality of the recovered products, the markets and, also, the understanding and compliance of citizens to source-separate recyclables. Even in European countries who have achieved high recycling rates and represent the most successful paradigms of sustainable waste management, by 2035 there will be at least 35% of post-recycling waste materials that, following the Waste Hierarchy, should go to WTE instead of landfilling.

The last and part of this study evaluated the environmental costs and benefits of landfill sites and WTE facilities in order to determine a “social cost” that was defined by considering costs and benefits that are not factored in the capital and operating costs required for sustainable infrastructure. The 'social cost' considered the cost of land consumed in landfilling, the direct CO_{2eq} emissions from each waste management method, the benefits from indirect CO_{2eq} savings, e.g. from the diversion of MSW from landfills, energy contribution to the national grid and metals recovered for recycling. The cost of air emissions and health risks were reviewed, but not fully quantified due to lack of time and data availability.

Results showed that the net carbon from landfilling is 0.5 and 1 ton CO_2/ton MSW higher than WTE. The 'social cost' of both alternatives is mainly determined by the social cost of carbon. This study used a price of CO_2 equivalent to US $ 5/ton, which is a CO2 tax regulated by under Law 20.780. However, this price is too low compared to estimates of over $50 per ton.

There are clear environmental, economic, and aesthetic benefits of WTE facilities as compared to landfills. If managed and maintained properly, WTE facilities can reduce CO_{2eq} emissions alleviate the public health effects of improper waste management, preserve valuable land, generate 10 times more energy, and recover metals and minerals for recycling.

However, WTE associates with high capital and operational costs which are not expected to decrease, considering significant factors that hinder the development in Chile, such as the lack of support from the public entities; inadequate public information; major contribution by informal recyclers, whose livelihood depends on the collection and sales of recyclables; low fees for the disposition of waste materials, and indirect advocacy of improper disposition of wastes in open dumps; institutional, and regulatory hurdles associated with permitting.

Considering the current situation of the improper landfilling of waste and the limited financial and technical capacity on WTE deployment, the Chilean Government must develop efficient collection of wastes and transform the open or improper landfills to engineered landfills with methane recovery and electricity generation as a short term solution to the challenge of waste management. A clear regulatory framework should be developed that advocates WTE, by the use of results-based financing mechanisms, as explained in detail in GPRBA, 2018; that will be the long and secure solution. In addition, pre-treatment systems should be developed to ensure minimum loss of quality of the waste materials.

For the future, value-based economic, financial and environmental life cycle models should be considered, by taking into account the resource productivity. For example economic output and materials input; and the environmental impact of the several waste management options, e.g. reusing, recycling/composting, energy recovery; in order to optimize the contribution of the waste products to the market, the economy, and the environment. I will also need to provide the tools to the stakeholders to deploy integrated sustainable waste management systems that recover materials through recycling and energy from the residual waste.

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1. Introduction

Waste-to-Energy, or WTE, is a term used to refer to a set of processes and technologies used to recover energy from waste materials, in the form of heat, electricity, or alternative fuels. It is a wide term that usually includes the combustion of municipal solid waste to produce heat or electricity, but can also include the combustion of forest residues, the use of methane gas from landfill and anaerobic digestion of sludge from wastewater treatment plants to produce biogas.

In this study, the term Waste-to-Energy is used to refer to modern WTE facilities that use municipal solid waste (MSW) as a fuel. These facilities are much more advanced compared to incinerators built for burning waste in the past, as they use the energy that comes from the combustion, and generally use advanced emissions controls systems to prevent the escape of post-combustion fly ash and harmful gases.

Ideally, WTE facilities are planned as part of integrated waste management systems that combine prevention, recycling of valuable waste materials, and leave WTE for the fraction of the waste that cannot be recycled, to avoid landfill. The Waste Management Hierarchy puts prevention, reuse and recycling first, followed by energy recovery and disposal as the least preferred option.

WTE facilities can also play a key role in the urban development, as suggested by the International Energy Agency on Figure 1, due to it´s potential to provide district heating/cooling as most of WTE plants in northern Europe. e.g. Considering an average EU-US calorific value of ~9-10 MJ/kg of waste, the electricity generation from WTE is between 0.5 to 0.6 MWh/ton processed, and district heating/cooling or industrial steam, e.g. for desalination is >0.6 MWh/ton.

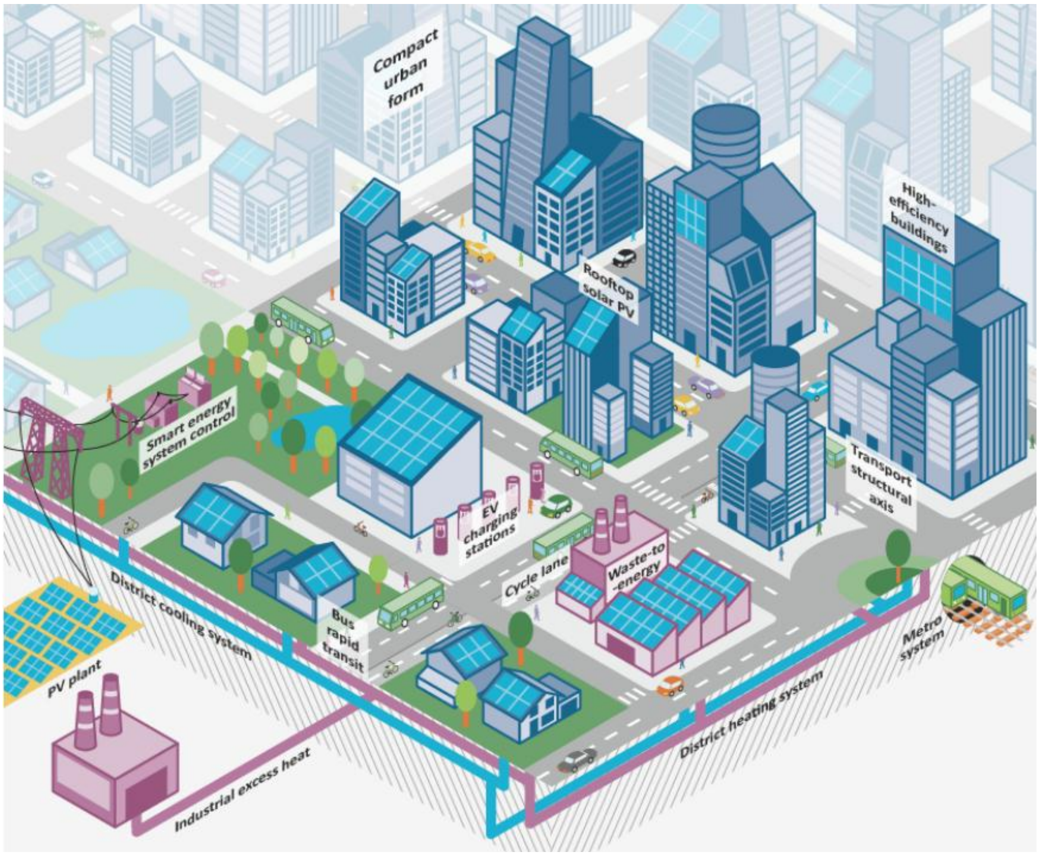

Figure 1: Cities lead the way on clean and decentralized energy solutions. IEA, 2017.

There are currently more than 1600 Waste-to-Energy facilities operating globally, concentrated in Europe, United States and Eastern Asia. WTE projects continue to be developed in some countries with growing economies, where a mix of regulation, policy incentives and land constrains for landfills take place. Currently the fastest growing capacity of WTE facilities is in China.

In Latin America there are no WTE facilities in operation. They have not been developed mainly due to the lack of regulation about integral waste management, and to the low cost waste disposal (less than US $20/ton).

At present time in Chile, a private waste management enterprise cannot afford to implement WTE in Santiago, for non-recyclable wastes unless the gate fee is increased from US $20/ton at landfills to US $45/ton at a WTE facility. However, the external environmental costs of landfilling are not factored in a fully private investment.

The main question to be answered through this study was, in my personal assessment, is it worth for the national government to cover the ~ US $25/ton shortfall in order for the nation to avoid the external environmental costs of landfill?

Specific objectives are:

1. Review previous feasibility studies for WTE projects in Chile.
2. Describe the status of the Chinese WTE market that indicated phenomenal growth by the construction of ~400 plants in <20 years.
3. Assess the limits of recycling and the role of WTE in circular economy.
4. Evaluate and compare the environmental costs and benefits of landfill and Waste to Energy facilities to determine the "social cost" of each method.

2. Waste Management in Chile

Chile generated 7.5 million tons of MSW in 2017. The Metropolitan Region accounts for 41.8%, followed by Valparaiso Region with 11,5% and Bío Bío Region with 7.5%. 97% of MSW is disposed, and only 3% is collected for recovery.

There are 38 sanitary landfills, 52 non-regulated landfills, and 38 dumpsites. 78.2% of the MSW generated nationwide is disposed in a sanitary landfill. The difference between this three forms of waste disposal is the following:

- A dumpsite is a place where waste is disposed, either spontaneously or scheduled, without any sanitary control or environmental protection.
- A non-regulated landfill is a place of final disposal of waste that was planned for that use, but that does not have the minimum sanitary measures established in Ministry of Health[1]'s Supreme Decree 189/2008, and for this reason, in general it is the focus of environmental problems.
- A sanitary landfill is a solid waste disposal facility in which household and similar solid waste is disposed; they are designed, built and operated to minimize health and safety risks for the population and environmental harm; waste is compacted in layers to the minimum practicable volume and are covered daily.

During the 2012-2017 the number of sanitary landfills increased by 8 facilities, which has allowed the closure of 52 non-regulated landfills.

Chile has a population of 17.6 million people, and generates 1.2 kilos per person per day. This rate is similar to the average in Latin America, and much lower than the average per capita rate of OECD countries.

Chile also generated 49.9 million tons of industrial non-hazardous waste, from which 65.7% comes from the manufacturing sector, 9.7% from the mining sector, and 6% from the energy sector. 70% of industrial non-hazardous waste is produced in the Metropolitan Region (SUBDERE, 2017).

Municipalities are responsible for the collection, transport and disposal of MSW, and there are many differences in waste management from one municipality to another. Each municipality defines and pays for the management of waste[2], and there is not much

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[1] Approves Regulations on Basic Health and Safety Conditions in Sanitary Landfill. Articles Nº16 establishes that all Sanitary Landfills that have a height higher than 6 meters, have to put in place a system to manage the biogas that the landfill produces.
[2] Law 18,695 that establishes the Organic Law of Municipalities.

municipal coordination, making it very challenging to implement common solutions to take advantage of economies of scale.

Waste management is paid through housing contributions. With the modification of Decree Law 3,063/2005 on Municipal Income, about 50% of the properties were exempt from payment of MSW collection, transport and disposal service. This exemption implied that part, or in some cases the entire expense, is covered with resources from the municipal budget (Ministry for the Environment of Chile, 2017). Only 11 municipalities of the 345 in Chile collect a fee that finances the costs of waste management services.

66% of waste management cost in Chile accounts for collection and transport, and 35% to disposal. It is expected that capacity shortages in landfills will result in increase of the cost of waste disposal.

In 2016, Chile passed Law 20,920 - Framework Law for Waste Management, Extended Producer Responsibility and Recycling Promotion, which aims to reduce the generation of waste and encourage its reuse, recycling and other types of waste valorization, through the establishment of Extended Producer Responsibility (EPR) and other waste management instruments. This Law prioritizes six products, which are: lubricating oils, electrical and electronic equipment, batteries, packaging and tires; that must comply with EPR. Currently, the Ministry for the Environment is working on the regulation to implement EPR.

3. Review of Previous Feasibility Studies for WTE Projects in Chile

There have been a number of case studies for WTE projects in Chile. Table 1 presents a summary of the following 4 studies:

- **Study 1**: WTE for Santiago, Chile. A Cost-Benefit Analysis (Estevez P., 2006).
- **Study 2:** Case Study of a WTE in Valparaíso, Chile (Themelis N. et al, 2013).
- **Study 3**: Pre-feasibility study of a WTE plant in Santiago, Chile. (Calixto S., 2017)
- **Study 4:** Technical – economic and environmental feasibility study of a WTE plant for the Metropolitan Region, Chile (Ministry of Energy and Metropolitan Regional Government of Chile, 2018).

Table 1. Comparison between different cost-benefit analyses of WTE plants in Chile. (Modified from Calixto S., 2017).

Category	Study 1[1]	Study 2[2]	Study 3[3]	Study 4[4]
Municipalities	La Florida/ Puente Alto	Valparaíso/ Viña del Mar	Metropolitan Region	Metropolitan Region
MSW generated (ton/year)	288,000	379,513	2.9 million	3.3 million
Installed Capacity (tons/year)	330,000	336,000	1,000,000	330,000
Calorific value MSW (MJ/kg)	9.5	9.4	8.73	10,94

Electricity production (kWh/ton)	600	540	650	600
Gate fee ($US/ton)	**14**	**14**	**18**	**17.6 (average in Metropolitan Region)**
Area (m2)	60,000	50,000	100,000	80,000
Land cost ($US/m2)	34	13	53	46.9
Capital cost ($US/ton of installed capacity)	260	670	300	615
Operating costs ($US/ton of installed capacity)	16	39	12	27.9
Electricity price ($US/MWh)	75.4	90-207	50	3 scenarios of average spot market projection.

[1] The study considered an exchange rate of CLP/USD = 530.

[2] Calorific value based on data from 2001. It is assumed a PPA contract, which was substantially lower than the electricity spot price, but constant along the time.

[3] This study considered an average currency exchange rate of CLP/USD = 677 (Dec 2016).

[4] This study considered a currency exchange rate of CLP/USD = 640 (2018). MSW also included commercial waste collected by municipalities, so the calorific value is higher than other studies.

The most recent study, by the Ministry of Energy and the Metropolitan Regional Government, assessed a WTE plant with annual waste capacity of 330,000 tons per year, grate combustion technology, and a capital cost of US $203 million or US $615 per ton with an EPC model. The main capital cost items are civil work (26%) and combustion chamber equipment (29%).

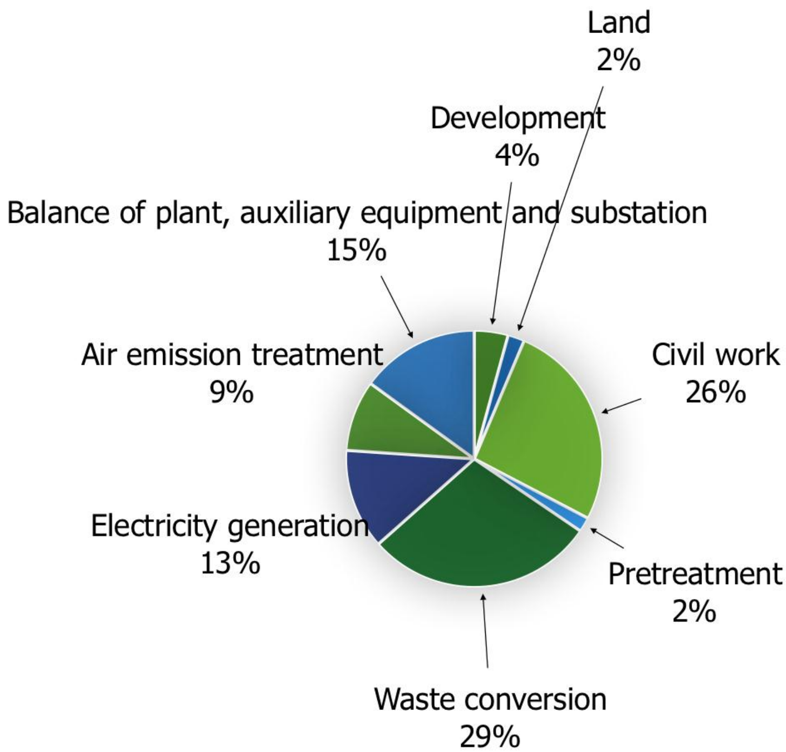

Figure 1: Distribution of capital costs for a WTE facility in Chile, annual capacity of 330.000 tons (Ministry of Energy and Metropolitan Regional Government of Chile, 2018).

Three main business models were assessed (public, concession, and private property), to get as a result the gate fee that the WTE facility would have to charge per tonne of waste in order to secure a discount rate previously defined for each business model.

Results for the concession model, which is assumed would be the most realistic model for a WTE project in Chile, showed that the gate fee required to obtain a discount rate of 8% would be US $43.6/ton (selling electricity only). This gate fee is 2.5 times higher than the average gate fee paid in landfill in the Region, of US $17/ton.

When considering a electricity price scenario under US $50/MWh by 2040, due to the current conditions of the electricity market in Chile, the gate fee would increase to US $66.7/ton, as there would be less revenues from the sales of electricity.

This means that income from waste disposal and energy sales is insufficient to cover full investment and operational costs.

On the other hand, Study Nº3 considered a much lower capital cost, of US $300/ton, using technologies developed in China. Although the design of the project is for an annual capacity of three times compared to Study Nº4, the capital cost is approximately half.

The following chapter describes the status of Chinese WTE market, in order to asses if the rapid WTE market development in China could result in capital cost drops that could decrease the gate fee in a WTE facility in Chile.

4. Waste to Energy in China

4.1 Current Status

China has the largest installed WTE capacity globally (7.3 GW), with 339 plants in operation at the end of 2017, capable of managing just about 130 million tons of solid waste per year, which is higher than the combined capacity of EU and the US, i.e. 127 million tons (International Energy Agency, 2018).

Over the past two decades, China has had a rapid development of WTE capacity, and built about 400 plants since 2000 (Wu J., 2018).

Capacity in China grew at an annual average growth rate of 26% over the past five years, compared with 4% in OECD countries over 2010-16. Consequently, WTE capacity in China is now equivalent to 40% of that installed in all OECD countries combined (Figure 2). It has been expanding more slowly in India, Indonesia, Pakistan, Thailand and Viet Nam, however, at an average rate of 16% annually (International Energy Agency, 2018).

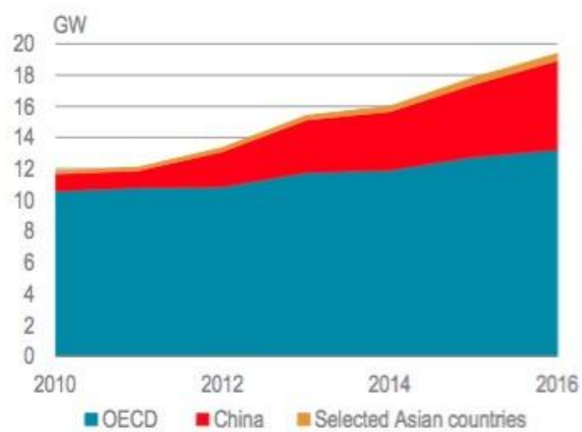

Figure 2: Global WTE capacity growth, 2010-16 (International Energy Agency, 2018)
Note: Selected Asian countries refer to India, Indonesia, Pakistan, Thailand and Viet Nam.

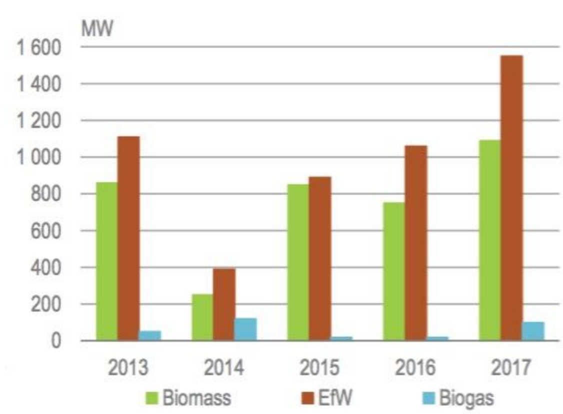

Figure 3: Bioenergy additions in China, 2013-17, including WTE (International Energy Agency, 2018).
Note: Biomass refers to fuels from agricultural and forestry sources.

It is expected that WTE capacity in China will continue to grow, as the country has showed strong commitment to enhance the implementation of WTE facilities for treating waste materials through it's National 13th Five-Year Plan (2016-2020). The Plan sets a target of 10 GW of WTE, of the 23 GW bioenergy target for 2020, which will account for more than 50% of MSW treatment nationwide. It allocated more than US $40 billion of funding to new facilities.

China's rapid WTE market development is due to a mix of policy, economic and sanitary factors. WTE in China is subsidized, mostly owned by State Owned Enterprises (SOE), and receive a feed in tariff for the energy they produce.

There is a government subsidy of 70-250 RMB (US $9.8-$35) per ton of waste annual capacity for investment costs. This figure depends on the economic conditions of different cities (Longjie Ji, et al, 2016).

A feed in tariff[3] of a RMB 0.65/kWh (US $91/MWh) has been in place since 2010. This tariff is higher than the tariff for coal plants. Chinese government is currently in the process of significantly changing its renewable power polices. Feed-in tariffs - which have been central to the Chinese wind and solar industries for the past decade—are being phased out and replaced with auctions and "renewable electricity consumption quotas" (Sandalow D., 2019).

In addition, WTE facilities are supported by the Chinese government by giving the land for free, having very short approval times for new projects, and low-cost loans and fiscal support.

The success experienced by the WTE sector is also attributed to the approach China has adopted over the years in many sectors of infrastructure and sustainability.

4.2 Capital Cost

All the factors mentioned above, have contributed to the large expansion of WTE facilities in China, achieving the lowest capital costs.

[3] In 2005, the National People's Congress passed the Renewable Energy Law, which set national renewable energy targets and established feed-in tariffs for renewable energy.

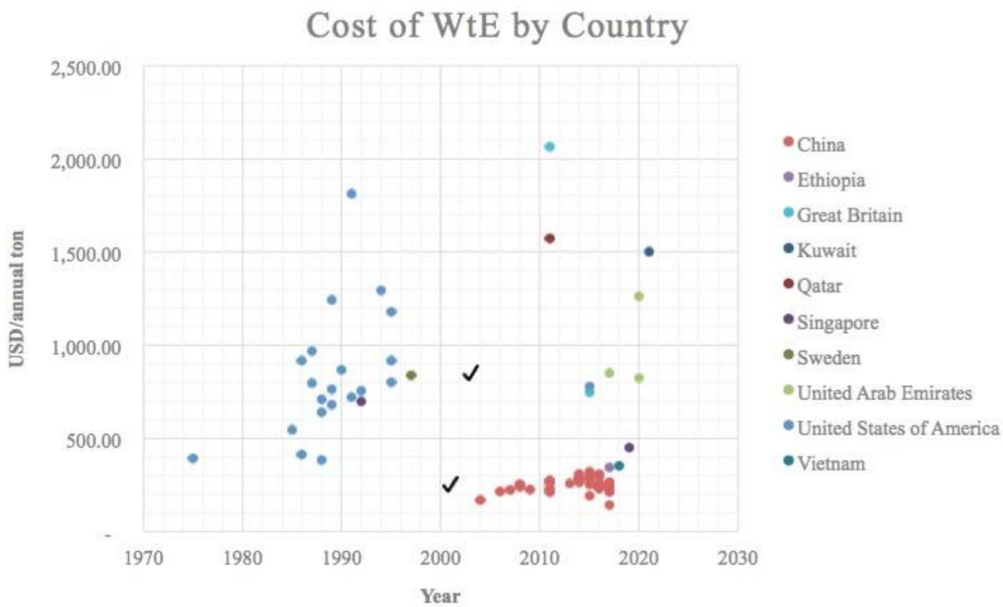

Figure 4: Capital Cost of WTE Facilites (Wu J., 2018).

As shown in Figure 4, the capital cost for Chinese facilities compared to many other countries is much lower, with an average rate of US $250/annual ton capacity (range of US $143-$320/annual ton), while U.S. facilities are constructed at a much higher cost rate at an average of US $840/annual ton capacity.

Two projects led by or with participation from Chinese companies achieved lower capital cost, located in Vietnam (at US $353/annual ton capacity for a 133.000 annual capacity) and Ethiopia (at US $343/annual ton capacity for a 350.000 tons of annual capacity).

China has adapted the moving grate technology that leads the global market, and also the fluidized bed combustion technology, and through cost savings on labor and its unique mass manufacturing and construction capabilities, has managed to achieve the lowest capital costs.

However, it is expected that capital cost for a WTE facility to be implemented in Chile, will not be like the average capital cost in China, as other factors weight in the final capital cost other than the cost of equipment. As showed in Figure 1, 52% of the CAPEX comes from the pretreatment, thermal conversion, generation and air emission treatment, areas where Chinese technology could have an impact in the decrease of costs. However, the rest of the CAPEX comes from development, land, civil works, and balance of plant, auxiliary equipment and substations, that depend on the construction and permitting times in the local country.

Social opposition also impacts on cost. One of the most important factors is the pretermitting time. In Chile it is expected that the first project will take at least 8 years, also considering the case of the WTE facility to be built in Sao Paulo, which started more than 10 years ago. Also, there are some risk of having Chinese State-Owned Entity (SOE) as partners, and financing would be even more challenging.

In conclusion, the results of the study by Ministry of Energy and the Metropolitan Regional Government are realistic in the current WTE market. Capital costs could eventually lower due to the Chinese expansion, a reasonable estimate would be US $450/ton of annual capacity, but it is also expected that the electricity prices will drop in the future due to more capacity additions of renewable energy.

So going back to the main question of this research, if it is worth for the national government to cover the ~$25/ton shortfall in order for the nation to avoid the external environmental costs of landfill?, it is advised that it should consider a shortfall in a range between US $25 to US $50 per ton of waste.

5. Limits of Recycling and Circular Economy

5.1.Waste hierarchy

Globally, there has been strong debate around the idea that WTE could create a desincentive to recycling, generating a dependency on waste generation. This section of this study aims to analyze this question, including the role of WTE on Circular Economy.

A starting point for this discussion is the Waste Hierarchy, as set by the European Union Waste Framework Directive[4]. The Hierarchy sets a priority order for all waste prevention and management legislation and policy, which should make any disposal of waste a solution the last resort, in the following order:

i. Prevention
ii. Preparing for re-use
iii. Recycling
iv. Other recovery, e.g., energy recovery
v. Disposal

The fraction of waste that cannot be recycled, should be used for recovery such as WTE, prior to its disposal in landfill.

5.2.Global recycling rates

When looking at the current recycling rates accomplished by the European Union, Figure 5 shows that in 2017 the average recycling rate for MSW was 46%, 29% was destined to WTE and 23% was landfilled. The countries with the highest recycling rates were Germany, Austria and Slovenia, while in the highest rates in WTE were Finland, Sweden, Denmark and Norway.

The main objective of the EU Directives, Guidelines and Communication documents is not to use land for the deposition of the waste materials and to develop integrated sustainable waste management systems that provide resources to the market/economy through recycling/composting, and energy through WTE from the residual waste, i.e. the materials

[4] In Chile, the waste hierarchy is also recognized by Law 20,920.

that do not have a value in the market, e.g. specific types of plastics, residues/losses from recycling facilities, etc.

In the successful paradigms of the Western and Northern EU, the objective was achieved by a combined effort of recycling and WTE, as can be seen in Fig. 5; proving that sustainability in waste management in accordance to the hierarchy, and with the current available technologies, can only be achieved that way.

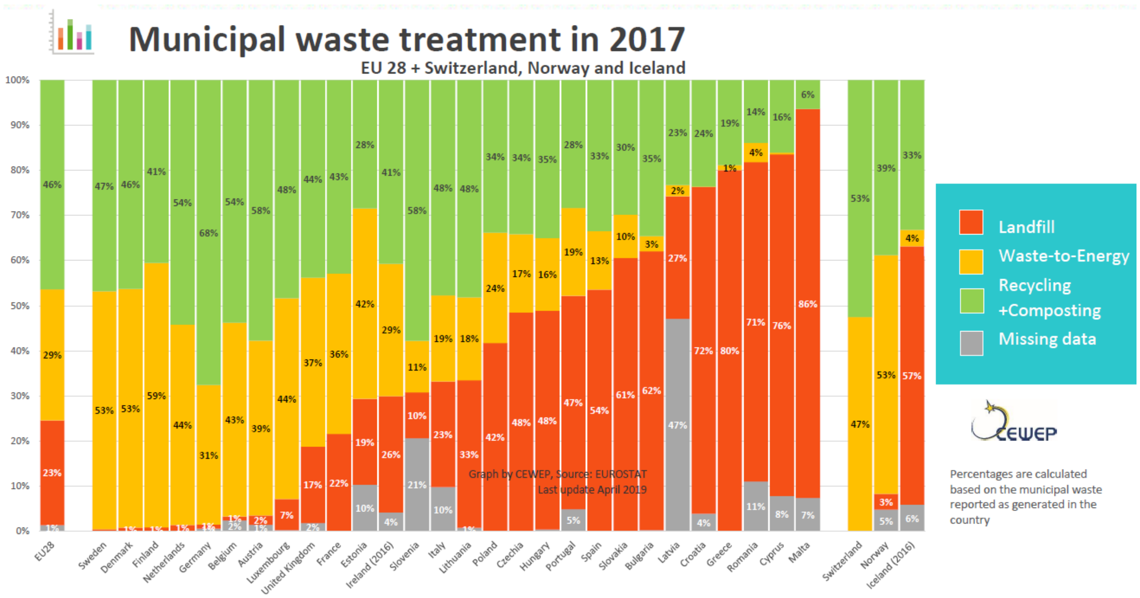

Figure 5: Treatment methods of MSW in 2017 in the European Union plus Switzerland, Norway and Iceland
Source: Confederation of Waste to Energy Plants, updated to April 2019.

In the new Waste Directive, the European Union has updated its goals: by 2035 65% of MSW by weight has to be reutilized and/or recycled. It would be expected from the Waste Hierarchy that the remaining fraction should go to WTE before being landfilled. According to a recent study by CEWEP, 2019 b, '142 million tonnes of residual waste treatment capacity will be needed by 2035 in order to fulfil the currently set EU targets on municipal waste and assuming that ambitious recycling targets will be achieved for commercial and industrial waste. Current Waste-to-Energy capacity is 90 million tonnes and the capacity for co-incineration is around 11 million tonnes. This leaves a gap of around 40 million tonnes'.

Table 2 shows the waste treatment methods in the six regions (by percentage). The highest recycling and composting rates are found in Europe, followed by North America, and the highest landfilling rates are in Latin America and the Caribbean.

	Landfill and other disposal	Incineration with energy recovery	Incineration without energy recovery	Other recovery (recycling and composting)	Waste unaccounted for
Asia Pacific	51.2	29.2	1.3	12.9	5.3
Europe	27.5	24.7	2.7	42.9	2.4
West Asia	89.5	0.0	0.7	15.5	0.02
Africa	93.1	0.0	1.6	2.3	3.0
North America	54.8	11.2	0.5	33.6	0.0
Latin American and the Caribbean	91.2	0.1	0.1	6.4	2.4
Global Average	59.8	15.2	1.2	22.2	2.4

Note: Estimation derived from latest available data from 122 countries, and extracted from the UNSD (2019), OECD (2019) and the World Bank (2018) "What a Waste 2.0" report. Years of data range from 2000 to 2016.
Incineration with energy recovery is often reported together with incineration without energy recovery as one combined category in waste databases, including at UNSD and the World Bank. Waste data reported by the OECD is the only data accounting for incineration with and without energy recovery. The percentage for incineration with energy recovery includes countries from the OECD with reported data, and assumes countries with reported data from the UNSD and the World Bank that own thermal WtE plants incinerate MSW with energy recovery.
"Waste unaccounted for" refers to the percentage of waste without a reported waste treatment method.

Table 2: Waste treatment methods in the six regions (by percentage), from UNEP, 2019.

A recent publication by the United Nations Environment Program, 2019, mentions that in many European countries, high recycling rates give the impression that WTE can complement recycling. However, the study drops this impression by analyzing the Lock-in Effect and the 3-R Trade Off.

The Lock-in Effect generally refers to a dedicated investment in a WTE facility, and the requirement of a fixed amount of waste for incineration over the plant's life. The Lock-in Effect could lead to undermining waste prevention, reuse and recycling policies and programmes due to lack of funds to develop those systems, or "put or pay" contracts that mandate municipalities to provide a fixed amount of waste to the WTE facility or pay a fine. These conditions pose a risk to the waste management hierarchy (UNEP 2019).

On the other hand, the 3-R Trade Off refers to the fact that WTE facilities require a minimum amount of feedstock for operations, and this could potentially divert waste away from the 3Rs (reduce, reuse and recycle) as the feedstock, such as plastics, paper, cardboard and wood, is often recyclable. WTE facilites also lack the ability to process a flexible, decreasing amount of waste (UNEP 2019).

Some European countries import waste to fuel WTE installed capacity, and also to produce energy for district heating networks. China is implementing wider recycling programs, that will result in less waste for WTE facilities. This is not the case for the US, as there is not extra WTE capacity.

On the other hand, a study by Brettler E., 2014, analyzed if a "community's use of a WTE plant to dispose of its waste impact the level of recycling in that community?". The paper examined recycling rates of 700 communities in 21 states in the United States, which rely on WTE for their waste disposal. It demonstrated that this means of disposal had no impact on recycling. In fact, overall communities using WTE had a slightly higher level of recycling than that observed across their states and across the nation.

The recycling market is very complex and develops because of policy efforts, but also, and most important, because of profit. According to Bloomberg NEF, 2019, the most common policy mechanisms for recycling are targets for MSW treatment. Targets are often one aspect of broader market- building strategies that include minimum recycled content for materials and recyclability standards for new products.

In 2018, China and other Asian countries banned the imports of waste materials for recycling, ending the reliance many countries had on China to take and process part of its paper and used plastic, among other materials. The un-sustainability of the export model for plastic recycling in particular was exposed.

At present time, support for recycling is notably absent despite the need for new capacity in high-income economies. The future of the international recycling market remains uncertain due to new trade restrictions such as the China Ban (Bloomberg NEF, 2019)

5.3.Circular Economy

Circular economy is explained as an economy "where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized" (EU Circular Economy Action Plan).

The European Union has been at the forefront of circular economy policy, which began as legislation on landfills and specific types of waste in the 1990s. The EU also implemented some of the earliest and most robust extended producer responsibility schemes in the world. In 2015, the European Commission adopted the Circular Economy Action Plan to offer an integrated policy framework (Bloomberg NEF, 2019).

In spite of high recycling rates in Europe, on average only 12% of material resources used in the EU in 2016 came from recycled products and recovered materials - thus saving extraction of primary raw materials. This indicator, called 'circular material use rate', measures the contribution of recycled materials to overall demand. The indicator is lower than recycling rates, which measure the share of waste which is recycled, because some types of materials cannot be recycled, e.g. fossil fuels burned to produce energy or biomass consumed as food or fodder (Eurostat, 2019).

Recycling has many limitations that relate to the quality of the recovered products, the markets and, also, the understanding and compliance of citizens to source-separate recyclables. Even in European countries who have achieved high recycling rates and represent the most successful paradigms of sustainable waste management, by 2035 there will be at least 35% of post-recycling waste materials that, following the Waste Hierarchy, should go to WTE instead of landfilling.

5.4.Critical aspects for Chile

The European Union has the highest recycling mandates: 65% of MSW by weight has to be reutilized and/or recycled by 2035. Still, this rate means that there will be an important fraction that can't be recycled.

In addition, the recycling rates that are published by countries do not represent the real amount of material recycled, as it only accounts for the material collected and there is no real accountability of what really happens after material is collected, sorted and bailed. Depending on the separation and collection system of recyclable materials, there is an important amount that is contaminated to go anywhere but landfill.

UNEP, 2019, recommended that in order to avoid the lock-in effect, countries should carefully project future waste amounts and enact a long-term plan for sustainable waste management that focuses on waste prevention, reuse, recycling, composting and anaerobic digestion systems. Countries should avoid put or pay contracts, as well as long-term contracts that lock them into decades of burning waste that could have been prevented, reused or recycled.

Considering these aspects, in Chile there is space for implementing WTE in Chile for non-recyclable waste as currently, only 1% of MSW is recycled. In the future, and through the implementation of the Waste Law, recycling and waste minimization are expected to increase and waste composition and quantity will change. It will be important to plan WTE facilities as part of an integrated waste management plan, and not as an individual initiative.

It is also important to note, that at present time, Chile is going through a very difficult period of social discomfort over issues that have been simmering for years, such as unequal wealth distribution and the rising cost of living. In this sense, this study briefly included an analysis of countries with WTE capacity and the index of inequality.

Figure 6 presents the relation between the Income Inequality between several developed countries, and the index of health and social problems. It shows that "countries that do worse, whatever the outcome, seem to be the more unequal ones, and the ones that do well seem to be the Nordic countries and Japan. So what we're looking at is general social disfunction related to inequality" (Wilkinson R., 2011).

What is interesting is that Nordic countries and Japan, which are the least unequal ones and offer better health and social services, also prove to be the ones that have achieved the highest recycling and WTE rates, with minimum landfilling. From this data, it is not possible to draw any further conclusions, but it would be interesting to deepen the analysis around the relation between income, wealth, social inequality and waste management, including recycling, WTE and landfill.

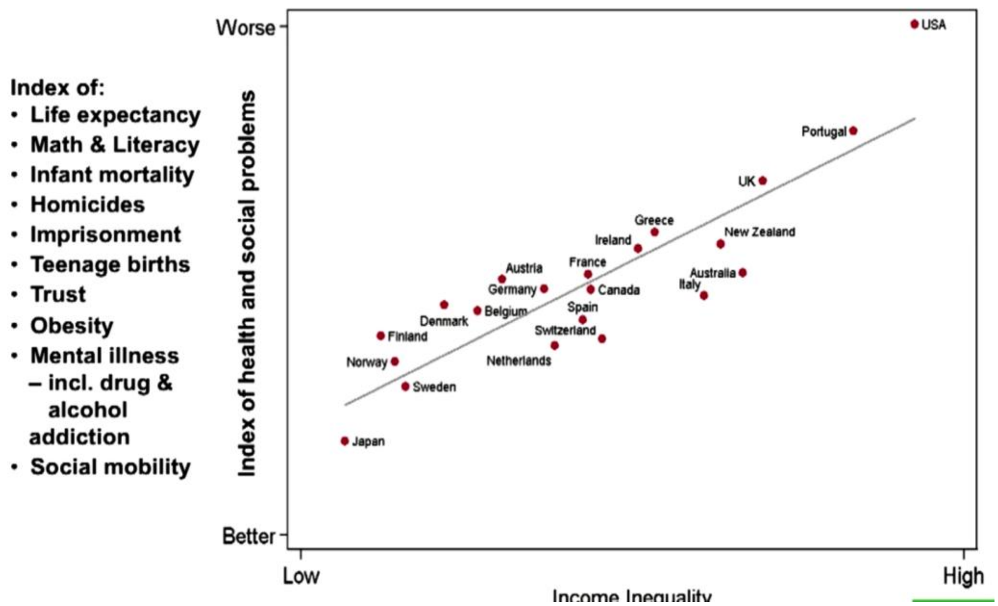

Figure 6: Relation between the Income Inequality of several developed countries, and the Index of Health and Social Problems (Wilkinson R., 2011).

6. Quantification of the environmental costs and benefits

6.1.Methodology

This study aimed to quantify and compare the environmental costs and benefits of landfill and Waste to Energy, that are not factored in a fully private investment, in order to determine a "social gate fee". Through literature review, the study quantified and priced the environmental costs of managing a tonne of MSW in the three following scenarios:

Scenario 1: Non regulated landfill
This scenario is the most basic waste management method. It assumes that the MSW would be disposed in a landfill that does not collect the methane produced through the natural process of decomposition of organic wastes, and without energy recovery. Also waste compaction is not efficient. Example of such non-regulated landfills in Chile is the Boyeco landfill, located in the Araucanía Region. Boyeco landfill was closed in 2016, after more than 20 years receiving 180.000 tonnes of waste per year. Currently the Temuco Municipality disposes its waste in Los Angeles Landfill, located 180 km from the city of Temuco.

It is important to note that scenario 1 assumed a sanitary landfill with no methane collection, however, according to section 2 of this study, in Chile 21,8% of the MSW that is generated goes to non-regulated landfills and dumpsites, with is a much worse scenario.

Scenario 2: Sanitary landfilling with electricity generation
This scenario assumes that the sanitary landfill that receives wastes, collects half of the landfill gas produced and it is used for electricity generation, which is a typical assumption, according to (Themelis and Ulloa, 2007). In Chile, out of the 38 sanitary landfills, 3 of them (El Molle in Valparaiso, Lomas Los Colorados and Santa Marta in the Metropolitan Region)

produce electricity. Lomas Los Colorado Landfill is located in Til Til, is owned by KDM, and receives waste from 31 municipalities, more than 1,7 million tonnes of MSW per year. It has an installed capacity of 20.2 MW.

Scenario 3: Waste to Energy facility with electricity generation
This scenario assumes that the MSW, unsorted, would directly go to a WTE facility with moving grate combustion technology and state-of-the-art air pollution control systems. After combustion, metals in the ash are recovered for recycling. The rest of the bottom ash goes to a sanitary landfill as daily cover, and the fly ash goes to a hazardous waste landfill after stabilization. There are no WTE facilities in Chile.

The following equation shows the calculation path in order to quantify and compare the environmental costs and benefits of the three scenarios, in order to get a 'social cost' in US$/ton of MSW:

SOCIAL COST US$/ton	=	**GATE FEE ($/ton)**	+	**COSTS ($/ton)** Land consumption Direct CO_{2eq} emissions Air emissions, health risks and other costs*	-	**BENEFITS ($/ton)** Diversion of MSW from landfill Energy displaced from the energy grid Metals recovered for recycling

*Cost of air emissions, health risks, and other costs were not priced into the 'social cost' due to lack of time, but are important factors to consider for decision making.

For scenarios 1 and 2, this study assumed the average gate fee for landfills in the Metropolitan Region is US $17.6/ton of MSW. The gate fee for 330,000 tons per year, according to section 3 of this study, would be between US $43.6 - $66.7/ton (Ministry of Energy and Metropolitan Regional Government of Chile, 2018).

6.2. Land consumption

This study assumed that there is a cost of land consumption of burying waste in landfills. Even when a landfill is closed, the land is not available for other purposes. This is not the case of a WTE facility, in which after its closure, the land can be used for other purposes.

According to Bourtsalas A. C. and Themelis N. J., 2019, the land consumption rate of sanitary landfills in the United States is 15.8 ton/m^2. This means that to dispose 15.8 tons of waste, 1 m^2 of land is needed. To dispose 330.000 tons of MSW per year, 2.08 hectares would be used annually. Assuming that the life span of a WTE facility is at least 30 years, in order to landfill the same amount of waste for 30 years, 62.5 hectares would be lost in landfill, compared to the 8 hectares that uses a WTE facility.

This study assumed that for scenario 1, the land consumption rate is twice as much than for scenario 2, to factor in the less compaction of waste that probably occurs in Chilean landfills that are less than 6 Mts height and that don't collect the biogas.

It would be ideal to have an economic model to value the land that would be lost through landfilling, such hedonic models, which are mathematical models that have been used to assess the contribution that previously identified variables have on the price of land. However, due to the lack of such a model for the conditions of this study, the market value has been used.

The study by the Chilean Ministry of Energy and the Metropolitan Regional Government in 2018, considered a price range of CLP $300.000.000 to $1,350,000,000 per hectare (~US $468,750 to 2,109,374), considering industrial sites near the Américo Vespucio Ring. This study used the lower cost of land, US $468,750/hectare, as landfills are generally located far away from the city center.

	Landfill	Sanitary landfill with electricity generation	WTE facility
Land consumption rate ton/m²	7.9	15.8	~ 0
Land cost US$/hectare	468,750		
Cost of land consumption US$/ton	5.9	2.96	~ 0

Table 3: Cost of land consumption.

6.3. Direct CO_{2eq} emissions

The decomposition of municipal waste in landfills is recognized as one of the largest sources of global anthropogenic methane emissions.

In this section this study quantified the actual amount of carbon dioxide equivalent (CO_{2eq}) emitted per ton of MSW in the three scenarios, considering CH_4 and CO_2 direct emissions from natural anaerobic digestion of biogenic waste in landfills and the emissions from the combustion of MSW in a WTE facility.

The emission factors of direct CO_{2eq} emissions for each scenario are based on data published by Lin Ao, 2018. The thesis considered the C-H-O molecular structure of the United States MSW calculated by Themelis, Kim et. al, on the basis of chemical analysis, assuming that MSW contains 60% of dry organics, and that only 50% of the landfilled biomass in MSW is actually reacted to methane.

- For scenario 1, a landfill with no methane collection, the emission factor for carbon dioxide equivalent is 1.73 tons CO_{2eq}/ton MSW.
- For scenario 2, assuming 50% landfilling gas would be collected for electricity generation, the emission factor is 0.95 tons CO_{2eq}/ton MSW.
- For scenario 3, Lin Ao, 2018 considered how MSW reacts in WTE combustion chambers. The amount of CO_2 emitted would be 0.755 CO_2/ton MSW. Also, the reduction of CO_2

emissions compared to the baseline scenario 1 is 0.975 tons of CO_2/ ton MSW, which is accounted in section 6.6.1 of this study.

On the other hand, a study by Bourtsalas A. C. and Themelis N. J., 2019, showed that the GHG emissions from U.S. landfills were 1.4 tonnes CO_{2eq}/ton of wastes landfilled. This factor is lower than the factor proposed to use for scenario 1, as it already considers the amount of methane and CO_2 captured at landfills for electricity generation that are under the US EPA Landfill Methane Outreach Program.

In Chile, in 2017 a CO_2 tax began to apply under Law 20.780, which is equivalent to US $ 5/ton. This value, determined by the Ministry of Social Development, seeks to internalize the social and environmental cost generated by carbon. The tax is to be applied to boilers and turbines, which individually or as a whole add up to a thermal power greater than or equal to 50 MWt (thermal megawatts), considering the upper limit of the calorific value of the fuel. This Carbon tax was used to price the direct CO_{2eq} emissions.

	Landfill	Sanitary Landfill with electricity generation	WTE facility
Generation of Carbon Dioxide Equivalent tons CO_{2eq}/ton MSW	1.73	0.95	0.75
Carbon Tax US$/ton		5	
Cost of direct CO_{2eq} emissions US$/ton	8.65	4.75	3.75

Table 4: Cost of direct CO2 emissions.

6.4. Air emissions and health risks

The incineration process can result in three potential sources of exposure: (1) emissions to the atmosphere, (2) via solid ash residues, and (3) via cooling water. Provided that solid ash residues and cooling water are handled and disposed of appropriately, atmospheric emissions remain the only significant route of exposure to people. This section of this study is thus concerned only with the health effects of emissions to air.

Both landfill and WTE facilities emit air pollutants that can pose risk to human health and the environment, and one critical determinant of the acceptability of these options is the different health risks associated with each. While some studies suggest that certain substances emitted from landfills and WTE facilities lead to birth defects, respiratory problems, and increased risk of cancer, other studies have found no significant health impact.

Both of these technologies have been improved in the last 30 years. In the US, modern landfills are required by Subtitle D rules of the Resource Conservation and Recovery Act, to include a non-permeable liner at the bottom, leachate collection, and gas emission collection, be capped at the top, and contain and treat emissions as much as possible. WTE facilities, through the implementation of EPA Maximum Achievable Control Technology (MACT) standards, have reduced emissions of certain hazardous materials including heavy metals and dioxins by a factor of almost 100 (Moy, P., et al, 2008).

Studies published in the scientific literature showing health effects in populations living around incinerators have, in general, been conducted around older incinerators with less stringent emission standards and cannot be directly extrapolated with any reliability to modern incinerators.

A study by Moy P., et al, 2008, performed a health risk assessments for landfill disposal versus WTE treatment options for the management of New York City's MSW, through analysis relying on published data and modeling of inhalation exposure. While studies showed that the health risks of both methods of disposal are largely insignificant, it showed that the cancer risks are 5 times higher with landfills, and also 5.2 higher for non-cancer health risks. These non-cancer health risks are caused predominantly by trucks used to transport wastes to landfill sites in other areas.

Based strictly on the outcome of health-risk assessments, it could be concluded that WTE treatment is a better option than landfilling for NYC MSW due to the differences in non-cancer and cancer health risks noted above. However, the limitations of the study should be kept in mind in order to make sound and acceptable decisions regarding the optimal handling of MSW.

In addition, a study by the UK's Health Protection Agency, 2009, concluded that "Modern, well managed incinerators make only a small contribution to local concentrations of air pollutants. It is possible that such small additions could have an impact on health but such effects, if they exist, are likely to be very small and not detectable".

Although the present study is not intended to put a cost on all air emissions and health risks, it made an effort to analyze the available data and studies, in order to get a good idea of the acceptability of the three scenarios.

- Dioxins

Dioxins are persistent organic pollutants, released into the environment from several sources. The health effects due to exposure to dioxins, have been studied extensively. Over 90 percent of human background exposure is estimated to occur through the diet, with food from animal origin being the predominant source. Dioxin contamination of food is primarily caused by deposition of emissions from various sources (e.g. waste incineration, production of chemicals) on farmland and waterbodies followed by bioaccumulation up terrestrial and aquatic foodchains (World Health Organization, 1998).

In the US, WTE facilities are required annually to measure total dioxin concentrations in the stack gas exhaust to demonstrate compliance with the US EPA standard.

In 2015, a study by Dwyer, H. and Themelis, examined the level of dioxin emissions to the atmosphere from various U.S. sources and the relative contribution of the WTE industry to the total dioxin emissions. The controlled sources of dioxins were grouped into five classes:

Waste to energy, Waste incineration (with no energy recovery), Electricity and heat generation: fuel combustion for electricity generation, heating, and vehicles, Metallurgical processes: metal processing and cement and asphalt production. Other sources were grouped into a sixth class Open burning processes: referred to minimally or non-controlled combustion including, backyard barrel burning, agricultural burning, construction debris, yard waste and fires (forest, vehicle, landfill, and building).

Results showed that the dioxin emissions of all US WTE plants in 2012 were 3.4 g TEQ (Toxic Equivalent) and represented 0.54% of the controlled industrial dioxin emissions and 0.09% of all dioxin emissions from controlled and open burning sources.

This assessment was done considering the 2012 dioxin emissions from 53 U.S. WTE power plants, which were compiled based on detailed data obtained from the two major U.S. WTE companies, representing 84% of the total MSW combusted (27.4 million metric tons).

In comparison, over three thousands of landfill fires reported in the U.S. National Fire Incident Reporting System, 2011, were estimated to emit over 600 grams TEQ.

WTE as a % of total dioxin emissions.

	1987	1995	2000	2012
Total controlled sources	14,024	2789	1173	634
WTE as % of controlled emissions	67.7	43.0	6.6	0.54
Total of all sources	16349	5123	4174	2901
WTE emissions as % of all sources	58.1	23.4	1.8	0.09

Table 5: United States WTE dioxin emissions (1987, 1995, 2000 and 2012). Dwyer, H. And Themelis, 2018.

As shown on the table above, dioxins emissions from WTE facilities in the US have decreased significantly, from 58.1% from controlled and uncontrolled sources in 1971, to 0.09%. This has been due to the higher US EPA standards, and the implementation of air control equipment.

To ensure minimum environmental and health impact, WTE plants should meet the most stringent emission standards. Yet in developing countries, there are often no, or less strict, incineration emission standards and/or related law enforcement for WtE. For example, in China and India, although national emission standards for waste incineration are available, requirements are less strict than European Union standards. Excessive dioxin emissions from WTE plants have been recorded in both countries. Poor operation and maintenance has resulted in higher dioxin emissions in plants in developed countries as well (UNEP 2019).

In conclusion, strict regulation and continuos monitoring is essential for low emissions of dioxin.

- Risk of fires

Landfill fires are primarily caused by spontaneous combustion of methane emitted from landfills. Fires and heat-generating reactions are often initiated or exacerbated through the introduction of air into the waste mass, creating exothermic decomposition reactions and potentially explosive conditions. Fires can be difficult to extinguish and can last weeks before even being discovered.

Although there are no statistics on the number of fires occurred in landfills in Chile, there have been recent incidents that caused great attention. One was the was a fire Santa Marta Landfill, located in the Metropolitan region, in January 2016.

Landfill fires cause harmful air emissions, and pose a risk to humans and the environment. This study assumes that WTE avoids the risk of landfill fires, as there is no methane production, and waste combustion is controlled. But this study could not get information on the probability of fires in landfill in Chile, the effects of landfill fires, and put a price per ton on MSW burnt directly in a landfill. However, risk of fires in landfill is an important factor to take into account for decision-making.

- Other emissions

WTE major pollutants of concern are considered to be Dioxins and related compounds (combined as TEQ), Heavy Metals such as Mercury, Cadmium, Lead, Particulate Matter (PM), Hydrogen Chloride (HCl), Sulfur Dioxide (SO_2) and Nitrogen Oxides (NO_x).

There are also significant emissions from open burning and fires in waste, of CO, HCs, PM, NO_x and SO_2. A study by Annepu, R., 2012, about sustainable solid waste management in India, found that open burning of solid wastes and landfill fires emit nearly 22,000 tons per year of pollutants into the air in the city of Mumbai alone. These pollutants include Carbon Monoxide (CO), Hydrocarbons (HC), Particulate Matter (PM), Nitrogen Oxides (NOx) and Sulfur Dioxide (SO2) plus an estimated 10,000 TEQ grams of dioxins/furans. Open burning was found to be the largest polluter in Mumbai, among the activities that do not contribute any economic value to the city. Since open burning happens at ground level, the resultant emissions enter the lower level breathing zone of the atmosphere, increasing direct exposure to humans.

6.5.Other social impacts

There are other environmental impacts from landfills and WTE facilities that should also be taken into account for decision-making.

One of them is odours. WTE facilities emit less odor compared to landfills, as the initial process of waste tipping and pretreatment is done inside a closed bunker, that has negative pressure that does not let bad smell escape from the building.

Another important environmental aspect is water pollution. In landfills, leachate produced has to be monitored and treated according to regulations. Any leakage will pollute the underground water and soils. However, WTE might have more public opposition as the emission are visible from the stack, and the emissions of landfills not visible to the public.

6.6.Diversion of MSW from landfill

WTE offsets CO_{2eq} emissions that would have been emitted by other sectors, thanks to the diversion of waste from landfills, the production of energy that would otherwise be generated by fossil fuel-powered plants and the recycling of metals and minerals (ESWET, 2019).

MSW typically contains about 30% carbon, two thirds of which are of biogenic origin (paper, wood, food wastes, etc.); using it as fuel reduces the amount of fossil fuel used (anthropogenic origin). Also, diverting MSW from landfills reduces the amount of methane emitted by landfills and one molecule of methane emitted to the atmosphere is equivalent to 21 molecules of carbon dioxide. Due to these two factors, one ton of MSW combusted rather than landfilled results in decreasing carbon emission by 0.5 to 1 ton of carbon dioxide, depending on the efficiency of landfill gas collection (WTE Guidebook, Themelis, N., et al, 2013)

As mentioned in section 6.3, the reduction of CO_2 emissions compared to the baseline scenario 1 is 0.975 tons of CO_2/ ton of MSW combusted. Multiplied by US $5/ton of CO_2, results in a benefit of US$4.75/ton of MSW combusted in a WTE facility.

6.7.Electricity generation

Electricity generation from landfills and WTE facilities displace energy produced from fossil fuel-powered plants on the electricity grid. This displacement is based under carbon neutrality assumptions, that in a global sense, means net zero emissions of anthropogenic CO_2. In the context of WTE, CO_2 released from biomass combustion is assumed to be offset by the CO2 initially absorbed through photosynthesis.

Generally speaking, WTE can generate an order of magnitude more electricity than landfills given the same amount of waste:

- WTE Facility: 0.5 MWh/ton of MSW
- Landfill: 0.05 MWh/ ton of MSW

For this study, the average emission factor of the National Electrical System in 2018 in Chile was used, which is 0.4187 tCO_{2eq}/MWh and the same carbon tax used in section 6.3.

	Landfill	Sanitary Landfill with electricity generation	WTE facility
Electricity generated per ton MSW MWh/ton	0	0.05	0.5
Average emission factor of the National Electrical System in 2018 tCO_{2eq}/MWh		0.4187	
CO2eq emissions displaced tCO_{2eq}/ton MSW		0.02	0.2

	Landfill	Sanitary Landfill with electricity generation	WTE facility
Carbon Tax US$/ton CO_{2eq}	5		
Energy displaced from the energy grid US$/ton		0,1	1

Table 6: Benefits from Energy displaced from the energy grid

The indirect savings of GHG emissions due to electricity generation account for US $ 0.1 per ton disposed in landfill, and US $ 1 per ton disposed in a WTE facility.

However, this saving are taking into account that the electricity generated by scenario 2 and 3 are carbon neutral. On one hand, only a fraction of waste is biogenic and could account for CO_2 reductions. And on the other hand, the carbon neutrality assumption is being challenged by a growing number of experts that have assessed the global warming potential of biomass-associated combustion, associated with the regrowth period of biomass.

Although this study did not look further into this discussion, it is important to note that not all energy produced by WTE facilities should be considered renewable or carbon neutral.

6.8. Metals recovered

The combustion process in WTE facilities produces bottom ash, which is the incombustible residual part of the incinerated waste. Important quantities of metals and minerals are present in these residues and offer opportunities for recycling.

Bottom ash is composed of inert, non-combustible materials that are left over after the combustion process: sand, stones, ashes from burnt material. It also contains metals that are embedded in the residual waste – such as thin aluminum foils – and therefore could not be separately collected. The metals can be extracted from the ashes and further used as secondary raw material – such as scrap aluminum – at a less environmental cost than the production of virgin metal.

According to the Confederation on European Waste to Energy Plants (CEWEP, 2019), approximately 20% of the weight of the waste treated in the plants results in bottom ash. Bottom ash is made up of 80–85 % minerals, with the remaining 10 -12% metals (steel and ferrous metals) and 2-5% of Non-ferrous metals (of which 2/3 aluminum).

This study assumed that a WTE facility could recover 50% of the metals contained in MSW bottom ash. Since the MSW in the Metropolitan Region in Chile contains 1.07% metals, then from every ton of MSW combusted approximately 5.35 kilograms of metal could be recovered for recycling.

According to Themelis, Krones et. al [22], the avoided GHG emissions by recycling over landfill disposal is 1.741 tons of CO_{2eq}/ton mixed metal, compared with sanitary landfilling.

The indirect savings of metals recovered for recycling are 0.00535 tons of metal recovered per ton on MSW x 1.741 tons of CO_{2eq}/ton mixed metal = 0.0093 tons of CO_{2eq}/ton of MSW. Considering a price of US $5/ton of CO_2, the saving are US $ 0.04.

Saving due to metal recovery in Chile are small, due to the amount of metals per ton of MSW is 1.07% compared to 9% in the US.

The inert part of the bottom ash, after metals recovery, can be used as construction material such as road construction, or act as aggregate for concrete. Many European countries are using bottom ash as an alternative to virgin material such as gravel and sand.

7. Results and discussion

Results showed that the net carbon from landfilling is 0.5 and 1 ton CO_2/ton MSW higher than WTE. The 'social cost' of both alternatives is mainly determined by the social cost of carbon. This study used a price of CO_2 equivalent to US $ 5/ton, which is a CO2 tax regulated by under Law 20.780. However, this price is too low compared to estimates of over $50 per ton.

		Landfill	Sanitary landfill with electricity generation	WTE facility	
		US$/ton of MSW			
Private Gate Fee		**17.6**	**17.6**	**43.6**	**66.7**
Additional cost	Land consumption	5.93	2.97		
	Direct CO_{2eq} emissions	8.65	4.75	3.75	3.75
Benefits	Diversion of MSW from landfill			-4.75	-4.75
	Energy displaced from the grid		-0.10	-1.05	-1.05
	Metals recycling			-0.05	-0.05
Social Gate Fee		**32.18**	**25.21**	**41.51**	**64.61**

Table 7: Summary of results - environmental costs of landfill and Waste to Energy facilities.

Table 7 summarizes the results of the evaluation of the environmental costs and benefits of landfill and WTE facilities in order to determine a "social cost". It considered the cost of land consumption and direct CO_{2eq} emissions, and the benefits from indirect CO2eq savings from diversion of MSW from landfill, energy displaced from the energy grid and metals recovered for recycling. The cost of air emissions and health risks were overviewed, but not fully quantified due to lack of time and available data

Results showed that considering the costs and benefits that are not factored in a fully private investment, gate fees varied according to the following:

- The gate fee for scenario 1 (landfill) increased from US $17.6/ton to US $32.18/ton.
- The gate fee for scenario 2 (sanitary landfill with electricity generation) increased from US $17.6/ton to US $25.21/ton.
- The gate fee for scenario 3 (WTE) decreased from US $43.6/ton to US $42.51/ton and from US $66.7/ton to US $66.7/ton

The 'social gate fee' of WTE continues to be higher than landfilling. A simple sensitivity analysis was done for the cost of land consumption, and the price of CO2 emissions, as shown in Table 8.

When modifying key criteria, doubling the price of a ton CO_{2eq} emissions or tripling the price of land, the 'social gate fee' for landfill without methane collection is higher than WTE. However, in all cases, the 'social gate fee' for sanitary landfill with electricity generation is lower than for WTE.

		landfill	Sanitary landfill with electricity generation	WTE facility	
		US$/ton of MSW			
Private Gate Fee		17.6	17.6	43.6	66.7
Social Gate Fee	US$5 /ton CO_2	32.18	25.21	41.51	64.61
	US$10 /ton CO_2	40.83	29.86	39.41	62.51
	US$15 /ton CO_2	49.48	34.50	37.32	60.42
	3 times more the price of land	44.05	31.15	41.51	64.61

Table 8: Sensitivity analysis.

8. Conclusions

There are clear environmental, economic, and aesthetic benefits of WTE facilities as compared to landfills. If managed and maintained properly, WTE facilities can reduce CO_{2eq} emissions alleviate the public health effects of improper waste management, preserve valuable land, generate 10 times more energy, and recover metals and minerals for recycling.

However, WTE associates with high capital and operational costs which are not expected to decrease, considering significant factors that hinder the development in Chile, such as the lack of support from the public entities; inadequate public information; major contribution by informal recyclers, whose livelihood depends on the collection and sales of recyclables; low fees for the disposition of waste materials, and indirect advocacy of improper disposition of wastes in open dumps; institutional, and regulatory hurdles associated with permitting.

Considering the current situation of the improper landfilling of waste and the limited financial and technical capacity on WTE deployment, the Chilean Government must develop efficient collection of wastes and transform the open or improper landfills to engineered landfills with methane recovery and electricity generation as a short term solution to the challenge of waste management. A clear regulatory framework should be developed that advocates WTE, by the use of results-based financing mechanisms, as explained in detail in GPRBA, 2018; that will be the long and secure solution. In addition, pre-treatment systems should be developed to ensure minimum loss of quality of the waste materials.

For the future, value-based economic, financial and environmental life cycle models should be considered, by taking into account the resource productivity. For example economic output and materials input; and the environmental impact of the several waste management options, e.g. reusing, recycling/composting, energy recovery; in order to optimize the contribution of the waste products to the market, the economy, and the environment. I will also need to provide the tools to the stakeholders to deploy integrated sustainable waste management systems that recover materials through recycling and energy from the residual waste.

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