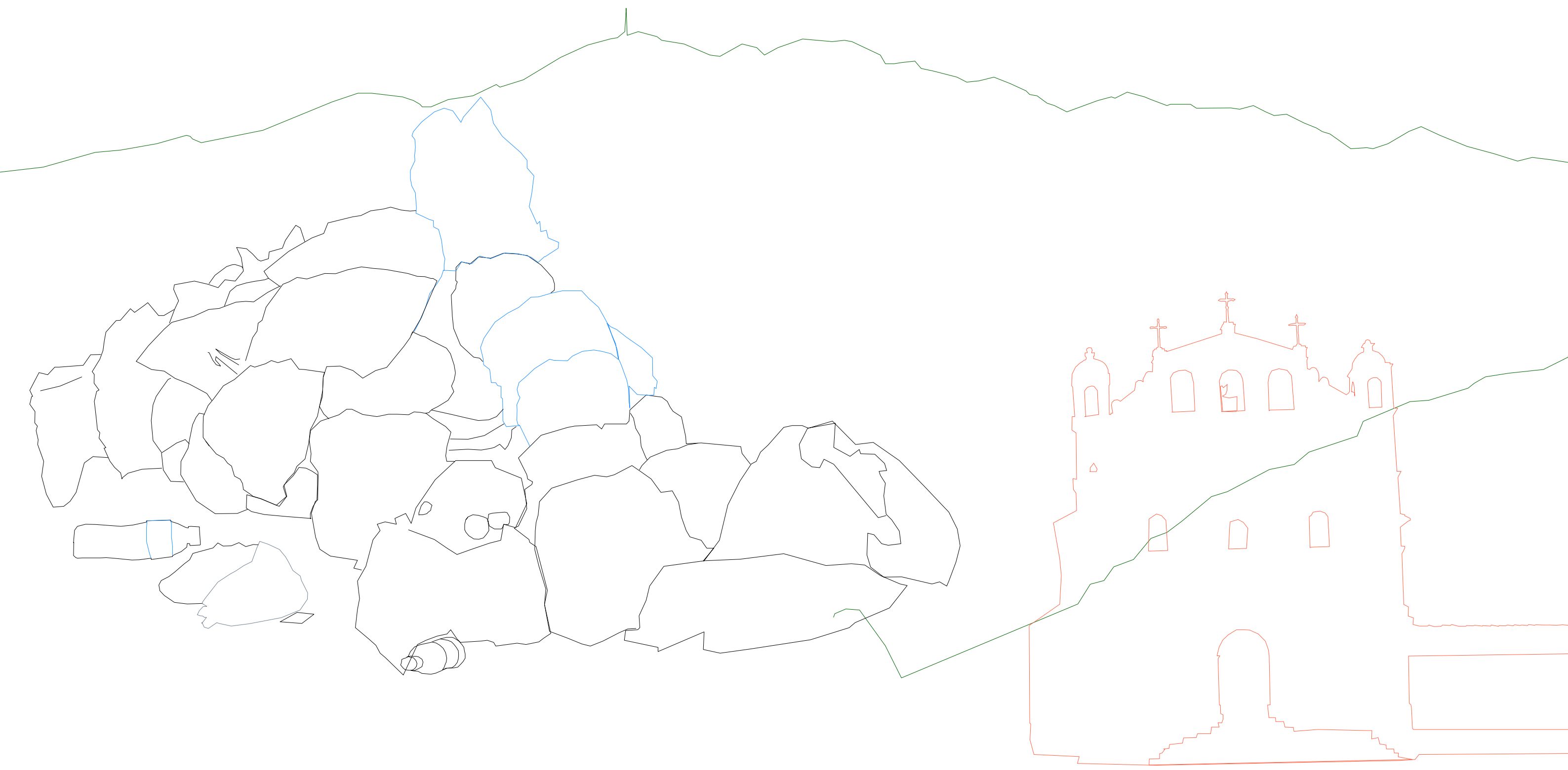
A circular economy approach to exploit the value of urban solid waste

Study case of San Cristobal de las Casas, south-east Mexico



Master Thesis Report

Valente Gonzalez Veugelers

Industrial Ecology

2020

A circular economy approach to exploit the value of urban solid waste

Study case of San Cristobal de las Casas, south-east Mexico

Thesis submitted in fulfillment of the requirements for the degree of
Master of Science in Industrial Ecology

Written by:
Valente González Veugelers

Supervised by:
Dr. José Manuel Mogollón (Institute of Environmental Sciences, Leiden University)
Dr. Ulf Hackauf (Department of Urbanism, Delft University of Technology)

June 18, 2020

Summary of the Research

The urban solid waste (USW) that is generated as a result of industrial and domestic activities pollutes water bodies, soil and the atmosphere when disposed on land or water. Currently, more than 50% of the USW that is generated in the world, and in Mexico, is disposed in landfills which generate large quantities of methane emissions and leachates that contain heavy metal and nutrients. However, it is possible to recover materials from USW and use them to create valuable goods and services; thus reduce the amount of USW that is disposed.

This coincides with circular economy, a concept that aims to maintain the value of a material or product active in the economy for as long as possible by incorporating it back into a product life cycle. This can be done through processes such as recycling, refurbishing or reusing products, or through thermal, mechanical and chemical processes, for the case of homogeneous material.

The purpose of this study is to explore possible solutions for the different types of USW, from which value can be recovered, based on the socio-economic context of a study case and on the concept of circular economy. This research takes San Cristobal de las Casas (SCLC) as a study case, a city in the south-east of Mexico where tourism is the main industry.

This research demonstrates a framework that considers the relation between the magnitude of the USW problem, waste treatment technologies and availability of markets to sell the processed USW; this ultimately determines the viability to recover value from USW. Additionally, this research provides an insight on the evolution of composition and waste generation rates per capita, and also a methodology which can be used to determined the USW footprint of the tourism sector. Additionally, this research is relevant for the city of SCLC, as the results can incentivise, with specific measures, the private and public sectors to exploit the economic value of USW and decrease the environmental damage of USW.

Approximately 280,000 kilograms of USW are generated and landfilled on a daily basis in SCLC; which is collected, transported and disposed by the municipal waste department. In this research the sources of USW have been divided in four, namely domestic, market, tourism and local businesses. Domestic USW amounts 140,000 kilograms per day, where the generation of USW per capita per day is estimated to be 0.6 kilograms. From the domestic waste approximately 50% is organic waste, 21% plastics, 8% toxic waste, 8% paper and cardboard, 5% glass and 2.4% metals. Local businesses generate roughly 91,000 kilograms of solid waste per day, while the USW collected from the deposit of the main market "Tivoli" amounts 43,000 kilograms per day. Through a sample study it was determined that tourists cause 0.4 kilograms of USW per day, generating in total roughly 8,600 kilograms per day, from which 50% is organic waste.

Currently in SCLC, there is an informal sector of waste pickers who recover polyethylene terephthalate (PET), cardboard, metal scrap and some other types of plastics. The price per mass of these materials where surveyed during this research, which is key information to determine whether it is economically viable to process a waste type within the city, or to canalise it to existing treatment facilities in other cities.

The second phase of this research consisted in a literature review of USW treatment techniques that can be implemented within the city to recover its value. This thesis emphasised on organic waste, given that it represents the majority of the USW in SCLC and is currently not exploited. It became evident that most of the treatment technologies for organic USW have specific feedstock requirements which can have impractical consequences on USW separation and collection. Additionally, some technologies are not sufficiently mature or their products are

not easily marketable. The most suitable treatment technique for organic USW, for the study case, is pyrolysis; a thermal process where waste is decomposed at high temperatures and from which tar, char and gas are obtained. The advantage of pyrolysis is that it is capable of processing large quantities of material in relatively short periods of time and has flexible feedstock requirements, in comparison to other techniques.

For SCLC it is more economically viable to sort, collect and to freight metal, nylon and PET waste to existing facilities where it can be turned into new products. For glass it is necessary to find innovative ways to reutilise glass within the city. Furthermore, paper and cardboard can be pyrolysed together with organic waste. It has been also found that it is necessary to establish a sorting and collection system for electronic waste (E-waste) to avoid it from landfilling, given that it is highly toxic and complex to recycle. Finally, it is necessary to create local solutions to treat hospital and personal hygiene waste, and the waste materials that do no fall in the aforementioned waste categories such as textiles and ceramics.

The third part of this research consisted in the development of a business case, where all organic USW in SCLC is processed with pyrolysis. The char and tar by-products would be utilised to producte charcoal briquettes. The use of these briquettes can reduce the demand of illegal firewood and charcoal in SCLC, which is estimated to be 159,000 kilograms per day. The yields of the pyrolysis process are 52%, 14% and 33% for char, tar and gas respectively. The parameters to obtain these yields are: a moisture content of 8% in the organic waste, a pyrolysis temperature of 650 °C, heating rate of 2 °C per second, a residence time of 6-10 minutes and an equivalence ratio of up to 0.2. A facility with the capacity to treat the 140,000 kilograms of organic USW per day would require an investment of at least 42,108,000 MXN. This business case can replace up to 27% of the local firewood demand, saving up to 18,537 trees per year, reducing 29,430 m^3 of landfilled USW per year and reducing the operation costs of the municipal waste collection vehicles by 440,000 MXN per year. The economic return of this case can be up to 6,513,000 MXN/month. Lastly, the social impact would be the creation of jobs and the accessibility to the charcoal briquettes at the same market price as char and firewood from illegal origin. Ultimately, this example demonstrates that a stream of USW can be employed to contribute to the solution of a local problem.

Conclusively, it is necessary to develop a holistic waste management system that includes setting up a USW separation scheme, logistic network to recover the sorted waste so that it can be treated, either within the city or elsewhere in the country. This requires the cooperation of the general population, informal waste collection sector, municipality and private sector, whether it is for separation, collection or investment in USW treatment technologies. With such measures at least 368,400 MXN can be recovered from the USW in SCLC on a daily basis.

Contents

Chapter 1

Introduction

1.1 USW an issue, circular economy an opportunity

Urban solid waste (USW) are non-liquid, non-gas residues that result from human domestic and economic activities that are considered obsolete and are discarded for that reason. Disposing USW on land or water bodies causes damage to the environment and human health (El-Fadel, Findikakis, & Leckie, 1997). On a global scale more than half of the USW is landfilled (Poulsen, 2014) and in the case of Mexico 70% of the 44 million tonnes of USW are generated on a yearly basis landfilled (Secretaría de Medio Ambiente y Recursos Naturales, 2019). Unless this practice is changed, the issues related to landfilled USW will aggravate given that the amount of USW increases simultaneously with population growth (Poulsen, 2014).

The are numerous environmental and social consequences from discarding USW in landfills in general (Poulsen, 2014) and in Mexico (Buenrostro & Bocco, 2003), yet three are prevalent. Firstly, that landfilling USW causes harm to the soil, water bodies and the atmosphere (Buenrostro & Bocco, 2003; Secretaría de Medio Ambiente y Recursos Naturales, 2019); areas of land are required to install disposal sites for USW (Botello Alvarez, Rivas García, Fausto Castro, Estrada Baltazar, & Gomez Gonzalez, 2003; Buenrostro, Bocco, & Vence, 2001); and that USW is not considered a source of materials from which goods and services can be created (Botello Alvarez et al., 2003; Buenrostro & Bocco, 2003).

The pollution from landfilled USW is mainly inflicted by methane emissions and leachates. The methane emissions in landfills are produced by the decomposition of organic matter and represent 10% of the global anthropogenic methane emissions (Ishii & Furuichi, 2013); this is a considerable magnitude considering that the global warming potential of methane is equivalent to 30 times that of carbon dioxide (Derwent, 2020). The heavy metals and excess of nutrients that are present in leachates pollute the soil and water bodies sites where USW is deposited (Jayawardhana, Y. and Kumarathilaka, P. and Herath, I. and Vithanage, M., 2016; Ramakrishnan et al., 2015). While heavy metals can enter the food chain or drinking water sources and, as a consequence, cause cancer to humans and other animals (Mishra, Karmakar, & Kumar, 2018), nutrients can cause eutrophication in water bodies.

There are technical measures that can limit the environmental impact of landfills, such as impermeable covers and pipes to capture some of the bio-gas that is generated; or an impermeable liner, underneath the landfill, to avoid leaching (Poulsen, 2014). Nonetheless, technical interventions do not alleviate the issues related to the use of land; once a landfill has reached its maximum capacity it has to be expanded, or a new one has to be built. The issue of new landfills, or expansion thereof, is particularly of concern in urban areas where land is increasingly scarce due to growing population and rapid urbanisation (Poulsen, 2014). Additionally, USW generation rates grow as the population increases; a challenging issue for cities (Letcher, T. and Vallero, D., 2019). For these reasons, landfilling is not a long term solution for USW management and it is opportune to implement different strategies to manage USW that are economically and less environmentally harmful.

One concept that can be incorporated into USW management is circular economy (CE). It aspires to maintain a material within an economy for as long as possible without degrading its value, although not necessarily in the same production loop (Geisendorf & Pietrulla, 2018; Ghisellini, Cialani, & Ulgiati, 2016). It is the opposite of linear consumption, which is manufacture, use and then dispose. CE originates in the concern that the continuous extraction and disposal of resources only leads to the depletion of resources. There are different mechanisms through which CE can be implemented, namely the creation of sustainable circular business models, a holistic waste management and waste value recovery processes. Furthermore, CE is put into practice at different scales; actually scholars have defined three levels: micro-level (a single company, product or consumer), meso-level (industrial symbiosis between multiple companies) and macro-level (geographical regions) (Ghisellini et al., 2016). Overall, CE can have environmental, economical and social benefits (Geisendorf & Pietrulla, 2018).

CE employs multiple processes to maintain, or regain, the value of materials and goods that are considered USW (Ghisellini et al., 2016). Some of the valorisation processes that are applied particularly to discarded goods are maintenance, reuse, redistribution, refurbishing, remanufacturing and recycling (Ellen MacArthur Foundation, 2017). In the case of homogeneous waste flows, it is possible to use pyrolysis, anaerobic digestion, combustion, melting and composting (Lewandowski, I., 2018). Nonetheless, there is an order of preference in these processes depending on the USWś quality, this is called the waste hierarchy.The waste hierarchy prioritises prevention of USW as first, then preparation for reuse, recycling, energy recovery and, lastly, disposal (European-Union, 2008). For instance, a material should be incinerated only when no value can be recovered from it other than heat and ashes.

Thermo-chemical conversion, chemical and food waste processing can be employed to recover value from organic waste streams. However, the value of the products obtained through these processes is, in general opposite to the amount of biomass used (Olsson et al., 2018). That is, the processes that create the highest value from biomass are require small volumes whereas the processes that create the least value use large quantities (Figure 1.1). Some examples of pharmaceutical and cosmetic products are alcohols, salts, minerals and food additives. For the middle section of the "biomass valorisation pyramid" the products are a range of chemical liquids, solids and gases which can be used as fertilisers or production materials. Lastly, high volumes of organic waste can be incinerated to obtain electricity and heat for instance.

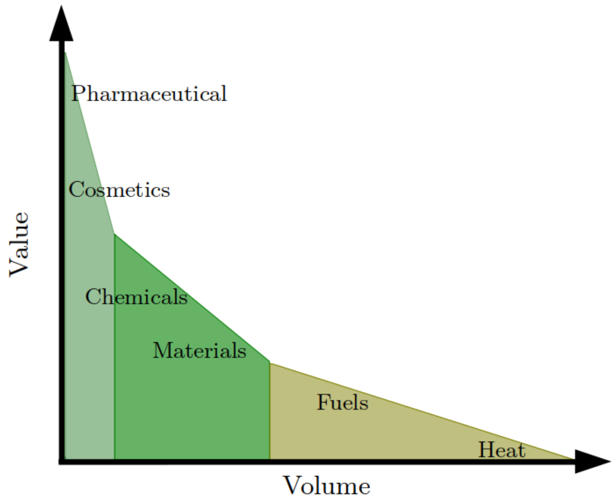


Figure 1.1: Biomass valorisation pyramid. Adapted from Van der Hoek, De Fooij, and Struker (2016)

The environmental benefits of circular economy are measurable in the quantities of energy, labour and materials that are saved in comparison to extracting new materials and manufacturing products with virgin materials (Ghisellini et al., 2016). From the social perspective, CE creates job opportunities and, as a consequence of limited environmental impact, increased public health (Ghisellini et al., 2016; Kalmykova, Sadagopan, & Rosado, 2018). Finally, the economic advantages are the exploitation of the economic value of what often is considered waste; and economic stimulus to the industries that are involved in recycling.

1.2 San Cristobal de las Casas and its current USW management system

This research takes the Mexican city of San Cristobal de las Casas (SCLC) as a study case. With a population of 209,591 (in 2015), it is the third most populated city of the state of Chiapas; the southernmost state of the country (INEGI, 2015b) (Figure 1.2).

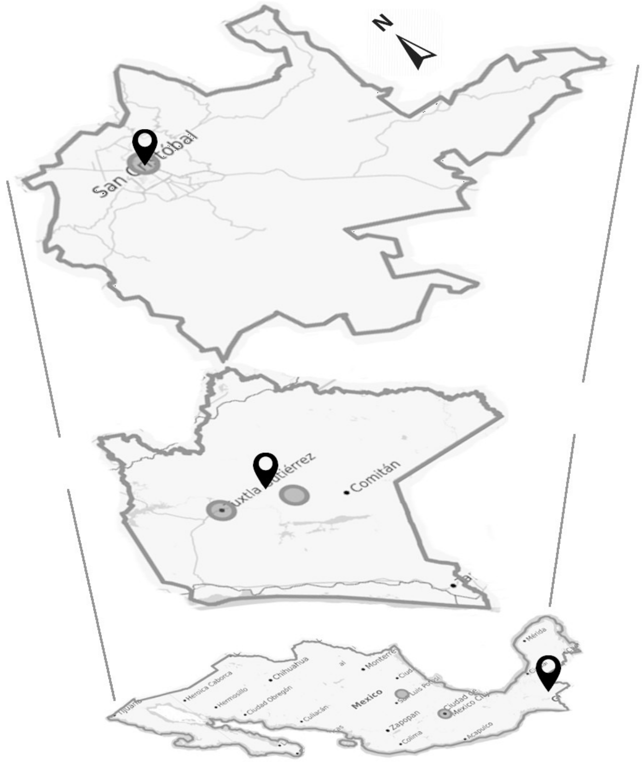


Figure 1.2: Geographic position of SCLC. From bottom to top: Mexico, Chiapas and municipality of SCLC.

The main economic sector in SCLC is tourism: hotels, hostels, restaurants and transport companies (Centro de Investigaciones Turísticas Aplicadas, 2013). In high season the inflow of tourist can be as high as 220,000; which is almost equal to the 2015's population of the city (Secretaría de Turismo del Gobierno de Chiapas, 2018). The USW footprint of the tourism industry is unknown as there is no data available regarding the amount of USW that is attributed to the tourists. Nonetheless, this sector yields potential to significantly contribute to the circular economy of the city as it is more feasible to implement a waste separation scheme at company level than at city level.

In Mexico it is the responsibility of municipalities to collect, transport, treat and dispose the USW from their territory (Congreso General de los Estados Unidos Mexicanos, 2003), excluding "dangerous" waste (Congreso General de los Estados Unidos Mexicanos, 2003). Municipalities have a waste department to manage USW with infrastructure, personnel and an inventory of equipment.

The infrastructure of the municipal waste department in SCLC includes four locations: offices, a station for the vehicle fleet, a USW deposit for the main market and the landfill (Figure 1.3). The USW deposit -named "Tivoli"- is a central collection point specifically built for the waste generated at the largest market of the city (Figure 1.4). In previous decades the final disposal site of USW of SCLC did not had a liner to avoid leaching (Nájera Aguilar, Vera Toledo, & Rojas Valencia, 2012); though, due to national environmental regulations it had to be closed. Consequently, the municipality utilises, since 2019, a landfill built with liner, to avoid leaching, and where the USW is regularly compacted and covered with soil by bulldozers (Ayuntamiento Constitucional San Cristóbal de las Casas, 2019). The new landfill lies at ten kilometres from the city centre with an ascend of 380 metres and a descend of 90 metres with respect to the altitude of the city (Figure 1.5); particularly the last 1.5 kilometres are of difficult access as the road has a steep ascend and is unpaved. The landfill lies in a communal land for which the municipality has to compensate the local community 300,000 Mexican Pesos (MXN) per month (Head of municipal waste management department, personal communication, November 04, 2019).

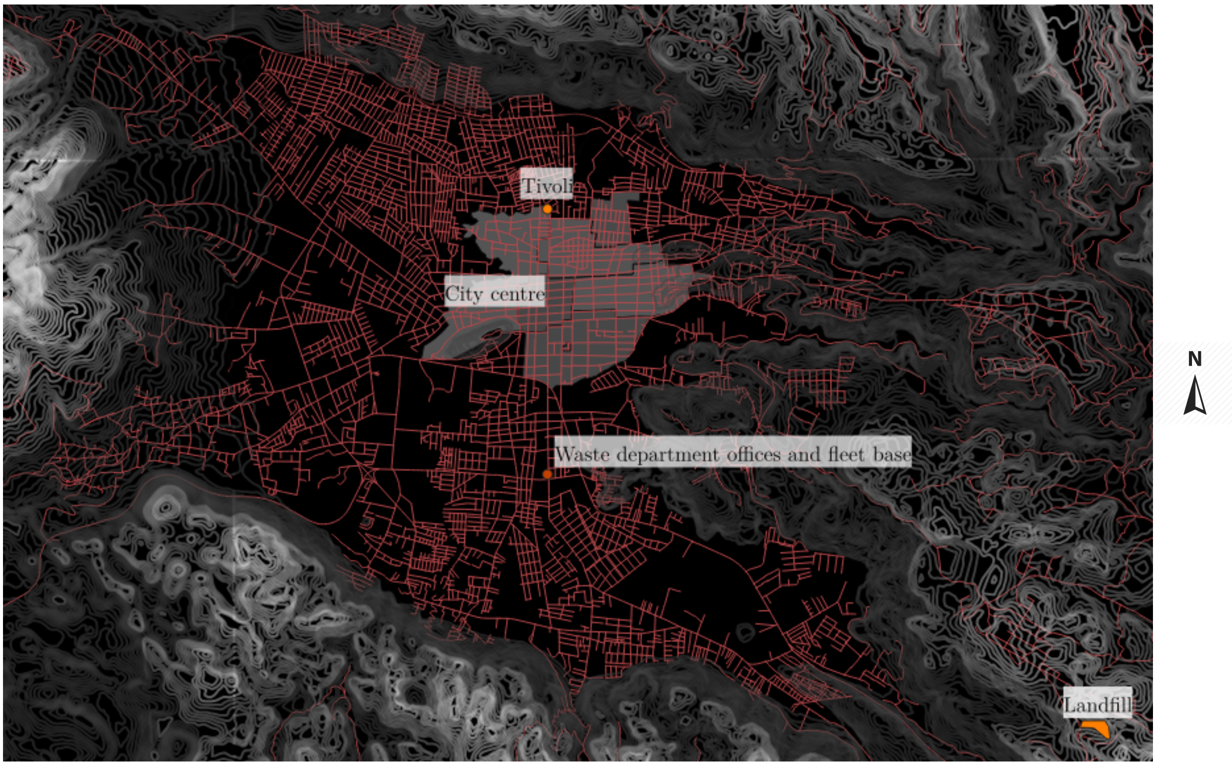


Figure 1.3: City layout of SCLC.

Figure 1.4: USW deposit for the main market in SCLC, "Tivoli".

Figure 1.5: Landfill in SCLC.

The personnel in these locations amounts 194 people; 153 of them work as waste collectors (street sweepers or lorry loaders) from which 40 are female street sweepers. The remaining 41 people are lorry drivers, supervisors, coordinators, personnel of "Tivoli" and landfill personnel.

The inventory of the department is what the waste department utilises to execute their duties. This includes equipment such as gloves, barrels, brooms, shovels, machetes, uniforms, vehicles, et cetera. The vehicle fleet has eight types of vehicle models, each with different carrying capacity (Appendix A). Furthermore, 20 vehicles travel various routes to collect waste throughout the city with different number of trips per day; the remaining three vehicles are reserves.

The waste collection system in SCLC is curbside collection. It begins at the vehicle station, where the empty lorries depart towards the beginning of their assigned route. The truck driver is accompanied by two or three persons to load the collected waste on the container. One person runs ahead of the truck from the beginning of the route announcing with a bell to the public that the waste will be collected in brief. Citizens are expected to bring their waste bins and bags to the corner of the street only when the runner announces the arrival of the waste lorry (Figure 1.6). The lorry only stops at the corner of each block to collect the waste that has been brought by the citizens. After completing one or more routes the lorry is fully loaded and transports its cargo to the municipal landfill, where the USW is compacted and buried (Ayuntamiento Constitucional San Cristóbal de las Casas, 2019). Currently, the municipal waste collection service covers approximately 95% of the city's streets (Ayuntamiento Constitucional San Cristóbal de las Casas, 2019). The municipality does not charge the population, nor businesses, for the service of waste collection.

Figure 1.6: The corners of the streets are USW deposit points right before it is collected by the waste collection vehicles.

Furthermore, the population, in general, does not sort their waste prior to collection (Ayuntamiento Constitucional San Cristóbal de las Casas, 2019), meaning that all types of waste are combined in the collection lorries and, finally, landfilled. The limited waste separation that takes place in the city is carried out by informal collectors, or the municipality's waste collectors. They collect metal cans, cardboard and plastic bottles and then sell them to scrapyards, who sell these recovered materials in bulk to recycling factories (Nájera Aguilar et al., 2012). There are no businesses or initiatives that recycle USW or reincorporate recycled materials to their production processes at a significant scale in the city.

This research will emphasise on organic USW for three reasons; firstly, because it is currently not exploited by informal waste collectors in SCLC, secondly it is the most abundant waste type and, thirdly, because nutrient leachates and methane emissions from landfills are mostly caused by the decomposition of organic waste (Ishii & Furuichi, 2013).

1.3 Aim of the research

Although the most effective way to avoid landfilling is waste prevention, it is still necessary to exploit resources that can be recovered from the waste that is generated by the population. Therefore, this research explores CE opportunities using USW, and considers the three pillars of the field of industrial ecology, namely environment, society and economy. Having stated the issues that arise by landfilling USW and the potential of the USW when implementing CE the following research question is formulated:

What circular economy solutions can be implemented in the city of San Cristobal de las Casas in order to, locally, exploit the economic potential of its urban solid waste while avoiding landfilling?

The first phase of the research is an evaluation of the magnitude and nature of the USW mass that is generated in the city; that is, the generation of waste per capita and its change through time; the composition of the waste that the population generates; and the relation between income and waste generation rates. In a sub-question that would be:

a) What is the mass and composition of the municipal solid waste of SCLC that is currently being collected per day? And what is the USW generation rate and composition of the solid waste generated by the tourism industry?

The second phase consists of an exploration and selection of techniques that can be employed to treat the different waste types and process them into materials or goods that can be exploited locally. The information is retrieved from literature. The criteria that is considered for the selection of suitable technologies is based on the price of the waste types, the feedstock requirements of the treatment processes, the complexity of the treatment technologies and the marketability of the final product or material. Also, the selection of technologies is based on the assumption that the USW of the city would be sorted and collected separately. Formulating the aforementioned into a sub-question:

b) What are the techniques and solutions that can be used to avoid landfilling and, if possible, upcycle the identified waste types specifically for the city of SCLC?

With one of the identified waste treatment technologies from sub-question "b" a business case is developed to a conceptual level. The scope of this business case is narrowed to the exploitation of organic USW that is generated in the city, where the value proposition should fit the context of the city. Furthermore, the impact of this business case, after implementation, has to be evaluated in environmental, social and economic terms. This results in the following two sub-questions:

c) How should a business case be set up in order to recover materials from the USW stream, reprocess it and reincorporate it to the local economy?

And,

d) What would the economic, environmental and social impact of the proposed business be if they would be implemented?

The results of these sub-questions comprise of: an overview of the mass and composition of the USW in SCLC; a list of viable waste treatment technologies; a business case based on organic waste and one technique to process it into a valuable product; an impact analysis of the business on the city and the current waste management system. In order to answer the main question the results of the sub-questions are merged to create a holistic USW management system that the public and private sector can execute in feasible steps to exploit the value of USW; this includes a set of recommendations for the logistics, waste separation scheme and possible bottlenecks that might be encountered.

This research is mostly of quantitative nature, as it is limited to the technical and economical feasibility of waste management strategy. Thus, the study does not include a thorough qualitative analysis on the acceptance of the results by the general population, private or public sector of the city.

1.4 Relevance of the research

The scientific relevance of this research lies in the framework that results from the relation between the magnitude of the USW waste streams in a city, waste treatment technologies and the marketability of the recovered materials. The combination of this applied to a specific urban context indicates the practices that can be adopted to manage USW and generate an economic return from it. Additionally, this investigation provides an insight of the local evolution of USW generation rates and composition, and its relation with population growth.

Furthermore, this investigation broadens the limited knowledge of USW footprint caused by tourism which is relevant for tourism-dependent cities tourism or academia. Also, the study sample that was carried out on hotels and restaurants to evaluate their USW footprint can be exemplary for future studies of tourism-related USW. Moreover, this thesis contributes to the field of IE with the application of engineering, mass flow analysis, geographical information system analysis and CE to generate practical solutions for USW management.

The pertinency to society lies in the reduction of the economic and environmental burden that can result from the implementation of a waste management strategy based on CE. Especially the economic return should incentivise the public and private sectors to take steps forward in sustainability and circular economy. Ultimately, the methodology developed in this research to map the status of USW, identify waste treatment technologies that fit the local context and the development of CE opportunities can be applicable to other cities.

Conclusively, this research is primarily an exploration of CE opportunities which can be implemented to exploit the value of USW and avoid landfilling.

1.5 Structure of the report

This report comprises eight chapters; the first one being this introduction. Chapter 2 summarises all the methodologies and databases that were used in this research.

Chapter 3 corresponds to the sub-question "a", thus it covers the process of gathering and interpreting the data about mass and composition of USW generated by the population of SCLC and its tourism industry.
Chapters 4 and 5 comprise of treatment techniques for organic USW and other types of waste respectively, which correspond to sub-question "b".

The sixth chapter explores, through one business case, the value that can be recovered from organic USW using one of the waste treatment techniques that are treated in Chapter 4. It includes a description of the business idea and the problem that the business strives to solve. Consecutively, the feasibility of the business case is evaluated through a mass, energy and economic balance. Subsequently, a site suitability analysis is done to determine the location where the business should be located. Ultimately, the last section quantifies the impact of the business case in terms of environment, economy and society.

Chapter 7 discusses the validity and relevance of the results obtained in the previous chapters.

The last chapter elaborates, based on the results of the research, on the solutions that can be applied in general and per waste type to locally exploit the value of USW in SCLC.

Chapter 2

Summary of Applied Research Methods and Data Sources

2.1 Methodologies applied to define the background and research problem of the study

To define the current status of the waste management system in SCLC a literature study and a field study were carried out. Some of the key documents in this review where facilitated by the municipal waste department; these are mainly the schedule and records of the USW collection fleet, the report of the domestic USW composition study. The status quo of the USW management in SCLC was also constructed from observations, made during a field study, of the waste collection scheme, the landfill and Tivoli.

During the research there was continuous communication with the association of hotels of SCLC and with the local representative of the Chamber of Restaurant and Prepared Food Industry (CANIRAC); through this communication the organisations contributed to broaden the context of USW management in the city and shared their aspirations with respect to USW in the city. The municipal waste department, through personal communication, shared information about their agreement with the community that own the land where the landfill is located.

The definitions of landfilling, hierarchy of waste recovery processes and CE where also constructed from a literature study.

2.2 Methodology applied to estimate the magnitude and composition of USW

The sub-question "a" —What is the mass and composition (types of waste) of the municipal solid waste of SCLC that is currently being collected per day? And what is the USW generation rate and composition of the solid waste generated by the tourism industry? —is answered in Chapter 3. This is done through an estimation of the total, main sources and composition of USW in SCLC. The data that was utilised for that chapter was obtained from a literature study, interviews and a field study. The main sources of USW that have been analysed in this study are domestic, touristic, local businesses and "Tivoli".

To compute the daily USW footprint from domestic origin two variables had to be calculated: the population of SCLC and the daily generation rate of USW per capita. The last population count of SCLC, as of this writing, dates from 2015 (INEGI, 2015b), thus it was necessary to estimate the population of 2019. This estimation was done by linear and exponential extrapolation (refer to Appendix B). The data that was used to compute the population was retrieved from the National Institute of Statistics and Geography (INEGI). Furthermore, the USW generation rate per capita was determined through a literature study of USW studies in Mexico and a linear extrapolation of the evolution of the found waste generation rates.

The USW mass from the storage site "Tivoli" was determined from the schedule and freight records of the municipal waste department's fleet.

The impact of the USW generated by tourism in SCLC was computed using statistic reports of tourist influx and hotel occupation percentages of Chiapas and a field study of the waste generated at tourism-related businesses. The field study entailed a sample study of the waste generated in hotel, restaurants and other food-related services. It was through the association of hotels and the CANIRAC, that multiple restaurants and hotels volunteered to be part of the sample study. Each of the sampled businesses shared information about the maximum capacity of their businesses.

More specifically, the sample study consisted in measuring and document the organic and remaining USW generated by the business on a daily basis during seven consecutive days. This required the personnel, of the participating businesses, to separate the waste in at least two separate bins; one for organic USW and one for the remaining waste. Some of the businesses already had a waste separation scheme for organic waste, PET and cardboard drinking packages; the two latter where also documented separately. For businesses without a sorting scheme prior to the survey, the sampling time was of eight days; the extra day would be so that the personnel could get accustomed to separate the waste. The mass of the bags that contained the USW was measured with a digital weighing scale. After being measured, the bags where marked with an "X" in order to prevent repeated measurements. The weight of bins was not included in the measurements in cases where the waste was stored in them. Moreover, the measurements where taken either at the end of the day or before the business would resume its activity. The results from this sample study also allowed to gain an insight of composition of tourism-related USW.

The magnitude of the USW waste stream caused by local businesses was deduced as the remainder of the total mass that is not attributed to tourism, Tivoli or domestic USW.

The composition of the domestic urban solid waste of SCLC was obtained from studies that have been carried out by the municipality and the research institute "Colegio de la Frontera Sur".

Lastly, the information about the waste types that are currently recovered by informal waste collectors and the prices of these materials where obtained from field observations and personal communication with waste buyers and waste collectors.

2.2. Methodologies and data used for Chapter 3

2.2.1. Total USW in SCLC

- Methodology: mathematical approach (product of the number of trips per USW collection vehicle and its capacity).
- Data source: operation schedule of the municipal waste department, and freight records of the USW collection fleet.

2.2.2. Footprint of domestic USW

- Methodology: literature review of USW generation rates in Mexico;
  mathematical approach (linear and exponential extrapolation of population of SCLC);
  mathematical approach (the product of USW rate and population in SCLC).
- Data source: USW generation rates in Mexico from Esquinca-Cano (1995), Gomez, Meneses, Ballinas, and Castells (2008), Quiroz González (2009),

Castillo Gonzalez and de Medina Salas (2013), Araiza Aguilar, Chávez Moreno, and Moreno Pérez (2017) and Secretaría de Ecología Estado de México (2000);
population data of 1990 from INEGI (1990),
population data of 1995 from INEGI (1995),
population data of 2000 from INEGI (2000),
population data of 2005 from INEGI (2005),
population data of 2010 from INEGI (2010a),
population data of 2015 from INEGI (2015b).

2.2.3. USW footprint from tourism

- Methodology: mathematical approach: product of the influx of tourists, hotel occupation percentage and generation rate of USW at restaurants and hotels sample study of USW from restaurants and hotels.
- Data source: monthly statistic reports of the Secretariat of Tourism of the state of Chiapas
  records obtained from the sample study.

2.2.4. USW from Tivoli

- Methodology: product of freight capacity of vehicles that collect waste from Tivoli and number of trips to Tivoli.
- Data source: municipal collection schedule and freight records of the USW collection fleet.

2.2.5. USW footprint from local businesses

- Methodology: subtraction of the identified USW sources from the total.
- Data source: results the the methodologies applied for sub-question "a".

2.2.6. Composition of USW in SCLC

- Methodology: literature study.
- Data source: Aguado Maya (1998) and Ayuntamiento Constitucional San Cristóbal de las Casas (2018).

2.3 Methodology applied to investigate waste treatment techniques to upcycle USW

The waste treatment technologies for organic USW and all other types were obtained from a literature study. The primary source of information for organic USW, in Chapter 4, was mostly based on a review of treatment techniques of organic waste elaborated by Lohri, Diener, Zabaleta, Mertenat, and Zurbrugg (2017). The reason for this is that the economic context of its review, namely middle and low income, is comparable with that of SCLC. The results from this methodology correspond to sub-question "b", "what are the techniques and solutions that can be used to avoid landfilling and, if possible, upcycle the identified waste types specifically for the city of SCLC?".

2.3. Methodologies and data used for Chapters 4 and 5

2.3.1. Waste treatment techniques for organic USW

- Methodology: literature study.
- Data source: Lohri et al. (2017) Basu, P. (2018) and Czajczynska et al. (2017).

2.3.2. Waste treatment techniques for other types of USW

- Methodology: literature study.
- Data source: from Feil, A. and Pretz, T. and Jorg, J. and Go, N. and Bosling, M. and Johnen, K. (2019) and Rao, S. (2006) for metal waste;
  from Scott, G. M. (2019) for paper and cardboard waste;

from Sethi, B. (2017) for polymers;
from Butler, J. H. and Hooper, P. D. (2019) for glass;
from Kaya, M. (2019), Zhao, S. and He, W. and Li, G. (2019), Lee et al. (2015) and Williams, K.S. and Mcdonnell, T. (2019) for toxic waste.

2.4 Methodologies applied for the development of the circular business case

The first methodologies used for the development of the circular business idea, in Chapter 6, are the compilation of data about the consumption of firewood and char per household in SCLC from INEGI (2015a), and a literature study about the consumption of per capita, the use of different tree species as firewood and their respective calorific values. This would support the idea of the business case in terms of market opportunities.

Secondly, a literature study was done to provide a deeper understanding of the pyrolysis technology; specifically for the product yields and process parameters, such as temperature, heating rate, equivalence ratio, moisture, and residence time.

The mathematical model of the mass balance is based on the amount of organic USW, estimated in Chapter 3, the product yield and moisture requirements of the pyrolysis process. The mathematical model of the energy balance of the business case required a literature study to compile information about thermo-physical properties of biomass and water, composition of the pyrolysis gas product, the heating values of the pyrolysis products and the efficiencies of the machinery.

The economic balance was computed based on the prices of the machinery required for the business case, rent and services, as well as the minimum salary of Mexico. The prices per weight of firewood and char in SCLC where surveyed during the field study.

The methodology employed for the site suitability consisted in the analysis of demographic, economic, infrastructure and geographic maps with a geographic information system (GIS) software. The data utilised for this analysis what obtained from INEGI.

The impact analysis of Chapter 6 consists of a comparison between the current status of the USW waste and the change inflicted by the circular business idea. The comparison is expressed in three categories, namely environmental, economic and social.

In summary, the sources of information and methodologies, applied in Chapter 6, to answer sub-questions "c) How should a business case be set up in order to recover materials from the USW stream, reprocess it and reincorporate it to the local economy?", and "d) What would the economic, environmental and social impact of the proposed business be if they would be implemented?" are the following:

2.4. Methodologies and data used for Chapter 6

2.4.1. Business case idea and market estimation

- Methodology: literature study and data compilation from statistical data.
- Data: sources of energy for cooking per households from INEGI (2015a);
  inhabitants per household from INEGI (2015b);
  consumption of firewood per capita in Chiapas from Alvarado Machuca, Alvarez Sánchez, Maldonado-Torres, and Sánchez Velez (2018); Burgos Lugo, Soto Pinto, Bello Baltazar, and Castellanos Albores (2020); Holz and Ramírez-Marcial (2011); Ramírez-López (2012);

species of firewood consumed in SCLC and Chiapas and their heating value from González, Estrada-Lugo, and Rivas (2012); Kumar-Jain (1992); Martínez Icó, Cetzal Ix, Noguera Savelli, and Hernández Juarez (2015); Núñez-Retana, Wehenkel, Vega-Nieva, García-Quezada, and Carrillo-Parra (2019).

2.4.2. Pyrolysis technology

- Methodology: literature study.
- Data: production of briquettes from Olugbade, Ojo, and Mohammed (2019); pyrolysis parameters Agar, Kwapinska, and Leahy (2018); Basu, P. (2018); Dong et al. (2016); Taghipour, Amjad, Aslani, and et al. (2016).

2.4.3. Mass balance

- Methodology: mathematical approach (product of feedstock by its composition and product yields from the pyrolysis processes).
- Data: pyrolysis parameters from the pyrolysis technology section and organic mass flows from Chapter 3.

2.4.4. Energy balance

- Methodology: mathematical approach (product of mass and the heating value of the products, and equation of heat demand to change the temperature of mass).
- Data: results from mass balance;
  calorific value of gas , liquids (Czajczynska et al., 2017) and char from Agar et al. (2018); Basu, P. (2018); Czajczynska et al. (2017);
  specific heat of biomass from Faitli, Magyar, Erdelyi, and Muranyi (2015).

2.4.5. Economic balance

- Methodology: mathematical approach (sum of operation and investment costs);
  Field survey.
- Data: machine unit prices from alibaba.com;
  minimum salary in Mexico from Secretaría del Trabajo y Previsión Social (2020);
  prices per weight of firewood and charcoal from field survey.

2.4.6. Site suitability

- Methodology: analysis of geographic data of infrastructure, demography, economy, relief and hydrography.
- Data: INEGI (2010b),INEGI (2017a),INEGI (2017b),INEGI (2017d),INEGI (2017c).

2.4.7. Impact analysis

- Methodology: mathematical approach (comparison of energy and biomass demand in SCLC with product yield of the business case and comparison of USW mass flows before and after hypothetical application of business case).
- Data: overall results from chapters 3 and 6.

Chapter 3

Urban Solid Waste Characterisation and Quantification

The first step in problem solving, in general, is knowing the magnitude and nature of the problem. In this research that requires an analysis of the waste management system of SCLC, the USW that is generated in the city and its composition. In fact this chapter replies to the first sub-question of the research namely,

a) What is the mass and composition of the municipal solid waste of SCLC that is currently collected per day? And what is the USW generation rate and composition of the solid waste generated by the tourism industry?

This chapter includes an estimation of the daily waste generation rate per capita, the total waste generation of the city, including the waste footprint of the population and tourism industry. Secondly, the composition of the city's USW is mapped. And finally, the quantities of each type of waste and their value are computed.

3.1 Daily waste generation rate per capita in SCLC

A study about USW generation and composition that has been executed in SCLC, in 1997, states that the daily waste generation rate per capita is of 0.42 kilogram (Aguado Maya, 1998); this figure reflects only the waste generated at household level. According to the municipal waste department the daily USW generation rate per capita per day in SCLC, in 2018, was 1.035 kilogram per person (Ayuntamiento Constitucional San Cristóbal de las Casas, 2018); however the method of calculation is not explained.

Studies about household waste generation rates in Mexico have demonstrated that daily waste generation rates depend on local context, yet they range between 0.38 and 0.99 kilogram (Araiza Aguilar et al., 2017; Castillo Gonzalez & de Medina Salas, 2013; Esquinca-Cano, 1995; Gomez et al., 2008; Quiroz González, 2009; Secretaría de Ecología Estado de México, 2000). The national average of waste generation rates per person per day is of 0.99 kilograms (Secretaría de Medio Ambiente y Recursos Naturales, 2015), while the waste generation rates in the southeast of Mexico, for being the poorest states in the country, are lower than the national average (Secretaría de Ecología Estado de México, 2000). Thus, the generation rate in SCLC should, in theory, be lower than what is reported by the municipality.

The Mexican Secretariat of Environment and Natural Resources (SEMARNAT) (2015) has observed that the daily USW generation rate per capita, on a national level, grew from 0.83 to 0.99 kg/capita/day from 1997 until 2012. Than is an increase of approximately 20%; or an increase of 1.3% per year. Assuming that this increase is linear and also holds for SCLC, the

USW generation rate in 2020 would be 0.55 kg/capita/day. As a comparison, a study has been conducted in 2016 in the municipality of Berriozabal, located in the same state as SCLC, where the daily waste generation per capita is of 0.619 kilogram (Araiza Aguilar et al., 2017). Having this in mind, 0.6 kilogram per person per day can be considered a probable household waste generation rate in SCLC for 2020.

3.2 Total USW generated in SCLC and its main contributors

The fleet of the waste municipal waste department collects up to 282,000 kilogram of USW on a daily basis. This quantity is the sum of the mass collected by the entire vehicle fleet during one week, divided by seven days of the week; this is under the assumption that the vehicles are loaded up to their maximum capacity (refer to Appendix A). Furthermore, this includes street litter which is collected by the street sweepers of the municipal waste department.

The USW generated by the population is computed as the multiplication of the population of the city times the daily waste generation rates per capita. The population of SCLC in 2019, estimated by linear and exponential extrapolation, amounts 228,800 and 240,000 persons, respectively (Figure 3.1).

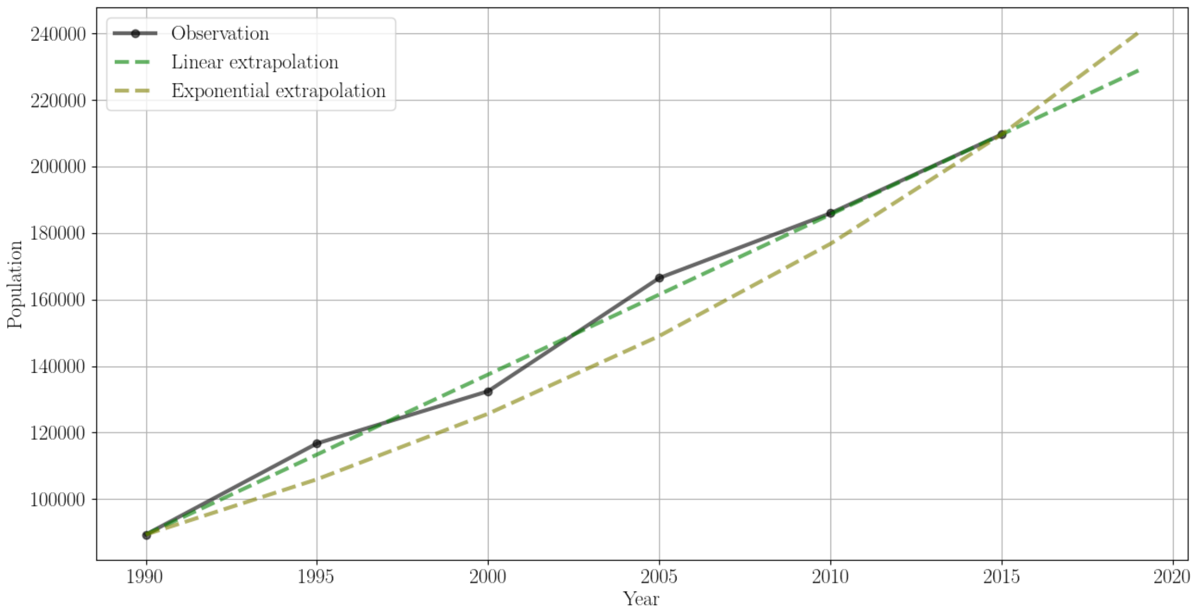


Figure 3.1: Estimation of population in SCLC by two extrapolation methods. Refer to Appendix B.

Considering a waste generation rate of 0.6 kilograms per person per day, the daily production of domestic USW is minimally 137,300 kilograms or maximum 144,100 kilograms; i.e. $140,700 \pm 3,400$ kilograms per day.

3.3 USW footprint of tourism in SCLC

In any context, a share of the USW that is generated by the local economy is caused by inhabitants who make use of health services, institutions, small scale manufacturing establishments and retail, to name a few. However, in the particular case of SCLC the economy is largely based on tourism. In fact, according to the National Statistic Directory of Economic Units (DENUE), 13.47 % of the local establishments are related to temporary accommodation (i.e. hotels) and food-and-beverages preparation services (restaurants, cafes, etc.), which are mainly oriented towards the visitors of the city (see Appendix C). To estimate the impact of tourism on the total generated USW it is necessary to know the amount of tourists that visit the city and the daily USW generation rate per tourist. While the statistics of tourists that visit SCLC are published by the Secretariat of Tourism of the state of Chiapas, the USW footprint per tourist had to be obtained during this research through a sample study.

With the data published by Secretariat of Tourism of the State of Chiapas (Appendix E), the influx of tourists in SCLC, and its fluctuation throughout the year, can be mapped (Figure 3.2). The trend of tourist influx is mostly followed by the occupation percentage of hotels (Figure 3.3).

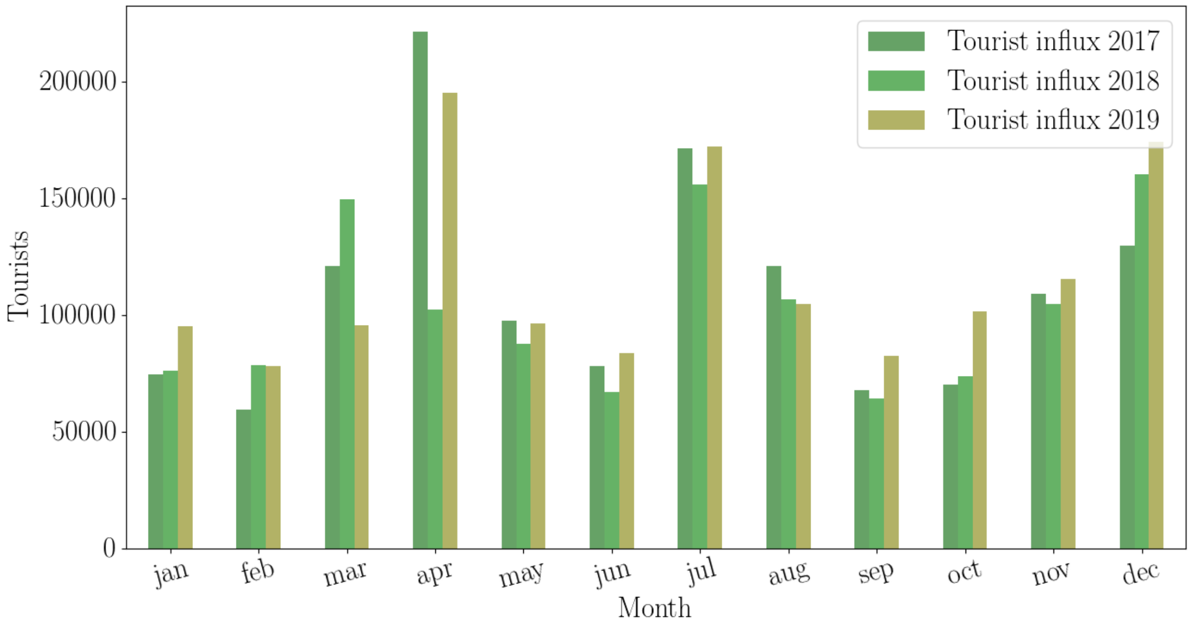


Figure 3.2: Influx of tourists in SCLC throughout the year.

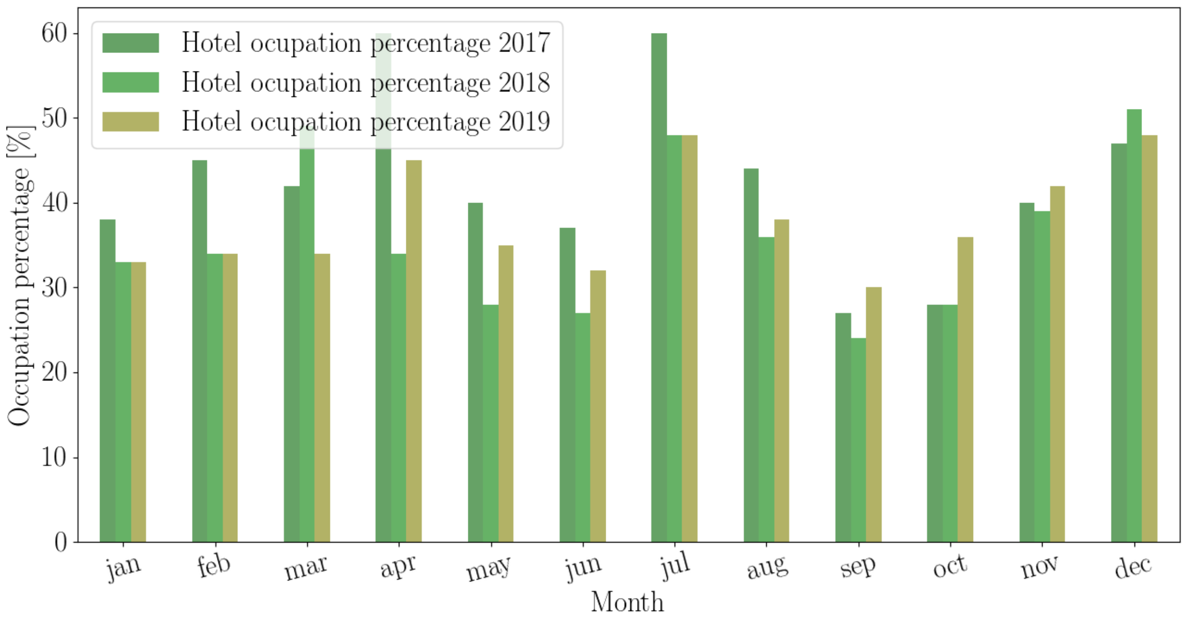


Figure 3.3: Hotel occupation percentages in SCLC throughout the year.

For the sample study, the USW mass of eleven tourism-related establishments was measured during seven days in SCLC. For the surveyed establishments that implemented waste separation for the first time, the sample included an extra test day so that the personnel could adjust to the sorting method; the sample from the test day did not count in the data log.

Six of the sampled establishments are restaurants and coffee bars, while the remaining five are hotels. The establishments taking part in the sampling where asked to separate their waste in two categories, namely organic and "Other" USW. Some of the sampled establishments already separate certain types of waste, such as PET plastic bottles and waxed cardboard drinking packages; these categories where also taken into account. The mass of the USW waste was measured with a digital weighing scale with a measuring capacity of 200 kilograms. The weight of waste bins was tared off during measurements, so that the real weight of the USW waste was recorded. The measured bags of USW where marked with "X" to ensure that they would not be weighed twice.

The arithmetic mean percentages of the composition and the total daily generation per establishment are given in Appendix D. The USW generation rate per customer of each sampled establishment is computed with the mean total of waste of the establishment, the maximum capacity of the establishment and the tourist occupation percentage during the sample study. During the sampling —October of 2019 —the average hotel occupation of the city was 36% (see Appendix E). The formula of the generation rate per customer is as follows:

$$USW generation\ rate\ [\frac{kg}{customer * day}] = \frac{mean\ total\ daily\ waste\ [kg/day]}{max\ capacity\ [customer] * 0.36}$$

The daily total USW of the sampled establishments differed largely due to their type of service and size. However, their mean daily waste generation per customer are comparable. These values ranged between 0.86 and 2.4 kilograms for the hotels, with an arithmetic mean of 1.3 kilograms per day per tourist. In the case of restaurants the USW generation rates lie between 0.1 and 0.8 kilograms per tourist per day; i.e. 0.5 kilograms per person per day on average.

The average influx of tourists per fluctuates throughout the year; it ranges between 2,380 and 3,650 city visitors per day. That means that the waste at restaurants, based on the generation rates per customer, can be as low as 1,070 kilograms per day, or as high as 2,560 kilograms per day; i.e. $1,800 \pm 800$ kilograms per day. Following the same estimation procedure, hotels generate somewhere between 2,990 and 7,240 kilograms of USW per day; in one figure $5,100 \pm 2.1$ kilograms per day.

The estimated waste quantities from restaurants, imply that all the customers are tourists visiting the city and do not account for the local inhabitants eating at restaurants. The waste caused by inhabitants at restaurants can be expected to be avoided at the household; thus, the household USW footprint of inhabitants includes, implicitly, their waste generated at restaurants.

3.4 Characterisation of USW in SCLC

The waste generation rate of per capita evolves through time, and so does the composition of their waste. The most significant changes in the characterisation of the domestic USW in SCLC are the decrease of organic waste and the increase of plastics (Figure 3.4); which can possibly be attributed to three: the advent of supermarkets in SCLC, an increase in consumption of processed packaged food and a decrease of extreme poverty. On the other hand metals, glass, paper and cardboard remained relatively stable. In the composition of 2019, 53% of the plastic stream are bags and other items, 11% polystyrene and 36% PET (Ayuntamiento Constitucional San Cristóbal de las Casas, 2019).

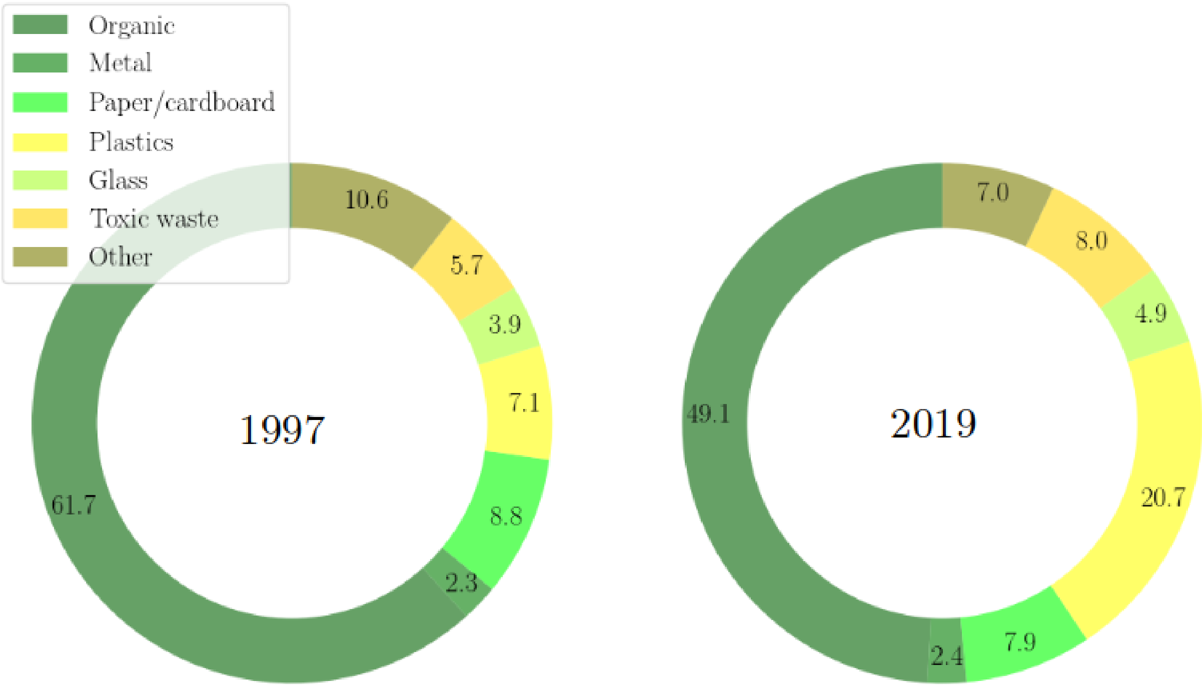


Figure 3.4: Percentages of the composition of domestic USW in SCLC. Note: data for composition of 1997 from Aguado Maya (1998) and 2019 from Ayuntamiento Constitucional San Cristóbal de las Casas (2019).

The share of organic solid waste of hotels and restaurants, 55.8% and 56.5% respectively, observed in the sample study is similar to that of the domestic USW (Table 3.1). Furthermore, the share of cardboard drinking package and PET plastic can only be considered as an indication of what is actually sorted by the sampled hotels and restaurants. For the case of waste-types such as glass, metals and toxic waste, they are implied in the category "Other".

Waste category	[%] **Restaurants**	[%] **Hotels**
Organic	56.5	55.8
Other	39.5	42.3
Cardboard drinking package	3.9	0.0
Plastic (PET)	0.02	1.9

Table 3.1: Waste characterisation from the sample study of USW of restaurants and hotels in SCLC.

3.5 Total USW generation quantities per category and their economic potential

The footprint of USW by the population, Tivoli and tourism are shown in Figure 3.5. Thus, the black segment of the fourth bar (from left to right) represents the USW footprint of local establishments, excluding tourism-related establishments.

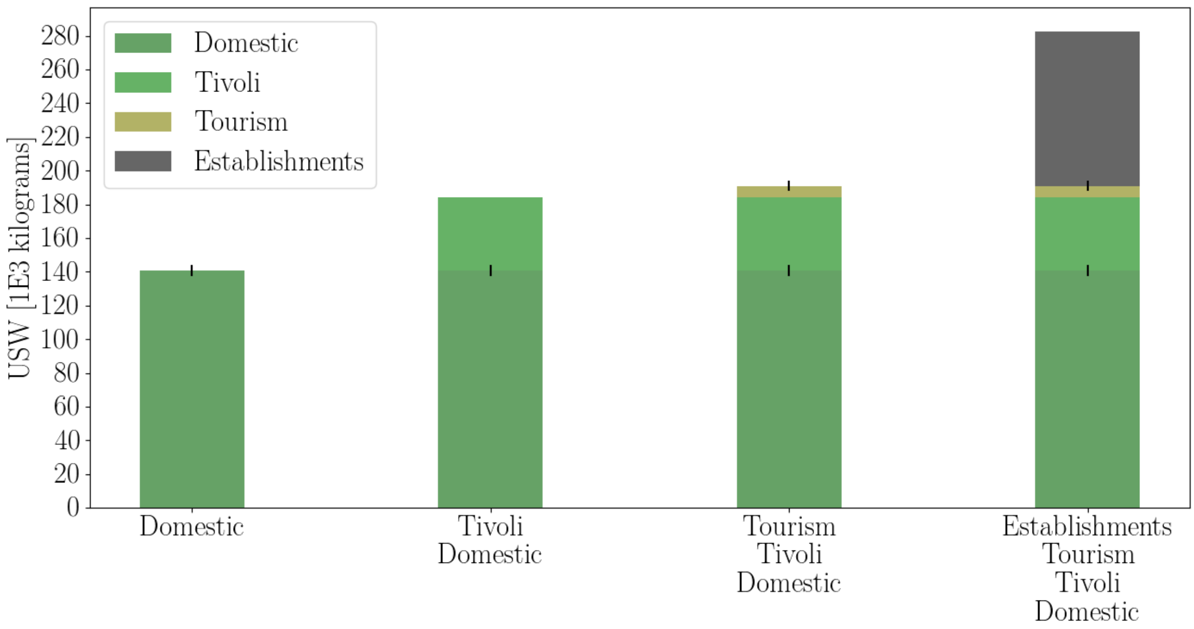


Figure 3.5: USW footprint of various sources in SCLC

The waste generated by the local economy is approximated as the difference between the total collected waste and the combined mass from Tivoli, households and tourism. Approximately 43,300 kilograms of USW is collected on a daily basis from the USW deposit "Tivoli" (refer to Appendix A) $140,700 \pm 3,400$ kilogram is generated by the population in their households and $6,800 \pm 2,900$ kilograms from tourism.

$$USW_{local\ economy} = USW_{total} - USW_{Tivoli} - USW_{household} - USW_{tourism}$$
$$USW_{local\ economy} = 282,000 - 43,300 - (140,700 \pm 3,400) - (6,800 \pm 2,900) = 91.9 \pm 6.3[kg]$$

The largest defined USW flows in SCLC are from organic, plastic, paper and cardboard; with a magnitude of approximately 140,000, 30,100 and 11,100 kilograms per day, respectively. The quantities of each type of waste are estimated by combining the composition percentages and net quantities per sector (see Appendix F). For these estimations it is assumed that the share of organic waste of the market deposit "Tivoli", and retail, institutions and other establishments is assumed to be 50%, as in the general household composition.

Other unknown is the composition of the non-domestic USW that is generated by local establishments; excluding tourism-related establishments and Tivoli. Furthermore, the category "Other" from the USW survey of hotels and restaurants (Table 3.1) has to be investigated. The share of copper, steel and aluminium in the "metal" waste type; and the share of paper and cardboard in the "paper and cardboard" category, have not been investigated either.

In SCLC there are eight materials that are recovered by informal waste collectors; namely, copper, aluminium, steel, paper, cardboard, glass, nylon and PET. The prices that intermediaries pay for the recovered material are listed in Table 3.2.

Material	Mass price [MXN/kg]
Copper	65.0
Aluminium	12.0
Nylon	2.0
PET	1.5
Steel	1.5
Paper	1.0
Cardboard	0.6
Glass	0.2

Table 3.2: The prices per weight of recovered types of waste. These where surveyed from waste material buyers in SCLC in November of 2019.

The most profitable waste type that is recovered in SCLC by the informal sector is metal (Figure 3.6); its value is approximately 41,000 MXN even though it is one of the least abundant waste type. This monetary value is under the assumption that the vast majority of the metal is aluminium. Contrarily, glass is one of the least profitable waste streams, from which 1400 MXN can be obtained. Altogether, the value that can theoretically recovered from domestic USW of SCLC, if metals, paper, glass and PET are recovered is of 64,500 MXN per day, approximately. This estimation is also based on the magnitude of the waste streams that have been quantified in this chapter.

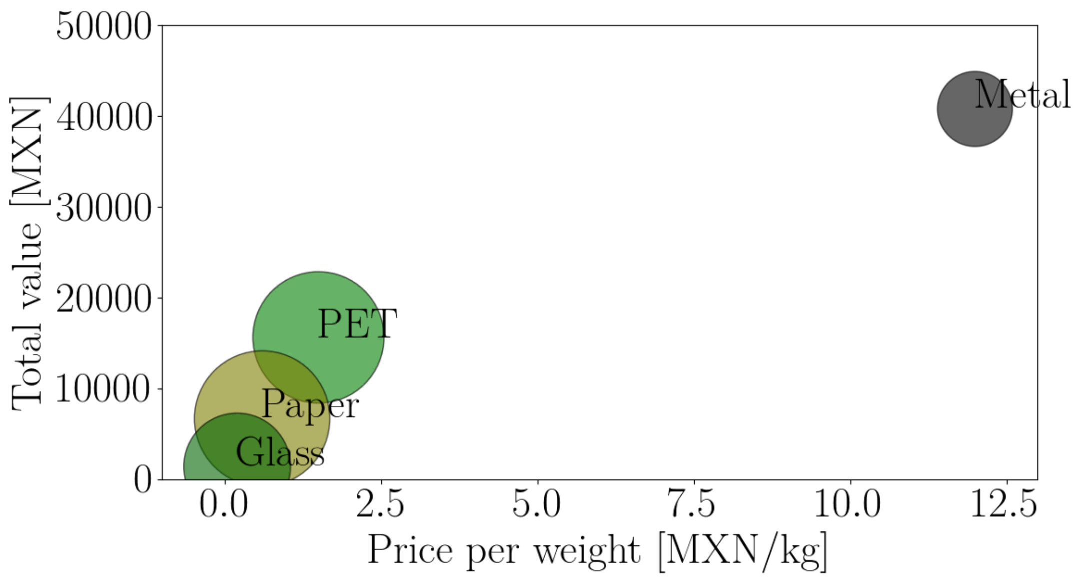


Figure 3.6: Price per wight versus the value of the waste stream, where the area of the circles represent the magnitude of the waste stream.

Chapter 4

Waste Processing Techniques for Organic USW

Biomass constitutes the largest waste stream; approximately 50% of the total mass that is landfilled in SCLC. Exploiting this USW type with a circular business case would significantly reduce the mass of landfilled USW, and prevent methane emissions and leachates rich in phosphate and nitrates (Jayawardhana, Y. and Kumarathilaka, P. and Herath, I. and Vithanage, M., 2016; Ramakrishnan et al., 2015).

This chapter comprises of the most common techniques to treat organic USW, which partially replies to the sub-question:

b) What are the techniques and solutions that can be used to avoid landfilling and, if possible, up-cycle the identified waste types specifically for the city of SCLC?

The last section of this chapter is a reflection about the most suitable technology to treat organic waste in terms of accessibility to the technology, feedstock requirements, scaleability and investment to install the technology.

4.1 Value recovery processes for organic waste

There are three main categories of processes to treat organic waste, namely direct use, biological treatment, physio-chemical treatment, thermo-chemical (Lohri et al., 2017).

- 4.1. Organic waste treatment processes
  - 4.1.1. Direct uses
    - 4.1.1.1. Direct land application
    - 4.1.1.2. Direct animal feed
    - 4.1.1.3. Direct combustion
  - 4.1.2. Biological treatments
    - 4.1.2.1. Composting
    - 4.1.2.2. Vermicomposting
    - 4.1.2.3. Black soldier fly treatment
    - 4.1.2.4. Anaerobic digestion
    - 4.1.2.5. Fermentation
  - 4.1.3. Physico-chemical treatments
    - 4.1.3.1. Transesterification

4.1.3.2. Mechanical compression

4.1.4. Thermo-chemical treatments

4.1.4.1. Pyrolysis

4.1.4.2. Liquefaction

4.1.4.3. Gasification

Direct applications of organic waste require limited expertise, infrastructure or set-up costs. The most common in this category are direct land application, direct animal feed and direct combustion (see listing below). The quality requirements for the input material for these techniques are flexible, as long it is organic waste. Yet, all have the risks of pathogen exposure to animals and humans, and accumulation of trace elements in the soil and organisms (Lohri et al., 2017).

- **Land application**. Note: data from Lohri et al. (2017).
  - Product and value: higher crop yield due to higher nitrate and phosphate content; low investment.
  - Risks and disadvantages: plant growth inhibition due to excessive microbial activity in the soil; health hazard to animals and humans due to exposure to pathogens.
  - Feedstock requirements: degradable organic waste; non-chemical or metal contaminated waste.
- **As animal feed**. Note: data from Lohri et al. (2017).
  - Product and value: potentially higher quality meat and milk; lower costs for farmers to feed their animals.
  - Risks and disadvantages: health hazard to animals and humans due to exposure to pathogens.
  - Feedstock requirements: lignocellulosic waste (for cattle); non-lignocellulosic waste (for poultry and pigs); no rotten waste; no animal by-products.
- **Direct combustion**. Note: data from Lohri et al. (2017).
  - Product and value: waste hygienisation; waste volume reduction.
  - Risks and disadvantages: significant greenhouse gas emissions to the atmosphere.
  - Feedstock requirements: any type of degradable organic waste.

Biological treatment processes are characterised by low investment costs and the possibility to install them with easily accessible technology and materials. Nevertheless, in practice these have proven to be hard to upscale to industrial levels due to inadequate design and maintenance. Another hinder can be little acceptance of these techniques from population due to vermin and odour (Lohri et al., 2017). The most explored processes of this type are composting, vermicomposting, black soldier fly treatment, fermentation and anaerobic digestion (see listing below).

- **Composting**. Note: data from Lohri et al. (2017).
  - Product and value: hygienic fertile soil which can be used for soil restoration, enhance crop yield and remediate pollution; the leachate fluid can be employed fertiliser.
  - Risks and disadvantages: large area requirements; methane emissions.
  - Feedstock requirements: food waste; garden waste; manure and septage; agricultural waste.

- **Vermicomposting**. Note: data from Lohri et al. (2017).
  - Product and value: fertile soil of higher quality than composting; worms and larvae as animal or human feed; leachate fluid as fertiliser; smaller area requirement in comparison to composting (by staking the containers).
  - Risks and disadvantages: revenue stream is not sufficient on a large scale; requires expertise about the life cycle of worms; limited marketing for the harvested worms and larvae.
  - Feedstock requirements: food waste; garden waste; sewage sludge; industrial degradable waste such a food, wood or paper; non dairy, meat nor fish; non fatty waste; non acidic waste (vinegar or citrus fruits); non salty food.
- **Back soldier fly treatment**. Note: data from Lohri et al. (2017).
  - Product and value: insect protein as animal feed; insect oil for bio-diesel; insect residue for soil amendment.
  - Risks and disadvantages: at industrial scales it requires a high investment for climate control, automation and hygiene; waste has to be shredded in small particles before feeding it to the larvae; requires expertise about the life cycle of organism; marketability challenges.
  - Feedstock requirements: food waste; garden waste; agriculture waste; manure, sewage sludge and excreta; fish waste; no high cellulosic waste.
- **Anaerobic digestion**. Note: data from Lohri et al. (2017).
  - Product and value: biogas as fuel; the nitrogen rich slurry, or digestate, can be utilised as fertiliser for agriculture; the technology is well developed.
  - Risks and disadvantages: poor design, maintenance and operation commonly cause the system to fail; no market for the digestate; lignocellulosic waste requires pretreatment so that it can be used in the process; the technical challenge and energy requirement to bottle methane gas only allows to use it on site which can be a limitation to find a market for it.
  - Feedstock requirements: slaughterhouse waste; animal manure; wastewater sludge; manure; agricultural waste; garden waste; food waste; non high cellulosic waste.
- **Fermentation**. Note: data from Lohri et al. (2017).
  - Product and value: bio-ethanol as fuel for internal combustion engines.
  - Risks and disadvantages: difficulty to suppress production costs which limits the competitiveness with petroleum-based fuels; cellulosic waste requires pretreatment which causes a large impact on the price of the production process; challenge to procure a steady input of adequate material.
  - Feedstock requirements: starch and sugar rich organic waste.

Physico-chemical treatments are applied to increase the energy density of the organic matter by chemical processes such as transesterification or by mechanical compression. Transesterification is a process in which the density of oils, or fats, is reduced in reaction with alcohol so that it can used as biodiesel for internal combustion engines. Densification is the compaction of shredded and dried biomass into pellets, or briquettes, for applications such as animal fodder, combustion or pyrolysis.

- **Transesterification**. Note: Data from Lohri et al. (2017)
  - Product and value: glycerol which can be converted to ethanol.

  - Risks and disadvantages: implementation at industrial scale is economically unfeasible as the ethanol is more expensive than petroleum-based fuel; procure a steady state of feedstock material.
  - Feedstock requirements: fatty degradable waste; restaurant grease waste, slaughterhouse fatty waste.

- **Mechanical compression**. Note: data from Lohri et al. (2017)
  - Product and value: biomass pellets and briquettes; the advantage is that the machinery required ranges from simple mechanical devices up to advanced hydraulic compaction systems.
  - Risks and disadvantages: profitable particularly for lignocellulosic waste; finding a market demand for the product; high wear and tear of the machinery.
  - Feedstock requirements: agriculture lignocellulosic waste such as straw, husks, bagasse, wood or nut shells.

Thermo-chemical processes decompose organic matter through chemical reactions at high temperatures, into chemical products; these are utilised for energy and chemical applications. These processes are characterised by large energy requirements, and technologies that are not easily available in all regions (Lohri et al., 2017). Nonetheless, the value of the final products is higher, the processing time of the input material is shorter and the input material requirements are more flexible in comparison to the other categories (Lohri et al., 2017). The quality of the products, in this category, depends on the composition, moisture content and particle size of the input material and parameters such as pressure, temperature or catalyser; all of which can be optimised (Basu, P., 2018; Lohri et al., 2017).

Pyrolysis is the process in which material is decomposed into liquid, char and gas due to high temperature exposure, between 100 and 900 °C, inside of a kiln in absence of oxygen (Basu, P., 2018). Gasification is similar to pyrolysis with the difference that it requires a gasification agent —i.e. oxygen, water or hydrogen —to facilitate the decomposition of the biomass. Liquefaction implies processing wet biomass in a hot environment, between 280 and 370 °C, at high pressures, from 7 up to 30 MPa, inside a tank. These processes are summarised in the next listing:

- **Pyrolysis**. Note: data from Lohri et al. (2017)
  - Product and value: char as fuel and as a medium to remediate water or soil; bio-oil as fuel; gas as fuel; technology can range between simple and primitive or highly complex machinery.
  - Risks and disadvantages: energy input requirement for the production process and to dry the input material; relation between quality of the products and complexity of the plant. Meaning, a higher investment to control the quality of the process; significant energy requirement to dry the feedstock.
  - Feedstock requirements: any type of dried biomass. (moisture$<$20%); polymers and paper can be included in the process (Czajczynska et al., 2017).

- **Liquefaction**. Note: data from Lohri et al. (2017)
  - Product and value: bio-crude.
  - Risks and disadvantages: the technology has only been proven on small scale; difficulty to enhance the quality of the bio-crude to obtain finer bio-oil; high capital investment to purchase adequate equipment to pressurise the process.
  - Feedstock requirements: wet biomass which may include fat, cellulose and high protein content.

- **Gasification**. Note: data from Lohri et al. (2017)
  - Product and value: syngas.
  - Risks and disadvantages: immature technology; few cases of application at industrial scale.
  - Feedstock requirements: homogeneous dry biomass (moisture$<$20%); small particle size.

4.2 Selection of a suitable treatment technique for organic USW

Multiple aspects have to be considered in order to find a suitable technology that would treat the organic USW in SCLC. For instance, the accessibility to the technology, scaleability, material input requirements and marketability of the final product.

Opting for direct use and biological treatment processes are feasible techniques, considering how accessible they are in terms of equipment. Direct use can be carried out only by setting up a logistic network, while the second category can be installed with common products that are found in most cities such as bins, pipes, cement, among other. Opposite to that are physio-chemical and thermo-chemical processes, which require reactor tanks, piping systems, pumps and machinery that are resistant to heat or pressure; these components are not available in all cities and require a significant investment. This factor that has the largest influence on the cost of the technology.

Scaleability can be related to two factors: the time required to process biomass into valuable products and a market to sell the final product. Direct use, biological treatment and transesterification techniques turn the biomass into valuable products in multiple days; whereas densification and thermo-chemical techniques can valorise the input material in hours. For the study case, if the technique cannot treat the input material sufficiently rapid it can cause stock issues. Furthermore, a setback for direct use treatment is that the local demand for biomass might not be as high as the daily supply of biomass and thus implementing it at full scale might not be attainable. The demand for fuel will, plausibly, always be present in any context and thus there is a great potential to implement thermo-chemical processes at full scale as long as they are price-competitive.

For each biomass treatment technology quality requirements for the input material have to be met. These requirements have implications on the practicality on the waste separation system. If these requirements are flexible, as with thermo-chemical process, then it is possible to assign more responsibility to the population to sort organic waste. On the other hand, if the material requirements are more specific, as with biological treatments, it can be challenging to successfully obtain a well sorted waste from the general public. In this case, a separation process would, most likely, be necessary prior to treatment and, as a consequence, raise production costs. In any case, waste separation still has to be implemented in SCLC; thus a flexible material input should be possible as a waste separation scheme evolves.

The above-mentioned indicates that thermo-chemical processes, although high-priced, are the most suitable to treat the organic fraction of the USW at a fast pace; nevertheless, not all of these are equally suitable. For instance, gasification requires water, hydrogen or oxygen as a catalyser; the acquisition of the last two can prove to be limited, or expensive, in the region. Furthermore, gasification is not yet a well established technology and has not been deployed on a large scale.

In terms of energy liquefaction has the advantage that it does not require dry input material, thus no drying process. Nonetheless liquefaction is carried out under high pressures which requires a considerable input of energy and an equipment that is specifically produced to withstand pressure.

The useability of products that are from thermo-chemical processes is also important. For instance, syngas obtained from gasification can be used directly. The gas, char and bio-oil product from pyrolysis can be used directly. On the contrary bio-oil obtained from liquefaction requires further treatment before it can be used as a high quality fuel.

Pyrolysis is the most versatile technology from all those that where considered in this chapter. Its input material can be biomass, paper, cardboard, polymers or a combination of these (Czajczynska et al., 2017). Moreover, pyrolysis can also be used to recover valuable elements from printed circuit boards, a common component of E-waste, if it the material is not combined with other types of waste (Kaya, M., 2019). The flexibility to treat different types of materials allows to adjust the business case when the final product of a certain feedstock renders economically unsustainable. Moreover, the process can be optimised to increase the quality and yield of the char, gas or liquid product. Finally, the complexity of pyrolysis technology can range from a primitive kiln, where only char and liquid are recovered, up to an industrial continuous process where the temperatures, rate of heating can be controlled, and where the all the by-products are captured (Basu, P., 2018). As a result, the investment can be increased parallel to the complexity of the equipment as the business case grows.

Chapter 5

Waste Processing Techniques for Other Types of USW

Valuable materials or energy can be recovered from all types of USW through technological processes and separation schemes. The suitability of such processes depends on the quality and composition of the collected waste and, conversely the collected waste has to separated so that it complies with the quality requirements of the treatment process.

The waste categories that are identified and quantified in SCLC are the following (refer to Section 3.4):

- Organic (Fruits, vegetables, flowers, leafs, branches, wood, food waste, leather)
- Metals (copper pipes, wiring, aluminium cans, aluminium foil, etc.)
- Paper/cardboard (cardboard drinking package, office paper, cardboard)
- Plastics (bottles, rigid packages, bags)
- Glass
- Toxic waste (sanitary waste, batteries, E-waste, light bulbs)
- Other (rubber, synthetic fibres cotton, ceramics, dust)

This chapter is a review of the processes that can be implemented to recover the value of the afore-listed waste categories, except organic waste, on a large scale. This is under the assumption that USW is sorted before collection. This chapter also evaluate whether these waste treatment techniques fit in the socioeconomic context of the study case. This corresponds, in combination with Chapter 4 to the sub-question:

b) What are the techniques and solutions that can be used to avoid landfilling and, if possible, up-cycle the identified waste types specifically for the city of SCLC?

5.1 Value recovery processes for metal waste

Metal recycling is a well established practice because the material properties of metals do not change after multiple recycling cycles, unless different metals are combined; this is the major difference with other types of waste such as plastics or paper (Feil, A. and Pretz, T. and Jorg, J. and Go, N. and Bosling, M. and Johnen, K., 2019). Additionally, the amount of energy that is required to recycle metal is approximately 70% lower than what is needed to produce virgin material (Feil, A. and Pretz, T. and Jorg, J. and Go, N. and Bosling, M. and Johnen, K., 2019). In fact, recycled metals have the same value as virgin material in the market.

Mixed metal waste from domestic USW is generally comminuted, cleaned and sorted. Comminution is the process in which the particle size of the material is reduced by machines, such as a shredder. After shredding, the material flow is freed of contaminants (dust and non metallic particles) in a cyclone, where air is blown through the material. Consecutively, the metal waste stream is sorted, in ferrous and non-ferrous, with a magnetic or Eddy current separator. While, the obtained ferrous metals can directly be molten into new products, the non-ferrous metals need to be sorted further into copper, brass, aluminium, zinc and lead.

Melting metals is done in blast, basic oxygen or electric arc furnaces (Rao, S., 2006). The molten metal is shaped into new products such as sheets, ingots, pipes, rods, beams, bars, etc. completing the circle of recycling of the material.

5.1. Metal waste treatment processes
  5.1.1. Metal separation and decontamination steps
    - Comminution with a shredding machine
    - Contaminant removal in cyclone
    - Separation of ferrous and non-ferrous metals by magnetic separators
  5.1.2. Metal melting options
    5.1.2.1. Blast furnace
    5.1.2.2. Basic oxygen furnace
    5.1.2.3. Electric arc furnace

5.2 Value recovery processes for paper and cardboard waste

The quality of paper for recycling depends on whether it is recovered before consumer use or after consumer use (Scott, G. M., 2019). Pre-consumer paper use consists of unprinted paper, cuttings and shavings. Some examples of post-consumer paper are mixed residential paper, (un)sorted office paper and old newspaper.

The quality of paper is categorised in "grades", where each grade requires different treatment processes so that the recovered paper can be turned into a new product. Additionally, the treatment processes also depend on the product that will be produced from the recovered material; that is paper to paper or paper to another product.

Mixed residential paper is the grade that is recovered from domestic USW. It is important to note that, when sorted out of the USW stream after collection, the paper is of the lowest quality as it is contaminated (Scott, G. M., 2019); hence, it is important that paper is separated at household level from the rest of USW and before collection so that it can be recycled.

Before treating the recovered paper it has to be sorted to become homogeneous material stock. The processes to remove contaminants from the sorted incoming paper are washing off soluble inks and fine particles; cleaning dirt, plastic and metals by gravity and screening; and flotation to remove non-soluble inks with detergents and aeration.

Recovered paper is broken down by mixing it with water and stirring, resulting in fibre pulp. Short fibres and long fibres, contained in the pulp, are separated into two material streams; this process is called "fractionation". The long fibre pulp is used to produce new paper and is refined to enable bonding between fibres. "Dispersion" is an operation that is used to remove non-soluble ink particles from the pulp. Finally, the pulp is dewatered, through press rolls and bleached to produce new paper. The use of water is intensive in paper recycling, as large quantities have to be removed and added between processes. Lastly, the mechanical properties of the fibres degrade in time and every time it is recycled, thus it is necessary to incorporate virgin wood pulp to produce high quality paper (Scott, G. M., 2019).

Paper that does not have sufficient quality to produce new paper can be used to create other products or value such as low-strength cartons, insulation or for energy purposes (Scott, G. M., 2019).

5.2. Paper and cardboard waste treatment processes

5.2.1. Paper separation and decontamination steps

- Homogenisation of input material by hand or automated selection
- Washing off soluble ink and fine particle from the paper in tanks with water.
- Screening other materials out of the paper pulp with settling tanks and rasters
- Flotation process to remove non-soluble ink with aeration and detergents.

5.2.2. Paper pulp treatment steps

- Repulping
- Fractioning
- Refining
- Dispersion
- Dewatering
- Bleaching

5.3 Value recovery processes for plastic waste

Polymers, or plastics, are categorised in two: thermosets and thermoplastics. The fundamental difference is that the mechanical properties of thermoset polymers change irreversibly after being molten, whereas with thermoplastics this does not occur. In other words, thermoplastics can be recycled as the same product continuously while with thermosets this is not possible. The most widely used types of thermoplastic polymers are polyethylene (PE, HDPE and LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA) and polyethylene terephthalate (PET). In fact, each of these have different melting temperature, density, solubility, tensile strength, Young's modulus and other material properties.

There are four major treatment categories for plastic waste: primary, mechanical, chemical treatment and energy recovery (Sethi, B., 2017). Primary material treatment consists of in-factory reuse of polymer waste in the production process.

In mechanical recycling, the post-consumer recovered material is converted into new products. It comprises of sorting, comminution, cleaning, colouring, extrusion of pellets and using the pellets to manufacture the final product (Sethi, B., 2017). Sorting is the process where plastic waste is separated by polymer type; this step is necessary because melting a mix of polymers results in a material with unknown material properties. Sorting can be a problematic process because the different types of polymers cannot be identified simply by sight or touch. This is often solved by sorting products that typically are made off the same material; for example, bottles are mostly made out off PET. The disadvantage is that a large portion of recovered plastic waste remains unidentified; automated sorting can successfully sort plastic waste, but requires a high capital investment. Comminution is the process where the sorted material is reduced to small chips with a shredding machine. The shredded material has a larger area to be exposed to detergent and water and thus can be cleaned more effectively. Drying the cleaned plastic chips is crucial to maintain the quality, as water and acidic residues contribute to the degradation of the polymer (Sethi, B., 2017). Colourants are added to the material to enhance its visual aspect. The cleaned plastic chips are extruded in thin filaments which are cut down in fine pellets. The melting temperature of polymers differs per type; heating above these temperatures can degrade and change mechanical properties of the material irreversibly. Therefore it is crucial to control the temperature of the extrusion process. Finally, the pellets are the primary material that is used to manufacture plastic products (Sethi, B., 2017).

Chemical recycling involves thermal processes, in some cases with added catalysers, to break the polymer molecules into smaller molecules, called "monomers". The process of breaking polymers is called "depolymerisation". The resulting products are liquids or gases of monomers, which are desirable products for energy or chemical applications. In fact, liquid monomers can be used to produce new polymers. The most widely studied processes in this category are pyrolysis, gasification and chemical cracking. Polymer pyrolysation exposes the material, in the absence of oxygen, to temperatures ranging between 400 and 500 °C to maximise the yield of liquids; here it is the temperature that breaks the polymer molecules into monomers. Gasification consists of the same process but differs in that water and carbon dioxide are added, as a catalyser, to obtain other types of monomer liquid and gas products. Catalytic cracking also breaks the polymer molecules with a catalyser but lower temperatures and faster pace, in comparison to pyrolysis and gasification. The disadvantage of catalytic cracking is that the acquisition costs of the catalysers can be high (Sethi, B., 2017).

Thermoplastic polymers can be recycled with all the aforementioned processes; on the other hand, thermosets can only be recycled by chemical recycling or energy recovery. Ideally, polymer treatment processes, except energy recovery, require a homogeneous feedstock of the same type of plastic. Energy recovery is the use of heat and power, that is obtained from the combustion of polymers, for heating purposes or generation of electricity (Sethi, B., 2017).

Finally, reusing plastic products, without treatment processes is another, but minor, form of recycling. However polymers can absorb pollutants which makes this approach unsuitable for food-related applications. This practice is neither possible for all plastic products, making the impact on the total amount of plastic waste insignificant (Sethi, B., 2017).

5.3. Plastic waste treatment processes
- 5.3.1. Primary material recycling
- 5.3.2. Secondary mechanical recycling steps
  - Sorting
  - Cleaning and drying
  - Comminution
  - Colouring
  - Pellet production by extrusion
  - Final product production
- 5.3.3. Thermo-chemical recycling techniques
  - 5.3.3.1. Gasification (thermal cracking)
  - 5.3.3.2. Pyrolysis (thermal cracking)
  - 5.3.3.3. Catalytic cracking
- 5.3.4. Energy recovery (incineration)
- 5.3.5. Product reuse

5.4 Value recovery processes for glass waste

There are two ways in which glass is recycled, namely by reusing glass products and by melting broken glass, or "cullet", into new products. Cullet is crushed glass that has been collected, cleaned and sorted by colour (Butler, J. H. and Hooper, P. D., 2019).

Reusing glass products, such as containers, is the most energy efficient manner to recycle glass. The processes needed for this practice are collection, cleaning and refilling the containers. This requires a logistic network, a profitable economic structure and favourable legislation. An effective system to incentivise the general public to return glass containers is the deposit system (Butler, J. H. and Hooper, P. D., 2019).

The production of glass is done by melting virgin silica sand to a temperature of 2300 °C in a furnace. The melting temperature can be lowered to 1500 °C when adding sodium oxide up to 15% of the total material mix. In addition, the durability of the material is enhanced with the addition of calcium oxide up to a percentage of 15% from the total mix. This process requires large quantities of energy to melt the feedstock and to maintain its molten state for up to 72 hours, depending on the required quality of the final product (Butler, J. H. and Hooper, P. D., 2019). The air pollution caused by glass production is significant as the amount of greenhouse gas emissions per ton lies between 480 and 640 kilograms (Butler, J. H. and Hooper, P. D., 2019).

The production of new glass products using cullet as input material, in comparison to using virgin silica, requires approximately 1.5 GJ/ton less of energy and avoids up to 250 kilograms of CO2 per ton of glass (Butler, J. H. and Hooper, P. D., 2019). Nonetheless, these energy savings remain true if the transportation distance of the cullet to the treatment plant is less than that of virgin material (Butler, J. H. and Hooper, P. D., 2019).

5.5 Value recovery processes for toxic waste

Toxic waste in SCLC includes mostly toilet paper, diapers, feminine hygiene products, light bulbs, electronic devices and batteries (Ayuntamiento Constitucional San Cristóbal de las Casas, 2018). This type of waste contains pathogens and chemicals that are toxic to humans and the environment (Letcher, T. and Vallero, D., 2019).

It is stipulated by the Mexican Secretariat of Environment and Natural Resources (SEMARNAT) that biological-infectious waste from hospitals must undergo a chemical, thermal and physical treatment that guarantees the eradication of pathogens and render the waste unrecognisable so that it can be disposed in landfills (Secretaría de Medio Ambiente y Recursos Naturales, 2002).The facilities to treat the waste accordingly do not exists in SCLC, nor in the state of Chiapas, as they are not registered in the National Statistic Directory of Economic Units database (DENUE). It thus probable that a large portion, if not all, of the hospital waste in SCLC is landfilled without treatment.

Furthermore, electronic device waste, or E-waste, was not included in the "toxic waste" category in the USW composition study of the municipality of SCLC. Yet, it is considered a toxic waste according to the federal norm of dangerous waste defined by the SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales, 2005). It is more likely that E-waste that is disposed with household USW in SCLC are batteries, lamps, small equipment, due to their small size; while large electronic devices are largely recovered by self-employed collectors.

Electronic devices are composed of cables, plastic casings, metal casings, printed circuit boards (PCBs), display screens, batteries and light bulbs (Kaya, M., 2019). In most cases the electronic devices are dismantled manually to sort the aforementioned components. Casings, made out of metal and plastics, can recycled as described in previous sections. Cables require simple methods to separate copper from the plastic coating in environmental friendly manner; that is, shredding, smashing and Eddy current separation (Kaya, M., 2019).

Display monitors, PCBs, light bulbs and batteries require complex proceedings to recover their valuable materials. Firstly, because they often contain toxic substances that can cause severe health effects on humans and the environment and, as a consequence have to be safe. Secondly, due to the application of thermo-chemical reactions to capture and purify the toxic substances (Kaya, M., 2019; Zhao, S. and He, W. and Li, G., 2019).

PCBs are made off glass fibre bonded with epoxy resin —a thermoset polymer —and plated with copper layers (Kaya, M., 2019). The components that are mounted on the PCB, such as heat sinks, resistors, capacitors and other, altogether contain about 40 elements from the periodic table (Kaya, M., 2019). The composition of a PCB is typically 40% metals, 30% ceramics and 30% polymers. Copper, iron, aluminium, lead, gold, palladium, silver are the most relevant metals that are gained from recycled PCBs (Kaya, M., 2019).

There are two categories of processes to recover valuable materials from PCBs, namely traditional and emerging techniques.

Traditional techniques are direct incineration or mechanical (Kaya, M., 2019). Direct incineration is used to recover a limited amount of copper, iron and aluminium. The issue with incineration is that lead, chromium and other heavy metals are emitted to the air; this is highly toxic to humans and the ecosystem. Mechanical processing, as with other types of waste, fall back to crushing and grinding, and then retrieve aluminium, copper, gold and silver by mechanical separation (Kaya, M., 2019).

Emerging techniques use thermal (pyrometallurgy) and chemical reactions (hydrometallurgy) to extract higher yields of valuable resources, such as gold and palladium, from PCBs (Kaya, M., 2019). Pyrometallurgy can be pyrolysis, gasification, incineration or melting. In these processes, gases have to be captured and purified to avoid heavy metals emissions from entering the ecosystem (Kaya, M., 2019). Hydrometallurgy consists of removing the metals from the PCB by dissolving them using strong acids or bacteria; and, finally, extracting them from the solution via purification processes such as precipitation, cementation, eletrowining, solvent extraction or ion exchange (Kaya, M., 2019).

- 5.6. PCB treatment processes
  - 5.6.1. Conventional PCB treatment techniques
    - 5.6.1.1. Mechanical treatment steps
      - Crushing
      - Grinding
      - Separation by gravity, magnetic, Eddy current and/or electrostatic
    - 5.6.1.2. Direct incineration
  - 5.6.2. Emerging PCB treatment techniques
    - 5.6.2.1. Hydrometallurgy: biometallurgical leaching or solvent leaching
    - 5.6.2.2. Pyrometallurgy: pyrolysis, gasification, melting in furnace with gas emission capture system, or incineration with gas emission capture system.
    - 5.6.2.3. Purification: chemical precipitation, cementation, electrowinning, solvent extraction, or ion exchange.

Spent batteries have to be discharged so that the possibility of short circuit and, consequently, combustion are eradicated; this is done by immersing them in a salt solution bath (Zhao, S. and He, W. and Li, G., 2019). The batteries are then disassembled and sorted by its components, i.e. shell, anode, cathode, binder, electrolyte (Zhao, S. and He, W. and Li, G., 2019). The shell is made off stainless steel or nickel-plated steel (Zhao, S. and He, W. and Li, G., 2019). The anode is a copper-coated graphite layer (Zhao, S. and He, W. and Li, G., 2019). Cathode is a lithium compound layer, $LiCoO_2$ the most widely used, coated with an aluminium foil (Zhao, S. and He, W. and Li, G., 2019). The electrolyte transfers charge between the anode and the cathode and is made of lithium-containing salts (Zhao, S. and He, W. and Li, G., 2019). Lastly, batteries also contain polymer separators (PP or PE) as a mechanism to prevent short circuit (Zhao, S. and He, W. and Li, G., 2019).

Metals and polymers can be easily retrieved by pulverising the components separately, and mechanical separation methods such as magnetic separation, Eddy current separation or sieving (Zhao, S. and He, W. and Li, G., 2019).

The most challenging aspect of recycling batteries is actually recovering cobalt, lithium and graphite; for these it is necessary to apply mechanical-chemical, heat treatment or hydrometallurgy refining processes (Zhao, S. and He, W. and Li, G., 2019).

Hydrometallurgycal processes require specific expertise and an intensive use of chemicals. Although less energy consuming in comparison to heat and mechanic treatments, they do generate large amount of chemical reagents waste and cause corrosion on industrial equipment (Zhao, S. and He, W. and Li, G., 2019).

End-of-life fluorescent lamps are crushed; where the dust is blown into a filtering and purification system. The crushed material is wet-cleaned from mercury, tungsten and phosphor (Lee et al., 2015). Consecutively, the glass is segregated from from metallic parts, for example by magnetic separation (Lee et al., 2015). Mercury is distilled out of the (wet) dust (Lee et al., 2015). And, lastly, phosphor is purified (Lee et al., 2015). Similar processes are applied to the different types of mercury-containing lamps (Lee et al., 2015).

Operations to retrieve valuable materials from display monitors, free of other components, are determined by the type of monitor, which can be out-phased cathode ray tube (CRT) televisions and monitors, liquid crystal display (LCD), plasma panel, organic light-emitting diode (OLED) or other types. CRT televisions contain leaded glass which has limited options to be used in new products (Mueller, Boehm, & Drummond, 2015). In particular case of LCD monitors, automated or manual disassembly are used to carefully remove lights that contain mercury and treat them with the processes described in the previous paragraph (Williams, K.S. and Mcdonnell, T., 2019). The liquid crystal can be retrieved by braking the glass screen, in which it is contained, separate it form the glass and purified it chemically so that it can be used again in the production of new screens (Williams, K.S. and Mcdonnell, T., 2019).

For all the types of E-waste is it crucial to have a system that properly captures and filters toxic fumes, or dust, so that they are not emitted to the ecosystem or humans are exposed to them.

Conclusively, the value that can be recovered from hospital and personal hygiene waste is heat and power from the incineration, as it is a mandatory process (Secretaría de Medio Ambiente y Recursos Naturales, 2002). The valuable materials that can be recovered from E-waste are liquid crystal, palladium, gold, silver, copper, lithium, chromium, cobalt, mercury, lead, glass, polymers, among other rare elements of the periodic table.

5.6 Reflection on the suitability of USW treatment techniques in SCLC

Plastics, the second largest waste type in SCLC, degrade throughout decennia when exposed to the combination of oxygen, ultraviolet light and bacteria (Sethi, B., 2017). When this material is buried in a landfill, without exposure to oxygen, the material is preserved and can be retrieved when treatment processes are available. It can be argued that landfilled plastic cannot be considered as harmful as leachates and gas from biomass, or heavy metals from E-waste; thus it is not the most urgent type of waste to be treated. Currently informal waste pickers collect most of PET products, a polymer that accounts for 7.4% of the total domestic USW (Ayuntamiento Constitucional San Cristóbal de las Casas, 2019). Regardless, a significant portion of the plastic waste are plastic bags which are landfilled (Figure 5.1).

Figure 5.1: Close-up of the landfill in SCLC, where plastic bags are prominent.

The daily amount of paper and cardboard that can, potentially, be recovered in SCLC is at least 11,000 kilograms. For such amount it is worth to explore the potential to recycle it, as long as the amount of water used in the treatment processes can be met in the local context. Such scenario would also eliminate the need to transport the material through long distances, making the profit higher. However, from a toxicity perspective, it is not a priority to treat it.

Treating "toxic waste" should be prioritised due to its toxic leachates from E-waste and pathogens from sanitary waste. Sanitary waste can be burned to harvest heat and power. The amount of E-waste is increasing rapidly in emerging economies (Kuehr, R., 2019) and thus it is necessary to establish a system to prevent it from reaching landfills. This requires advanced technologies and intensive labour where humans are exposed to fumes that are hazardous for health (Kaya, M., 2019; Williams, K.S. and Mcdonnell, T., 2019); and still, treating such waste would not significantly reduce the mass of USW that is landfilled. Instead, it would be more practical to implement a collection scheme such that the recovered material is transported to facilities, within Mexico, that can safely treat the material. There are approximately six companies that specialise in E-waste collection and treatment —Remsa, Trioelectro, Ecorecicla, Recycel, Recall and Reciclacomputadoras —located in Mexico City, Queretaro or Monterrey.

Turning metal waste into a usable product requires a large input of energy for melting and shaping the material. For this it is necessary, especially in large scale operations, to have access to melting furnaces, heat resistant equipment and, depending of the final product, expertise of metallurgy. The disadvantage is that such equipment and knowledge does no exist in the state of Chiapas, as it not registered in DENUE; thus it has to be brought from afar. Besides, metal is one of the most profitable waste types for informal waste collectors (see Table 3.2); therefore a large, but unknown, share of it is already sorted and sold to metal scrap yards by the informal sector. In terms of toxicity metals can be conceived as one of the most toxic waste types, second to E-waste. Aluminium specifically can react with other landfilled substances can change the composition of leachates (Stark, Martin, Gerbasi, Gortner, & Thalhamer, 2012). Iron, copper and zinc leachates can enter underground waster systems and can cause harm to human health humans through water consumption; even when landfills are built with a liner (Mishra et al., 2018).

Chapter 6

A Circular Business Case Using Organic USW

6.1 Circular business idea to reuse organic USW

The main goal of the circular business case is to replace the supply of firewood and char, which is obtained from illicit logging, that is used as cooking fuel in SCLC. This would be done by providing an alternative fuel, namely charcoal briquettes. The charcoal briquettes would be produced from organic USW and targeted, primarily, to users of wood and char who are unable to afford liquefied petroleum gas (or LPG).

This business case has the potential to create economic, environmental and social value for a wide range of people and organisations. The most relevant value is that firewood users can have access to a renewable fuel of higher energy content at an affordable price without having to adjust their cooking methods. Additionally, the combustion of biochar emits less smoke and fine particles than wood (Kurniawan, Amirta, Budiarso, & Arung, 2019); meaning that by using bio-char briquettes, users are less exposed to harmful smoke in comparison to firewood.

Access to wood in rural communities is increasingly scarce, which exerts pressure on management of communal forests and forces the population to purchase firewood or coal from informal providers (Burgos Lugo, Soto Pinto, Bello Baltazar, & Castellanos Albores, 2020; Ramírez-López, 2012). If the current retail and distributors of firewood and char are included in the network of the business, they will also no longer have to obtain extract biomass from forests illegally.

The problems that can be alleviated for the municipality are more of economic nature. In SCLC the share of organic USW is the largest and, due its moisture content, the heaviest. If the briquette factory is placed in a location within the city, it would diminish travel distance of the waste department's fleet. It would also decrease the amount of trips from the city to the inaccessible landfill; meaning less fuel and wear of the fleet. Using the biomass within the city would also drastically decrease the use of the landfill and leachates. As a consequence, the life time of the landfill can be extended while the municipality can find solutions for the other types of waste.

All of the aforementioned would showcase to the general public the value that can be obtained from a stream of material that is considered useless.

6.2 Energy and mass demand of firewood in SCLC

The use of firewood and char in SCLC takes place majorly in the population sector that is characterised by economic poverty (INEGI, 2015b, 2018). The monthly income per household in this contexts is on average 1,442 Mexican Pesos (MXN), while the price of the smallest LPG tank —20 kilograms—is of 345 MXN (Comisión Reguladora de Energía, 2018; INEGI, 2018); or the price of electricity is 0.8 MXN/(kW hr), where the minimum electricity bill is of 20 MXN (O. Comisión Federal de Electricidad, 2020). As a result this population group cannot easily afford expenses on gas nor electricity for stoves and, as a consequence, the most viable alternative is wood from their surrounding forests (Alvarado Machuca et al., 2018).

Studies about firewood consumption in Mexico, and particularly in rural communities in Chiapas, have observed that the daily use of firewood mass per capita ranges between 2.0 and 3.9 kilograms (Alvarado Machuca et al., 2018; Burgos Lugo et al., 2020; Holz & Ramírez-Marcial, 2011; Ramírez-López, 2012). Actually, the amount of firewood used for cooking depends on whether it is hardwood or softwood, and on the age of the trees that are harvested (Holz & Ramírez-Marcial, 2011; Ramírez-López, 2012). Other variables that influence wood consumption are the climate type (Alvarado Machuca et al., 2018) and the number of inhabitants per household (Holz & Ramírez-Marcial, 2011; Ramírez-López, 2012).

The preferred tree species for firewood in SCLC and Chiapas, with known calorific value, are *quercus rugosa* (i.e. oak), *pinus pseudostrobus*, *pinus ayacahuite* and *pinus montezumae* (i.e. pine trees), which have a value of 19.5 MJ/kg, 21.6 KJ/kg, 18.59 KJ/kg and 20.14 MJ/kg, respectively (González et al., 2012; Kumar-Jain, 1992; Martínez Icó et al., 2015; Núñez-Retana et al., 2019).

The vast majority of households in SCLC use LPG to cook, while the share of households that utilise firewood or char as fuel for cooking in SCLC is 19.4%; i.e. 9,961 households (INEGI, 2015a); yet, considering that the average number of inhabitants per household is 4.1 (INEGI, 2015b), there are 40,840 users of firewood in the city. If we consider that the maximum consumption of firewood per capita per day is 3.9 kilograms, the total demand of firewood in SCLC can reach up to 159,000 kilograms per day . Utilising the calorific value of *pinus ayacahuite* —18.59 MJ/kg —this demand can be expressed in a energy demand of 2.961E6 MJ per day. This is the equivalent of up to 365,460 young trees, or 64,484 mature trees, that are felled on a yearly basis; the assumed biomass-to-tree ratio is derived from Holz and Ramírez-Marcial (2011).

6.3 Pyrolysis technology and briquette production process

Charcoal briquettes are made out off bio-char, which is the combustible portion, and a binding material. Common binders are starch, sewage sludge, cattle dung, molasses and paper pulp (Olugbade et al., 2019). The binder and the bio-char are mixed until a moist homogeneous material is obtained; subsequently the paste is compressed into a brick shape and, finally, dried. Furthermore the mix ratio of bio-char and binders depends on the binding material. As concluded from Chapter 3, the bio-char would be obtained from pyrolysed organic USW. The organic USW would be obtained from what is collected by the municipal waste department with a separation scheme in place. The binding material has to be selected is such a way that is readily available within the city, is economically viable, is environmental-friendly and does not affect the combustion performance of the bio-char.

The complete sequence of processes to produce briquettes (Figure 6.1) includes screening the incoming material by removing other types of waste such as metals and polymers. The cleaned material has to be milled into fine particles and then dried, to reduce its moisture content. The dried material is pyrolysed from which three products are obtained: tar, gas and char. The gas is composed of carbon dioxide (CO_2), carbon monoxide (CO), ethane (C_2H_4), ethylene (C_2H_6), hydrogen (H_2), methane (CH_4), nitrogen (N_2) and oxygen (O_2) (Agar et al., 2018); and can be utilised as fuel for the drying and pyrolysis processes. The char is mixed with a binder and extruded into briquettes; the tar can either be used as fuel for the production process, as a binder for the briquettes or as another type of product. The briquettes are dried and packed for distribution.

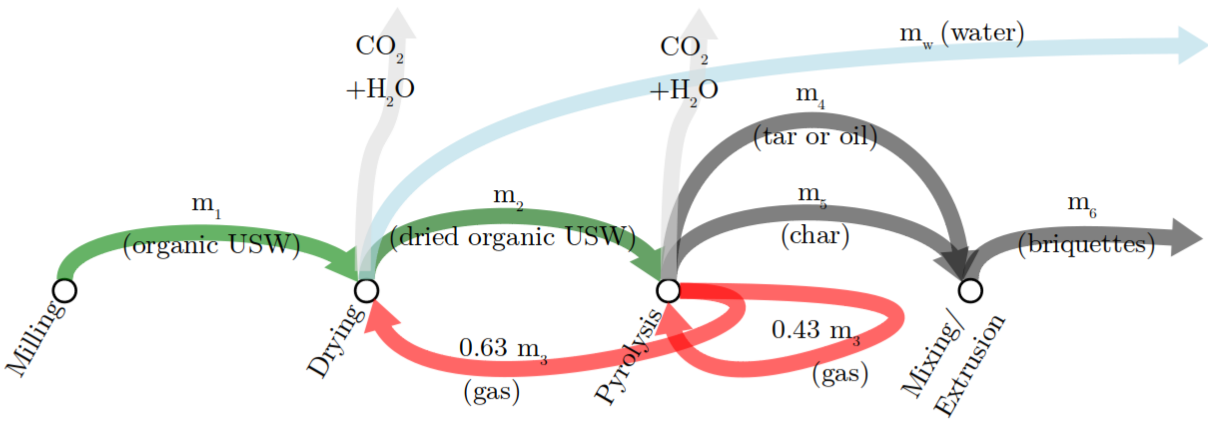


Figure 6.1: Diagram of the briquette production process.

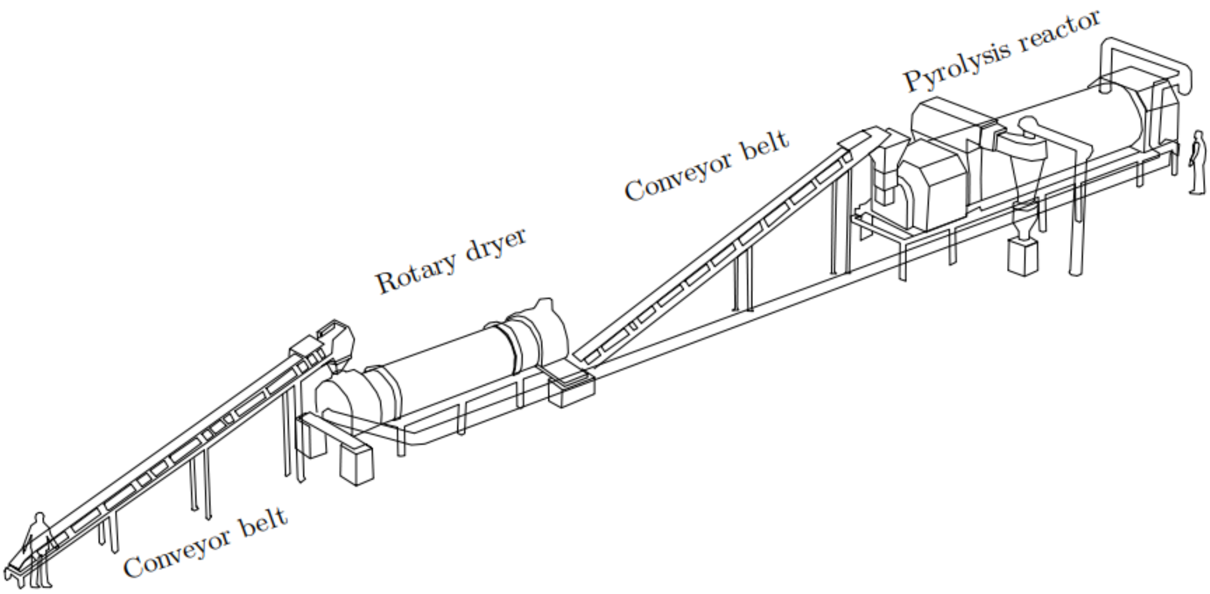


Figure 6.2: Basic continuous pyrolysis installation.

A rotary dryer is the most widely used technology to dry biomass (Rousselet & Dhir, 2016). This machine conveys a constant mass flow from one end of a pipe to another, while hot air is blown through it, to heat the material and evaporate the moisture (Rousselet & Dhir, 2016). The energy consumption of this process depends on multiple factors such as the temperature and velocity of the hot air, temperature and moisture of the biomass when entering the dryer, mass flow of biomass, retention time of the biomass inside the pipe, dimensions of the pipe, retention time of biomass inside the pipe and particle size of the biomass (Zabaniotou, 2000).

The quality and quantity of pyrolysis products depend on the temperature at which the biomass is exposed; heating rate, residence time in the reactor, the air to biomass ratio —also referred to as equivalence ratio (ER) —, the moisture content of the biomass and its composition (Basu, P., 2018). The highest yield of char is obtained at pyrolysis temperatures that range between 100 and 400 °C, in combination with a slow heating rate of approximately 2 °C per second, and long residence time. At higher temperatures the char yield decreases, but its calorific value increases due to the higher carbon content; this effect plateaus at approximately 600 °C (Basu, P., 2018). It is important to note that at high temperatures oxygen will burn the charcoal and thus the process must be in the absence of oxygen (i.e. anoxic).

The liquid product, or tar, from the pyrolysis is the least desired as it is difficult to find a commercial application for it. The highest yield of liquid product is at the temperature range of 400-600 °C (Basu, P., 2018).

Gas yield is majorly determined by the ER; high availability of air in the reactor results in high the gas production but with lower calorific value. The opposite occurs with a shortage of air in the reactor, as it increases the calorific value but less gas is produced. At a temperature of approximately 650 °C and an ER lying between 0 and 0.2 the calorific value of gas is the highest Dong et al. (2016). The formation of methane and hydrogen is favoured with long residence time in the reactor; as a result, the calorific value increases (Agar et al., 2018).

It can be concluded, from the aforementioned, that the optimum pyrolysis temperature lies between 600 and 650 °C, at heating rate of 2 °C/s and a residence time of 6-10 minutes (Agar et al., 2018). An approximation of the yield percentages, using the organic fraction of USW in such conditions, are obtained through a literature review (see Table 6.1).

	A	**B**	**C**	**D**	**E**
gas yield (%):	60.1	28	26	24	33
liquid yield (%):	11.0	34	37	27	14
char yield (%):	11.9	39	25	18	52

Table 6.1: The parameters for each column are:
A (T=650 °C, municipal solid waste, <20% moisture)
B (T=650 °C, grape bagasse)
C (T=600 °C, switchgrass)
D (T=600 °C, bamboo, 100 °C/min)
E (T=700 °C, organic fines USW, 8.5% moisture)
Where T=temperature. Note: data for A from Dong et al. (2016); B from Encinar et al. (1996); C from Kan et al. (2016); D from Czajczynska et al. (2017); and E from Agar et al. (2018).

The pyrolysis product yield percentages "E", from Table 6.1, are used in the mass balance calculations. This is because it corresponds to organic USW, as in this business case, and the priority is to have a high yield of char with high calorific value. To compute the mass balance, the moisture content of organic portion of USW is 57% Taghipour et al. (2016), and should be reduced to 8.5% in the drying process as stated in column "E".

6.4 Mass balance of the charcoal briquette production facility

The mass balance is computed for two scenarios using the parameters from the previous paragraph (refer to Appendix G). In the first scenario (Scenario 1), only the daily organic waste from the tourism industry and the USW deposit, "Tivoli", is utilised to produce briquettes. This based on the reasoning that it is necessary to start the business case on a pilot-scale. Scenario 1, is also based on the assumption that in a short term, it is feasible to recover a sorted material stock from hotels, restaurants and from the market deposit "Tivoli". The second (Scenario 2) includes all the organic waste from the city; which can be regarded as the goal for the business case. The input of biomass for scenarios 1 and 2 are 26,000 and 140,000 kilograms per day, respectively. The calculated mass balance of "Scenario 1" and "Scenario 2" are given in Figure 6.3 and 6.4, respectively. The approximate production mass of Scenario 1 is 8,065 kilograms per day, while for Scenario 2 that would be 43,420 kilograms.

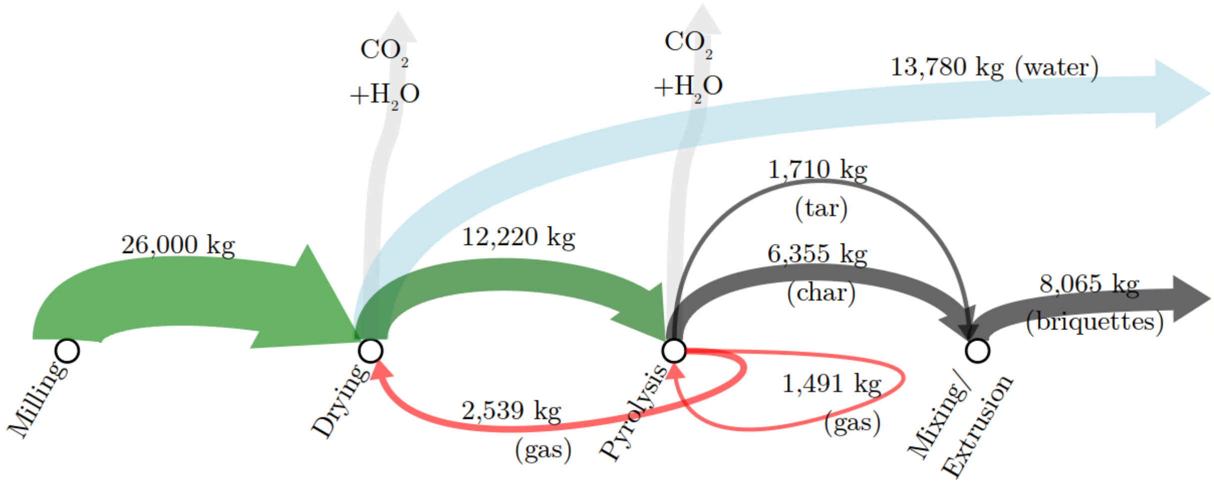


Figure 6.3: Daily mass balance for "Scenario 1" where the charcoal briquettes are produced from the organic waste from restaurants, hotels and "Tivoli".

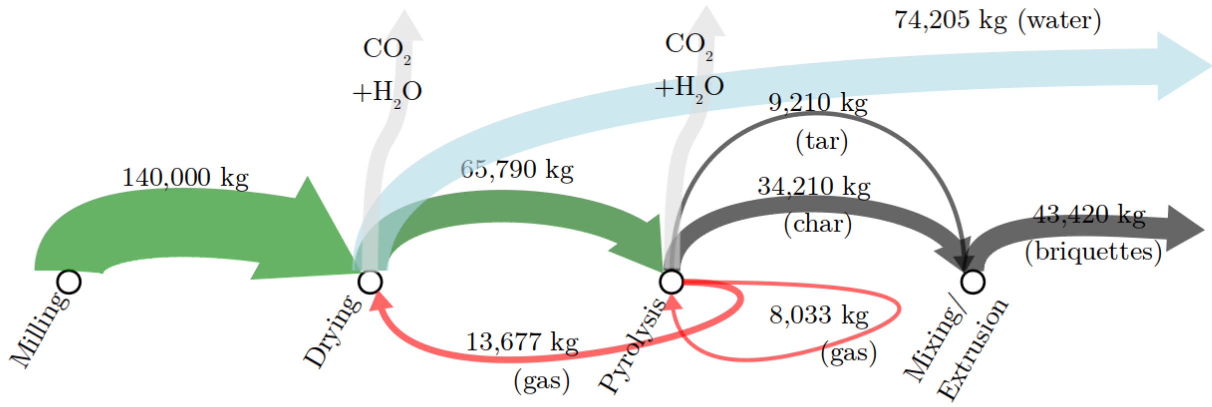


Figure 6.4: Daily mass balance for "Scenario 2" where the charcoal briquettes are produced from the organic waste from the entire city of SCLC.

6.5 Energy balance of the charcoal briquette production process

The energy production and demand, for both scenarios, is given in Table 6.2. The energy embedded in the gas and briquettes is the produced energy. The energy demand is the heat required for the drying and pyrolysis process. That is, heating wet biomass from ambient temperature (20 °C) to just above the boiling temperature of water (101 °C) in order to vaporise moisture; and pyrolysing the dried biomass from 101 °C up to 650 °C. The estimated demand represents a minimum energy requirement because it does not account for energy losses nor heat requirement during residence time in pyrolysis. It is also assumed that the mass is immediately pyrolysed after drying.

There is a energy surplus of roughly 17% in gas for both scenarios, which most likely will be used to cover heat losses and required energy and pyrolysis residence time. In addition, using waste heat from the pyrolysis process in the drying step can significantly reduce the overall energy demand.

	Scenario 1 [MJ/day]	**Scenario 2 [MJ/day]**
Gas	88,050	474,336
Briquettes	185,525	993,400
Heat to 100 °C	-7,476	-40,315
Drying	-36,657	-197,395
Pyrolysis	-29,238	-157,412

Table 6.2: Energy production and demand for "Scenario 1" and "Scenario 2"

The energy production is based on the lower calorific value of 18.2 MJ/m^3 for gas (Agar et al., 2018), 15 MJ/kg for tar (Czajczynska et al., 2017) and 25 MJ/kg for char (Basu, P., 2018). The energy demand is calculated with the composite specific heat of biomass before and after drying (see Appendix G); which is constructed from the specific heat of water (4.2 kJ/(kg K)) and biomass (2.7 kJ/(kg K)) (Faitli et al., 2015).

6.6 Economic balance of the charcoal briquette production facility

The price of one kilogram of char in SCLC ranges between 7 MXN and 10 MXN, while that of firewood ranges between 6.45 MXN and 60 MXN. In order to compete directly with these fuels, the retail price of charcoal briquettes should be also approximately 7 MXN per kilogram. Additionally, the business case should use the existing selling channels for firewood and char so that distribution costs are suppressed and users have equal access to the briquettes. As of 2020 there are 67 registered businesses where charcoal and firewood are sold 6.5.

Figure 6.5: Firewood and charcoal retail businesses in SCLC, indicated as orange points.

The implication would be that the briquettes have to be sold at a lower price to existing retailers so that they also can profit and incentivise their customers to buy the briquettes. Assuming a factory price of 5 MXN the monthly revenue in Scenario 1 would be 1,209,750 MXN;

in Scenario 2 the revenue is 6,513,000 MXN/month.

The initial minimum investment to install a plant with sufficient capacity to treat the feedstock of Scenario 1, amounts 22,157,000 MXN (see Appendix H). It includes one milling machine, a rotary biomass dryer, a fluidised bed reactor, a briquette extrusion machine and four conveyor belts to interconnect the mass flow between the machines. The minimum monthly expenses to operate the plant are 167,500 MXN which account for personnel, building rent, and services. Some of the expenses that are not accounted for are working tools, administration, taxes, distribution and packaging of the final product.

Considering that the minimum income per month, after expenses, is that of Scenario 1, namely 1,042,250 MXN/month, the return on investment is of 19 months (Figure 6.6). If the daily feedstock reaches 70,000 kilograms after 19 months, it will be necessary to invest 413,575 MXN in an extra milling machine, extrusion machine and conveyor belt to increase the factory capacity ("b" in Figure 6.6). With the monthly revenue that corresponds to a feedstock of 70,000 kilograms per day, it would be possible, after 7 months, to invest in an extra pyrolysis reactor and conveyor, which would require an additional 19,536,700 MXN. This is necessary to increase the plant's feedstock capacity to 140,000 kg/day ("c" in Figure 6.6). Thus, the total investment for a briquette factory that can process up to 140,000 kilograms per day amounts at least 42,108,000 MXN, where the minimum time to recover the investment is 26 months.

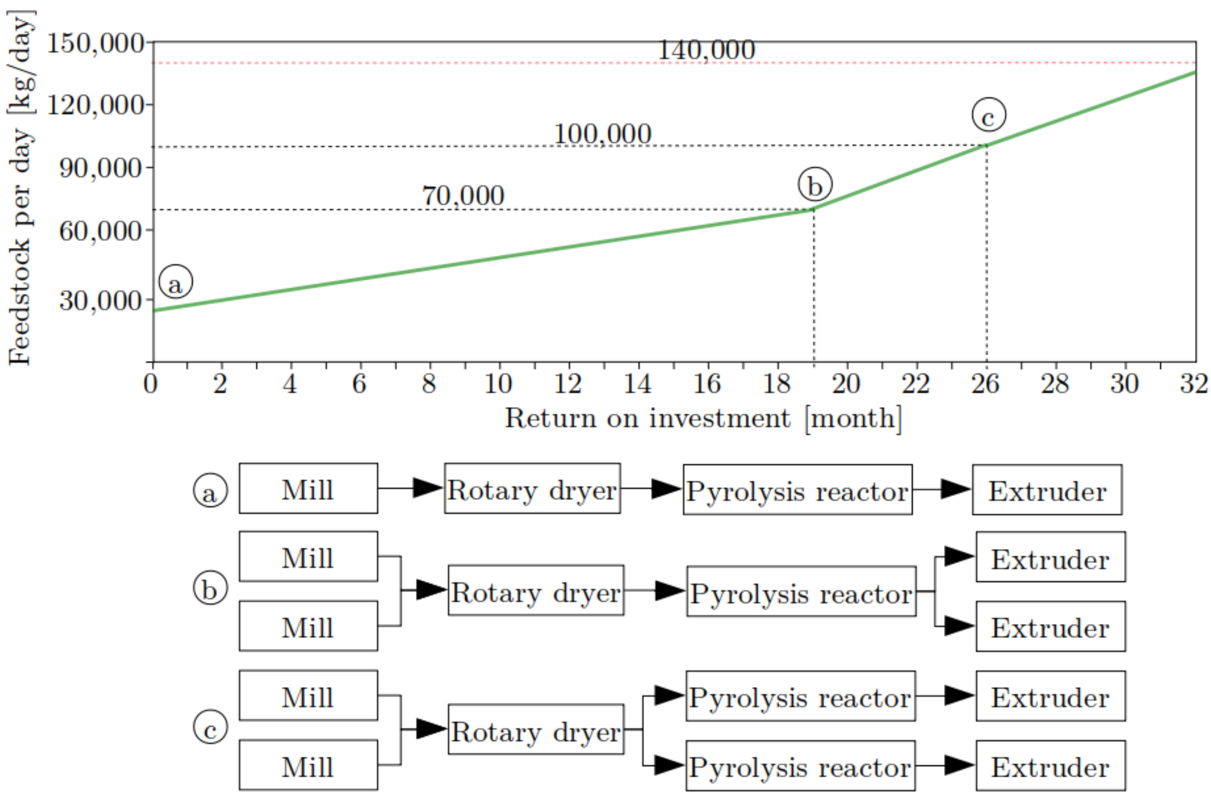


Figure 6.6: Progression of the charcoal factory in terms of capacity and investment. Where "a" is initial investment, "b" second investment to increase the plant capacity, and "c" the third investment so that up to 140,000 kilograms of organic waste can be treated per day.

Ultimately, the return on investment time is dictated by the rate at which the daily feedstock is increased, which goes in hand with the implementation of a USW separation in the city. Additionally, the retail price of the charcoal briquettes, and other expenses, such as taxes, will influence the time to recover the investment.

6.7 Site suitability analysis for the briquette factory

In order to determine a suitable site to install a production facility for charcoal briquettes, it is necessary to, firstly, locate all sites within the city that are not in use, i.e. empty buildings or empty plots of land. These locations are obtained from INEGI's "exterior numbers and locality blocks vectorial information" data base and are filtered by discarding out all vector points that are not described as "empty building" or "empty plot". The resulting potential locations for the business case are rendered on a map along vector layers of relief, hydrology, the current landfill, and road infrastructure (Figure 6.7). The initial number of available spaces in the city is 3,656.

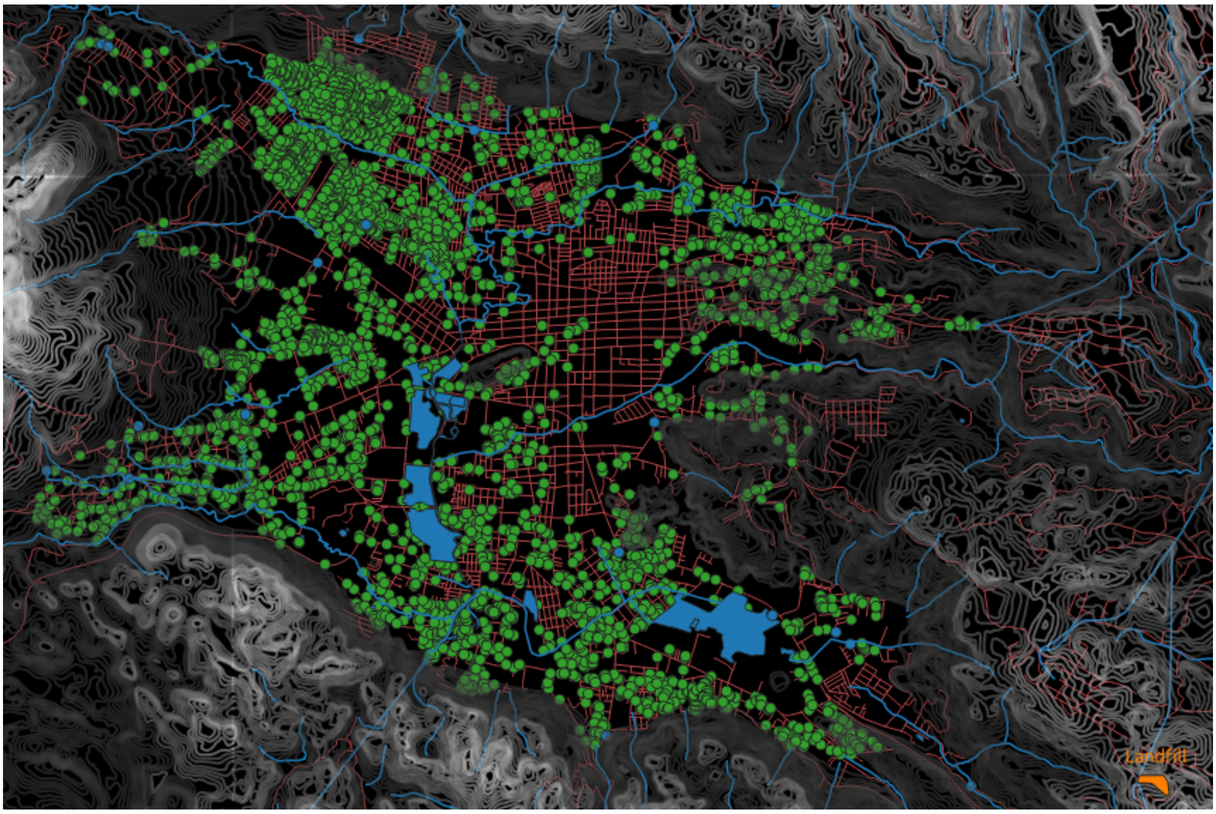


Figure 6.7: Available land in SCLC

The potential sites are narrowed down by defining criteria for the location of the production facility. The first criteria is that the facility should be at least 200 metres away from medical services and from schools (Figure 6.8). The reasoning for this is that organic waste can cause a smell nuisance to the surrounding population, which can result in complaints; vehicles bringing the feedstock towards the facility pose a traffic risk to conglomerated locations; and to avoid exposing a large number people to danger in case of a fire calamity, or similar, at the facility.

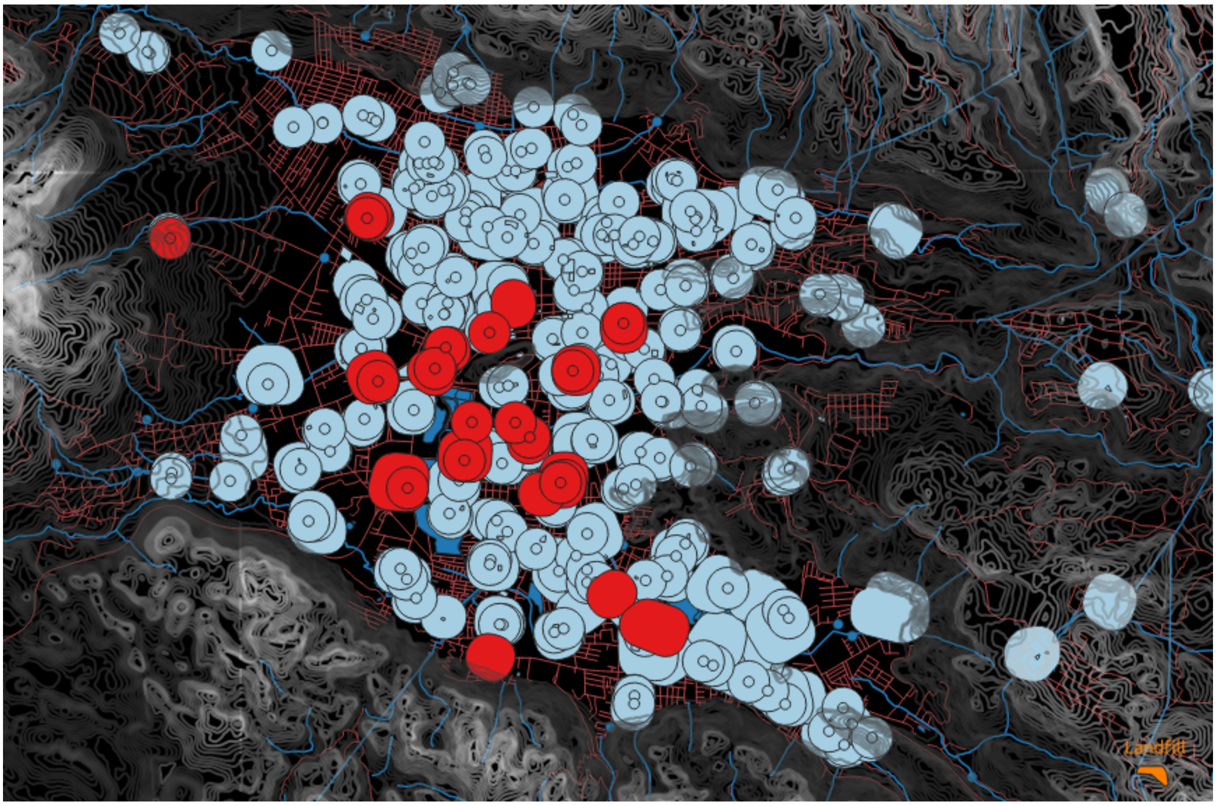


Figure 6.8: 200 metre buffer radius around points of medical services and schools.

The second criteria consists in considering only potential sites that are located in blocks with the lowest household density (Figure 6.9). This part of the analysis was done by rendering the density of household per block in ten categories; only the sites located in blocks of the lowest category where taken into consideration. The justifications for this, as in the previous criteria, are possible smell nuisance, traffic safety and calamity safety.

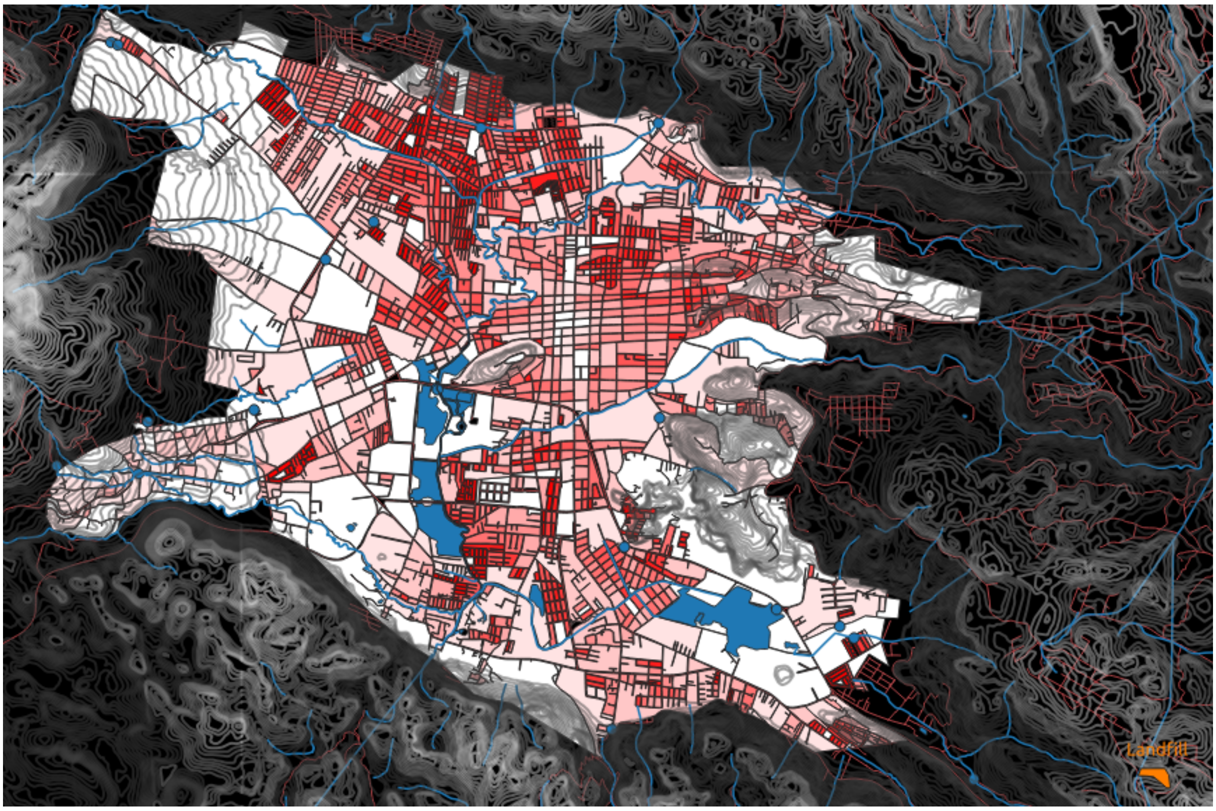


Figure 6.9: Household density per blocks in SCLC; from white to dark red indicates least to most dense.

Another criteria accounted for the accessibility of the briquette factory by the waste collection vehicles, for which the potential sites have to be within a range of 100 metres from avenues, boulevards, ring roads and other main roadways (Figure 6.10). The reasons to why large roadways where considered are that waste collection lorries should be able to enter the facility without manoeuvre in small streets and without hindering traffic.

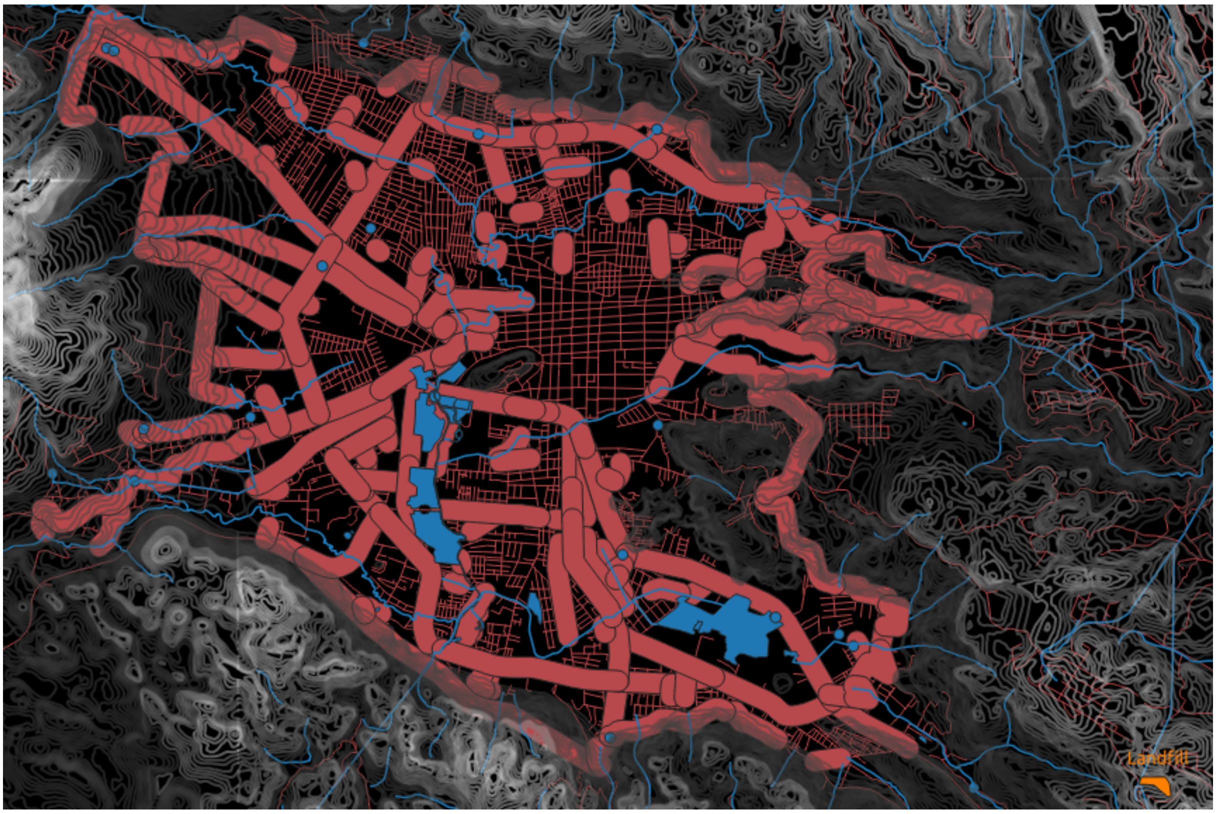


Figure 6.10: 100 metre buffer zone around main roadways.

An important factor is that the business case should be within the city's boundaries, to reduce transportation distance; and at an altitude range of 2000-2140 metres above sea level —the altitude of SCLC —to avoid uphill traffic of loaded waste vehicles; this should limit the energy spent to transport the waste streams. And lastly, the potential sites should be outside of flood-prone regions, given that it could jeopardise the operation of the factory.

The blocks with lowest household density are also categorised by the density of suitable sites that they contain. This, ultimately, demonstrated the regions of the city where it is most likely to find a plot of land or building that complies with the site suitability criteria (6.11).

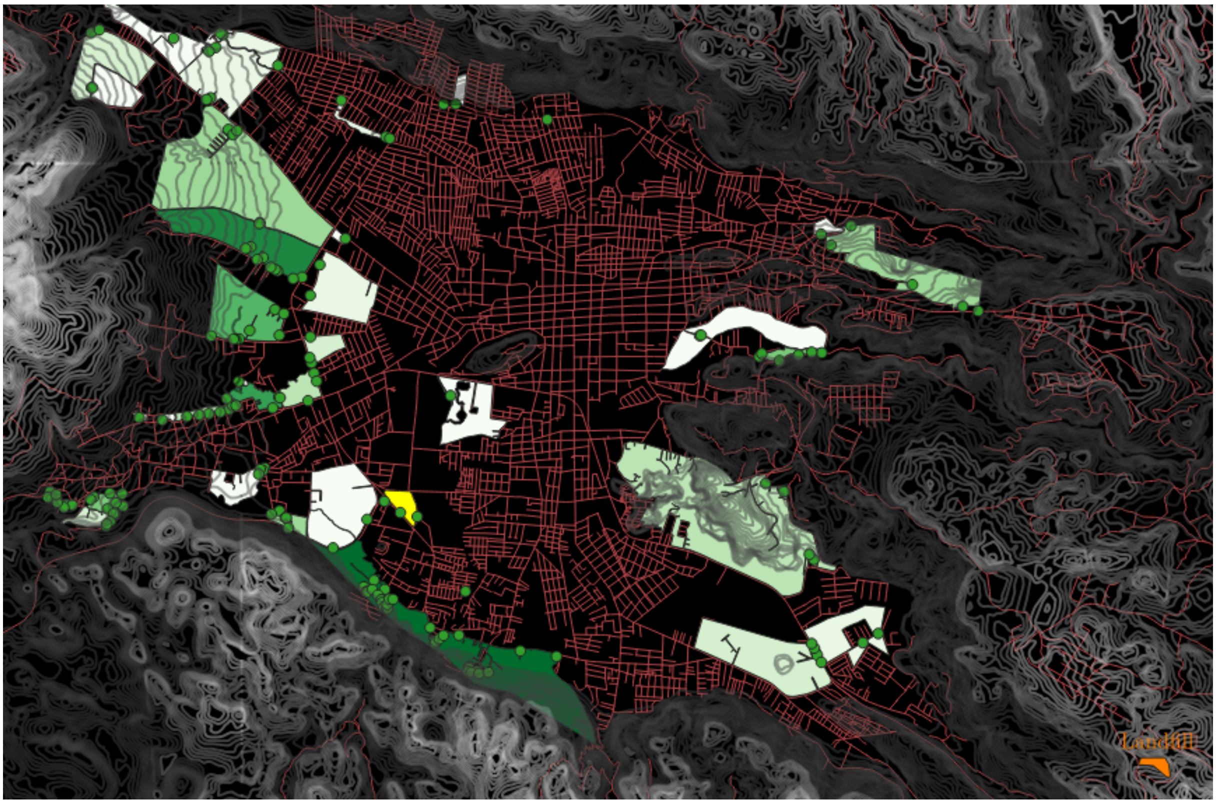


Figure 6.11: Suitable blocks (green areas) and sites (green dots) according to the selection criteria; where white are the blocks with least number of suitable sites and dark green blocks with most suitable sites. Highlighted in yellow, one of the most suitable sites for the charcoal briquette factory.

Figure 6.12: Layout of the highlighted block.

Based on observations from the field study and knowledge of the city, one location can be considered as the most suitable from the final selection selection of blocks (Figure 6.11). It is located near one the main exists of the city towards the capital of the state, has good accessibility from all directions, a low number of households in the vicinity and large lots within the block that could be acquired in cooperation with the municipality (Figure 6.12).

6.8 The impact of the business case

The briquette idea can have an economical, environmental and social impact in the city, which can be quantified. The environmental benefits can be estimated, firstly, by the avoided illegal firewood and char that would be replaced by the charcoal briquettes and its equivalent in saved trees. Secondly, the CO2 emissions that would be avoided if the organic UWS of SCLC is transported to the briquette factory within the city instead of to the landfill. Lastly, the saved volume at the landfill of all the organic waste that would not longer be landfilled.

The impact that briquettes can have on the demand of biomass and energy in SCLC, in "Scenario 2", would be approximately of 27% and 33%, respectively. This is represented as areas in Figure 6.13. The figure compares the magnitude of the biomass and energy demand in SCLC with what can be supplied by the business case in both scenarios.

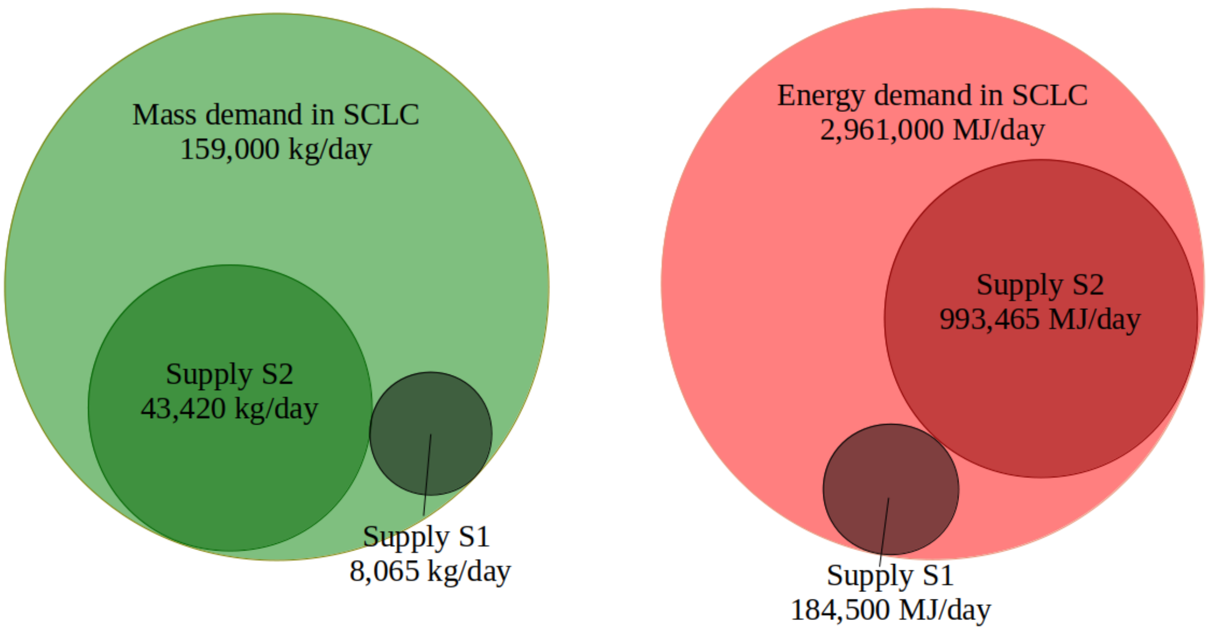


Figure 6.13: Mass and energy comparison of demand versus supply expressed in areas.

The mass of firewood that can be replaced by the supply of charcoal briquettes in Scenario 2 is equivalent to saving 99,800 young trees, or 17,609 mature trees, on a yearly basis. For scenario Scenario 1 that would be 18,537 young trees per year, or 3,270 mature trees per year. This equivalence is an approximation based on the number of trees per metric ton of firewood from Holz and Ramírez-Marcial (2011) and where the age of young trees is 7 years and mature trees 11 years.

In the site suitability analysis it was established that, in order to limit transportation costs, the briquette factory should be placed within SCLC. The mass treated at the briquette factory would avoid the transportation of USW to the landfill, which lies 4.5 kilometres out of the city boundaries (Figure 6.14). This would result in a reduction of trips, by the municipal USW collection vehicles, to the landfill. Three lorry trips would be avoided in Scenario 1, which is the equivalent of 33 kilograms of CO_2 per day. For Scenario 2, 16 trips would be avoided which is a

CO_2 reduction of 176 kilograms per day. For both cases the CO_2 equivalents are obtained from a emission calculator for lorry freight (Sustainable Freight, 2020); the considered capacity of a lorry is of 8,900 kilograms (refer to Appendix A) and the minimum avoided distance per trip is 4.5 kilometres.

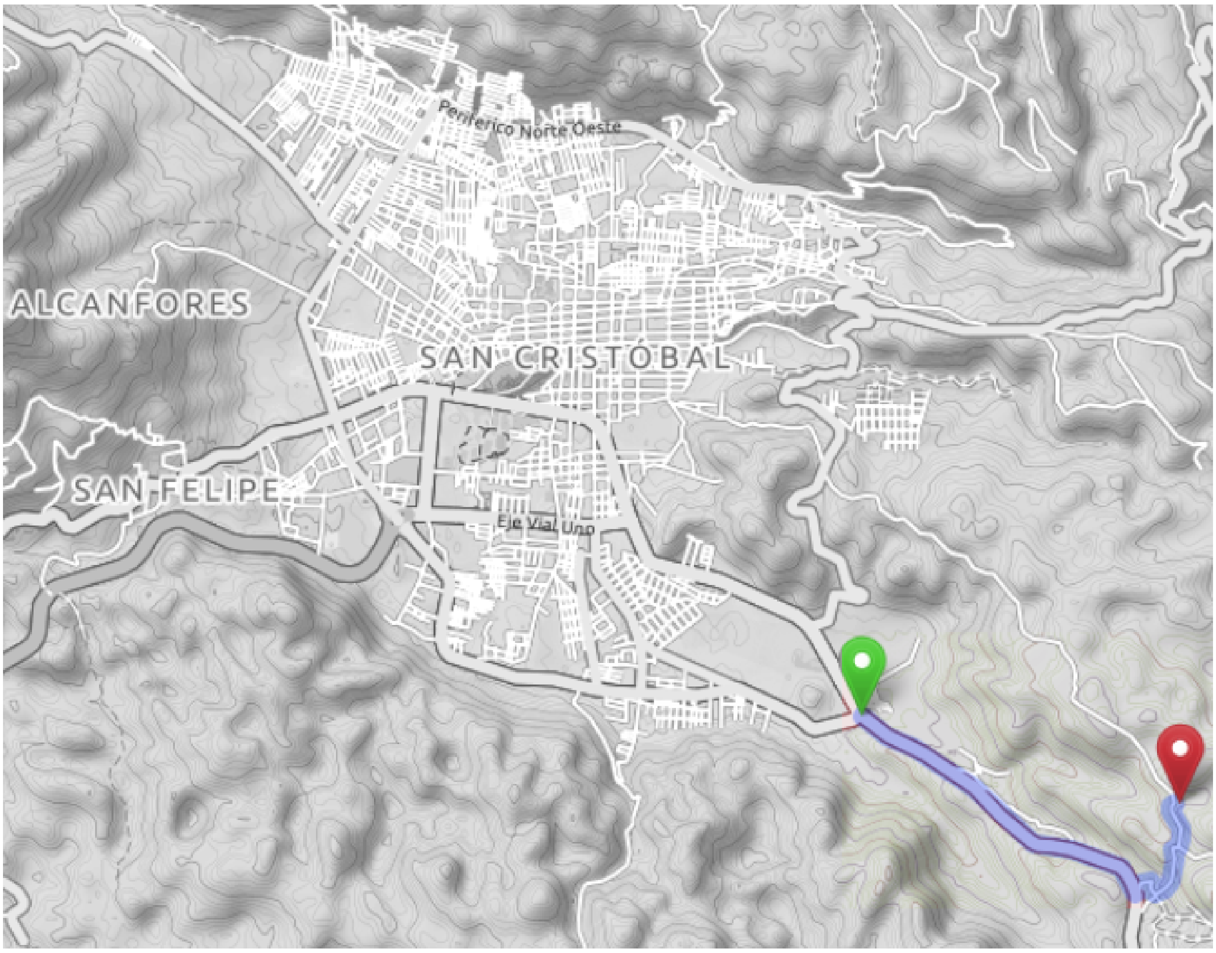


Figure 6.14: Minimum avoided distance to transport USW from the city boundaries.

The daily carbon dioxide emissions caused by the consumption of 159,000 kilograms of firewood in SCLC, under ideal combustion, amounts approximately 293,200 kilograms (refer to Appendix I); while the generation of methane (CH_4) from the landfill is equivalent to 48,000 kilograms of CO_2 (Figure 6.15). The generation of methane at the landfill is caused mainly by the decomposition of organic USW (Ishii & Furuichi, 2013). The implementation of the business case would increase the net CO_2 emissions by approximately 100,000 kilograms per day. This can be attributed to the combustion of the charcoal briquettes. In the post-implementation scenario, the generation of methane emissions from the landfill would decrease almost entirely, however the emissions to produce the briquettes would be approximately equivalent to that of what would be avoided at the landfill (Figure 6.16).

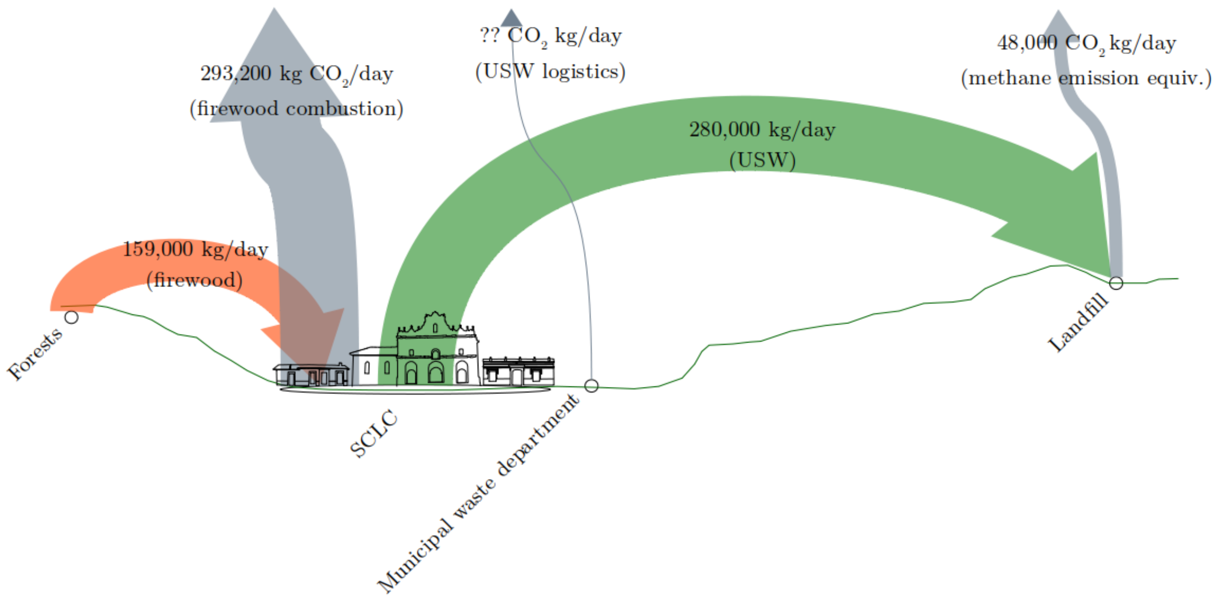


Figure 6.15: Carbon dioxide fluxes before the implementation of the business case.

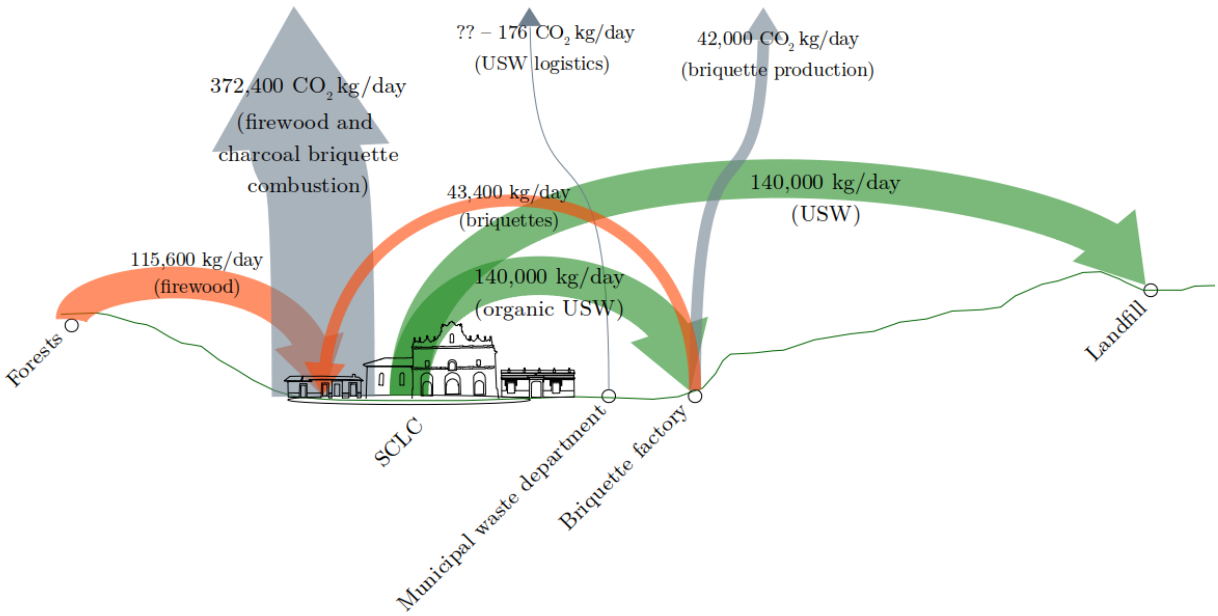


Figure 6.16: Carbon dioxide fluxes after the implementation of the business case.

Furthermore, the use of 26,000 kilograms of organic waste for Scenario 1 would lead to a reduction in landfilled mass of 17,623 m^3 on yearly basis; while in Scenario 2 that would result in 94,893 m^3 per year. This estimation is based on an average landfill density of 538.5 kg/m^3 (Faitli et al., 2015).

The economic benefits of the business would manifest on the reduction of operation costs of the municipality's waste collection fleet and the profit from the briquettes which is distributed on the enterprise, the employers of the factory, the retailers of the product.

From an economic point of view, the reduced number of trips by the municipal USW collection fleet would also save up at least 82,000 MXN and 440,000 MXN per year on fuel costs only, for Scenario 1 and Scenario 2 respectively. This is based on 18.85 MXN as the diesel price per litre. Additionally, with a retail price of 7 MXN per kilogram and a factory price of 5 MXN the monthly revenue in Scenario 1 would be 1,693,650 MXN from which, 483,900 MXN would be distributed among the retailers of the business case and 124,000 MXN to the staff (Figure 6.17).

Figure 6.17: Distribution of the economic value of the business case in Scenario 1.

Finally, the social on impact of the business idea can be measured by the minimum number of new direct jobs that would be generated: 19 in Scenario 1 and 33 in Scenario 2. This business case would not jeopardise the jobs in the municipal waste department nor in the retail of firewood and charcoal. The salary for factory workers considered in the economic balance is 4000 MXN, which is 1.3 larger than the minimum salary (Secretaría del Trabajo y Previsión Social, 2020). If the hired staff would be from the social sector where the monthly income per household is 1,442 the socio-economic impact would be even-more significant.

Chapter 7

Discussion

7.1 Findings of the mass and composition of USW in SCLC

Total mass of USW generated in SCLC was estimated to be 282,000 kg/day, which coincides with the estimation of the municipality of 280,000 kg/day. However, the innovative aspect of this research is that the sources that generate this amount of waste have been mapped. This was done by the combination of literature about waste generation rates per capita in Mexico, the collection schedule of the municipality and a small scale survey about waste composition in restaurants and hotels. It was found that approximately 50% of the USW in SCLC is generated by inhabitants in their households, 15% is deposited at the USW storage "Tivoli", around 35% is generated by the local economy, and 3% of the total waste can be directly attributed to tourists visiting the city.

With the aforementioned results, composition data and waste prices, the magnitude of each type of waste and their economic value have been estimated. This ultimately served to develop solutions for each type of waste. Though, the accuracy of USW quantities per waste type is limited due to missing fragments of information, such as the waste composition of businesses, services and institutions.

The share of organic waste from Tivoli is assumed to be 50% in this research, given that the real composition from that source is also unknown. Nevertheless, its organic fraction is probably higher given that it is the USW storage of the largest market in SCLC where perishable products, such as food and vegetal ornaments are discarded. This has implications on the mass balance of the biochar briquette business case (in Chapter 6). Other markets also have an USW deposit with an important amount of organic waste; this can be deduced from the city blocks with highest food-service-related businesses density which coincide with the location of markets (Figure 7.1). The amount of mass collected at these points cannot be estimated, as with Tivoli, from the collection routes of the municipal waste department; instead it must determined by a survey.

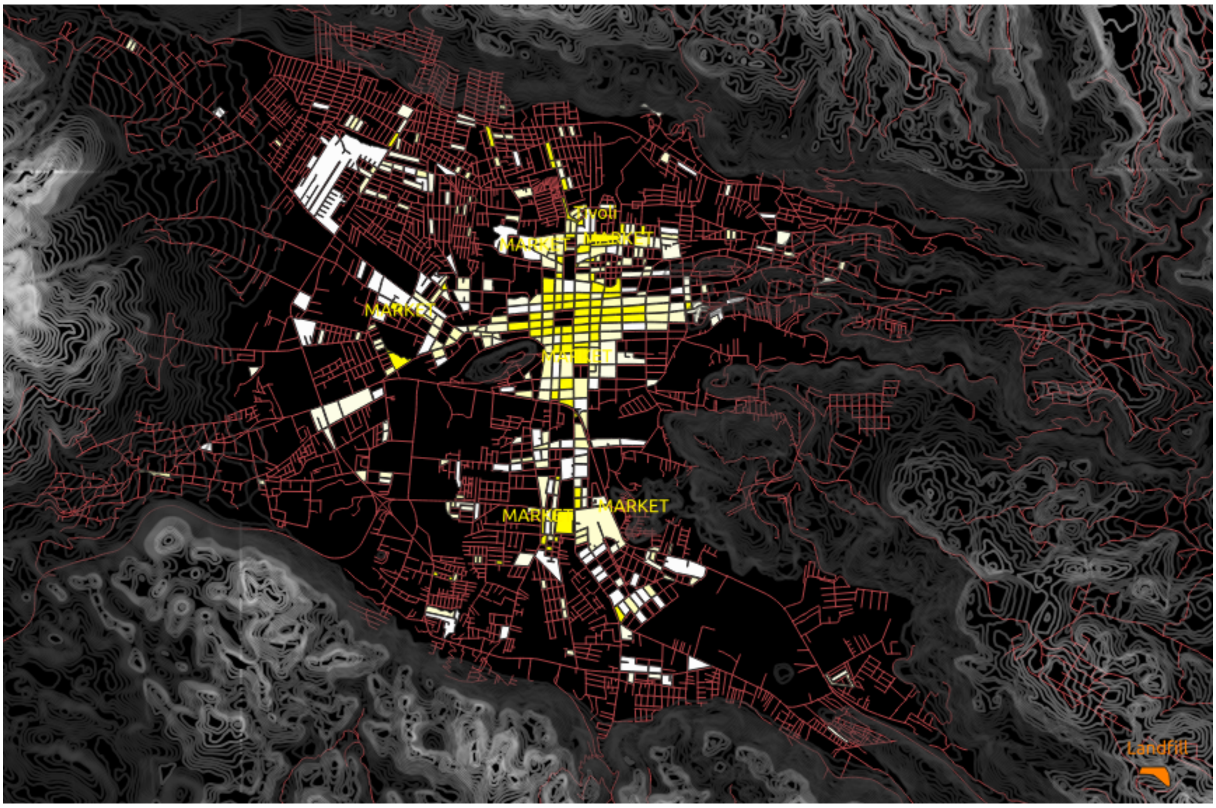


Figure 7.1: Density of hotels and food-related establishments per block; where from white to dark yellow indicates lower to higher density. Some blocks of high density coincide with the location of markets.

Based on a literature review, the household USW generation rate per capita in SCLC for 2020 is estimated to be 0.6 kg/day; this contradicts the generation rate of 1.035 kg/day per capita that was published by the municipality. This is a relevant finding because the rate of 1.035 kg day^{-1} $capita^{-1}$ would suggest that approximately 75% of the USW comes from households, 15% from Tivoli and the remaining 10% from all businesses and services in the city .

The household USW generation rate per capita found in this study indicates that the share of non-domestic USW, from Tivoli and local economy, out of the total is of 50%. The composition of this fraction has not been studied, but its magnitude highlights the need to investigate it. Such information would allow to approximate the mass of each type of waste and their potential economic value in a more precise manner.

A sample study was carried out in this research to determine the composition —organic and non-organic —and mass of USW generated in hotels and restaurants and which is attributed to tourists. With the collected data it was determined that its USW footprint is of approximately 6.9 ± 2.9 kilograms per day; which is insignificant in comparison to the total USW.

The sample study of hotels and restaurants was limited to 12 businesses out of 200 hotels and 1436 food-preparation services that are registered in DENUE. This means that the sample size of the survey is not sufficiently large to obtain statistically representative results. Nonetheless, its relevance lies in that it is the first study of this kind in SCLC and that it is not a broadly studied phenomenon in general. Additionally, this sample study provides an insight of the magnitude of the USW generated by tourism and its organic fraction.

The survey also demonstrated that the amount of waste per business varies greatly. This observation can be explained by the influential factors such as the capacity of the company, the day of the week, the price category of the business, the type of product that they offer, whether the hotels included a food services or not, and the business had a garden. The latter has an influence, particularly, on the amount of organic waste.

The business case is based on the assumption that the organic fraction is sorted before collection. This has significant practical implications because the concept of separation is foreign to a large portion of the population. This was particularly observed during the sampling study; where the sorted USW included items that did not correspond to their type type. This was more often the case in businesses where the personnel was not accustomed to separation scheme prior to the sample study. Thus, there is a need to execute a large education programme in the city to familiarise the general public about USW separation.

Some of the enterprises, that partook in the survey, agreed to sort their waste in no more than two categories due to the lack of space to place bins for other waste types. This is a practical limitation that must be considered when carrying out a similar waste survey or when implementing a USW separation system in the city.

Finally, the USW sample study from restaurants and hotels is relevant for the study of USW because it demonstrates practical details that have to be considered in the methodology.

7.2 What waste treatment technologies are adequate for SCLC?

Four aspects that play a significant role in the selection of a waste management can be identified from the review of waste treatment processes in Chapter 3. These are: scaleability of the technology, requirements of the input material, marketability of the final product and access to the technology and expertise.

Firstly, the scale at which the technology can operate is limited, for instance, by the speed at which the waste type is processed or the marketability of the product. If both of these conditions are not met then the feedstock or produce can accumulate at the waste treatment facility.

The quality requirements of some treatment processes have practical limitations on how waste streams have to be sorted before and after collection. For example, sorting paper and cardboard at household level according to the requirements of a paper pulp recycling facility would require an intensive effort to educate the population; and still the feedstock would have to be inspected and cleared of undesired items. In many cases, the extend to which people can sort their waste is limited by odour nuisance, lack of space and awareness; which has to be counterbalanced by sorting waste after collection and prior to the treatment process.

The access to the waste treatment technology has a direct impact on the investment and operation costs. This goes in relation with the specific knowledge of complex chemical, thermal and mechanical phenomena that is required to operate the processes; and, the distance from which the machinery has to be brought in. Additionally, it is important that the technology is mature and can match the magnitude of the waste streams; otherwise time and capital have to be spent in research and development.

Some waste streams, such as E-waste and metals, might not be sufficiently large to invest in the technology to treat it in SCLC. This is more apparent for cases where the technology is complex, expensive or more energy-efficient for large quantities. Instead, it might be more sensible to set up a network to recover the material and sell it to companies that can effectively treat the waste. Alternatively, if the profit from the waste stream is not sufficient cover the logistic expenses to transport the material to an existing facility, as is often the case with glass, then it is more sensible to find an alternative local solution for the waste type. In such cases, it can be also reasonable to lay out a logistic network to collect the waste stream from the city and neighbouring regions, and invest in a facility within the city.

Plastic, the second largest waste category by mass in SCLC, is partially sorted by informal waste collectors, who recover PET bottles to sell them. Regardless of the amount PET that is recovered, most of other types of polymers remain unsorted and are landfilled. Adequate techniques to recycle these polymers are mechanical or thermo-chemical. For that it is indispensable to investigate the composition of the plastic waste stream, and consider the large quantity of contaminated thermoplastic bags that are disposed. Should the majority of the landfilled polymers be thermoplastics, then it is more sensible to install a mechanical recycling facility. In such case it is important to consider that the final product must contain as much material per unit as possible and a market demand for the product, so that most of the plastic waste is recycled. On the other hand, if thermoset polymers are the most abundant it would be more sensible to consider a thermo-chemical treatment facility to produce fuels or chemicals.

Finally, the reviewed waste treatment techniques are the most conventional. Some of these are more likely to be implemented in SCLC than other, depending on the waste type. For instance, metals are already recovered by informal waste collectors; and, although the exact mass flow in these collection networks is unknown, it might be more convenient to further develop this sector. Paper can be included in the business case for pyrolysis without the need to sort it; as long as paper is sorted prior to collection it is, in theory, dry mass which can be pyrolysed directly without drying process. Glass is a waste stream that is low in cost per weight; thus, treating this waste type within the city is plausible.

7.3 Reflection on the results of the organic waste circular business case

Organic USW is the largest waste stream in SCLC, and yet, it is currently not being exploited, and thus, its value is explored in this research. It was found in Chapter 4 that pyrolysis is one of the most suitable processes to treat organic waste. The goal of the business case, in Chapter 6 is to convert organic waste, through a pyrolysis process, into charcoal briquettes. This is a fuel product that should replace firewood and char from illicit origin for cooking purposes in the impoverished population of SCLC and surroundings.

For this business case it is estimated that charcoal briquettes, using all the organic USW of the city, can replace 27% of the firewood and char demand in SCLC, or 33% of the energy demand of biomass. Nevertheless, this is based on a "worst case" scenario; that is, considering the highest consumption of firewood per capita and assuming that the consumed biomass has the lowest calorific value. The lowest heating value corresponds to the species *pinus ayacahuite*. These assumptions would imply that more wood has to be used for cooking in comparison to when firewood of high heating value is used. In addition, the data on number of households and their cooking fuel types dates from 2015, and it is possible that the demand of firewood and char has reduced from that year. The energy and mass supply where also considered in a "worst case" scenario; namely, the lower heating value of pyrolysis char was taken for the calculation, and the organic fraction from Tivoli might in fact be larger than 50%. Thus, the impact of the business case can actually be even higher than what was estimated.

The energy balance that was calculated for this business case provides an insight of the minimum energy demand at a conceptual level; however it does not account for heat losses, nor the energy requirement during pyrolysis residence time. Nonetheless, the results show that there is approximately a 17% surplus of gas, which will most likely be used in the production process to cover the unaccounted energy requirements. The energy balance was based on the lower heating value of the gas —18.2 MJ/kg —which, in a optimised pyrolysis process, can be higher. It was also considered in this balance that the dried material enters the pyrolysis reactor immediately after the drying process, at a temperature of 101 °. This means that the production process is more energy efficient if it is continuous, as proposed in this research. Additionally, the waste heat from the pyrolysis process can be incorporated in the drying process to reduce the overall energy demand.

The area of the suitable sites was not included in the site suitability analysis for a production facility. Regardless, the relevance of site suitability results lie in the found regions of the city, where the population is the lowest and where availability of land is the highest. Furthermore, the database of the available land is not actualised, which means that the unused plots of land, in the analysis, might currently have a use. However this accentuates the validity and relevance suitable blocks, rather than specific plots.

The main objective of the diagrams of carbon dioxide emissions (Figures 6.15 and 6.16) are to indicate how they change before and after the implementation of a charcoal briquette factory that would utilise all the organic USW of the city. In reality the magnitude of these fluxes is much more complex and differ in magnitude from what is displayed. That is because the carbon emissions from the logistics of the USW collection fleet and the methane emissions from the landfill are unknown. The CO2 emissions of the landfill in Figure 6.15 are based on a conversion ratio of 30 units of carbon dioxide for every unit of methane and a generation rate that was listed by Sauri Riancho et al. (2013), namely 54 gr m^{-2} d^{-1}. However, the rate of methane emissions of a landfill is specific to its location and fluctuates through time as moisture, ambient temperature and other factors change (Ishii & Furuichi, 2013). In fact, methane emission rates can be significantly larger according to the results of (Sauri Riancho et al., 2013). Furthermore, the methane emissions would not cease immediately after organic USW is no longer landfilled; actually the organic waste that has been landfilled already still has to decompose. The estimated emissions caused by the consumption of firewood is based on the composition of pine tree wood; this is to maintain consistency with the energy demand calculation of firewood in SCLC, which is based on the calorific value of *pinus ayacahuite*. Lastly, the CO_2 emission estimations from the pyrolysis gas product, firewood and charcoal briquettes are under the assumption of ideal combustion; i.e. the all the material is burned with sufficient oxygen and, thus, no production of carbon monoxide or other compounds occurs. Considering the aforementioned, it is possible that the current net emissions of carbon dioxide remain approximately the same after the implementation of the business case, unless the production emissions are captured at the factory for instance.

This business case idea complies with two concepts that are defined in Section 1.1: circular economy and waste hierarchy, more specifically the "biomass pyramid". The business idea retains the material, in this case organic USW, for a longer cycle in the local economy while actually upgrading its value in comparison to its current value in SCLC. The life cycle in which the material is reincorporated is different, namely in the sector of energy, where it actually has an impact on the extraction of firewood from the surrounding forests. In other words, a reduction in the extraction of new resources. The circular idea takes place at a meso-level as it requires a interaction, or symbiosis, between different organisations. Furthermore, a thermo-chemical process is employed to valorise the waste stream instead of resorting to landfilling or energy recovery from combustion, which are the least desired methods of the "waste hierarchy". As in the biomass pyramid (Figure 1.1, the value of the product, the charcoal briquettes, is low but in large quantities its total value is significant.

In summary, the main benefits of the business case are a 30% decrease in demand of firewood from the surrounding forests, a reduction of costs for the municipality to manage the USW in SCLC, no damage to the existing jobs related to retail of firewood, an equal price for firewood users to use the charcoal briquettes and a decrease of up to 50% of landfilled USW. The latter would significantly decrease methane emissions and nutrient leachates to the surroundings.

7.4 Reflection of future considerations of the organic waste circular business

There are multiple aspects have to be considered for the implementation of the business model. Nonetheless, the most relevant are the financing plan for the investment of the production facility, the economic perspective of the logistic network to retrieve the organic USW, the challenges that can limit the introduction of charcoal briquettes into the local market, among other technical details.

Financial support from municipal, state of federal government for the operation or investment of the production facility can be discontinued when a new governmental administration takes place; therefore considering private investment for the business case is important. The economic balance suggests that the return on investment can be relatively short which can be the incentive to attract private investors.

The strongest incentive to establish a logistic network to recover the organic USW in SCLC is its economic value. Firstly, the municipal waste department can reduce the expenses of its logistic operations by transporting the organic waste to the briquette factory. In exchange the business case would, ideally, receive the organic USW without costs. In fact, the business case can be compensated economically by the municipality, as a service to take the responsibility of the municipality to treat all the organic USW, which is approximately 50% of the total. In that scenario the municipality could negotiate a monetary compensation with the owners of the land, where the landfill is located, for every vehicle that disposes USW instead of the current monthly fixed fee of 300,000 MXN.

Moreover, the feedstock of the factory can be increased by including paper waste streams. If separation can be effectively implemented in such a way that paper is sorted prior to collection, without contaminants or moisture, this material flow could be pyrolysed without a drying process. This would mostly increase the yield of gas (Czajczynska et al., 2017) without an increase in energy demand from the drying process.

A limitation for the introduction of charcoal briquettes into the local market is that a fraction of the current firewood users fell trees for own consumption, due to their limited economic capacity to purchase fuels. Meaning that this sector is one of the most difficult to reach with the product. A strategy that may change this, although with limited effect, would be to offer employment opportunities to this group in the production facility, in the logistic network to obtain the feedstock, or in the distribution network of the final product.

The technical aspects that have to investigated are the product yields, specifically for the parameters that where established for this study case, namely temperatures, ER, feedstock material, et cetera. This would increase the accuracy of the mass and energy balances and consequently the economic balance. For this it is necessary to do experimental research or construct a numerical model capable of computing the pyrolysis process for different operation parameters.

There are two main concerns from a product quality perspective; namely, the ratio of binder to char of the briquettes and the possible presence of metals in the briquettes. Firstly, the binding material of the charcoal briquettes, in this study case, is the tar that is obtained from the pyrolysis process. The char-to-tar ratio from the computed mass balance is approximately 4:1. This ratio might have to adjusted to ensure that the briquettes can be handled without easily breaking them. If the percentage of binding material is not sufficient to produce briquettes of acceptable quality, either the parameters of the pyrolysis process have to be adjusted or a complementary binding material has to used. Paper pulp, for example, is a suitable binder for the production of charcoal briquettes (Olugbade et al., 2019). Alternatively, the plastic bags wherein the population dispose their USW could be included in the feedstock, as co-pyrolysis of polymers and biomass increase the yield of tar and decrease the yield of char (Chattopadhyay, Kim, Kim, & Pak, 2008; Fan, Gu, Hu, Yuan, & Chen, 2019). Secondly, alkali metals, such as sodium, potassium and calcium, have been found in the char product from pyrolysis biomass and become volatile at high temperature (Dawei, Zhimin, Shuting, & Hongxing, 2006; Fan et al., 2019). Traces of alkali metals in the char increase when polymers, such as PE, are added to the feedstock (Fan et al., 2019). The presence of heavy metals, such as zinc, lead, chromium and copper, increase when PVC is added to the input material (Yu et al., 2016). These can be inhaled by during the combustion of the product, thus evaluating this risk is necessary to increase the feasibility of this idea.

The mass of water that is removed during the drying process to reduce the moisture content of the feedstock to 8.5% is significant; in fact in accounts for approximately 47% of the incoming mass. Exploring the possible uses for that "waste" stream can be one of the key activities in latter stages of the business case.

One of the strengths of the pyrolysis technologies is that, although the investments costs are high, it can be expanded or adapted if the business case is not economically viable. This can be by orienting the char product from the pyrolysis to other applications, such as soil and water remediation, or soil enhancement for agriculture purposes. Also, the pyrolysis parameters can be adapted to obtain different product yields or using other types of feedstock. For example fuels from plastics, activated char or biomass pyrolysed at higher temperatures for water treatment.

The business case, as developed in this research has the potential to save trees, create monetary value which can be canalised to economically vulnerable people, significantly reduce the mass of landfilled USW and reduce greenhouse gas emissions attributed transportation and landfilling. With charcoal briquettes produced from organic waste as a source of energy, it can be demonstrated that value can be recovered from USW, and also it can be done with a circular business case that actually tackles a local problem.

7.5 Conclusive reflection of the research results

The strategy to achieve a management system, where the economic value of the USW in SCLC is exploited locally, can be developed for the local socio-economic context through different pathways. One possible way is to modify the current curbside USW collection scheme to one where the informal USW collectors gather drinking packages, clean plastic, paper, cardboard and metal waste from the entire city. However, with the same frequency and routing as the municipality USW collection fleet. If the waste collection is sufficiently frequent then the lack of space at household level for all the categories of waste should no longer be an issue.

Simultaneously, the municipal waste fleet narrows its operation to collect organic waste, and remaining waste, excluding E-waste, separately on different days. The organic waste would be transported to the charcoal briquette factory, while the remaining waste would still be landfilled until a circular solution can be implemented to recover waste from it.

Furthermore, for glass and E-waste supervised central collection points should be installed; this would ensure that the disposal of waste is done in accordance to the categories and to prevent robbery or vandalisation of the collected waste.

With these measures the municipality would reduce the freight requirement of USW by approximately 36%. The informal collectors would benefit from a higher income due to a higher mass of materials which would be already sorted and less contaminated. The remaining concern would be to find circular solutions for the textile, ceramic and sanitary waste.

Chapter 8

Conclusions: Potential circular solutions for UWS in SCLC

Each of the waste types, that have been identified for SCLC, require a different treatment technique to exploit their value. This depends on the combination of quantity, price per weight, treatment costs and available market for the final product. Seven waste categories have been identified in this research, namely organic, plastics, toxic waste, paper, glass, metals and "other". To cease the practice of landfilling in SCLC it is necessary to develop a comprehensive infrastructure to treat 280,000 kilograms of USW on a daily basis that includes a separation scheme, a logistic network and waste treatment technologies.

Organic waste is the largest waste category in the city. It accounts for approximately half of the total USW; i.e. 140,000 kilograms per day. Pyrolysis is a thermo-chemical technique that can be employed to treat this waste stream given that it is capable of treating large amounts of mass on a daily basis and generates char, tar and gas from it.

Polymers, or plastics, account for 21% of the domestic USW in the city, which is least 30,000 kilograms per day. Secondary mechanical and thermo-chemical processes are waste treatment technologies that are suitable to treat plastic waste in SCLC. The latter require a large investment to install a recycling plant; yet, it can turn thermoset and thermoplastic polymers into liquid and gases for chemical or energy applications. Mechanical treatment can only recycle thermoplastics from which a wide range of product can be manufactured.

Toxic waste is the third largest waste category in SCLC —11,200 kilograms per day, or 8% of household USW—but also, arguably, the most hazardous. Toxic waste includes E-waste, sanitary waste and, possibly, hospital waste. E-waste is composed mostly of printed circuit boards, light bulbs, screens, batteries, cables and casings. Most of these components require complex treatments technologies due to the range and toxicity of elements that are contained therein. The share of E-waste is presumably little; therefore, the most viable solution is to establish a collection and sorting scheme to, finally, sell E-waste to existing treatment facilities. For the remaining fraction of toxic waste there are limited options to recover value other than heat and power.

With at least 11,000 kilograms per day, paper waste represents around 8% of domestic USW. The conventional recycling method is to convert the paper into pulp and turn it into new paper or cardboard. However, it also can be employed as feedstock for pyrolysis to produce gas and char.

The magnitude of the waste category "other" in the city is 9,900 kilograms per day, which is 7% of the domestic USW. This mass flux contains ceramics, textiles and fine dust. While ceramics and dust can be used as construction aggregate, textiles can be recycled to produce new fibres.

Approximately 6,900 kilograms of glass waste are generated from households on a daily basis in SCLC. Glass is the waste type with lowest price per weight, rendering it economically unsustainable for collection and shipping to a recycling plant in other cities. Additionally, melting glass and moulding it into new products requires a high investment of energy and capital. Considering these two conditions it seems unreasonable to install a glass recycling facility in SCLC unless there is a sufficiently large demand of glass products in the region. Hence, this particular waste stream requires an exploration for other innovative local solutions that may be more economically and environmentally sound.

Metal waste is currently recovered informal waste collectors and sold to intermediaries; the latter sell the recovered material in bulk to recycling plants elsewhere in the country. It accounts for 2.4% of domestic USW, one of the smallest waste streams; but one of the most profitable in price per weight. Therefore, formalising the current recovery network to recover the entire metal waste stream might be a more reasonable strategy, in terms of monetary and energy investment, than implementing a foundry to treat it locally.

The main sources of USW in SCLC that have been identified are households, local businesses, tourists and the main market; where their share on the total USW is roughly 50%, 32%, 3% and 15% respectively. While the composition domestic waste has been studied (Figure 8.1), that of local businesses and markets is still unknown. This research included a field study on the composition and generation of USW caused by tourism, which consisted in surveying the waste of hotels and restaurants. The results demonstrated that half of the USW attributed to tourists is organic mass; and that the USW footprint of tourism is not significant in comparison to that of the local population and local economy. This is relevant information because the implementation of a waste separation scheme in SCLC can start at hotels,restaurants and other businesses from which sorted materials can be recovered.

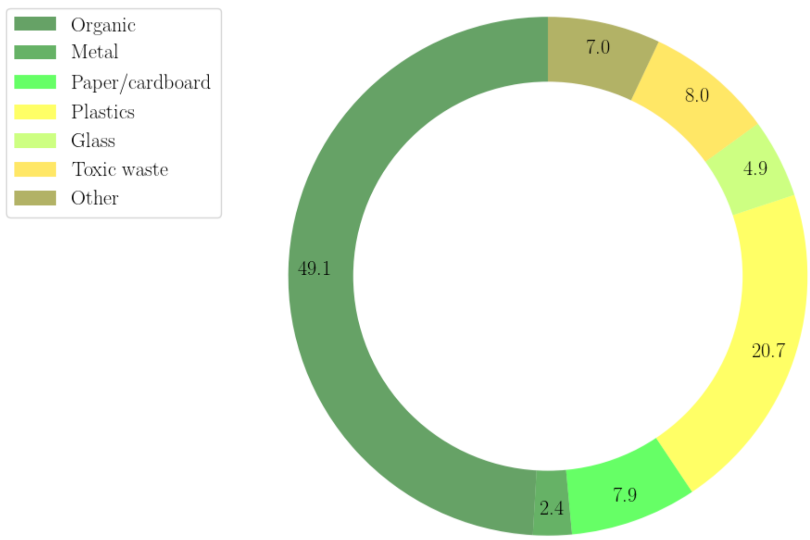


Figure 8.1: Composition of domestic USW in SCLC in 2019. Note: data from Ayuntamiento Constitucional San Cristóbal de las Casas (2019).

In this research a circular solution was developed for biomass particularly, where the organic USW of the city is pyrolysed to obtain char, tar and gas. The char and tar can be turned into charcoal briquettes, which has the potential to substitute up to 30% of the local demand of firewood and char. This can have a positive effect on the environment becasue firewood is from illegal origin and increasingly scarce in the surroundings of SCLC. This business case would require a minimum investement of 42,108,000 MXN to treat all the organic USW in SCLC; i.e. 140,000 kilograms per day. This business case can be considered as a circular solution because the organic USW is retained longer as a valuable material with environmental, social and economical benefits.

The value generated by the charcoal business case would have have a positive impact on environment, local economy and society. The environmental impact would be a reduction of demand of illicit firewood and charcoal, thus saving trees from being felled; and a reduction of 50% in the mass of landfilled USW, which would significantly diminish the generation of methane gas and nutrient rich leachates. The economic benefits would be measurable in the revenue of the existing retail of firewood and charcoal, the budget of the municipality, the salary of the factory workers. Conclusively, the social benefits would be the creation of new direct jobs without affecting employment in the USW collection sector or the retail of firewood and charcoal.

By managing the USW in SCLC with the aforementioned technologies and strategies at least 368,400 MXN can be generated on a daily basis. However, in order to do so it is necessary to consider the following recomendations:

- An educational campaign targeted to the entire population to instruct on how to sort waste according to the established categories.
- Implement a waste collection system based on the cooperation of the informal sector; where the USW is sorted in categories within a limited area or neighbourhood and expand the strategy gradually to the entire city.
- Sort waste at domestic level in at least three bins: one bin for organic waste; one bin for the combination of clean plastic, drinking packages, metals, cardboard and paper; and one bin for sanitary waste, ceramics, textile and remaining waste.
- Install supervised central collection points for glass and E-waste, for example private parking spaces or retail establishments.
- A treatment plant for organic USW, such as the charcoal briquette factory herein described.
- Explore and implement solutions to recover value from sanitary waste, textiles ceramics and the remaining waste.

Appendices

Appendix A

Freight Capacity of the Municipal Vehicle Fleet for USW Collection

Vehicle Nr.	**Vehicle Model**	**Max Capacity [kg]**	**Trips per Week**	**[kg/week]**	**Tivoli**
DL-P	Chevrolet	3,000		0	
DL-Y	Chevrolet	3,000	12	36,000	
Ranger	Ford	3,000	14.5	43,500	
DL-AD	Freightliner	8,920	28	249,760	249,760
DL-AF	Freightliner	8,920	12	107,040	
DL-AK	Freightliner	8,920	23	205,160	53520 (6 trips per week)
DL-B	International	8,210	6	49,260	
DL-S	International	8,210	14	114,940	
DL-T	International	8,210	12	98,520	
DL-V	International	8,210	14	114,940	
DL-W	International	8,210	13	106,730	
DL-X	International	8,210	12	98,520	
DL-AI	International	8,210	11	90,310	
DL-AJ	International	8,210	12	98,520	
DL-AM	International	8,210	14	114,940	
DL-AN	International	8,210	25	205,250	
DL-AL	International	8,210		0	
DL-AO	International	8,210		0	
DL-AP	International	8,210		0	
DL-G	Mercedes Benz	3,260	14	45,640	
DL-R	Mercedes Benz	8,210	14	114,940	
OM-05	Mercedes Benz	3,260	7	22,820	
DL-AH	Sterling	5,000	11	55,000	
	Total fleet capacity	162220			
	Collected Waste (Daily Mean)			**281,684 [kg/day]**	
	Tivoli				**43,325 [kg/day]**

Appendix B

Population Estimation

B.1 Linear extrapolation of population

The equation of linear population growth:

$$P(t) = at + b$$

Where the growth rate "a" is:

$$a = \frac{P_2 - P_1}{t_2 - t_1}$$

After computing the growth rate between every five years (when national sensus have taken place) from 1990 until 2015, and taking the arithmetic mean of the rates, the resulting exponential equation is:

$$P(t) = 4810.2t + 89335$$

Computing the population of SCLC of 2019; where the 29 is the number of years from 1990 until 2019, and 89335 is the initial population at year t=0:

$$P(29) = 4810.2(29) + 89335$$
$$P(29) = 228832$$

B.2 Exponential extrapolation of population

The equation of linear popualtion growth:

$$P(t) = P_0 e^{rt}$$

Where the exponential growth rate "r" is:

$$r = \frac{ln(\frac{P_2}{P_1})}{t_2 - t_1}$$

After calculating the growth rate between every sensus, from 1990 until 2015, and taking their arithmetic mean as the growth the exponential equation becomes:

$$P(t) = 89335e^{0.03411t}$$

The time difference between 1990, where the initial population is 98335, and 2019 is 29. 1990 is in this case t=0. The population of SCLC in 2019 by exponential extrapolation is:

$$P(29) = 89335e^{0.03411(29)}$$
$$P(29) = 240227$$

Year	Population	Linear growth rate (a)	Exponential growth rate (r)
1990	89335	-	-
1995	116729	5478.8	0.05349
2000	132421	3138.4	0.02522
2005	166460	6807.8	0.04575
2010	185917	3891.4	0.02211
2015	209591	4734.8	0.02397
	Average	4810.2	0.03411

Table B.1: Note: data from INEGI (1990),INEGI (1995),INEGI (2000),INEGI (2005),INEGI (2010a) and INEGI (2015b)

Appendix C

Types and Percentage of Businesses in SCLC

Business type	**Number**	**Percentage**
Agriculture, animal husbandry, forestry, fishing and hunting	3	0.02
Mining	5	0.03
Electric energy generation, transmission and distribution, gas and water distribution by pipes to final consumer	14	0.08
Construction	44	0.26
Manufacturing industries	1,536	8.99
Large scale retail	372	2.18
Small scale retail	8,358	48.91
Transport, mail and storage	142	0.83
Mass media information	32	0.19
Finance and insurance services	121	0.17
Real-estate services	126	0.74
Professional, scientific and technical services	257	1.50
Business support, waste management and remediation services	288	1.69
Educational services	337	1.97
Social support and health services	548	3.21
Sports, cultural and other recreational services	194	1.14
Temporary accommodation and food-and-beverages preparation services	2,303	13.48
Other services (except government services)	2,274	13.31
Legislative, government, justice, international organisation and extraterritorial organisation services	135	0.79
Total	**17,089**	**100**

Table C.1: Note: data from https://www.inegi.org.mx/app/mapa/denue/default.aspx with the following filters: Actividad económica=Todas las unidades; Tamaño del establecimiento=Todos los tamaños; Área geográfica= San Cristóbal de las Casas.

Appendix D

Sample Study of Hotel and Restaurants

Total avg.= Total average Est. cap.= Establishment capacity Gen. rate per pers.= Generation rate per person

Hotels
Hotel Cdd Rl

Day	**Organic [kg]**	**Other [kg]**	**Cardboard drinking package [kg]**	**Plastic (PET) [kg]**
1	10.55	7.58	NaN	2.3
2	32.25	13	NaN	NaN
3	24.5	17.75	NaN	NaN
4	11.05	23.16	NaN	1.54
5	44.65	24.95	NaN	9.66
6	35.3	47.1	NaN	2.11
7	18.75	56.6	NaN	1.75
Average	25.3	27.2	0.0	2.5
Composition [%]	46.0	49.4	0.0	4.5

Table D.1: Total avg.: 55 kg/day. Est. cap.: 64 persons. Gen. rate per pers.: 2.38 kg/person/day

Hotel Csa Mrda

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	0.9	0.6	NaN	NaN
2	0.8	0.75	NaN	NaN
3	0.8	0.35	NaN	NaN
4	16	2.65	NaN	0.65
5	19.85	1.15	NaN	NaN
6	1.2	3.3	NaN	NaN
7	4.7	5.5	NaN	NaN
Average	6.3	2.0	0.0	0.1
Composition [%]	74.7	24.2	0.0	1.1

Table D.2: Total avg.: 8.46 kg/day. Est. cap.: 20 person. Gen. rate per pers.: 1.17 kg/person/day

Hotel Csa Mxcn

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	41.1	26.75	NaN	NaN
2	6.2	NaN	NaN	0.4
3	7.6	2.7	NaN	NaN
4	8.95	20.15	NaN	NaN
5	45.45	13.3	NaN	NaN
6	24.35	23.65	NaN	NaN
7	31.25	24.5	NaN	NaN
Average	23.6	15.9	0.0	0.1
Composition [%]	59.7	40.2	0.0	0.1

Table D.3: Total avg.: 39.5 kg/day. Est. cap.: 110 person. Gen. rate per pers.: 1.0 kg/person/day

Hotel Grnd Mria

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	5.55	3.85	NaN	NaN
2	10.35	2.2	NaN	NaN
3	12	15	NaN	NaN
4	8.1	9.85	NaN	0.45
5	9.15	14.7	NaN	3.7
6	12.3	11.5	NaN	NaN
7	7.4	12.45	NaN	NaN
Average	9.3	9.9	0.0	0.6
Composition [%]	46.8	50.2	0.0	3.0

Table D.4: Total avg.: 19.8 kg/day. Est. cap.: 63 person. Gen. rate per pers.: 0.87 kg/person/day

Hotel Plza Mgnls

Day	**Organic [kg]**	**Other [kg]**	**Cardboard drinking package [kg]**	**Plastic (PET) [kg]**
1	39.9	39.8	NaN	NaN
2	62	50.35	NaN	3
3	27	43.75	NaN	NaN
4	35.5	30.45	NaN	1.15
5	36.35	42.3	NaN	NaN
6	80.25	56.05	NaN	NaN
7	68.25	59.3	NaN	NaN
Average	49.9	46.0	0.0	0.6
Composition [%]	51.7	47.7	0.0	0.6
Average composition [%]	55.8	42.3	0.0	1.9

Table D.5: Total avg.: 96.49 kg/day. Est. cap.: 312 person. Gen. rate per pers.: 0.86 kg/person/day

Restaurant/ cafe
Cafe Ccao Ntva

Day	**Organic [kg]**	**Other [kg]**	**Cardboard drinking package [kg]**	**Plastic (PET) [kg]**
1	3.0	6.7	NaN	NaN
2	2.15	3.4	0.4	NaN
3	1.45	3.85	0.5	NaN
4	1.8	5.5	2.2	NaN
5	2.05	2.95	3.55	NaN
6	2.9	5.5	3.6	NaN
Average	2.2	4.6	1.7	0.0
Composition [%]	25.9	54.2	19.9	0.0

Table D.6: Total avg.: 8.58 kg/day. Est. cap.: 250 person. Gen. rate per pers.: 0.1 kg/person/day

Restaurant Chmchrri

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	1.6	1.4	NaN	NaN
2	1.1	0.8	NaN	NaN
3	2.65	5.35	NaN	NaN
4	2.15	1.5	NaN	NaN
5	4.9	0.9	NaN	NaN
6	7.9	1.6	NaN	NaN
7	6.2	3.6	NaN	NaN
Average	3.8	2.2	0.0	5.9
Composition [%]	63.6	36.4	0.0	0.0

Table D.7: Total avg.: 5.95 kg/day. Est. cap.: 36 person. Gen. rate per pers.: 0.43 kg/person/day

Restaurant Crdmm

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	3.55	0.45	0.4	NaN
2	3.55	0.5	0.25	NaN
3	2.5	0.55	NaN	NaN
4	4.7	0.32	0.2	NaN
5	3.5	1.15	0.1	NaN
6	4.75	0.75	0.2	NaN
7	2.85	0.95	NaN	NaN
Average	3.6	0.7	0.2	0.0
Composition [%]	81.3	15.0	3.7	0.0

Table D.8: Total avg.: 4.46 kg/day. Est. cap.: person. Gen. rate per pers.:

Restaurant Csa dl Pn

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	20.05	NaN	0.2	0.2
2	22.85	NaN	NaN	NaN
3	40.75	5.5	NaN	NaN
4	32.7	11.75	NaN	NaN
5	6.75	24.35	NaN	NaN
Average	33.0	8.3	0.04	0.04
Composition [%]	74.6	25.2	0.1	0.1

Table D.9: Total avg.: 33 kg/day. Est. cap.: 210 person. Gen. rate per pers.: 0.44 kg/person/day

Cafe Dñ Isbl

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	1.9	2.35	NaN	NaN
2	2.2	7.65	NaN	NaN
3	2.05	3.2	NaN	NaN
4	4.0	1.7	NaN	NaN
5	2.05	2.0	NaN	NaN
6	2.0	8.3	NaN	NaN
7	1.65	1.55	NaN	NaN
Average	2.3	3.8	0.0	0.0
Composition [%]	37.2	62.8	0.0	0.0

Table D.10: Total avg.: 6.1 kg/day. Est. cap.: 21 person. Gen. rate per pers.: 0.8 kg/person/day

Restaurant L Lpe

Day	Organic [kg]	Other [kg]	Cardboard drinking package [kg]	Plastic (PET) [kg]
1	59.2	45.65	NaN	NaN
2	36.7	96.55	NaN	NaN
3	131.25	29.25	NaN	NaN
4	91.7	41.9	NaN	NaN
5	45	116.45	NaN	NaN
6	134.05	89.1	NaN	NaN
7	108	46.5	NaN	NaN
Average	86.6	66.5	0.0	0.0
Composition [%]	56.6	43.4	0.0	0.0
Average composition [%]	56.5	39.5	3.9	0.02

Table D.11: Total avg.: 153 kg/day. Est. cap.: 700 person. Gen. rate per pers.: 0.61 kg/person/day

Appendix E

Influx of tourists and hotel occupation percentages in SCLC

Month	No. of tourists (2017)	Hotel occupation [%] (2017)	No. of tourists (2018)	Hotel occupation [%] (2018)	No. of tourists (2019)	Hotel occupation [%] (2019)
January	74,469	38	76,242	33	95,145	34
Feburary	59,486	45	78,448	34	78,188	33
March	121,003	42	149,411	49	95,452	34
April	221,416	60	102,368	34	195,186	45
May	97,607	40	87,725	28	96,161	35
June	78,001	37	67,132	27	83,776	32
July	171,618	60	155,879	48	172,167	48
August	120,797	44	106,641	36	104,748	38
September	67,603	27	63,986	24	82,580	30
October	70,129	28	73,636	28	101,508	36
November	109,261	40	104,657	39	115,289	42
December	129,797	47	160,160	51	174,163	48

Table E.1: Note: data from 2020.

Appendix F

Net mass of USW per type from all the sources in SCLC.

Source	**Mass [1E3 kg]**	**Waste Type**	**Share**	**Mass [1E3 kg]**
Domestic	140.7 ± 3.4	Organic	49.1	69.0
		Plastic	20.7	29.1
		Toxic	8.0	11.2
		Paper/ cardboard	7.9	11.1
		Other	7.0	9.9
		Glass	4.9	6.9
		Metals	2.4	3.4
USW deposit "Tivoli"	43.3	Organic	49.1	21.3
		Other	50.9	22.0
Hotels	5.1 ± 2.1	Organic	55.8	2.8
		Other	42.3	2.2
		Plastic (PET)	1.9	1.0
Restaurants	1.8 ± 0.8	Organic	56.5	1.0
		Other	39.5	0.7
		Cardboard drinking package	3.9	0.07
Retail, institutions and other establishments	91.9 ± 6.3	Other	100	91.9

Appendix G

Mass and Energy Balance

G.1 Mass balance

x_{water1} = 0.57 (Moisture content before drying)
$x_{biomass1}$ = 1-X_{water} = 0.43 (dry mass content)

x_{water2} = 0.085 (Moisture content after drying)
$x_{biomass2}$ = 1-X_{water} = 0.0915

$yield_{gas}$ = 33%
$yield_{liquid}$ = 14%
$yield_{char}$ = 52%

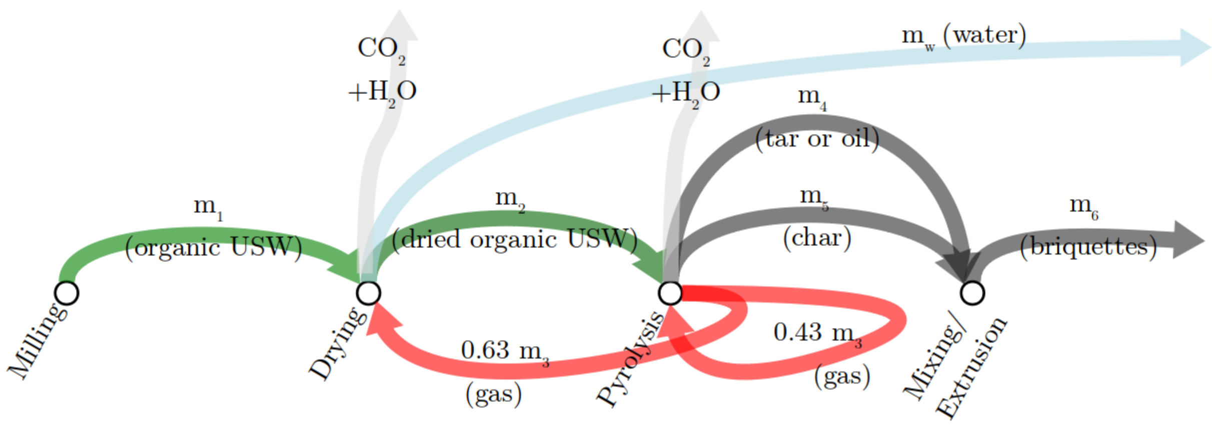


Figure G.1

Scenario 1:
Before drying:
m_1 = 26,000 [kg]
m_1 = $m_{moisture1}$ + $m_{biomass}$

$$m_{biomass} = X_{biomass1} * m_1$$
$$m_{biomass} = 0.43 * 26,000 \ [kg]$$
$$m_{biomass} = 11,180 \ [kg]$$

After drying

$$
\begin{aligned}
m_{biomass} &= 11,180\ [kg] \\
m_{biomass} &= x_{biomass2} * m_2 \\
11,180\ [kg] &= 0.0915 * m_2 \\
m_2 &= 12,220\ [kg] \\
m_w &= m_1 - m_2 \\
m_w &= 26,000\ [kg] - 12,220\ [kg] \\
m_w &= 13,780\ [kg]
\end{aligned}
$$

After pyrolysis

$$
\begin{aligned}
&m_3 = yield_{gas} * m_2 = 0.33 * 12,220\ [kg] = 4,030\ [kg] \\
&m_4 = yield_{liquid} * m_2 = 0.14 * 12,220\ [kg] = 1,710\ [kg] \\
&m_5 = yield_{char} * m_2 = 0.52 * 12,220\ [kg] = 6,355\ [kg] \\
&m_6 = m_4 + m_5 = 8,065\ [kg]
\end{aligned}
$$

Scenario 2:
Before drying:
m_1 = 140,000

$$
\begin{aligned}
m_{biomass} &= X_{biomass1} * m_1 \\
m_{biomass} &= 0.43 * 140,000\ [kg] \\
m_{biomass} &= 60,200\ [kg]
\end{aligned}
$$

After drying

$$
\begin{aligned}
m_{biomass} &= 60,200\ [kg] \\
m_{biomass} &= x_{biomass2} * m_2 \\
60,200\ [kg] &= 0.0915 * m_2 \\
m_2 &= 65,790\ [kg] \\
m_w &= m_1 - m_2 \\
m_w &= 140,000\ [kg] - 60,200\ [kg] \\
m_w &= 79,800\ [kg]
\end{aligned}
$$

After pyrolysis

$$
\begin{aligned}
&m_3 = yield_{gas} * m_2 = 0.33 * 65,790\ [kg] = 21,710\ [kg] \\
&m_4 = yield_{liquid} * m_2 = 0.14 * 65,790\ [kg] = 9,210\ [kg] \\
&m_5 = yield_{char} * m_2 = 0.52 * 65,790\ [kg] = 34,210\ [kg] \\
&m_6 = m_4 + m_5 = 43,420\ [kg]
\end{aligned}
$$

G.2 Energy balance

The equation of heat required to change the temperature of mass is:

$$Q_{req} = c_p * m * (T_2 - T_1)$$

Where:
c_p = specific heat of the mass
m = mass
T_2 = End temperature
T_1 = Start temperature
Q_{req} = Heat requirement

Changing the composition of the material changes its specific heat. Therefore the specific heat of the material has to be determined before and after the drying process, according to its moisture, as:

$$
\begin{aligned}
c_p &= (X_{water} * c_{pwater}) + (X_{biomass} * c_{pbiomass}) \\
c_{p\ before\ drying} &= (0.57 * 4.2\ [\frac{kJ}{kg * K}]) + (0.43 * 2.7\ [\frac{kJ}{kg * K}]) && = 3.55\ [\frac{kJ}{kg * K}] \\
c_{p\ after\ drying} &= (0.085 * 4.2\ [\frac{kJ}{kg * K}]) + (0.915 * 2.7\ [\frac{kJ}{kg * K}]) && = 2.83\ [\frac{kJ}{kg * K}]
\end{aligned}
$$

Where:
c_{pwater} = 4.2 kJ/(kg * K)
$c_{pbiomass}$ = 2.7 kJ/(kg * K)

The lower heating value of the gas product from organic USW pyrolysed at 700° is taken as 18.2 MJ/m^3 (Agar et al., 2018); this value corresponds to the pyrolysis conditions as from the product yields. Given that the pyrolysis gas is estimated in mass and the lower heating value is expressed as unit of energy per volume it is necessary to estimate the volume of the pyrolysis gas so that the energy embedded in the gas can be calculated.

In order to convert mass to volume, the composite density of the gas has to be defined based on its composition. Table G.1 displays the composition of the gas obtained from organic UWS pyrolysed during 6 minutes at 700°.

Gas	**Percentage [%]**	**Density (ρ) [kg/m^3]**
Carbon monoxide (CO)	27	1.165
Carbon dioxide (CO_2)	5	1.840
Ethane (C_2H_4)	2	1.265
Ethylene (C_2H_6)	9	1.260
Hydrogen (H_2)	10	0.090
Methane (CH_4)	25	0.670
Nitrogen (N_2)	5	1.165
Oxygen (O_2)	4	1.330

Table G.1: Note: data of weight percentage retrieved from Agar et al. (2018)

The composite density is computed as:

$$\rho_{composite} = \Sigma(Percentage * Density) = 0.833\ [kg/m^3]$$

Furthermore the calorific value of liquids is 15 MJ/kg (Czajczynska et al., 2017) and 25 MJ/kg for char (Basu, P., 2018).

Scenario 1:
The energy required to heat m_1 from 20 °C (T_1 = 293 K) to 101 °C (T_2 = 374 K) prior to drying is:

$$Q_{pre\ drying} = c_{p\ before\ drying} * m_1 * (T_2 - T_1)$$
$$Q_{pre\ drying} = 3.55\ [\frac{kJ}{kg * K}] * 26,000[kg] * (374 - 293)\ [K]$$
$$Q_{pre\ drying} = 7,476,300\ [kJ] = 7,476\ [MJ]$$

The energy required to evaporate one mol of water is 40.7 kJ/mol. The energy required to evaporate the water content of m_1 until a moisture content of 8.5% is obtained is the product of m_w (in Figure G.1) and Δ $H_[vap]$. For this it is necessary to express the mass of the water that has to be evaporated in mol. The molar mass of water is 0.018 kg/mol; its inverse is 55.55 mol/kg. An efficiency of 85% is assumed for the rotary dryer (Chun, Lim, & Yoshikawa, 2012).

$$m_w = 13,780\ [kg] * 55.55\ [mol/kg] \qquad = 765,555.55\ [mol]$$
$$Q_{drying} = \Delta H_{vap} * m_w$$
$$Q_{drying} = 40.7\ [kJ/mol] * 765,555.55\ [mol] \qquad = 31,158\ [MJ]$$
$$Q_{req\ drying} = Q_{drying} * \frac{1}{0.85} \qquad = 36,657\ [MJ]$$

Consecutively, the energy required m_2 from 101 °C (T_3=374 K) to 650 °C (T_4=923 K) during pyrolysis is the following:

$$Q_{pyrolysis} = c_{p\ after\ drying} * m_2 * (T_4 - T_3)$$
$$Q_{pyrolysis} = 2.83\ [\frac{kJ}{kg * K}] * 12,220[kg] * (923 - 374)\ [K]$$
$$Q_{pyrolysis} = 18,985,850\ [kJ] = 18,985.9\ [MJ]$$

Assuming that the mass in the pyrolysis reactor is heated by a boiler, the thermal efficiency in this process, at 0% excess of air and 650 °C, is of 65% (Hall, S. M., 2018).

$$Q_{req\ pyrolysis} = Q_{pyrolysis}\ \frac{1}{0.65} = 29,238.29\ [MJ]$$

The energy embedded in the products is:

$$E_{gas} = \frac{m_3}{\rho_{composite}} * 18.2\ [\frac{MJ}{m^3}] = \frac{4,030\ [kg]}{0.833\ [kg/m^3]} * 18.2\ [\frac{MJ}{m^3}] \qquad = 88,050[MJ]$$
$$E_{liquid} = m_4 * 15\ [\frac{MJ}{m^3}] = 1,710\ [kg] * 15\ [\frac{MJ}{m^3}] \qquad = 26,650[MJ]$$
$$E_{char} = m_5 * 25\ [\frac{MJ}{m^3}] = 6,355\ [kg] * 25\ [\frac{MJ}{m^3}] \qquad = 158,875[MJ]$$
$$E_{briquette} = E_{char} + E_{liquid} \qquad = 185,525[MJ]$$

Scenario 2:
Iterating the computation for energy demand for drying and and pyrolysis:

$$Q_{pre\ drying} = c_{p\ before\ drying} * m_1 * (T_2 - T_1)$$
$$Q_{pre\ drying} = 3.55\ [\frac{kJ}{kg * K}] * 140,000[kg] * (374 - 293)\ [K]$$
$$Q_{pre\ drying} = 40,257,000\ [kJ] = 40,257\ [MJ]$$

$$m_w = 74,205\ [kg] * 55.55\ [mol/kg] \qquad = 4,122,087.75\ [mol]$$
$$Q_{drying} = \Delta H_{vap} * m_w$$
$$Q_{drying} = 40.7\ [kJ/mol] * 4,122,087.75\ [mol] \qquad = 167,785.7\ [MJ]$$
$$Q_{req\ drying} = Q_{drying} * \frac{1}{0.85} \qquad = 197,395\ [MJ]$$

$$Q_{pyrolysis} = c_{p\ after\ drying} * m_2 * (T_4 - T_3)$$
$$Q_{pyrolysis} = 2.83\ [\frac{kJ}{kg * K}] * 65,790[kg] * (923 - 374)\ [K]$$
$$Q_{pyrolysis} = 102,215,949\ [kJ] \qquad = 102,216\ [MJ]$$
$$Q_{req\ pyrolysis} = Q_{pyrolysis} * 1.54 \qquad = 157,412.6\ [MJ]$$

The energy embedded in the products is:

$$E_{gas} = \frac{m_3}{\rho_{composite}} * 18.2\ [\frac{MJ}{m^3}] = \frac{21,710\ [kg]}{0.833\ [kg/m^3]} * 18.2\ [\frac{MJ}{m^3}] \qquad = 474,336[MJ]$$
$$E_{liquid} = m_4 * 15\ [\frac{MJ}{m^3}] = 9,210\ [kg] * 15\ [\frac{MJ}{m^3}] \qquad = 138,150[MJ]$$
$$E_{char} = m_5 * 25\ [\frac{MJ}{m^3}] = 34,210\ [kg] * 25\ [\frac{MJ}{m^3}] \qquad = 855,250[MJ]$$
$$E_{briquette} = E_{char} + E_{liquid} \qquad = 993,400[MJ]$$

Appendix H

Economic Balance

H.1 Investment for the machinery

Machine	Capacity [kg/day]	Unit cost [MXN]
Mill	70,000	311,575
Rotary biomass dryer	288,000	2,157,060
Fluidised bed pyrolysis reactor	48,000	19,512,700
Briquette extrusion machine	24,000	78,000
conveyor belt	-	24,400

Table H.1: Required investment for machinery (approximation. Note: unit prices data from alibaba.com)

H.2 Economic balance of Scenario 1

Monetary input S1
Income = 5 MXN/kg * 8,065 kg/day * 30 day/month =1,209,750 MXN/month
Monetary output S1
Staff (19) (-30,000 - (2*15,000) - (16*4000)) = -124,000 MXN/month
Building rent = -40,000 MXN/month
Services (electricity, communication, water) = -3500 MXN/month
Monetary surplus S1
Total = 1,042,250 MXN/month

H.3 Economic balance of Scenario 2

Monetary input S2
Income = 5 MXN/kg * 43,420 kg/day * 30 day/month = 6,513,000 MXN/month
Monetary output S2
Staff (33) (-30,000 - (2*15,000) - (30*4000)) = -180,000 MXN/month
Building rent = -40,000 MXN/month
Services (electricity (I. Comisión Federal de Electricidad, 2020), communication, water) = -3500 MXN/month
Monetary surplus S2
Total = 6,289,500 MXN/month

Appendix I

Pre and Post Business Case Carbon Dioxide Emissions

I.1 Pre business case carbon dioxide emissions

Emission from firewood combustion:

The average composition of wood from pine tree species is given in the following table:

Compound	**weight percentage [%]**	**Chemical formula**	**Molar mass [gr/mol]**
Cellulose	45.84	$C_6H_{10}O_5$	186
Hemicellulose	24.5	$C_{18}H_{32}O_{16}$	504
Lignin	27.9	$C_{31}H_{34}O_4$	470

Table I.1: The formula of cellotriosly is taken as the one for hemicellulose. Note: Data from weight percentage from Honorato Salazar et al. (2017)

Stoichiometry of the combustion of wood components:

$$
\begin{aligned}
C_6H_{10}O_5 + 6O_2 &-> 6CO_2 + 5H_2O \\
C_{18}H_{32}O_{16} + 18O_2 &-> 18CO_2 + 16H_2O \\
C_{31}H_{34}O_4 + 37.5O_2 &-> 31CO_2 + 17H_2O
\end{aligned}
$$

Molar mass of each compound per kilogram of firewood from *Pinus sp.*, and mol of CO_2 per compound after combustion:

Compound	**[mol/kg]**	**[CO_2 mol/kg]**
Cellulose	2.46	14.76
Hemicellulose	0.486	8.75
Lignin	0.594	18.41
Total	-	41.92

The molar mass of carbon dioxide is 44 gr/mol. For every kilogram of burned pine wood, under the assumption of ideal combustion, 41.92 mol of CO_2 are emitted; i.e. 1.84 kilograms.

CO_2 equivalent emission from landfill:

Landfill area = 29,700 m^2
Methane emission rate of the landfill = 54 gr m^{-2} d^{-1} (Sauri Riancho et al., 2013).

Methane global warming potential equivalence in CO_2 1:30 (Derwent, 2020).
Equivalent CO_2 emissions = 29,700 m^2 * 54 gr m^{-2} d^{-1} * 30 = 48,114,000 gr/day = 48,114 kg/day

I.2 Post business case carbon dioxide emissions

Pyrolysis gas combustion:

The composition of the pyrolysis gas is given in the following table:

Compound	**weight percentage [%]**	**Chemical formula**	**Molar mass [gr/mol]**
Carbon monoxide	27	CO	28
Carbon dioxide	5	CO_2	44
Ethane	2	C_2H_4	28
Ethylene	9	(C_2H_6)	30
Methane	25	(CH_4)	16

Table I.2: Note: data of weight percentage retrieved from Agar et al. (2018).

The stoichiometry of combusted pyrolysis gas is the following:

$$CO + 0.5O_2 -> CO_2$$
$$C_2H_4 + 3O_2 -> 2CO_2 + 2H_2O$$
$$C_2H_6 + 3.5O_2 -> 2CO_2 + 3H_2O$$
$$CH_4 + 2O_2 -> CO_2 + 2H_2O$$

Compound	**[mol/kg]**	**[CO_2 mol/kg]**
Carbon monoxide	9.64	9.64
Carbon dioxide	1.14	1.14
Ethane	0.71	1.42
Ethylene	3	6
Methane	15.62	15.62
Total	-	33.82

Table I.3

For every kilogram of burned pyrolysis gas, under the assumption of ideal combustion, 33.82 mol of CO_2 are emitted; i.e. 1.94 kilograms.

Briquette combustion:

Under the assumption that the combustion of the charcoal briquettes is mostly carbon and chemical compounds of single carbon the stoichiometric combustion is:

$$C + O_2 -> CO_2$$

The molar mass of carbon is 12 gr/mol. The number of carbon mol per kilogram of briquette is 83.3 which is the same number of mol of CO_2 per kilogram of burned briquette; that is 3.66 kilograms of CO_2.

References

Agar, D., Kwapinska, M., & Leahy, J. (2018). Pyrolysis of wastewater sludge and composted organic fines from municipal solid waste: Laboratory reactor characterisation and product distribution. *Environmental Science and Pollution Research, 1-9.*. doi: 10.1007/s11356-018-1463-y

Aguado Maya, J. J. (1998). Residuo sólidos domésticos en San Cristóbal de las Casas, Chiapas: Generación per cápita y caracterización. *El Colegio de la Frontera Sur. http://bibliotecasibe.ecosur.mx/sibe/book/000020015 (accessed: 10.08.19).*

Alvarado Machuca, S., Alvarez Sánchez, M., Maldonado-Torres, R., & Sánchez Velez, A. S. (2018). Agroforestería para la conservación de los recursos naturales y productividad. Ch. 4. Consumo de leña en México: hábitos de uso, problemática asociada y alternativas sostenibles de solución. *Universidad Autónoma de Chapingo.*. Retrieved from `https://www.researchgate.net/publication/331100897_Consumo_de_lena_en_Mexico_habitos_de_uso_problematica_asociada_y_alternativas_sostenibles_de_solucion(accessed:27.02.20)`

Araiza Aguilar, J. A., Chávez Moreno, J., & Moreno Pérez, J. (2017). Cuantificación de residuos sólidos urbanos generados en la cabecera municipal de Berriozábal, Chiapas, México. *Universidad Nacional Autónoma de México.*. doi: 10.20937/RICA.2017.33.04.12

Ayuntamiento Constitucional San Cristóbal de las Casas, O. (2018). *ESTUDIO DE CARACTERIZACIÓN DE LOS RESIDUOS SÓLIDOS URBANOS DEL MUNICIPIO DE SAN CRISTÓBAL DE LAS CASAS, CHIAPAS.*

Ayuntamiento Constitucional San Cristóbal de las Casas, O. (2019). *Programa para la prevención y gestión de los residuos sólidos urbanos del municipio de San Cristóbal de las Casas.*

Basu, P. (2018). *Biomass Gasification, Pyrolysis and Torrefaction - Practical Design and Theory - 5.1.1 Historical Background.* (3rd ed. ed.). Amsterdam: Elsevier/Academic Press.

Botello Alvarez, J., Rivas García, P., Fausto Castro, L., Estrada Baltazar, A., & Gomez Gonzalez, R. (2003). Informal collection, recycling and export of valuable waste as transcendent factor in the municipal solid waste management: A latin-american reality. *Journal of Cleaner Production, 182, 485-495.*. doi: 10.1016/j.jclepro.2018.02.065

Buenrostro, O., & Bocco, G. (2003). Solid waste management in municipalities in mexico: goals and perspectives. *Resources, Conservation & Recycling, 39(3), 251-263.*. doi: https://doi.org/10.1016/S0921-3449(03)00031-4

Buenrostro, O., Bocco, G., & Vence, J. (2001). Forecasting generation of urban solid waste in developing countries–a case study in Mexico. *Journal of the Air & Waste Management Association (1995), 51(1), 86-93.*. doi: 10.1080/10473289.2001.10464258

Burgos Lugo, D. E., Soto Pinto, M. L., Bello Baltazar, E., & Castellanos Albores, J. (2020). CONSUMO DE LEÑA Y SU IMPACTO AMBIENTAL Y EN LA SALUD EN UNA COMUNIDAD DEL NORTE DE CHIAPAS. *Memoria en Extenso del X Simposio Internacional y V congreso Nacional de Agricultura Sostenible Vol. 6*. Retrieved from `https://www.researchgate.net/publication/266439697_CONSUMO_DE_LENA_Y_SU_IMPACTO_AMBIENTAL_Y_EN_LA_SALUD_EN_UNA_COMUNIDAD_DEL_NORTE_DE_CHIAPAS(accessed:27.02.20)`

Butler, J. H. and Hooper, P. D. (2019). *Waste: A handbook for management. Chapter 15 - Glass Waste.* (2nd ed. ed.). Amsterdam: Elsevier/Academic Press.

Castillo Gonzalez, E., & de Medina Salas, L. (2013). *GENERACIÓN Y COMPOSICIÓN DE*

RESIDUOS SÓLIDOS DOMÉSTICOS EN LOCALIDADES URBANAS PEQUEÑAS EN EL ESTADO DE VERACRUZ, MÉXICO. Universidad Veracruzana. Retrieved from http://www.scielo.org.mx/pdf/rica/v30n1/v30n1a7.pdf(accessed:09.12.19)

Centro de Investigaciones Turísticas Aplicadas, I. (2013). *Diagnóstico de competitividad y sustentabilidad turística del pueblo mágico: San Cristóbal de las Casas.* Retrieved from http://www.sectur.gob.mx/gobmx/pueblos-magicos/san-cristobal-de-las-casas-chiapas/(accessed:29.02.20)

Chattopadhyay, J., Kim, C., Kim, R., & Pak, D. (2008). Thermogravimetric characteristics and kinetic study of biomass co-pyrolysis with plastics. *Korean Journal of Chemical Engineering, 25(5), 1047–1053..* doi: https://doi-org.tudelft.idm.oclc.org/10.1007/s11814-008-0171-6

Chun, Y. N., Lim, M. S., & Yoshikawa, K. (2012). Development of a high-efficiency rotary dryer for sewage sludge. *The Journal of Material Cycles and Waste Management, 14(1), 65–73..* doi: https://doi.org/10.1007/s10163-012-0040-6

Comisión Federal de Electricidad, I. (2020). *Tarifas.* Retrieved from https://app.cfe.mx/Aplicaciones/CCFE/Tarifas/TarifasCREIndustria/Tarifas/DemandaIndustrialSub.aspx(accessed:10.04.20)

Comisión Federal de Electricidad, O. (2020). *Tarifa 1A. Servicio doméstico para localidades con temperatura media mínima en verano de 25 grados centígrados.* Retrieved from https://app.cfe.mx/Aplicaciones/CCFE/Tarifas/TarifasCRECasa/Tarifas/Tarifa1A.aspx(accessed:15.02.20)

Comisión Reguladora de Energía, O. (2018). *Precios al público del gas LP reportados por los distribuidores/1.* Retrieved from https://www.gob.mx/cms/uploads/attachment/file/336113/20180531_Precios_GLP.pdf(accessed:15.02.20)

Congreso General de los Estados Unidos Mexicanos, O. (2003). *LEY GENERAL PARA LA PREVENCIóN Y óN INTEGRAL DE LOS RESIDUOS.* Retrieved from https://www.gob.mx/cms/uploads/attachment/file/131748/23._LEY_GENERAL_PARA_LA_PREVENCI_N_Y_GESTI_N_INTEGRAL_DE_LOS_RESIDUOS.pdf(accessed:03.10.19)

Czajczynska, D., Anguilano, L., Ghazal, H., Krzyzzynnska, R., Reynolds, A., Spencer, N., & Jouhara, H. (2017). Potential of pyrolysis processes in the waste management sector. *Thermal Science and Engineering Progress, 3, 171-197..* doi: 10.1016/j.tsep.2017.06.003

Dawei, A., Zhimin, W., Shuting, Z., & Hongxing, Y. (2006). Low-temperature pyrolysis of municipal solid waste: influence of pyrolysis temperature on the characteristics of solid fuel. *International Journal of Energy Research, 30(5), 349–357..* doi: https://doi.org/10.1002/er.1152

Derwent, R. (2020). Global Warming Potential (GWP) for Methane: Monte Carlo Analysis of the Uncertainties in Global Tropospheric Model Predictions. *Atmosphere 2020, 11, 486..* Retrieved from 10.3390/atmos11050486

Dong, J., Chi, Y., Tang, Y., Ni, M., Huang, Q., Nzihou, A., & Weiss-Hortala, E. (2016). Effect of operating parameters and moisture content on municipal solid waste pyrolysis and gasification. *Energy and Fuels, 30(5), 3994-4001..* doi: 10.1021/acs.energyfuels.6b00042

El-Fadel, M., Findikakis, A., & Leckie, J. (1997). Environmental impacts of solid waste landfilling. *Journal of Environmental Management, 50(1), 1-25..* doi: 10.1006/jema.1995.0131

Ellen MacArthur Foundation, O. (2017). *Infographic, Circular Economy System Diagram.* Retrieved from https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic(accessed:03.10.19)

Encinar, J., Beltrán, F., Bernalte, A., Ramiro, A., & Gonzalez, J. (1996). Pyrolysis of two agricultural residues: Olive and grape bagasse. influence of particle size and temperature. *Biomass and Bioenergy, 11(5), 397-409..* doi: 10.1016/S0961-9534(96)00029-3

Esquinca-Cano, F. (1995). *CARACTERIZACIÓN Y GENERACIÓN DE LOS RESIDUOS SÓLIDOS DE TUXTLA GUTIÉRREZ, CHIAPAS.* Secretaría de Ecología Recursos Naturales y Pesca, sección Chiapas. Retrieved from www.bvsde.paho.org/bvsaidis/resisoli/mexico/03364e14.pdf(accessed:09.12.19)

European-Union, O. (2008). *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Brussels).* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0098(accessed:03.10.19)

Faitli, J., Magyar, T., Erdelyi, A., & Muranyi, A. (2015). Characterization of thermal properties of municipal solid waste landfills. *Waste Management, 36, 213-221.*. doi: 10.1016/j.wasman.2014.10.028

Fan, H., Gu, J., Hu, S., Yuan, H., & Chen, Y. (2019). Co-pyrolysis and co-gasification of biomass and polyethylene: thermal behaviors, volatile products and characteristics of their residues. *Journal of the Energy Institute, 92(6), 1926–1935.*. doi: https://doi.org/10.1016/j.joei.2018.11.002

Feil, A. and Pretz, T. and Jorg, J. and Go, N. and Bosling, M. and Johnen, K. (2019). *Waste: A handbook for management. Chapter 10. - Metal Waste.* (2nd ed. ed.). Amsterdam: Elsevier/Academic Press. doi: https://doi.org/10.1016/B978-0-12-815060-3.00010-4.

Geisendorf, T., & Pietrulla, F. (2018). The circular economy and circular economic concepts—a literature analysis and redefinition.
doi: 10.1002/tie.21924

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production, 114, 11-32.*. doi: 10.1016/j.jclepro.2015.09.007

Gomez, G., Meneses, M., Ballinas, L., & Castells, F. (2008). *Characterization of urban solid waste in Chihuahua, Mexico.* Waste Management. doi: 10.1016/j.wasman.2007.10.023

González, A., Estrada-Lugo, E., & Rivas, G. (2012, 06). Uso de la leña y conservación del bosque en el volcán huitepec, chiapas, méxico. *LiminaR*, *10*, 138-158. doi: 10.29043/liminar.v10i1.41

Hall, S. M. (2018). *Rules of Thumb for Chemical Engineers. - 21.6 Thermal Efficiency.* (6th ed. ed.). Amsterdam: Elsevier/Academic Press.

Holz, S., & Ramírez-Marcial, N. (2011). La leña, principal recurso energético en las comunidades rurales. Metodologías para la estimación y producción de leña a partir de árboles nativos. *Red de Espacios de Innovación Socioambiental.* Retrieved from http://bibliotecasibe.ecosur.mx/sibe/book/000035201(accessed:27.02.20)

Honorato Salazar, J. A., Apolinar Hidalgo, F., & Colotl Hernández, G. (2017). Composicion lignocelulosica de pinus ayacahuite ehrenb. ex schltdl., p. leiophylla schlecht. & cham. y p. herrerae martinez. *Revista Mexicana De Ciencias Forestales, 7(34), 047-056.*. doi: https://doi.org/10.29298/rmcf.v7i34.82

INEGI. (1990). *Conteo de Población y Vivienda 1990. Chiapas.* Retrieved from https://inegi.org.mx/contenidos/programas/ccpv/1990/tabulados/CPyV90_Chis_Poblacion.xlsx(accessed:20.11.19)

INEGI. (1995). *Conteo de Población y Vivienda 1995. Chiapas.* Retrieved from https://inegi.org.mx/contenidos/programas/ccpv/1995/tabulados/Cont95Enum_Chis_Poblacion.xlsx(accessed:20.11.19)

INEGI. (2000). *Conteo de Población y Vivienda 2000. Chiapas.* Retrieved from https://www.inegi.org.mx/contenidos/programas/ccpv/2000/tabulados/CPyV2000_Chis_Poblacion.xlsx(accessed:20.11.19)

INEGI. (2005). *Conteo de Población y Vivienda 2005. Chiapas.* Retrieved from https://www.inegi.org.mx/contenidos/programas/ccpv/2005/tabulados/Cont2005_Chis_Poblacion.xls(accessed:20.11.19)

INEGI. (2010a). *Conteo de Población y Vivienda 2010. Chiapas.* Retrieved from https://www.inegi.org.mx/contenidos/programas/ccpv/2010/tabulados/Basico/01_01B_MUNICIPAL_07.xls(accessed:20.11.19)

INEGI. (2010b). *Vectorial de localidades amanzanadas y números exteriores, Urbanas. Cierre de planeación del Censo de Población y Vivienda 2010. San Cristóbal de las Casas.* Retrieved from https://inegi.org.mx/app/biblioteca/ficha.html?upc=

702825298234(accessed:15.02.20)

INEGI. (2015a). *Encuesta Intercensal 2015. Vivienda. Chiapas.* Retrieved from https://inegi.org.mx/contenidos/programas/intercensal/2015/tabulados/14_vivienda_chis.xls(accessed:15.02.20)

INEGI. (2015b). *Panorama sociodemográfico de Chiapas.* Retrieved from https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825003348(accessed:04.10.19)

INEGI. (2017a). *Carta topográfica. E15D51f.* Retrieved from https://inegi.org.mx/app/biblioteca/ficha.html?upc=889463531371(accessed:15.02.20)

INEGI. (2017b). *Carta topográfica. E15D52d.* Retrieved from https://inegi.org.mx/app/biblioteca/ficha.html?upc=889463531388(accessed:15.02.20)

INEGI. (2017c). *Carta topográfica. E15D61c.* Retrieved from https://inegi.org.mx/app/biblioteca/ficha.html?upc=889463531395(accessed:15.02.20)

INEGI. (2017d). *Carta topográfica. E15D62a.* Retrieved from https://inegi.org.mx/app/biblioteca/ficha.html?upc=889463531401(accessed:15.02.20)

INEGI. (2018). *Encuesta Nacional de Ingresos y Gastos de los Hogares (ENIGH).* Retrieved from https://www.inegi.org.mx/contenidos/programas/enigh/nc/2018/doc/enigh2018_ns_presentacion_resultados_chis.pdf(accessed:15.02.20)

Ishii, K., & Furuichi, T. (2013). Estimation of methane emission rate changes using age-defined waste in a landfill site. *Waste Management, 33(9), 1861–1869.*. doi: https://doi.org/10.1016/j.wasman.2013.05.011

Jayawardhana, Y. and Kumarathilaka, P. and Herath, I. and Vithanage, M. (2016). *Environmental materials and waste : resource recovery and pollution prevention. Chapter 6 - Municipal Solid Waste Biochar for Prevention of Pollution From Landfill Leachate.* London: Academic Press. doi: https://doi.org/10.1016/B978-0-12-803837-6.00006-8

Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018). Circular economy - from review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling, 135, 190-201.*. doi: 10.1016/j.resconrec.2017.10.034

Kan, T., Strezov, V., & Evans, T. (2016). Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renewable and Sustainable Energy Reviews, 57, 1126-1140.*. doi: 10.1016/j.rser.2015.12.185

Kaya, M. (2019). *Electronic waste and printed circuit board recycling technologies.* Cham: Springer International Publishing. doi: https://doi.org/10.1007/978-3-030-26593-9_2

Kuehr, R. (2019). *Waste: A handbook for management. Chapter 25 - Waste Electrical and Electronic Equipment.* (2nd ed. ed.). Amsterdam: Elsevier/Academic Press. doi: https://doi.org/10.1016/B978-0-12-815060-3.00025-6

Kumar-Jain, R. (1992). Fuelwood characteristics of certain hardwood and softwood tree species of india. *Bioresource Technology, 41(2), 129-133.*. doi: 10.1016/0960-8524(92)90182-W

Kurniawan, E., Amirta, R., Budiarso, E., & Arung, E. (2019). Optimization of temperature and time pyrolysis from white charcoal briquette production of wasted oil palm shell and acacia bark with rsm method. *Russian Journal of Agricultural and Socio-Economic Sciences, 95(11), 166-170.*. doi: 10.18551/rjoas.2019-11.21

Lee, C., Popuri, S., Peng, Y., Fang, S., Lin, K., Fan, K., & Chang, T. (2015). Overview on industrial recycling technologies and management strategies of end-of-life fluorescent lamps in taiwan and other developed countries. *Journal of Material Cycles and Waste Management : Official Journal of the Japan Society of Material Cycles and Waste Management and the Korea Society of Waste Management, 17(2), 312-323.*. doi: 10.1007/s10163-014-0253-y

Letcher, T. and Vallero, D. (2019). *Waste: A handbook for management* (2nd ed. ed.). Amsterdam: Elsevier/Academic Press.

Lewandowski, I. (2018). *Bioeconomy : Shaping the transition to a sustainable, biobased economy.* (1st ed. ed.). Cham, Switzerland:: Springer Open.

Lohri, C., Diener, S., Zabaleta, I., Mertenat, A., & Zurbrugg, C. (2017). Treatment technologies for urban solid biowaste to create value products: A review with focus on low- and middle-income settings. *Environmental Science and Biotechnology, 1-50, 1-50.*. doi: 10.1007/

s11157-017-9422-5

Martínez Icó, M., Cetzal Ix, W. R., Noguera Savelli, E., & Hernández Juarez, R. (2015). Flora vascular de la comunidad de Bazom, los Altos de Chiapas, México. *Botanical Sciences. vol. 93, no. 1, p. 53-72. ISSN: 2007-4298.*. Retrieved from `Retrievedfrom:http://bibliotecasibe.ecosur.mx/sibe/book/000029742(accessed:02.03.20)`

Mishra, H., Karmakar, S., & Kumar, R. (2018). A long-term comparative assessment of human health risk to leachate-contaminated groundwater from heavy metal with different liner systems. *Environmental Science and Pollution Research International, 25(3), 2911-2923.*. doi: 10.1016/j.wasman.2012.03.004

Mueller, J., Boehm, M., & Drummond, C. (2015). Direction of crt waste glass processing: Electronics recycling industry communication. *Waste Management, 32(8), 1560-1565.*. doi: 10.1016/j.wasman.2012.03.004

Nájera Aguilar, H., Vera Toledo, P., & Rojas Valencia, M. (2012). INVESTIGACIÓN DEL SITIO DE DISPOSCIÓN FINAL DE RESIDUOS SÓLIDOS DE LA CIUDAD DE SAN CRISTÓBAL DE LAS CASAS, CHIAPAS. *Revista de Ingeniería y Ciencias Ambientales: Investigación, desarrollo y práctica. Vol. 5, Nr. 1 (67-78).*. Retrieved from `http://www.journals.unam.mx/index.php/aidis/article/view/07`

Núñez-Retana, V., Wehenkel, C., Vega-Nieva, D., García-Quezada, J., & Carrillo-Parra, A. (2019). The Bioenergetic Potential of Four Oak Species from Northeastern Mexico. *Forests, 10(10).* doi: 10.3390/f10100869

Olsson, O., Roos, A., Guisson, R., Bruce, L., Lamers, P., Hektor, B., & Hildebrandt, J. (2018). Time to tear down the pyramids? a critique of cascading hierarchies as a policy tool. *Wiley Interdisciplinary Reviews: Energy and Environment, 7(2).*. doi: 10.1002/wene.279

Olugbade, T., Ojo, O., & Mohammed, T. (2019). Influence of Binders on Combustion Properties of Biomass Briquettes: A Recent Review. *Bioenerg. Res. 12, 241–259*. doi: https://doi-org.tudelft.idm.oclc.org/10.1007/s12155-019-09973-w

Poulsen, T. (2014). Landfilling, past, present and future. *Waste Management and Research : The Journal of the International Solid Wastes and Public Cleansing Association, Iswa.* doi: 10.1177/0734242X14524132

Quiroz González, S. A. (2009). *LOS RESIDUOS SÓLIDOS URBANOS: EL CASO DEL MUNICIPIO DE HUANUSCO, ZACATECAS.* Universidad Autónoma de México. Retrieved from `http://132.248.9.195/ptd2009/noviembre/0651035/Index.html(accessed:26.12.19)`

Ramakrishnan, A., Blaney, L., Kao, J., Tyagi, R., Zhang, T., & Surampalli, R. (2015). Emerging contaminants in landfill leachate and their sustainable management. *Environmental Earth Sciences, 73(3), 1357-1368.*. doi: 10.1007/s12665-014-3489-x

Ramírez-López, J. M. (2012). Demanda y déficit de leña en comunidades cafetaleras: el caso de Maya-Vinic, Chenalhó, Chiapas. Retrieved from `http://bibliotecasibe.ecosur.mx/sibe/book/000004098(accessed:27.02.20)`

Rao, S. (2006). *Resource recovery and recycling from metallurgical wastes* (Volume 7 ed.). Amsterdam: Elsevier/Academic Press.

Rousselet, Y., & Dhir, V. (2016). Numerical modeling of a co-current cascading rotary dryer. *Food and Bioproducts Processing, 99, 166-178.*. doi: 10.1016/j.fbp.2016.05.001

Sauri Riancho, M., Reza Bacelis, G., Stentiford, E. I., Cahuich Poot, N., Gamboa Marrufo, M., & Méndez Novelo, R. (2013). Superficial methane emissions from a landfill in merida, yucatan, mexico. *Ingenieria, Investigacion Y Tecnologia, 14(3), 299-310.*. doi: https://doi.org/10.1016/S1405-7743(13)72244-3

Scott, G. M. (2019). *Waste: A handbook for management. Chapter 14 - Recovered Paper* (2nd ed. ed.). Amsterdam: Elsevier/Academic Press. doi: https://doi.org/10.1016/B978-0-12-815060-3.00014-1

Secretaría de Ecología Estado de México, I. (2000). *Estudio de generación y caracterización de residuos sólidos municipales.*

Secretaría del Trabajo y Previsión Social, O. (2020). *Salarios Mínimos 2020.* Retrieved from https://www.gob.mx/cms/uploads/attachment/file/525061/Tabla_de_salarios_m_nmos_vigentes_apartir_del_01_de_enero_de_2020.pdf(accessed:24.04.20)

Secretaría de Medio Ambiente y Recursos Naturales, O. (2002). *NORMA OFICIAL MEXICANA NOM-087-SEMARNAT-SSA1-2002, PROTECCION AMBIENTAL- SALUD AMBIENTAL - RESIDUOS PELIGROSOS BIOLOGICO-INFECCIOSOS - CLASIFICACION Y ESPECIFICACIONES DE MANEJO.* Diario Oficial de la Federación, O. Retrieved from http://dof.gob.mx/nota_detalle.php?codigo=2091984&fecha=14/09/2005(accessed:24.03.20)

Secretaría de Medio Ambiente y Recursos Naturales, O. (2005). *NORMA Oficial Mexicana NOM-052-SEMARNAT-2005, Que establece las características, el procedimiento de identificación, clasificación y los listados de los residuos peligrosos.* Diario Oficial de la Federación, O. Retrieved from https://www.dof.gob.mx/normasOficiales/1055/SEMARNA/SEMARNA.htm(accessed:24.03.20)

Secretaría de Medio Ambiente y Recursos Naturales, O. (2015). *El medio ambiente en México 2013-2014.* Retrieved from https://www.academia.edu/16060991/El_Medio_Ambiente_en_Mexico_2013_2014(accessed:09.01.20)

Secretaría de Medio Ambiente y Recursos Naturales, O. (2019). *VISIÓN NACIONAL HACIA UNA GESTIÓN SUSTENTABLE: Cero residuos.* Retrieved from https://www.gob.mx/cms/uploads/attachment/file/435917/Vision_Nacional_Cero_Residuos_6_FEB_2019.pdf(accessed:21.05.20)

Secretaría de Turismo del Gobierno de Chiapas, O. (2018). *Reporte estadístico de indicadores del sector turístico del estado de Chiapas, enero-abril 2018.* Retrieved from www.turismochiapas.gob.mx/institucional/estadisticas/formatos/Abril_2018.pdf(accessed:04.10.19)

Secretaría de Turismo Gobierno de Chiapas, O. (2020). *Reportes estadístico de indicadores del sector turístico del estado de Chiapas.* Retrieved from www.turismochiapas.gob.mx/institucional/estadisticas/(accessed:04.10.19)

Sethi, B. (2017). *Recycling of Polymers - Methods, Characterization and Applications.* John Wiley and Sons.

Stark, T., Martin, J., Gerbasi, G., Gortner, R., & Thalhamer, T. (2012). Aluminum waste reaction indicators in a municipal solid waste landfill. *Journal of Geotechnical and Geoenvironmental Engineering, 138(3), 252-261..* doi: 10.1061/(ASCE)GT.1943-5606.0000581

Sustainable Freight, w. (2020). *Truck Fuel, Emissions and Cost Calculator and Comparison Tool.* Retrieved from http://www.sustainablefreight.com.au/tools-and-programs/emission-calculators/truck-fuel-emissions-and-cost-calculator-and-comparison-tool

Taghipour, H., Amjad, Z., Aslani, H., & et al. (2016). Characterizing and quantifying solid waste of rural communities. *J Mater Cycles Waste Management 18, 790–797.* doi: https://doi-org.tudelft.idm.oclc.org/10.1007/s10163-015-0365-z

Van der Hoek, J., De Fooij, H., & Struker, A. (2016). Wastewater as a resource: Strategies to recover resources from amsterdam's wastewater. *Resources, Conservation and Recycling v113 (53-64).* doi: https://doi.org/10.1016/j.resconrec.2016.05.012

Williams, K.S. and Mcdonnell, T. (2019). *Waste Electrical and Electronic Equipment (WEEE) Handbook. Chapter 12 - Recycling liquid crystal displays.* (2nd Ed. ed.). Oxford: Woodhead Publishing.

Yu, J., Sun, L., Wang, B., Qiao, Y., Xiang, J., Hu, S., & Yao, H. (2016). Study on the behavior of heavy metals during thermal treatment of municipal solid waste (msw) components. *Environmental Science and Pollution Research International, 23(1), 253–265..* doi: https://doi.org/10.1007/s11356-015-5644-7

Zabaniotou, A. (2000). Simulation of forestry biomass drying in a rotary dryer. *Drying Technology, 18(7), 1415-1431..* doi: 10.1080/07373930008917785

Zhao, S. and He, W. and Li, G. (2019). *Recycling Technology and Principle of Spent Lithium-Ion Battery. In: An L. (eds) Recycling of Spent Lithium-Ion Batteries.* Cham: Springer.