Organic waste to energy: resource potential and barriers to uptake in Chile

Abstract
Achieving net-zero greenhouse gas emissions by 2050 requires a step-change in resource management, and the utilisation of organic waste is currently an untapped opportunity in Latin America. This study carries out a quantitative and qualitative assessment of organic waste-to-energy potentials for the Chilean context. First, it produces a comprehensive quantification of organic waste, including annual crop residues, horticulture residues, livestock manure and OFMSW by region; then it estimates the energy potential of these bioresources; and finally, it conducts a series of stakeholder interviews determining barriers to greater waste-to-energy utilisation. The results show that the total bioenergy potential from waste is estimated at 78 PJ/yr (3.3% of annual energy demand), being livestock manure (41%) and annual crop residues (28%) the main sources, arising mostly from three regions. The stakeholder elicitation concluded that financial, technical, and institutional barriers prevent waste utilisation, highlighting the needs to address elevated investment costs and high reliance on landfilling practices, which together with public policies could enable the full exploitation of these resources to ensure energy security and resource efficiency.

Keywords: Bioenergy potential, bioenergy from waste, biomass, agricultural residues, municipal solid waste, waste-to-energy.

1 Introduction
Many countries have targeted net-zero greenhouse gas (GHG) emissions by 2050 (Levin and Davis, 2020), which will require rapid transitions and nation-specific solutions that lean on their strengths. Organic waste-to-energy (OWtE) technologies can provide low carbon energy whilst reducing waste to landfill (Silva-Martínez et al., 2020), but in Latin America and the Caribbean (LAC) countries the vast majority of organic waste is landfilled (Margallo et al., 2019).

During the last 40 years, local experiences with OWtE technologies have varied amongst LAC countries regarding implementation strategies and applications among different sectors, due to political contexts, geographic and resource availability among regions, and technological changes in the period. High upfront costs, deficiency in access to sophisticated technologies, lack of participation of stakeholders, and public policy deficiencies have not allowed for an appropriate implementation of relevant technologies for biowaste treatment (Silva-Martínez et al., 2020). On the other hand, the continuing increase of electricity demands in the region has forced local stakeholders to find ways to optimise existing waste treatment options which could allow energy recovery (Koldisevs, 2014). One such country is Chile, whose energy imports currently represent approximately 65% of its primary energy (Simsek et al., 2019) and 90% of its fossil fuels (Comisión Nacional de Energía, 2018a). However, Chile has a prominent silvoagricultural[1] sector: the agricultural, livestock, and forestry sectors account for around 2.9% of the country's GDP (Oficina de Estudios y Políticas Agrarias, 2019). This sector generates large amounts of organic residues from the production and export of products (Rodríguez-Monroy et al., 2018), but most is dumped or sent to landfill (Ministerio del Medio Ambiente, 2013). However, the utilisation of agricultural residues for energy remains very low. A total installed capacity of 42 MWe across eight biogas plants contributed to 0.4% of Chile's electricity supply in 2014. Two landfills in Santiago (Capital city) produce 83% of the nation's biogas, while 15% is produced in wastewater treatment plants, and 3% from manure and organic waste (Gaete-Morales et al., 2018). Biomass electricity which is mainly powered with inputs from the forestry sector contributes 2% of the country's total installed capacity, with around

[1]Forestry and agriculture

500 MWe (Tapia, 2019). A greater utilisation of waste-to-energy could contribute to climate change targets, waste reduction, increased energy security, resource efficiency, and air pollution reduction.

In Chile, 24% of primary energy in 2018 came from wood biomass (Comisión Nacional de Energía, 2018a). Firewood is primarily used for residential heating and cooking, while biomass is mainly used by cellulose and paper industrial sectors to self-supply electricity (Román-Figueroa et al., 2017). However, the informal nature of Chilean firewood markets results in degradation of forests and generates unwanted pollution (Schueftan et al., 2016). Also, as a result of widespread use of firewood for residential heating and cooking purposes, seven southern Chilean cities were ranked amongst the 10 most polluted cities in Latin America and the Caribbean in 2018 (IQAir AirVisual, 2018). The successful development of sustainable bioenergy depends firstly on the identification of biomass resources, as well as information regarding availability, characteristics, and geographical location. Secondly, the use of biomass should be managed and regulated carefully in order to guarantee sustainable outcomes (Rodríguez-Monroy et al., 2018).

Chile also produces 7.5 Mt/year of municipal solid waste (MSW), the third highest producer per capita in South America (D-Waste, 2020), where most is sent to dumps or sanitary landfill (SUBDERE, 2018a). This represents an under-exploitation of resources, but also results in the release of methane due to biogenic decomposition, and the importance of managing these emissions is gaining more and more prominence (European Commission, 2020). Municipalities pay an average of $40 per ton of waste to be collected, transported, and disposed (Martínez Arce et al., 2010), so there is also a cost incentive to divert organic waste from landfill, as well as resource efficiency, reduction of pollution due to waste transport, and environmental and social incentives.

Consequently, this research fills the knowledge gap of determining national organic waste potentials for bioenergy, by producing a comprehensive, up-to-date inventory and characterisation of organic waste in Chile, estimating the resource potential across different regions. Furthermore, this study conducts a series of stakeholder interviews and a proceeding policy assessment to determine barriers, and potential regulatory solutions, to enable greater utilisation of bioenergy from waste. The underlying data output from this study may be used by academia, industry, and policy makers to develop national and international decarbonisation pathways; energy, and waste valorisation policy; and to inform opportunities for investment in energy from waste processes.

2 Literature review

Bioenergy comes in several forms and can be derived from many sources, but whilst the theoretical potential bioenergy resource may appear high, several environmental, social, and economic constraints, which determine its sustainability credentials, substantially reduce it (Levidow, 2013). For example, the potential impact of bioenergy crops on afforestation and the availability of land for food significantly reduces available land for bioenergy crops (Searle and Malins, 2015). With respect to feedstock, dedicated perennial crops using marginal lands may be most economically and environmentally viable as they can exploit economies of scale (Whitaker et al., 2018) without distorting food markets (Searle and Malins, 2015). However, this is contested with research regarding further social implications. For example Montefrio (2012) argues that traditional agricultural practices of indigenous people can be at risk by large global biofuel demands. Furthermore, Raman and Mohr (2014) discuss that current global biomass commodity chains consist on poorer countries (Global South) exporting raw materials to the Global North, instead of exporting higher-value biofuels, which they argue is what was initially envisioned by early promoters of bioenergy.

The utilisation of Organic Waste-to-Energy (OWtE) technologies provides the potential for utilising biowaste (household organic waste, forest and agricultural residues) as bioenergy sources, without incurring in these issues (Silva-Martínez et al., 2020). Bentsen et al. (2014) demonstrated that there are considerable biomass resources that are technically available from agricultural residues alone.

Municipal solid waste (MSW) production rates are also expected to increase in around 8% globally from 2020 to 2025, given increasing urbanisation rates (Ali et al., 2020).

Each country has different resource and technology constraints and availabilities for OWtE, and present different barriers for uptake, depending on geolocations, climate, policies in place, competition with other sources, etc. Ali et al. (2021) compare a set of energy policies in Pakistan and analyse their impact on bioenergy development. The authors measure the effectiveness of these policies in terms of sustainability, understood as energy equity, security, environmental impacts, and economic aspects. They conclude that the share of bioenergy in the total energy mix is low, and among other measures they recommend diversifying the current national scope on bagasse, to other bioenergy sources such as agricultural and forestry residues, and municipal waste. They also recommend setting targets to promote the use of underutilised bioenergy resources in the country, and tailoring policies accordingly. Welfle and Alawadhi (2021) appraise bioenergy opportunities, barriers, and challenges in the Arabian Peninsula. This study firstly quantifies current MSW, crop residues, and indigenous resources, and estimates potential bioenergy generation from them. Secondly, the authors conduct a series of interviews and surveys to understand perceptions on bioenergy and barriers for its deployment. They identified that the greatest barrier in the Gulf Cooperation countries is high availability of cheap fossil fuels and fossil fuel subsidies. Cross et al. (2021) analyse the effectiveness of support policies for bioenergy (including waste-to-energy) in the UK, Denmark, Finland, and Sweden, through statistical tests and stakeholder interviews. They conclude that wider factors that are country-specific have greater impacts in bioenergy uptake than specific policies, and that countries should develop their own policy interventions to address their challenges. Some of the challenges identified in LAC towards the adequate implementation of OWtE technologies are classified mainly as institutional, financial, technical, and educational (Silva-Martínez et al., 2020), with achieving economic feasibility of the projects being one of the main ones(Silva-Martínez et al., 2020) due to high technology, production and maintenance costs involved. The cost from generating biofuels or biogas from residues in the region are, in general, still higher than the fossil fuels resources tariff currently in the market (Silva dos Santos et al., 2018). All these studies show that barriers for uptake of bioenergy from waste technologies are highly dependent on each country’s conditions, in terms of available resources, policies, and economies.

Other studies have assessed the potential of specific bio-waste streams for energy generation. For example, Chang et al. (2019) appraise the bioenergy production potential form biomass waste of rice paddies and forest sectors in Taiwan. They conclude that current bioenergy levels can be more than tripled by converting biowaste to bioethanol and/or combusting it. Afolabi et al. (2021) assess Nigeria’s bioenergy potential from agrifood loss and waste, finding that generation potential is enough to supply national 2030's bioenergy targets, and concluding with a set of recommendations for sustainable uptake of bioenergy generation from agrifood waste. Mai-Moulin et al. (2021) state that sustainability criteria and regulation must be in place to ensure that bioenergy from waste actually represents an enhancement to sustainability.

With regards to Chile, many studies have considered the potential for biofuels to contribute to the country’s sustainable energy future. Rodríguez-Monroy et al. (2018) describe Chile’s status regarding non-conventional renewable electricity generation, focusing on biomass. They found that while the country has a high potential for producing and utilising biomass and biofuels, there is a low use of these sources of energy for electricity generation. Moreover, the authors suggest that Chile should further develop research in the production of liquid biofuels for use in industrial processes and transportation systems in order to diversify its energy matrix, reduce its dependency on fossil fuels, and increase its sustainability. García et al. (2011) describe Chile’s status regarding the production of liquid biofuels. They conclude that second-generation technologies for synthesising biofuels from forestry and agricultural waste and residues are promissory for reducing the country’s dependence on liquid fuels, and reducing its GHG emissions. Bidart et al. (2014) perform a national assessment of energy generation potentials from manure and crop residues. They find that biomass is concentrated in a few zones and suggest implementing a bioenergy policy focused on specific regions, articulated with local governments. The authors also conclude that producing electricity from manure and crop residues is more economically feasible than producing biogas, and that farms could produce heat and electricity for self-use, or for injecting into the grid, providing flexibility to energy projects. Seiffert et al. (2009) focus more specifically on the potential for biomethane production, concluding that approximately 84% of natural gas consumption in 2015 could be substituted with biomethane produced from the forest sector and wood processing industry. The idea of searching for and implementing affordable waste-to-energy (WtE) strategies has been lately gaining momentum and fostering debate on whether specialised technologies, such as thermochemical or biochemical, could assist on supplying local energy demands (Silva-Martínez et al., 2020). Table 1 shows previous studies that have quantified organic waste sources and estimated different energy generation potentials in Chile, describing their main focus. Findings from these four studies will be presented and compared with results from this current work in Section 4.

Table 1: Previous studies quantifying energy potentials from different organic waste and residue sources in Chile.

Reference	Main focus
Chamy and Vivanco (2007)	Estimate biogas generation potential from residual or waste biomasses from different sectors (industrial, agriculture, wastewater treatment).
Zaror et al. (2009)	Estimate agricultural residue energy potential based on total arable landmass.
Bidart et al. (2013)	Technoeconomic assessment to estimate gas-to- energy, waste-to-energy, and gas collecting potentials from MSW.
Bidart et al. (2014)	Estimate electricity and bio syngas generation potential form manure and agricultural residues.

At smaller scales, several authors have investigated the potential of biowaste-to-energy technologies for specific case studies in Chile. Román-Figueroa et al. (2017) estimate the potential for producing electricity from wheat straw residues in the Araucanía Region in Chile. They found that 5MWth fluidised bed gasifiers followed by a combined cycle of gas and steam were the recommended technologies for this region, due to spatial dispersion of residues. Montalvo et al. (2020) evaluate the potential for biogas production from a vineyard site waste. They characterised the different residues physically and chemically, showing that all had favourable properties for producing methane. The authors concluded that using the different residue streams with adequate technologies, the potential biogas production was enough to cover all the energy needs from the plant. Casas-Ledón et al. (2019) perform a techno-economic and environmental analysis of implementing small-scale gasification systems with internal combustion engines into sawmills in Chile, to understand potentials for forestry residues for heat and electricity onsite generation. They conclude that although the systems are not economically viable due to high capital costs, they could bring good environmental benefits and aid in the Chilean energy system's decarbonisation. While all these studies show that many of the biowaste resources remain un/underexploited, there is limited data available on the specific characteristics of agricultural and municipal waste across Chile, which is required to estimate the bioenergy potentials. Furthermore, several socio-economic and regulatory barriers may exist to greater uptake of bioenergy from waste technologies, but these remain so far unexplored.

As highlighted in this review of the literature, previous studies show that barriers for uptake of bioenergy from waste technologies are highly country-specific and should be addressed with tailored policy instruments that take into account each country's available resources, current policies, economies, and local barriers. The novelty of this work is that it firstly spatially quantifies and characterises organic waste-to-energy potentials for the case study of Chile, and secondly identifies barriers for deployment and subsequent tailored policy recommendations.

3 Methods

This study applies quantitative and qualitative methods to assess the energy potential and future exploitation of bioenergy from waste in Chile. Section 3.1 details the quantitative framework for estimating the energy potential from bioresources across the country and its regions; while section 3.2 describes the qualitative assessment framework that was carried out to identify barriers and enablers to exploit bioenergy in Chile.

3.1. Energy potential from bioresources from waste – quantitative assessment

The quantitative assessment framework starts with quantifying the bioresources from waste considered in this study and their data collection approach. After that, energy potential is estimated based on the methodological framework defined for each bioresource. To avoid bias toward specific technologies such as those based on biogas, this study uses embodied energy concept to estimate the energy potential of bioresources, from here on called bioenergy potential. Following, a description of each bioresource is presented, followed by the data collection and finally the methodology to quantify the resources and further bioenergy potential of each bioresource.

3.1.1. Definition and data collection of bioresources

In total, the Chilean mainland covers 75.6 million hectares (Paneque et al., 2011), with 21 million hectares used by the forestry and silvoagricultural sectors. In the silvoagricultural sector, annual crops (cereals) and perennial are the largest land users with 1.3 million hectares while forage consists of 0.4 million hectares, as seen in Figure 1.

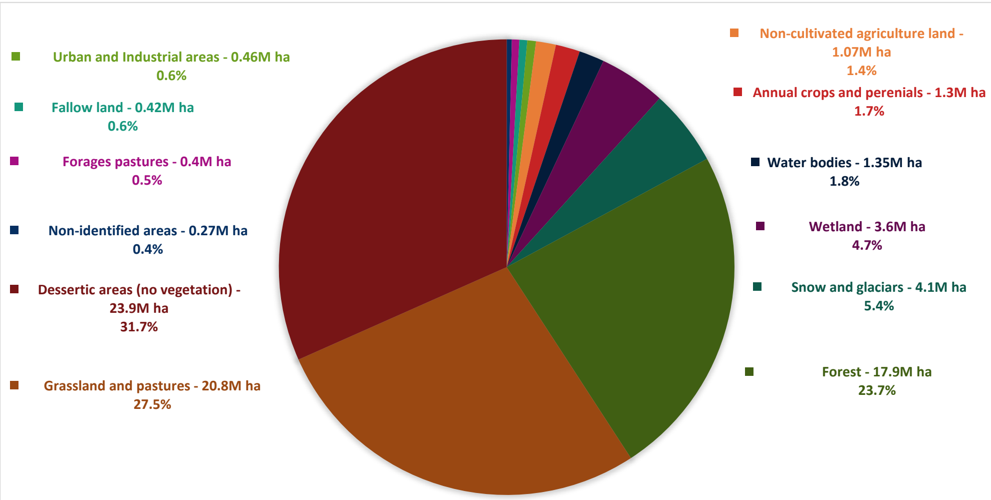


Figure 1. Distribution of land use in Chile by activity. Figure adapted from (Paneque et al., 2011).

Annually, Chilean households produce around 0.51 tonnes per household of food waste, nearly 2.5 times more than in Europe (Muñoz et al., 2018). The organic fraction of municipal solid waste (OFMSW) is also considered as a bioenergy resource under suitable conditions (Moya et al., 2017). This is particularly true in countries with a high OFMSW like Chile, where over 50% of MSW represent organic components (Muñoz et al., 2018). Landfilling, in legal and illegal facilities, is still the main waste management option for municipal waste in Chile. In addition to sanitary and economic issues, waste disposal contributes to climate change, adding 3.1% of total GHG emissions of the country (Sánchez Ramírez et al., 2018). These are some of the drivers to explore the valorisation potential, in this case as waste-to-energy, of bioresources that could contribute to economic and social development (i.e. Sustainable Development Goals (SDG) 12, 7 (United Nations, 2020)) reduce costs associated to waste management and energy generation, and finally reduce or avoid emissions associated to these activities.

Based on this information and data availability, this study accounts for the following bioresources: at farm gate, annual crops and horticultural residues, and livestock manure. OFMSW has been included because of the low utilisation when considering the large amount produced in the country. Although forestry residues and wastewater sludge are a key component of the bioenergy potential of Chile, they were not considered as they are already used for heating and electricity generation by their correspondent sectors (Rodríguez-Monroy et al., 2018). Some studies have already estimated the potential energy contribution of forest biomass (Bertran Spichiger and Morales Verdugo, 2008), and the potential of different bioenergy outcomes including electricity, biodiesel and ethanol from forestry and agricultural wastes Paneque et al. (2011). Following, a description of each bioresource and data acquisition.

3.1.2. Bioresources

Livestock manure*:* the manure generated by six main animal species, including bovine for meat and dairy, equine, poultry (chicken and turkey), ovine and goats, and swine. Inventory data was obtained from (Oficina de Estudios y Políticas Agrarias, 2021b); Oficina de Estudios y Políticas Agrarias (2020), where information about type of livestock raring by year and the proportion of livestock age and gender were found to determine annual stock (heads). This information was then used together with data about manure, which was estimated using literature (American Society of Agricultural and Biological Engineers, 2005; Einarsson and Persson, 2017; Riva et al., 2014).

Crop residues*:* consists of residues from annual crops (20 categories) and horticulture (21 categories of vegetables and 25 of fruits[2]). The inventory was built using data obtained from national statistics (Oficina de Estudios y Políticas Agrarias, 2021a; Oficina de Estudios y Políticas Agrarias, 2020) and FAO (Food and Agriculture Organization of the United Nations, 2019).

Organic fraction of municipal solid waste (OFMSW): accounts for the organic components of the municipal waste, which in Chile is 58% on average (SUBDERE, 2018b). The total amount of organic residues is determined using data from Ministry of the Environment (MMA, 2018) for the country and Sub secretary of Regional and Administrative Development (SUBDERE, 2018b) per region.

Biomass feedstock supply and quality is inherently variable (Kenney et al., 2013) including interannual variability at the same sites (Stephen et al., 2010), while bioenergy generators require predictable feedstock supply to justify capital expenditure.. Hence, to address this variability and ensure a comprehensive and robust analysis, this study uses data spanning 10 years, during the agricultural period between 2007/08 to 2017/18. The energy potential is then assessed based on an average from the last 10-year period, including minimums and maximums to account for variability and for the appraisal of projects that require a “minimum” level of residues. Details of annual crops, horticulture, and livestock manure calculations can be found in Table S1-3 in the Supplementary Information (SI). Due to lack of available information at the time of this study, OFMSW only considers data from 2017 (SUBDERE, 2018b). For details, see Table S6 in the SI.

It is also important to note that in the 10-year period considered in this study, geopolitical changes were implemented in Chile. These changes refer to increasing the number of regions from 13 to 16. During 2006/07, two new regions – Arica y Parinacota (XIV) and Los Ríos (XV)- were declared and implemented, re-structuring the geopolitical organisation of the country (MinInterior, 2007a, b). Similarly, in 2017/18 a sixteenth region, Region Ñuble (XVI), was created (MinInterior, 2017). Hence, regional data produced by Office of Agrarian Studies and Policies (ODEPA) have changed in structure

[2] Residues from wine and pisco grape production are also included as part of the fruit category. The inventory was built using data obtained from national statistics Oficina de Estudios y Políticas Agrarias, O., 2020. Estadísticas productivas. Oficina de Estudios y Políticas Agrarias, ODEPA. and literature.

across the period of this study, which is reflected in this analysis. To account for these changes, this paper considers the changes up until 2006/07 (15 regions). The last partition, Region Ñuble (XVI), is aggregated with Region Biobío. Table 2 shows the regions considered in this study with their number correspondence and abbreviations.

Table 2: Chilean regions from north to south – Official names, numbers, and abbreviations used in this study. A map of these regions is given later in Figure 6.

Region	Abbreviation	Number	Population	Land area (km^2)
Región de Arica y Parinacota	Arica y Parinacota	XV	226,000	16,873
Región de Tarapacá	Tarapacá	I	331,000	42,226
Región de Antofagasta	Antofagasta	II	608,000	126,049
Región de Atacama	Atacama	III	286,000	75,176
Región de Coquimbo	Coquimbo	IV	758,000	40,580
Región de Valparaíso	Valparaíso	V	1,816,000	16,396
Región Metropolitana de Santiago	Metropolitana	XIII	7,113,000	15,403
Región del Libertador General Bernardo O'Higgins	O'Higgins	VI	915,000	16,387
Región del Maule	Maule	VII	1,045,000	30,296
Región del Biobío + Región de Ñuble	Biobío & Ñuble	VIII	2,037,000	37,069
Región de La Araucanía	La Araucanía	IX	957,000	31,842
Región de Los Ríos	Los Ríos	XIV	385,000	18,430
Región de Los Lagos	Los Lagos	X	829,000	48,584
Región Aysén del General Carlos Ibáñez del Campo	Aysén	XI	103,000	108,494
Región de Magallanes y de la Antártica Chilena	Magallanes	XII	167,000	132,297

3.1.3. Bioenergy potential

To estimate the bioenergy potential (Ep) of each bioresource, first we need to estimate the feedstocks that are available for this purpose. This study follows the methodologies described by (Riva et al., 2014) (see Figure 2).*Theoretical biomass potential* ($ThBP$) is the maximum value produced and acts as the upper limit (Daioglou et al., 2016). The relevant product to ratio (RPR) refers to how much unused crop residue could remain after harvesting a crop (Long et al., 2013), while B is the biomass production. The *Technical biomass potential* (TBP), is used for determining the livestock manure and crop residues that could be realistically collected or recovered. In other words, it refers to the portion of the theoretical biomass potential that would be available for energy applications, once current uses (Riva et al., 2014) and logistical factors, such as losses from collection and storage have been considered (Long et al., 2013). For these cases, N is the number of animal heads, and L is the average manure generated by each livestock type, per year. Similarly, in the case of crop and horticultural residues, *Sustainably available biomass* (SAB) accounts for the proportion of the theoretical biomass potential that realistically could not be collected due to ecological reasons (Daioglou et al., 2016), for example due to the threat of soil erosion or nutrient loss (Searle and Malins, 2015). Here, MC represents moisture content. The availability factor (AF) determines the technical and sustainably available biomass through accounting for technical and ecological losses. AF is obtained from the literature (see details in Table S1 in the SI). Finally, LHV is the lower heating value of each waste stream.

Figure 2 summarises the step-by-step methods to estimate the resource and energy potential for each bioresource included in this study. For detailed methodology, see the Supplementary Information (SI).

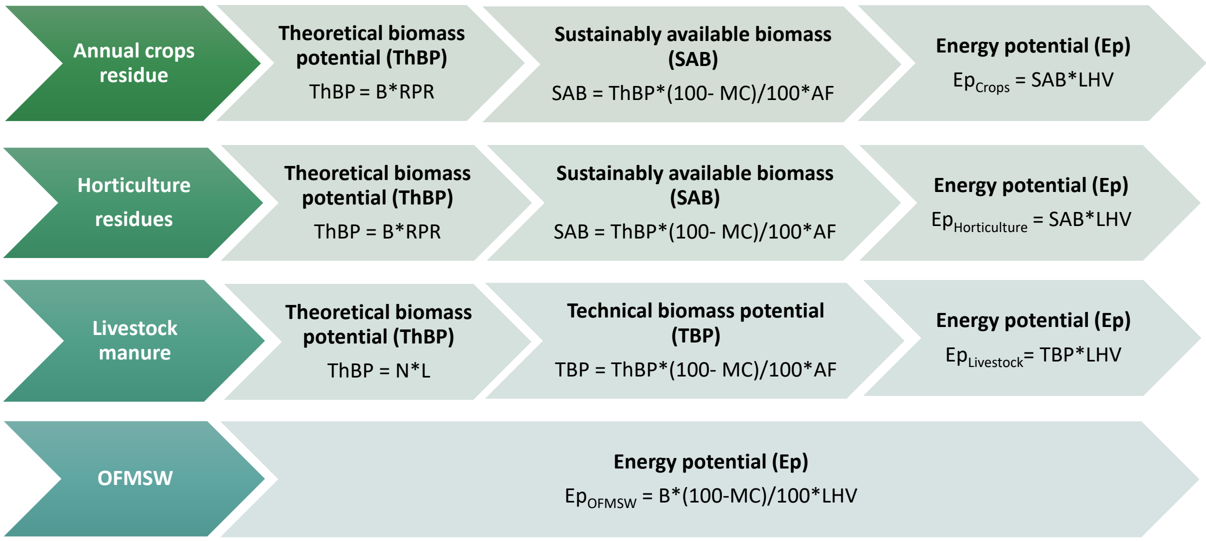


Figure 2. Methodology for estimating energy potential from bioresources, adapted from (Avcıoğlu et al., 2019; Daioglou et al., 2016; Long et al., 2013). *Detailed description in SI. [**B**: Biomass production, in this case crop production (t); **RPR:** Relevant Product to Residue ratios; **ThBP:** Theoretical Biomass Potential (t); **MC:** Moisture Content (%); **AF:** Availability Factor also known as recoverability factor; **SAB:** Sustainably Available Biomass (t); **Ep:** Energy potential of residue (MJ); **LHV:** Low Heating Value (MJ/t); **N:** number of animal (heads); **L:** Average manure generated by each livestock type]*

Tables S1-3 and S6 in the SI summarise data use for estimating the resource potential and bioenergy potential of annual crops, horticulture, livestock and OFMSW. It should be noted that some crop residues are already used as animal feed (Ji, 2015; Scarlat et al., 2015) and manure is widely used as a fertiliser or soil amendment (de Groot and Bogdanski, 2013), whilst other agricultural residues are used as raw materials for industrial uses (Ji, 2015) such as medicine and biomaterial production (Scarlat et al., 2015). However, very little information exists on current uses of residues in the Chilean context, and the information found is based on isolated initiatives of private companies, or general information stating that crop residues are burnt in fields (Gaete-Morales et al., 2018). Consequently, alternative uses are not considered within this study.

3.2. Qualitative assessment framework

The aim of the qualitative assessment of bioenergy potential is to investigate the socio-political, economic, and institutional conditions under which relevant actors from the bioenergy supply chain operate. To answer the defined research question on barriers to bioenergy proliferation in Chile, the qualitative assessment was undertaken in two parts. An initial literature review was conducted to give insights on the topic within the Chilean context, and to study the methods deployed for information gathering in similar barrier analyses for the renewable energy sector. Having consulted other barrier analyses such as barriers to renewable energy in the Caribbean (Blechinger et al., 2015); barriers to energy efficient technologies in buildings (Dadzie et al., 2018); and barriers for the biogas sector in India (Mittal et al., 2018); semi-structured interviews were found to be a commonly deployed data gathering tool. This type of data collection offers a flexible approach based on open-ended questioning (Dadzie et al., 2018) and places emphasis on the expertise and insights of the respondents, allowing the interviewer to pursue in-depth information around the topic (Zou et al., 2019).

3.2.1. Sampling

As in Zou et al. (2019) and Carleton and Becker (2018), purposive sampling was conducted to assess prospective respondent's potential contribution to the knowledge about bioenergy potential in Chile and barriers to development of this sector. The expertise of the respondents was clustered into four broad disciplines: waste generation; waste management; bioenergy researchers and developers; and professionals working energy and environmental policy. The invited interviewees were considered based on: i) significant experience and knowledge of the discipline and ii) knowledge of the discipline within the Chilean context. Table 3 lists the respondents selected for the interview along with their roles in the sector.

Table 3. Profile of the interviewees

Respondent[a]	Discipline	Occupation
R1	Bioenergy R&D	Academic, Bioenergy research
R2	Energy and Environmental Policy	2 interviewees (in the same interview): Office for Circular Economy, Ministry of the Environment
R3	Waste Management	Municipal-level project manager in waste
R4	Waste Management	Community-level waste manager
R5	Bioenergy R&D	Decision-maker at a company that develops biogas installations in the agricultural sector
R6	Energy and Environmental Policy	Sustainability professional at non-profit thinktank
R7	Energy and Environmental Policy	Social science researcher with expertise in environmental policy
R8	Bioenergy R&D	Professional working at a non-profit dedicated to development of bioenergy in Latin America
R9	Bioenergy R&D	Decision-maker at company that develops bioenergy installations from energy crops
R10	Bioenergy R&D	Director at a company working in bioenergy generation and co-generation
R11	Energy and Environmental Policy	Professional from the Sustainable Energy Agency
R12	Bioenergy R&D	Researcher at a biotechnology company
R13	Bioenergy R&D	Decision-maker from a forestry and paper product company
R14	Waste generation	Environmental manager at a recognised Chilean vineyard
R15	Waste Management	Professional with experience with energy generation from landfill
R16	Energy and Environmental Policy	Professional at the Environmental Impact Service
NR (8)	No Response	Eight identified stakeholders did not accept invitation to participate

[a] Participants were presented with information about the study prior to interviews and gave permission for their responses to be used for qualitative analysis, MSc Thesis, and this publication.

3.2.2. Semi-structured interview

Interview questions were designed to: i) contextualise the socio-political and regulatory conditions under which possible bioenergy projects must operate; ii) identify where bioenergy projects are succeeding and failing, and why; iii) identify policy and governance mechanisms, voluntary or compulsory, that could serve as solutions to the identified barriers. A set of guidelines including a list of questions was used to give thorough attention to issues identified during review of the literature. However, supplementary questions were added depending on the responses received during the interview, thus remaining receptive to any additional relevant information that the interviewee had to offer. The interview questions have been included in Table S8-9 in the SI, in English and Spanish. In total, 24 stakeholders were invited to participate in the study, with 16 interviews conducted overall.

3.2.3. Interview analysis

Our analysis of the semi-structured interviews was based upon deductive thematic analysis (Nowell et al., 2017). Thematic analysis was selected because it offers an iterative, flexible framework for analysing interview data, which was desirable considering the mixed methodology of this paper. The deductive approach was favoured because it enables interview data to be framed within a real-world context, which gives the data meaning (Vaismoradi et al., 2013).

Each interview was summarised following Braun & Clarke's six-phased framework for thematic analysis (Nowell et al., 2017), used to identify emergent themes from the interviews. These were organised into Table 4, where a tally of references to themes by respondents is given. These themes were iteratively reviewed across several team meetings to ensure their coherence before the authors clustered the themes into four broader organising themes, or core themes. The naming and inclusion of some themes and core themes changed throughout this process. Once finalised, a detailed analysis was then conducted on each theme and cross-referenced with the literature, which formed the basis of the qualitative results and parts of the discussion.

4. Results and discussion

This section first presents the results of the quantitative assessment, starting with the estimations of bioenergy potential (section 4.1) followed by an analysis of the opportunities ant preliminary strategies for the use of these bioresources across the country (section 4.2). After this, the results of the qualitative assessments are presented and discussed (section 4.3).

4.1. Bioenergy potential in Chile

The total bioenergy potential from the assessed bioresources across Chile is estimated to be 78 PJ/yr. Putting this in context, total final energy demand from all sectors in Chile in 2018 was 2,380 PJ (Comisión Nacional de Energía, 2018b). The potential bioenergy is thus 3.3% of total Chilean energy demand. It must be noted that not all this bioenergy potential would meet demand due to conversion efficiency losses. Nevertheless, with conversion efficiencies of ~60% as per anaerobic digestion (AD) processes (Whiting and Azapagic, 2014), this represents a substantial opportunity.

The bioenergy potential varies widely across regions, as shown in Figure 3. Regions with the largest bioenergy potential were O'Higgins and Metropolitana, which together contribute 43% of total resource (see Table S1-4 in the SI), but only 4% of total land area.

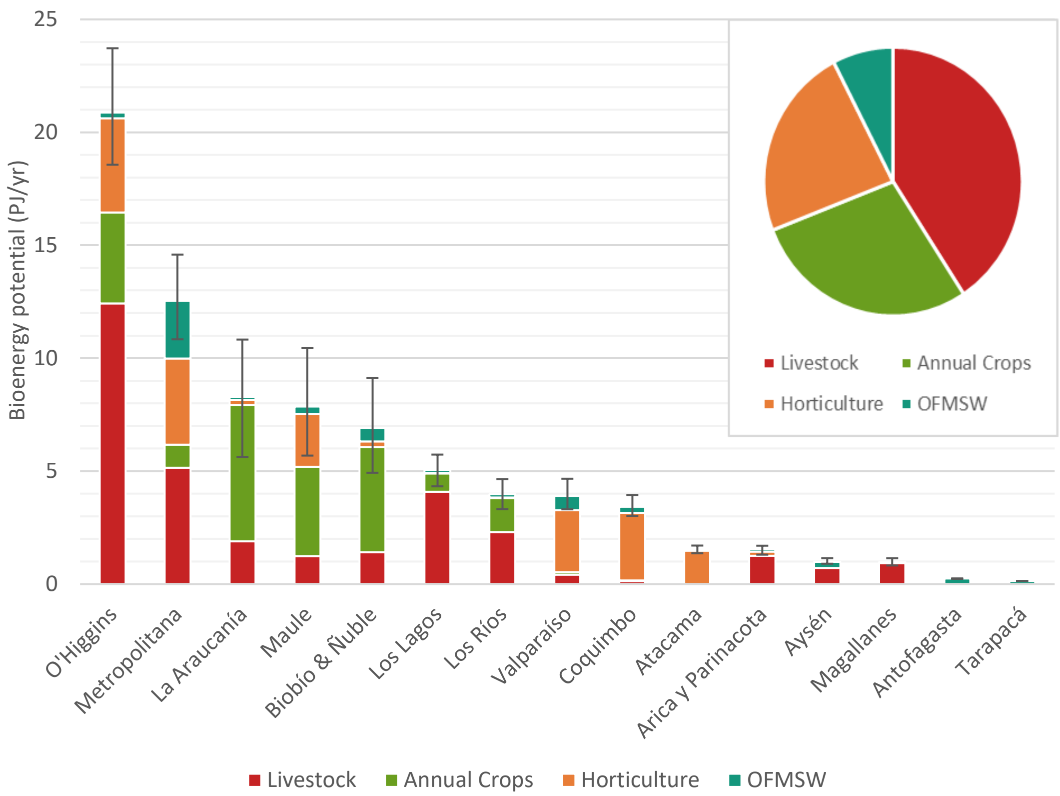


Figure 3. Summary of bioenergy potential for each region in Chile, divided by the type of bioresource, ranked by total contribution. The inset figure (top-right) summarises the total bioenergy potential per resource.

The main bioresource is livestock manure, contributing 41% of total, followed by annual crops contributing 28%, horticultural crops 23% and OFMSW 8%. Almost all residues mainly come from three regions, O'Higgins, Metropolitana and Maule, as indicated in Figure 4. These regions together contribute 59%, 41%, 57% and 53% to livestock, annual, horticulture and OFMSW respectively. The other key contributing region are Bíobío & Ñuble and La Araucanía which together produce ~48% of annual crop residues.

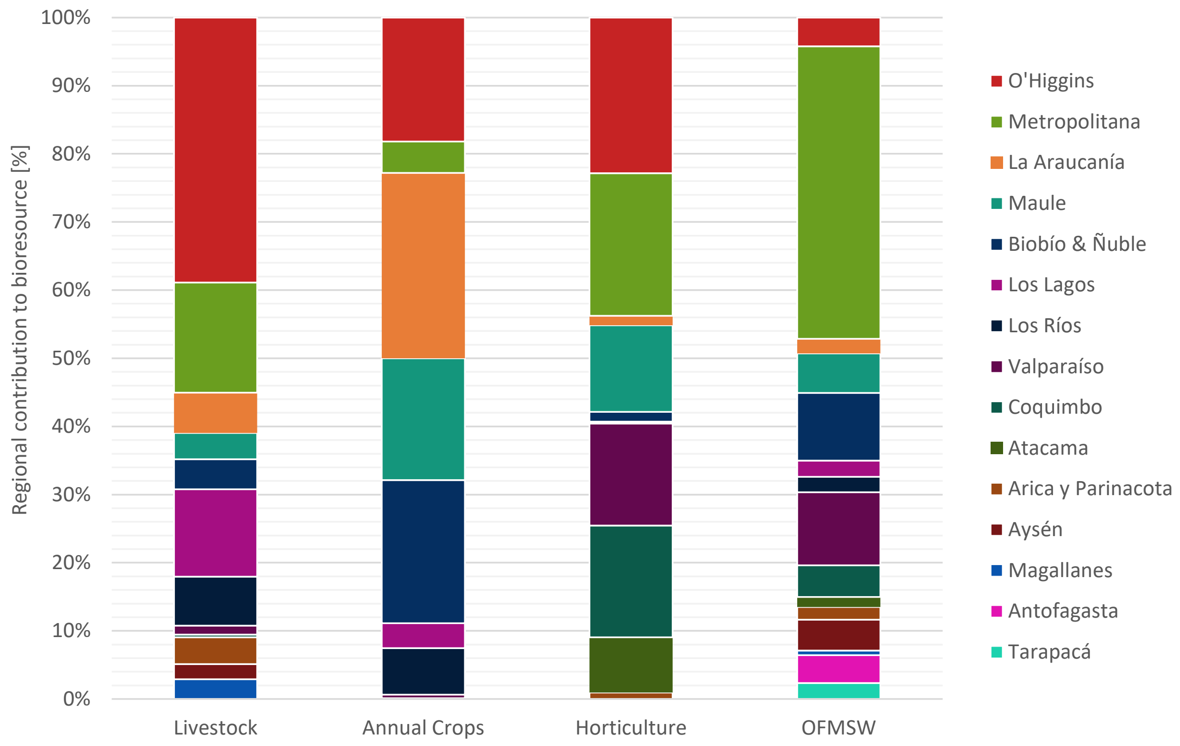


Figure 4. The contribution of each region to total waste bioenergy resource category, in the order to total contribution

Livestock manure has the potential to generate 31.9 PJ; O'Higgins region contributes 39% of the bioenergy potential, followed by Metropolitana (16%) and Los Lagos (13%). Manure from chicken and dairy cows are the largest sources, generating nearly 70% of the bioenergy. Manure from swine is the third contributor with 19%. Figure S1 and Table S4 in the SI show detailed results.

Residues from annual crops could produce 22.2 PJ, distributed mainly in four regions – O'Higgins (18%), Maule (18%), Bíobío & Ñuble (21%) and La Araucanía (27%). Across 20 crop categories, three bioresources dominate: rice straw (30%), wheat (26%) and maize stalks (17%). More details in Figure S2 and Table S5 in the SI.

Bioresources from horticulture production contribute 24.2 PJ with nearly 90% coming from fruit residues and the rest from vegetable residues (see Figure S3 in the SI). Overall, five regions contribute up to 90% of the potential bioenergy generated by horticulture residues, namely Coquimbo (18%), Valparaiso (13%), Metropolitana (18%), O'Higgins (23%) and Maule (17%). Olives, oranges and wine grapes account for 54% of the bioenergy potential (see Figure S4 in the SI). Similarly, the bioenergy potential of vegetable residues is driven by onions, corn and carrots, adding together 43% (see Figure S5 in the SI). Table S7 in the SI summarises bioenergy potential from horticulture.

Figure 5 shows the comparison of these results with the available literature for the Chilean context. Four studies were found and able to use for the comparisons. Chamy and Vivanco (2007) estimate the biogas potential for various waste resources including MSW, wine, agricultural crops and livestock. Bidart et al. (2013) estimate the resource potential of energy from MSW in Chile for different end-use applications, whereas another paper by the same authors (Bidart et al., 2014) estimates resource potential for livestock and crop residues. For OFMSW our results are bounded by those from Chamy and Vivanco (2007) and Bidart et al. (2013). For livestock, our estimate is similar to Chamy and Vivanco (2007), but substantially higher than Bidart et al. (2013) who do not include poultry, which is a substantial contributor to our study, and key food source in Chilean diets. For agriculture, our study is 3.7 times larger than the other two estimates. It is not clear how the Chamy and Vivanco (2007) estimate is developed, whereas Zaror et al. (2009) provide a simple estimate of agricultural residue energy potential based on total arable landmass. We suggest that our figure includes a more comprehensive range of agricultural activities, including crops that have not been studied before such as annual and horticultural, and estimates specific residue generation for each product and thus may represent a more comprehensive estimate than previous studies.

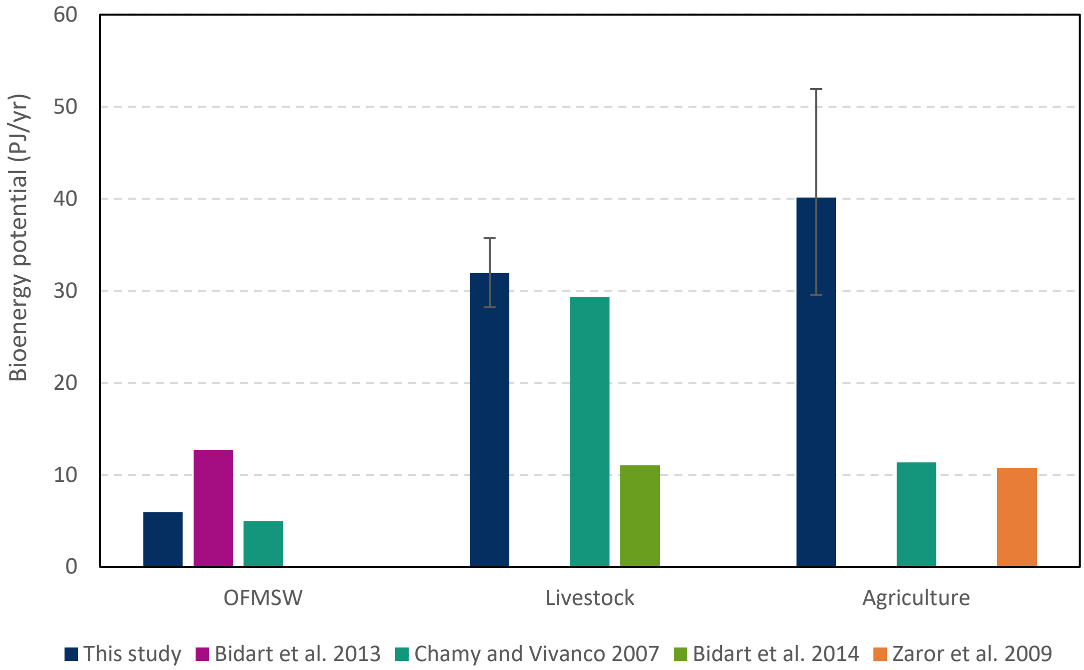
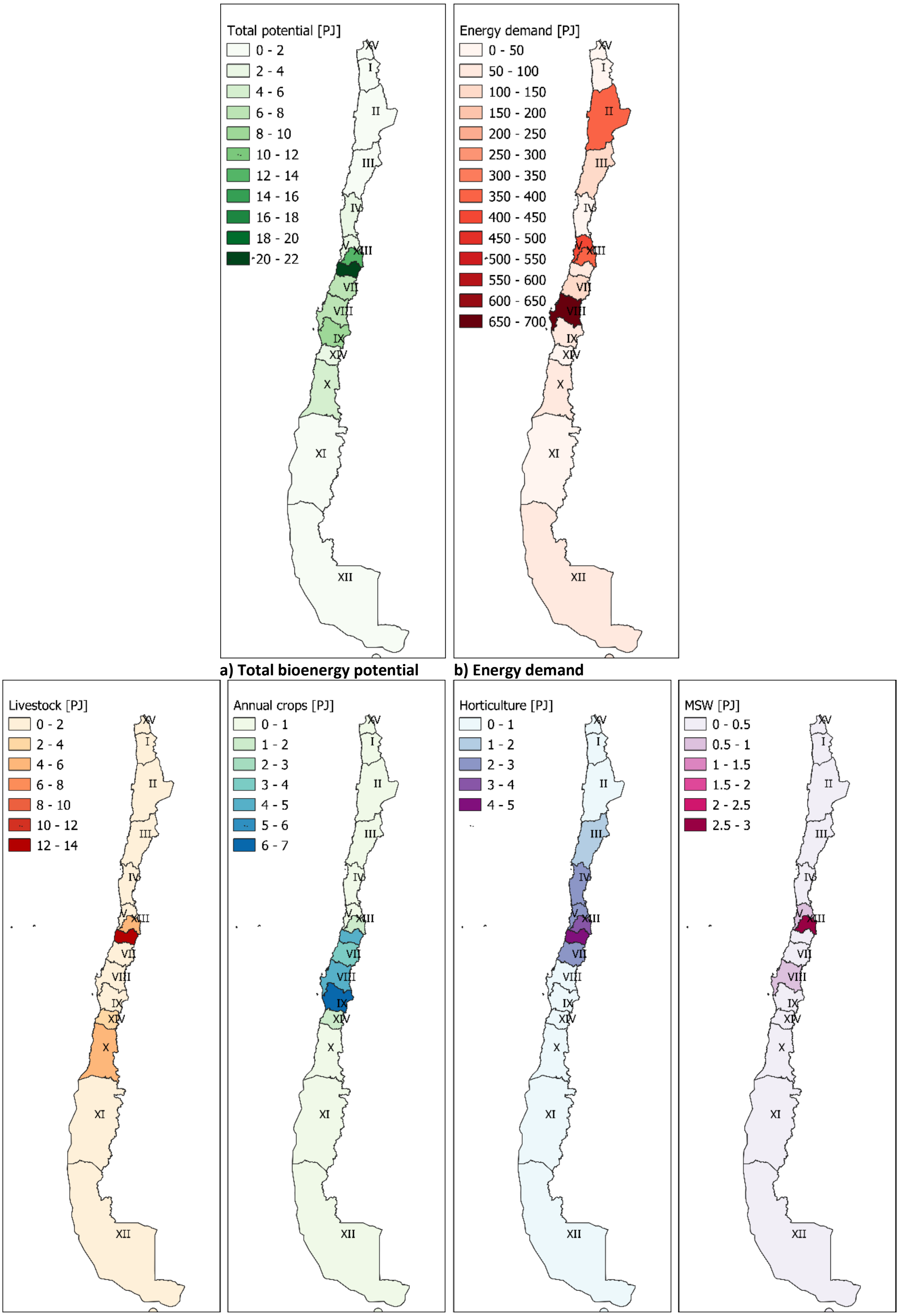


Figure 5. Comparison of results with other studies for OFMSW, Livestock and agricultural residues. Estimates are adapted into comparable units assuming anaerobic digestion efficiency of 75%, biogas LHV of 22 MJ/m³ and methane fraction of 60%w/w. Source: (Bidart et al., 2013, 2014; Chamy and Vivanco, 2007)

4.2. Regions with greatest potential for utilisation

As described previously, there is a large variation in bioresources throughout the country with two regions producing 42% of the total bioenergy potential. But in order to be cost-effective for utilisation, those with large resource much also be matched with appropriate demand and a proximity to this demand, among other factors. The scope of this study does not include sufficient granularity to estimate proximities of specific waste generators and consumers, but we utilise regional characteristics to infer the areas with greatest potential for waste utilisation, namely land area, population and energy demand. Each region has different combinations of land area, energy demand, bioresource potentials of different categories as shown in Figure 6.



a) Total bioenergy potential **b) Energy demand**

c) Bioenergy potential per bioresources

Figure 6. Regional breakdown of total bioenergy potential (a) compared with total energy demand (b), and breakdown of bioenergy potential from specific categories of bioresource (c)

As shown in Figure 6a&c, the central and central-south regions typically produce the greatest quantity of bioresources and possess the largest bioenergy potential. Additionally, they have the lower land areas, increasing the likelihood that resource may be closer to the demand (see Figure

6b). Figure 7 shows the different regions bioenergy potential versus land area, where those with higher potential and smaller area may be favourable from a cost-effectiveness perspective; for instance Maule, Metropolitana, and the O'Higgins regions present the most favourable scenarios, with the largest bioenergy potential (more than 50% of the bioenergy potential, see Figure 4) and some of the smallest areas.

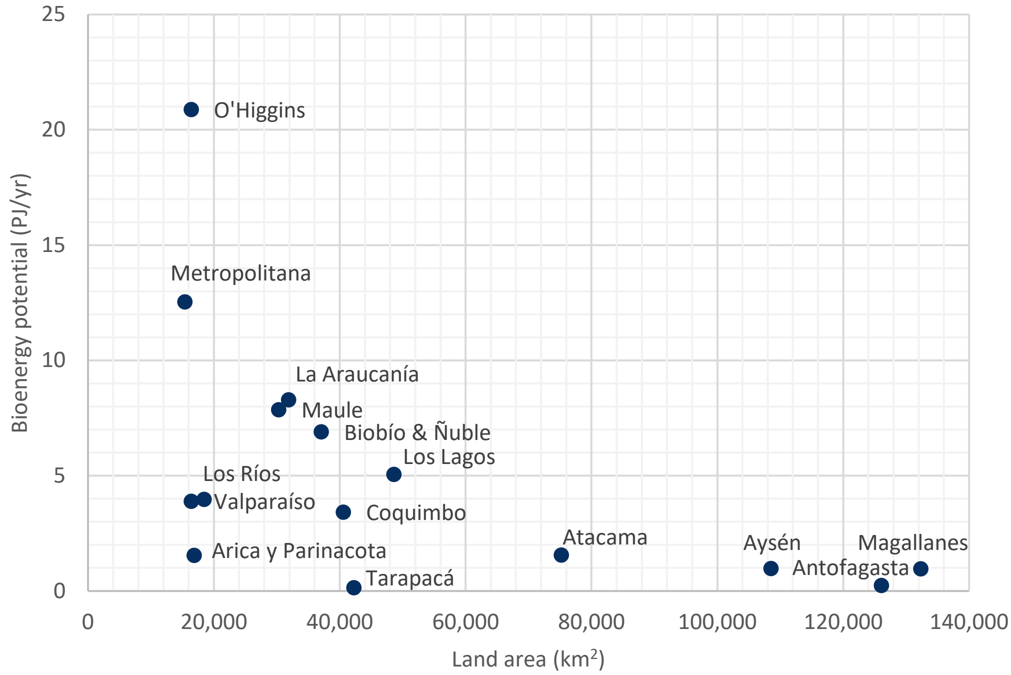


Figure 7. A comparison of the total regional waste bioenergy resource potential for each region versus the region's land area.

The potential contribution of bioenergy to meet demand is compared against each region's population density in Figure 8. To provide a fairer comparison in meeting demand, a conversion efficiency is assumed from embodied energy in the biowaste to either biogas. It is assumed that MSW and manure are converted to biogas via anaerobic digestion at 75% efficiency (Global Methane Initiative, 2014). Crop waste is assumed to be converted to syngas via gasification at 62% efficiency (Sikarwar et al., 2016). Resource potential is compared against regional natural gas demand, implying that demand for natural gas can be offset by the upgrading of biogas.

Greater feasibility of utilisation or greater impact is implied with a higher contribution to total demand (greater magnitude) and with higher population density (greater proximity). There are only 4 regions with substantial natural gas demand, Metropolitana (46 PJ/yr), Valparaiso (56 PJ/yr), Antofagasta (41 PJ/yr) and Magallanes (53 PJ/yr). All other regions use less than 5 PJ/yr. Of the 4 high gas demand regions, only two produce substantial quantities of biowaste. Metropolitana has a potential energy contribution of 19% and with an order of magnitude higher population density than most other regions. Valparaiso also offers a potential large contribution with 5% of gas demand and population density of 110/km^2.

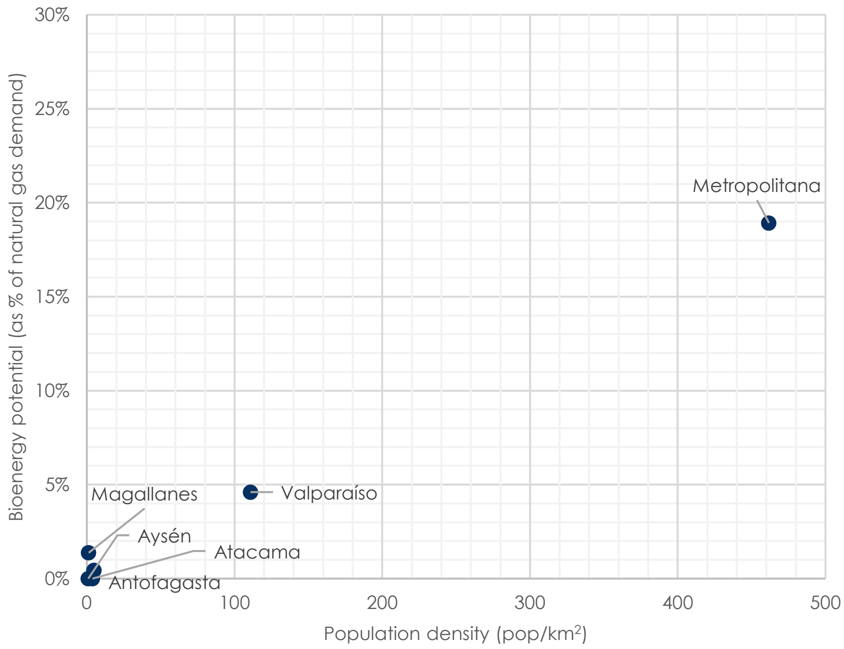


Figure 8. Waste bioenergy resource potential for each region expressed as a percentage of the regional natural gas demand, by land area. Resource potential assumes conversion of wet biomass (MSW and manure) via anaerobic digestion at a conversion efficiency of 75%, and dry biomass (horticultural and annual crops) via gasification at a conversion efficiency of 62%.

4.3. Qualitative assessment - Barriers for uptake

In summary, 14 different key barriers were identified from the interviews, categorised as either social, technical, economic, or institutional. In reality, there are various crossovers between categories, which are summarised in Table 4 and detailed within the present section.

Table 4. A summary of social, technical, economic and institutional barriers to greater uptake of biogenic waste valorisation

Theme	Sub-theme	Details	Count [a]
Social	Awareness of technology	Low awareness of technology	**7**
	Culture	No culture of separation, recycling of organic products	**5**
		Culture of firewood for heating, cooking	**5**
Technical	Technological barriers	High incidence of technical difficulties in the country e.g. in biogas	**9**
	Skills	Need to develop expertise in bioconversion technologies	**8**
Economic	Feedstock procurement	Cost of collecting, storing and transporting feedstock before treatment	**8**
		Seasonal and annual variability in feedstock availability	**5**
	Investment cost & Low investment attractiveness	Capital cost is prohibitively high	**12**
		Limited access to finance and provision of incentives	**12**
	Lack of competitiveness	Influx of solar and wind has lowered electricity prices. Not competitive against fossil fuels given low carbon price.	**10**
	Lack of formal market for products	Multiple revenue streams often needed to make bioenergy profitable, but lack of market for heat and digestate	**10**
	Cost of access to Infrastructure	Access to distribution and transmission infrastructure	**3**
Institutional	Policy-related challenges	Limited policy support, market intervention or absent regulation for waste management and energy recovery	**10**
	Disconnectedness of stakeholders	Limited cross-sectoral cooperation to develop sector (e.g. lack of national strategy between different Ministries)	**7**

[a] Count of references to 14 sub-themes given by respondents; these were used to defined core *themes.*

4.3.1. Social barriers

According to seven interviewees, the awareness of biomass conversion technologies, especially amongst waste generators, had been a barrier to uptake necessitating the establishment of a regulatory framework and regional or national-level programmes. While such a legal framework was established for biogas in 2016 (Ministerio de Energía, 2017) and has long existed for liquid biofuels (Rodríguez-Monroy et al., 2018), industry figures are still calling for a law to guide the energy valorisation of solid biomass (Tapia, 2019).

Two interviewees believed the poor levels of public knowledge of biomass and its role in Chile's energy system (Tapia, 2019) disadvantaged the sector both at a project and policy level. Additionally, with no regulatory signal to promote the separation of organic waste, there is currently no culture of organic waste recycling. South Korea has been able to achieve high food recycling rates since a 2005 law that banned the landfilling of food waste (Jain et al., 2019). Chile's Ministry of Environment has begun to work closely with Canada through the Reciclo Orgánicos programme (Reciclo Orgánicos, 2019) to give support to municipalities to reduce the landfilling of organic waste, as well as with the Italian embassy to develop a strategy around the valorisation of organic waste (Molina Alomar, 2019).

Four interviewees stressed the importance of educational initiatives to promote buy-in. Note that there is strong national opposition to the installation of anymore landfill sites (Bergamini et al., 2017) which offers an opportunity for the promotion of waste conversion technologies as a valuable alternative.

Meanwhile, the cultural significance of firewood for cooking and heating was also identified by three interviewees as a barrier to valorising residual biomass through lower-impact heating methods, particularly in Southern regions (Schueftan et al., 2016). However, one interviewee suggested that preferences are more influenced by the low cost of burning unregulated firewood and people would adapt if economically incentivised.

4.3.2. Technical barriers

It was suggested by eight interviewees, and in the literature, that the biogas (Salazar et al., 2016) and wider bioenergy sector's progress has been hamstrung (Rodríguez-Monroy et al., 2018) by the need to secure trained personnel for design, construction, operation and maintenance of bioenergy technologies. For example, in the agricultural sector, where 90% of agricultural land is owned by small and medium sized family-owned companies (Domínguez et al., 2019), there is limited practical experience in energy generation. To bridge this barrier, an understanding of both the business case and how to implement such a project is needed (Berg et al., 2013): Three interviewees said this was desperately lacking some years ago where there was greater momentum within the sector, before the creation of the regulatory framework. Government bodies attempted to rectify this through the provision of public training initiatives such as Constructing Skills for the Operation of Biogas in Chile (Universidad Adolfo Ibánez, 2018) and Specialised Training Course in Biogas for Professionals (Acuña and Moraga Paredes, 2017), which were supported by the Energy Ministry to complement the newly established regulatory framework.

However, the perceived risk of technical failure remains a barrier to adoption according to three interviewees. Indeed, the failure rate of 18% of the 104 attempted biogas projects in Chile so far suggests that improvements must be made (Sánchez Lizama, 2017). Similarly, evidence show that that over half of AD equipment is not operating correctly (Universidad Austral de Chile (2019).

To illustrate technical obstacles, one interviewee referenced the incorporation of AD in dairy farming. Principally located in IX and X regions where there is high incidence of rainfall, technical issues related to the storage and processing of the very wet slurry, which ultimately impacted the supply of feedstock to the digester. Furthermore, much of the equipment is adapted from other uses to lower costs, which can help explain the failures (Ávila Grothusen et al., 2016).

4.3.3. Economic barriers

4.3.3.1. Feedstock

Eight interviewees emphasised that accessing a secure feedstock supply ranked amongst the largest hurdles for bioenergy development in Chile. This challenge is consistent with the experience in most countries (Zandi Atashbar et al., 2017). Crops are harvested in certain months and it is costly to collect, dry and store residues (Lautala et al., 2015). Animal wastes cannot be exploited at all times since they are not always held in stables (Ávila Grothusen et al., 2016), and collection of manure from pastures is not technically nor economically feasible.

Two interviewees stressed that Chile's complex geography created unique challenges for the economics of bioenergy project development. The distribution and heterogeneity of biogenic waste streams means that it is difficult to find suitable quantities of feedstock. Transport distances are an important indicator for economic viability (Román-Figueroa et al., 2017), and with long transport distances, as well as insufficient and dispersed volumes of waste, costs become prohibitive (Einarsson and Persson, 2017). Three interviewees also noted how unlike countries where crops are grown for energy generation, Chile did not have surplus fertile land available for growing energy crops. This observation was referenced in (Rodríguez-Monroy et al., 2018).

4.3.3.2. Investment cost

Twelve interviewees identified the capital cost of bioenergy technologies as prohibitive (Carrasco Allendes, 2015). In the case of biogas production, investment cost was identified as US$3500/kW compared to only US$800-1048/kW for dispatchable gas-fired plants and US$970 for solar (Comisión

Nacional de Energía, 2019). Recent analysis shows important cost reductions for biogas, although this remains someway behind gas and solar generation (Bnamericas, 2020).

As an example, in this work we assume gasification and anaerobic digestion technology efficiencies to produce biogas from organic waste streams. Chanthakett et al. (2021) assess different gasification projects, obtaining payback periods between 8 and 18 years depending in the technologies and waste streams chosen. Anaerobic digestion projects have been found to have lower payback periods (3.8-9 years (Chowdhury, 2021; Huiru et al., 2019; Sganzerla et al., 2021)).

Seven interviewees said that for decision-makers at municipal or farm levels, where there are constrained budgets and competing needs, it is hard to justify capital expenditures such as anaerobic digestors or biomass boilers. For example, one interviewee revealed that the payback period of a biomass boiler at their vineyard extended beyond the company's permitted payback period for capital expenditure. Economies of scale can help improve the viability of bioenergy projects, with respect to lowering capital cost and diversifying feedstock supply. Several neighbouring waste generators may direct their residues towards a centralised facility (Lauer et al., 2018), as is commonly practiced in Denmark (Al Seadi et al., 2018). However, two interviewees argued that such cooperation was not in-tune with Chilean commercial culture.

Furthermore, as the government prepares to launch its first organic waste strategy, there is a declared preference for industrial and domestic composting schemes (Molina Alomar, 2020b), which have been shown to have lower capital cost and shorter payback periods (Cueto Codorniú, 2017).

4.3.3.3. Lack of competitiveness

Ten interviewees confirmed that a critical barrier for bioenergy development was the lack of competitiveness versus other generation methods. In Chile, electricity generation is selected via marginal economic dispatch (Rodríguez-Monroy et al., 2018). In recent years, average power prices have fallen sharply due to influx of wind and solar technologies, (International Energy Agency (IEA, 2018), enabling a more dynamic electricity market while delivering more renewable energy than is required by quota. During solar auctions average prices as low as US$32.5/MWh have been achieved with winning bids as low as US$21.48/MWh (Jäger-Waldau, 2019). This is considerably cheaper than the levelised cost of electricity for biomass of US$80/MWh (Revista Electricidad, 2019), which is also not needed to meet Renewable Energy Quotas.

Chilean energy law allows for the sale of heat and power to private clients, away from the regulated market where prices are higher, for generation over 500 kW. Two interviewees said that bioenergy generators can generate immediate value by entering such an arrangement. However, this does depend somewhat on co-location of bioenergy generation to nearby businesses, as well as securing demand for co-products.

Two interviewees suggested the marginalist pricing system put bioenergy projects at a disadvantage, by disregarding the multiple social and economic benefits generated such as reduced pollution, job creation and a high plant factor (Berg et al., 2013).

While bioenergy generation is stimulated in other countries through guaranteed subsidy payments or tax credits (Edwards et al., 2015), in recognition of these benefits, no such incentives are available in Chile's liberalised electricity market (Simsek et al., 2019) apart from a US$5/kg CO2 carbon tax levied on utility-scale power generation from which bioenergy is exempt and is anyway insufficient to impact bioenergy projects, according to three interviewees.

4.3.3.4. Lack of formal markets for co-products

Nine interviewees agreed that for bioenergy projects to become economically viable, waste generators need to identify markets for all available co-products of bioenergy from waste, including heat and digestate production as well as electricity or biomethane. Exploiting these co-products delivers essential environmental benefits (Tricase and Lombardi, 2012) by offsetting the use of alternative sources and conforms with the principles of a circular bioeconomy (De Schoenmakere et al., 2018) where energy and non-energy opportunities of residual biomass are exploited (Pfau et al., 2017).

Digestate can replace the use of imported fertilisers, which currently contributes 14.5% of Chile's GHG emissions from agriculture (Food and Agriculture Organization of the United Nations, 2019). A study found that maximum environmental benefits was obtained from an AD combined heat and power (CHP) plant where synthetic fertiliser was substituted with digestate (Whiting and Azapagic, 2014). However, there have been issues regarding the creation of a market for digestate (Universidad Austral de Chile, 2019) due to legal ambiguity regarding classification of digestate as a fertiliser. Since digestate is legally regarded as a by-product rather than a commercial good, the creation of a consolidated market is not presently possible (Universidad Austral de Chile, 2019). Consequently, digestate is sold very cheaply, at a price well below that of compost-derived fertiliser (Carrasco Allendes, 2015).

Amid growing renewable power sources in Chile (Simsek et al., 2019), several interviewees suggested an increased role for bioenergy in heat generation to improve project economics. In Chile's case, there are compelling socioecological arguments for directing bioenergy technologies towards heat generation. This could simultaneously lower pollution (Schueftan and González, 2013) and alleviate deforestation (Azócar et al., 2019). However, there is a clear preference for firewood for heating, the most readily available option (Schueftan et al., 2016). Additionally, storing and transporting the heat would imply prohibitive costs (Sartor and Dewallef, 2017) that would necessitate significant government support.

Studies are being conducted to assess the viability of technologies such as district heating to complement Chile's broad biomass options (Stemmelen, 2018). This is being trialled in the worst-affected cities such as Temuco and Coyhaique (EBP Chile, 2016), and although woody biomass would be the preferred feedstock, district heating fuelled by agricultural waste such as straw is already utilised in other countries (Al Seadi et al., 2018).

Where there is no local heat demand, another commercial opportunity is the upgrading of the gas to produce biomethane. Unlike the UK and Germany (Horschig et al., 2016), Chile does not have an extensive natural gas network (Edwards et al., 2015; Horschig et al., 2016), which may reduce economic viability in some regions, but alternatives include liquefaction or compression of small volumes e.g. for transport fuel (Ogden et al., 2018). Currently, the goal is that all public transport in urban areas is electric in Chile by 2040 (Gobierno de Chile, 2020), whilst studies are emerging on the use of renewable hydrogen (Fúnez Guerra et al., 2020) for use in a fuel-cell or to be blended with natural gas. Given hydrogen's synergistic relationship with solar and wind, where Chile has considerable potential (Simsek et al., 2019), it is foreseeable that green hydrogen will leapfrog bio-based fuels.

4.3.3.5. Access to distribution and transmission infrastructure

Each energy project is guaranteed access by law to the transmission and distribution system. However, in practice, this is one of the most variable costs of the project due to geographical considerations (Comisión Nacional de Energía, 2019), such as distances and complex geography, as well as the costs of land.

Two interviewees explained that in the case of distributed bioenergy projects, these geographical challenges are not only more pronounced, but the projects ultimately have lower generation capacity than large thermal projects, meaning that this cost becomes a disproportionately large percentage of overall costs. One interviewee estimated this to represent between 25-50% of project cost, depending on generation size.

When also factoring the need to secure land rights this creates overwhelming obstacles for bioenergy projects that have electricity generation as an objective. Hence, it may be beneficial to target a different outcome for bioenergy generation.

4.3.4. Institutional barriers

4.3.4.1. Policy challenges

Ten interviewees cited inadequacies in national laws and regulations regarding waste management and valorisation, both in the agricultural sector and municipalities. Given the slim margins, for example, for small-scale dairy farms as cited by two interviewees, unsupported investment in waste conversion technologies is not prudent. However, evidence shows that Chile has one of the lowest expenditures on agricultural subsidies as a percentage of GDP globally (Domínguez et al., 2019), which could be extended if Chile wishes to create a more sustainable agriculture (Odepa, 2018).

Six interviewees also suggested that the limited bioenergy development in Chile is explained by the lack of energy policy oriented towards its promotion compared to other countries. For example, Edwards et al. (2015) identified the link between growth of biogas in Germany and Britain and performance-based incentives directed at small-to-medium capacity generation. Bangalore et al. (2016) suggest that adoption of biomass valorising technologies owed more to policy incentives than feedstock availability or technology.

Seven interviewees said that Chilean biogas projects had suffered from legal ambiguity before the creation of a regulatory framework (Ministerio de Energía, 2017), which established the minimum safety requirements that biogas plants must meet for design, construction, operation, maintenance, inspection and operation. However, this has not since triggered a noticeable increase in installations.

Three interviewees also emphasised that Chile was a pioneer in the integration of renewable energy, driving down solar and wind prices to challenge fossil-based generation in competitive auctions (International Energy Agency (IEA), 2018). Hence, one interviewee questioned whether state expenditure on an area (bioenergy) where Chile did not hold a competitive advantage could be justified.

Meanwhile, to increase the availability of appropriate bioresources nationally, seven interviewees said the development of a governmental organic waste strategy should be prioritised, as the laws are inadequate to promote activities to valorise biomass. Until 2016, when Chile enacted the Extended Producer Responsibility (EPR) Law, there was scarce regulation incentivising recycling. Still now biogenic residues remain absent from priority areas included within environmental law (Bergamini et al., 2017). Landfill gas can legally be captured for CHP generation or biomethane upgrading, but only a few sites have been fitted with this technology (Rodríguez-Monroy et al., 2018). There has not been a suitable incentive to valorise the organic element of Chile's municipal waste (Molina Alomar, 2020a), and a strong incentive exists for private firms to send high volumes of municipal waste to Chile's landfills (Bergamini et al., 2017). This must be changed to incentivise the diversion of biogenic resources from landfill. Five interviewees believe the creation of an organics law disincentivising landfill will drive businesses and local planners to pursue energy valorisation of bioresources. However, whilst such a law is mooted to arrive in 2020, it will likely not promote energy recovery technologies (Molina Alomar, 2020b).

4.3.4.2. Disconnectedness of stakeholders

Seven interviewees advocated greater collaboration between government departments and industry to unlock the energy potential of Chile's biomass resources. Bioenergy involves a high degree of complexity due to the broader range of stakeholders involved than most energy technologies (Berg et al., 2013). Thus, so far actors from the Ministry of Agriculture, the Ministry of Environment, Ministry of Energy, the Agricultural Innovation Foundation (FIA) and CORFO have cooperated to promote the use of bioenergy technologies in strategic sectors, such as in dairy production and forestry (Ávila Grothusen et al., 2016). The government strategies of Biogas in Dairy (Ministerio de Energía, 2020) and Promoting the Development of Energy in Selected Agricultural SMEs show some state participation.

However, Chile does not have a national strategy for bioenergy or the bioeconomy (Berg et al., 2013), unlike other OECD countries such as Ireland and the UK (Berg et al., 2013), or like Brazil, Argentina and Uruguay (Rodríguez, 2017). Chile is one of the only Latin American nations with no policies, strategies or commission driving the creation of a bioeconomy. Furthermore, technologies are scarcely mentioned in important policy documents such as Energy 2050 (Ministerio de Energía, 2015). Indeed, Energy 2050 is credited by the IEA as an outstanding example for energy policy formulation globally (International Energy Agency (IEA), 2018) but it contains scarce mention of biofuels, biogas or strategies for heat decarbonisation.

In general, the identified barriers are consistent with the challenges in the LAC region and, the development of technologies that are economically feasible for the region are transcendental of OWtE to thrive (Silva-Martínez et al., 2020). Considering that the utilisation of organic waste to produce energy represents a part of an integrated waste management strategy, particular analysis should be carried out for evaluating which technology to use. Further investigations are needed to accurate seek for the contributions these technologies can provide to reduce GHG emissions and for the viability to foster WtE technologies to promote sustainable energy systems in the region.

5. Conclusions

This study estimates a total bioenergy potential, considering primary energy content, from waste in Chile at 78 PJ/yr, representing 3.3% of Chile's total energy demand. The main source of waste bioresource is livestock manure, contributing 41% of total, with annual crop residues contributing 28%, horticultural crops residues 23% and OFMSW 8%. Three central and central-south regions - O'Higgins, Metropolitana and Maule- have the highest bioenergy potentials, with 40-60% of the national total. Additionally, La Araucanía produces 27% of annual crop residues. When comparing with literature, the results are within the range for OFMSW and livestock manure; only the energy from agriculture shows 3.7 times higher values than literature, however this study includes a larger dataset, which is the main reason of the difference.

Using a series of semi-structured interviews conducted with relevant stakeholders, this research identifies the lack of a national strategy and limited cross-sectoral cooperation as two important obstacles for developing a bioenergy economy**.** It has then been highlighted the considerable potential that waste bioresources could offer in contrast with stakeholders' statements, who mainly remarked the difficulties of handling, storing and managing bioresources such as manure, the high cost of investment, and lack of clarity of government's position on policy and support. Hence, there is a need for incentives or subsidies that address the high investment costs and financing options available for bioenergy projects, in addition to reducing reliance on landfilling practices. It is recommended that this programme goes hand-in-hand with further training initiatives in how to extract the value from residual biomass streams, and on best practices for successful operation, in order to create expertise and avoid technology failure. This is particularly important if potential national targets refer to valorisation of 60-70% of organic waste by 2040.

Therefore, the outputs of this research will contribute with evidence for Chile's updated NDCs, in the country's vision that "seeks to move from a linear 'extract-use-discard' economic model, towards a circular model that utilizes and optimizes stocks and flows of materials, energy and waste". Furthermore, it is recognised that the implementation of OWtE technologies will be crucial for the sustainable development of not only Chile but the entire LAC region, and to significantly contribute to improve waste and energy systems, along with several social and economic benefits.

Consequently, this study shows how the bioresource availability and its energy potential matches spatially with demand, showing how regional characteristics could be taken into consideration when developing regional programmes and help decentralise the country's strategies while increasing energy security and resource efficiency at regional and country level. Techno-economic analysis including temporal and spatial aspects in addition to understanding of complementary valorisation routes should be the next research steps to identify regional and country level strategies to implement circular economy principles and decarbonisation pathways. Further work shall demonstrate the applicability of small and large-scale OWtE treatment plants throughout Latin-America and the Caribbean regions.

Acknowledgements

This research was supported by the Sustainable Gas Institute at Imperial College London and by Universidad de Santiago de Chile through the DICYT (Dirección de Investigación Científica y Tecnológica) grant 021812GL. X. Schmidt Rivera is supported by the Institutional QR Global Challenges Research Fund. F. Jalil-Vega acknowledges the support of ANID through Complex Engineering Systems Institute PIA/BASAL AFB180003, and through ANID/FONDAP/15110019 SERC-Chile.

References

Acuña, C., Moraga Paredes, C., 2017. Curso de Formación Especializada en Biogás para Profesionales. EBP.
Afolabi, O.O.D., Leonard, S.A., Osei, E.N., Blay, K.B., 2021. Country-level assessment of agrifood waste and enabling environment for sustainable utilisation for bioenergy in Nigeria. Journal of Environmental Management 294, 112929.
Al Seadi, T., Stupak, I., Smith, C.T., 2018. Governance of environmental sustainability of manure-based centralised biogas production in Denmark, in: Murphy, J.D. (Ed.). IEA Bioenergy.
Ali, J., Rasheed, T., Afreen, M., Anwar, M.T., Nawaz, Z., Anwar, H., Rizwan, K., 2020. Modalities for conversion of waste to energy — Challenges and perspectives. Science of The Total Environment 727, 138610.
Ali, Z., Liaquat, R., Husain Khoja, A., Safdar, U., 2021. A comparison of energy policies of Pakistan and their impact on bioenergy development. Sustainable Energy Technologies and Assessments 46, 101246.
American Society of Agricultural and Biological Engineers, 2005. Manure Production and Characteristics.
Avcıoğlu, A.O., Dayıoğlu, M.A., Türker, U., 2019. Assessment of the energy potential of agricultural biomass residues in Turkey. Renewable Energy 138, 610-619.
Ávila Grothusen, M., Sotomayor Bohle, E., Erlwein Vicuña, A., Cerda Rosenberg, F., 2016. Biogás de Residuos Agropuecuarios en la Región de Los Ríos - Aspectos Generales, Experiencias y Potencial de Producción, Programa de Valorización de Residuos de la Actividad Silvoagropecuaria, Valdivia, Chile.
Azócar, L., Hermosilla, N., Gay, A., Rocha, S., Díaz, J., Jara, P., 2019. Brown pellet production using wheat straw from southern cities in Chile. Fuel 237, 823-832.
Bangalore, M., Hochman, G., Zilberman, D., 2016. Policy incentives and adoption of agricultural anaerobic digestion: A survey of Europe and the United States. Renewable Energy 97, 559-571.
Bentsen, N.S., Felby, C., Thorsen, B.J., 2014. Agricultural residue production and potentials for energy and materials services. Progress in Energy and Combustion Science 40, 59-73.
Berg, A., Bidart, C., Espinoza, D., Flores, M., Moraga, A., Müller, M., Segura, C., 2013. Informe Final Estudio Recomendaciones para la elaboración de una Estrategia Nacional de Bioenergía. Unidad de Desarrollo Tecnológico, Universidad de Concepción.

Bergamini, K., Irarrázaval, R., Monckeberg, J.C., Pérez, C., 2017. Principales problemas ambientales en Chile: desafíos y propuestas Temas de la agenda pública. Pontificia Universidad Católica de Chile, Centro de Políticas Públicas.
Bertran Spichiger, J., Morales Verdugo, E., 2008. Potencial de Biomasa Forestal - Potencial de Generación de Energía por Residuos del Manejo Forestal en Chile. Comisión Nacional de Energía (CNE), Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Santiago, Chile.
Bidart, C., Fröhling, M., Schultmann, F., 2013. Municipal solid waste and production of substitute natural gas and electricity as energy alternatives. Applied Thermal Engineering 51, 1107-1115.
Bidart, C., Fröhling, M., Schultmann, F., 2014. Livestock manure and crop residue for energy generation: Macro-assessment at a national scale. Renewable and Sustainable Energy Reviews 38, 537-550.
Blechinger, P., Richter, K., Renn, O., 2015. Barriers and Solutions to the Development of Renewable Energy Technologies in the Caribbean, in: Groh, S., van der Straeten, J., Lasch, B.E., Gershenson, D., Filho, W.L., Kammen, D.M. (Eds.), Decentralized Solutions for Developing Economies: Addressing Energy Poverty Through Innovation. Springer International Publishing, Switzerland, pp. 267-284.
Bnamericas, 2020. Las centrales eléctricas más baratas de Chile en términos de inversión, https://www.bnamericas.com/es/reportajes/las-centrales-electricas-mas-baratas-de-chile-en-terminos-de-inversion.
Carleton, L.E., Becker, D., 2018. Forest Biomass Policy in Minnesota: Supply Chain Perspectives on Barriers to Bioenergy Development. Forests 9.
Carrasco Allendes, J., 2015. Evaluación técnica y económica de una planta de biogás para autoabastecimineto energético: Una estrategia para diferentes contextos., Departamenteo de Ingeniería Civil en Biotecnología. Universidad de Chile.
Casas-Ledón, Y., Flores, M., Jiménez, R., Ronsse, F., Dewulf, J., Arteaga-Pérez, L.E., 2019. On the environmental and economic issues associated with the forestry residues-to-heat and electricity route in Chile: Sawdust gasification as a case study. Energy 170, 763-776.
Chamy, R., Vivanco, E., 2007. Identificación y clasificación de los distintos tipos de biomasa disponibles en Chile para la generación de biogás, Proyecto Energías Renovables No Convencionales. Comisión Nacional de Energía (CNE), Santiago, Chile, p. 82p.
Chang, K.-H., Lou, K.-R., Ko, C.-H., 2019. Potential of bioenergy production from biomass wastes of rice paddies and forest sectors in Taiwan. Journal of Cleaner Production 206, 460-476.
Chanthakett, A., Arif, M.T., Khan, M.M.K., Oo, A.M.T., 2021. Performance assessment of gasification reactors for sustainable management of municipal solid waste. Journal of Environmental Management 291, 112661.
Chowdhury, T.H., 2021. Technical-economical analysis of anaerobic digestion process to produce clean energy. Energy Reports 7, 247-253.
Comisión Nacional de Energía, 2018a. Balance Nacional de Energía.
Comisión Nacional de Energía, 2018b. Energía Abierta. Balance Energético: BNE - Consumos Regionales de Energía Comisión Nacional de Energía (CNE).
Comisión Nacional de Energía, 2019. Informe de costos de tecnologías de generación. Comisión Nacional de Energía.
Cross, S., Welfle, A.J., Thornley, P., Syri, S., Mikaelsson, M., 2021. Bioenergy development in the UK & Nordic countries: A comparison of effectiveness of support policies for sustainable development of the bioenergy sector. Biomass and Bioenergy 144, 105887.
Cueto Codorniú, A., 2017. Evaluación de tecnologías para la reutilización, valorización y disposición de residuos orgánicos, Departamento de Ingeniería Química. Universidad de Chile, Chile.
D-Waste, 2020. Waste Atlas. D-Waste.
Dadzie, J., Runeson, G., Ding, G., Bondinuba, F.K., 2018. Barriers to Adoption of Sustainable Technologies for Energy-Efficient Building Upgrade—Semi-Structured Interviews. Buildings 8.
Daioglou, V., Stehfest, E., Wicke, B., Faaij, A., van Vuuren, D.P., 2016. Projections of the availability and cost of residues from agriculture and forestry. GCB Bioenergy 8, 456-470.

de Groot, L., Bogdanski, A., 2013. Bioslurry = Brown Gold? A review of scientific literature on the co-product of biogas production. Food and Agriculture Organization of the United Nations, FAO, Rome, Italy.
De Schoenmakere, M., Hoogeveen, Y., Gillabel, J., Manshoven, S., 2018. The circular economy and the bioeconomy - Partners in sustainability. European Environment Agency, Luxembourg.
Domínguez, J.I., Vergara, M.M., Aguirre, R., Barrera, D., Montero, J., Cáceres, L., Eguillor, P., Espinoza, A., García, A., Reyes, A., Pino, G., Pizarro, M.J., Tapia, B., Acuña, D., Laval, E., Yañez, L., Muñoz, M., Cartes, G., Contreras, P., Valdés, A., Galán, M., 2019. Chilean Agriculture Overview, in: Agriculture, O.o.A.S., Policies of the Chilean Ministry, o. (Eds.). ODEPA, Ministerio de Agricultura.
EBP Chile, 2016. Estudio de ingeniería de detalle para proyecto de Calefacción Distrital en Coyhaique. EBP Chile.
Edwards, J., Othman, M., Burn, S., 2015. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renewable and Sustainable Energy Reviews 52, 815-828.
Einarsson, R., Persson, U.M., 2017. Analyzing key constraints to biogas production from crop residues and manure in the EU—A spatially explicit model. PLOS ONE 12, e0171001.
European Commission, 2020. Communication from the Commssion to the European Parliament, the Council, the European Economic and Social Comittee and the Committee of the Regions on an EU strategy to reduce methane emissions. European Commission,, Brussels.
Food and Agriculture Organization of the United Nations, 2019. FAOSTAT.
Fúnez Guerra, C., Reyes-Bozo, L., Vyhmeister, E., Jaén Caparrós, M., Salazar, J.L., Clemente-Jul, C., 2020. Technical-economic analysis for a green ammonia production plant in Chile and its subsequent transport to Japan. Renewable Energy 157, 404-414.
Gaete-Morales, C., Gallego-Schmid, A., Stamford, L., Azapagic, A., 2018. Assessing the environmental sustainability of electricity generation in Chile. Science of The Total Environment 636, 1155-1170.
García, A.E., Carmona, R.J., Lienqueo, M.E., Salazar, O., 2011. The current status of liquid biofuels in Chile. Energy 36, 2077-2084.
Global Methane Initiative, 2014. Summary of Findings Anaerobic Digestion for MSW - Agriculture, Municipal Solid Waste, Municipal Wastewater Subcommittee Meeting, Florianopolis, Brazil.
Gobierno de Chile, Consejo de Ministros para la Sustentabilidad,, 2020. Chile's Nationally Determined Contribution, update 2020.
Horschig, T., Adams, P.W.R., Röder, M., Thornley, P., Thrän, D., 2016. Reasonable potential for GHG savings by anaerobic biomethane in Germany and UK derived from economic and ecological analyses. Applied Energy 184, 840-852.
Huiru, Z., Yunjun, Y., Liberti, F., Pietro, B., Fantozzi, F., 2019. Technical and economic feasibility analysis of an anaerobic digestion plant fed with canteen food waste. Energy Conversion and Management 180, 938-948.
International Energy Agency (IEA), 2018. Energy policies beyond IEA countries, Chile 2018. IEA.
IQAir AirVisual, 2018. 2018 World Air Quality Report, Region & City PM2.5 Ranking.
Jäger-Waldau, A., 2019. PV Status Report 2019, EUR 29938 EN. Publications Office of the European Union, Luxembourg.
Jain, S., Newman, D., Nizhou, A., Dekker, H., Le Feuvre, P., Richter, H., Gobe, F., Morton, C., Thompson, R., 2019. Global Potential of Biogas. Wolrd Biogas Association.
Ji, L.-Q., 2015. An assessment of agricultural residue resources for liquid biofuel production in China. Renewable and Sustainable Energy Reviews 44, 561-575.
Kenney, K.L., Smith, W.A., Gresham, G.L., Westover, T.L., 2013. Understanding biomass feedstock variability. Biofuels 4, 111-127.
Koldisevs, J., 2014. Biogas production in rural areas of Mexico.
Lauer, M., Hansen, J.K., Lamers, P., Thräna, D., 2018. Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry. Applied Energy 222, 621-636.

Lautala, P.T., Hilliard, M.R., Webb, E., Busch, I., Richard Hess, J., Roni, M.S., Hilbert, J., Handler, R.M., Bittencourt, R., Valente, A., Laitinen, T., 2015. Opportunities and Challenges in the Design and Analysis of Biomass Supply Chains. Environmental Management 56, 1397-1415.
Levidow, L., 2013. EU criteria for sustainable biofuels: Accounting for carbon, depoliticising plunder. Geoforum 44, 211-223.
Levin, K., Davis, C., 2020. What Does "Net-Zero Emissions" Mean? 6 Common Questions, Answered. World Resources Institute, https://www.wri.org/blog/2019/09/what-does-net-zero-emissions-mean-6-common-questions-answered.
Long, H., Li, X., Wang, H., Jia, J., 2013. Biomass resources and their bioenergy potential estimation: A review. Renewable and Sustainable Energy Reviews 26, 344-352.
Mai-Moulin, T., Hoefnagels, R., Grundmann, P., Junginger, M., 2021. Effective sustainability criteria for bioenergy: Towards the implementation of the european renewable directive II. Renewable and Sustainable Energy Reviews 138, 110645.
Margallo, M., Ziegler-Rodriguez, K., Vázquez-Rowe, I., Aldaco, R., Irabien, Á., Kahhat, R., 2019. Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: A review for policy support. Science of The Total Environment 689, 1255-1275.
Martínez Arce, E., Daza, D., Tello Espinoza, P., Soulier Faure, M., Terraza, H., 2010. Regional Evaluation on Urban Solid Waste Management in Latin America and the Caribbean: 2010 Report.
MinInterior, M.d.I., 2007a. Ley 20.174 - Crea la XIV Región de Los Ríos y la Provincia de Ranco en su territorio, in: Interior, M.d. (Ed.), 20.174, Dierio Oficial.
MinInterior, M.d.I., 2007b. Ley 20.175 - Crea la XV Región de Arica y Parinacota y la Provincia del Tamarugal en la Región de Tarapacá, in: Interior, M.d. (Ed.), 20.175, Diario Oficial.
MinInterior, M.d.l., 2017. Ley 21.033 - Crea la XVI Región del Ñuble y las Provincias de Diguillín, Punilla e Itata, in: Pública, M.d.I.y.S. (Ed.), Dierio Oficial.
Ministerio de Energía, 2017. Aprueba Reglamento de Seguridad de las Plantas de Biogás e Introduce Modificaciones al Reglamento de Instaladores de Gas, https://www.leychile.cl/Navegar?idNorma=1099847&idParte=.
Ministerio de Energía, 2020. Biogás Sector Lechero. Ministerio de Energía.
Ministerio de Energía, Gobierno de Chile,, 2015. Energía 2050 - Política Energética de Chile.
Ministerio del Medio Ambiente, 2013. Nationally Appropriate Mitigation Action, Catalyzing Industrial Organic Waste Management in Chile. Center for Clean Air Policy (CCAP).
Mittal, S., Ahlgren, E.O., Shukla, P.R., 2018. Barriers to biogas dissemination in India: A review. Energy Policy 112, 361-370.
MMA, M.d.M.A., 2018. Informe consolidado de Emisiones y Transferencia de Contaminantes 2005 - 2016.
Molina Alomar, J., 2019. Medio Ambiente apunta a crear una estrategia para el reciclaje de residuos orgánicos con la experiencia de Italia como referente, Ciudad / Residuos domiciliarios. País Circular, https://www.paiscircular.cl/ciudad/medio-ambiente-apunta-a-crear-una-estrategia-para-el-reciclaje-de-residuos-organicos-con-la-experiencia-de-italia-como-referente/.
Molina Alomar, J., 2020a. Estrategia Nacional de Residuos Orgánicos abre discusión sobre cobro de derechos de aseo e incrementar costo de disponer en relleno sanitario - País Circular, Ciudad / Reciclaje. País Circular, https://www.paiscircular.cl/ciudad/estrategia-nacional-de-residuos-organicos-abre-discusion-sobre-cobro-de-derechos-de-aseo-e-incrementar-costo-de-disponer-en-relleno-sanitario/.
Molina Alomar, J., 2020b. Gobierno afina estrategia para reciclaje de residuos orgánicos a través de compostaje domiciliario, comunitario e industrial, Consumo y Producción / Compostaje urbano. País Circular, https://www.paiscircular.cl/consumo-y-produccion/gobierno-afina-estrategia-para-reciclaje-de-residuos-organicos-a-traves-de-compostaje-domiciliario-comunitario-e-industrial/.

Montalvo, S., Martinez, J., Castillo, A., Huiliñir, C., Borja, R., García, V., Salazar, R., 2020. Sustainable energy for a winery through biogas production and its utilization: A Chilean case study. Sustainable Energy Technologies and Assessments 37, 100640.
Montefrio, M.J.F., 2012. Privileged Biofuels, Marginalized Indigenous Peoples: The Coevolution of Biofuels Development in the Tropics. Bulletin of Science, Technology & Society 32, 41-55.
Moya, D., Aldás, C., Jaramillo, D., Játiva, E., Kaparaju, P., 2017. Waste-To-Energy Technologies: an opportunity of energy recovery from Municipal Solid Waste, using Quito - Ecuador as case study. Energy Procedia 134, 327-336.
Muñoz, P., Muñoz, L., Cordero, C., Bibire, L., Morales, M.P., 2018. Assessment of economical biogas production from Chilean municipal solid waste in a decentralized off-grid strategy. Applied Ecology and Environmental Research 16, 2423-2439.
Nowell, L.S., Norris, J.M., White, D.E., Moules, N.J., 2017. Thematic analysis: Striving to meet the trustworthiness criteria. International journal of qualitative methods 16, 1609406917733847.
Odepa, O.d.E.y.P.A.M.d.A., 2018. Consideraciones Ambientales para una Agricultura competitiva y sustentable al 2030, Agricultura Chilena: Reflexiones y Desafíos al 2030.
Oficina de Estudios y Políticas Agrarias, ODEPA, 2019. Panorama de la agricultura Chilena. ODEPA.
Oficina de Estudios y Políticas Agrarias, ODEPA, 2021a. Catastros frutícolas.
Oficina de Estudios y Políticas Agrarias, ODEPA, 2021b. Informe detallado por especie o categoría (Pecuario).
Oficina de Estudios y Políticas Agrarias, O., 2020. Estadísticas productivas. Oficina de Estudios y Políticas Agrarias, ODEPA.
Ogden, J., Jaffe, A.M., Scheitrum, D., McDonald, Z., Miller, M., 2018. Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature. Energy Policy 115, 317-329.
Paneque, M., Román-Figueroa, C., Vázquez-Panizza, R., Arriaza, J.M., Morales, D., Zulantay, M., 2011. Bioenergía en Chile. Organización de las Naciones Unidas para la Alimentación y la Agricultura; Facultad de Ciencias Agronómicas, Universidad de Chile.
Pfau, S.F., Hagens, J.E., Dankbaar, B., 2017. Biogas between renewable energy and bio-economy policies—opportunities and constraints resulting from a dual role. Energy, Sustainability and Society 7, 17.
Raman, S., Mohr, A., 2014. Biofuels and the role of space in sustainable innovation journeys. Journal of Cleaner Production 65, 224-233.
Reciclo Orgánicos, 2019. Gestión de residuos orgánicos en rellenos sanitarios y cambio climático - Programa Reciclo Orgánicos: @reciclorganicos.
Revista Electricidad, L.R.E.d.C., 2019. Biomasa: potencial al alza. Electricidad, La Revista Energética de Chile, https://www.revistaei.cl/reportajes/biomasa-potencial-al-alza/#.
Riva, G., Foppapedretti, E., de Carolis, C., Giakoumelos, E., Malamatenios, C., Signanini, P., Giancarlo, C., Di Fazio, M., Gajdoš, J., Ručinský, R., 2014. ENergy Efficiency and Renewables–SUPporting Policies in Local level for EnergY - Handbook on renewable energy sources. ENER SUPPLY.
Rodríguez-Monroy, C., Mármol-Acitores, G., Nilsson-Cifuentes, G., 2018. Electricity generation in Chile using non-conventional renewable energy sources – A focus on biomass. Renewable and Sustainable Energy Reviews 81, 937-945.
Rodríguez, A.G., 2017. The Bioeconomy: opportunities and challenges for rural, agricultural and agro-industrial development in Latin America and the Caribbean. Food and Agriculture Organization of the United Nations (FAO) Economic Commission for Latin America and the Caribbean, pp. 1-16.
Román-Figueroa, C., Montenegro, N., Paneque, M., 2017. Bioenergy potential from crop residue biomass in Araucania Region of Chile. Renewable Energy 102, 170-177.
Salazar, F., Martínez-Lagos, J., Alfaro, M., Rodríguez, M., Soto, C., Gontupil, J., Belmar, J., 2016. Promoviendo el desarrollo de la energía a biogás en pequeñas y medianas agroindustrias seleccionadas. INIA, Instituto de Investigaciones Agropecuarias.
Sánchez Lizama, I., 2017. Contexto Nacional de Energía del Biogás - Situación actual e iniciativas en Chile, in: Ministerio de Energía, D.E.R. (Ed.), Chile.

Sánchez Ramírez, M., Pizarro Gariazzo, R., Serrano Ulloa, M., Barrera Curihuentro, M., Riveros Pizarro, V., Lara Molina, P., Gajardo Devia, C., Figueroa Serrano, N., Lizama Farías, H., Figueroa Olivera, D., 2018. Informe Consolidado de Emisiones y Transferencias de Contaminantes. 2005-2016, RETC, in: Departamento de Información Ambiental, D.d.I.y.E.A. (Ed.). Ministerio del Medio Ambiente, Santiago, Chile.
Sartor, K., Dewallef, P., 2017. Optimized Integration of Heat Storage Into District Heating Networks Fed By a Biomass CHP Plant. Energy Procedia 135, 317-326.
Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development 15, 3-34.
Schueftan, A., González, A.D., 2013. Reduction of firewood consumption by households in south-central Chile associated with energy efficiency programs. Energy Policy 63, 823-832.
Schueftan, A., Sommerhoff, J., González, A.D., 2016. Firewood demand and energy policy in south-central Chile. Energy for Sustainable Development 33, 26-35.
Searle, S., Malins, C., 2015. A reassessment of global bioenergy potential in 2050. Gcb Bioenergy 7, 328-336.
Seiffert, M., Kaltschmitt, M., Miranda, J.A., 2009. The biomethane potential in Chile. Biomass and Bioenergy 33, 564-572.
Sganzerla, W.G., Buller, L.S., Mussatto, S.I., Forster-Carneiro, T., 2021. Techno-economic assessment of bioenergy and fertilizer production by anaerobic digestion of brewer's spent grains in a biorefinery concept. Journal of Cleaner Production 297, 126600.
Sikarwar, V.S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M.Z., Shah, N., Anthony, E.J., Fennell, P.S., 2016. An overview of advances in biomass gasification. Energy & Environmental Science 9, 2939-2977.
Silva-Martínez, R.D., Sanches-Pereira, A., Ortiz, W., Gómez Galindo, M.F., Coelho, S.T., 2020. The state-of-the-art of organic waste to energy in Latin America and the Caribbean: Challenges and opportunities. Renew Energ 156, 509-525.
Silva dos Santos, I.F., Braz Vieira, N.D., de Nóbrega, L.G.B., Barros, R.M., Tiago Filho, G.L., 2018. Assessment of potential biogas production from multiple organic wastes in Brazil: Impact on energy generation, use, and emissions abatement. Resources, Conservation and Recycling 131, 54-63.
Simsek, Y., Lorca, Á., Urmee, T., Bahri, P.A., Escobar, R., 2019. Review and assessment of energy policy developments in Chile. Energy Policy 127, 87-101.
Stemmelen, J., 2018. Preliminary Study of a District Heating Project in Temuco, Chile. Engie Latin America.
Stephen, J.D., Sokhansanj, S., Bi, X., Sowlati, T., Kloeck, T., Townley-Smith, L., Stumborg, M.A., 2010. Analysis of biomass feedstock availability and variability for the Peace River region of Alberta, Canada. Biosystems Engineering 105, 103-111.
SUBDERE, 2018a. Línea Base Diagnóstico y Catastro de RSD año 2017. Subsecretaría de Desarrollo Regional y Administrativo (SUBDERE).
SUBDERE, S.d.D.R.y.A., 2018b. Línea Base Diagnóstico y Catastro de RSD año 2017, Programa Nacional de Residuos Sólidos. Subsecretaría de Desarrollo Regional y Administrativo, Subsecretaría de Desarrollo Regional y Administrativo.
Tapia, D., 2019. Biomasa en Chile: En búsqueda de un mayor fortalecimiento. Revista Nueva Minería y Energía, http://www.nuevamineria.com/revista/biomasa-en-chile-en-busqueda-de-un-mayor-fortalecimiento/.
Tricase, C., Lombardi, M., 2012. Environmental analysis of biogas production systems. Biofuels 3, 749-760.
United Nations, 2020. Sustainable Development Goals.
Universidad Adolfo Ibánez, 2018. Noticias UAI - "Construyendo Capacidades para la Operación de Plantas de Biogás en Chile". Universidad Adolfo Ibánez.
Universidad Austral de Chile, 2019. Estudio de Mercado de la Utilización de Digestato Proveniente de Plantas de Digestión Anaeróbicas en Chile, Informe Final. Universidad Austral de Chile.

Vaismoradi, M., Turunen, H., Bondas, T., 2013. Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. Nursing & Health Sciences 15, 398-405.
Welfle, A., Alawadhi, A., 2021. Bioenergy opportunities, barriers and challenges in the Arabian Peninsula – Resource modelling, surveys & interviews. Biomass and Bioenergy 150, 106083.
Whitaker, J., Field, J.L., Bernacchi, C.J., Cerri, C.E.P., Ceulemans, R., Davies, C.A., DeLucia, E.H., Donnison, I.S., McCalmont, J.P., Paustian, K., Rowe, R.L., Smith, P., Thornley, P., McNamara, N.P., 2018. Consensus, uncertainties and challenges for perennial bioenergy crops and land use. GCB Bioenergy 10, 150-164.
Whiting, A., Azapagic, A., 2014. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. Energy 70, 181-193.
Zandi Atashbar, N., Labadie, N., Prins, C., 2017. Modelling and optimisation of biomass supply chains: a review. International Journal of Production Research 56, 3482-3506
Zaror, C., Berg, A., Bidart, C., 2009. Challenges for Sustainable Biomass Utilisation : Proceedings of the Chilean-German Biociclo Workshop (Karlsruhe, 26.03.2009), in: Hiete, M., Ludwig, J., Bidart, C., Schultmann, F. (Eds.). Universitätsverlag Karlsruhe, Karlsruhe.
Zou, P.X.W., Wagle, D., Alam, M., 2019. Strategies for minimizing building energy performance gaps between the design intend and the reality. Energy and Buildings 191, 31-41.