Fernández-Puratich, H.; Rebolledo-Leiva, R.; Hernández, D.; Gómez-Lagos, J.; Armengot-Carbó, B.; Oliver Villanueva, JV. (2021). Bi-objective optimization of multiple agro-industrial wastes supply to a cogeneration system promoting local circular bioeconomy. Applied Energy. 300:1-14. https://doi.org/10.1016/j.apenergy.2021.117333

Applied Energy

Optimization of biomass supply to a CHP system based on multiple agro-industrial wastes under Mediterranean conditions: a tactical strategy for a circular bioeconomy system.

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research Paper
Keywords:	biomass logistics; bioenergy; agricultural waste; circular bioeconomy; optimization
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Abstract:	This research analyses and proposes an optimization model for the supply of biomass to a small-scale CHP system with a supply of different biomasses at a local level under Mediterranean conditions. The research aims to quantitatively assess whether it is economical and environmentally beneficial to transport various types of biomasses to the CHP plant, instead of landfilling, determining the biomass required according to the availability of power generation for each biomass of agricultural and agro-industrial origin. To do this, a representative case study has been developed in the Maule Region (Chile) to supply power and heat to the public, private, and residential buildings. The main biomasses analyzed are olive pomace, fruit pits (cherries, peaches, plums) and vineyard pruning. The results demonstrate that the supply of residual biomass to the CHP plant avoids the emission of CO2e generated by final disposal (landfilling or burning). Regarding the minimization of CO2e emissions, pruning residues are identified as the first supply option, due to their high calorific value. Regarding cost minimization, olive pomace is identified as the first option, followed by fruit pits and pruning material. Furthermore, transport is not a major contributing cost or environmental factor when biomass sources are close to the CHP system, up to a maximum supply radius of 30 km. Finally, despite seasonality of agricultural biomass supply under Mediterranean conditions, it is feasible to adequately supply a small-scale CHP plant. However, this increases the storage costs involved. Other lignocellulosic biomasses (e.g. forest residues) could be used to optimize costs and environmental benefits.
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	Biomass supply chain management Mathematical modeling and optimization Multi-criteria decision making Simulation Life cycle assessment

Highlights

- Biomass supply to CHP plant avoids CO_2 emissions generated by final disposal.
- Pruning residues are identified as the first supply option to minimize carbon footprint.
- Olive pomace is identified as the first supply option to minimize costs.
- Transport is not a major cost up to a supply radius of 30 km.
- Seasonality can be compensated with additional supply of forest biomass.

TALCA
UNIVERSIDAD
CHILE

March 24, 2021

Dear Dr. Jinyue Yan

Editor in Chief
Applied Energy

We are enclosing here with the manuscript entitled "*Optimization of biomass supply to a CHP system based on multiple agro-industrial wastes under Mediterranean conditions: a tactical strategy for a circular bioeconomy system*" submitted to Applied Energy for possible evaluation. The submitted manuscript corresponds to an original research paper.

The manuscript submitted represents a potential contribution to the journal, considering that this research proposes a bi-objective optimization model for the supply of combustible material to a CHP system with a supply of different biomasses at a local level under Mediterranean conditions. Besides, this work quantitatively assesses whether it is economical and environmentally beneficial to transport various types of biomasses to the CHP plant, instead of landfilling, determining the biomass required according to the availability of power generation for each biomass of agricultural and agro-industrial origin.

We consider that this paper is relevant for this journal because it presents an optimization model that can be useful decision makers in renewable energy sources in a circular bioeconomy framework. In this case, to supply power and heat to the public, private, and residential buildings, through multiple biomass sources.

The manuscript has been checked by a native tongue speaker with expertise in the field and we consider that can be attractive to a scientific audience. Besides, we are available as reviewers for new articles submitted to the journal.

Moreover, we believe that this paper demonstrates that the supply of residual biomass to the CHP plant avoids the emission of CO2e generated by final disposal. The article indicates that the best biomass selection depends on the desired objective: minimization of costs or emissions. Moreover, it is carried out a sensibility analysis to evaluate changes in the supply system under demands and capacity variations.

Finally, we would like to undertake that the above-mentioned manuscript has not been published elsewhere, accepted for publication elsewhere or under editorial review for publication elsewhere.

Sincerely,

Ricardo Rebolledo-Leiva, MSc.
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CRediT authorship contribution statement

H. Fernández-Puratich: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **R. Rebolledo-Leiva**: Conceptualization, Methodology, Formal analysis, Investigation, Software, Writing - Original Draft, Writing - Review & Editing, Visualization. **D. Hernández:** Conceptualization, Methodology, Investigation, Resources, Writing - Review & Editing, Visualization. **J. E. Gómez-Lagos**: Conceptualization, Methodology, Software, Writing - Original Draft, Writing - Review & Editing, Visualization. **B. Armengot-Carbo:** Writing - Review & Editing, Visualization. **J. V. Oliver-Villanueva**: Conceptualization, Writing - Review & Editing, Visualization.

Optimization of biomass supply to a CHP system based on multiple agro-industrial wastes under Mediterranean conditions: a tactical strategy for a circular bioeconomy system.

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ABSTRACT: This research analyses and proposes an optimization model for the supply of biomass to a small-scale CHP system with a supply of different biomasses at a local level under Mediterranean conditions. The research aims to quantitatively assess whether it is economical and environmentally beneficial to transport various types of biomasses to the CHP plant, instead of landfilling, determining the biomass required according to the availability of power generation for each biomass of agricultural and agro-industrial origin. To do this, a representative case study has been developed in the Maule Region (Chile) to supply power and heat to the public, private, and residential buildings. The main biomasses analyzed are olive pomace, fruit pits (cherries, peaches, plums) and vineyard pruning. The results demonstrate that the supply of residual biomass to the CHP plant avoids the emission of CO_2e generated by final disposal (landfilling or burning).

Regarding the minimization of CO_2e emissions, pruning residues are identified as the first supply option, due to their high calorific value. Regarding cost minimization, olive pomace is identified as the first option, followed by fruit pits and pruning material. Furthermore, transport is not a major contributing cost or environmental factor when biomass sources are close to the CHP system, up to a maximum supply radius of 30 km. Finally, despite seasonality of agricultural biomass supply under Mediterranean conditions, it is feasible to adequately supply a small-scale CHP plant. However, this increases the storage costs involved. Other lignocellulosic biomasses (e.g. forest residues) could be used to optimize costs and environmental benefits.

Keywords: biomass logistics; bioenergy; agricultural waste; circular bioeconomy; optimization

1. INTRODUCTION

One of the priorities for sustainable development is an efficient use of the available resources with the development of circular bioeconomy being fundamental for this (EU Commission, 2015). Bioeconomy utilizes the bio-based renewable resources to produce energy, products, and materials in all possible economic sectors [1]. Therefore, this concept is a key factor for establishing and maintaining a circular economy with a constant supply of renewable energy, materials, and feedstocks [1,2]. The circular economy approach emphasizes reuse, remanufacturing, refurbishment, repair, as well as solar, wind, biomass and waste-derived energy utilization throughout the product value chain and cradle-to-cradle life cycle [3]. In this context, biomass is considered as a significant resource for the emerging low carbon and circular bioeconomy [4,5]. The Mediterranean agroindustry sector across the world (Southern Europe, Chile, California, South Africa and Australia) provides a wide source of biomass resources, due to different fruit plantations, such as vineyards, blueberries, apples, sweet cherry, hazelnut, olive trees, walnut trees, among others. As both the waste generated after cultural treatments [6] and industrial transformations [7–11] constitute an important source of agro-industrial waste that can be valorized, contributing to a social, economic, and environmental improvement for the entire community. In this way, avoiding burning the pruning residues and considering them as resources with an economic value may involve agro-industrial decision-makers to apply a circular bioeconomy model. Besides, the risks of fires or pests is reduced in the natural environment [12]. In this sense, not only pruning waste, but also cherry pits, olive and vine pomace, hazelnut shells and walnuts, among others, can be used for energy purposes, and their consumption as energy sources may reduce CO_2 emissions [7,9,13]. In this way, by concentrating on alternative low-carbon energy sources, communities and businesses can reduce their dependence on fossil fuels. Therefore, a better understanding of the connection between different flows of biomass at different spatial scales and energy demand is needed for an effective transition towards a circular bioeconomy [14].

As a general characteristic, biomass is a resource dispersed throughout the territory and on many occasions, it has no known use [15,16]. This dispersion entails not only different direct economic costs, which refers to the proximity to the center of consumption of one or another source of resources [17], but also different levels of CO_2 emissions. Otherwise, regardless of the distance to the consumption center from the place of waste generation, the biomass can be more profitable due to the energy characteristics it has compared to other waste, located at a shorter distance [18]. Therefore, the high cost of biomass logistics represents one of the barriers in their widespread use for energy production [19]. To face this issue, different optimization models have been proposed considering different biomass characteristics such as seasonal availability, sparse spatial distribution, and energy quality variations. The incorporation of all these aspects in the optimization models makes them differ significantly in logistics planning [19,20]. Traditionally, the optimization models proposed for biomass logistics focused on total supply chain cost reduction, which included localization, biomass harvest, transport, and storage [21]. Therefore, some research objectives are: to select the most efficient supply chain configuration, to optimize sizing of supply chain components to minimize cost, or to optimize scheduling of supply chain operations [22]. However, optimization models can be differentiated according to the number of objective functions considered (single objective or multiple objectives). In this sense, the inclusion of environmental concerns related to emissions from logistics activities received limited attention [19,23]. Some studies that consider both economic and environmental objectives (i.e, multi-objective optimization) can be [24], which consider the total profit, fossil energy input, and CO_2 emissions for biofuel supply chain. [25] maximize net present value and minimize greenhouse gas (GHG) emissions for pyrolysis processes. [26] minimizes supply chain costs and GHG emissions for the location, capacity, and technology decisions to find the optimal combination of bioenergy systems. [27] maximize job creation, net present value and GHG emissions saving potential of a forest-based biorefinery supply chain. [28] minimize the total costs, CO_2 emissions and social impacts of delivering biofuels. [29] maximize economic, environmental, and social performance of the bioethanol supply chain. [30] consider carbon-pricing policies to obtain the tradeoff between cost and emissions of biomass supply chain models. [31] maximize the profit and minimize the total distance between poultry farms and biogas facilities. In the literature, optimization biomass supply studies are mainly focused on conversion process such as gasification, combustion, biofuel production, pyrolysis, pelletisation, and few of them concentrate on conversion processes for the combination of heat and power [32].

Cogeneration systems (CHP), which combine heat and electricity, constitute today a technological alternative to take advantage of these agro-industrial wastes with different characteristics in a circular bioeconomy system. In this way, it is possible to obtain electrical and heating energy efficiently from a single system for the community, residential complex, public buildings, or industries [33–35] in a distributed system (DH). Nevertheless, several environmental and technical barriers must be overcome to develop these integral projects under Mediterranean agroforestry conditions. Particularly, ensuring sustained feedstock supply is critical for the viable commissioning of a CHP plant [36].

Therefore, the main aim of this paper is to propose an optimization model for the supply of combustible material to a small-scale CHP system (1 MW electric and 3 MW thermal energy) with a supply of different agro-industrial biomass at the local level under Mediterranean conditions. This research aims to quantitatively assess whether it is environmentally and economically beneficial to transport various types of biomass to the CHP plant, instead of disposed of as is traditionally done. In this way, the variety of biomass required is determined according to the availability of power generation for each type of biomass of agricultural as well as agro-industrial origin. The research results should serve as a basis for the development of bioenergy CHP system projects in rural communities or regions that base their economy under agro-industrial activities with a Mediterranean climate.

The remainder of the paper is structured as follows: Section 2 presents the materials and method with the description of biomass supply to small-scale CHP system, biomass identification and its analysis, and the optimization model. Section 3 presents the results obtained and discusses the main findings, while the final section contains the most important conclusions of this study.

2. MATERIALS AND METHODS

2.1. Biomass supply to small-scale CHP systems

This paper focuses on designing a tactical strategy for an optimized supply of multiple type of biomass for energy production in a CHP plant considering sustainability aspects. To supply feedstock to the CHP system, residues produced by agricultural and agroindustry activities are considered. Food and agro-industries generate waste residues in huge volume, and it has been a matter of concern for environmental pollution [37]. Agricultural residues can be categorized into field residues and process residues. The first ones are those, which are left behind in the field after harvest, and correspond mostly to stems, stalks, dry leaves, and seed pods of the crops. The high volume of field residue, unless managed properly, can cause environmental impact and problems for next cropping practices [38]. The second ones refer to residues after processing valuable resources. For instance, in the process of making rice from paddy, husk comes out as residue [39]. This agroindustry also generates a great number of organic residues that can be obtained from different food processing industries such as juice, meat, confectionery, dairy, and brewery. Residues that can be obtained are fruit peels, fruit pomace, oil cakes, and whey, among others[40]. These residues are generated according to each seasonal production, and traditionally are disposed (agroindustry) or burned (agriculture) [41].

A CHP system can use these residues to provide electricity and heating energy to a local community, but first it is necessary to evaluate some difficulties, such as how much time is feasible to store these residues, from what sources it is possible to obtain the amount required, how much of biomass can be obtained from each source, or when these resources can be obtained, since each biomass depends on their productive season. These are the questions that this research tries to answer. Therefore, a CHP system is modelled that is supplied by different sources of biomass considering two scenarios. The first one considers the use of biomass to supply a CHP system to provide energy to public buildings, while the second one considers traditional final disposition biomass, send them to a landfill or burned them as it is represented in Figure 1.

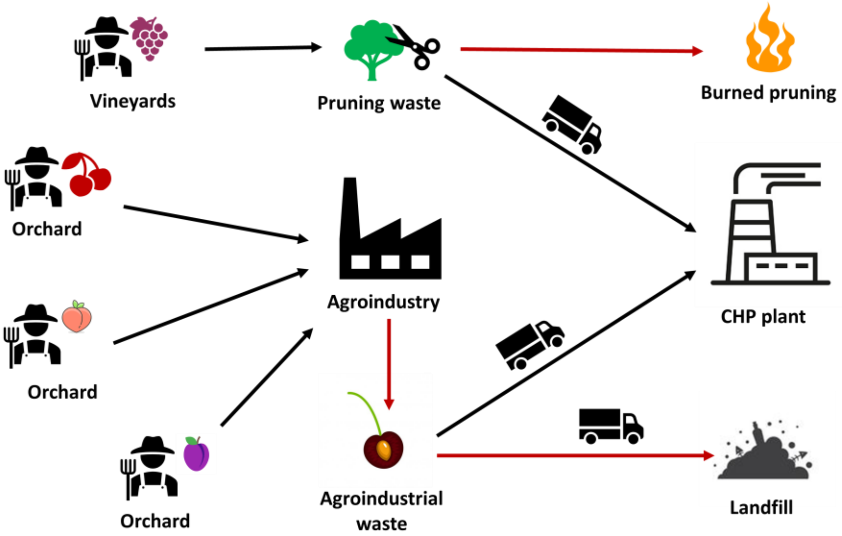

Figure 1. Proposed system for the CHP system supply

2.2. Case study

The pilot area to model this system is located in Zona Centro Sur de Chile, specifically in the Maule Region, which is a representative region with agriculture, agroindustry and forestry under Mediterranean conditions. The CHP system must supply power and heat to the public, private, and residential buildings in the area known as Romeral (15,187 inhabitants).

2.3. Biomass identification and sampling in the study areas

Although there is no developed market to use agricultural waste for energy purposes in the Mediterranean regions of Chile, it should be noted that in the pilot area, there are several agricultural companies, identified as potential suppliers of their waste to the CHP system from different communes in the region, which are shown in the following map in Figure 2.

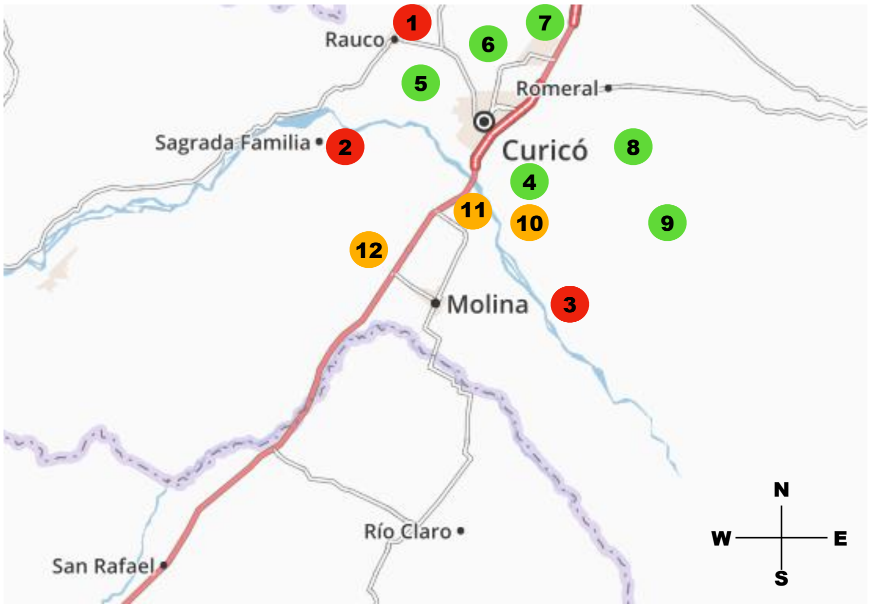

Figure 2. Agro-industrial sources under study (red: olive pomace, green: fruit pits, orange: pruning)

Each company, within the study area, was consulted on the amount (t) of waste generated annually. The most abundant wastes from the companies consulted are fruit pits with an availability of 70,000 t year^{-1}. Olive pomace is found in much less quantity with 1,400 t year^{-1}, and 1,320 t year^{-1} of vine pruning waste in the companies involved. Table 1 presents the amount obtained from this biomass in each season, the seasonality, and calorific value of each one.

Table 1. Description of waste from agro-industrial sector in the Maule region.

Residue	Biomass sources location (Fig. 2)	Feedstock	Higher Calorific Value (average) (MJ kg^{-1})	Lower Calorific Value (average) (MJ kg^{-1})	Distance (km)	Seasonality	Amount (t $year^{-1}$)
Olive pomace	1	Olive	22.6	19.8	19.9	May-June	300
	2				62.4		600
	3				14.9		500
Fruit pits	4	Cherries, peaches, plums	18.1	17.9	6.5	December-May	12,000
	5				5.9		9,000
	6				9.6		12,000
	7				0.3		14,000
	8				5.3		14,000
	9				5.2		9,000
Pruning	10	Vineyards	17.8	18.8	12.5	May - August	150
	11				31.5		70
	12				17.6		1,100

Sampling for energy analysis in the laboratory varied according to the type of waste. In this way, in the case of pruning fruit trees, samples were taken randomly from the pruning that are collected at the edge of the path in each corridor.

a) Fruit pits: using a mechanical system, the waste is deposited directly into a tow truck that is pulled by a 100 hp tractor. Subsequently, the waste is collected in the sector of the agricultural property closest to the road where it will be removed by a 20-ton 150-hp truck. The truck will be loaded with the waste using an 80 hp machine with a mechanical shovel. From here, 30 kg per type of fruit pits are sampled for transfer to the laboratory.

b) Olive pomace: From the outlet of the mill through a 10-inch diameter tube fed with an endless screw system, it will be directly deposited into a 20-ton 150-hp truck. From here, 30 kg per type of fruit pits are sampled for transfer to the laboratory.

c) Pruning: Pruning waste is accumulated on the roadside for removal and/or crushing. From here, samples of woody material of 30 kg were collected to be examined in the laboratory.

2.4. Waste material analysis

The residues were characterized to establish their capacity as solid biofuel. The energy characterization was determined in dry matter at 0% humidity. It is intended to know the density, the calorific value and ash percentage.

a) Sampling and preparing of waste material.

To determine the quality of the waste material (olive pomace, fruit pits and pruning), one kg of each residue collected was extracted in triplicate using a 250 cm^{-2} dredger sediment sampler (Van Veen, 12.110 model, Sidmar) in the laboratory. While in the case of fruit trees pruning, three samples of 3 kg per species were extracted in polyethylene bags and analyzed [9]. It should be noted that the newly extracted samples were taken directly to the laboratory for analysis, so they had not achieved their natural drying. Consequently, it was necessary to dry them, considering that when the wood has water, its calorific value is reduced, firstly by the water content itself and secondly because part of the wood's heat energy is invested in evaporating water [42]. In order to carry out the following tests, it was necessary to transform the samples into sawdust or fragments <5 mm. In the case of samples with diameters <7.0 cm, a portable Garland crusher model BGS 2400 was used. After being crushed, the material was fragmented into smaller parts in an IKA-Werke model M20 mill, obtaining sawdust. In branches with diameters ≥ 7,0 cm, once the chips were obtained (5 cm maximum length), they were left to dry for 2 days, to be placed into an Oliotechnology hammer model ETCR110 11 kW crushers/refiner, obtaining sawdust (0.5 mm - 5 mm).

Each sample was analyzed in triplicate and the methods used in the analysis were standardized according to Deutsches Institut für Normung (DIN) and AOAC INTERNATIONAL (AOAC INTERNATIONAL, 2016). Whose procedures are oven method - AOAC 945.15 for moisture content, muffle method – AOAC 940.26 for ashes, and Norm DIN Serie 51.900 for higher heating value. These processes are already described in [9].

b) Bulk density determination

Following EN 15103, bulk density has been determined. The sample was greater than 1 g, weighed on an empty container resistant to deformation to prevent any variation in form and volume. Its capacity is 5 l (0.005 m^3). The container was filled pouring the sample from a height of 200-300 mm above the superior border until it formed a cone of the maximum height possible. The material was shaken until it settled and then filled once again until it reached the final volume of exactly 5 l, weighing the container with the sample on a precision scale (0.0001 g). The procedure was replicated, and the sample's moisture content determined according to the norms 14774-1 and 14774-2 immediately after the bulk density was determined. The calculation form is presented in Eq. (1):

$$\mathrm{BDar\ (a\ Mar)} = \frac{m_2 - m_1}{V} \qquad (1)$$

Where:

m_1 is the mass, in kilograms, of the sample;

m_2 is the mass, in kilograms, of the container and the sample;

V volume of the container in m^3.

c) Energetic value (HHV)

The method applied was based on Norm DIN 51.900, in which a Cal2k calorimeter (Eco + lab model) was used. The samples were analyzed in triplicate, taking one gram of homogeneous sample for each case.

d) Ash content

The method applied to determine ash was AOAC 940.26, where a Vulcan brand muffle (model 1000) was used. The samples were analyzed in triplicate taking one gram of homogeneous sample for each case.

2.5. Biomass demand of a small-scale CHP plant

The CHP system designed to meet energy demand, has an installed capacity of 1 MWe and 3 MWth with a 24-hour operation, with April until October (winter months) as the months of greatest demand. The energy supply is constant, except for plant maintenance. The criteria for estimating fuel demand are as follows: i) heating season starts on April 15 and lasts until November 15 and ii) the energy characteristics of the waste (MJ kg^{-1}) and its availability (t).

The calculation of agroforestry biomass (olive pomace, fruit pits and fruit pruning) necessary to supply the 1 MWe plant, under the necessary power of the referential boiler of 2760 [kW] and the plant's efficiency being 90%, has been determined based on Eq. (2):

$$Biomass\ \left[\frac{kg}{yr}\right] = \frac{Steam\ power\ required\ [kW]}{PCI\ \left[\frac{Kg}{hr}\right]} \qquad (2)$$

The calculation of agroforestry biomass (olive pomace, fruit pits and fruit pruning) necessary to supply the 1 MWe plant has been determined based on the following calculation:

$$PCI\ olive\ pomace\ \left[\frac{MJ}{kg}\right] = 19.8$$

$$PCI\ fruit\ spits\ \left[\frac{MJ}{kg}\right] = \ 18.7$$

$$PCI\ pruning\ \ \left[\frac{MJ}{kg}\right] = 16.8$$

$$Necessary\ power = 2762\ [kW] x\ 860 \left[\frac{kcal}{kg}\right] x\ 4{,}1855\ [Kj] = 9{,}941{,}901.86\ \left[\frac{kJ}{kg}\right]$$

Knowing that the operating time of the boiler will be 24 hours for 8 months:

$$Olive\ pomace\ \ \left[\frac{kg}{hr}\right] = \frac{9{,}941{,}901.86\ \left[\frac{kJ}{kg}\right]}{19830 \left[\frac{kJ}{kg}\right]} = 501.36 \frac{kg}{hr} x\ 24\ hr\ x\ 30\ days\ x\ 8\ months = 2887\ \frac{t}{year}$$

$$Fruit\ spit\ \ \left[\frac{kg}{hr}\right] = \frac{9{,}941{,}901.86\ \left[\frac{kJ}{kg}\right]}{17900 \left[\frac{kJ}{kg}\right]} = 555.41 \frac{Kg}{hr} x\ 24\ hr\ x\ 30\ days\ x\ 8\ months = 3199\ \frac{t}{year}$$

$$Pruning\ \ \left[\frac{kg}{hr}\right] = \frac{9{,}941{,}901.86\ \left[\frac{kJ}{kg}\right]}{16800 \left[\frac{kJ}{kg}\right]} = 591.78 \frac{Kg}{hr} x\ 24\ hr\ x\ 30\ days\ x\ 8\ months = 3408\ \frac{t}{year}$$

In this way, to cover the demand for raw material, between 2,887 and 3,408 t year^{-1} are needed. Which will vary depending on the energy capacity, cost per ton, availability of each type of biomass, among other variables that will be analyzed in this study.

2.6. Economic and CO_2e emissions parameters

Given the geographical and logistic characteristics of Chile, road truck is the main alternative for load movements, since load trains is not fully available in this country, and air transport is focused on international markets.

i. *CO_2e emissions:* emission factors for transport and final disposition at landfill are obtained through Simapro software v9.1.0.8. with ecoinvent v3.6 database. Regarding pruning burning emission, it takes into account factors emission from the IPCC guide, considering non-CO_2 emissions from fire, since biogenic CO_2 emissions are regarded as contemplate neutral [43] .

ii. *Economic costs:*

- *Storage cost*: For this item, a cost value of 7.4 USD t^{-1} is considered, an average value of warehouse rental according to the physical space used.
- *Transport cost*: Biomass is transported by trucks of 4.5, 12.5 and 18.8 tons, with a cost of USD 0.04 tkm^{-1}, according to the available offer of local transport companies.
- *Purchase cost*: A value of 2.58 USD t^{-1} is considered according to values reported by local companies.

2.7. Bi-objective optimization model and scenarios analysis

In this research, a mixed integer linear programming model is developed, which considers economic and environmental aspects by a bi-objective approach. The model aims to design the biomass supply to CHP plant by making decisions corresponding to; (1) inventory and distribution planning to meet the energy demand of a particular area, (2) selection of the type of biomass according to their calorific value and season availability, (3) selection of the biomass source from which the biomass will be purchased. The bi-objective model determines the optimal supply configuration considering the tradeoffs between economic costs and CO_2e emissions. In this context, two possible scenarios are analyzed:

- Scenario 1: the source stores the residue from one period for the next moment when the vehicle removes the biomass. While the amount of biomass that is not acquired is burned (pruning) or sent to the landfill (fruit pits and olive pomace).
- Scenario 2: the supplying source does not store the biomass in the collection period. Therefore, it is burned (pruning residues) or sends the residues (fruit pits and olive pomace) to the landfill not removed.

The model includes environmental and economic objectives, these are: (1) minimization of total costs and (2) minimization of CO_2e emissions. The economic objective minimizes the total costs of the collection system, which includes the purchase, transport and storage of biomass. The environmental objective is related to transportation and biomass final disposition, such as burning pruning or disposing in landfill. This trade-off approach is necessary because although biomass is considered a renewable energy source, the amount of fossil fuel consumed for its logistics can offset the reduction in emissions from the use of biomass in conversion facilities [19,44]. The notations of the parameters and variables of mathematical formulations are presented in Table 2.

Table 2. Notations of mathematical formulations

Item	Symbol	Description	Unit
Sets	N	Biomass source	-
	K	Vehicles	-
	R	Types of biomass	-
	T	Time period	-
	F_r	Sources that generate the type of biomass r	-
Parameters	p	Vehicle load capacity	t
	o_{rit}	Amount of type biomass *r* generated in source *i* in period *t*	t
	m_t	Demand for the CHP plant in period *t*	kWh
	d_i	Distance to the point *i*	km
	q	Maximum storage capacity at the CHP plant	t
	e_r	Calorific value of type biomass *r*	kWh
	ct	Transportation cost per quantity of biomass from source to CHP plant	USD tkm^{-1}
	ca_r	Storage cost per amount of biomass in CHP plant	USD t^{-1}
	cv_r	Purchase cost of biomass	USD t^{-1}
	emt	Emission factor by transport	kg CO_2 tkm^{-1}
	emp_r	Emission factor for end-life disposition type according to biomass type *r*	kg CO_2 t^{-1}
	SS_t	Safety stock at CHP plant in period *t*	t
Variables	z_{rit}	Amount of biomass type *r* that is collected in source *i* in period *t*	t
	l_{rt}	Amount of biomass type *r* that is stored in the CHP plant at the end of period *t*	t
	ll_{irt}	Amount of biomass type *r* that is stored in source *i* at the end of period *t*	t
	qem_{rt}	Amount of biomass type *r* consumed in the CHP plant in period *t*	t
	v_{it}	$\in \{0,1\}$ $v_{it} = 1$ if the source *i* is visited in period *t*	-

a) Objective functions

$$\min z_1 = \sum_{r\in R}\sum_{i\in F_r}\sum_{t\in T} cv_r z_{rit} + \sum_{t\in T}\sum_{i\in C} ct d_i v_{it} + \sum_{r\in R}\sum_{t\in T} ca_r l_{rt} \tag{3}$$

$$min\, z_2 = emt \sum_{t\in T}\sum_{r\in R}\sum_{i\in F_r} d_i z_{irt} + \sum_{r\in R} emp_r \left(\sum_{i\in F_r}\sum_{t\in T} o_{irt} - \sum_{i\in F_r}\sum_{t\in T} z_{irt}\right) + emtv \sum_{r\in R}\sum_{i\in F_r} dv_i \left(\sum_{t\in T} o_{irt} - \sum_{t\in T} z_{irt}\right) \tag{4}$$

b) Restrictions for inventory depending on data sources

Restriction (5) limits the amount of biomass that can be obtained from each offering source *i* to the number of trips made to that source multiplied by the capacity of the truck.

$$z_{irt} \leq pv_{irt} \qquad r \in R, i \in F_r, t \in T, \tag{5}$$

Restriction (6) indicates the initial inventory accumulated in each source.

$$ll_{ir0} = o_{ir0} - z_{ir0} \qquad r \in R, i \in F_r, \tag{6}$$

Constraint (7) indicates that the total biomass stored in the source i (ll_{rit}) must be equal to the total biomass available at the location of origin *i* in the previous period (ll_{rit-1}), plus the new amount of biomass produced at the source and less the biomass sent to the CHP plant.

$$ll_{irt} = ll_{irt-1} + o_{irt} - z_{irt}, \quad r \in R, i \in F_r, t \in T - \{0\} \tag{7.a}$$

$$ll_{irt} = o_{irt} - z_{irt}, \qquad r \in R, i \in F_r, t \in T - \{0\} \tag{7.b}$$

Here the formulation is differentiated for the two possible scenarios: in the first one, the producer stores the biomass for the next period $(7.a)$, while, in the second one, the producer burns or sends the biomass not removed during a period to the landfill $(7.b)$.

c) Restrictions in CHP plant

In order to ensure that the volume stored in a CHP plant never exceeds the capacity of the plant, the restriction (8) is formulated. Capacity is defined as the sum of the biomass stored at the end of the period and the amount of biomass transported from sources during period *t*:

$$SS_t \leq \sum_{r \in R} l_{rt} \leq q \qquad t \in T \tag{8}$$

In addition, restrictions must be expressed that guarantee that the demand of the CHP plant is satisfied. The demand of the CHP plant in period *t* is denoted by m_t. This demand is expressed in terms of energy (kWh), however, all products transported to the heating plant are expressed in units of mass. Therefore, it is necessary to introduce conversion factors from volume to energy (e_r):

$$\sum_{r \in R} e_r qem_{rt} = m_t \qquad t \in T \tag{9}$$

Constraint (10) shows the initial inventory level at the CHP plant:

$$l_{r0} = \sum_{i \in N} z_{ri0} - qem_{r0} \qquad r \in R \tag{10}$$

Constraints (11) and (12) present the inventory level in the next period at the CHP plant:

$$l_{rt} = l_{rt-1} + \sum_{i \in FR_i} z_{rit} - qem_{rt} \qquad r \in R, t \in T - \{0\} \tag{11}$$

$$l_{r,|T|-1} = SS_{|T|-1} \tag{12}$$

Finally, restrictions (13) and (14) impose the nature of the decision variables.

$$z_{rit}, l_{rt}, ll_{rit}, qem_{rt} \geq 0 \qquad r \in R, i \in F_r, t \in T \tag{13}$$

$$v_{it}, \in \mathrm{Z}^+, i \in C, t \in T. \tag{14}$$

Finally, it is important to highlight that the purpose of analyzing these two scenarios is quantifying the impact that a biomass supplier source does not store these resources for the next withdrawal period. A widely known approach to solve a multi-objective model is the ε-constraint method [45]. This method generates a set of Pareto-optimal solutions showing the trade-offs among multiple criteria. Through this technique, the problem is reformulated as a single objective problem where one of the objective functions (selected arbitrarily) is kept and the other objectives are considered as additional constraints restricted within user-specified ε scalar values (utopic and nadir value).

3. RESULTS AND DISCUSSION

In this section, firstly, the results about biomass characteristics and properties are presented. Secondly, the results obtained from the optimization model are presented and they will be discussed under a sensitivity analysis.

3.1. Biomass characteristics and properties

a) Bulk density and energetic value

The results of each individual measurement are rounded to the nearest 0.1 kg m^{-3}. The average value of the individual results was calculated rounding to the nearest 10 kg m^{-3}. Table 3 establishes that these residues have important energy properties demonstrating their potential as raw materials to be used with these fines.

Table 3: Results of the physical-chemical analyses for samples of olive pomace and pruning residues in initial conditions.

Samples	Moisture content (% wb)** Oven method - AOAC 945.15	Higher heating value (MJ kg^{-1})* Norm DIN Serie 51.900	Ashes (% wb)* Muffle method – AOAC 940.26
Olive pomace	77.7±0.11	22.3±0.06	3.2±0.12
Pruning residues	18.9±0.29	17.8±0.45	2.1±0.11
Fruit pits	16.54±0.12	19.3±0.21	2.92±0.4

*Dry base; **wet base

Humidity is one of the key physicochemical characteristics in the use of biomass as fuel. [46] has shown that particle size and moisture content reduce its HHV, combustion temperature and causes ignition difficulties and instability during the process. In addition, the moisture in the biomass hinders homogeneous heating and leads to the overlapping of combustion stages and increased conversion time [47,48].

It is important to mention that the values reported in Table 3 for HHV are higher than the quality standards ISO 17225-4 for chips and ISO 17225-6 for non-woody. Calorific values that correspond to ≥16.5 MJ kg^{-1} for domestic use and ≥14.5 MJ kg^{-1} for industrial use. Studies in solid waste from olive production by [9,49,50] present, on average, calorific values from 15.6 to 19.8 MJ kg^{-1}. In this sense, these results coincide with those obtained in the laboratory, which, on average, correspond to 22.3 MJ kg^{-1}. In woody waste from pruning in vineyards, studies carried out by [6,51–53] Spinelli et al. (2012), obtained average values from 17.1 to 19.2 MJ kg^{-1}. Results that coincide with those obtained in the laboratory, which, on average, correspond to 17.8 MJ kg^{-1}. Regarding fruit pits from the canning agroindustry, studies carried out by [54–56], obtained average values from 17.7 to 20.7 MJ kg^{-1} for different fruit pits. Results that coincide with those obtained in the laboratory, which, on average, correspond to 19.3 MJ kg^{-1}. In this way, the energy suitability of the studied biomass is corroborated. However, in the case of olive pomace the HHV of 22.3 MJ kg^{-1} is achieved at 0% humidity. Therefore, a significant prior drying of the material is needed to obtain that value, and therefore an increase in costs, since its initial average moisture content is 77.7%. For the purposes of the study and to determine if the material is efficient under normal conditions for energy purposes, its calorific value was determined at 35% moisture content of the material. This percentage is achieved by natural drying in 30 days, which reduces the drying cost to the maximum [57]. Generally, CHP equipment, from this moisture content can have an optimal performance in power generation [58]. In this work, considering these technical and economic conditions, it has been possible to determine that the calorific value of olive pomace at 35% is 19.23 MJ kg^{-1}, coinciding with the values obtained by [51,58,59].

b) Ash content

Regarding ash, Table 3 shows that the values obtained for all the wastes studied are similar. In this way, olive pomace contains 3.2%, pruning fruits 2.1% and fruit pits 2.9%. [51–53,60] obtained average values ranging from 2.4% to 5.3% in woody waste from vine pruning, which are relatively higher values than those obtained in this research. This may be because the samples collected are not uniform in climate, time of year, type of soil, part of the plant and the presence of additional contaminants like sand that contributes to increase the ash content [61,62]. Regarding fruit pits, studies carried out by [54–56,63] obtained average values of 1.0 to 5.6% for different fruit pit. Results that coincide with those obtained in the laboratory, in which a range of 2.1 to 3.2% was obtained. These results are within the values indicated by the ISO 18122 standard as optimal to be used for energy purposes.

In order to avoid an increase in the percentage of ashes, it is recommended that the biomass delivered to the plant should meet the minimum requirements that guarantee adequate humidity, and equipment that allows the fuel supplied to be weighed [64]. Therefore, with the results obtained, it can be concluded that these residues can be perfectly used as an energy source, contributing to the development of a circular bioeconomy system.

3.2. Sensitivity analysis

To analyze the behavior of the results with respect to the desired objectives, a sensitivity analysis is carried out based on the variation of two parameters: vehicle capacity and energy demand. In this context, the capacities of 4.5 t, 12.5 t and 18.8 t are considered for transportation. While 0.5

MWe, 1 MWe, and 2 MWe are considered for energy demand. Consequently, there are nine cases for each evaluated scenario. In Table 4, the cases considered, and the notation used are presented.

Table 4. Parameters for sensitivity analysis

Vehicle capacity (t)	Energy demand (MW)	Scenario 1 Notation	Scenario 2 Notation
4.5	0.5	S1 4.5 ton/ 0.5 MW	S2 4.5 ton / 0.5 MW
	1	S1 4.5 ton / 1 MW	S2 4.5 ton / 1 MW
	2	S1 4.5 / 2 MW	S2 4.5 ton / 2 MW
12.5	0.5	S1 12.5 ton / 0.5 MW	S2 12.5 ton / 0.5 MW
	1	S1 12.5 ton / 1 MW	S2 12.5 ton / 1 MW
	2	S1 12.5 ton / 2 MW	S2 12.5 ton / 2 MW
18.8	0.5	S1 18.8 ton / 0.5 MW	S2 18.8 ton / 0.5 MW
	1	S1 18.8 ton / 1 MW	S2 18.8 ton / 1 MW
	2	S1 18.8 ton / 2 MW	S2 18.8 ton / 2 MW

3.3. Optimization model results

The bi-objective model was implemented in OPL software and solved using the commercial solver CPLEX 12.9. Results are exposed comparing the two scenarios analyzed, the first one, when biomass is not collected, it is stored in the source location for the next period. Otherwise, the second one, the rest of the biomass that is not used is burned (pruning residues) or it is sent to a landfill (fruit pits). Pareto optimal solutions are presented in Figure 3 according to the sensibility analysis presented in Table 4. These results show the trade-off between both objective functions. This is mainly since the biomass with the best ratio cost-calorific value is, in turn, the one with the worst ratio CO_2e emission-calorific value. Therefore, there is a change in the composition of the biomass according to the objective that is the most important for the decision maker.

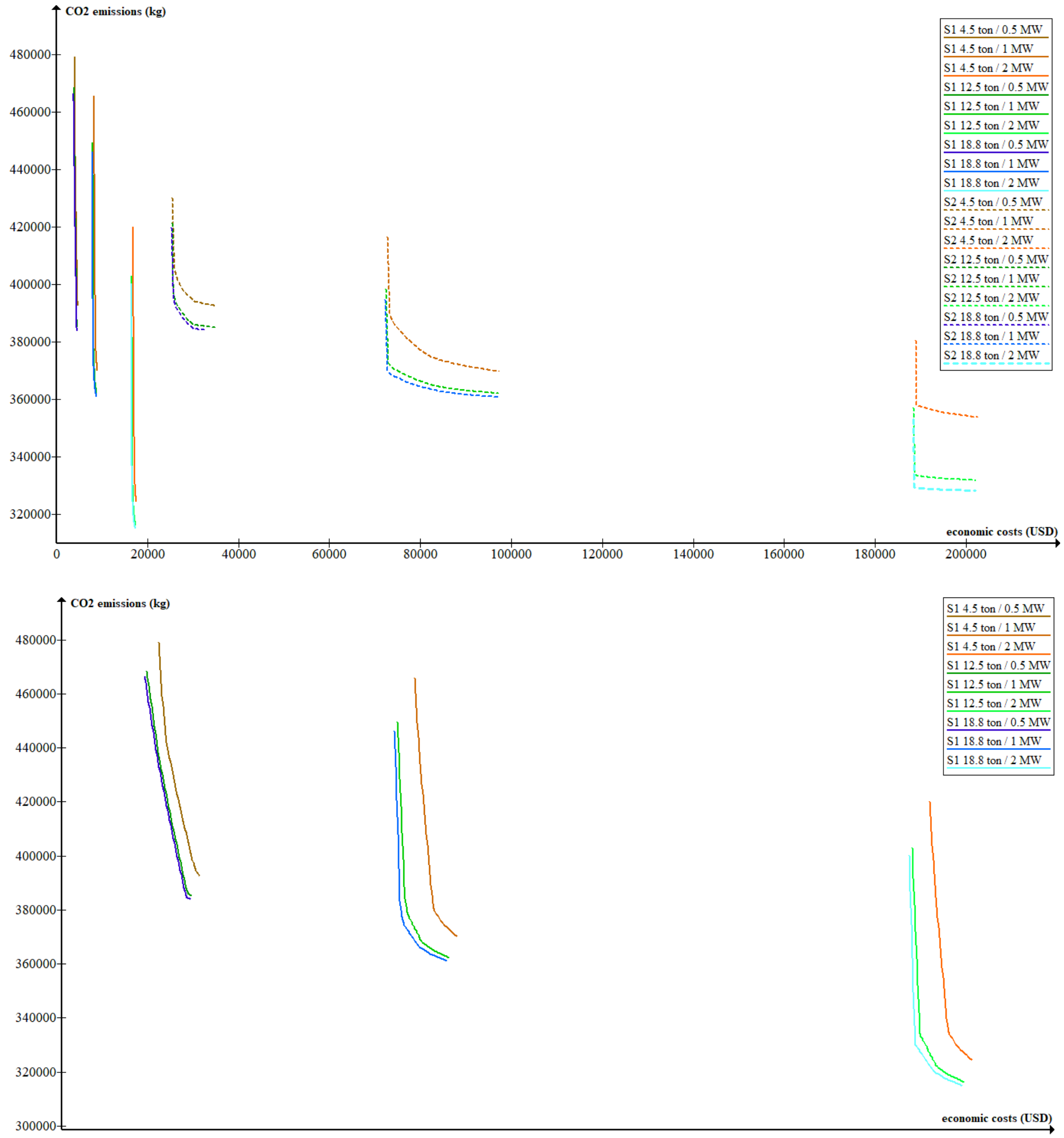

Figure 3. Pareto optimal solutions

Regarding the factors that contribute to CO_2e emissions (Figure 4 and 5), it is identified that the factor that contributes the most is the transport of biomass to the landfill. Because the largest amount of available biomass is not used to supply the cogeneration system. On the other hand, the factor that contributes the least to CO_2e emissions is the transport of biomass to the CHP system. Mainly because of the proximity to the supplying sources and the amount of biomass required to be transported. Therefore, from these results, it is observed that supply biomass for the

CHP system generates an environmental benefit compared to the traditional disposal of biomass. Finally, in relation to operating costs (Figure 6 and 7), if we focus on the first scenario, they are mainly made up of purchase costs, because of the closeness between the sources and the CHP plant, transporting a ton of biomass is cheaper than buying it. While storage costs remain relatively constant since the supplying sources store the biomass. Therefore, the cogeneration system operates with the minimum necessary stock. Regarding the second scenario, the storage cost predominates, based on the need for the CHP system to store the biomass during the months in which no source generates biomass supply.

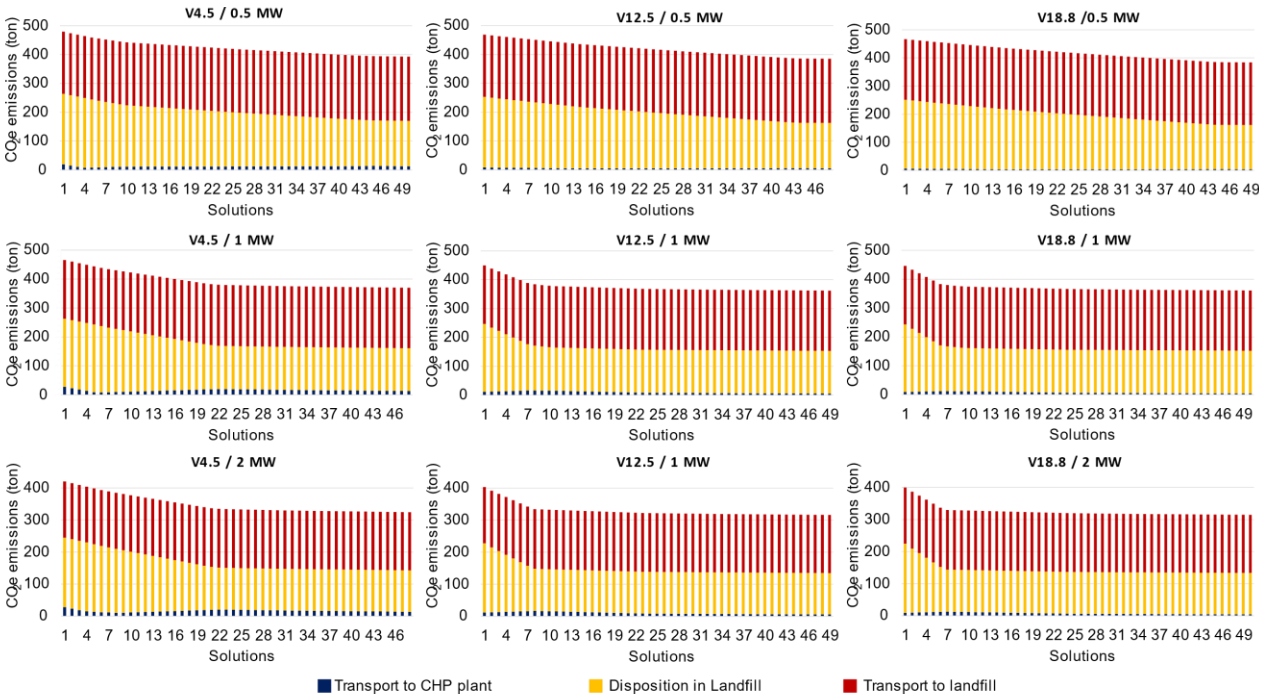

Figure 4. CO_2e emissions for scenario one

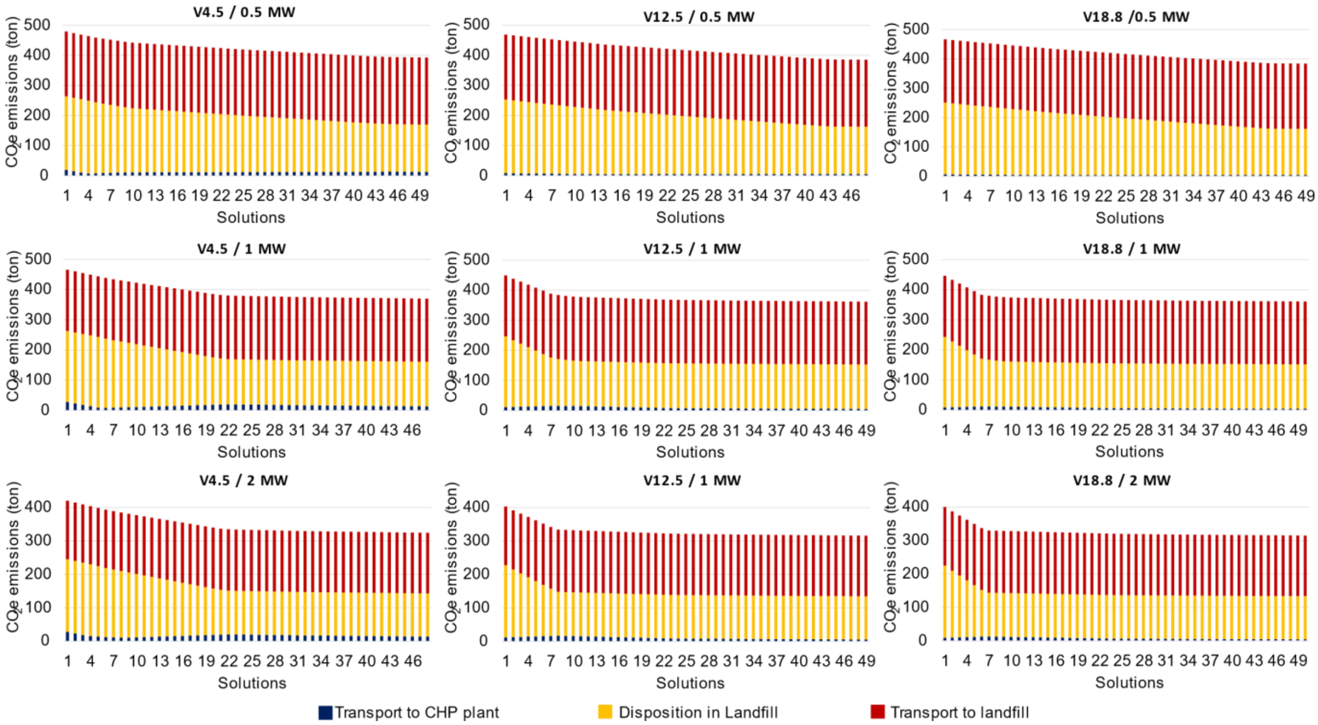

Figure 5. CO$_2$e emissions for scenario two

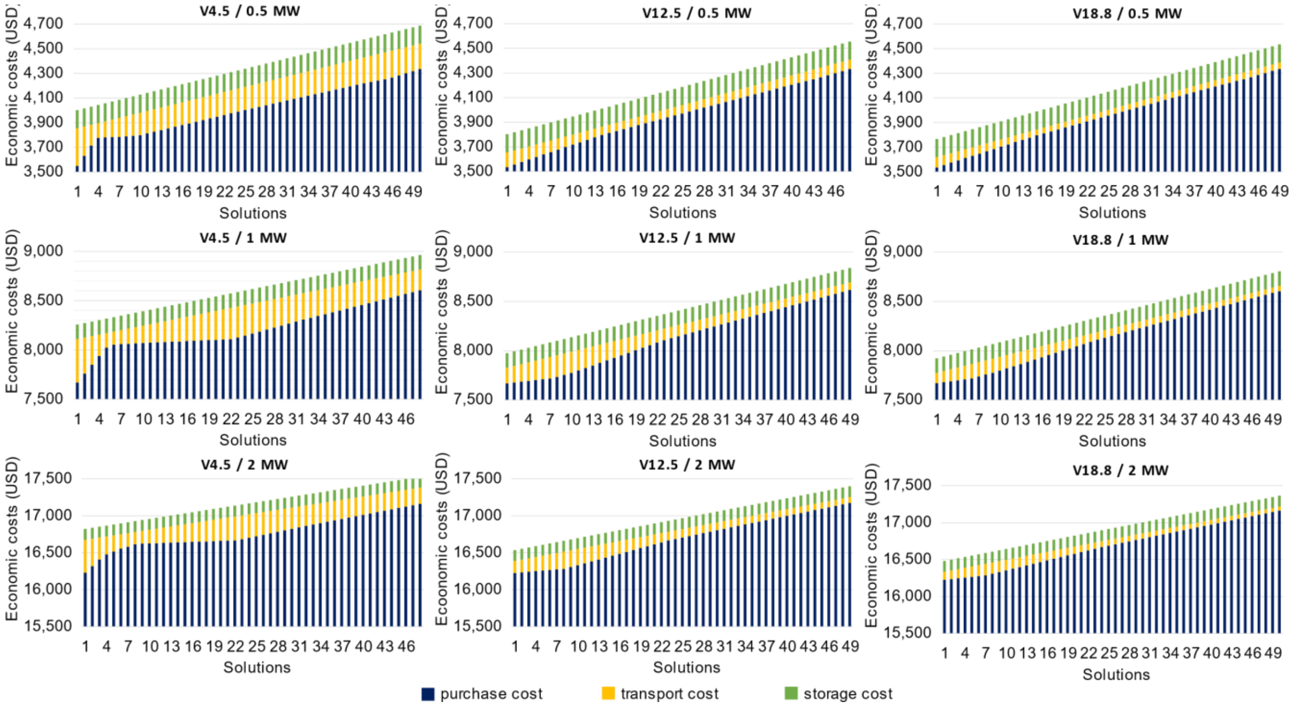

Figure 6. Cost composition for scenario one

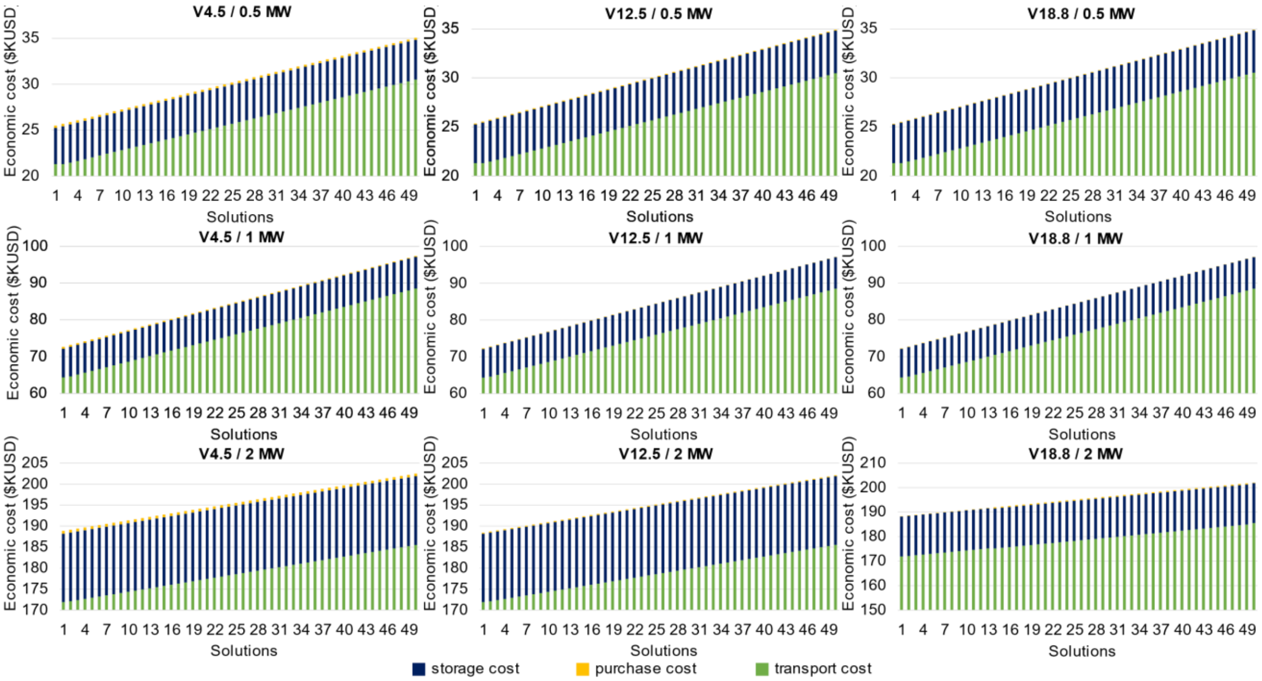

Figure 7. Cost composition for scenario two

When comparing both scenarios, Scenario 2 presents a higher cost due to an increase in storage costs, since it is necessary to store the biomass in the CHP system in order in order to avoid a stockout in the months in which biomass is not generated. Regarding environmental impacts, in both scenarios a great contribution is observed in the use of transport. Due to a greater use of biomass since the CHP plant must use biomass with a lower calorific value. On the other hand, the management that can be carried out to reduce CO_2e emissions is more limited, since the amount of waste to be transported is limited to the capacity of the CHP plant.

By increasing the capacity of the vehicle, a decrease in costs is observed, because fewer trips are made. However, this decrease is not significant, because of the low percentage that transportation represents in total costs. With respect to environmental impacts, a decrease is observed due to the increase in the amount of pruning residues that is sent to the CHP system. Mainly due to greater profitability in the shipment of this biomass by increasing the capacity of the vehicle. There is also a lower impact since fewer trips are made, and because the ratio of CO_2e emissions per ton transported is lower in vehicles with higher capacity.

As the demand for energy increases, it is observed that all costs rise, due to the increase in biomass that must be acquired to meet the energy demand. Therefore, an increase in CO_2e emissions associated with the transport of biomass to the CHP system is obtained. However, this increase is offset by the decrease in disposal and consequently transportation to the landfill. In this sense, in an environmental approach, it is better to transport the biomass to the cogeneration system than to dispose of it.

Regarding the type of biomass needed to supply the CHP system (see Figure 8 and 9), it is observed that pruning is the most environmentally favorable biomass, but less economically advantageous due to its lower calorific value. While olive pomace is the most economically profitable, but environmentally, it is the least favorable. On the other hand, there is a preference for fruit pits as there is an increase in energy demand, given the low availability of pruning fruit in the study area. Regarding the sources offering biomass, it is identified that the system is supplied mainly from three sources: number 3 (olive pomace), 7 (fruit pits) and 12 (pruning fruit). In general, these sources generate the highest amount of biomass available and are located closer to the CHP plant. In this sense, the distance also varies depending on the desired objective. When the goal is to minimize economic costs, the maximum supply radius is 60 km. Since, as it is biomass dispersed in the territory and small-scale pieces, the cost of collection and transport begins to be higher [65]. While when CO2e emissions are minimized the maximum radius decreases to 30 km. In this way, a result like the distance proposed by [57] of 25 km in radius is obtained for the use of biomass for energy purposes. It is the maximum exploitation distance for a system with these characteristics [66,67].

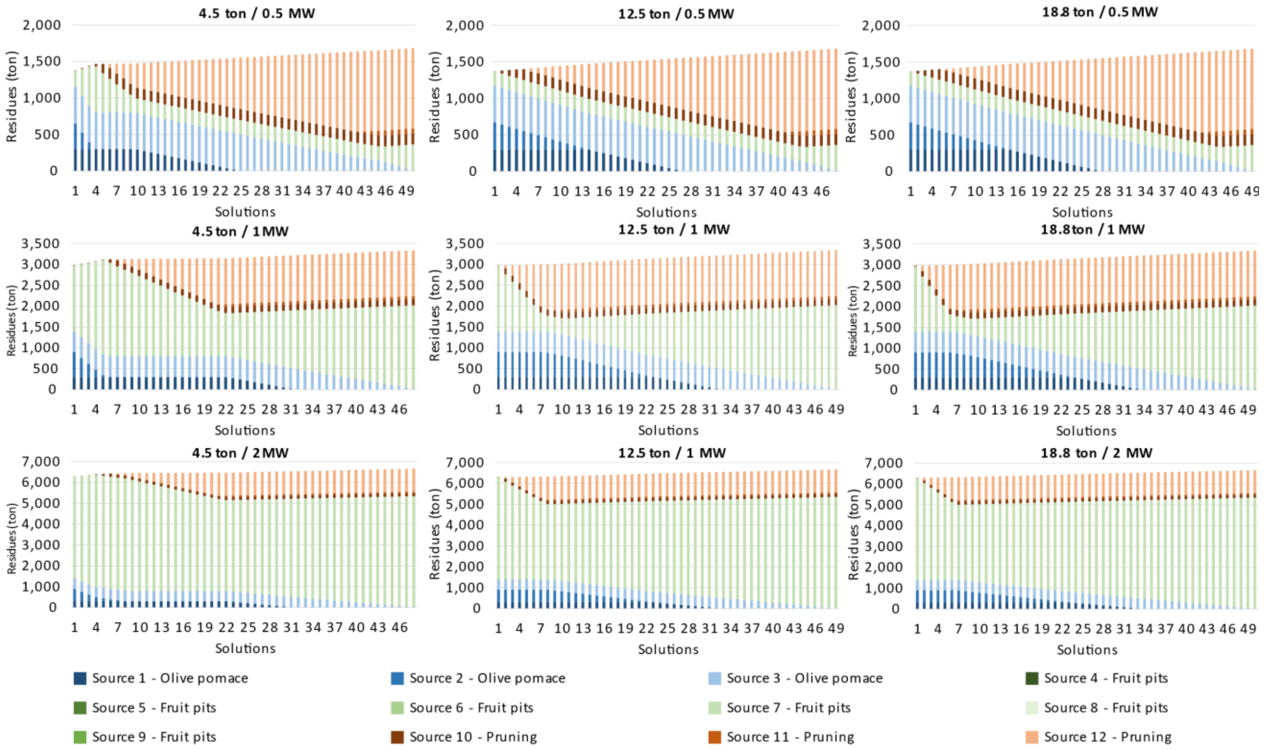

Figure 8. Type of waste consumed for case one

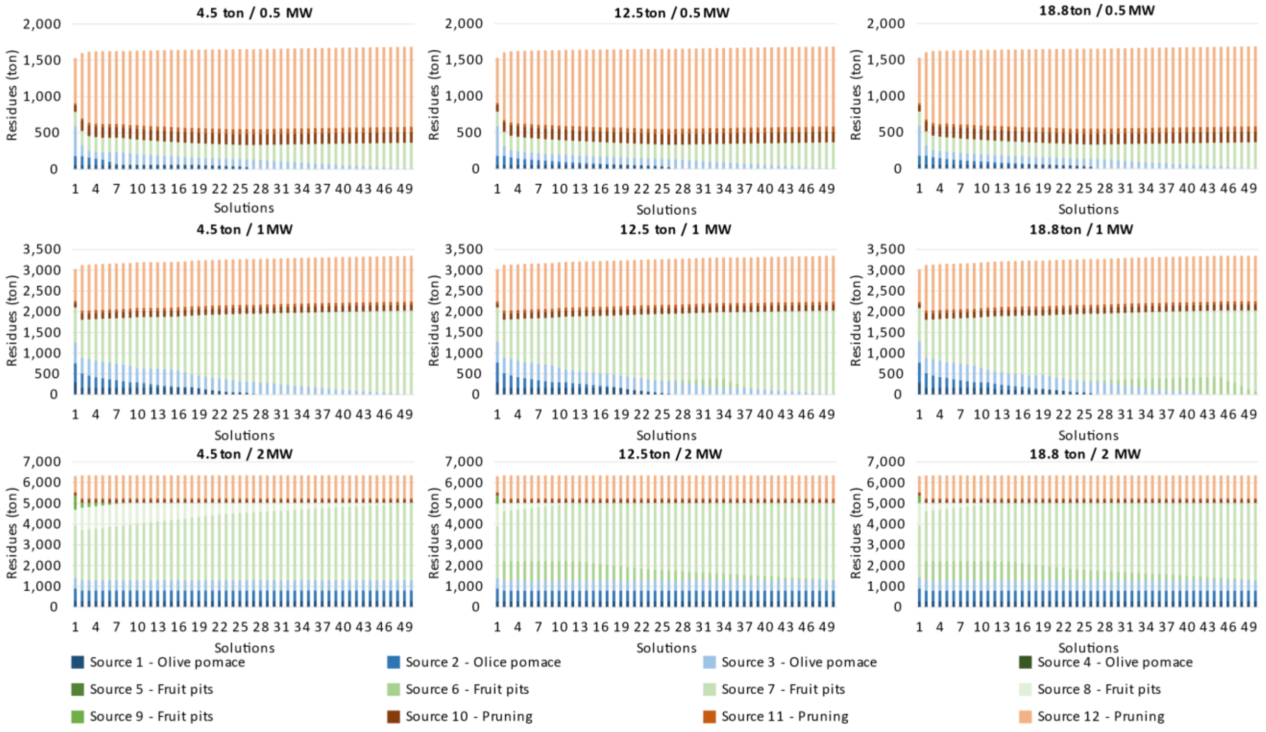

Figure 9. Type of waste consumed for scenario two

4. CONCLUSIONS

This paper proposes a bi-objective optimization model for different agro-industrial biomass supplies to a small-scale CHP system at a local level under Mediterranean conditions. The research aims to quantitatively assess environment and economic benefits of provide multiples types of biomass to the CHP plant, avoiding their traditional disposition. Thus, scenarios with different energy demands and transport capacities were analyzed to identify the best tactical decision for operating the CHP system. In this way, it is possible to conclude that the implementation of a CHP system generates environmental benefits. The supply of biomass to the CHP plant avoids the emission of CO_2e generated by final disposal in a landfill or burning of this waste. In this sense, the minimization of CO_2e emissions, by using a diverse variety of biomass, pruning residues are identified as the first option for the supply of the CHP system, due to their relationship between mass and calorific value. Fruit pits follow, when energy demand increases, and the availability of pruning and olive pomace residues ends. While when the cost minimization is desired, olive pomace is identified as the first option, followed by fruit pits and pruning material.

On the other hand, transport is not a major contributing factor when biomass sources are close to the CHP system. However, as expected, since the distance increases, such as the case of transport from sources (fields and factories) to the landfill, CO_2e emissions and carbon footprint increase considerably, given the high level of transported cargo. Therefore, under the conditions studied, a distance limit can be established in the supply of raw material to the CHP plant within a maximum radius of 30 km and an increase depending on the costs.

Moreover, despite the seasonality in the availability of the different biomass available in the Mediterranean regions, both those from the field (pruning waste) and those from the factories (fruit bones or olive pomace), it is feasible to adequately supply the CHP plant. However, this increases the storage costs involved. Therefore, it may be advisable to analyze other sources of lignocellulosic biomass to reduce these costs during the period of unavailability, for example biomass derived from forestry activities or silvicultural treatments (clearings to prevent bushfires, thinnings or feven inal cuttings) or residues from forest industries (bark, side-boards or sawdust).

Finally, it is expected that these results should serve as a basis for decision-makers to develop bioenergy CHP systems projects in regions whose base their economy under agro-industrial activities to provide environment and economic benefits for their communities.

ACKNOWLEDGEMENTS

Ricardo Rebolledo-Leiva would like to thank CONICYT-PFCHA/Magíster Nacional/2019-22190179 for their financial support. Javier E. Gomez-Lagos would like to thank CONICYT-PFCHA/Doctorado Nacional/21191364 for their financial support. Diogenes Hernández acknowledges funding from FONDECYT, Chile, project Nº. 11200398.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: