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The economic value of olive sector biomass for thermal and electrical uses in Andalusia (Spain)

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A B S T R A C T

Olive sector residues could contribute to increased use of renewable energies, especially in those areas where the olive crop is produced. This paper determines the maximum amount of electrical and thermal energy which could be obtained in Andalusia from olive sector residues, and the economic value that could be obtained from these energy uses. For this, the current data on installed power and electrical and thermal generation are compared with the calculated potential data which would be obtained at full capacity. The results show there is a 69.23% wastage of olive sector residues for energy purposes. Thus, using the resources at full capacity, 3.9 million tons of biomass per year could be obtained for energy purposes. Currently, only 2 million tons of biomass are used for energy purposes. This wastage translates into a below potential generation of electrical and thermal energy. The full use of these residues would allow 83.9% and 64.9% higher generation of electrical and thermal energy, respectively. The results obtained also show that the economic value of olive sector biomass is higher than the market price value, with the average values for each use being 248.20 €/t for domestic thermal use, 165.04 €/t for electrical use and 139.50 €/t for industrial thermal use. Thus, it is considered feasible that the olive sector biomass could be used to a greater degree than at present. In this sense, it is recommended that more electricity generation plants and thermal-generating systems be put into operation.

1. Introduction

Traditionally, the evolution of the global economy has been dominated by a linear model of production and consumption. This model is based on the manufacture of products from raw materials that are subsequently sold, used, and then discarded as waste residues [1]. The bioeconomy aims to change this scenario. For this, a new economic model is established, based on improving the use of residues in a sustainable manner [2]. In the European Union (EU), this objective is included in the Horizon 2020 Programme, where a series of measures are established to promote the bioeconomy, especially in rural areas [3,4].

The bioeconomy offers various environmental benefits, among which are emphasized the reduction of greenhouse gas emissions (GHG), a decrease in dependence on fossil resources, smarter management of natural resources and greater food security [2]. In this way, the bioeconomy is considered a key pillar of strategic innovation within the EU [5]. An economy founded on biomass, instead of fossil fuels, represents a significant change in socioeconomic, agricultural, energy and technical systems [2]. In Europe, biomass is made up of residues from various economic activities, such as: agriculture, forestry, urban waste management (solids and liquids) and food waste [5]. Biomass from agricultural activities is particularly relevant as a key raw material for European bioenergy. This is due to the plentiful residues and waste that those activities generate [5]. Among the main residues from agricultural activities, those from the olive sector stand out.

Consequently, the importance of the use of by-products from the olive sector, as an alternative to fossil energy, has aroused great interest among the scientific community. Proof of this is provided by the reviews on the potential use of by-products from the sector [6–8]. Most of these studies focus on Mediterranean countries, where the presence of this crop is plentiful. Therefore, an adequate use of olive sector by-products would allow effective implementation of the concept of bioeconomy, established by the EU [9]. However, olive sector by-products have other bioeconomy alternatives to those for energy purposes, such as the production of animal feed [10]. These reviews demonstrate the high value of olive sector residues.

Therefore, the main focus of this paper is on olive biomass, as an energy source, which has great value to launch the bioeconomy model. It is thus worth highlighting the relevance of this agro-food sector for the areas where the crop is grown, especially in the EU, where the olive

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List of abbreviations including units and nomenclature

€/t	Euro/tons
€	Euro
AEMET	State Meteorological Agency
BE	Biomass value for electrical uses (€/t)
BTH	Biomass value for household thermal uses (€/t)
BTI	Biomass value for industrial thermal uses (€/t)
CNMV	Comisión Nacional del Mercado de Valores (National Securities Market Commission)
CO2	Carbon dioxide
EE	Electrical energy generated (GWh)
EP	Quantity of extracted pomace (t/year)
ERDF	European Regional Development Fund
ESYRCE	Encuesta sobre Superficies y Rendimientos Cultivos (Crop Areas and Yields Survey)
ET	Thermal energy generated (GWh)
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse gas emissions
GIS	Geographic information system
GJ	Gigajoul
GVA	Gross Value Added
GWh	Gigawatt hours
h	Annual hours of operation
HVAC	Heating, ventilation and air conditioning
IDAE	Institute for Diversification and Energy Saving
kcal	Kilocalorie
kg	Kilogram
LA	Amount of wood from the oil olive grove (t/year)
LM	Amount of wood from the table olive grove (t/year)
m	Kilogram of biomass/year
mE	Amount of biomass useful for electrical use (t/year)
mE	Quantity of biomass useful for electrical use (t/year)
mT	Amount of biomass useful for thermal use (t/year)
mT	Quantity of biomass useful for thermal use (t/year)
MW	Megawatt
MWh	Megawatt hours
ni	Number of table/oil olive trees in year i
ni+1	Number of table/oil olive trees in year i + 1
ºC	Degrees Celsius
OL	Quantity of leaves from olives for milling (t/year)
OMIE	Iberian Energy Market Operator
OP	Quantity of olive pomace (t/year)
OSA	Quantity of stones from milling olives (t/year)
OSM	Quantity of table olive stones (t/year)
PCI	Lowest calorific value of biomass (kcal/kg)
Pe	Electrical power (MW)
pE	Unit price of electricity generated with biomass (€/kWh)
Pt	Thermal power (MW)
pTH	Unit price of thermal energy for household use (€/kWh)
pTI	Unit price of thermal energy for industrial use (€/kWh)
RA	Amount of branch from the oil olive grove (t/year)
RM	Amount of branch from the table olive grove (t/year)
VE	Economic value of electricity (€)
VTH	Economic value of thermal energy for household use (€)
VTI	Economic value of thermal energy for industrial use (€)
xi	Productivity of the table/oil olive grove in year i
xi+1	Productivity of the table/oil olive grove in year i + 1
ZA	Quantity of olives for milling (t/year)
ZM	Quantity of table olives (t/year)
μ	Electrical conversion performance
μt	Thermal conversion performance

grove has a greater presence [11,12].

Internationally, olive groves occupy a total of 11.5 million hectares, which represents 1% of the arable land on the planet [13]. There is a solid and growing agri-food sector around this crop, which includes 14, 000 oil mills, distributed throughout the world [14]. These are located mainly in Europe (with a little more than 7200), followed by Africa (with almost 4700), Asia (with just over 1600), America (with 268) and Oceania (with 34) [14]. The number of olive pomace extractors and olive oil refineries stands at 253 and 83, respectively. This contributes to making biomass one of the predominant renewable energy sources in the energy mix, worldwide [15].

In Europe, 80% of the olive groves are mainly concentrated in the Mediterranean countries, with Spain being the country with the most land devoted to this crop (2.69 million hectares in 2018) [16,17], followed by Italy (1.23 million hectares in 2017) and Greece (1.13 million hectares in 2017) [18]. Therefore, Spain is placed first in global and European olive oil production, with Spanish production representing approximately 60% of EU production, and 45% of global production [19]. These land use statistics favor the use of olive sector by-products for energy generation, which places Spain in a leading position among the countries with the highest production of olive biomass. Most of the olive crop in Spain is in Andalusia. This region has 60% of the land cultivated for olive groves at the national level (1.63 million hectares in 2018), and 30% at the European level [17,20].

Likewise, the bioeconomy content established in the EU Horizon 2020 Programme has been transferred to the national, and regional, level in many countries [21]. In Spain, the Spanish Bioeconomy Strategy aims to boost the competitiveness of Spanish biotechnology and agri-food [22]. For its part, Andalusia has launched the Andalusian Circular Bioeconomy Strategy. This aims to contribute to the growth and sustainable development of Andalusia, as well as to promote actions aimed at development of the production of resources and renewable biological processes, such as olive biomass [23].

In this way, the olive sector would provide an opportunity to establish the bioeconomy model at the national and regional level. The plentifulness of this crop has forged a powerful agri-food sector in Spain, mainly in Andalusia. This region concentrates most of the existing facilities nationwide. In 2017, in total, there were 844 oil mills (48% of the national total), 219 table olive industries (45% of the national total), and 45 olive pomace extractors (71% of the national total) [24]. Therefore, Andalusia is one of the European regions with the most opportunities to obtain residues from this sector. Specifically, Jaen Province in Andalusia is the main olive oil producing area in the world [5].

Similarly, this region stands out for the number of biomass power generation plants, nationwide. Currently, there are 18, and 13 of them use by-products from the olive sector for power generation [25]. This region is the leading user of biomass for thermal energy generation at national level, with olive biomass representing 42% of that used in its generation [26,27].

In short, Andalusia is in a leading position regarding the use of biomass, at the national level, in electrical and thermal applications [28]. However, despite the importance that olive biomass has for Andalusia, the energy wastage in this sector is high [12].

Recently, numerous studies have focused on enhancing the importance of olive biomass, mainly to respond to the energy problem, or as a means to combat climate change. One of the most recent studies is that by Montanaro et al. (2018) [29], which highlights the importance of agriculture and, especially, the olive grove as a renewable energy source. The purpose of that study is to publicize its energy value in order to reduce greenhouse gases. Some studies have assessed the potential of this type of biomass, or similar, in countries such as Italy [30–32], Greece [33,34] and Spain [35–38]. In this sense, it is worth highlighting the study by Di Fraia et al. (2020) [32], which makes it possible to quantify the biomass from various crops, among which is olive grove biomass. A methodological process is used that does not make a specific distinction between the by-products obtained in this agro-industrial sector. To obtain the results, the researchers used statistical and bibliographic data from different official sources. Alternatively, the study by Manzanares-Secades et al. (2017) [35] uses a methodological process based on surveys, to collect data from the olive oil agro-industrial sector. These researchers only consider three by-products: tree pruning biomass, extracted olive pomace and olive leaves. Furthermore, García-Martín et al. (2020) [39] used a methodological process allowing the biomass from the olive grove sector to be determined. Using that approach, all the by-products from this sector can be obtained. This approach is similar to the one proposed by the Andalusian Energy Agency [25] to obtain by-products from the olive grove sector [25]. The latter is the one used to obtain the results of this study. Finally, the studies by Alatzas et al. (2019) [33], Rosúa et al. (2012) [36], Algieri et al. (2019) [30], Velázquez-Martí (2011) [37] and García-Maraver et al. (2012) [38] focus on quantifying the biomass from olive grove pruning. All these papers are relevant to be able to obtain quantitative data from the olive grove biomass sector. In fact, all these investigations are developed for Mediterranean countries. However, the methodology used by Civantos López-Villalta (1981) [40] is the one that best fits the analysis proposed in this research, since it uses a methodology in which all the by-products from pruning are differentiated. In addition, the researchers adjust this mathematical model to the characteristics of the plantation, the land, the productive capacity or frequency of pruning of this crop, in the region of Andalusia (Spain). This means that it has been used in research at the regional level of Andalusia to obtain its results. An example of this is the paper by Medina et al. (2006) [41]. In this way, the Civantos López-Villalta methodology continues to be valid, since when it was developed, the intensive and traditional olive grove areas were taken into account. Currently, these forms of cultivation represent 95% of the olive grove area in Andalusia, compared to 2.5% of the super-intensive olive grove.

It is also worth mentioning that, in the case of Spain, most researchers focus their attention on the region of Andalusia, where this organic matter assumes an important role, given the plentiful residues. For example, the study by García-Maraver et al. (2012) attempts to reveal the potential of olive grove biomass for electrical and thermal uses in Andalusia, as well as the positive impact that this potential has for the environment and energy efficiency [38]. In this regard, the use of olive grove residues for energy purposes would allow the implementation of the concept of bioeconomy and circular economy [42], which has become a very relevant aspect in recent years, and the object of many studies. A significant example is that by D'Adamo et al. (2019), which evaluates the opportunities associated with the development of these circular economy models [43]. In parallel, these studies aim to promote olive sector biomass, in order to encourage economic development in rural areas, or job creation [44,45].

Based on these previous studies, this paper aims to expand on the different research described above. This study not only intends to highlight the high potential of olive sector biomass in Andalusia, for thermal and electrical uses, as has been done in previous literature for other regions and time periods, but also to highlight the value chain of such biomass. This is a novel analysis, since there is no research on this aspect. In order to achieve this objective, it is necessary to carry out a prior analysis of the biomass potential, consisting of quantifying the olive sector by-products, for the period 2004–2016. Subsequently, the power and the potential thermal and electrical energy generation can be obtained and compared with the current data offered by official data sources. Thus, the degree of wastage can be observed with greater accuracy through the results. Finally, and in a novel manner, the value chain of thermal and electrical uses of biomass allows the uses that generate the greatest wealth in the region to be established. For this last procedure, the data offered by the different official sources for the period 2009–2016, are considered. In this sense, knowing the economic value of olive grove biomass for thermal and electrical uses in Andalusia could be of great interest to companies in the sector, as it would help them to better understand the advantages of a better use of these residues in economic terms. In the same way, this analysis would allow the opening of new lines of research, focused on forecasting the value of these residues for thermal and electrical uses in the future. For this, there are previous studies that use various methodologies that may be useful, when forecasting the value of olive grove biomass in a given future [46,47].

The structure of this paper is as follows. Following this introduction, Section 2 describes the methodology used. The data used is shown in Section 3. The results are given in Section 4. Section 5 discusses the results, and finally, Section 6 details the latest conclusions.

2. Methodology

The methodological procedure of this paper is developed in three parts. In the first, the amount of biomass which can be obtained from the olive sector residues is determined. To determine the amount of biomass that can be obtained from the residues generated from the manufacturing of olive oil and table olives, the methodology of the Andalusian Energy Agency [25] is used. To determine the amount of biomass that can be obtained from the residues generated from olive grove pruning, the methodology of Civantos López-Villalta [40] is used. These two methodologies best fit this study, since they allow a detailed determination of the different residues that are covered in the results of this paper. The period considered is 2004–2016.

In the second part, the maximum amount of electrical and thermal energy which can be obtained from said residues is determined. The results of this analysis are obtained by applying the data, obtained from several statistical and bibliographic sources, to the different mathematical equations; the period considered is 2004–2016.

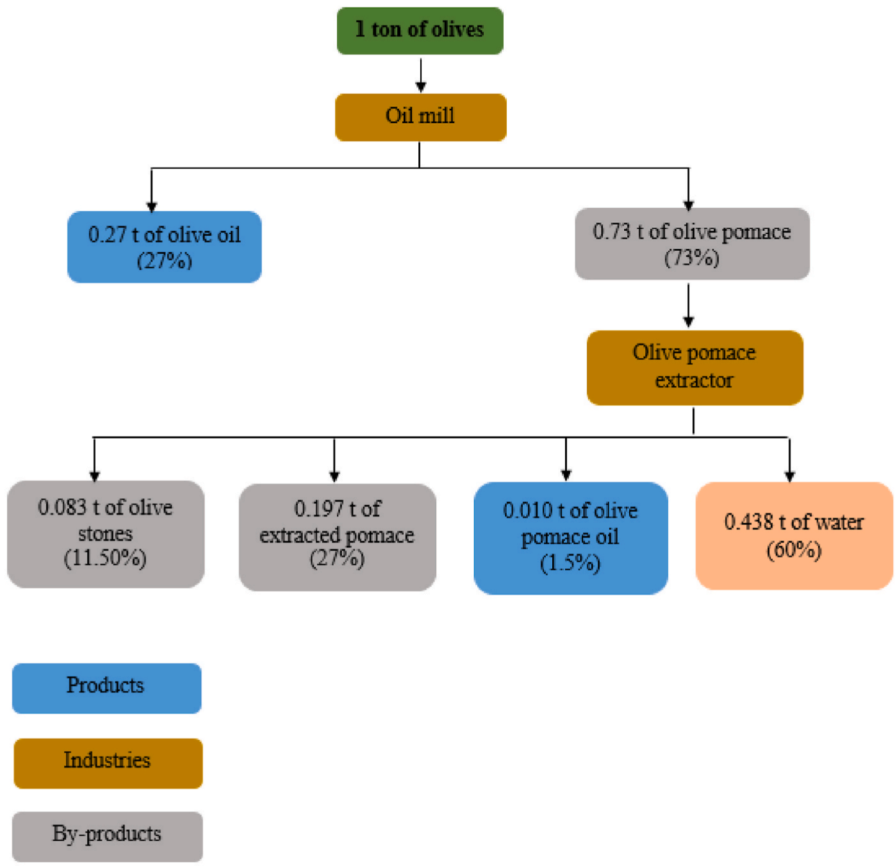
In the third part, the economic value of thermal and electrical uses is determined. This part presents a novel analysis, as there are no previous investigations in this regard. To determine the results of this process, the potential biomass results obtained in this paper, and the data offered by different official statistical and bibliographic sources, are used. In this case, given the availability of the data, the period considered is 2009–2016.

The methodological process of each of these parts is detailed below.

2.1. Methodology used to calculate the biomass derived from olive sector residues

This first part of the methodology determines the amount of biomass that can be obtained from the residues, generated from the manufacturing of olive oil and table olives, and from olive grove pruning.

The calculation of the biomass obtained in the olive oil manufacturing process is determined from the information offered by the Andalusian Energy Agency [25]. This is summarized in Fig. 1. One ton of olives generates 27% olive oil and 73% olive pomace. From this 73% olive pomace, 30% goes to the generation of electricity, and the rest to the production of olive pomace oil [25]. In the process of making olive oil, the by-products of olive pomace oil (1.5%), water (60%), olive stones (11.50%) and extracted pomace (27%), are obtained. These last two by-products are suitable for the generation of renewable energy. Likewise, biofuel, fertilizer, and water for irrigation, can be obtained from the 60% water (called olive exudate). However, since its use is not very widespread [48], and as the focus here is on solid biomass, this paper does not include this renewable energy. Thus, only the renewable energy obtained from the olive pomace, extracted pomace and olive stones, is assessed.



Source: Andalusian Energy Agency [25] and own elaboration.

Fig. 1. Balance of the production process of olive oil and olive pomace oil by mass.

The calculation of the biomass obtained in the olive oil manufacturing process is carried out, according to the following equations:

$$O_P = 0.73\ \ Z_A \cdot 0.3 \quad [1]$$

$$O_{SA} = 0.73\ \ Z_A \cdot 0.115 \cdot 0.7 \quad [2]$$

$$E_P = 0.73\ \ Z_A\ \cdot 0.27\ \cdot 0.7 \quad [3]$$

where;

O_P = quantity of olive pomace (t/year).
Z_A = quantity of olives for milling (t/year).
O_{SA} = quantity of stones from milling olives (t/year).
E_P = quantity of extracted pomace (t/year).

When cleaning the olives, prior to the process of olive oil and olive pomace oil manufacture, olive leaves are extracted, which represent 8% of the weight of the olive crop sent for milling [25]. These can be destined for electric power generation. In this case, 1 ton of olives for milling, generates 0.08 tons of olive leaves.

$$O_L = 0.08\ Z_A \quad [4]$$

where;

O_L = quantity of leaves from olives for milling (t/year).
Z_A = quantity of olives for milling (t/year).

Information from the Andalusian Energy Agency is also used for the calculation of the biomass obtained in the table olive production process. In these industries, approximately 80% of table olives are pitted, to be sold as stoneless olives [25]. In this case, after passing through the processes of the table olive industry, olive stones are obtained which are commonly used in boilers for thermal energy uses. Since the olive is composed of 85% flesh, and 15% stone, of the 80% of table olives that are stoneless, 15% stone is obtained. Therefore, from 1 ton of table olives, 80% are destined for stoneless olives, from which 15% of stones are obtained,

$$O_{SM} = 0.8\ \ z_M \cdot 0.15 \quad [5]$$

where;

O_{SM} = quantity of table olive stones (t/year).
Z_M = quantity of table olives (t/year).

The methodology proposed by Civantos López-Villalta [40] is used to calculate olive grove pruning (composed of branches and wood). There are some studies that quantify the olive grove biomass in Spain [35–38], however, as explained below, that of Civantos López-Villalta [40] is the one that best fits the characteristics of this work.

It should be noted that olive growing methods have been changing over the years [49]. At the end of the 70s, the foundations of modern olive growing were laid, with intensive olive grove coexisting with the traditional. This situation continues to this day where, in 2018, 95% of the olive grove area corresponds to these types. At the end of the 20th century, and on an experimental basis, the super-intensive 'hedgerow' olive grove system began to be introduced in Andalusia. Despite this, the works carried out on the use of olive grove biomass use the formula of Civantos López-Villalta [40], to evaluate the amount of available biomass [41]. This methodology has favorable characteristics, since the establishment of a mathematical formula that quantifies the biomass of the super-intensive 'hedgerow' olive grove, requires real experiences to allow the equation to be determined. Thus, the current scarce surface area of this type of cultivation (2.5% of the total), the need to develop optimal plantations and the mechanization of all the agronomic operations, including pruning, requires more work to be developed by technicians and scientists in olive growing. However, there are some experimental works that show a biomass production of the order of 2 or 3 times that obtained in the traditional and intensive olive grove [50].

Civantos López-Villalta shows that there is a linear relationship between the weight of wood and branches, and the olive production of the tree [40]. Also, the mathematical approach takes into account factors such as the age of the olive tree, variety, system and frequency of pruning, location of olive trees (plains, mountains, etc.), size and productive capacity. In this way, the amount of branch and wood can be quantified by means of the following linear equations:

- Branch quantification → $y_1 = 0.88\,x + 4.76$
- Wood quantification → $y_2 = 0.74\,x - 6.48$

where, "x" is the average productivity (kg of olive/olive tree), the parameters y_1 and y_2 provide the quantity of branch and wood, respectively, that can be extracted from an olive tree which produces "x" kilograms of olives, both for table and oil. In the case of trees producing olives destined for oil, which are pruned biennially, the values obtained from both equations will be divided by two, obtaining the annual biomass per olive tree.

The annual quantity of branch produced by table olive trees in Andalusia is calculated according to equation [6]:

$$R_M = \frac{(x_i \cdot 0.88 + 4.76)\cdot n_i}{2\cdot 10^3} \quad [6]$$

The annual quantity of branch that oil olive trees generate is calculated according to equation [7]:

$$R_A = \frac{\left(\frac{x_i + x_{i+1}}{2}\cdot 0.88 + 4.76\right)\cdot \frac{n_i + n_{i+1}}{2}}{2\cdot 10^3} \quad [7]$$

Furthermore, the following equation is used to obtain the annual quantity of wood produced by table olive trees in the region:

$$L_M = \frac{(x_i \cdot 0.74 - 6.48)\cdot n_i}{2\cdot 10^3} \quad [8]$$

Finally, the calculation of the annual quantity of wood produced by oil olive trees is made according to equation [9]:

$$L_A = \frac{\left(\frac{x_i + x_{i+1}}{2}\cdot 0.74 - 6.48\right)\cdot \frac{n_i + n_{i+1}}{2}}{2\cdot 10^3} \quad [9]$$

where;

R_M = amount of branch from the table olive grove (t/year).
R_A = amount of branch from the oil olive grove (t/year).
L_M = amount of wood from the table olive grove (t/year).
L_A = amount of wood from the oil olive grove (t/year).
x_i = productivity of the table/oil olive grove in year i.
x_{i+1} = productivity of the table/oil olive grove in year i + 1.
n_i = number of table/oil olive trees in year i.
n_{i+1} = number of table/oil olive trees in year i + 1.

2.2. Methodology used to calculate the electrical and thermal energy derived from olive sector residues

Once all the by-products, or biomass, that can be extracted from the olive sector are determined, the second part of this methodology quantifies those that are suitable, for each of the uses, the amount of energy that could be generated in GWh, if these by-products were fully used, can be determined. Once this value has been calculated, it can be compared with the current data offered by the Andalusian Energy Agency [25] to show what potential for thermal and electrical uses would be wasted.

For classification of the different by-products, according to the electrical and thermal uses, the following equations apply. It is considered that the quantity of extracted pomace is 50% for each of the uses, since this by-product is suitable for both uses:

$$m_E = O_P + 0.5E_P + O_L + R_M + R_A \quad [10]$$

$$m_T = O_{SA} + 0.5E_P + O_{SM} + L_M + L_A \quad [11]$$

where.

m_E = amount of biomass useful for electrical use (t/year).
m_T = amount of biomass useful for thermal use (t/year).

The calculation of the electrical power that can be obtained in MW, with the full use of these by-products, is calculated as follows:

$$P_e = \frac{m \cdot PCI}{(h \cdot 860)\cdot 10^3}\cdot \mu \quad [12]$$

Similarly, for thermal power the calculation is:

$$P_t = \frac{m \cdot PCI}{(h \cdot 860)\cdot 10^3}\cdot \mu t \quad [13]$$

where.

P_e = Electric power (MW).
P_t = Thermal power (MW).
m = Kilogram of biomass/year.
PCI = lowest calorific value of biomass (kcal/kg).
h = annual hours of operation.
μ = electrical conversion performance.
μt = thermal conversion performance.

Once the results are obtained, they can be compared with the installed power data from the Andalusian Energy Agency, for both thermal and electrical uses.

Finally, the electrical and thermal energy generated is calculated as follows:

$$E_E = \frac{Pe \cdot 6500}{1000} \quad [14]$$

$$E_T = \frac{Pt \cdot 3700}{1000} \quad [15]$$

where;

E_E = electrical energy generated (GWh).
E_T = thermal energy generated (GWh).
P_e = electrical power (MW).
P_t = thermal power (MW).

2.3. Methodology used to calculate the economic value of the energy generated for thermal and electrical uses, derived from olive sector residues

Finally, in the third part of this methodology, the economic value of the energy generated for thermal and electrical uses is determined. For this, the economic value obtained by using the biomass for both energy uses is compared. To obtain the results, the following methodology is used.

First, the economic value of the generated electric and thermal energy is calculated, as expressed in equations [16] and [17 and 18], respectively. In the case of thermal energy, household (equation [17]) and industrial (equation [18]) use is considered:

$$V_E = E_E 10^6 \cdot p_E \quad [16]$$

$$V_{TH} = E_T 10^6 \cdot p_{TH} \quad [17]$$

$$V_{TI} = E_T 10^6 \cdot p_{TI} \quad [18]$$

where;

V_E = economic value of electricity (€)
V_{TH} = economic value of thermal energy for household use (€)
V_{TI} = economic value of thermal energy for industrial use (€)
p_E = unit price of electricity generated with biomass (€/kWh)
p_{TH} = unit price of thermal energy for household use (€/kWh).
p_{TI} = unit price of thermal energy for industrial use (€/kWh)

The p_E corresponds to the sum of the specific remuneration price of electricity from biomass (feed-in tariff) and the Spanish electricity market price (pool).

Secondly, from the expressions [16–18], the biomass value is calculated for each of the uses considered:

$$B_E = \frac{V_E}{m_E} \quad [19]$$

$$B_{TH} = \frac{V_{TH}}{m_T} \quad [20]$$

$$B_{TI} = \frac{V_{TI}}{m_T} \quad [21]$$

where;

B_E = biomass value for electrical uses (€/t).
B_{TH} = biomass value for household thermal uses (€/t).
B_{TI} = biomass value for industrial thermal uses (€/t).
m_E = quantity of biomass useful for electrical use (t/year).
m_T: quantity of biomass useful for thermal use (t/year).

Finally, based on the values obtained for biomass in the different uses, it is established which of them allows a greater value chain. The higher the biomass value, the greater the value chain. Value chain means the different operations to which biomass is subjected: harvest, conditioning, storage and energy conversion.

3. Data

The data used in this study are directly related to the three methodological parts explained in the previous section. The frame of reference is the region of Andalusia, located in southern Spain. The study period, depending on the available data, covers the period 2004–2016.

3.1. Data for the calculation of biomass from olive sector residues

The data used to calculate the amount of biomass that can be obtained from the olive sector residues in different processes, are the following;

To calculate the biomass obtained in the olive oil and table olive sectors, for the calculation of equations [1–5], the data referring to quantities of olives for oil and table offered by the Ministry of Agriculture, Livestock, Fisheries and Rural Development of Andalusia are used [51]. These data are offered annually and are expressed in tons.

Fig. 2 shows the production of oil mill olives (left axis) and table (right axis), respectively. In it, it can be observed that olive production for oil is much higher than that for table olives. This is mainly due to the greater number of olive trees destined for oil production. In addition, there are a number of olive groves that are of dual purpose, whose olives can be destined for both oil and table. The dual purpose olive groves have increased, throughout the period, to the detriment of the lands destined for table olive groves [17]. The use of olives produced for oil or table, depends primarily on the weather. In periods of drought the development of the olive is reduced. Consequently, many farmers choose to let them ripen more, carrying out the olive harvest months later. This coincides with the harvest of the olives for oil, which is later. Furthermore, Fig. 2 shows that table olive production remained practically constant during the 2004–2016 period. However, olive production for oil decreased considerably during some years, specifically in 2005, 2012 and 2014. Among other factors, this was due to the replacement of old olive groves with new plantations, climatic conditions or pest incidents.

In order to calculate the pruning quantities, to calculate the results of equations [6–9] which provide the tons of branch and wood that are obtained for each year, it is necessary to first calculate the productivity of the groves producing olives for table and oil, that is, kilograms of olive per olive tree. The data of kilograms of olive for each variety are obtained from those offered by the Ministry of Agriculture, Livestock, Fisheries and Rural Development of Andalusia [51]. Data regarding the number of olive trees are calculated from the cultivated hectares of both varieties, and the number of olive trees per hectare are obtained from the *Encuesta sobre Superficies y Rendimientos Cultivos* (ESYRCE - Survey on Crop Areas and Yields) of the Ministry of Agriculture, Fisheries and Food of Spain [17]. The ESYRCE collects data on the hectares of olive groves suitable for producing table olives, oil and dual purpose olives. The dual purpose olive grove is suitable for producing both table and oil olives. For classification into one variety or another, the information from the Olive Grove Master Plan [20] has been followed, which states that 90% of the olive grove is dedicated to obtaining oil olives, and 10% to table olives. In addition, from the Olive Grove Master Plan [20] it is known that the average olive tree density of Andalusian olive farms is around 132 trees per hectare.

In the same way, it should be noted that Junta de Andalucía publications [52], allow us to identify the number of trees per hectare up to 1, 000, from which point the focus is on the so-called super-intensive 'hedgerow' olive grove. In 2018, this type of olive grove was equivalent to only 2.5% of the total, so currently the count can be used as a method to establish the total number of olive trees. Undoubtedly, the increase of these hedgerow plantations (growth of 115.6% in the period 2015–2018) will require new quantification systems in the medium-term future, perhaps similar to those used for agricultural land with other crops, and will only refer to the total existing area.

Currently, Andalusian olive groves occupy 1.63 million hectares. The table olive groves occupy 3.45% of the surface, while the dual purpose and oil olive groves occupy 6.51% and 90.03%, respectively [17]. As can be seen in Table 1, the number of olive trees in the region has increased from 195.65 to 208.67 million, a 7% increase over the period 2004–2016. The number of olive trees destined to produce table olives has decreased over the period by 22.92% to 8.23 million. On the contrary, the number of olive trees for oil production has increased by 8.36%, reaching 200.43 million trees.

Furthermore, Fig. 3 shows the differential in terms of productivity. The table olive grove has a higher productivity than the oil olive grove, because given the smaller number of olive trees, its production is higher. The years with the highest productivity were 2014, 2015 and 2016. This is largely due to the increase in the number of olive groves in the last three years, which has grown by 62.85%.

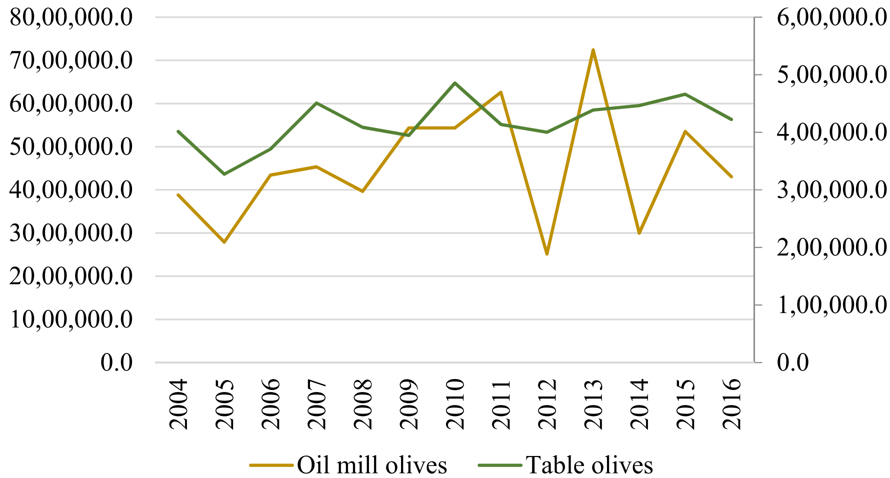


Fig. 2. Production of olives for oil and table (Unit: tons).

Table 1
Number of oil and table olive trees.

Year	Number of oil mill olive trees	Number of table olive trees
2004	184,965,000	10,683,156
2005	185,944,176	10,347,216
2006	187,832,964	10,155,288
2007	190,762,308	9,259,800
2008	193,615,488	9,614,352
2009	194,420,556	9,626,760
2010	195,359,366	9,196,150
2011	196,240,004	8,720,620
2012	196,786,669	8,443,103
2013	196,235,371	8,393,405
2014	197,077,558	8,244,614
2015	198,722,819	8,170,549
2016	200,431,387	8,234,477

Source: ESYRCE [17] and own elaboration.

3.2. Data for the calculation of electrical and thermal energy derived from olive sector residues

Calculating equations [10,11], that is, calculating the tons of by-products or biomass that is suitable for electricity and thermal generation, we follow the classification proposed by the Andalusian Energy Agency [25]. As the extracted pomace is suitable for both uses, we consider that 50% is destined for electrical uses and the other 50% for thermal uses.

In order to calculate equations [14,15], that is to calculate the electrical and thermal energy derived from the olive sector residues, it is necessary to initially calculate the electrical (P_e) and thermal (P_t) power, according to equations [12,13].

In calculating P_e, it is considered that the PCI is equivalent to 4410.67 kcal/kg and that the annual hours of operation (h) are 6500 [26]. Likewise, a performance (μ) of 24% is considered, this being the minimum required for plants over 20 MW, according to Royal Decree 413/2014.

In calculating P_t, it is considered that the PCI is 4410.67 kcal/kg, that the annual hours of operation (h) are 3700 [26] and that the thermal conversion performance (μt) is 80%.

In calculating both P_e and P_t, the value of m is obtained from the results of equations [1–9].

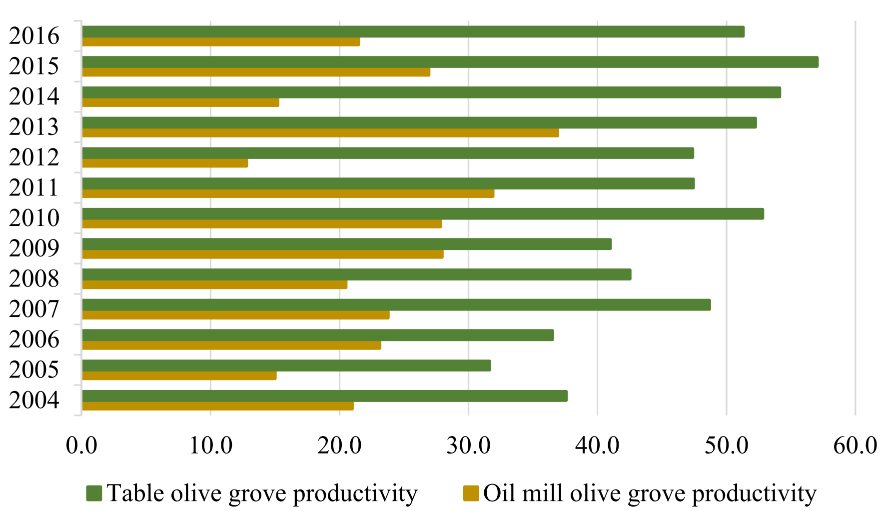


Fig. 3. Productivity of oil and table olive groves (Unit: kg of olive/olive tree).

3.3. Data for the calculation of the economic value of the energy generated for thermal and electrical uses, derived from olive sector residues

The data necessary for the calculation of equations [16–18], that is, for the calculation of the economic value of generated electric and thermal energy, are those referring to generated energy and energy price. Data on generated energy come from the results of equations [14, 15].

The thermal energy price data come from Eurostat statistics. In particular, the data for "gas price for household consumers (band 20 GJ-200GJ)" [53] and "gas price for non-household consumers (band 10, 000 GJ-100,000 GJ)" [54] have been selected. All prices exclude taxes and levies. These thermal energy data have been chosen as they are the only official data published.

The price of electricity from biomass is equivalent to the sum of the specific remuneration price of electricity from biomass (feed-in tariff) and the Spanish electricity market price (pool). The specific remuneration data comes from the "Result of the annual compensation payments of the renewable energy, cogeneration and waste production facilities" of the National Energy Commission (CNMV) [55]. The market price data come from those published by OMIE [56].

Finally, the results of equations [16–18] are used to calculate equations [19–21], to determine the biomass value for each of the uses considered.

The energy prices used correspond to the current value of each of the years, which have been deflated by the Consumer Price Index at constant 2016 values.

The analyzed period will correspond to the years 2009–2016, due to the availability of remuneration data for electricity from biomass.

4. Results

The results obtained allow the determination of the thermal and electrical energy that could be obtained from the Andalusian olive sector biomass, if all its by-products were used at full capacity. Likewise, these results also determine the economic value that both energy uses could generate. The results are presented following the three phases that have been performed for their calculation.

4.1. By-products generated by the olive sector in Andalusia

Table 2 shows the amount of by-products obtained from Andalusian oil mills, olive pomace extractors, and table olive industries, during the 2004–2016 period, according to equations [1–5]. It should be noted that oil milling is the sector of the olive industry which brings more quantity of by-products to the energy sector. During the study period, this industry produced an average of 1.62 million tons per year ($O_P + O_{SA} + O_L$), while the olive pomace extractors produced an annual average of 0.63 million tons of extracted pomace (E_P), and the table olive industries produced an average of 0.05 million tons of table olive stones (O_{SM}).

It is important to highlight that the quantity of by-products offered annually is very variable. This variability depends, among other factors, on the climate, the incidence of pests (such as the olive tree borer), and the evolution of the areas dedicated to olive farming. Regarding the latter point, it is worth mentioning that these areas have increased by 10% throughout the period 2004–2016. This increase has had an impact on the number of olive plantations and, therefore, on the production of olives and pruning [17]. Regarding climate, it should be noted that the olive harvesting campaigns with higher production coincide with a less warm and wetter climate. Thus, through the data offered by the State Meteorological Agency (AEMET), the years 2010 and 2013 were the most favorable in terms of climate. In 2010, the average temperature was 14.98 °C, and the average rainfall was 855 mm, the latter exceeding the normal average value by more than 30% (from the reference period 1971–2000) [57]. As a consequence, the 2011 olive harvest of olives was favored, producing 6.67 million tons [51]. In turn, this benefited the generation of by-products, producing 3.15 million tons in that year. The year 2013 was a wetter year than normal, with an average rainfall of 715 mm, which was 10% more than the average value of the 1971–2000 reference period, and the average temperature was 14.97 °C [57]. This year coincided with the greatest olive production over the period analyzed (7.68 million tons) [51]. The by-product production was 3.64 million tons. Likewise, the climate also damaged production in 2012 and 2014. These years were characterized by being dry, with a low humidity index and reduced rainfall [57].

Table 3 shows the annual amount of olive grove pruning obtained from equations [6–9]. The second and third columns (R_M and R_A) show the quantity of branch obtained from the olive grove, according to their typology, and the fourth and fifth (L_M and L_A) the quantity of wood. It should be noted that the table olive grove is pruned every year, while the oil mill olive grove is pruned every two years.

As shown in Table 3, of the by-products obtained from olive grove pruning, it is the branch which generates the most tonnage per year (an average of 2.69 million tons between the table olive grove and the oil mill olive grove). As regards wood, this contributes 30.8% of the by-products generated by olive grove pruning. The average production for the period is 1.2 million tons per year.

Similarly, Table 3 shows that the production of wood and branch is very variable, depending on the climatic values, the incidence of pests, and the area used for the plantations of this crop. Thus, the years with the highest wood and branch production, coincide with the years in which the climate is less dry and wetter [57].

Table 2
By-products obtained from Andalusian oil mills, olive pomace extractors and table olive industries (Unit: tons).

Year	Olive pomace (O_P)	Stones from olive milling (O_{SA})	Extracted pomace (E_P)	Leaves from olive milling (O_L)	Table olive stones (O_{SM})
2004	850,033	228,092	535,521	310,514	48,162
2005	610,805	163,899	384,807	223,125	39,270
2006	950,939	255,169	599,092	347,375	44,490
2007	992,502	266,321	625,276	362,558	54,097
2008	868,645	233,087	547,247	317,313	49,052
2009	1,189,977	319,310	749,685	434,695	47,348
2010	1,190,242	319,382	749,852	434,792	58,265
2011	1,370,569	367,769	863,459	500,665	49,630
2012	550,620	147,750	346,890	201,140	48,005
2013	1,585,911	425,553	999,124	579,328	52,631
2014	656,440	176,145	413,557	239,795	53,546
2015	1,171,867	314,451	738,276	428,079	55,914
2016	942,248	252,836	593,616	344,200	50,680
Period Average	994,677	266,905	626,646	363,352	50,084

Source: Own elaboration.

Table 3
Branch and wood obtained from olive grove pruning (Unit: tons).

Year	Branch from the table olive grove (R_M)	Branch from the oil olive grove (R_A)	Wood from the table olive grove (L_M)	Wood from the oil olive grove (L_A)
2004	202,027	1,909,366	113,892	633,569
2005	168,631	2,012,117	87,570	712,457
2006	187,308	2,402,868	104,282	1,028,416
2007	220,376	2,328,369	136,782	950,614
2008	202,755	2,529,374	120,106	1,110,055
2009	196,536	2,855,021	114,812	1,379,324
2010	235,532	3,038,067	149,860	1,528,481
2011	202,747	2,398,917	124,784	987,273
2012	196,110	2,615,483	120,657	1,169,398
2013	212,941	2,722,551	135,071	1,258,670
2014	215,950	2,305,696	138,381	901,613
2015	224,471	2,600,091	145,935	1,140,384
2016	205,430	2,600,652	129,588	1,129,560
Period Average	205,447	2,486,044	124,748	1,071,524

Source: Own elaboration.

4.2. Energy potential of the Andalusian olive sector for thermal and electrical uses

Olive sector by-products can be classified for electrical or thermal use, according to equations [10,11]. Table 4 shows the total quantities of by-products obtained from the olive sector at full capacity, according to use. In general terms, by-products that can be used for electrical use are more abundant than by-products for thermal use.

Table 5 shows the energy potential of olive sector biomass in Andalusia in the 2004–2016 period. Following the classification of Table 4, the data have been calculated from equations [12–15]. The average potential electric power, with full use, is 826.2 MW, with the ability to generate 5370.2 GWh per year. Likewise, the potential average thermal power is 2372.9 MW, with the ability to generate 8779.9 GWh per year. It should be noted that the data offered fluctuate, depending on the annual biomass productions. Thus, in 2013, olive sector biomass is an important contribution for both uses, in terms of installed power and power generation. On the contrary, 2004 is the year with the lowest energy potential for both uses.

The potential results obtained can be compared with the current data observed in the Andalusian region. Table 6 shows, on the one hand, the data of installed power and energy generated in Andalusia in 2016, from olive biomass and, on the other, the power and energy generation that Andalusia could have had, on average, if the olive sector biomass had been fully exploited. It can be seen that for both electrical and thermal uses, the potential value is clearly higher than that which took place in 2016.

Thus, while in 2016 the installed power for electrical uses was 158.6 MW, and the generated energy was equal to 1030.9 GWh, the results of the potential analysis raise these figures to 826.2 MW and 5370.2 GWh, respectively. Furthermore, in the case of thermal energy production, in 2016, the installed power was 1279.2 MW, and the generated energy was equal to 4733.1 GWh, the potential usage almost doubled these figures to 2372.9 MW and 8779.9 GWh, respectively. The full use of olive sector biomass, for both uses, would mean an increase in terms of installed power and electricity generation. Thus, if the olive sector biomass was fully utilized, the electric power would be 83.9% higher, and the thermal power 64.9% higher, increasing the generation of both uses in the same proportion.

In the same way, it is worth highlighting the results obtained for each of the uses to appreciate the important potential that thermal uses have, compared to electric uses, since it accounts for 62% of the total generation from both uses.

Table 4
Total quantities of by-products or biomass from the olive sector for electrical and thermal uses (Unit: tons).

Year	Biomass useful for electrical use (m_E)	Biomass useful for thermal use (m_T)
2004	3,539,701	1,559,235
2005	3,207,082	1,388,003
2006	4,188,037	2,031,448
2007	4,216,443	2,033,091
2008	4,191,711	2,059,546
2009	5,051,071	2,610,479
2010	5,273,559	2,805,841
2011	4,904,628	2,392,916
2012	3,736,797	1,832,700
2013	5,600,293	2,871,049
2014	3,624,659	1,683,243
2015	4,793,646	2,394,960
2016	4,389,338	2,156,280
Period Average	4,362,843	2,139,907

Source: Own elaboration.

Table 5
Data of olive sector biomass for potential electrical and thermal uses.

Year	Electrical power equivalent in MW	Electricity generation in GWh	Thermal power equivalent in MW	Thermal generation in GWh
2004	670.3	4357.0	1729.0	6397.5
2005	607.3	3947.5	1539.2	5694.9
2006	793.1	5155.0	2252.7	8334.9
2007	798.5	5190.0	2254.5	8341.7
2008	793.8	5159.5	2283.8	8450.2
2009	956.5	6217.3	2894.8	10,710.7
2010	998.6	6491.1	3111.4	11,512.2
2011	928.8	6037.0	2653.5	9818.0
2012	707.6	4599.6	2032.3	7519.5
2013	1060.5	6893.3	3183.7	11,779.8
2014	686.4	4461.5	1866.6	6906.3
2015	907.8	5900.4	2655.8	9826.4
2016	831.2	5402.8	2391.1	8847.1

Source: Own elaboration.

Table 6
Actual data and potential results of olive biomass in Andalusia.

	CURRENT DATA (year 2016)		POTENTIAL RESULTS (Period average 2004–2016)	
	Installed power in MW	Energy generated in GWh	Installed power in MW	Power generation in GWh
Electrical uses	158.6	1030.9	826.2	5370.2
Thermal uses	1279.2	4733.1	2372.9	8779.9

Source: Andalusian Energy Agency [25] and own elaboration.

If the olive sector biomass was fully utilized, the electricity generated would be 5370.2 GWh, which would mean almost four times the total energy generated from biomass in Andalusia, during 2016 (1484.8 GWh). This would also account for 40.6% of the total renewable electricity. Similarly, with the full utilization of the olive sector biomass, the thermal energy generated would be 8779.9 GWh, which would mean almost 10% more than the energy generated from biomass in 2016 (7975.9 GWh). This would mean 98.6% of the total renewable thermal energy.

4.3. The economic value of olive sector biomass for thermal and electrical uses in Andalusia

Table 7 shows the economic value of the energy produced from olive sector biomass for the different uses, according to equations [16–18].

In the case of electricity, the average annual value of olive sector biomass, in the period 2009–2016, was € 771.40 million, the highest value being obtained during 2013 (€ 974.60 million). The reason is that, during this year, the electricity generation (6893.39 GWh) was 19.9% higher than the average for the period 2009–2016, and the unit price of the electricity generated with biomass in this year (€ 141.39/MWh), was 5.5% of the period average.

Regarding the thermal uses analyzed (household and industrial), the average annual value of olive sector biomass, for the period 2009–2016, was € 450.0 million. The maximum value was also obtained in 2013. As already seen in the case of electricity, the highest production in 2013, and the highest unit price of thermal energy (8.8% for household use and 12.7% for industrial use), determine the highest value of thermal energy.

In relation to thermal uses, the uses destined for industry and household have been differentiated. For each of these uses, the same amount of biomass has been considered, so the results obtained for each use cannot be combined. It is observed how household use would have an average impact, for the period, of € 574.90 million, and industrial use, € 325.10 million. Regarding electricity generation, the impact would be € 771.40 million (0.5% of Andalusia's GDP), directly impacting the Andalusian agricultural sector. The GVA of the primary sector in Andalusia for 2016 was € 9448.40 million [58], representing 6.0% of the regional total.

From the average values obtained for the 2009–2016 period, it can be seen how, in 2016, the electrical and thermal use of olive sector biomass in households would have an impact on the Andalusian economy of € 1346.30 million, equivalent to 0.9% of Andalusia's GDP, while the electrical and thermal use for industrial use would have an impact of € 1096.50 million (0.7% of Andalusia's GDP).

Fig. 4 shows the biomass value for the three specified uses. These are obtained from equations [19–21]. Throughout the entire period, the value of thermal energy for household use was higher than for other uses. Thus, while the average value of this use in the period considered is 248.20 €/t, the average value of electricity is 165.04 €/t, and that of thermal industrial use is 139.50 €/t. Fig. 4 shows that the evolution of the biomass value for industrial and electrical thermal use is similar for the period although, from 2014, there is a reduction in the value for industrial use. In the case of household thermal uses, the value increases by 36.66% in 2012, compared to 2011. Starting this year, the value of biomass for household thermal uses ranges from 288 €/t (year 2014) to 253.20 €/t (year 2016).

Table 7
Economic value of the energy produced from olive sector biomass for the different uses (Unit: euros).

Year	Electric power	Thermal energy for household use	Thermal energy for industrial use
2009	705,216,324	585,254,561	345,590,156
2010	868,395,355	566,984,894	350,814,183
2011	845,894,155	469,190,916	331,829,102
2012	662,220,837	491,155,990	291,935,151
2013	974,622,802	775,542,362	451,202,886
2014	555,155,311	484,788,029	261,367,064
2015	842,304,084	680,181,443	331,008,180
2016	717,186,922	546,057,342	237,027,348
Average	771,374,474	574,894,442	325,096,759

Source: Own elaboration.

5. Discussion

The results obtained reflect the high potential that Andalusia has within the olive biomass sector. These results are not far from the potential quantified by various authors in recent years, a relevant example of this is García-Maraver et al. (2012). In that study, the authors quantify a potential of 4.2 million tons per year of olive grove pruning (branches and leaves) in the region of Andalusia (Spain) [38]. While, in this current paper, the olive grove pruning (branches and wood), in this same region for the period analyzed, produces an average of approximately 3.9 million tons per year. Similarly, the potential of olive sector biomass has been studied in many countries, but mainly in those located in the Mediterranean basin, where this crop has a special relevance. Thus, it is worth noting the studies carried out for the Calabria region in southern Italy, or the Crete or Thessaly regions in Greece. These regions show the high value of agriculture for biomass generation. Among the different residues are those from the olive grove. In these countries, the olive grove has an important presence. The quantified potential for the Calabria region (Italy) is 820,000 tons of biomass residues, among which are those of the olive grove [30]. In the regions of Crete and Thessaly (Greece), this is approximately 2 million tons of lignocellulosic biomass, which also contains olive grove residues [33]. Thus, it is important to highlight the importance of this crop for energy generation.

However, despite the importance that olive grove residues have for energy generation, their use is scarce. Thus, if the real data is compared with the potential results, the high wastage of the by-products from the olive sector in Andalusia for thermal and electrical uses, in the period 2004–2016, can be reflected. In the total olive sector biomass, only approximately 2 million tons a year are used for energy purposes. Nevertheless, the olive sector generates an average of 6.5 million tons of residues each year. In this way, 69.23% of the by-products would be wasted for energy purposes. Among the main causes of such waste that stand out are the high costs of labor and transport, the unfavorable legislation in force in the national framework since 2012, and the meagre economic incentives to promote it [59].

The methodologies used to obtain the results of the biomass potential in Andalusia correspond to the Andalusian Energy Agency [25] and Civantos López-Villalta [40]. These best fit the analysis developed in this paper. In the case of the first, this institution is based on recent methodology that allows obtaining the different by-products of the agro-industrial sector of the olive grove. This methodology is based on obtaining biomass production data through field experiences and processing them through a geographic information system (GIS). In addition, similar methodologies are used to obtain these same results, and an example of this is the work of García-Martín et al. (2020) [39]. Otherwise, the methodology proposed by Civantos López-Villalta makes it possible to obtain the quantities of branches and wood, and then classify them, according to thermal or electrical uses. The methodology was composed taking into account the characteristics of the terrain, plantation or frequency of pruning of the olive grove in this region. Although the characteristics of this crop have evolved over the years to be classified as an intensive, super-intensive or traditional olive grove, the Civantos López-Villalta methodology has continued to be used to quantify the olive grove biomass [41]. With the establishment of a mathematical formula that quantifies the biomass of the super-intensive 'hedgerow' olive grove, this methodology has favorable characteristics, which require real experiences that allow the equation to be determined. Thus, the current scarce surface of this type of cultivation (2.5% of the

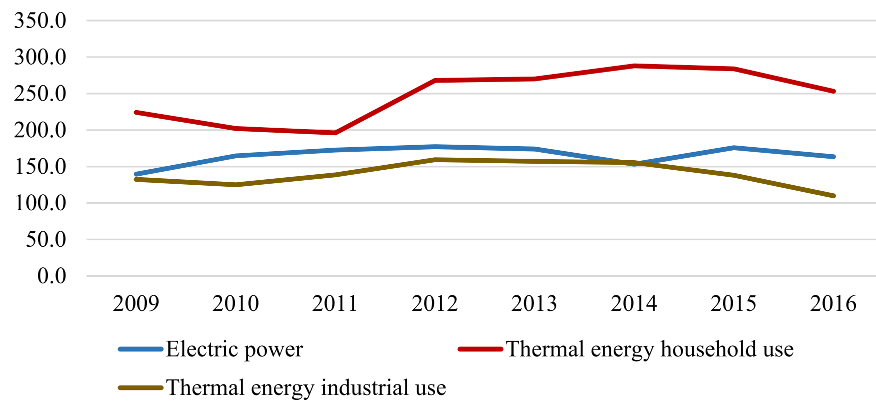


Fig. 4. Biomass value for different uses (Unit: €/t).

total), the need to develop optimal plantations, and the mechanization of all the agronomic operations, including pruning, requires more development by olive growing technicians and scientists. There are, however, some experimental works that show biomass production in the order of 2 or 3 times that obtained in the traditional and intensive olive grove [50].

As a result of this paper, it is worth noting the loss of opportunities, in energy terms, caused by the scarce use of this organic matter. In the case of this study, olive sector biomass for electrical uses accounted for 10.7% of total biomass generation in 2016, and 1.2% of renewable electricity generation. Thermal uses accounted for 16% of the total biomass generation, and 14.4% of the renewable thermal generation. Thus, if there were full use of the by-products, the olive sector biomass would represent 55.6% of the total electricity generation with biomass, and 29.8% of the total thermal generation with biomass. Likewise, this would represent 6.2% of renewable electricity generation, and 26.7% of renewable thermal generation. In other words, the full use of by-products from the olive sector would be an important alternative, when it comes to meeting the objectives, set by the EU and the national and regional governments, in terms of energy and the environment. Similarly, it would be an opportunity to launch the economic model, based on the circular economy and the bioeconomy [60]. In this way, the production cycle of these sectors could be closed with the use of these by-products. This would translate into greater economic and social benefit.

For its part, a better use of these by-products would mean an increase in the number of power generation plants and thermal systems. In 2016, there were 17 biomass power generation plants, of which 13 used olive sector by-products [25]. The installed power in these 13 plants was 158.6 MW. Thus, if all the residues from the olive sector were used at full capacity, the installed capacity would be 826.2 MW, which would lead to the opening of 55 more plants, with an average power similar to the current plants (12.2 MW/plant). In that same year, there were 20,190 thermal systems that used olive sector biomass [25], with an installed capacity of 1279.20 MW. In this sense, full use would increase these systems by 17,262, with an average power similar to the current 0.06 MW/system. The commissioning of this new power would require an investment of approximately € 2293 million, in the case of electricity, and € 414 million in the case of biomass for thermal use.

So far, studies aimed at quantifying the biomass potential from the olive sector have limited themselves to highlighting the wasted amounts of this organic matter. These also highlight the losses that are caused in energy, environmental and social terms. However, this paper goes one step further than previous research. In addition to assessing the potential of olive sector biomass and the losses, in energy terms, this paper highlights the economic value of biomass in the olive grove sector in the Andalusia region, making a differentiation between electrical and thermal uses (for industrial and domestic use). Therefore, this novel analysis allows us to economically assess which uses have a higher value, and which quantities would be being lost, in economic terms.

The energy use of biomass comprises an extensive value chain for this fuel. This ranges from obtaining the biomass to the operation of the power generation systems. These operations are: procurement tasks in the sector, conditioning (packaging, chipping, pelletizing, etc.), transportation, amortization of the investment of the system and its maintenance. In the particular case of the conditioning of the biomass, this can be very different for household thermal uses, than for industrial or electricity uses. Household uses require biomass with more homogeneous characteristics, such as pellets, high-quality stones, or wood chips with reduced grain size and low humidity. The other uses allow a greater range of biomass characteristics, basically summarized in a greater range of grain size and humidity.

The total cost of the value chain for each type of use analyzed, must be less than the value of the biomass that has been calculated, so that its use is profitable. As can be seen in Fig. 5, there is a gross margin (difference between the value of biomass and its market price) for each of the energy uses studied. In the case of biomass for thermal generation for household use, its economic value, in 2016, was 253.20 €/t, being higher than the biomass prices published in Spain [61]. For these uses, the market price of biomass, in that year, ranged from between 183.60 €/t (pellet) and 90.00 €/t (wood chip and stone). Therefore, this type of energy use would be viable, especially in the case of wood chip and stone, since the calculated value has a margin over the biomass market price of 163.20 €/t.

Regarding industrial electricity and thermal uses, in 2016, the value obtained for biomass was 109.90 €/t and 163.40 €/t, respectively. Biomass prices in that year, for these uses, were 84.3 €/t for bulk stone, 46.0 €/t for crude wood chip, and 21.3 €/t for extracted pomace. Likewise, considering the difference that exists between the value obtained and the market price, it is considered feasible that the olive sector biomass could be used to a greater degree than at present.

6. Conclusions

The olive sector by-products can contribute to the growth of energy products that are an alternative to fossil fuels. This is especially the case in Mediterranean countries, such as Spain and in its region of Andalusia. Thus, the use of these by-products for energy purposes is considered an essential element to reduce CO_2 emissions, and to combat climate change. Additionally, a better use of these by-products would allow the economic model of bioeconomy and circular economy, proposed by the EU, to be implemented with greater intensity.

This paper determines the maximum amount of electrical and thermal energy that can be obtained in Andalusia from olive sector residues. Accordingly, it has established which uses generate the greatest wealth

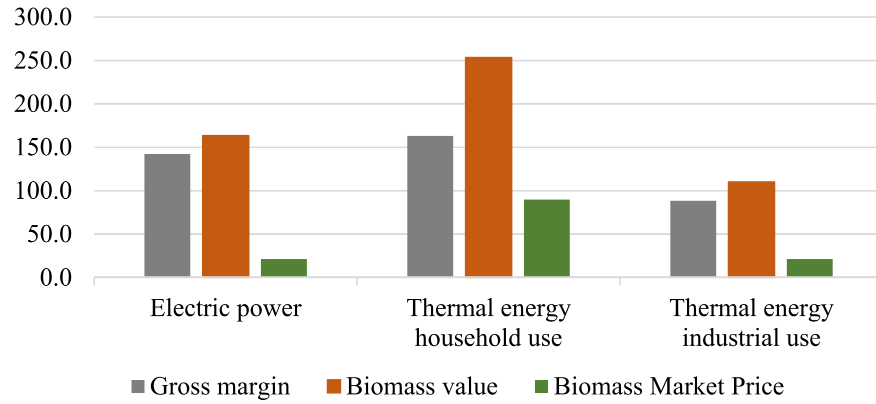


Fig. 5. Margin of the biomass economic value over its market price (Unit: €/t).

in the region. For this, official data referring to the period 2009–2016 were used. For this purpose, a three-part methodological procedure has been developed. Firstly, the amount of biomass that can be obtained from the olive sector residues was calculated. Secondly, the amount of electrical and thermal energy that can be obtained from said residues was calculated. Finally, the economic value of the thermal and electrical uses were determined.

The results show that there is a high wastage of olive sector residues for energy purposes. Specifically, when comparing the potential data with the real data for 2016, a wastage of 69.23% of the by-products generated, can be accounted for. This wastage translates into lower electrical and thermal energy generation than would be possible if all residues were used. If the biomass from the olive sector were fully used, the generation of electrical energy would be 83.9% higher and thermal generation, 64.9% higher. In short, full energy use of these residues would represent 55.6% of the total electricity generation with biomass, and 29.8% of total thermal energy generated with biomass. This would represent 6.2% of renewable electricity generation, and 26.7% of renewable thermal generation. Therefore, it would contribute to achieving national and regional objectives for the use of renewable energy.

The results obtained also show that the economic value of the olive sector biomass is enough to cover the value chain that the energy use of the biomass represents. The uses for thermal energy generation, in industry and electric power generation, are especially interesting. In this energy resource, industry could find an excellent ally in reducing its greenhouse gas emissions, and thus be more independent of the emissions trading market. Regarding the exploitation of the entire olive sector biomass potential for electrical uses, this would require having a system of remuneration for electrical energy from renewable sources, thereby assuring its viability in Spain.

The maximum use of all the olive sector biomass would require the adoption of various measures. On the one hand, agricultural policy, subsidy systems and mandatory regulations could be established, encouraging agricultural operations that reduce the environmental impact of the sector. On the other hand, different incentive programs could be provided through energy policy and greater promotion. Thus, the role of biomass for manageable electric energy could be highlighted, compared to other renewable energies (wind or photovoltaic). This characteristic provides greater operational security to the electrical system. Likewise, it would be necessary to establish specific auction systems for this biomass, in order for new generation facilities to be put into operation. Regarding thermal energy, it is essential to develop district HVAC systems in Spain and Andalusia, as well as in large industrial facilities. This could use existing European funds (in the case of the ERDF), and establish regulations which promote the use of biomass over fossil fuels. Finally, the importance the use of biomass offers for the reduction of depopulation in rural areas could be highlighted, through social and rural policies.

In parallel to these agricultural, energy and social policy measures, it would be necessary to add other measures aimed at solving the main obstacles faced by this sector. It would be advisable to establish incentive programs, aimed at reducing transport and waste collection costs, thus establishing a certain profitability for entrepreneurs in the sector.

In short, better use of the by-products of the olive sector would tend to improve energy efficiency and reduce greenhouse gas emissions into the atmosphere. This would be a benefit to combat climate change and improve environmental quality. In addition, it would bring with it a positive effect for societal development, and economic activity in general. Thus, this paper serves as a prelude to further research. These could be oriented to the effects full use of the olive sector biomass would have on GDP, the level of employment, and the energy remuneration conditions that must exist to enable the growth of the use of olive sector biomass for energy.

Credit author statament

Jesús Marquina: Data curation, Formal analysis, Methodology, Writing- Original draft preparation Maria José Colinet. Data curation, Methodology, Resources, Supervision María P. Pablo-Romero: Conceptualization, Methodology, Supervision. Writing- Reviewing and Editing, Funding acquisition.

Declaration of competing interest

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.

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