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S. Moreno*, K. Guerra, D. van der Slikke, W. de Jong, P. Haro*

Sustainable Low-Carbon Hydrogen Potential from the Olive Oil Industry Waste: A Case Study in Western Andalusia

Abstract: The olive oil market, valued at almost €14 billion in 2023 has tripled its production over the last 60 years, reaching $3.27 \cdot 10^9$ kg in 2020. Spain leads the production, accounting for 70% in the European Union and 45% worldwide. This land-intensive industry has significant social, environmental, economic, and territorial impacts, with decentralized waste generation being a major concern. Sustainable waste management is a fundamental objective. One potential solution is using this waste for low-carbon hydrogen production through thermochemical processes (e.g. gasification or pyrolysis). This is particularly relevant when hydrogen-consuming industries are nearby. Given this context, this work proposes a methodology for assessing the potential of olive grove residues from a sustainability perspective. Our approach uses high-level data from public sources to estimate transport costs and greenhouse gas emissions associated with biomass collection. We identify and quantify suitable waste sources, their locations, and associated hydrogen production potential. The application of the method is validated through a case study in southern Spain, a major olive oil producer with significant industrial hydrogen consumers nearby. Results indicate that using only available olive grove residues is not

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currently sustainable for meeting the region's hydrogen demand, covering merely 0.6% of requirements. This result is the consequence of the current use of olive grove biomass, suggesting the need for revised waste management strategies or alternative resources to increase sustainable hydrogen production. The application of the proposed methodology to other regions can help identify the sustainable potential of using this and similar wastes to produce low-carbon hydrogen.

1 Introduction

1.1 Brief history of renewable energy developments

The growing demand for energy is still largely satisfied by non-renewable fossil fuels, contributing to the deterioration of the climate and scarcity of resources. In this regard, the Paris Climate Agreement, adopted in the context of the United Nations Framework Convention on Climate Change and signed by 197 countries in 2015, can be considered the first global agreement on climate change. The main objective of this agreement is to stabilize greenhouse gas (GHG) emissions at a level that limits the global temperature increase to 2 °C above pre-industrial levels [1].

Thus, one of the great challenges of recent years has been the development of an energy model based on renewable sources to reduce GHG emissions [2]. To this end, the European Union (EU) has gone further, creating a strategy that aims to achieve emission neutrality by 2050, the European Green Deal, in which renewable energy sources play a key role [3]. As a result of these policies, research into the application of renewable energy sources on a commercial scale has grown exponentially, which aims to provide an economically profitable alternative to meet current demand.

Within this framework, the use of hydrogen as an energy carrier has become one of the most promoted alternatives [2]. Hydrogen has the potential to ease the variability of solar photovoltaic (PV) or wind energy thanks to its capacity of (chemical) energy storage and controlled conversion into energy carriers or chemicals (dispatchability). In this way, hydrogen makes it possible to decouple electricity supply from demand [4].

1.2 Current and future uses of hydrogen

Hydrogen is currently produced from non-renewable sources (around 96% oil, coal, and natural gas) [2], and its main uses are its application in oil refineries and as a raw material in the chemical industry to produce ammonia, methanol, and others.

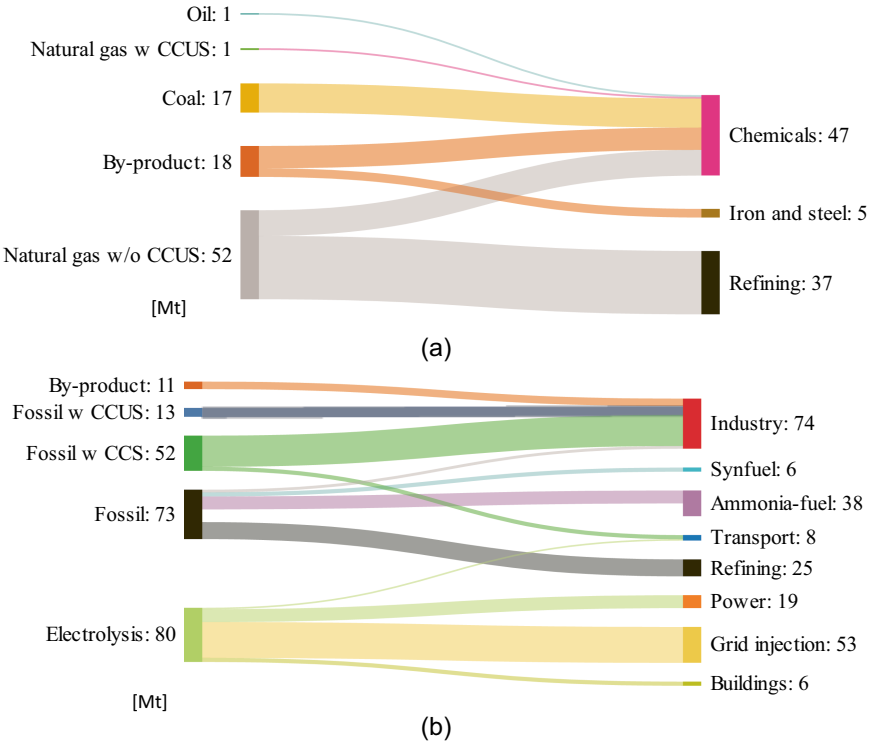


Figure 1: Global hydrogen sources and demand (in Mt = 10^9 kg) in (a) 2020 and (b) 2030 (elaborated based on [5, 6]).

Figure 1 shows the expected growth in demand for hydrogen, as well as a diversification of end uses. In 2020, global demand of hydrogen was $8.9 \cdot 10^{10}$ kg, while by 2030, global demand is expected to reach $2.29 \cdot 10^{11}$ kg. This increase is mainly due to the recent attractiveness of hydrogen for injection into the gas grid, or for the decarbonization of other energy sectors like heavy-duty (long-distance) transport among others.

The estimate on demand and sources of production has been made by the International Energy Agency (IEA), based on a zero net emission scenario (NZS)[1] for 2050 [7]. Even though supplying future demand is a major challenge in terms of developing and deploying an effective and cost-efficient system, it also offers the possibility of lowering the production price by developing technologies that use renewable sources to produce hydrogen.

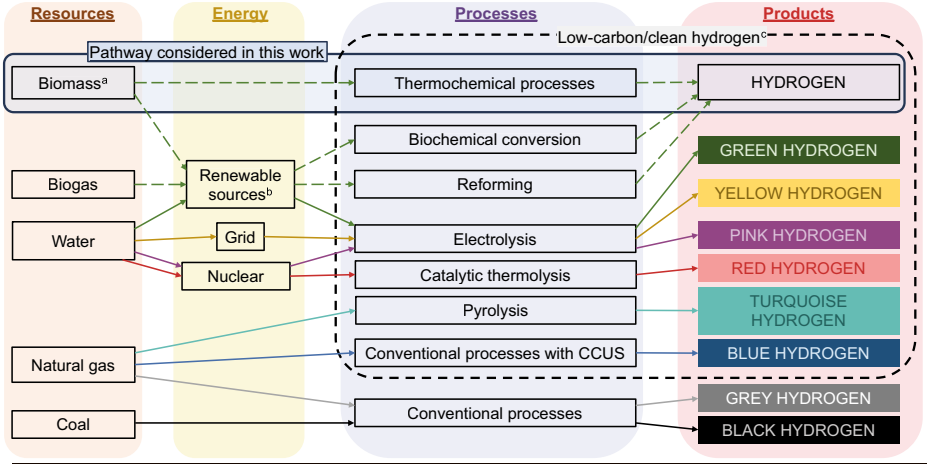
1 Policy scenario proposed by the IEA that proposes a feasible pathway to achieve decarbonization of the energy system with zero net emissions by 2050.

1.3 Resources for low-carbon hydrogen

Depending on the pathway, hydrogen can be classified as renewable hydrogen, clean hydrogen, low-carbon hydrogen or fossil-based hydrogen. This classification also depends on each country's regulation. In this way, the EU considers low-carbon hydrogen to be hydrogen with production life-cycle emissions of less than 3.38 kg CO_2 eq./kg H_2 [8]. According to the US definition of clean hydrogen, carbon intensity during its production should be equal or less than 2 kg CO_2 eq./kg H_2 produced in situ [9]. Almost all hydrogen produced today is fossil, being grey hydrogen the most common [10]. In 2022, grey hydrogen production accounted for 62% of global production. This implies that it is produced from natural gas and without carbon capture, utilization and storage. The rest of the production corresponds to 21% from coal and 16% as a by-product [7].

Regarding renewable or green hydrogen, its definition according to the European Commission is as follows: the hydrogen that is produced from renewable sources other than biomass and whose production process involves a 70% reduction in GHG emission compared to fossil fuels [11]. Under this definition, in Europe, hydrogen produced through thermochemical conversion of biomass (i.e. gasification or pyrolysis) is not considered as renewable hydrogen. However, this chapter considers the thermochemical conversion of waste biomass, as it has a great potential to produce low-carbon/clean hydrogen [5].

Figure 2 shows the different colours and pathways considered in this chapter, according to EU regulations.



[a] In this work, biomass will be considered as a resource if it is produced as a renewable residue.
[b] Renewable energy sources: solar, wind, hydro, tidal/ocean, geothermal, biomass.
[c] Low-carbon hydrogen considered in this work is based in EU regulation (emissions < 3.38 kg CO_2 eq./kg H_2).

Figure 2: Hydrogen production methods from renewable and fossil energies.

The most widely used technologies are based on the splitting of water molecules, such as electrolysis, thermolysis, photocatalytic, and thermochemical splitting, as well as the dehydrogenation of hydrogen-bearing molecules [6]. Among these technologies, water electrolysis is currently the most mature alternative and the only commercially available, even if at a reduced scale [3].

Nevertheless, technologies using biomass as feedstock for hydrogen production are being investigated as they have many advantages over those based on water. Firstly, biomass can be more readily accessible than water in some regions and can even have a low cost or, in some cases, generate an income through an input fee when waste biomass is considered [12]. Secondly, related to the cost, the price estimation for hydrogen production from biomass (€1.6–8.6/kg) is more promising than using solar (€2.9–8.3/kg) or wind energy (€3.2–11.0/kg) [13]. Finally, biomass can be stored and transported, making it a dispatchable energy source [14].

Hydrogen production from waste biomass has great potential not only in terms of cost but also in terms of environmental impact [15, 16]. However, when analysing the literature, most of the works focus on technological studies, either experimentally or through simulation. Melikoglu et al. [17] studied the pyrolysis of different agricultural residues experimentally. Another experimental work was conducted by Cerqueira et al. [18] to analyse the potential of autothermal reforming in terms of hydrogen production using olive mill wastewater as feedstock. Karaci et al. [19] also worked on pyrolysis but in this case using neuronal network systems to predict the yield of a hydrogen-rich gas from tea waste and olive husks among others. There are also some studies focussing on biorefineries. Within this context, Najafi et al. [20] studied experimentally the performance of olive waste for energy production. Rodriguez-Fernandez et al. [21] have used a mathematical optimization approach to design a biorefinery considering the most abundant types of biomass in Spain.

Some environmental analyses have also been found. Ncube et al. [22] have worked out a life cycle assessment (LCA) study applied to the olive oil supply chain in Italy to valorize by-products to replace fossil fuels. Khounani et al. [23] also carried out an LCA study focussing on the transformation from a linear economy to a circular bioeconomy with the olive oil industry at the core of the study. In the study conducted by Ozturk et al. [24], the LCA is conducted considering a specific type of gasification and using olive pomace as feedstock.

Regarding the availability of olive sector's by-products, Manzanares et al. [25] have studied the availability and characterization of different types in Spain using a biorefinery approach. Galán-Martín et al. [26] analysed the olive agroecosystems of the main olive oil producing countries in the EU (i.e. Spain, Italy, Portugal, and Greece) to assess the potential in the carbon dioxide removal. Finally, the work conducted by van der Slikke et al. [27] introduced the availability of waste biomass in western Andalusia for its use as a feedstock in the production of low-carbon hydrogen.

1.4 Olive oil industry worldwide, in Europe, Spain, and Andalusia

The olive oil industry is an important agricultural sector due to the high nutritional value of the products it generates and acceptance of the consumers worldwide. The relevance of this sector is crucial in terms of its contribution to the development of the territories, as well as its contribution to health [28]. Over the last 60 years, this industry has tripled its production, reaching $3.27 \cdot 10^9$ kg in the year 2020 (2019/2020 crop) [29]. Figure 3(a) shows the world's major producers and their associated olive oil production, which highlights the importance of the Mediterranean region for this type of crop.

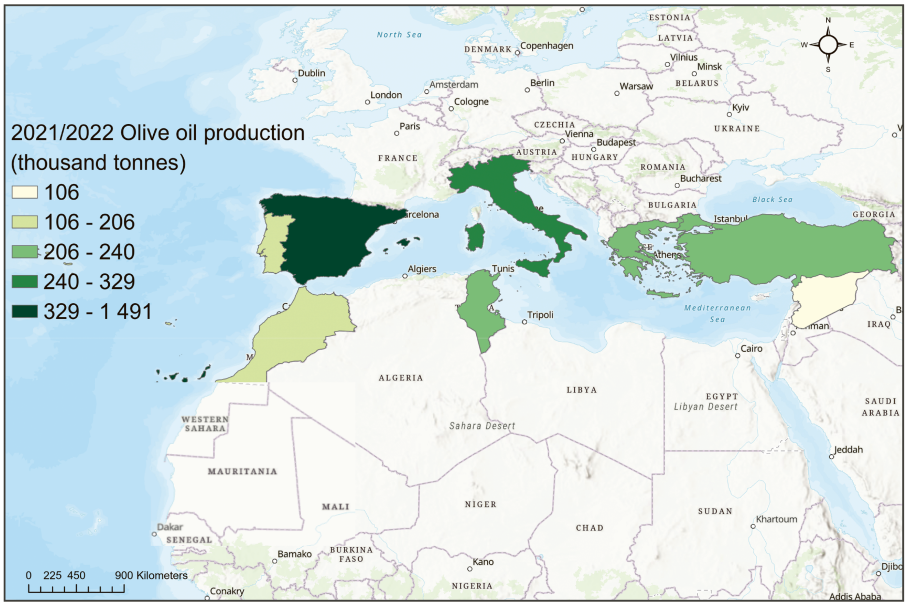
Within this context, the EU accounts for approximately 67% of world olive oil production. The main producers, as well as consumers, are Spain and Italy [31], with a total production in these countries for the 2021/2022 crop reaching $1.49 \cdot 10^{12}$ and $3.29 \cdot 10^{11}$ kg, respectively.

The largest concentration of olive groves in Spain is in the south (Andalusia). The area of olive groves in the region is almost $1.5 \cdot 10^4$ km^2, which accounts for 30% of the agricultural area of the region [32]. Figure 3(b) shows the olive tree area in this region.

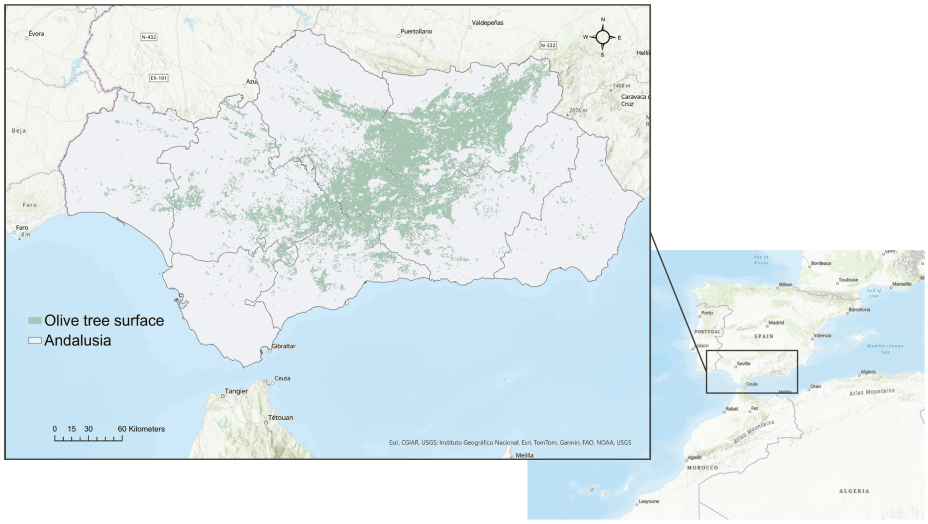
1.5 Motivation of the study

A systematized evaluation for low-carbon hydrogen production is proposed. The dispatchability of waste biomass is an advantage that needs to be assessed. The chapter analyses the availability of by-product biomass, in particular from the olive industry, and considers the reduction of the transport distance to the conversion facilities, as it has a major impact on GHG emissions and costs [33]. The analysis is tailored for regions with large waste biomass generation, such as the Mediterranean area [34].

The analysis has been conducted using as a case study an industrial area demanding hydrogen in the south of Spain. To the authors' knowledge, there are no localized studies in western Andalusia that analyse the real availability of by-products from the olive industrial sectors and their seasonality, even if this type of study is of vital importance to: (i) determine the potential for low-carbon hydrogen production and (ii) to set up the olive industrial sector's by-products supply chain, a major challenge in ensuring the economic and environmental viability of this resource at the local level.



(a)



(b)

Figure 3: (a) Main olive oil global producers and total olive oil production (prepared using data from [29]) and (b) olive tree surface in Andalusia (prepared using data from [30]).

2 Methodology

2.1 Resources for hydrogen using public data

The biomass considered in this chapter is olive sector's by-products. Data on the amount of olive sector's by-products produced are published in different reports of the Andalusian Energy Agency [34]. To begin with, a selection will be made based on the availability in kilograms (dry basis: db) in the provinces of Cadiz, Seville, and Huelva.

Olive sector's by-products with an availability of less than $5 \cdot 10^7$ kg (db) per year will be discarded from the study. This requirement is imposed because of the theoretical yield for hydrogen production from waste biomass by thermochemical conversion. A hydrogen yield of 0.04 kg/kg of waste biomass (db) was adopted for this analysis. This value is based on literature for the gasification of forest biomass, which is considered compositionally similar to the olive industry by-products studied in this chapter [35]. Furthermore, the aim is to avoid competition for other uses of the by-products under consideration. Therefore, the current uses of olive sector's by-products have been studied. This information can also be found published in regional reports [34].

2.2 Hydrogen potential (yields)

After the first screening had been carried out, a literature search was conducted to identify the technologies used to produce hydrogen, as well as to obtain the hydrogen potential from each of the selected by-products. Olive sector's by-products that have not been used experimentally to produce hydrogen or for which no information could be found shall be discarded at this point.

2.3 Hydrogen production methods

According to literature studies, the most efficient technologies for hydrogen production from biomass are thermochemical processes, especially gasification, partial oxidation, and steam reforming. If it is the biological conversion that is considered, dark fermentation is more cost-effective than photo-fermentation [36].

Regarding the technologies used to produce hydrogen from the feedstock selected in this chapter, the following technologies have been considered in this chapter: gasification, hydrothermal gasification, and pyrolysis.

2.4 Identification of hydrogen consumers, producers, and prosumers

With the aim of creating a global hydrogen market to meet the challenges of decarbonization, the establishment of new value chains has been identified as necessary. One of the fundamental aspects to planning the cities of the future and adapting current models to the hydrogen economy is the identification of all energy stakeholders as producers, consumers, or prosumers [4]. The concept of prosumers emerges in a context where European policies implement several directives targeting the energy sector to avoid global warming and meet the challenges of decarbonization. Among these policies, the "Clean Energy for All Europeans" package focusses specifically on consumers, seeking to encourage their active participation in the energy sector, making them protagonists [37]. It is in this way that the term prosumers arises, referring to those passive consumers who have become active prosumers, producing, and consuming the energy generated, thanks mainly to the rise of distributed generation technologies, such as PVs [38]. While efforts are mainly focussed on the industrial scale in the case of green hydrogen, small-scale on-site production is expected to develop in parallel as it could be more attractive than commercially supplied hydrogen when compared economically for some applications [39]; in particular when long-distance transport is required [40]. In this regard, the early implementation of PV panels will facilitate the deployment of small-scale hydrogen production technologies. However, most of the current studies on hydrogen systems for building energy supply assume that hydrogen is produced using electricity from the grid, rather than considering PV generation.

As previously mentioned in Section 1.2, current applications of hydrogen are mainly found in industry as a raw material, principally in oil refining and in the production of ammonia. Since hydrogen is intended to be employed also as a substitute for conventional fuels, the envisaged uses that are expected to be of most relevance are injection to the gas grid, as a fuel for vehicles, or its transformation into electricity for the grid. Analysing these traditional and new uses, refineries, chemical fertilizer industries, the automotive industries, and energy companies can be identified as potential consumers. In terms of stakeholders, these include governments importing and exporting energy, renewable electricity suppliers, car manufacturers, oil and gas companies, cities with major ports, and others [41].

Potential low-carbon hydrogen consumers should be identified to minimize distances between waste biomass generation and hydrogen consumers' hubs. In this sense, considering the Mediterranean regions with an important area of olive grove and where there is an industrial hub that can be a hydrogen consumer, western Andalusia has been identified. In this region, located in the south of Spain, there are two refineries, current consumers of grey hydrogen. In this way, apart from ensuring the sustainability of the process by shortening the distance between resource and industry (the longest distance between olive sector's by-product generation areas and refineries is just over 200 km), the demand for hydrogen is also assured.

2.5 Olive sector's by-products in western Andalusia (case study)

To begin with, the selection of olive sector's by-products was based on the following factors:

- Generation of a significant amount of by-products and on a relatively concentrated surface area
- High energy density
- Existence of technologies capable of harnessing by-products for energy purposes

Data of olive sector's by-products considered, and its availability is accessible in [34]. Further details on the potential and availability of by-products can be found in the regional reports published by the Andalusian Energy Agency [42]. The different by-products considered have been classified, depending on where they are produced, into agricultural stage, and agro-food industrial stage. Olive by-products generated in the agricultural stage are those from pruning, such as branches and dry leaves. This kind of by-product is also found in the industrial stage, since it is usually transported with the batches of olives that are sent to the oil mills. In addition, olive stones and exhausted wet pomace are also generated as by-products in the industrial stage [43].

The transformation of by-products into hydrogen is conducted in refineries to leverage existing technologies. The impact of GHG emissions generated during the transportation can be considerable, making it crucial to develop an optimal supply chain for the transport of waste biomass. In addition, data on the availability of each of the selected sources, as well as their lower heating value (LHV), have been included.

Based on the total amount of each of the selected resources and according to the geographical location of each of them, a density map was generated for the three provinces in which the study is applied. This map has been represented with the help of ArcGIS software (cloud-based mapping and analysis solution).

2.6 Identification of the optimal supply chain

With the aim of identifying the optimal supply chain, the following assumptions have been considered: (i) hydrogen will be produced in the refineries, avoiding the risks associated with transporting hydrogen [44] and (ii) olive mills (industries where olives are processed to produce olive oil) are used as potential pre-treatment hubs, as the biomass selected as feedstock is produced there. The pre-treatment includes drying and pelletization to make the feedstock suitable for the gasifier. Since there are two refineries in the area of study, a pre-allocation is made to determine the biomass that is transported to each refinery, based on distance. A separate assessment is then conducted for each refinery where the biomass is sorted according to distance. Locations where the by-product generation is less than the capacity of the truck set-up are not considered in the study.

Distances from by-product generation points and refineries were calculated using a Python code previously developed by the team. The locations where the olive industry by-products are produced have been obtained from a regional report [42]. Considering that the distances between the refineries and the most distant by-product generation point do not exceed 200 km, the by-products will be transported by road [45]. As olive industry by-products are transported in the form of pellets, a dumper truck with a capacity of 25 tonnes has been selected for the study [46]. According to the legislation in force in Spain regulating the transport of goods, the truck selected correspond to category N3 + O4 articulated vehicles with a maximum authorized mass of 40 tonnes [47].

The developed code allows calculating the shortest route between the origin and destination coordinates (the origin being the generation points of each by-product and the destination being the refineries). For this purpose, a road shapefile of the study area is used. In this case, the shapefile contains information on roads of the following types: highways, freeways, conventional roads, and multi-lane roads, all of which are passable by trucks.

3 Results and discussion

3.1 Olive sector's by-products in western Andalusia (case study)

Once the olive sector's by-products available in the study area are obtained, a first selection is made based on their availability in kilogram. To this end, it has been proposed to discard those by-products whose production would be less than $5 \cdot 10^7$ kg (db). This constraint is based on the low-hydrogen yield of biomass feedstock processes. In so doing and considering the current demand of grey hydrogen in western Andalusia, the selected restriction would allow 3.3% of the demand to be satisfied [48]. Table 1 shows the mass potential for the olive sector's by-products in Seville, Huelva, and Cadiz.

Table 1: Selected technologies for the conversion of olive by-products to hydrogen.

Type of waste biomass		By-product generation (tonnes/year db)	Selected technology	H_2 yield (kg H_2/kg by-xproduct)	References
Olive agricultural by-products	Olive pruning	219,683	Gasification	0.037	[49, 50]
Agro-food industrial by-products	Olive tree pruning	18,490	Gasification	0.037	[49, 50]
	Olive stone	69,845	Gasification	0.034	[50, 51]

Table 1 (continued)

Type of waste biomass		By-product generation (tonnes/year db)	Selected technology	H_2 yield (kg H_2/kg by-xproduct)	References
	Exhausted wet pomace	125,535	Hydrothermal gasification	0.034	[52, 53]
			Pyrolysis	0.012	[54]

db, dry basis.

3.2 Hydrogen yield determination

Table 1 shows the different technologies selected for the conversion of olive sector's by-products to hydrogen and their respective yields. Even though olive tree pruning did not meet the restriction on the amount of by-product generated (its production only reaches $1.8 \cdot 10^7$ kg/year), it has continued to be considered as a possible resource. That is because it belongs to the olive industry stage and, together with olive stones and exhausted wet pomace, all three are produced in the same place and reach the restriction imposed.

3.3 Provision in western Andalusia

Once the maximum hydrogen production potential had been estimated with each of the by-products studied, the aim was to analyse the data in greater depth to include the seasonality of production and the percentage that is not currently used for other purposes.

Following a literature evaluation, it has been found that the current use of the olive sector's by-products is only available for olive by-products generated at the industry stage and not for by-products from agriculture, thus, the analysis in this part of the chapter has been conducted only for by-products from the olive industry.

This analysis is founded on the dataset and methodologies from [34]. From this source, it has been obtained: (i) the monthly production data for each olive by-product, (ii) the yield percentages to correlate by-products with oil production (Figure 4), and (iii) data on the current uses of this biomass. The data on current uses, derived from an average of the 2011–2014 campaigns, was selected to establish a robust baseline, thus reducing uncertainty from annual fluctuations.

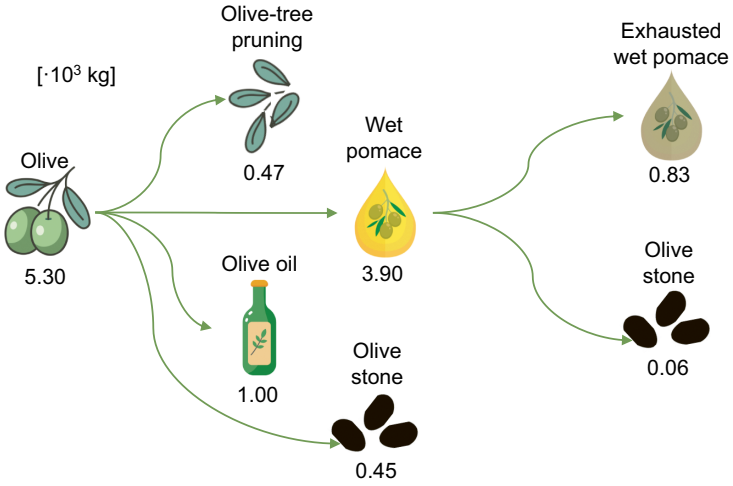


Figure 4: Average amount of resource required and by-products generated to produce 1 tonne of olive oil [42].

Using this information, the total hydrogen production potential has been calculated. This was done by applying the by-product yield percentages to the oil production for campaigns between 2017 and 2021 [55–58], Figure 5 shows this monthly potential for Cadiz, Seville, and Huelva. Finally, the calculation was refined by considering the "real availability" of the by-products, accounting for its current uses [34].

Since a large part of the waste generated in the olive industry is used for energy purposes, this chapter considers as available the quantities that refer to uses that do not compete with another sector. In the case of olive mill, they are those that are managed as waste (from which an economic benefit could even be obtained from their administration), those that are burnt, those that are handled through intermediaries and those whose application is unknown. In this way, up to $3.49 \cdot 10^6$ kg of olive tree pruning and up to $1.80 \cdot 10^7$ kg of olive stones could be obtained from olive mills located in western Andalusia. In the case of the olive extractors, it has been considered that the quantities of by-products that are currently exported or managed by intermediaries could be used for hydrogen production. This implies up to $3.22 \cdot 10^6$ kg of stone and $1.32 \cdot 10^7$ kg of exhausted wet pomace.

Considering the whole olive sector's by-product generation dedicated for low-carbon hydrogen with respect to the total olive sector's by-products generated is 18%, since the rest of this residue is currently used for energy purposes. Considering only olive sector's by-products without current use, and assuming that the industrial demand for hydrogen in the region in 2020 was about 115,000 tonnes [48], the total coverage of the industrial demand for hydrogen in western Andalusia would be 1.1%.

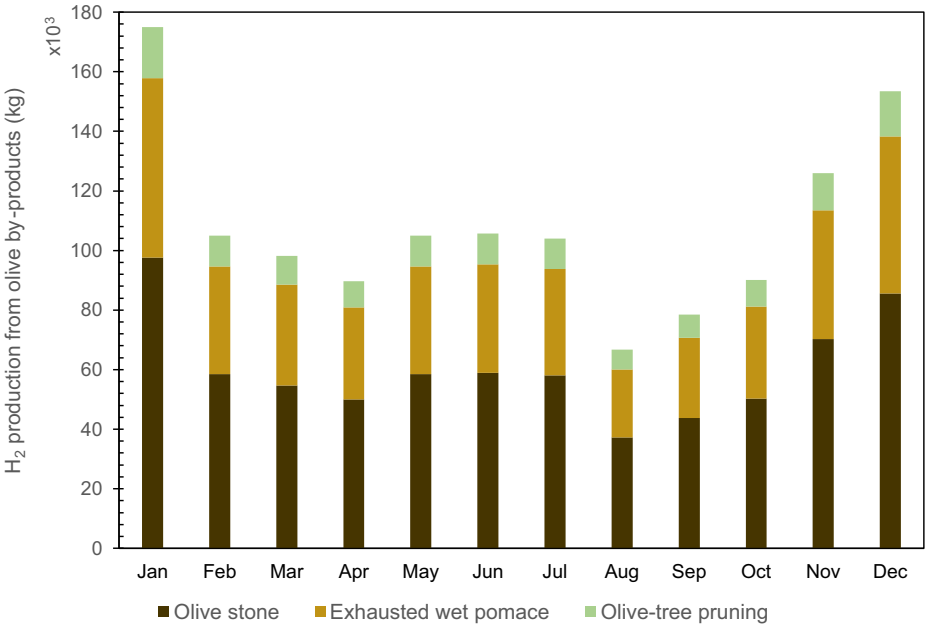


Figure 5: Potential amount of "real" hydrogen in western Andalusia (Seville, Cadiz, and Huelva) from olive industry by-products considering availability.

When comparing hydrogen production using the olive sector's by-products available in western Andalusia, and assuming that industrial hydrogen consumption is constant throughout the year, it can be seen that:

- The month in which most hydrogen is produced is January, in which 1.83% of the western Andalusia demand in that month would be supplied. Compared to the national demand (assuming that the annual demand is evenly distributed each month), a 0.42% would be supplied.
- In the case of the month with the lowest production, August, 0.70% would be covered in the case of the area of study and 0.16% if national demand is considered.
- The percentages obtained considering only the available olive sector's by-products are very low, although this waste biomass is abundant in the region. The reason could be that almost all industrial olive sector's by-products are used for electricity generation. When analysing the percentage of demand covered in the study area if the current use of olive sector's by-products is not considered (including olive by-products generated at the agriculture and industry stage), 13.4% would be covered. This percentage is also low, indicating that this type of by-product cannot be a primary feedstock to produce low-carbon hydrogen for current industrial uses.

– The month in which the least hydrogen is produced from olive sector's by-products match the month with the most hours of sunshine, and therefore the month in which the most hydrogen could be produced by electrolysis from solar energy.
– Likewise, the month in which the most hydrogen is produced from olive sector's by-products correspond to the month with the fewest hours of sunshine. This demonstrates a complementarity of olive sector's by-products with current mainstream technology.

Figure 6 presents the energy potential of the available raw biomass and its equivalent in renewable hydrogen. To quantify this, a uniform LHV of 17 MJ/kg was assumed for all by-products. This average value was chosen as it reflects the typical energy content for a mix of olive stone, pomace, and pruning by-products, in line with findings from specialized literature [59]. This approach simplifies the regional assessment while maintaining representative results.

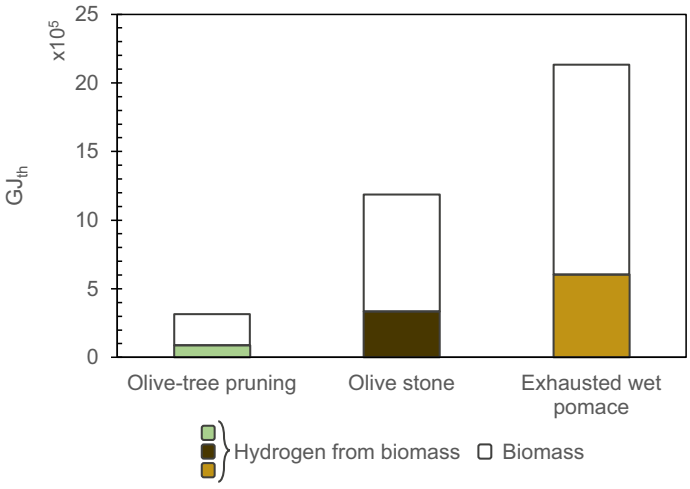


Figure 6: Comparison of energy produced as hydrogen from olive industry by-products and energy contained in by-products (db, LHV basis).

The fact that real data on quantities, energy, seasonality, and location of renewable resources for hydrogen production have been considered in this study is an important approach to overcome the dispatchability barriers of the renewable sources currently used (solar and wind). Unlike the former, olive industry by-products production is more predictable, as well as easily storable and transportable.

3.4 Optimal supply chain

The cost and GHG emissions of transport have been calculated according to the type of truck selected and its capacity (Grupo Tragsa, 2024). For the transportation cost analysis, a standard unit cost of €1.62/km was adopted. This value is derived from the official data published by the Spanish National Observatory of Road Transport Costs for a 25-tonne articulated dump truck. The fare represents the cost of a fully loaded trip, based on the most up-to-date fares available (January 2025) [60].

The environmental impact is calculated in this study using the GWP100 (global warming potential) [61].

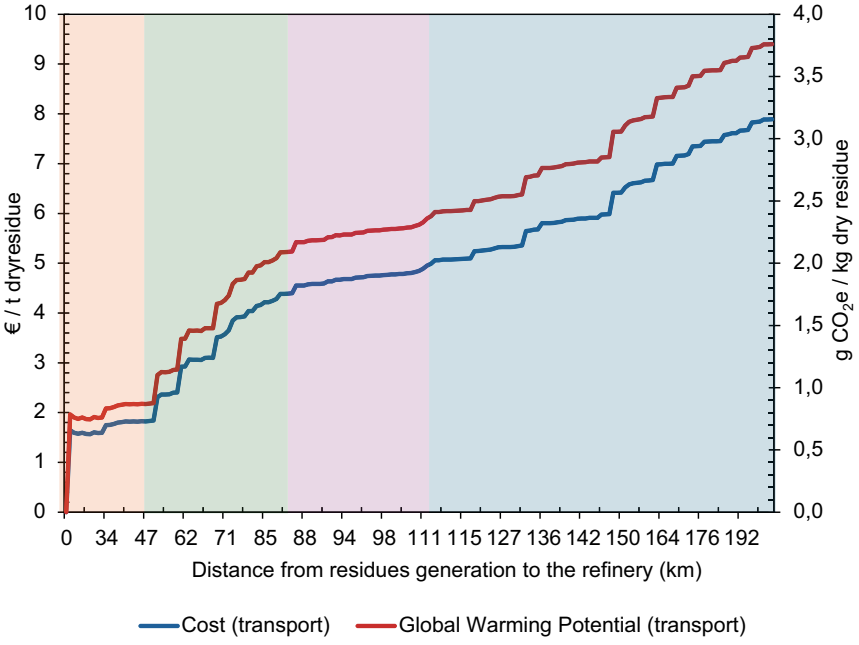


Figure 7: GWP100 and cumulative transport costs of by-products.

As shown in Figure 7, the transport cost and emission curves per quantity of dry by-product transported show four zones, differentiated in the graph by different colours. The orange and pink zones show parts in which the slope becomes smoother, and both the cost and emissions during transport hardly increase at all. This is the case for distances up to about 50 km, and for distances between 90 and 110 km. In the other differentiated zones (represented by the green and blue colours), the slopes of both curves increase. Thus, it seems advisable that the maximum transport distance should be around 110 km. For short distances between 50 and 90 km, the increase in price and emissions of transport with a minimum distance variation can be considerable.

3.5 Future work

After studying the availability of olive industry by-products in western Andalusia, this chapter serves as a basis for determining the location and quantity of other biomass resources that can be used as raw materials to produce renewable hydrogen. It also provides monthly information on the hydrogen potential that could be produced from each of the by-products studied.

Following the study of the sources of production, it remains to determine the location of the mills (industries where the by-products are generated) to pose a location-allocation problem to obtain an optimal solution that minimizes transportation costs. Although it is true that one of the possible scenarios is the on-site conversion of by-products for hydrogen production, the low technological maturity and lack of experience of the industries producing the by-products studied make this option unrealistic.

For this reason, one of the options proposed for future work is the adaptation of refineries close to the generation of olive industry by-products for the in situ production of low-carbon hydrogen. In the specific case proposed in this study, the refineries that could be studied as receptors for the waste biomass analysed are *La Rábida* (Huelva) and *San Roque* (Cadiz).

3.6 Limitations

According to the limitations of this study in regards with the use of olive industry by-products as raw material, it should be considered that the yields used to calculate the total amount of hydrogen production as well as the energy involved in the process, are referenced on a dry basis. This means that the energy needed to dry the biomass is not considered. However, its moisture content is an important limitation in the thermochemical processes considered in this chapter (pyrolysis and gasification) [62]. The average moisture content of the waste biomass considered (olive tree-pruning, exhausted wet pomace, and olive stone) is 40%, whereas for gasification or pyrolysis, the moisture content must be less than 15% [63, 64]. A prior drying is needed and will also increase the calorific value of the waste biomass. Figure 8 shows the net calorific value of olive grove residues compared to other waste biomass in the region as a function of moisture content. Since all the residues, except for rice, had very similar values and the lines overlapped, a zoom has been applied based on the typical range of moisture content of the selected waste biomass (20–46%).

Nevertheless, biomass drying processes have some issues as energy efficiency, environmental impacts (related to emissions of particulate matter that may harm the local environment), risk of fire, and costs [65]. Since it is an energy-intensive process, it can have an important impact on the economic viability and the sustainability of the overall process. To fill this gap, solar drying of waste biomass is proposed to re-

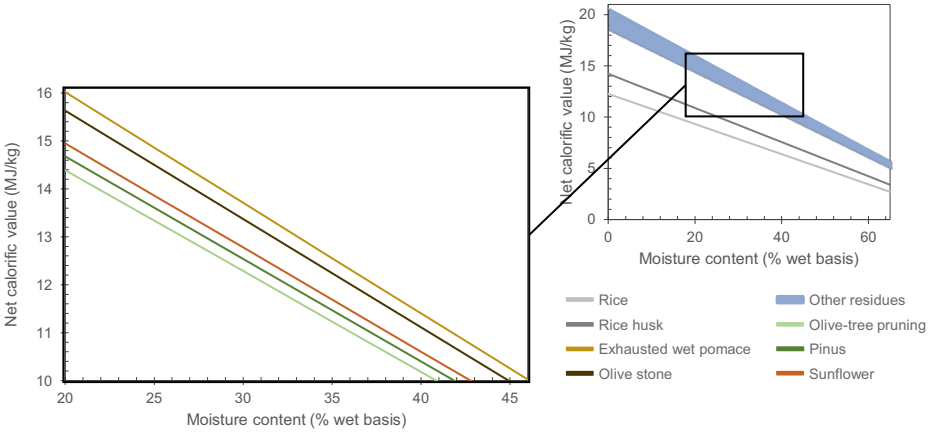


Figure 8: Net calorific value of olive industry by-products compared to other waste biomass in the region as a function of moisture content.

place conventional drying methods. Although one of the main limitations of this technology is geographical location [66], in study of this chapter, solar energy is a plentiful resource and available for much of the year. Solar drying biomass allows to decentralize the drying process and to situate it near to the by-product source, reducing the transport cost and increasing the overall efficiency of energy production [67].

Another important limitation to consider when using this type of raw material is its geographical dispersion. Locations where the by-products considered in this study generated are many and varied. This underlines the necessity of a detailed study of the supply chain required for the transport of olive industry by-products. Thus, to make a previous screening to try to reduce GHG emissions during the transport is crucial as it can account for most of the CO_2 emissions during the process [68]. In this sense, this chapter can serve as a basis to make a prior quantification of the olive industry by-products that can be used as a raw material, not only for its conversion to produce hydrogen, but also for its accessibility and management as a resource.

4 Conclusions

This chapter serves as a basis for identifying, quantifying, and locating olive industry by-products for low-carbon hydrogen production. Considering the importance of the supply chain when using biomass as feedstock, the approach used in this chapter can serve as a preliminary stage to establish a location-allocation problem to determine the optimal location of olive by-products hubs, minimizing operating cost and greenhouse emissions.

The proposed approach provides the maximum capacity of hydrogen production using the olive industry by-products available in the region assessed. In addition, the seasonality of production can be evaluated, thus highlighting one of the advantages of using biomass as an energy source, i.e. its dispatchability. It can be established for each month, what waste will be accessible and what maximum amount of hydrogen (in kg, db) can be produced, as shown in Figure 5. This advantage can be useful for studying the coupling of this resource with variable renewable energy such as solar or wind.

As a result of applying this approach in region with high generation of olive industry by-products and existing consumers of industrial hydrogen (western Andalusia), it has been calculated that the maximum potential for hydrogen generation could reach approx. $1.75 \cdot 10^5$ kg in the month of peak production (using the real amount of available olive industry by-products), adding the yields obtained for exhausted wet pomace, olive stones and olive tree pruning. This amount represents a limited coverage of the monthly demand in the study area (around 1%). This is due to the high percentage of waste already used for other purposes such as electricity or heat generation. Hence, olive industry by-products are not a significant feedstock to produce low-carbon hydrogen in the assessed region.

Based on the results obtained, it has been verified that the proposed methodology can be used to determine whether a potential by-product is viable for hydrogen production in a sustainable way and using public data. The proposed sustainability criteria are based on the amount of by-product available, to secure a minimum coverage of demand in the area, as well as real availability of the waste to avoid competition with other sectors.

Abbreviations

CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
DRI-EAF	Direct reduced iron and electric arc furnace
EU	European Union
GHG	Greenhouse gas
HT	High temperature
HTG	Hydrothermal gasification
LCA	Life cycle assessment
LOHC	Liquid organic hydrogen carrier
NG	Natural gas
OFMSW	Organic fraction of municipal solid waste
PNIEC	National Integrated Energy and Climate Plan
SMR	Steam methane reforming
db	Dry basis

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