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Development of Net-Zero Emission Olive Oil Mills in the Island of Crete, Greece

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ABSTRACT: Olive oil industry is one of the main industries in the island of Crete, Greece. Olive oil is extracted in around 550 small-size olive oil mills in the island. These olive oil mills are characterized by low energy consumption utilizing grid electricity for powering the machinery and solid biomass for heat generation. Olive oil mills can generate in situ the electricity required in their operation while the can use olive kernel wood, produced in olive pomace plants, for heat production. Replacement of grid electricity with solar electricity generated by a solar photovoltaic system and using olive-based biomass for heating purposes an olive oil mill can eliminate all the net-carbon emissions during its operation. Solar photovoltaics systems are broadly used in Crete for green power generation while olive-based solid biomass is extensively used for heat production. An olive oil mill producing annually around 200 tons of olive oil can eliminate all the operational carbon emissions with the installation of a solar photovoltaic system with nominal capacity 13.33 kW_p and with the use of 9,524 kg/year of olive kernel wood for heat production. Our work indicates that the use of reliable, mature and cost-efficient renewable energies in olive oil mills in Crete can achieve their complete decarbonization. The results could be useful to olive oil mills' owners and to policy makers who can promote the decarbonization of the main food industry in the island.

KEYWORDS: biomass, by-products, carbon emissions, Crete-Greece, olive oil mill, olive residues, solar energy, wastes

1. INTRODUCTION

Reducing or zeroing the net-carbon footprint in industries is prerequisite for achieving net-zero emissions societies by 2050. The olive oil extracting industry is an important industry in the food sector using mainly grid electricity and heating fuels. Apart from olive oil, olive groves and olive oil mills produce residues, by-products and liquid wastes that can be used for energy generation [1], [2], [3]. Solid and liquid biomass resources, based on olive trees and olive oil mills can be used with various technologies including burning, gasification, anaerobic digestion and co-generation of heat and power for heat and electricity generation [4], [5], [6], [7], [8]. Several studies have estimated the power and heat demand in olive oil mills [9], [10], [11]. Solar energy and biomass, which are abundant in Crete, can be used for electricity and heat generation meeting all the energy demand in olive oil mills [12], [13], [14], [15].

The aim of the current work is the estimation of the renewable energies that can be used in olive oil mills in the island of Crete, Greece replacing the use of fossil fuels, zeroing their net-carbon emissions.

The text is structured as follows: After the literature survey the production of olive oil in Crete and the energy consumption in olive oil mills are analyzed. In the following two sections the concept of net-zero carbon emission industries and the possibility of using renewable energies in olive oil mills in Crete are mentioned. Next, the elimination of the carbon footprint in olive oil mills in Crete is mentioned. The text ends with discussion of the findings, the conclusions drawn and the citation of the references used.

The text is innovative since there are not similar studies published so far in this topic while it covers a research gap regarding the development of net-zero emission olive oil mills in Crete. It could be useful to policy makers, to olive oil mills' owners, to farmers, to energy producing companies and to stakeholders of the olive oil industry in Crete.

2. LITERATURE SURVEY

The energetic valorization of olive biomass including olive tree pruning, olive stones and pomace has been explored [1]. The authors stated that olive oil industry is one of the most important industries worldwide producing $2X10^7$ tons olives per year. They mentioned that the by-products of the olive oil industry including olive pruning, olive stones and pomaces should be used for energy generation. The biomass recovery from olive oil producing plants using two different techniques has been studied [2]. The authors stated that the ratio of energy output to energy input varied in the range of 23.81-32.80. They estimated the energy consumption in the range of 0.38-0.40 kWh per kg of olive oil produced. Various aspects of Cretan olive groves have been examined [3]. The authors examined different types of olive farms including organic, conservation, low-input and standard farms estimating their productivity, profitability and technical efficiency. They stated that organic farms had the best indexes while standard farms the worst. The syngas production from olive tree pruning and olive kernels in a gasifier has been investigated experimentally [4]. The authors gasified the olive biomass in temperatures 750-950 ^oC and in air equivalence ratios 0.12-0.42. They stated that the main products in the gas phase were CO, CO_2, H_2 and CH_4. The environmental benefits of olives' by-products have been explored [5]. The authors stated that the biomass energy potential of olive groves was estimated at 25-28 MWh/ha primary from woody biomass and pomace. They mentioned that the circular strategy, reusing residues, byproducts and wastes, has an economic benefit at around 70 $/ha while the residues in olive farming can be considered as valuable resources. The biogas production from olive mills' by-products has been studied [6]. The authors investigated experimentally the possibility of producing biogas from olive pomace and olive oil mills' wastewater. An integrated gasification plant for power generation from wet biomass in Spain has been studied [7]. The proposed process consisted of a pelletizer, a gasifier, a gas cooling and cleaning unit and a microturbine for power generation. They stated that the olive pomace continuously produced in olive oil mills can be dried using the hot gases, at temperature around 300 ^oC, produced by the microturbine. The possibility of energy generation from olive tree residues, by-products and wastes in Crete, Greece has been examined [8]. The author stated that these residues, by-products and wastes in Crete include: a) olive tree pruning at 570,000 tons, b) olive kernel wood at 155,000 tons, and c) liquid wastes from olive mills at 100,000 m^3. The energy requirements in extra virgin oil production have been explored [9]. The authors analyzed three systems of olive tree cultivation: the traditional, the intensive and the super intensive. They stated that olive tree cultivation has a share of over 90% in the life cycle of olive oil production. The energy efficiency in olive oil mills in Spain and Portugal has been studied [10]. The authors estimated the power consumption in an olive oil mill with annual production capacity 1,600 tons of olive oil at 0.18 kWh/kg of olive oil and the heat consumption at 0.21 kWh/kg of olive oil. They also evaluated the power consumption in an olive oil mill with annual production capacity 300 tons of olive oil at 0.104 kWh/kg of olive oil and the heat consumption at 0.2 kWh/kg of olive oil. The energy efficiency in olive oil mills has been analyzed [11]. The authors stated that their energy efficiency can be improved with interventions in machinery, with the use of biomass for heat production and with insulation in the pipes transporting hot water. The installation of solar-PV systems and batteries in olive oil mills has been examined [12]. The authors studied three olive mills with different capacities, small, medium and large. They stated that for the small and medium size olive mills installing a solar-PV system with capacity 3 to 6 KW_p can result in direct self-consumption indexes up to 80%. The use of solar-PV systems in olive oil mills in Spain has been explored [13]. The authors stated that a self-sufficiency index of 40% maybe achieved on olive harvest basis. They mentioned that the solar-PV array tilt and the orientation angle can improve the self-sufficiency. The use of renewable energies in olive oil mills including solar energy, wind energy and biomass located in Andalusia, Spain has been examined [14]. The authors used the HOMER software to simulate the use of several renewable energies stating that the proposed solar-PV system was in the range of 6 to 40 kW_p depending on the capacity of the olive mill. The use of solar-PV systems with batteries in olive oil mills has been studied [15]. The authors stated that the produced solar electricity can cover between 11% to 84.7 % of the mills' energy consumption while their carbon footprint can be reduced by 22% to 119%. A report regarding a zero-emissions olive oil mill has been published [16]. Olive oil is produced in a three-phase olive oil mill while the residue is anaerobically digested producing biogas which is used for heat and power co-generation. The economic value of biomass produced in the olive oil sector in Andalusia, Spain has been estimated [17]. The authors stated that the olive sector in Andalusia produces around 3.9 mil. tons of biomass annually while part of it is used for power generation and for domestic and industrial thermal use. They mentioned that olive related-biomass can be further used for heat and electricity generation. The energy performance of two olive oil producing processes- batch and continuous has been compared [18]. The author stated that the overall equipment effectiveness in continuous process is almost double than in batch process. The energy efficiency in olive groves and olive oil mills has been studied [19]. The authors estimated the direct energy use in olive groves and the electric and thermal energy consumption in olive mills stating that for production of 300 ton per year olive oil the electricity consumption is at 31,160 kWh/year and the thermal energy consumption at 60,000 kWh/year. The possibility of developing zero CO_2 emission olive pomace plants due to energy use in Crete has been analyzed [20]. The author stated that 42.86% of the produced olive kernel wood is consumed in the factory for heat production while the rest 57.14% is sold to external users. He also mentioned that heat demand has a share at 99.1% in the total energy balance in the factory while electricity demand has a low share at 0.9%. The electricity demand in these olive pomace plants can be generated by solar electricity. The energy saving in olive oil producing plants has been examined [21]. The authors stated that in olive oil mills with capacity 500 kg/h the installed power of the machines was 42.48 kW while the specific energy consumption was at 169.39 kJ/kg. The best practices for improving the energy efficiency in olive oil mills have been analyzed [22]. The authors stated that in an olive oil mill which produces 300 tons of olive oil annually the heat consumption was around 200 kWh/ton while the electricity consumption was at around 95 kWh/ton. A zero-energy olive oil mill by using waste valorization has been explored [23]. The authors proposed an integrated olives' processing system consisted of olive oil extraction, briquetting and a cogeneration unit. The authors stated that the power generated from the cogeneration unit meets the energy requirements of the integrated system. The production and marketing of Cretan olive oil and wine have been studied [24]. The author stated that the structure of olive farms in Crete consists of thousands of small businesses in which individual farmers have limited contact with consumers while the small size of the farms does not allow the use of modern methods of processing their residues. The climate suitability for olive groves in Greece has been analyzed [25]. The authors stated that although the olive tree is one of the best acclimated species its cultivation may be impacted by climate change. They mentioned that the suitability of olive cultivation is high in Greece. The recent advances and the future perspectives in valorization of olive biomass including pruning residues, leaves, pomace and olive stones have been investigated [26]. The authors stated that olive biomass biorefineries offer significant potential for sustainable production while there are many challenges hindering the deployment of biomass biorefineries. An off-grid biomass gasification CHP plant for an olive oil mill in Morocco has been assessed [27]. The authors stated that many olive oil mills in Morocco are off-grid powered by diesel generators. They mentioned that a CHP plant based on olive cake and olive tree pruning with electrical efficiency at 18% and total efficiency at 35% has a payback period at 7-8 years. The circular bioeconomy of olive oil industry particularly the profitability of olive pomace gasification has been investigated [28]. The authors stated that this kind of projects have high capital requirements and uncertain profitability. They mentioned that their estimations indicated that they have positive net present value and internal rate of return at 9.7%. An olive mill wastewater biorefinery has been techno-economically assessed [29]. The authors stated that biorefineries may have a significant contribution in the transition towards a sustainable and circular economy. The authors proposed a holistic bottom-up approach which facilitates the implementation of the complex biorefinery process. The electricity and heat consumption in olive oil mills are presented in Table 1.

Table 1. Electricity and heat use in olive oil mills

Authors, year	Electricity use (kWh_{el} per ton of olive oil)	Heat use (kWh_{th} per ton of olive oil)	Total energy use (kWh per ton of olive oil)
Cappelletti et al, 2014			167
Rabaze et al, 2015	145	170	315
Murchio et al, 2016	172	210	382
Romaniello et al, 2024			390
Baptista et al, 2023	104	200	304

Source: several authors

3. PRODUCTION OF OLIVE OIL IN CRETE

Olive oil production in Crete is one of the most important agricultural and cultural activities on the island, deeply rooted in its history, economy and daily life. Often referred to as "liquid gold," olive oil has been produced in Crete for thousands of years, shaping both the landscape and the identity of its people. The origins of olive oil production in Crete date back to the Neolithic and Minoan periods, when early inhabitants began cultivating olive trees and extracting oil using primitive techniques such as crushing and pressing olives by hand. Archaeological evidence from sites like Knossos shows that olive oil played a central role in the economy and daily life of the Minoan civilization, being used not only for food but also for lighting, medicine, and religious rituals. Over time, olive cultivation expanded significantly, and today olive groves cover about 65% of the island's agricultural land, with millions of trees producing a substantial share of Greece's olive oil. The production process of olive oil in Crete has evolved considerably, combining traditional knowledge with modern technology. The process begins with the harvesting of olives, usually between late autumn and early winter. Farmers either hand-pick the olives or use mechanical methods to collect them from the trees. It is essential that the olives are transported quickly to olive oil mills to preserve their quality. Olive oil mills are at the heart of production on the island. Traditionally, mills used stone grinders and hydraulic presses to extract oil. Olives were crushed into a paste, which was then pressed to separate the oil from the solids. However, since the late 20th century, most Cretan mills have adopted modern centrifugal systems. These systems separate oil, water, and solid residues more efficiently, improving both yield and quality. Modern mills often process olives on the same day they are harvested, ensuring that the oil retains its freshness, aroma, and nutritional value. Olive oil mills in Crete are not only production facilities but also important social and economic centers. Many farmers do not own their own mills; instead, they bring their olives to local mills, where the oil is extracted either for a fee or in exchange for a percentage of the final product. This system reflects the cooperative and community-based nature of rural life on the island. In recent decades, many olive oil mills have modernized further by incorporating environmentally friendly practices, such as improved waste management and the use of renewable energy sources. Today, Crete produces between 80,000 and 120,000 tons of olive oil annually, the majority of which is extra virgin olive oil known for its high quality and health benefits. The island's mild climate, fertile soil, and long-standing expertise contribute to the exceptional characteristics of its olive oil. Therefore, olive oil production in Crete represents a unique blend of ancient tradition and modern innovation. From the cultivation of olive trees to the operation of advanced olive oil mills, the process reflects centuries of accumulated knowledge and cultural significance. Olive oil remains a cornerstone of Cretan life, symbolizing both heritage and sustainability in the modern world. The characteristics of olive oil production in Crete are presented in Table 2.

Table 2. Characteristics of olive oil production in Crete

Number of olive trees in Crete	Approx. 35 million trees
Cultivated area with olive trees	195,780 ha
Annual olive oil production	80,000-120,000 tons
Number of olive oil mills	Approx. 550
Share of olive oil production in Crete in the total olive oil production in Greece	30-35%

Source: own estimations

4. ENERGY CONSUMPTION IN OLIVE OIL MILLS IN CRETE

Energy consumption in olive oil mills in Crete is a crucial aspect of the production process, influencing both economic efficiency and environmental sustainability. As olive oil production remains one of the island's most important agricultural activities, understanding how energy is used—and increasingly optimized—has become essential in modern Cretan industry. Olive oil mills require energy in two main forms: electrical and thermal. Electrical energy is primarily used to power machinery involved in olive processing, including conveyors, washing systems, crushers, mixers and centrifuges that separate oil from water and solid residues. Thermal energy, on the other hand, is necessary for heating water and maintaining optimal temperatures during the malaxation phase, usually around 30°C, which helps improve oil extraction efficiency. In general, energy consumption varies depending on the size, technology, and production capacity of each mill. Studies show that electricity consumption in olive oil mills can range roughly between 160 and 210 kWh per ton of produced oil, with larger and more modern mills typically achieving greater efficiency. This reflects the importance of technological advancement: newer mills in Crete often incorporate automated systems and improved machinery that reduce energy waste and optimize performance. The distribution of energy use in olive oil mills is relatively balanced between electrical and thermal energy. Approximately less than half of total energy demand is electrical, while the other is thermal. However, in terms of cost, electricity represents the dominant expense—accounting for up to 75–83% of total energy costs—since thermal energy is often generated from low-cost or self-produced biomass fuels. A distinctive feature of energy consumption in Cretan olive oil mills is the use of by-products as energy sources. Olive pomace (the solid residue left after oil extraction) and olive pits are widely used as biomass fuel. These materials are burned in boilers to generate heat, significantly reducing reliance on fossil fuels. In fact, olive kernel wood—a by-product of processing—has high calorific value and is often used internally for heat generation, with some facilities consuming a large portion of their own biomass for energy needs. In recent years, there has been a growing shift toward renewable energy solutions in Crete's olive oil sector. Many mills are adopting solar photovoltaic systems to offset electricity consumption from the grid. In some cases, small-scale olive mills have achieved near energy self-sufficiency by combining solar power with biomass utilization. Additionally, innovative approaches such as anaerobic digestion of olive mill waste to produce biogas are being explored, offering further opportunities to transform waste into energy and reduce environmental impact. Energy efficiency is now a major concern for the industry, not only to reduce costs but also to meet environmental regulations and sustainability goals. Improvements focus on optimizing high-energy stages such as crushing, malaxation, and centrifugation, as well as better insulation, heat recovery systems, and smart energy management techniques. Therefore, energy consumption in olive oil mills in Crete reflects a dynamic balance between traditional practices and modern innovation. While the production process is energy-intensive, especially in its mechanical and thermal stages, the widespread use of biomass and the increasing adoption of renewable energy technologies have significantly improved sustainability. As the industry continues to evolve, energy efficiency and environmental responsibility will remain key factors shaping the future of olive oil production on the island. The energy requirements to obtain 1 liter of virgin olive oil are presented in Table 3 while the electricity consumption in olive oil mills in Table 4 and the energy consumption in olive oil mills in Table 5.

Table 3. Energy requirements to obtain 1 liter of virgin olive oil

System	Olives’ production (MJ)	Olives’ transport (MJ)	Production of olive oil (MJ)	Total (MJ)
1	8.2-8.4	0.1	0.5-0.7	9.0-9.3
2	10.3-10.7	0.1	0.5-0.7	11.1-11.6
3	10.3-10.9	0.1	0.5-0.7	11.1-11.5

Source: [9]

Table 4. Energy consumption in olive oil mills

Classification of olive oil mills	Capacity of olive mills (production in tons)	Electricity consumption (kWh_{el})	Heat consumption (kWh_{th})
Small	< 1,000	92,000	108,000
Medium	1,000-5,000	435,000	510,650
Large	< 5,000	922,500	1,082,900

Source: [14]

Table 5. Energy consumption in olive oil mills

Characteristics of olive oil mills	Annual capacity of 1,600 tons of olive oil	Annual capacity of 300 tons of olive oil
Installed electric power	1,600 kW_{el}	217 kW_{el}
Installed heat power	1,330 kW_{th}	175 kW_{th}
Electricity consumption	288,000 kWh_{el}/year	31,160 kWh_{el}/year
Heat consumption	336,000 kWh_{th}/year	60,000 kWh_{th}/year
Total energy consumption	624,000 kWh/year	91,160 kWh/year
Electric efficiency	0.18 kWh_{el}/kg of olive oil	0.104 kWh_{el}/kg of olive oil
Heat Efficiency	0.21 kWh_{th}/kg of olive oil	0.20 kWh_{th}/kg of olive oil
Total energy efficiency	0.39 kWh/ kg of olive oil	0.304 kWh/kg of olive oil

Source: [19], [11]

5. NET-ZERO CARBON EMISSION INDUSTRIES

The need for net-zero emission industries has become one of the most urgent priorities of the 21st century. As global temperatures rise and environmental degradation accelerates, industrial activity stands out as one of the largest contributors to greenhouse gas emissions. Achieving net-zero emissions — where the amount of carbon emissions produced is balanced by the amount removed from the atmosphere — is essential to mitigating climate change and ensuring a sustainable future. An olive oil mill can be considered as a net-zero emission factory if it does not use any fossil fuels and generates carbon-free electricity equal with the grid electricity consumed annually.

Industries are responsible for a significant share of global emissions due to their reliance on fossil fuels, energy-intensive processes, and large-scale production systems. The scientific consensus, supported by organizations such as the Intergovernmental Panel on Climate Change, makes it clear that limiting global temperature rise to 1.5°C requires rapid and deep reductions in industrial emissions. Transitioning to net-zero industries involves a combination of technological innovation, policy support, and changes in business practices. One of the most important steps is the shift from fossil fuels to renewable energy sources such as solar, wind, biomass and hydropower. Electrification of industrial processes, where feasible, can significantly reduce emissions when powered by clean energy. In addition, energy efficiency improvements—such as optimizing machinery, recovering waste heat, and adopting smart energy management systems—can lower overall energy demand. Furthermore, the adoption of circular economy principles—reducing waste, reusing materials, and recycling resources—can significantly decrease the environmental footprint of industrial activities. The benefits of achieving net-zero emissions extend beyond environmental protection. Economically, industries that invest in clean energy technologies often experience long-term cost savings through improved efficiency and reduced dependence on volatile fossil fuel markets. Moreover, the transition creates new opportunities for innovation, job creation, and competitiveness in emerging green markets. Governments and international organizations are increasingly supporting this shift through regulations, incentives, and climate agreements such as the Paris Agreement, which aims to unite countries in the fight against climate change. Despite these advantages, the transition to net-zero industries also presents challenges. High initial investment costs, technological limitations, and the need for skilled labor can slow progress, particularly in developing regions. Additionally, industries must balance environmental goals with economic growth and social responsibility, ensuring that the transition is just and inclusive for workers and communities. Therefore, the shift toward net-zero emission industries is not merely an environmental necessity but a comprehensive transformation of how economies function. It requires coordinated efforts across governments, businesses, and society, as well as sustained investment in innovation and infrastructure. While the path may be complex, the long-term benefits—ranging from climate stability to economic resilience—make the pursuit of net-zero emissions essential. By embracing this transition, industries can play a leading role in shaping a cleaner, more sustainable future for generations to come.

6. POSSIBILITY OF USING RENEWABLE ENERGIES IN OLIVE OIL MILLS IN CRETE

The possibility of using renewable energy in olive oil mills in Crete is increasingly becoming both a practical and necessary solution for improving sustainability in the agricultural sector. As one of the largest olive oil producing regions in Greece, Crete relies heavily on energy-intensive processes for oil extraction. Integrating renewable energy sources into these mills offers significant environmental, economic, and social benefits. One of the most promising renewable energy sources for olive oil mills in Crete is solar power. The island enjoys high levels of solar radiation throughout the year, making solar photovoltaic systems highly effective. By installing solar panels on rooftops or nearby land, olive oil mills can generate electricity to power machinery such as crushers, malaxers, and centrifuges. In many cases, solar energy can cover a substantial portion of a mill's electricity needs, reducing dependence on the national grid and lowering operational costs over time. In addition to solar energy, biomass represents another valuable renewable resource. Olive oil production generates significant quantities of by-products, such as olive pomace and pits. These materials can be used as biomass fuel to produce thermal energy required in the production process, particularly for heating water during malaxation. This approach not only reduces waste but also creates a closed-loop system in which the by-products of production are reused as energy inputs. Another emerging possibility is the use of biogas production through anaerobic digestion of olive mill wastewater and organic residues. This process converts waste into methane-rich gas that can be used for heat or electricity generation. Although still at an early stage in Crete, such technologies have strong potential to enhance energy self-sufficiency while addressing environmental concerns related to waste disposal. The adoption of renewable energy in olive oil mills also aligns with broader environmental goals, including the reduction of greenhouse gas emissions and compliance with European sustainability policies. By decreasing reliance on fossil fuels, mills can significantly lower their carbon footprint and contribute to climate change mitigation efforts. Furthermore, renewable energy investments can improve the long-term economic resilience of producers by protecting them from fluctuating energy prices. However, challenges remain. The initial cost of installing renewable energy systems can be high, especially for small, family-run olive oil mills. Technical expertise, maintenance requirements, and regulatory frameworks may also pose barriers. Despite these obstacles, financial incentives, government support, and technological advancements are gradually making renewable energy solutions more accessible. Therefore, the integration of renewable energies in olive oil mills in Crete is not only feasible but highly beneficial. Solar-PV power, biomass utilization, and biogas production offer practical pathways toward more sustainable and efficient operations. As the industry evolves, embracing renewable energies will play a key role in ensuring both environmental protection and the long-term viability of olive oil production on the island. The use of renewable energies in olive oil mills in Crete is presented in Table 6.

Table 6. Use of renewable energies in olive oil mills in Crete

Energy source/fuel	Technology	Produced energy	Use	Current applications
Solar energy	Solar photovoltaic panels	Electricity	Lighting and powering several machines in the olive oil mill	Few
Olive kernel wood	Burning	Heat	Meeting all the heating needs in the olive oil mill	Yes
Waste water produced in the olive oil mill	Anaerobic digestion and cogeneration of heat and power	Electricity and heat	Meeting the needs of the olive oil mill -possibility of selling energy to several consumers and to the grid	No

Source: own estimations

7. ELIMINATION OF THE CARBON FOOTPRINT DUE TO ENERGY USE IN OLIVE OIL MILLS IN CRETE

For the estimation of the energy consumption in olive oil mills in Crete the following assumptions have been made.

a) Total olive oil production in Crete 100,000 tons/year,
b) Number of olive oil mills in Crete 500,
c) Average production in a typical olive oil mill 200 tons of olive oil per year
d) Average electricity consumption in an olive oil mill = 100 kWh_{el}/ton of olive oil produced,
e) Average annual electricity consumption in an olive oil mill 200 tons/year X 100 kWh_{el}/kg of olive oil per year = 20,000 kWh_{el}/year
f) Average heat consumption in an olive oil mill = 200 kWh_{th}/ton of olive oil produced,
g) Average annual heat consumption in an olive oil mill 200 tons/year X 200 kWh_{th}/ton = 40,000 kWh_{th}/year,

It is also assumed that the annual electricity demand will be covered with the installation of a grid connected solar-PV system with the existing net-billing regulations while the annual heat demand will be covered with the use of olive kernel wood as fuel. Additionally, it is assumed that the solar-PV panels in Crete generate 1,500 kWh/kW_p annually while the heating value of olive kernel wood is at 4.2 kWh/kg.

The size of the required solar-PV system in a typical olive oil mill is estimated at 20,000 (kWh/year)/1,500 (kWh/kW_p year) = 13.33 kW_p. The required quantity of olive kernel wood to cover the heat demand in an olive oil mill is estimated at 40,000 (kWh)/4.2 (kWh/kg) = 9,524 kg of olive kernel wood annually.

The total capacity of the required solar-PV systems to generate all the power required annually in the 500 existing olive oil mills in Crete is estimated at 13.33 kW_p X 500 = 6,665 kW_p. The total quantity of olive kernel wood to cover all the annual heat demand in all olive oil mills in Crete is 9,524 kg/year X 500 = 4,762 tons/year. The elimination of carbon emissions due to operational energy use in olive oil mills in Crete is presented in Table 7.

Table 7. Elimination of carbon emissions due to operational energy use in olive oil mills in Crete

Parameter	Value
Olive oil production	200 tons/year
Electricity consumption	20,000 kWh_{el}/year
Heat consumption	40,000 kWh_{th}/year
Total energy consumption	60,000 kWh/year
Nominal power a of solar-PV system meeting all the annual power demand in the olive oil mill	13.33 kW_p
Quantity of olive kernel wood required to meet all the annual heat demand in the olive oil mill	9,524 kg/year

Source: own estimations

8. DISCUSSION

The development of net-zero emission olive oil mills in the island of Crete, Greece using solar energy and solid biomass has been studied. The size of a solar-PV system which can generate the electricity that is used annually in olive oil mills has been estimated as well as the quantity of olive kernel wood, produced in olive pomace plants, that is required to meet the annual heat demand in mills. Olive groves, olive oil mills and olive pomace plants produce several olive-based residues, by-products and wastes which can be used for energy generation with various processes. Olive tree pruning, olive kernel wood, and liquid wastes produced in olive mills can be used for heat and power generation. Currently, olive tree pruning and olive kernel wood are extensively used in Crete for heat generation in buildings, in industry and in agricultural greenhouses. The size of a typical olive oil mill in Crete is small while the average size of olive groves in Crete is also small. This does not facilitate the use of their residues, by-products and wastes for energy generation with modern technologies. Our results indicate that deployment of net-zero emission olive oil mills in Crete can be easily achieved using solar energy and biomass taking into account that the required technologies are mature, reliable and cost-efficient. However, several existing barriers hinder their development. Our estimations are limited to an average size olive oil mill based on average heat and electricity consumption. Future research should be focused on accurate estimations based on the actual heat and power consumption in different size olive oil mills in Crete evaluating the cost and the profitability of using renewable energies for the elimination of their carbon footprint.

9. CONCLUSIONS

The renewable energies that can be used in olive oil mills in the island of Crete, Greece replacing the use of fossil fuels, zeroing their net-carbon emissions, have been estimated. The following conclusions have been drawn.

1. The average total energy consumption in olive oil mills varies in the range of 167-390 kWh per ton of produced olive oil,

2. Olive oil mills consume slightly more heat than electricity,
3. The annual olive oil production in Crete varies in the range of 80,000-120,000 tons olive oil per year,
4. There are approx. 550 olive oil mills operating in Crete,
5. Olive oil mills in Crete can utilize solar energy for power generation and solid biomass (olive kernel wood) for heat production,
6. Cultivation of olive trees and production of olive oil generates residues, by-products and wastes which can be used for heat and power generation with various technologies such as burning, gasification, CHP generation, anaerobic digestion et cetera, and
7. Elimination of carbon emissions due to operational energy use in a typical olive oil mill in Crete with capacity 200 tons olive oil per year can be achieved with the installation of a grid-connected solar-PV system with nominal capacity 13.33 kW_p and the use of 9,524 kg olive kernel wood annually.

Our work indicates that zeroing the carbon emissions during the operation of olive oil mills in Crete is technically feasible and economically attractive using local renewable energy resources. The required technologies are mature, reliable and cost-efficient.

REFERENCES

1. Garcia Martin, J.F., Cuevas, M., Feng, C-H., Mateos, P.A., Torres Garcia, M. & Sanchez, S. (2020). Energetic valorization of olive biomass: Olive tree pruning, olive stones and pomace, Processes, 8, 511. doi:10.3390/pr8050511
2. Romaniello R., Perone C., Berardi A., Leone A. & Tamborrino A. (2024). Biomass Recovery from Olive Oil Extraction Line: Opportunities for Reuse of By-products and Energy Saving, Chemical Engineering Transactions, 109, 25-30. DOI:10.3303/CET24109005
3. Sintori, A., Konstantidelli, V., Gouta, P. & Tzouramani, I. (2023). Profitability, Productivity, and Technical Efficiency of Cretan Olive Groves across Alternative Ecological Farm Types, Agriculture, 13, 2194. https://doi.org/10.3390/agriculture13122194
4. Skoulou, V., Zabaniotou, A., Stavropoulos, G., & Sakelaropoulos, G. (2008). Syngas production from olive tree cuttings and olive kernels in a downdraft fixed-bed gasifier. International Journal of Hydrogen Energy, 33(4), 1185-1194. https://doi.org/10.1016/j.ijhydene.2007.12.051
5. Alharbi, A. & Ghonimy, M. (2025). Environmental Benefits of Olive By-Products in Energy, Soil, and Sustainable Management, Sustainability, 17, 4722. https://doi.org/10.3390/su17104722
6. Di Mario, J., Ranucci, A., Gambelli, A.M., Rallini, M., Priolo, D., Brienza, M., Puglia, D., Del Buono, D. & Gigliotti, G. (2025). Biogas Production from Olive Oil Mill Byproducts: A Comparative Study of Two Treatments for Pursuing a Biorefinery Approach, Agriculture, 15, 2204. https://doi.org/10.3390/agriculture15212204
7. Aguado, R., Vera, D., Jurado, F. & Beltran, G. (2025). An integrated gasification plant for electric power generation from wet biomass: towards a sustainable production in the olive oil industry, Biomass Conversion and Biorefinery, 15, 29893-29912.https://doi.org/10.1007/s13399-021-02231-0
8. Vourdoubas, J. (2017). Possibilities of energy generation from olive tree residues, by-products and waste in Crete, Greece, Journal of Agricultural Studies, 5(4), 110-122. doi:10.5296/jas.v5i4.12114
9. Cappelletti, G.M., Iopollo, G., Nicoletti, G.M. & Russo, C. (2014). Energy requirement of extra virgin olive oil production, Sustainability, 6, 4966-4974. https://doi.org/10.3390/su6084966
10. Baptista, F., Silva, L.L., Murcho, D. Sagarna, J. et al. (2014). Energy efficiency in olive oil mills. Available from: https://www.researchgate.net/publication/303766686_Energy_efficiency_in_olive_oil_mills
11. Baptista, F., Silva, L.L., Murchio, D., Sagarna, J. et al. (2016). Energy efficiency in olive oil mills. Available from: https://www.researchgate.net/publication/303766686_Energy_efficiency_in_olive_oil_mills
12. Sanchez-Jimenez, J.L., Munoz-Rodriguez, F.J., Jimenez- Castillo, G., Martinez-Calahorro, A.J. & Rus-Casas, C. (2024). Analysis of Different Scenarios to Include PV Rooftop Systems with Battery Energy Storage Systems in Olive Mills, Energies, 17, 144. https://doi.org/10.3390/en17010144
13. Jimenez-Castillo, G., Munoz-Rodriguez, F.J., Martinez-Calaborro, A.J. et al. (2020). Impacts of array orientation and tilt angles for photovoltaic self-sufficiency and self-consumption indices in olive mills in Spain, Electronics, 9, 348. https://doi.org/10.3390/electronics9020348
14. Rabaza, O., Contreras-Montes, J., Espin-Estrella,A. & Gomez-Lopente, D. (2015). Model to maximize self-consumption of olive mills powered by a mixed system of renewable energies, International Conference on Renewable Energies and Power Quality, La Coruna, Spain, 25-27 March, 2015. Available from: https://icrepq.com/icrepq%2715/263-15-rabaza.pdf

15. Cinardi, G., D’ Urso, P.R. & Arcidiacono, C. (2025). Integrating Rooftop Grid-Connected Photovoltaic and Battery Systems to Reduce Environmental Impacts in Agro-Industrial Activities with a Focus on Extra Virgin Olive Oil Production, Clean Technology, 7, 91. https://doi.org/10.3390/ cleantechnol7040091
16. The first zero-impact olive mill to produce energy, 2016. Available from: https://www.oliveoiltimes.com/world/first-zero-impact-olive-mill-produce-energy/53172
17. Marquina, J., Colinet, M.J. & Del. P. Pablo-Romero, M. (2021). The economic value of olive sector biomass for thermal and electrical uses in Andalusia, Spain, Renewable and Sustainable Energy Reviews, 148, 111278. DOI: 10.1016/j.rser.2021.111278
18. Perone, C., Romaniello, R., Leone, A., Berardi, A. & Tamborrino, A. (2022). Towards energy efficient scheduling in the olive oil extraction industry: comparative assessment of energy consumption in two management models, Energy Conversion and Management X, 16, 100287. https://doi.org/10.1016/j.ecmx.2022.100287
19. Baptista, F., Silva, L.L. & Fitas da Cruz, V. (2023). Energy efficiency in the olive groves and in olive oil mills. Available from: https://dspace.uevora.pt/rdpc/bitstream/10174/35616/1/Paper_Expoliva2023_ENERGY%20EFFICIENCY%20IN%20THE%20OLIVE%20GROVES%20AND%20MILLS_VFinal.pdf
20. Vourdoubas, J. (2016). Possibilities of creating zero CO_2 emission olive pomace plants due to energy use in Crete, Greece, Open Journal of Energy Efficiency, 5, 78-87. DOI: 10.4236/ojee.2016.53008
21. Cini, E., Recchia, L., Daou, M. & Boncinelli, P. (2008). Human health benefits and energy saving in olive oil mills, International Conference “Innovation Technology to Empower Safety, Health and Welfare in Agriculture and Agrifood Systems”, September 15-17, 2008, Ragusa, Italy. Available from: https://www.academia.edu/127647586/Human_health_benefits_and_energy_saving_in_olive_oil_mills
22. Murcho, D., Baptista, F., Silva, L.L. & Silva, J.R. (2016). Best practices for improving energy efficiency in Olive Oil Mills. Available from: https://live-blog-jornada-tesla.chil.me/download-file/036fe5cd-2d96-4368-a446-45527aa5925a/
23. Genk, S., Bozcurt, E. & Yildirim, N. (2016). Zero energy olive oil production plant design by using waste valorization, in Heiselberg, P. K. (Ed.) (2016). CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3. Aalborg: Aalborg University, Department of Civil Engineering. Available from: https://www.researchgate.net/publication/310334892_Zero_Energy_Olive_Oil_Production_Plant_Design_by_Using_Waste_Valorisation
24. Nikolaidis A. Production and marketing of Cretan olive oil and wine. In: van der Ploeg J. (ed.). Strengthening endogenous development patterns in European agriculture. Chania : CIHEAM, 1993, p. 233-243 (Options Méditerranéennes: Série A. Séminaires Méditerranéens; n. 23).
25. Charalampopoulos, I., Droulia, F., Mavridi, A. & Roussos, P.A. (2025). Mapping the Climatic Suitability for Olive Groves in Greece, Agronomy, 15, 2604. https://doi.org/10.3390/agronomy15112604
26. Moran-Alarcon, L.C., Galan,-Martin, A., del Mar Contreras, M. & Castro, E. (2026). Recent advances and future perspectives in the valorization of olive biomass for sustainable biorefinery applications, Renewable and Sustainable Energy Reviews, 226, 116438. https://doi.org/10.1016/j.rser.2025.116438
27. Sánchez-Lozano, D., Escámez, A., Aguado, R., Oulbi, S., Hadria, R. & Vera, D. (2023). Techno-Economic Assessment of an Off-Grid Biomass Gasification CHP Plant for an Olive Oil Mill in the Region of Marrakech-Safi, Morocco, Applied Sciences, 13, 5965. https://doi.org/10.3390/app13105965
28. Polonio, D., Gomez-Limon, J.A., La Cal, J.A. & Villanueva A.J. (2024). The circular bioeconomy of the olive oil industry: Deterministic and probabilistic profitability of olive mill by-product gasification, Biomass and Bioenergy, 189, 107350. https://doi.org/10.1016/j.biombioe.2024.107350
29. Mouzakitis, Y. & Adamides, E.D. (2022). Techno-Economic Assessment of an Olive Mill Wastewater (OMWW) Biorefinery in the Context of Circular Bioeconomy, Eng, 3, 488–503. https://doi.org/10.3390/eng3040035