Engineering and Technology Journal e-ISSN: 2456-3358

Volume 11 Issue 04 April-2026, Page No.-9549-9558

DOI: 10.47191/etj/v11i04.28, I.F. – 8.595

Carbon Emissions Due to Wine Making in the Island of Crete, Greece

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ABSTRACT: Elimination of carbon emission is a priority for the achievement of net-zero emission societies in the coming decades. Winemaking is an old traditional industry in Crete interconnected with the local culture, history and economy. Estimation of the carbon emissions in winemaking in Crete has been conducted using data from existing literature. The possibility of using sustainable fuels and benign energy sources in winemaking industry in Crete has been also examined. The area of vineyards in Crete is 7,762 ha having a share at 12.05% in total Greek vineyards. Findings indicate that carbon emissions in the life cycle of winemaking are low. Vineyards in Crete can be used for power and heat generation installing agrivoltaics generating electricity and exploiting the pruning and residues of vines as solid fuel. It has been also indicated that several mature, reliable and cost-efficient renewable energy technologies can be used in winemaking plants reducing or eliminating their carbon footprint. Our results indicate that decarbonization of winemaking in Crete is technically and economically feasible while the barriers hindering the deployment of benign energy technologies in Cretan winemaking industry should be removed. Our findings could be useful to policy makers, local authorities and to all stakeholders of the Cretan wine industry.

KEYWORDS: Crete-Greece, energy consumption, net-zero emissions, solar energy, vineyard, wine

1. INTRODUCTION

Mitigation of climate change requires the decrease of fossil fuels use and their replacement with renewable energies and low carbon energy technologies in various sectors. Production of grapes and winemaking is an old tradition in Crete interwoven with the life of the people and the local agricultural economy. Currently the island hosts more than 7,500 ha of vineyards producing many commercial wines. The energy consumption [1], [2] and carbon emissions [3], [4], [5], [6] in vineyards and wineries have been studied extensively and the use of local renewable energies in them has been proposed. Agrivoltaics can be installed in vineyards [7], [8], [9] while their residues and pruning can be processed, standardized and used as solid biomass fuel [10], [11], [12]. Renewable energy technologies such as solar-PV, solar thermal, heat pumps and solid biomass burning can be used in wineries for heat and power generation replacing the use of fossil fuels [13], [14], [15]. Growth of vines sequestrate atmospheric CO_2 while the pomace of the winemaking process can be composted and used as an additive in vineyards.

The aim of the current work is the estimation of the carbon footprint in winemaking industry in the island of Crete, Greece and the exploration of low-carbon energy technologies which can be used in local wineries.

The text is structured as follows: After the literature review the vine cultivation in Crete and the wine production in the island are stated. Next, the existing wineries in the island and the energy consumption in vineyards and wineries are mentioned. After that, the carbon emissions in wineries in Crete are evaluated followed by a section mentioning the production of solid biomass fuel from residues and pruning in vineyards. In the following two sections the use of agrivoltaics in vineyards and the concept of net-zero emission wineries are stated while the text ends with discussion of the findings, the conclusions drawn and the citation of the references used.

The current research is innovative since there are not many studies in this field so far while it covers a gap regarding the carbon emissions in winemaking industry in Crete. The results could be useful to policy makers and to stakeholders of the winemaking industry in the island.

2. LITERATURE REVIEW

The energy efficiency in the winemaking industry has been studied [1]. The authors stated that electricity is the main energy source in winemaking having a share at around 90% in the total energy consumption. They mentioned that fermentation accounts for 45-90% in total energy consumption while bottling and storage contribute at around 18% of it. The energy use and the carbon footprint (CF) of wine and wine grapes in Turkey have been estimated [2]. The authors estimated the CF at 3.3 $kgCO_2e$ per 0.75 l of bottled wine. They stated that the highest contribution in the total CF was in electricity (49.2%) followed by growth of grapes (26.4%) and glass bottling (16.1%). The life-cycle carbon emissions of the Greek organic red wine have been assessed [3]. The authors stated that life cycle analysis (LCA) indicated that wine is a carbon emitter and its emissions are in the range of 0.69 - 1.14 $kgCO_2e$ per 0.75 l of bottled wine. They also mentioned that according to existing studies the carbon emissions in winemaking – from cradle to grave - in Mediterranean region are in the range of 0.79 to 1.70 CO_2e per 0.75 l of bottled organic red wine. The carbon emissions in winemaking industry have been examined [4]. The authors stated that the CF of wine is relatively low. They mentioned that the average CF of Australian wine varies in the range of 0.6 to 1.4 $kgCO_2e$ per liter. They also stated that CO_2 emissions during fermentation were not included in the evaluation of the CF of wine. They estimated that emissions in wineries contribute at 17% in the total CF while emissions in vineyards at 15%. The CF from the Italian wine sector analyzing data from 33 wines has been estimated [5]. The authors stated that the CF – from cradle to grave – were in the range of 0.899 to 1.882 $kgCO_2e$ per 0.75 l of bottled wine. They mentioned that the main contributors to GHG emissions were: a) glass bottle (29%), b) electricity (14%), c) transport and distribution of the final product (13%), d) heat used in the winery (9%), and e) fossil fuels used in the vineyard (8%). The CF in a winery located in northern Greece has been evaluated [6]. The authors stated that scope 3 carbon emissions have a share of 54% in the total CF followed by scope 1 emissions at 25% and scope 2 at 21%. They mentioned that vineyard's emissions had a share at 32% in total emissions while winery emissions at 68%. They also estimated that carbon sequestration during vines' growth corresponds at 52% of total emissions. The use of agrivoltaics in the wine industry has been examined [7]. The authors proposed the installation of a pilot solar photovoltaic (solar-PV) system in a vineyard stating that it has many benefits without disrupting the production of grapes. The social perspective of agrivoltaics systems in vineyards in south-eastern Spain has been evaluated [8]. The authors have explored the attitudes of wine tourists towards vertically integrated agrivoltaic systems in vineyards. The authors stated that tourists have positive perception regarding the use of agrivoltaics in vineyards. The benefits of agrivoltaic installations in vineyards in southern Spain have been analyzed [9]. The authors stated that installation of agrivoltaics in vineyards can influence the microclimate and enhance their resilience, improve the productivity per unit of area and offer an additional income to farmers. The use of vineyards' residues for the production of solid densified biomass fuel in the Republic of Moldova has been examined [10]. The authors estimated that about 1,013 kg/ha of waste biomass can be collected from vineyards with net calorific value of 15.6 MJ/kg. The value of winery residues has been assessed [11]. The authors stated that these residues can be used for the production of new products. They mentioned that innovative processes can be adopted in winery residues according to the biorefinery approach. An EU funded project [LIFE VINEYARDS4HEAT] regarding the use pf vineyard residues for heat generation has been implemented [12]. The pruning and residues of vineyards are collected and transported to biomass boilers for burning providing heat to wineries and to a local district heating system. The use of renewable energies in wineries and in agricultural machinery used in vineyards have been studied [13]. The authors proposed the installation of solar-PV systems combined with electric batteries in the winery and in the irrigation system as well as replacing the use of diesel fuel in agricultural machinery with green hydrogen. The solar-PV installations in American and European wineries have been explored [14]. The author stated that there are 184,300 wineries worldwide while only 293 have installed solar-PV systems. He mentioned that the average size of solar-PV systems installed in Californian wineries is 169.1 kW_p while in European wineries 77.8 kW_p. The use of solar energy in wineries has been examined [15]. The authors stated that solar energy can be used in wineries replacing the use of fossil fuels. They mentioned that among 101 solar wineries identified in Europe, 85% of them were using solar-PV systems, 11% were using combined solar-PV and solar-thermal systems while 4% of them were using only solar-thermal systems. The carbon emissions in the agricultural phase of wine production in Tuscany, Italy have been evaluated [16]. The authors estimated the CF of four wines in the range of 0.7 to 1.3 $kgCO_2e$ for a 0.75l of bottled wine. They stated that the agricultural phase has a share at 22% in the total CF while the glass bottle had the highest share in the overall CF. The energy flow, the GHG emissions and the biofuels' production in organic and conventional vineyards in northern Greece have been studied [17]. The authors stated that energy input and GHG emissions were significantly lower in organic vineyards while vine pruning were significantly higher in organic vineyards. The CF of indigenous and introduced grape varieties in Cyprus focusing on 90 vineyards has been estimated [18]. The authors stated that the CF was in the range of 0.283 to 0.846 $kgCO_2e$ per kg of grapes. They mentioned that the CF can be reduced by 40-67% by applying locally produced animal manure and by reducing tillage frequency. The use of vineyards' pruning residues as an energy source has been studied [19]. The authors stated that they can be used as a solid biomass fuel for heat generation instead of burning them in open space. They mentioned that vineyards' pruning residues can be used for production of wood chips while due to high ash content they are categorized as second quality fuel which is not suitable for domestic applications. The environmental impacts associated with vineyards and winemaking in a mountain winery in northern Spain have been assessed [20]. The authors estimated the CF of the wine at 2.34 $kgCO_2e$ per 0.75l bottled wine stating that the value is consistent with the values reported in literature (0.2 to 2.5 $kgCO_2e$ per 0.75l of bottled wine). They mentioned that 40% reduction in the CF can be achieved by reusing part of the wine bottles and by composting the organic wastes. The development of net-zero emission olive oil mills in Crete, Greece has been studied [21]. The author stated that an olive oil mill with annual production capacity 200 tons olive oil can eliminate all its net-carbon emissions with the installation of a solar-PV system with nominal power 13.33 kW_p generating the power demand and using 9,524 kg/year olive kernel wood for heat generation. The decarbonization of the cheese making industry in Crete, Greece has been studied [22]. The author stated that a small-size cheese making plant with annual production capacity 120 tons cheese can eliminate all its net-carbon emissions with the installation of a solar-PV system with nominal power 88 kW_p and consuming 62.86 tons olive kernel wood annually for heat generation. The energy production from residues and wastes of vineyards and winemaking in Sicily, Italy has been examined [23]. The authors stated that the largest Sicilian winery has launched a project to construct a 1-MW electricity generation plant that uses the residues in vineyards as well as the pomaces and wastes from the winemaking process to cogenerate heat and power. The environmental sustainability in vineyards installing solar-PV systems in Spain has been explored [24]. The authors used questionnaires to examine to opinion of the local community about the installation of agrivoltaics in vineyards. Around one third of the responders did not approve the use of agrivoltaics in vineyards while the rest wanted the preservation of the landscape quality in vineyards after the installation of agrivoltaics. The energy use and the carbon emissions in Cretan vineyards have been assessed [25]. The authors used data from thirty vineyards in Crete to develop a digital decision support tool calculating the energy use and the GHG emissions in vineyards. The reuse of CO_2 produced in alcoholic fermentation has been studied [26]. The authors stated that CO_2 emission rates were in the range of 0.20 to 1.68 gCO_2 per liter per hour among different grape varieties. They mentioned that CO_2 capture in wineries does not require major modifications in the plant. The capture of CO_2 from fermentation of grape must has been examined [27]. The authors stated that the fermentation gas is naturally enriched with aromatic substances and it can be used for the production of carbonated beverages. The installation of solar-PV panels on vineyards to improve the wine quality has been reported [28]. It is stated that agrivoltaic systems improve the water stress in the plants, protect the grapes in extreme weather events, reduce the water consumption, improve the land yield and produce an additional income. The carbon footprint in a mature vineyard has been evaluated [29]. The authors stated that the main emissions in the vineyard were attributed to soil management and the consumption of fuel in the machinery while the vineyard was potentially able to offset carbon emissions. They estimated that carbon emissions in vineyards at 0.39 $kgCO_2e$ per kg of grapes. Table 1 indicates the carbon emissions in vineyards and wineries in several countries.

Table 1. Carbon emissions in vineyards and wineries in several countries

Authors/year	Life cycle carbon emissions in wineries ($kgCO_2e$ per 0.75l bottled wine)	Comments
Bosco et al, 2011	0.7-1.3	Tuscany, Italy
Tsalidis et al, 2025	0.69-1.14	Organic red wine, Greece
Tsalidis et al, 2025	0.79-1.70	Mediterranean region
Guner et al, 2026	3.3	Turkey
D’Amaro et al, 2021	0.899-1.882	Italy
Laca et al, 2021	2.34	Northern Spain
Abbott et al, 2019	0.45-1.05	Australia
	Carbon emissions in vineyards ($kgCO_2e$ per kg of grapes)	
Marras et al, 2015	0.39	Sardinia, Italy
Litskas et al, 2017	0.283-0.846	Cyprus

Source: several authors

3. VINE CULTIVATION IN CRETE

Vine cultivation in Crete is one of the oldest and most significant agricultural traditions on the island, deeply intertwined with its history, culture, and economy. With a winemaking heritage that dates back over 4,000 years to the Minoan civilization, Crete stands as one of the oldest wine-producing regions in Europe. The island’s unique geography and climate create ideal conditions for viticulture, allowing both indigenous and international grape varieties to thrive. Vineyards are often located at varying altitudes, from sea level up to over 800 meters, which contributes to a wide range of microclimates. The Mediterranean climate, with its long, hot summers and mild winters, is particularly favorable for grape growing. One of the most distinctive aspects of Cretan viticulture is its emphasis on indigenous grape varieties. White grapes such as Vidiano, Vilana, and Dafni are widely cultivated and produce aromatic, fresh wines with unique character. Red varieties like Kotsifali and Mandilaria are also prominent, often blended to create balanced wines with rich flavors and aging potential. The main vine variety cultivated in Crete is Liatiko having a share at 33.2% in the wine making vineyards in 2020 in Crete (www.statistics.gr). Traditional vine cultivation methods still play an important role in Crete, although modern techniques have also been adopted to improve quality and efficiency. Economically, vine cultivation is a vital sector for Crete. It supports thousands of local families and contributes significantly to the island's agricultural output. Therefore, vine cultivation in Crete is more than just an agricultural activity; it is a living tradition that reflects the island's history, environment, and way of life. Table 2 indicates the area of vineyards producing wine in Crete.

Table 2. Area of vineyards producing wine in Crete, Greece

	2020	2015
Area of vineyards producing wine in Crete	7,762 ha	7,750 ha
%, Crete/Greece	12.05%	12.25%

Source: www.statistics.gr

4. PRODUCTION OF WINE IN CRETE

Wine production in Crete is a dynamic and historically rich process that reflects the island's long-standing relationship with viticulture. The process begins with the careful cultivation and harvesting of grapes, which typically takes place from late August to early October. Growers monitor the ripeness of the grapes closely, ensuring the right balance of sugar, acidity, and flavor before picking. Once collected, the grapes are transported quickly to wineries to begin the transformation into wine. At the winery, the grapes are sorted and crushed to extract their juice. Fermentation is a crucial stage in wine production, during which natural or cultured yeasts convert sugars into alcohol. Temperature control during this phase is essential, as it influences the wine's final character. After fermentation, the wine may undergo aging, depending on the desired style. Some wines are aged in stainless steel tanks to maintain their fresh and fruity profile, while others are matured in oak barrels to gain complexity, structure, and subtle notes such as vanilla or spice. Blending is another important step, particularly in Crete, where winemakers often combine different grape varieties to achieve balance and harmony. Indigenous grapes such as Vidiano, Vilana, Kotsifali and Mandilaria are frequently used, either on their own or in blends, to produce wines that express the island's identity. Modern technology has significantly improved the consistency and quality of wine production in Crete. Finally, the wine is filtered, bottled, and distributed both locally and internationally. Today, Cretan wines are gaining recognition worldwide for their quality and uniqueness. Each stage of the process contributes to the creation of wines that not only showcase the island's natural resources but also tell the story of its rich cultural heritage. Assuming that the average production of wine in Greece is around 2,000,000 hl (www.statista.com) and that Cretan vineyards correspond at 12.05% of vineyards in Greece (www.statistics.gr) the average annual production of wine in Crete is estimated at around 250,000 hl.

5. WINERIES IN CRETE

Crete is one of the most important wine-producing regions in Greece, combining a long historical tradition with a rapidly developing modern industry. Today, the island hosts approximately 38–45 organized wineries, a number that has grown significantly over the past two decades as small, quality-focused producers have emerged alongside older cooperative structures. In terms of size, Crete possesses one of the largest vineyard areas in the country. The island's vineyards cover roughly 7,000–8,000 hectares, representing about 11–15% of Greece's total vineyard surface**.** Annual production is around 25,000 hectoliters of wine, confirming Crete's significant contribution—around 12%—to national output. Despite this, vineyard ownership is highly fragmented: thousands of small growers cultivate plots often smaller than a few hectares, while only a limited number of wineries operate at larger commercial scales. Most viticultural activity is concentrated in the northern and eastern parts of Crete, where climatic conditions—such as cooling sea winds and moderate rainfall—favor grape cultivation. The region of Heraklion forms the core of wine production, with extensive vineyard areas, while important secondary zones include Chania**,** Rethymno**,** and Lasithi**.** These areas correspond to the island's main Protected Designation of Origin (PDO) zones, such as Peza, Dafnes, and Sitia. Overall, the Cretan wine sector is characterized by a large but fragmented vineyard base**,** a moderate number of mostly small-to-medium wineries, and a geographical concentration in the northern belt of the island.

6. ENERGY CONSUMPTION IN VINEYARDS AND WINERIES IN CRETE

Energy consumption in vineyards and winemaking in Crete is an increasingly important topic, as the island balances its long viticultural tradition with modern sustainability challenges. In Cretan vineyards, energy consumption is largely linked to field operations and water management. Tractors and agricultural machinery used for pruning, soil cultivation, and harvesting typically rely on diesel fuel, contributing to greenhouse gas emissions. Due to hot, dry summers and limited rainfall during the growing season, many vineyards depend on irrigation systems that require energy for water pumping and distribution. This demand can be especially high in low-altitude or coastal areas where drought conditions are more intense. However, traditional practices in Crete can help reduce energy use. Additionally, there is a growing shift toward sustainable viticulture, including organic farming, cover cropping, and the use of renewable energy sources such as solar-powered pumps. In the winemaking stage, energy consumption becomes more concentrated within winery facilities. One of the most energy-intensive processes in Crete is temperature control during fermentation. Given the island's high summer temperatures, wineries must use cooling systems to maintain stable fermentation conditions, ensuring the preservation of aromas and overall wine quality. Refrigeration is also essential during storage, particularly for white and rosé wines, which are sensitive to heat. Other processes, such as grape crushing, pressing, pumping, filtration, and bottling, also require electricity. Cleaning and sterilization of equipment, essential for maintaining hygiene standards, further add to energy demand. Importantly, renewable energy is playing a growing role in reducing the environmental footprint of winemaking in Crete. Solar energy, in particular, is highly suitable due to the island's abundant sunshine. Many wineries are installing solar photovoltaic panels to power their operations, while others are improving insulation and adopting heat recovery systems to minimize waste. Solar thermal systems can generate the low-enthalpy heat that is also required in them while boilers powered by biomass can generate steam. Table 3 indicates the energy and fuels used in wineries in different regions while Table 4 the distribution of solar wineries per country in Europe.

Table 3. Energy and fuels used in wineries in different regions (%)

Fuel/energy source	California	New Zealand	Germany	South Australia
Electricity	50	73	23	34
LPG	21	4		
Gasoline	10			
Diesel oil	19	5	32	
Natural gas		18	9	
Transport fuels				56
Stationary fuels				10
Heating oil			36	
Total	100	100	100	100

Source: [15]

Table 4. Distribution of solar wineries per country in Europe

Country	%, Solar wineries
Germany	45
France	11
Switzerland	1
UK	1
Italy	25
Spain	8
Israel	2
Portugal	1
Austria	5
Greece	1
Total	100

Source: [15]

7. CARBON EMISSIONS IN WINEMAKING IN CRETE

Carbon emissions in winemaking in Crete have become an important concern as the island's wine industry seeks to align its traditional practices with modern environmental standards. A significant portion of carbon emissions in Cretan winemaking originates in the vineyard. The use of diesel-powered machinery for plowing, spraying, and harvesting contributes directly to greenhouse gas emissions. In addition, irrigation—often necessary due to Crete’s hot, dry summers—requires energy for pumping water, which can further increase emissions, especially when powered by non-renewable energy sources. The production and transport of fertilizers and pesticides also add indirect emissions, although many Cretan producers are reducing these inputs through organic and low-intervention farming practices. Within the winery, energy use is a major contributor to carbon emissions. Temperature control during fermentation is particularly energy-intensive, as cooling systems must operate continuously in the island’s warm climate to maintain optimal conditions. Refrigeration during storage, as well as electricity used for crushing, pressing, pumping, and bottling, further increases the carbon footprint. Packaging and transportation are also key factors. Glass bottle production is energy-intensive and generates significant carbon emissions. Heavier bottles, often used for premium wines, further increase emissions during transport. Since many Cretan wines are exported to international markets, shipping—especially by road and sea—adds another layer of carbon output.

Assuming that the average life cycle carbon emissions in bottled wine produced in Crete are 1.2 $kgCO_2e$ per 0.75l of bottled wine (Table 1) or 1.6 $kgCO_2e$ per l of bottled wine, the total annual carbon emissions in Crete are 25,000,000 l/year X 1.6 $kgCO_2e/l$ = 40,000,000 $kgCO_2e$/year or 40,000 $tnCO_2e$ per year. Assuming the all the wine produced in Crete is bottled and taking into account that the population in Crete is 624,408 residents (census 2021) the life cycle carbon emission per capita of winemaking in Crete is 40,000 $tnCO_2e$/year / 624,408 residents = 0.064 $tnCO_2e$ per capita per year. This can be compared with the total carbon emissions per capita in Greece in 2023 at 4.46 $tonsCO_2$ (www.iea.org). Table 5 indicates the life cycle carbon emissions in winemaking in Crete, Greece.

Table 5. Life cycle carbon emissions in winemaking in Crete, Greece

Parameter	Value
Vineyards’ area in Crete (2020)	7,762 ha
Annual production of wine in Crete	25,000,000 l/year
Average life cycle carbon emissions in wine making	1.6 $kgCO_2e$ per l of bottled wine
Annual life cycle carbon emissions from wine making in Crete (assuming that all the wine produced is bottled)	40,000 $tnCO_2e$ per year
Annual life cycle carbon emissions from wine making per capita in Crete	0.064 $tnCO_2e$ per capita
%, Annual life cycle carbon emissions from wine making per capita in Crete per total carbon emissions per capita in Greece	1.43%

Source: own estimations

8. PRODUCTION OF SOLID BIOMASS FUELS FROM VINEYARDS’ RESIDUES AND PRUNING

The utilization of vineyard residues for the production of solid biomass fuels represents a promising and sustainable approach to agricultural waste management. Vineyards generate significant quantities of organic residues each year, primarily from pruning, harvesting, and vine replacement. Converting these residues into solid biomass fuels offers both environmental and economic benefits. One of the main types of vineyard residues used for energy production is pruning waste. This material can be collected, dried, and processed into solid fuels such as pellets or briquettes. These fuels have a relatively high calorific value and can be used for heating in households, greenhouses, or even small-scale industrial applications. These products are easy to store, transport, and use, making them a practical alternative to conventional fossil fuels. In addition to pruning residues, grape pomace—the solid remains of grapes after pressing—can also contribute to biomass fuel production, although it is more commonly used for composting or extracting valuable compounds. By utilizing vineyard residues, farmers can reduce the need for open-field burning, thereby lowering greenhouse gas emissions and improving air quality. Moreover, biomass fuels are considered carbon-neutral, as the carbon dioxide released during combustion is offset by the carbon absorbed by the plants during their growth cycle. This contributes to a more sustainable energy system. Economically, the production of solid biomass fuels can provide an additional source of income for vineyard owners and rural communities. It can also reduce energy costs, particularly in regions where heating demands are high. Therefore, transforming vineyard residues into solid biomass fuels is an effective way to promote sustainability in agriculture.

9. USE OF AGRIVOLTAICS IN VINEYARDS

Agrivoltaics—the combined use of land for both agriculture and solar energy production—is emerging as an innovative solution in vineyard management. By installing elevated or semi-transparent photovoltaic panels above grapevines, farmers can simultaneously produce renewable energy while maintaining agricultural output. This dual-use approach is particularly relevant in viticulture, where climate change poses increasing challenges such as heatwaves, drought, and excessive sun exposure. Solar panels provide partial shading, which can protect grape clusters from sunburn and reduce water stress. This is especially valuable in warm regions, where excessive heat can accelerate ripening and negatively affect grape quality. By moderating temperature and reducing evapotranspiration, agrivoltaic systems can help preserve acidity and improve the balance of sugars and phenolic compounds in the grapes. At the same time, vineyards equipped with solar panels can generate significant amounts of electricity, contributing to farm income and sustainability goals. Panel height, spacing, and orientation must ensure sufficient sunlight reaches the vines, as too much shading could reduce yields. Despite its promise, agrivoltaics in vineyards is still in an experimental phase in many regions. Initial investment costs and technical complexity remain barriers. Nevertheless, as technology advances and climate pressures intensify, agrivoltaics offers a promising pathway toward more resilient and sustainable viticulture while the generated solar electricity can offset the grid electricity used in wineries.

10. NET-ZERO EMISSION WINERIES: A SUSTAINABLE FUTURE FOR WINEMAKING

The global wine industry faces growing pressure to address climate change, as viticulture is highly sensitive to shifts in temperature, water availability, and soil health. In response, net-zero emission wineries are emerging as a sustainable solution, aiming to balance carbon emissions with removals and drastically reduce their environmental footprint. The use of solar energy in wineries in Crete is favorable since winemaking is taking place in September when the solar irradiance in the island is high. Benign energy sources and technologies can eliminate scope 1 and scope 2 emissions in wineries. Sustainable vineyard practices—like cover cropping, reduced tillage, and organic fertilization—enhance soil carbon sequestration while protecting biodiversity. Transportation and packaging innovations also contribute. Lightweight bottles, recycled materials, and local distribution networks minimize emissions from logistics. Some wineries are exploring carbon-neutral shipping methods, including electric vehicles and optimized routing. Beyond environmental benefits, net-zero emission wineries offer economic and marketing advantages. Additionally, energy efficiency and resource optimization can lower operating costs over time. By integrating energy saving, renewable energy, sustainable vineyard practices, and efficient logistics, these wineries not only mitigate climate change but also set a benchmark for responsible production in the global wine sector. Their rise marks a critical step toward a more resilient and eco-conscious future for winemaking. Table 6 indicates several low-carbon energy technologies which can be used in vineyards and wineries replacing fossil fuels, and grid electricity used in vineyards, wineries and transportation of final products.

Table 6. Low-carbon energy technologies and fuels that can be used in vineyards and wineries

Sector	Technology	Low/zero-carbon energy source or fuel
Vineyards	Solar-PV systems	Production of electricity
Vineyards	Use of residues for solid biofuel production	Production of solid biomass fuels
Vineyards	Machineries using biofuels	Use of bioethanol and biodiesel
Winery	Use of solar-thermal systems	Production and use of heat
Winery	Use of solar-PV systems	Production and use of electricity
Winery	Use of solid biomass	Production and use of heat
Winery	Use of heat pumps	Production and use of heat and cooling
Transportation of wine	Electric vehicles	Use of green electricity
Transportation of wine	Vehicles using biofuels	Use of bioethanol and biodiesel

Source: own estimations

11. DISCUSSION

The life cycle carbon emissions of winemaking in the island of Crete, Greece have been estimated and the renewable energy technologies which can be used in vineyards and in wineries have been mentioned. The life cycle carbon emissions in winemaking are not high while they can be partly or completely eliminated with the use of alternative energy sources and fuels in vineyards, wineries and in wine transportation. Solar photovoltaic systems can be used in vineyards (agrivoltaics) and in wineries while mixture of residues and pruning in vineyards can be used for heat generation. Solar thermal energy can be used in wineries for heat production, solid biomass boilers for steam production and heat pumps for heat and cooling production. Several solar wineries have been reported in literature while the abundant solar energy in Crete during August, September and October can be utilized in the local winemaking industry. The abovementioned sustainable energy technologies are broadly used in Crete in various sectors. Our work implies that the concept of net-zero emission wineries can be realized in Crete using mature, reliable and cost-efficient benign energy sources and technologies. Taking into account that the main energy sources used in wineries are electricity and heat at low temperatures the use of local renewable energy sources can meet all their energy demand. Our study has several limitations. Carbon emission data for vineyards and wineries from published literature have been used in the present study that might be different from the actual emissions in winemaking industry in Crete. The estimation of the wine produced in Crete is also based on some assumptions and the actual production might be slightly different. Evaluation of the life cycle carbon emissions in winemaking in Crete is based on the assumption that all the wine produced in Crete is bottled which is not real. Additionally, the limited existing data are referred in different years (area of vineyards in Crete in 2000, population in Crete in 2021, carbon emissions per capita in Greece in 2023) which affect the accuracy of the results. Future work should be focused on energy analysis of a medium-size winery operating in Crete estimating its actual carbon emissions. Additionally, on the design of a medium-size winery with net-zero carbon emissions due to operating energy use in the island.

12. CONCLUSIONS

Estimation of the carbon footprint of winemaking industry in the island of Crete, Greece and the exploration of the low-carbon energy technologies which can be used in local wineries have been conducted. The main conclusions include:

a) The cultivated area of vineyards in Crete in 2020 was 7,762 ha corresponding at 12.05% of Greece's area of vineyards,

b) The annual wine production in Crete is estimated at 250,000 hl,

c) The annual life cycle carbon emissions from wine making in Crete (assuming that all the wine produced is bottled) is 40,000 $tnCO_2e$ per year or 0.064 $tnCO_2e$ per capita,

d) The vineyards in Crete can be used for electricity generation with installation of agrivoltaics and heat production using the residues and pruning of vines,

e) Several renewable energies and low-carbon energy technologies can be used in Cretan wineries such as: solar-PV systems, solar thermal systems, solid biomass burning and heat pumps. These technologies are mature, reliable and cost-efficient while they are currently used in many sectors in the island, and

f) Net-zero carbon wineries in Crete can be easily achieved in Crete using several sustainable energy technologies.

Therefore, the barriers hindering the development of sustainable energies in the local winemaking industry should be removed facilitating its decarbonization.

REFERENCES

1. De Castro, M., Baptista, J., Matos, Ch., Valente, A. & Briga-Sa, A. (2024). Energy efficiency in wine making industry: Challenges and opportunities, Science of The Total Environment, 930, 172383. https://doi.org/10.1016/j.scitotenv.2024.172383
2. Guner, V. & Candemir, S. (2026). Energy use and carbon footprint of wine and wine grapes, Applied Fruit Science, 68, 15. https://doi.org/10.1007/s10341-025-01728-6
3. Tsalidis, G.A., Kryona, Z.-P., Hatzisavva, K., Korevaar, G. & Rapsomanikis, S. (2025). Carbon Assessment of Greek Organic Red Wine with Life Cycle Assessment and Planetary Boundaries, Sustainability, 17, 3006. https://doi.org/10.3390/su17073006
4. Abbot, T. & Wilkes, E. (2026). Understanding carbon emissions in the wine industry. Available from: https://www.awri.com.au/wp-content/uploads/2025/12/s2083.pdf
5. D' Amaro, D., Capri, E., Valentino, F., Grillo, S., Fiorini, E. & Lamastra, S. (2021). Benchmarking of carbon footprint data from the Italian wine sector: A comprehensive and extended analysis, Science of The Total Environment, 779, 146416. https://doi.org/10.1016/j.scitotenv.2021.146416
6. Karalis, D. & Kanakoudis, V. (2023). Carbon footprint of products and services: The case of winery in Greece, Science of The Total Environment, 878, 162317. https://doi.org/10.1016/j.scitotenv.2023.162317
7. Lauer, F., Rudiger Kaufmann, H., Muller, W., Schafer, T., Sold, S., Sonnik, S. & Radle, M. (2025). Agrivoltaics in the wine industry. URBAN INNOVATION: TO BOLDLY GO WHERE NO CITIES HAVE GONE BEFORE. Medium sized cities and towns as a major arena of global urbanization. Proceedings of REAL CORP 2025, 30th International Conference on Urban Development, Regional Planning and Information Society. pp. 97-107. ISSN 2521-3938. DOI: 10.48494/REALCORP2025.1117

8. Arias-Navarro, I., Miras-Cabrera, B., Toledo, C., Agulo-Torres, A.M. et al. (2026). Assessing the social perception of agrivoltaics systems in vineyards. A case study of an integrated trellis-based configuration in south-eastern Spain, Renewable Energy Focus, 57, 100812. https://doi.org/10.1016/j.ref.2026.100812
9. Solar, A.F., Hanrieder, N., Kujawa, A., Rodriguez, S.G., Landes, M. et al. (2026). Benefits of an agrivoltaics installation in an ecological vineyard in southern Spain. Available from: https://elib.dlr.de/216934/1/EUPVSEC_Laujar_4DO.4_2.pdf
10. Marian, G., Alexiou Ivanova, T., Gudima, A., Nazar, B., Malai, L., Marian, T. & Pavlenco, A. (2024). Biomass Resources from Vineyard Residues for the Production of Densified Solid Biofuels in the Republic of Moldova, Agronomy, 14, 2183. https://doi.org/10.3390/agronomy14102183
11. Rodrigues, R.P., Gando-Ferreira, L.M. & Quina, M.J. (2022). Increasing Value of Winery Residues through Integrated Biorefinery Processes: A Review, Molecules, 27, 4709. https://doi.org/10.3390/molecules27154709
12. Vineyards for carbon footprint reduction: a sustainable strategy to use biomass for heat & cold in wineries. Reference: LIFE13 ENV/ES/000776 | Acronym: LIFE VINEYARDS4HEAT (V4H), Available from: https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE13-ENV-ES-000776/vineyards-for-carbon-footprint-reduction-a-sustainable-strategy-to-use-biomass-for-heat-cold-in-wineries
13. Carroquino, J., Garcia-Casarejos, N. & Gargallo, P. (2017). Introducing renewable energy in vineyards and agricultural machinery: A way to reduce emissions and provide sustainability, Wine Studies, 6, 6975. doi:10.4081/ws.2017.6975
14. Smyth, M. (2012). Solar photovoltaic installations in American and European winemaking facilities, Journal of Cleaner Production, 31, 22-29. https://doi.org/10.1016/j.jclepro.2012.02.019
15. Jia, T., Dai, Y. & Wang, R. (2018). Refining energy sources in winemaking industry by using solar energy as alternatives for fossil fuels: A review and perspective, Renewable and Sustainable Energy Reviews, 88, 278-296. https://doi.org/10.1016/j.rser.2018.02.008
16. Bosco, S., Di Bene, C., Galli, M., Remorini, D., Massai, R. & Bonari, E. (2011). Greenhouse gas emissions in the agricultural phase of wine production in Maremma rural district in Tuscany, Italy, Italian Journal of Agronomy, 6, e15. doi:10.4081/ija.2011.e15
17. Kavargiris, S.E., Mamolos, A.P., Tsatrarelis, A., Nikolaidou, A.E. & Kalburtji, K.L. (2009). Energy resources' utilization in organic and conventional vineyards: Energy flow, greenhouse gas emissions and biofuel production, Biomass and Bioenergy, 33, 1239-1250. doi:10.1016/j.biombioe.2009.05.006
18. Litskas, D.V., Irakleous, Th., Tzortzakis, N. & Stavrinides, C.M. (2017). Determining the carbon footprint of indigenous and introduced grape varieties through life cycle assessment using the island of Cyprus as a case study, Journal of Cleaner Production, 156, 418-425. DOI: 10.1016/j.jclepro.2017.04.057
19. Giorio, C., Rizzini, S., Marchiori, E., Piazza, R. et al. (2019). Sustainability of using vineyard pruning residues as an energy source: combustion performances and environmental impact, Fuel, 243, 371-380. https://doi.org/10.1016/j.fuel.2019.01.128
20. Laca, A., Gancedo, S., Laca, A. & Diaz, M. (2021). Assessment of the environmental impacts associated with vineyards and wine making. A case study in mountain areas, Environmental Science and Pollution Research, 28, 1204-1223. https://doi.org/10.1007/s11356-020-10567-9
21. Vourdoubas, J. (2026). Development of net-zero emission olive oil mills in the island of Crete, Greece, Engineering and Technology Journal, 11(4), 9374-9382. DOI: 10.47191/etj/v11i04.07
22. Vourdoubas, J. (2026). Decarbonization of the cheese making industry in the island of Crete, Greece, International Journal of Current Science Research and Review, 9(4), 1813-1913. DOI: 10.47191/ijcsrr/V9-i4-13
23. Corona, G. & Nikoletti, G. (2010). Renewable energy from the production residues of vineyards and wine: evaluation of a business case, New Medit, 4, 41-47. Available from: https://sebina.iamb.it/sebina/repository/catalogazione/immagini/pdf/41Corona.pdf
24. Arias-Navarro, I., Del Campo-Gomis, F.J., Agulló-Torres, A.M. & Martinez-Poveda, Á. (2023). Environmental Sustainability in Vineyards under a Protected Designation of Origin in View of the Implementation of Photovoltaic Solar Energy Plants, Land, 12, 1871. https://doi.org/10.3390/land12101871
25. Pilafidis, S., Kosmas, E., Livieratos, I. & Gkisakis, V.D. (2023). Assessing energy use and greenhouse gas emissions in Cretan vineyards for the development of a crop-specific decision support tool, Environment, Development and Sustainability: A Multidisciplinary

Approach to the Theory and Practice of Sustainable Development, 26(9), 24415-24452. DOI: 10.1007/s10668-023-03649-4

26. Gueddari, A., Alonso-Moreno, C., Canales-Varquez, J. & Garcia-Yuste, S. (2025). Evaluating the integration of biogenic CO_2 from alcoholic fermentation in carbon dioxide (CDU) strategies: A comprehensive review, Journal of CO2 Utilization, 96, 103094. https://doi.org/10.1016/j.jcou.2025.103094
27. Prusova, B., Humaj, J., Kulhankova, M., Kumsta, M., Sochor, J. & Baron, M. (2023). Capture of Fermentation Gas from Fermentation of Grape Must, Foods, 12, 574. https://doi.org/10.3390/foods12030574
28. Photovoltaic solar panels on vineyards to improve wine quality. Available from: https://www.clustercollaboration.eu/content/photovoltaic-solar-panels-vineyards-improve-wine-quality
29. Marras, S., Masia, S., Duce, P., Spano, D. & Sirca, C. (2015). Carbon footprint assessment on a mature vineyard, Agricultural and Forest Meteorology, 214-215, 350-356. https://doi.org/10.1016/j.agrformet.2015.08.270
30. www.statistcs.gr
31. www.statista.com
32. www.iea.org