Leveraging Artificial Intelligence to Manage a Sustainable Transition In Viticulture "STIV"

MODULE 3: Green and energy transition in viticulture

This module explores key sustainability strategies in viticulture, from regenerative soil management and water efficiency, to biodiversity conservation and responsible energy use. Innovative technologies and agroecological practices that reduce the environmental footprint and increase the resilience of vineyards to climate change are analyzed. The aim is to understand how green practices become an essential pillar for competitive, sustainable viticulture aligned with the European Green Deal.

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Content

1. Green Practices in Viticulture: Fundamentals and Strategies

The transition to sustainable viticulture requires a comprehensive vision that encompasses all components of the production ecosystem. The vineyard, as an agroecosystem, depends on soil health, efficient water use, biodiversity conservation and responsible energy management. These four interconnected pillars make it possible to reduce the environmental impact of winemaking, increase resilience to climate change and guarantee the quality of wine in the long term.

1.1. Sustainable Soil Management in Viticulture

Sustainable soil management is one of the fundamental pillars in the green transition of viticulture. The soil is not only the physical support of the vine, but also a living ecosystem that regulates fertility, the water cycle, microbial biodiversity and the resilience of the crop to the impacts of climate change (Bavaresco et al., 2016). In this context, conventional practices based on intensive tillage, excessive use of chemical fertilizers and synthetic herbicides have demonstrated negative effects such as soil compaction, loss of organic matter and decrease in biodiversity (Morlat & Symoneaux, 2008). Faced with this scenario, there is a need to implement regenerative and sustainable strategies that optimize soil health and strengthen wine ecosystems.

Importance of soil health in viticulture

Soil acts as a reservoir of nutrients and water, regulates gas exchange, and hosts microorganisms essential for mineralization and nutrient availability (Tautges et al., 2019). Recent studies have shown that soil degradation in wine-growing regions, caused by over-tillage and loss of organic matter, reduces the soil's ability to retain water, increasing the vulnerability of vineyards to drought (Van Leeuwen et al., 2019). In addition, its physical structure directly influences the vigour of the vine, the quality of the grapes and, consequently, the sensory profile of the wine (Bordelon et al., 2020).

Green roofs: an essential practice

The implementation of vegetation covers in the vineyard is one of the most effective strategies for improving soil health. Permanent or temporary covers reduce water erosion, improve water infiltration and contribute to carbon fixation, mitigating climate change (Celette et al., 2008). They also promote the increase of organic matter and microbial activity, key elements for soil fertility (Abad et al., 2021).

For example, in Mediterranean vineyards, the planting of leguminous species (clover, vetch) as green cover has shown significant increases in the available nitrogen content, reducing dependence on synthetic fertilizers (Ruiz-Colmenero et al., 2013). In addition, the covers favor functional biodiversity, offering habitats for auxiliary insects that contribute to the biological control of pests (Garcia et al., 2018).

Figure 1. Vegetation cover in vineyard. *Source: La Rioja Alta*

Reduced tillage and minimal handling

Intensive tillage causes the breakage of soil aggregates, loss of porosity and decrease in organic matter, accelerating erosion processes (Prosdocimi et al., 2016). In contrast, reduced or no-tillage practices have been consolidated as sustainable alternatives that preserve the soil structure, improve infiltration, and reduce carbon loss (Novara et al., 2019).

A study in vineyards in Alto Monferrato (Italy) showed that the combination of vegetation cover with reduced tillage significantly decreased runoff and soil erosion, as well as improved aggregate stability and infiltration compared to bare soils (Biddoccu et al., 2016). Coincidentally, recent reviews highlight that the use of herbaceous covers in vineyards can reduce soil losses by between 30% and 70%, depending on the species used and climatic conditions (Abad et al., 2021; SARE, 2022). Likewise, synthesis work in

Europe has confirmed that minimum tillage not only contributes to preserving the soil structure, but also reduces energy consumption and emissions from the use of agricultural machinery (López-Vicente et al., 2020).

Increasing organic matter and use of biofertilizers

The incorporation of compost and biofertilizers is a key tool for the regeneration of degraded soils. The incorporation of wine residues such as pomace and lees into composting can improve compost properties, such as physical structure and humidity, contributing to the recycling of nutrients in the vineyard (Arqueros et al., 2023). Soil organic matter is also associated with a greater cation exchange capacity, better water retention in the field, and promotion of the beneficial microbiota (Ismail, 2025; Lal, 2020; Ankenbauer & Loheide, 2016)

Various studies have shown that the incorporation of compost from winery waste improves soil organic matter, increases its water retention capacity and stimulates beneficial microbial activity, thus favouring the fertility and resilience of the agroecosystem (Lucchetta et al., 2025; Moral et al., 2016). Although the quantitative effects vary according to the region, type of compost and frequency of application, the evidence points to significant increases in organic carbon and soil microbial biomass after several application campaigns.

Figure 2. Use of wine bagasse for biofertilizers.

Practices to Improve Water Retention

In a context of extreme weather events and reduced water availability, increasing the soil's capacity to retain water is essential. The use of vegetation covers in vineyards improves soil structure, increases its porosity and promotes better water infiltration and retention (Morlat & Jacquet, 2003). Likewise, the application of organic mulching – such as straw or plant remains – helps to conserve surface moisture by reducing evaporation and improving the capacity of available water, especially in semi-desert Mediterranean agricultural ecosystems (Hueso-González et al., 2016; Wikipedia, n.d.).

Examples and certifications

Numerous wineries have implemented these practices under certifications such as **"Sustainable Winegrowing"** (California) or **"HVE – Haute Valeur Environnementale"** (France), which promote sustainable soil management strategies. In Spain, projects such as **"Viñas Vivas"** have demonstrated 40% reductions in the use of herbicides thanks to the implementation of vegetation cover and biofertilization (MAPA, 2022).

1.2. Water Use Efficiency and Irrigation Technologies in Sustainable Viticulture

Water is one of the most limiting resources in viticulture, especially in Mediterranean regions where rainfall is irregular and heat waves are becoming more frequent due to climate change (Ollas et al., 2019). In this context, efficiency in the use of water not only represents an agronomic requirement, but also an ethical and regulatory obligation to guarantee the sustainability of the vineyard (Jones et al., 2010). Efficient water management involves applying water in the right quantity, at the right time and in the right area, avoiding losses due to evaporation, deep percolation or runoff (Allen et al., 1998).

Figure 3. Drip irrigation system. *Source: Lena Ti*

Importance of Sustainable Water Management

The vine is a plant considered moderately drought tolerant, but severe water stress during stages such as flowering and fruit set can severely reduce yield and fruit quality

(Medrano et al., 2015). However, controlled water deficit has been shown to improve parameters such as anthocyanin concentration and colour intensity in wine (Intrigliolo & Castel, 2011). In addition, the adoption of smart irrigation systems that combine techniques such as regulated deficit irrigation (RDI), sensors, modeling, and remote technologies, is gaining ground in areas with limited water resources, improving water management and water use efficiency (Mirás-Avalos et al., 2021).

Key Technologies for Water Efficiency

a) Drip and Subsurface Irrigation

Drip irrigation is the most widespread technique in modern viticulture due to its high efficiency in bringing water directly to the root zone and minimising losses due to evaporation, percolation and runoff. In countries such as Spain, especially in areas with little rainfall such as Castilla La Mancha, drip irrigation is widely adopted. In addition, subsurface irrigation (SDI) or variants such as direct root zone irrigation are demonstrating further improvements in water use efficiency and yield; for example, the study "Optimization of Vineyard Water Management: Challenges, Strategies, and Perspectives" conducted in 2021 reported increases of 9–12% in production and 9–11% in water efficiency compared to surface irrigation

b) Humidity and Water Potential Sensors

The incorporation of soil moisture sensors, such as tensiometric, capacitive or temporal domain reflectometry (TDR), allows us to know the volumetric content of water in real time and improve the programming of irrigation in crops. Recent studies highlight that the integration of these tools in water balance models helps to optimize water use, avoiding excesses and reducing losses due to percolation or runoff (Jones, 2004).

In addition, physiological technologies such as sap flow sensors provide direct information on the plant's water demand. These systems allow early detection of stress situations before reductions in photosynthesis or yield occur, offering a more accurate basis for decision-making in irrigation management (Kumar, 2022; Jones, 2004).

Figure 4. Sap flow sensor. Source: Agronic

c) Water Balance and DSS Models

The use of models such as FAO-56 forms the basis for estimating the evapotranspiration of vineyards, by integrating climatic parameters (ET_0), crop coefficients and water stress factors (Allen et al., 1998). Advanced models such as AquaCrop have proven their usefulness in viticulture: in table vineyards in Mexico, the model recommended irrigation volumes approximately 50% lower than those traditionally applied

by farmers, which resulted in an improvement of close to 45% in water productivity (Er-Raki, 2024).

In a complementary way, water balance tools such as SIMDualKc, based on the double crop coefficient, have made it possible to accurately estimate evapotranspiration in rainfed vineyards by combining climate data with information on the water balance in the soil, showing a high degree of adjustment with real observations (Almeida et al., 2024).

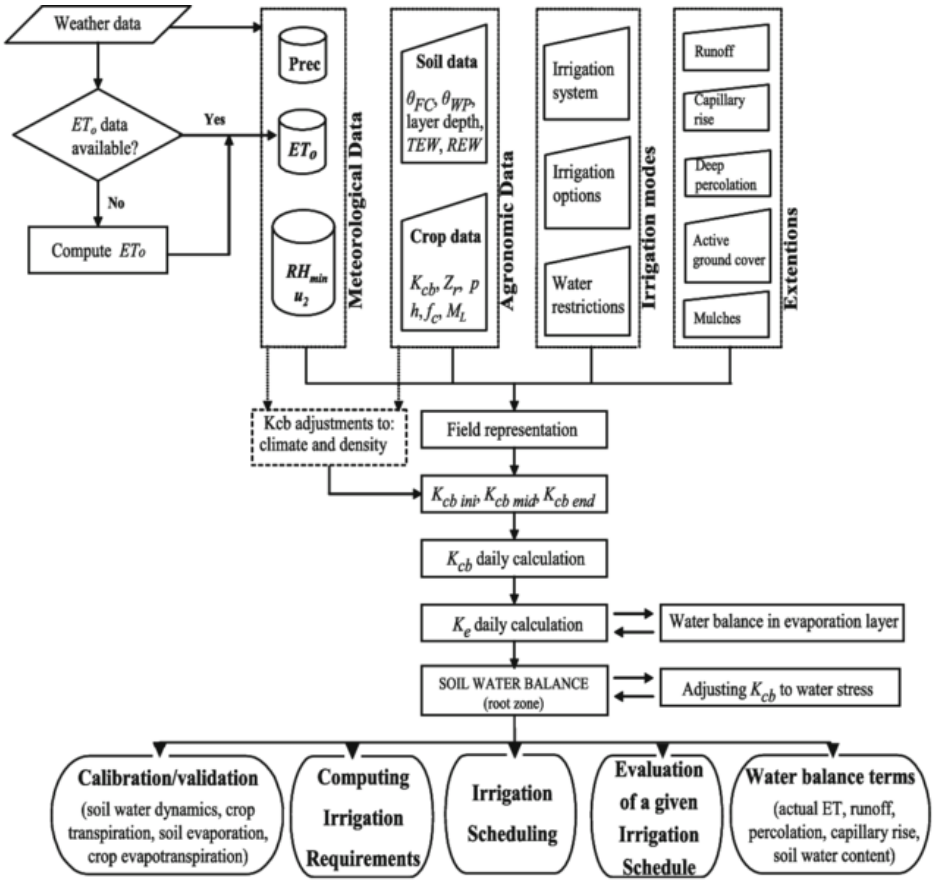

Figure 5. SIMDualKc Model FlowchartSource: Paço et al. 2011

d) Precision Irrigation with IoT Technology

The Internet of Things (IoT) has revolutionized irrigation management in viticulture through digital platforms that integrate humidity sensors, weather stations, and automated valves. An example is CropX, which allows irrigation management from a mobile app and valves to be activated remotely thanks to integration with irrigation controllers (CropX, 2023a; CropX, 2023b). In regions with limited connectivity, low-power network protocols such as LoRaWAN and NB-IoT are essential, offering long range, low power consumption,

and reliable transmission in rural environments (Promwad, 2025; Singh et al., 2020; Semtech, 2025).

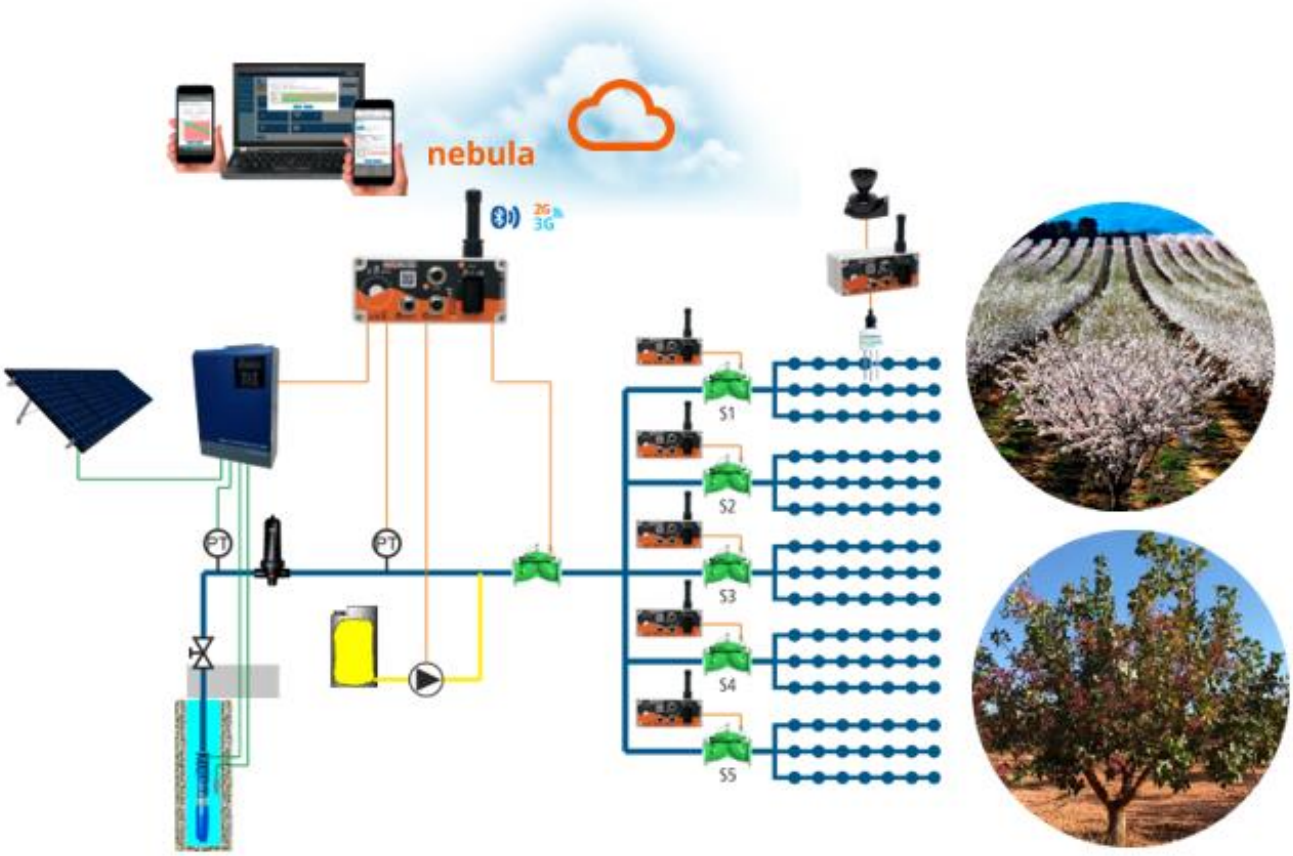

Figure 6. Precision irrigation with IoT. Source: Orionis Smart Water Network

Complementary Agronomic Strategies

In addition to smart irrigation, soil management is key to the water conservation of the vineyard. Groundcovers help reduce evaporation, increase infiltration, and improve water availability in the soil profile (Celette, Gaudin, & Gary, 2008). Likewise, the selection of drought-tolerant rootstocks is an effective strategy to increase the resilience of the vineyard to water scarcity (Gambetta, Herrera, Dayer, Hochberg, & Castellarin, 2020).

Proven Benefits and Economic Return

Water savings in vineyards not only reduce direct costs, but also contribute to energy sustainability, given that mechanized irrigation and pumping are large consumers of energy (GESTI, 2025). In addition, there is evidence that implementing smart irrigation systems, such as continuous monitoring and automation, can significantly reduce water and energy consumption, with reported savings of between 20% and 50% depending on the crop (FreshPlaza, 2022).

On the other hand, as mentioned above, controlled water stress has positive effects on wine quality, by improving the concentration of phenolic components and the aromatic complexity that characterize high-end wines (Van Leeuwen & Darriet, 2016).

Implementation Examples

- **California:** E&J Gallo **reported** savings in water consumption after implementing humidity sensors and DSS linked to drip irrigation (Gallo Winery, 2021).
- **Australia:** Pilot projects with **IoT and telemetry** managed to reduce water consumption by 1,000 m^3/ha without compromising production, combining water balance and controlled deficit irrigation (SmartAqua Project, 2020).
- **Spain (Ribera del Duero):** The **WANUGRAPE 4.0** system integrated NDVI maps, soil sensors, and automated irrigation, achieving 30% water savings and a 20% reduction in energy costs (WANUGRAPE, 2023).

1.3. Biodiversity Management in the Vineyard

Biodiversity is a fundamental pillar in sustainable wine systems. Maintaining high biological diversity in the vineyard not only contributes to ecosystem health, but also improves resilience to pests, diseases, and extreme weather events (Altieri & Nicholls, 2017). Functional biodiversity favours ecological balance, reduces dependence on agrochemicals and promotes essential ecosystem services such as pollination, biological control and improved soil fertility (Bàrberi et al., 2010).

Figure 7. Prevention of pests through the use of ladybugs on vines. *Source: Familia Torres, 2020*

Importance of Biodiversity in Viticulture

Intensive monocultures in viticulture have led to the simplification of agroecosystems, reducing biodiversity and increasing the vulnerability of the vineyard to pests and diseases (Altieri & Nicholls, 2002). On the contrary, the adoption of structural diversification strategies, such as the incorporation of trees, hedgerows, or green roofs, contributes to reducing the incidence of pests, reducing the use of agrochemicals, and promoting the delivery of key ecosystem services (Favor et al., 2023).

Strategies to Increase Biodiversity

a) Vegetation Covers

Permanent or temporary green covers are a key practice to promote biodiversity. These herbaceous species, implanted between the rows, increase floristic diversity, harbor natural enemies of pests, and improve soil structure (Celette et al., 2009). In addition, they contribute to reducing erosion, increasing water infiltration and improving organic fertility. For example, studies in vineyards in Languedoc-Roussillon showed that the presence of grass and legume covers reduced the population of thrips and mites by 30% compared to bare soils (Ripoche et al., 2011).

b) Ecological Corridors and Hedges

The establishment of perimeter hedges and green corridors connects the vineyard with natural habitats, creating refuges for birds, pollinators and beneficial arthropods (Bàrberi et al., 2010). In Tuscany, the incorporation of hedges of native species in organic vineyards increased the presence of natural parasitoids of Lobesia botrana, reducing the use of insecticides (Gurr et al., 2017).

c) Integration of Polycultures and Refuge Areas

The combination of vineyards with olive groves, orchards or small patches of natural vegetation generates an agroecological mosaic that enhances biodiversity. This strategy, known as integrated viticulture, is promoted by the OIV (International Organization of Vine and Wine) as a model of transition towards resilient systems (OIV, 2020).

d) Conservation of Auxiliary Fauna

Species such as lacewings, ladybugs, and spiders are natural predators that help control pests. Reducing the use of broad-spectrum insecticides and promoting refuges for these organisms are essential to keep their population stable (García et al., 2018). In Bordeaux, the implementation of nest boxes for insectivorous birds reduced the pressure of the cluster moth (Lobesia botrana) by 50% in organic vineyards (Maison & Filaine, 2021).

Benefits of Biodiversity in the Vineyard

1. **Natural biological control:** Less dependence on plant protection products.
2. **Improved soil health:** Increased organic matter and water retention capacity.
3. **Erosion reduction:** Groundcovers protect against soil loss from runoff.
4. **Climate resilience:** Biodiverse vineyards are better able to withstand heat waves and droughts (Altieri & Nicholls, 2017).
5. **Added value and marketing:** Certifications such as *the Biodiversity & Wine Initiative* or regenerative viticulture labels are valued by consumers (Stolz et al., 2011).

Figure 8. Organic wine certificates. Source: piece-meal

Challenges in Implementation

The incorporation of measures to promote biodiversity in the vineyard represents a key strategy towards a more sustainable and resilient viticulture. However, its implementation is not without difficulties. The challenges cover both economic and technical aspects as well as social and cultural aspects, reflecting the complexity of integrating ecological criteria in a sector traditionally oriented towards oenological production and quality. These factors are compounded by climate uncertainty, lack of adequate support structures, and market constraints, which can slow down the widespread adoption of these practices. Identifying and understanding these challenges is essential to offer solutions adapted to each wine-growing territory.

- **High initial cost:** The installation of hedges, floral strips or green roofs involves a significant economic investment, both in materials and labour. In addition, the ecological and productive benefits derived from these measures usually manifest themselves in the medium or long term, which can generate reluctance in winegrowers who work with tight margins or who are looking for quick returns. In

many cases, lack of access to economic incentives or support programs exacerbates this obstacle.

- **Agronomic conflicts:** The introduction of vegetation cover can compete with the vine for water and nutrients, especially in regions with dry climates or in less fertile soils. Poor species selection or improper management (e.g. not mowing in time or not adjusting densities) can increase pressure on the vineyard, reduce yield or even favour the emergence of pests and diseases. This requires careful technical handling and planning adapted to each plot.

- **Lack of technical knowledge:** The successful implementation of biodiversity promotion practices requires training in agroecology, functional ecology, and integrated pest and soil management techniques. Many workers and field managers lack the necessary training, which increases the risk of errors in the planning and maintenance of these measures. The lack of specialist wine-growing advisers also limits access to practical and tailored guidance.

- **Social and cultural acceptance:** In traditional wine-growing regions, there may be resistance to modifying practices that have been maintained for generations. The perception that a vineyard "with herbs" or with "uncultivated areas" is poorly maintained can lead to tensions within the local community, making it difficult to adopt more biodiverse approaches.

- **Regulatory and certification constraints:** Although the agricultural policies of the European Union or other regulatory frameworks provide incentives for sustainable practices, the associated bureaucracy and lack of clarity in requirements can discourage producers. In addition, some certification schemes may not adequately recognize the benefits of these measures, reducing the motivation to adopt them.

- **Complex monitoring and evaluation:** Measuring the real impact of biodiversity management measures on the vineyard is not easy. It requires monitoring tools, biodiversity indicators and, in many cases, collaboration with research institutions. Without this monitoring, it is difficult to justify the costs and efforts invested or communicate the benefits to consumers and regulatory bodies.

- **Climate risks and interannual variability:** Factors such as prolonged droughts, heavy rainfall or sudden changes in temperature can make it difficult to implement and maintain hedges or roofs. In climate change scenarios, these uncertainties increase, raising doubts about the long-term viability of certain measures.

- **Market and limited demand:** Although more and more consumers value sustainability and respect for biodiversity, they are not always willing to pay a premium price for wines produced under these principles. This disconnect between productive effort and recognition in the market can discourage initial investment.

Examples of Successful Implementation

Despite the challenges it may present in various communities, the potential of biodiversity management in vineyards is demonstrated in several success stories at the international level:

- **France (Champagne)** The systematic introduction of vegetation covers, hedgerows and green corridors in the Champagne region led to a 40% reduction in the use of herbicides over a period of 5 years (Comité Champagne, 2022). In addition to the environmental benefits, this strategy strengthened the image of the denomination as a benchmark in sustainability, generating added value in international markets.

- **Spain (Ribera del Duero):** The Viñas con Vida project established biodiversity refuges, including insect hotels, nest boxes for insectivorous birds and planting of honey species. As a result, a notable increase in the presence of pollinators and a strengthening of ecosystem services were observed in the participating vineyards. Thanks to these measures, several wineries in the area obtained the Wildlife Friendly Alliance (WFA) certification, which was a differentiating element in the market.

- **South Africa** The Biodiversity and Wine Initiative (BWI) is one of the pioneering programs worldwide. Through agreements between producers and conservation organizations, more than 112,000 hectares of natural habitats adjacent to vineyards have been protected (BWI, 2021). This strategy not only conserved endemic species of flora and fauna, but also generated a sustainability narrative that positioned South African wines in a global market that is increasingly sensitive to environmental issues.

- **Italy (Tuscany and Sicily)** Several wineries have opted for agroforestry projects in vineyards, integrating trees and shrubs between plots to promote pollination and regulate the microclimate. These mixed systems have shown improvements in water retention, erosion reduction and greater landscape attractiveness, also benefiting wine tourism.

- **Chile (Colchagua Valley)** In collaboration with environmental NGOs, some vineyards have established biological corridors that connect areas of fragmented native forest. This has favoured the presence of wildlife such as foxes and birds of prey, while contributing to the reduction of pests in the vineyard through natural biological control.

1.4. Sustainable Use of Energy in Vineyards

The efficient and sustainable use of energy in viticulture is an essential component to reduce the sector's carbon footprint and move towards a low-emission economy. The energy is used in various stages of the production cycle, from soil tillage, irrigation and

phytosanitary protection, to harvesting operations and transport to the winery. According to the *International Organisation of Vine and Wine* (OIV, 2021), energy consumption in conventional viticulture can account for up to 25% of operating costs, mainly due to the use of fossil fuels in agricultural machinery and electricity for pumping and irrigation systems.

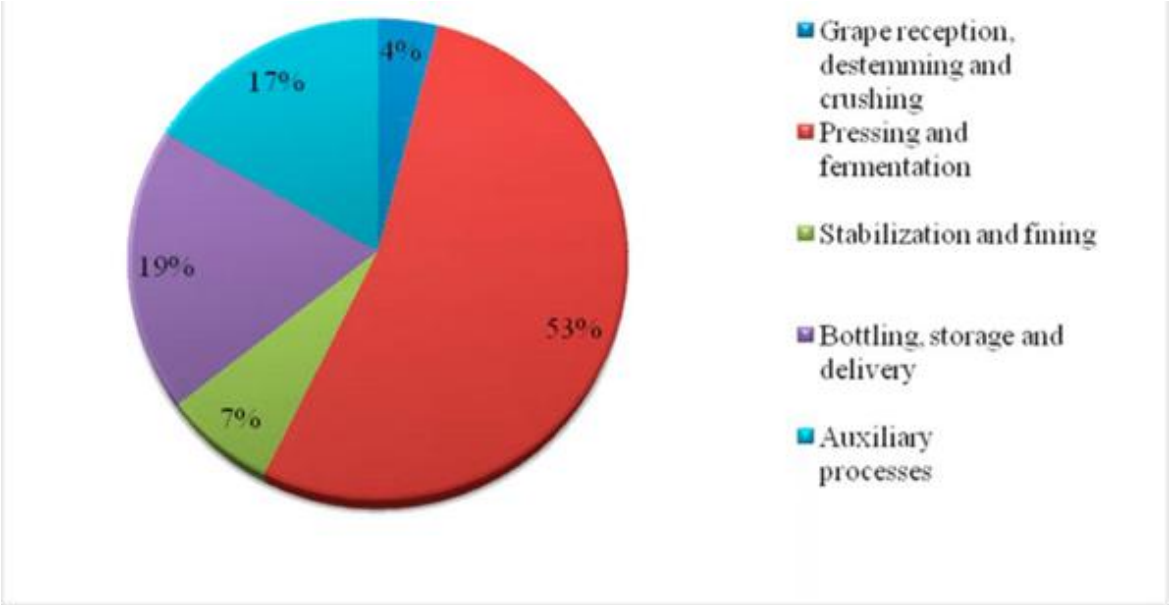

Figure 9. Distribution of energy consumption in wine production in an Italian winery. Source: Malvoni et al. 2017

Strategic Importance of Energy Saving in Viticulture

The current context of climate change, energy crisis and decarbonisation policies (Paris Agreement, European Green Deal) forces wine farms to optimise their energy consumption, incorporating renewable sources and efficiency technologies (European Commission, 2020). The concept of *climate neutrality* in viticulture is increasingly present, especially in designations of origin that promote sustainability seals such as *International Wineries for Climate Action* (IWCA, 2022).

Energy efficiency in viticulture is a priority objective, as consumption in irrigation and vineyard management can account for a significant part of operating costs and emissions. Life cycle assessment (LCA) studies have shown that most of the carbon footprint comes from phases such as bottling, cellar energy, and packaging materials, rather than from the crop itself (Pattara et al., 2012).

The adoption of sustainable practices and the deployment of eco-innovative technologies contribute to improving operational sustainability and responding to consumer demands aware of climate change (Brito et al., 2024).

Main Strategies for Sustainable Energy Use

a) Energy Audits and Consumption Monitoring

Before implementing measures, it is essential to know the energy profile of the vineyard. The audits make it possible to identify critical points of consumption, such as pumping for irrigation, air conditioning in facilities or the use of tractors. Tools such as **EnergyCheck Viticulture** or **Intelligent Rural Energy** make it possible to monitor consumption in real time, facilitating decision-making (FAO, 2020).

b) Efficiency in Agricultural Machinery

Using more efficient and well-maintained machinery is a basic practice. Replacing diesel tractors with hybrid or electric tractors, such as the New Holland T4 Electric Power model, can reduce direct emissions by up to 90% and fuel costs by 50% (New Holland, 2022). In addition, GPS guidance systems and precision agriculture reduce unnecessary journeys, optimizing consumption (Matese & Di Gennaro, 2015).

c) Irrigation Optimization

Irrigation accounts for 40% to 60% of the vineyard's energy consumption (Allen et al., 1998). Technologies such as variable frequency drives in pumps, soil moisture sensors, and the integration of solar energy for photovoltaic pumping are key. In Spain, the Solarwine project managed to reduce the energy cost of pumping by 70% by installing solar panels in wine cooperatives (IDAE, 2021).

d) Incorporation of Renewable Energies

The installation of photovoltaic systems is the most widespread option. Vineyards in La Rioja and Bordeaux have implemented solar roofs in warehouses and light structures on rows, generating energy for pumping and sensorization systems. In windy regions, complementary wind energy is also used to power weather stations and monitoring systems (Bindi & Olesen, 2011).

e) Energy Recovery and Storage

The use of storage batteries and hybrid systems ensures continuity of supply in rural areas with limited connectivity. In addition, microgrids have been implemented that connect several farms, reducing the unit cost of renewable energy (Kamilaris et al., 2017).

f) Digitalisation and Smart Energy Management

The concept of smart vineyards also applies to energy consumption. IoT platforms such as **VitiEnergy** integrate sensor data, weather predictions, and optimization algorithms to automatically trigger irrigation, lighting, and winery processes at times of lower energy cost (Wolfert et al., 2017). This allows demand to be shifted to off-peak periods and minimises consumption peaks.

Benefits of Energy Efficiency in Vineyards

- **Reduction of operating costs:** The implementation of energy efficiency measures – such as the modernisation of irrigation systems, the replacement of luminaires with LED technology or the incorporation of renewable energies – can lead to savings of between 20% and 40% in the total energy consumption of a vineyard and its associated winery. These savings are particularly significant in regions where

electricity accounts for a significant part of production costs, and allow economic resources to be freed up that can be reinvested in innovation, oenological quality or environmental management.

- **Lower carbon footprint:** Reducing fossil fuel consumption and optimizing efficiency in key processes (irrigation, pumping, refrigeration, internal transport) allows greenhouse gas emissions to be significantly reduced. This not only contributes to compliance with increasingly stringent environmental regulations, but also facilitates the obtaining of sustainable certifications (IWCA, WFA, etc.), which have become a strategic value in sustainability-sensitive international markets.

- **Energy resilience:** Diversifying energy sources by incorporating solar, wind, or biomass reduces dependence on fossil fuels and global energy market fluctuations. In a context of volatility in energy prices, having their own facilities allows vineyards to shield themselves against unexpected increases and guarantee the continuity of operations, even in energy crisis scenarios.

- **Added value in marketing:** Energy efficiency not only generates internal benefits, but can also be communicated as part of the brand identity. Concepts such as carbon neutral wine or net zero winery offer a clear differentiating factor in an increasingly competitive market. For the conscious consumer, a wine produced with a low energy impact conveys a tangible commitment to the environment, which increases its attractiveness and can justify a higher perceived value.

Challenges for the Energy Transition in Vineyards

- **High initial investment:** The installation of photovoltaic systems, micro wind turbines or storage batteries requires considerable CAPEX, especially in medium-sized or small vineyards, where profit margins are tight. Although profitability is achieved in the medium and long term, the initial outlay can be a barrier for producers without access to credit or specific financing.

- **Maintenance and technological updating:** Renewable generation and energy efficiency technologies require regular checks, spare parts and software updates. In rural areas, where specialized technical support is limited, these tasks can lead to downtime or additional costs. In addition, rapid technological advancement means that equipment installed just 10 years ago is already less efficient or lacks adequate technical support.

- **Lack of clear incentives:** Although there is aid under the CAP, European programmes (Horizon Europe, LIFE) or national energy transition initiatives, access to it is often conditioned by complex bureaucracy, long deadlines and technical requirements that are difficult to meet. This discourages the participation of small and medium-sized producers, who often lack administrative personnel to manage requests.

- **Knowledge gap:** The digitalization and automation of energy systems (sensors, management software, smart panels) require a level of technical training that is not always present in vineyard work teams. Without specific training, there is a risk of inefficient or even incorrect use of technologies, reducing the expected benefits. The lack of training programs adapted to the wine sector continues to be a challenge to be overcome.

Examples of Successful Implementation

- **Familia Torres (Spain):** This winery has made a firm commitment to the energy transition, installing photovoltaic systems that cover around 25% of its electricity demand and investing in electric tractors to progressively replace its combustion fleet. Thanks to these measures, it achieved a 30% reduction in its total CO_2 emissions (IWCA, 2022). In addition, it has combined these actions with carbon capture projects through reforestation and soil regeneration.

Figure 10. Photovoltaic installations of the Torres Family. *Source: Familia Torres*

- **Jackson Family Wines (USA):** Headquartered in California, this company implemented an ambitious renewable energy plan that includes micro wind turbines, solar pumps, and energy storage. As a result, it achieved annual savings of more than 2 million kWh, strengthening its resilience to droughts and frequent power outages in the region (Sustainable Winegrowing Alliance, 2021). His model has been replicated as a benchmark in American viticulture.

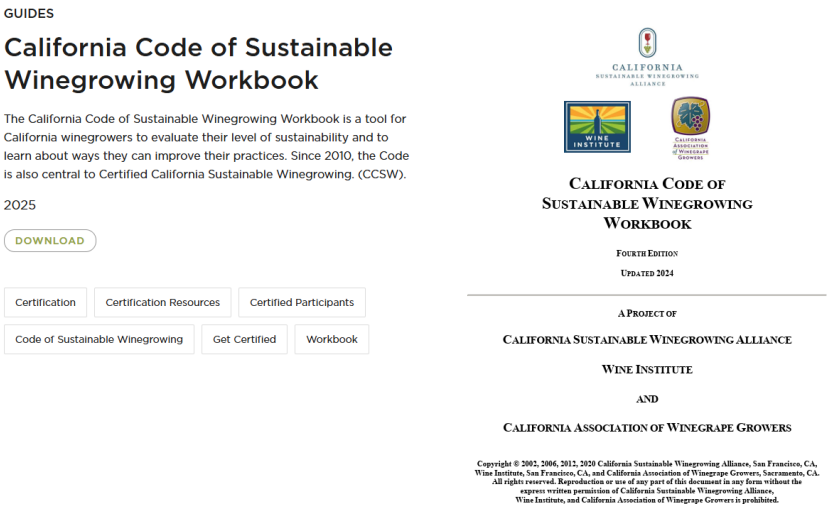

Figure 11. California Sustainable Viticulture Code Manual. Source: California Sustainable Winegrowing Alliance

- **Château Smith Haut Lafitte (France):** This Bordeaux winery adopted an exemplary sustainable approach, combining biodiversity, circular economy and energy efficiency. The estate pioneered capturing the CO_2 released during fermentation and reusing it to produce baking soda, a unique innovation in the wine world, as part of a low-energy underground cell known as the "Stealth Cellar." In addition, this project also incorporates elements such as solar energy, geothermal heat exchange, rainwater harvesting, and local materials to maintain a stable temperature without the need for intensive mechanical cooling systems. The initiative goes beyond energy efficiency: it favors a circular economy model, in which agricultural waste and by-products from the winery are used in multiple ways. For example, for the production of beauty products, reinforcing a sustainable model on the farm.

Figure 12. CO2 collector for fermentation processes.Source: Château Smith Haut Lafitte

1.4. Valorisation of Pruning Residues and Vineyard Biomass

The management of pruning residues and woody biomass generated in vineyards represents a strategic component of the transition toward more circular, climate-resilient production systems. Traditionally, grapevine prunings and other woody residues have been removed from the field or burned on-site. These practices generate direct greenhouse gas emissions, particulate pollution, and the loss of potentially valuable organic resources.

Within sustainable viticulture frameworks, these materials are increasingly recognised as strategic inputs capable of enhancing soil fertility, increasing water retention capacity, and contributing to long-term carbon sequestration. This shift in perspective — from waste disposal to resource management — positions the winegrower as an active steward of biogeochemical cycles within the farm system.

The European Commission and the FAO have highlighted the increase of soil organic carbon as one of the most effective measures for improving soil health and climate adaptation (European Commission, 2021; FAO, 2017). In this context, reintegrating vineyard biomass into the soil represents a practice with high environmental and agronomic potential.

From Waste to Resource: Circular Economy Principles in the Vineyard

The valorisation of pruning residues is grounded in the principles of circular economy applied to agriculture: closing nutrient loops within the farm. Instead of relying exclusively on external mineral fertilisers, vineyards can reuse part of the biomass generated annually to maintain or improve soil physical, chemical, and biological properties.

Scientific literature shows that agricultural systems incorporating organic residues tend to progressively increase soil organic carbon levels, improving soil structure and aggregate stability (Lal, 2004; FAO, 2017). In Mediterranean regions, where soils often have low organic matter content and are highly vulnerable to erosion, this practice is particularly relevant.

From an economic perspective, internal reuse of biomass reduces dependency on external inputs and strengthens the environmental image of the winery — an increasingly important factor in international markets and sustainability certification schemes.

Figure 14. Adhesion of pruning debris to the ground

Main Valorisation Pathways

The practical implementation of biomass reuse can follow different approaches depending on soil conditions, climate, available machinery, and production goals.

- **Shredding and Direct Incorporation:** Pruning residues are mechanically shredded and distributed across the soil surface or lightly incorporated. This accelerates decomposition and contributes to humus formation. Mediterranean viticulture studies have shown increases in soil organic carbon and improvements in structural stability under systematic shredding practices (Martínez-Casasnovas et al., 2012).

- **Composting:** Composting stabilises organic material and produces a more homogeneous soil amendment. It reduces sanitary risks and allows better control of the carbon-to-nitrogen balance, preventing temporary nitrogen immobilisation (FAO, 2017).

- **Mulching or Surface Cover:** Shredded biomass left on the surface acts as protective mulch, reducing evaporation, suppressing weeds, and protecting soil from water erosion. This is particularly effective in sloped vineyards prone to runoff.

- **Biochar Production:** Through pyrolysis, woody residues can be transformed into biochar — a highly stable carbon material capable of remaining in soil for decades. Biochar improves soil structure and water retention and has significant carbon sequestration potential (Woolf et al., 2010). While it requires technological investment, its long-term climate mitigation capacity is considerable.

Observed Agronomic Benefits

European and Mediterranean research consistently identifies several positive effects when pruning residues are reintegrated over multiple seasons:

- Increased soil organic carbon content
- Improved aggregate stability and soil structure
- Enhanced water infiltration and retention
- Increased microbial activity
- Reduced erosion in sloped vineyards

The FAO emphasises that increasing soil organic matter strengthens resilience to drought and extreme climatic events (FAO, 2017). Furthermore, studies indicate that combining biomass incorporation with cover crops amplifies improvements in soil physical properties and water dynamics (Martínez-Casasnovas et al., 2012).

Technical Considerations and Limitations

The valorisation of pruning residues offers clear agronomic and environmental benefits, but its success depends on proper implementation. Reincorporating woody biomass into the vineyard system must be planned carefully to avoid unintended nutritional or phytosanitary effects.

One of the main concerns relates to **phytosanitary risks**. Pruning wood may contain fungal spores or pathogens from previous seasons. In areas with high disease pressure, residues should be finely shredded to accelerate decomposition, and visibly infected material should not be reincorporated. Adequate monitoring and advisory support are essential to prevent inoculum carryover (Rossi et al., 2012).

Another key factor is the **carbon-to-nitrogen (C/N) ratio**. Woody residues are carbon-rich and may temporarily immobilise soil nitrogen during decomposition. Although this effect is usually short-term, fertilisation plans should anticipate possible temporary deficits, particularly in low-fertility soils (FAO, 2017).

The **rate of decomposition** depends on shredding quality, moisture, temperature, and soil biological activity. Finer particle size and favourable environmental conditions enhance breakdown and integration into stable organic matter (Lal, 2004).

Operational considerations must also be addressed. Shredding requires machinery and additional labour time, which may represent a constraint for small vineyards. Cooperative equipment-sharing systems can reduce this barrier and facilitate adoption.

Residue incorporation must be compatible with other soil practices, including cover crops and mechanical operations. Integrated soil management planning maximises benefits and reduces conflicts (Martínez-Casasnovas et al., 2012).

Finally, **soil improvement is gradual**. Monitoring indicators such as soil organic matter, infiltration capacity, and vine performance is necessary to evaluate long-term impact (European Commission, 2021).

When properly managed, pruning residue valorisation strengthens soil resilience and supports climate mitigation goals. When poorly planned, it may introduce avoidable agronomic risks. Success depends on integration, monitoring, and adaptation to local conditions.

Economic Dimension

Although environmental benefits are well documented, winegrowers must also evaluate financial implications. Initial investments in shredding equipment or additional labour time may be required. However, regenerative soil practices have been shown to reduce long-term fertilisation and irrigation costs while improving resilience (FAO, 2017).

Economic viability is strongest when biomass valorisation is embedded within a comprehensive sustainability strategy, where environmental improvements translate into market differentiation and added brand value.

Success Cases:

- **VineAdapt (Spain):** The LIFE VineAdapt project evaluated climate adaptation measures in Spanish vineyards. The use of shredded residues as surface mulch demonstrated reduced evaporation rates and improved soil water retention, contributing to lower irrigation requirements under drought conditions.

- **VITIREG (Spain, Portugal and France):** The VITIREG project worked on promoting regenerative practices in vineyards, including the shredding of vine shoots and their return to the soil as a strategy to increase organic matter and improve soil structure.

  The trials demonstrated that the continuous incorporation of biomass promotes biological activity and contributes to increased resilience to drought, especially in Mediterranean areas with low natural fertility.

Figure 14. VITIREG consortium

- **Institut Français de la Vigne et du Vin (France):** The IFV has conducted long-term experimental programs on shredded pruning residue incorporation. Results indicate progressive increases in soil organic carbon and improved structural stability, particularly when combined with permanent cover cropping.

2. Energy Transition in the Wine Industry

The energy transition is one of the greatest challenges and, at the same time, one of the main opportunities for the wine industry in the current context of climate crisis and transformation towards a low-carbon economy. The wine sector, traditionally intensive in the use of energy in phases such as winemaking, storage, air conditioning and transport, faces the need to reduce its dependence on fossil fuels and to move towards production models aligned with the European Green Deal and international commitments to mitigate climate change (European Commission, 2020).

In this scenario, the incorporation of renewable energies, the optimisation of energy efficiency and the adoption of digital management systems become strategic pillars. These measures not only reduce greenhouse gas (GHG) emissions, but also contribute to improving competitiveness, reducing operating costs and strengthening wineries' reputation for sustainability in the eyes of increasingly conscious consumers (OIV, 2021).

The energy transition in viticulture, therefore, should not be understood only as an environmental obligation, but as a structural change that drives technological innovation, promotes the circular economy and opens up new opportunities for differentiation in a highly competitive global market.

Figure 15. Installation of the "intelligent shading" of the San Gabriel Winery. Source: Laura Cano Liébana, 2022

2.1. Integration of Renewable Energies in the Wine Industry

The main objective of the energy transition in the wine industry is to reduce dependence on fossil fuels and minimise the carbon footprint, in line with international commitments to climate change and the guidelines of the European Green Deal (European Commission, 2020). The integration of renewable energies in wineries and vineyards not only responds to an environmental requirement, but also to an economic opportunity, as it

reduces energy costs in the long term, guarantees energy autonomy and improves the image of sustainability in the eyes of increasingly aware consumers (Stolz et al., 2011).

The International Organization of Vine and Wine (OIV) has identified energy as a key factor in the sector's sustainability strategy, promoting the incorporation of renewable systems as a fundamental pillar to achieve climate neutrality (OIV, 2021). Among the main renewable sources that can be integrated into the wine industry are:

a) Photovoltaic and Solar Thermal Energy

Solar energy is the most widely adopted renewable option in viticulture and wineries due to the abundant solar radiation in Mediterranean, Latin American and Californian wine regions (FAO, 2020). There are two main technologies:

- **Photovoltaic (PV) systems:** They transform solar radiation into electricity through panels installed on the roofs of wineries, warehouses or even on rows of vineyards (*agrivoltaic*). This energy powers pumping equipment for irrigation, refrigeration systems in the winery and electrical machinery. Studies in vineyards in Castilla-La Mancha and Bordeaux show reductions of up to 70% in electricity bills by combining photovoltaic self-consumption with batteries (IDAE, 2021).

- **Solar Thermal Energy:** Used mainly to heat water in barrel cleaning processes, tanks and in cellar air conditioning systems. An emblematic case is that of **Bodegas Torres (Spain),** which incorporated solar thermal collectors, reducing gas consumption for hot water by 30% (IWCA, 2022).

Advantages:

- Reduction of direct emissions and energy dependence.

- Possibility of *agrivoltaics*, which reduces evaporation in the vineyard and generates beneficial shade in hot climates (Ravi et al., 2022).

- Energy resilience in the face of crises and price volatility.

  Added value in marketing (carbon neutral wine) with access to green financing and tax incentives, increasingly linked to sustainable projects.

- Improved traceability and transparency, by being able to monitor consumption in real time.

Challenges:

- High initial investment and need for installation space.

- Intermittent production requiring storage or grid connection systems.

- Maintenance and technological updating in rural areas.

- Lack of clear incentives and complex bureaucracy.

- Technical knowledge gap.
- Geographical and climatic conditions.
- Return on investment in the medium/long term.
- Possible landscape or heritage incompatibilities, especially in historic vineyards.
- Dependence on external technology providers, which can lead to additional costs or lack of autonomy.

Figure 16. Agrivoltaics. Source: Iberdrola

b) Wine Biomass: Recovery of Pomace and Vine Shoots

Viticulture generates large volumes of organic waste every year, including pomace, stems, lees and vine shoots. Traditionally, these by-products were considered to have low added value, in many cases intended for disposal or limited use in agricultural amendments. However, within the framework of the circular economy and the energy transition, this waste has been revalued as strategic sources of renewable energy and as inputs for improving sustainability in wine systems (Pérez-Pérez et al., 2021).

Wine biomass can be used through different technologies: direct combustion, gasification, anaerobic digestion for biogas, or pyrolysis for the production of biochar and bio-oils. These applications make it possible to transform waste into thermal and electrical energy, reducing dependence on fossil fuels and avoiding emissions associated with the transport and final disposal of waste. In addition, the use of biomass contributes to closing the vineyard's production cycle, returning nutrients and stable carbon to the soil in the form of biochar, with benefits for fertility and water retention capacity.

- **Pomace:** Winemaking residue composed of skins, seeds and pulp remains. It can be dried and used as solid biomass or transformed into pellets for biomass boilers. In La Rioja, the Biovino project managed to get several wineries to cover 100% of their winter thermal needs with dried pomace, avoiding the emission of about 1,500 tonnes of CO_2 per year (González et al., 2022).
- **Vine shoots:** Vine pruning waste that, once crushed and dried, is used as biomass for boilers or as raw material for the production of biochar. The latter not only generates energy in the production process, but when applied to the soil improves nutrient and water retention, and acts as a carbon sink in the long term (Lehmann & Joseph, 2015).

Advantages

- Reduction of waste and reduction of management costs.
- Partial or total substitution of fossil fuels.
- Synergy with soil fertilization if biochar is produced.
- Local use of resources, reducing transport costs and increasing the energy autonomy of the winery.
- Contribution to climate mitigation, through carbon sequestration and emission reductions compared to the use of diesel or natural gas.

Challenges:

- Need for logistics for the collection, drying and storage of waste.
- Specific machinery requirements for pelletization or conditioning of the material.
- Seasonal variability in the availability of biomass, which forces planning for accumulation and storage to cover annual demand.
- Possible emissions of particles in combustion, which require filtering systems and compliance with environmental regulations for their control.

Figure 17. Collection of the vine shoot for its recovery. Source: John O'Ryan

c) Microwind and Geothermal

Although less widespread than solar and biomass, these technologies are emerging in pilot projects, especially in wineries with high thermal demand or located in windy regions.

- **Micro-wind:** Small-scale turbines (powers of less than 50 kW) installed in areas with regular winds. They are used to power refrigeration systems, lighting or charging electrical machinery. The **Jackson Family Wines** group in Oregon incorporated microturbines in combination with photovoltaic panels, generating 40% renewable energy on-site (Sustainable Winegrowing Alliance, 2021).

Figure 18. Wind power in vineyards. Source: Diario de Jerez.

- **Geothermal energy:** It consists of taking advantage of the thermal energy of the subsoil through **geothermal heat pumps**, which extract heat in winter and dissipate it in summer. This technology is ideal for wineries, as it allows a stable temperature to be maintained in aging rooms, reducing air conditioning electricity consumption by up to 50% (FAO, 2020). In Bordeaux, the **Château Smith Haut Lafitte** winery combines geothermal and biomass to cover its thermal demand, achieving a reduction of 180 tonnes of CO_2 per year (Bindi & Olesen, 2011).

Figure 19. Geothermal installation at the Château Smith Haut Lafitte winery *Source: VitiViniCultura*

Advantages:

- High energy efficiency (COP of 3 to 5 in geothermal heat pumps).
- Quiet technology with low space occupation.
- Significant reduction in CO_2 emissions compared to fossil fuels.
- Complementarity with other renewables, such as solar or biomass, to diversify the energy matrix.

Challenges:

- Need for logistics for the collection, drying and storage of waste.
- Specific machinery requirements for pelletization or conditioning of the material.
- Seasonal variability in the availability of biomass, which forces planning for accumulation and storage to cover annual demand.
- Possible emissions of particles in combustion, which require filtering systems and compliance with environmental regulations for their control.

2.2. Planning and Implementation of Energy Systems in Wineries

The energy transition in the wine sector is not limited to the incorporation of renewable technologies, but involves a comprehensive process of diagnosis, planning, execution and monitoring. This process must be adapted to the specific reality of each winery, considering factors such as size, location, production capacity, climate and available budget. The aim is to maximise energy efficiency and reduce greenhouse gas

emissions without compromising wine quality, business operability or profitability (Finger et al., 2019).

1. Initial Energy Diagnosis

The first step is to carry out an energy audit to identify the critical points of consumption. According to studies by the OIV (2021) and the Institute for Energy Diversification and Saving (IDAE), in a typical winery the main sources of consumption are:

- **Winemaking processes:** pumps, presses, controlled fermentation systems.
- **Air conditioning and refrigeration:** temperature maintenance in tanks and rearing rooms (can account for up to 50% of total consumption).
- **Lighting and administrative offices.**
- **Irrigation and pumping in the vineyard.**

A proper diagnosis makes it possible to calculate the energy index per litre of wine produced, compare it with industry standards (benchmarking) and define reduction targets (IDAE, 2021).

2. Design of the Energy Plan

Once the consumption pattern has been identified, a Comprehensive Energy Plan is designed, which must include:

- **Definition of strategic objectives:** reduction of consumption by X% in 5 years, carbon neutrality by 2030, etc.
- **Optimal technological selection:** based on technical, climatic and economic feasibility analysis.
- **Life Cycle Assessment (LCA):** to estimate the total environmental impact of the proposed solutions.

It is recommended to apply methodologies such as Multicriteria Analysis (CMA) to prioritize investments (Pardo et al., 2019). This approach allows for the weighting of criteria such as investment cost, expected savings, environmental impact, ease of integration and useful life.

3. Implementation of Hybrid Technologies and Solutions

In practice, most wineries opt for **hybrid combinations** that integrate various renewable technologies along with energy-efficient systems. Examples:

- **Solar + Biomass hybridization:** photovoltaic panels to cover daytime electricity consumption, biomass for heating in winter.

- **Geothermal + Solar Thermal:** for stable air conditioning in aging rooms and reduction of electricity use in refrigeration.

- **Energy storage systems:** lithium batteries or emerging technologies such as flow batteries, to improve autonomy and demand management.

In California, the *Robert Mondavi Winery* installed a hybrid system that combines photovoltaic (1 MW), Tesla Powerpack batteries and biomass boilers, reducing its dependence on the electricity grid by 35% and achieving annual savings of more than $300,000 (IWCA, 2022).

4. Digital Management and Automation

The energy transition in viticulture is closely linked to **digitalisation**. Energy **management platforms (EMS)** enable:

- Monitor consumption and generation in real time.

- Predict peaks in demand using predictive algorithms.

- Automate the operation of equipment, optimizing the generation-consumption relationship.

A pioneering case is that of **SmartVitis** in Italy, which integrates energy, irrigation, and climate data to schedule agricultural operations based on renewable availability (Moriondo et al., 2020).

5. Financing and Incentives

One of the main challenges for the implementation of sustainable energy systems is the **high initial cost**, which can range from **€50,000 to €500,000**, depending on the size and technology selected (Boraud et al., 2022). To overcome this barrier, the following have been developed:

- **Public subsidies:** such as aid from the EU's Rural Development Programme (RDP) and **Green Deal funds**.

- **Innovative financing models:**

    - **Energy leasing**: the supplier company installs the system and the winegrower pays a monthly fee lower than the previous energy bill.

    - **Power Purchase Agreements (PPA):** long-term contracts for the purchase of renewable energy without an initial investment.

    - **Cooperative systems:** several wineries are grouped together to share facilities and reduce unit costs.

6. Monitoring and Continuous Improvement

Energy planning does not end with installation; there must be a **continuous monitoring and evaluation system**. The most commonly used metrics are:

- **kWh of renewable energy generated/annually.**
- **Reduction of tonnes of CO_2 equivalent.**
- **Energy cost per litre of wine produced.**

The current trend is towards certification under standards such as **ISO 50001 (Energy Management)** and **ISO 14064 (Carbon Footprint),** which not only guarantee regulatory compliance, but also add value in the marketing of wine (González-Fernández et al., 2022).

2.3. Strategies to Reduce the Carbon Footprint in Wine Production

Reducing the carbon footprint in the wine industry is one of the most important strategic axes within the **energy transition and sustainability**. The wine sector, although less emissions-intensive than other agro-industrial branches, generates CO_2 and other greenhouse gases (GHG) at all stages of the production cycle: from the vineyard to the distribution of wine (Jones et al., 2010). This impact is mainly due to:

- **Energy consumption in wineries:** air conditioning, refrigeration, pumping, bottling.
- **Use of fertilizers and phytosanitary products:** which emit N_2O and CO_2.
- **Mechanized operations:** field work, internal transport and distribution.
- **Management of by-products and waste:** fermentation, pomace, shoots.
- **Packaging and logistics:** glass bottle production and international transport.

The strategy to reduce this footprint involves a comprehensive and systematic approach, with coordinated actions in energy, production processes, materials and logistics.

1. Measuring the Carbon Footprint as a Starting Point

Reducing emissions in the wine industry requires, as an initial step, a **precise quantification of the carbon footprint of** the winery and the vineyard. Measuring allows us to know the magnitude of the problem, identify the main sources of emissions and establish a **baseline** against which to evaluate future progress.

There are several internationally recognized methodologies for measurement:

- **ISO 14064**: International standard for quantifying and reporting greenhouse gas (GHG) emissions and reductions.
- **GHG Protocol**: methodology that organises emissions into three scopes:
    - *Scope 1*: direct emissions (fuels, own processes).
    - *Scope 2*: indirect emissions associated with the energy purchased.
    - *Scope 3*: emissions from the value chain (transport, packaging, distribution).
- **CO_2 equivalent (CO_2e):** indicator that allows the climate impact of different GHGs (CO_2, CH_4, N_2O) to be homogenized.

In viticulture, the measurement must cover both the **agricultural phase** (tillage, fertilisers, phytosanitary products, irrigation, machinery) and the **winery phase** (energy in fermentation, air conditioning, bottling, storage) and the **logistics phase** (transport and distribution).

The **OIV (2021)** and organisations such as **International Wineries for Climate Action (IWCA)** recommend establishing this baseline and repeating the assessment **each wine season**, as variations in climate, production and energy consumption significantly affect emissions.

An illustrative example is that of **Bodegas Torres (Spain**), which calculated its carbon footprint and determined that:

- **40%** of emissions came from the **manufacture of glass bottles**,
- **24%** of **energy consumption in the winery**,
- **16%** of **transportation**.

Thanks to this analysis, the winery was able to prioritise measures in **lighter and more recyclable packaging** and in the **incorporation of renewable energies**, which has made it possible to substantially reduce its footprint in recent years (IWCA, 2022).

2. Energy Optimization and Use of Renewables

Energy consumption represents between 20% and 40% of the total footprint (Pardo et al., 2019). Some key strategies:

- **Installation of photovoltaic solar panels** for electricity self-consumption, reducing dependence on the grid and emissions associated with fossil fuels.
- **Use of wine biomass** (vine shoots, pomace) for heating and thermal energy generation, reducing the use of diesel or natural gas (Brunori et al., 2020).
- **Heat recovery** in fermentation and distillation processes to reduce the use of boilers.
- **LED lighting and variable frequency drives** in pumps and equipment, optimizing consumption.

Jackson Family Wines (USA) combines solar energy (6.7 MW installed) and refrigeration efficiency, achieving a 33% reduction in its emissions in the winery (IWCA, 2022).

3. Soil Management and Carbon Sequestration

The vineyard can become a **carbon sink** if regenerative practices are applied that favor the fixation of CO_2 in the soil:

- **Permanent vegetation covers:** increase organic matter and sequester carbon (Chirivella et al., 2021).
- **Reduction of tillage:** to avoid the release of carbon from the soil.
- **Application of organic compost and biochar:** improves fertility and acts as a stable carbon store.

Studies in Bordeaux and Tuscany indicate that these practices can offset between 8% and 12% of the vineyard's annual emissions (Brunori et al., 2020).

4. Reducing Emissions in Logistics and Transportation

Transporting bottled wine to international markets is a relevant factor in the carbon footprint. Some solutions applied are:

- **Use of lightweight packaging**: reducing the weight of bottles by 100 g can reduce emissions by 6% (OIV, 2021).
- **Alternatives to traditional glass**: recycled PET bottles, aluminium or Bag-in-Box packaging for local markets.
- **Route optimization and load consolidation**: supported by digital tools to minimize empty routes.

Concha y Toro (Chile) reduced the weight of its bottles by 400 g, achieving a 13% reduction in emissions associated with transport (IWCA, 2022).

5. Circular Economy and Recovery of By-products

Organic waste, such as pomace and lees, can be converted into energy sources or inputs for other sectors:

- **Biogas production** through anaerobic digestion.
- **Extraction of polyphenols and antioxidants** for the food and cosmetics industry.
- **Biomass pellets** for internal heating and sale to third parties.

In Rioja, the **VINySOST** project developed systems to convert winemaking waste into biomass and biofertilisers, reducing the total footprint by 20% (AENOR, 2022).

6. Certification and Communication of Climate Commitment

More and more consumers value wines with environmental certifications, such as:

- **Carbon Neutral Wine** (ISO 14064 certified).
- **IWCA Gold Standard**.
- **Organic and biodynamic certification**.

Yealands Estate (New Zealand) became the first winery to be certified as *"Carbon Neutral",* integrating solar energy, biomass and reduction of heavy bottles. Transparent communication on labels and digital channels reinforces the brand and allows access to premium markets sensitive to sustainability.

2.4. Digital Tools for Carbon Footprint and Energy Consumption Monitoring

The digital transformation applied to viticulture is not only limited to agronomic monitoring, but plays an essential role in **the management of sustainability and the energy transition**. Reducing **the carbon footprint** and optimizing energy use require **real-time monitoring systems**, predictive analytics, and integrated platforms that turn data into strategic decisions (Wolfert et al., 2017; Verdouw et al., 2021). This section explores the most relevant tools and technologies for the control and monitoring of environmental impact in vineyards and wineries.

1. Digital Carbon Footprint Management Platforms

Emissions monitoring systems allow wineries to calculate and report their climate impact following international protocols such as **ISO 14064**, **GHG Protocol** or **PAS 2050**.

These tools connect with energy, production, and transportation data to generate certified reports.

- **Outstanding examples:**
    - **SustainaWine®**: a platform developed in the EU that integrates carbon, water and energy footprint indicators, offering automatic recommendations to reduce emissions (CORDIS, 2021).
    - **Wine Carbon Calculator (California Sustainable Winegrowing Alliance):** calculates emissions from input production to bottling and logistics, including "what if" scenarios to plan improvements.
    - **IWCA Tool**: Official tool of *the International Wineries for Climate Action* for the measurement and verification of emissions according to the **Scope 1, 2 and 3** methodology (IWCA, 2022).

These platforms not only quantify emissions, but also integrate **scenario simulation modules**: for example, calculating the impact of replacing traditional glass with lightweight packaging or installing photovoltaic panels.

2. IoT Sensors and Real-Time Monitoring of Energy Consumption

The deployment of **the Internet of Things (IoT)** in wineries and vineyards has revolutionized the ability to measure and optimize energy consumption:

- **Electrical and thermal flow sensors**: measure the energy consumed by pumps, refrigeration systems, presses and air conditioning equipment.
- **Smart meters** connected to cloud platforms: generate alerts in the event of abnormal peaks in consumption.
- **Integration with BMS (Building Management Systems)** to optimize cooling in fermentation and storage rooms.

Château Larose-Trintaudon (France) implemented IoT sensors connected to the **Wattsense** platform, achieving an 18% reduction in electricity consumption through air conditioning optimization algorithms (European Commission, 2022).

3. Digital Twins and Predictive Analytics

The concept of **Digital** Twin applied to wineries makes it possible to simulate energy scenarios, optimize processes and evaluate the impact of strategic decisions. These models integrate real-time data with predictive algorithms to:

- **Predict energy consumption** according to the workload (harvest campaign, bottling).
- **Simulate the incorporation of renewable technologies** and calculate the return on investment (ROI) and emission reduction.

- **Optimize irrigation and pumping scheduling**, synchronizing it with the hours of lowest energy cost and lowest footprint (Verdouw et al., 2021).

The **VitiGEOSS** project (H2020) implements digital twins to integrate energy, water and logistics in southern European wine farms, anticipating climate and market scenarios (CORDIS, 2022).

4. Artificial Intelligence and Big Data for Energy Efficiency

AI applied to the energy transition in viticulture focuses on:

- **Energy demand prediction** using neural networks that combine history, weather, and process scheduling.
- **Analysis of the energy-production-quality relationship**: correlating data to identify the optimal consumption per liter of wine produced.
- **Automatic detection of inefficiencies**: algorithms that compare real consumption with benchmarks and propose corrective actions.

EnergyMind® **software** uses machine learning to identify patterns of energy waste in warehouses, adjusting equipment operation in real time.

5. Blockchain for Energy Traceability and Transparency

More and more wineries are looking to **communicate their sustainable commitment** with verifiable data. Blockchain technology is used to:

- Certify the origin of renewable energy used in the winery.
- Ensure transparency in the value chain.
- Provide data on smart labels that show the carbon footprint per bottle.

The **GreenChain Wine** project in Italy integrates blockchain to certify renewable energy and emission reduction, providing data accessible to the consumer through QR codes on the label.

6. Integration into Integrated Management Platforms (Agronomic ERP)

The challenge is not only to measure, but **to integrate** energy information with the rest of the winemaking processes:

- ERP systems such as **AgriWebb, Farm360 and Vite.net®** incorporate energy and sustainability modules.
- Leading wineries use unified dashboards where they can visualize energy consumption, emissions, agronomic indicators and financial status in real time.

This allows **decisions to be made based on data** rather than intuition, aligning energy efficiency with quality and profitability.

2.5. Energy Cooperativism in Winegrowing Communities

The decarbonisation of viticulture does not depend solely on field-level agronomic practices. Energy use in irrigation, machinery, refrigeration, and winery operations represents a significant share of the sector's carbon footprint and production costs. In this context, energy cooperativism has emerged as a strategic pathway for winegrowing communities seeking to increase energy autonomy, reduce costs, and accelerate the transition toward renewable sources.

Energy cooperatives are collective initiatives in which producers jointly invest in renewable energy infrastructure — typically photovoltaic installations — and share production, costs, and benefits. This model aligns with European energy transition policies that promote citizen and community energy projects as instruments for decentralised, democratic energy systems (European Commission, 2019).

Figure 19. Westmill Solar Co-operative members *Source: Westmill Solar Co-operative*

In viticulture, where many producers operate within geographically concentrated areas and often already collaborate through traditional agricultural cooperatives, energy cooperativism represents a natural extension of existing collective structures.

Strategic Rationale

Energy has become a strategic variable for winegrowing territories. Beyond being a simple operating cost, electricity and fuel increasingly shape competitiveness, risk exposure, and the feasibility of climate adaptation. This is particularly relevant in viticulture because energy demand is not constant: it typically concentrates in specific periods of the year (irrigation in summer; cooling and processing around harvest and winemaking), which can amplify the impact of price spikes and supply constraints.

In vineyards, electricity demand is often driven by irrigation pumping, especially in warmer regions where drought and heatwaves have made supplementary irrigation more common. In wineries, demand is concentrated in cooling and temperature control (fermentation management, cold stabilisation, storage), and it is reinforced by bottling and processing lines, compressed air systems, and general facility loads (lighting, cleaning systems, auxiliary motors). As digitalisation advances, energy use also grows through monitoring and control systems (connectivity equipment, sensors, automation, data logging, and occasionally edge devices), which increases the value of stable and predictable electricity supply.

This context matters because the profitability of energy-intensive activities is highly sensitive to market volatility. The IEA has documented how the global energy crisis translated into major price spikes and volatility (especially through gas and electricity markets), directly affecting affordability and planning for businesses. More recent IEA analysis also highlights structural shifts in power markets (including more frequent hours with negative wholesale prices in some European systems since 2022), illustrating how electricity price dynamics are becoming more complex and less predictable—reinforcing the value of hedging and self-consumption strategies.

Against this backdrop, energy cooperativism (or cooperative energy models) offers a practical response: it allows winegrowing communities to invest collectively in renewable generation—most commonly solar PV—and manage energy as a shared strategic resource. When producers cooperate, they can typically access better project design, economies of scale, stronger bargaining power, and shared expertise that individual farms might lack. At the territorial level, it can also strengthen cohesion by creating shared assets, shared savings, and shared governance.

Collective renewable investment can deliver four strategic benefits:

- **Lower long-term energy costs,** by replacing part of grid purchases with self-generated electricity over the lifetime of the installation.
- **Greater price stability,** because part of the energy supply becomes less exposed to market swings (a core advantage in volatile markets).
- **Improved environmental performance,** by reducing operational emissions and supporting sustainability reporting and certification narratives.
- **Stronger territorial cohesion,** since the model relies on shared decision-making and shared value creation rather than isolated investments.

Finally, these projects align strongly with EU climate and energy objectives. EU legislation introduced and strengthened the role of energy communities—specifically "citizen energy communities" and "renewable energy communities"—as a pillar of decentralised energy transition. This is particularly relevant for wine regions where cooperation already exists through cooperatives, growers' associations, or inter-professional structures.

Technical and Organisational Models

Energy cooperativism in viticulture can be implemented through several practical configurations. The most effective model depends on local constraints (available roof/land,

grid connection, regulatory options, demand profile) and on how the community wants to govern investment and benefit-sharing.

1) Shared Photovoltaic Installations

This is the most common and easily understood approach: producers jointly finance a PV installation located on cooperative winery roofs, shared facilities, suitable land, or near irrigation infrastructure. The electricity can be used for collective self-consumption, allocated to members under an agreed distribution rule, or used to offset part of each member's grid consumption.

What makes the model viable is the combination of: (a) predictable solar generation; (b) energy demand that is often significant during daylight hours (pumping, cooling equipment, general operations); and (c) the possibility of distributing benefits across multiple members. In practice, the cooperative must define: who invests, how participation shares are allocated, how electricity is distributed, and how savings are measured and communicated.

A relevant operational reference is the practical guidance and service design offered by Som Energia for collective self-production arrangements (including management of the collective self-consumption framework). While not wine-specific, it shows how cooperative actors structure collective schemes and reduce transaction complexity for participants.

2) Energy Communities under the EU Framework

Under the "Clean energy for all Europeans" package, the EU formally embedded energy communities in legislation—especially through the concepts of citizen energy communities and renewable energy communities—enabling local actors to produce, consume, store, and sell renewable energy collectively.

For wine territories, this matters because it provides a policy backbone for models that go beyond "one installation for one site." Energy communities can integrate multiple users and uses (wineries, irrigation entities, municipal buildings, local SMEs) and can potentially combine generation with other services such as shared monitoring, demand management, and future storage.

In Spain, the institutional environment has increasingly supported community energy development through national planning and dedicated programmes (e.g., PNIEC framework and energy community support lines). This is important for vineyards because cooperative projects often improve viability when paired with public support and a clear legal framework.

3) Irrigation–Energy Integration

In many Mediterranean wine regions, irrigation is simultaneously a climate adaptation tool and a growing cost driver. Solar-powered pumping systems—whether deployed by an irrigation community or a cooperative of growers—can reduce reliance on

grid electricity during peak price periods and can also reduce diesel dependence where it still exists.

Collective solar pumping becomes especially attractive when vineyards share pumping stations, reservoirs, or coordinated irrigation schedules. Because irrigation demand often peaks in sunny periods, solar generation and pumping needs can be well aligned on many days, improving self-consumption rates (and thus economic returns). The cooperative approach also helps manage complexity: instead of each grower installing small systems, a shared asset can be designed for the territory's real load profile.

Environmental and Economic Benefits

The benefits of cooperative renewable models should be framed in a way that makes sense to growers and wineries: not as abstract sustainability claims, but as practical improvements in cost control, operational planning, and risk reduction.

From an environmental perspective, replacing grid electricity with renewable self-consumption reduces operational emissions and supports climate mitigation goals. The IEA has repeatedly underlined the role of renewables as a stabilising and expanding component of energy supply during the recent crisis period. For wineries, the impact is particularly visible when solar generation coincides with daytime demand (pumps, cooling auxiliaries, processing loads), which is common during summer and harvest.

From an economic perspective, the most valued effect is often predictability. Cooperative investment can reduce each member's capital burden (shared investment rather than duplicated investments), improve access to technical expertise, and strengthen access to public incentives or dedicated community-energy programmes. In Spain, for example, IDAE has specific incentive programmes for energy community pilot projects, illustrating the policy direction toward collective models.

Cooperative governance can also distribute risk more effectively. Instead of one farm carrying the full uncertainty of technology performance, maintenance, and regulatory changes, the cooperative shares responsibilities and can professionalise operations (maintenance contracts, monitoring routines, compliance). Over time, this tends to strengthen local resilience because energy savings remain in the territory and can be reinvested in further adaptation measures (water efficiency, soil health, digital tools).

Case of Success: Cooperative Energy Models Across European Wine Regions

Energy cooperativism in viticulture is not an isolated national phenomenon but part of a broader European transition toward decentralised, community-based renewable systems. Across several wine-producing countries, cooperative and community energy initiatives have demonstrated that collective investment in renewable infrastructure can reduce costs, increase resilience, and reinforce territorial cohesion.

Although the regulatory frameworks differ among Member States, the underlying principle remains consistent: local actors — including wineries, growers' associations, irrigation communities, and municipalities — collaborate to produce, manage, and

consume renewable energy collectively under the framework enabled by the EU Clean Energy Package.

1. France – Territorial Renewable Cooperatives in Wine Regions

In France, renewable energy cooperatives have become increasingly integrated into rural development strategies. In wine-producing regions such as Occitanie and Nouvelle-Aquitaine, collective photovoltaic projects have been implemented through cooperative structures such as SCICs (Sociétés Coopératives d'Intérêt Collectif). These initiatives often involve wineries, agricultural cooperatives, and local authorities jointly investing in rooftop solar installations on winery facilities or agricultural buildings.

The French model highlights the territorial dimension of energy cooperativism: projects are embedded within broader regional climate strategies, linking energy autonomy with rural development and agricultural sustainability. For vineyards facing rising irrigation and cooling demands, shared solar production has helped stabilise operating costs and reinforce environmental positioning in competitive export markets.

2. Italy – Renewable Energy Communities in Agricultural Clusters

Italy has actively developed Renewable Energy Communities (Comunità Energetiche Rinnovabili – CER), particularly in agri-food territories. In wine-producing regions such as Emilia-Romagna and Veneto, pilot projects have connected wineries, irrigation consortia, and agro-industrial facilities within shared photovoltaic systems.

The Italian experience demonstrates how agricultural clusters can pool rooftops and land resources to create distributed energy systems that benefit multiple actors. Importantly, these projects are often supported by national incentives and simplified administrative procedures, illustrating how EU directives can translate into concrete rural implementation when aligned with domestic policy frameworks.

3. Germany – Long-standing Energy Cooperatives in Rural Areas

Germany offers one of the most established traditions of energy cooperatives (Energiegenossenschaften). In wine regions such as Baden-Württemberg and Rhineland-Palatinate, cooperatives have financed solar installations on winery roofs and shared agricultural buildings, sometimes integrating energy monitoring systems and storage solutions.

The German approach emphasises financial transparency, member participation, and long-term planning. It illustrates how cooperative energy models can evolve into innovation platforms, combining renewable generation with digital management tools to optimise consumption patterns and increase self-consumption rates.

4. Portugal – Solar Solutions in Irrigated Wine Landscapes

In Portugal's Douro Valley and Alentejo, where irrigation demand is high and drought pressure is increasing, collective solar pumping systems have emerged as practical responses to rising electricity costs. Agricultural associations and local cooperatives have invested in shared photovoltaic installations to supply irrigation infrastructure and winery facilities.

These projects demonstrate the strategic alignment between climate adaptation (water management) and energy transition, particularly in Mediterranean environments where solar availability and irrigation needs coincide seasonally.

5. Spain – Citizen Energy Cooperatives and Agricultural Participation

Spain also provides relevant examples through citizen-led renewable cooperatives and collective self-consumption initiatives. In several rural areas, photovoltaic systems installed on cooperative winery roofs or shared agricultural facilities have enabled members to reduce electricity purchases from the grid and increase energy autonomy.

Spanish experiences show the importance of intermediary organisations that provide technical guidance, regulatory support, and governance structures. These actors reduce administrative complexity and help winegrowers navigate collective self-consumption frameworks. National strategies promoting citizen energy communities and rural energy transition have further facilitated these developments.

Challenges and Requirements

Despite its potential, energy cooperativism is not "automatic." Success depends on treating the project as both a technical system and a governance system.

A first **requirement is clear governance:** transparent rules for participation, investment shares, benefit allocation, decision-making processes, and dispute resolution. This is essential because members must trust that the cooperative is fair and professionally managed—especially when payback periods span years.

Second, **projects require regulatory and administrative capacity.** Energy communities exist within legal frameworks that define rights and obligations, and cooperative projects must handle permitting, grid connection, contractual structures, and compliance. EU guidance and legislation explicitly frame energy communities as part of the electricity market design and consumer empowerment rules, reinforcing the need for clear governance and consumer protection.

Third, there is the **challenge of initial capital mobilisation and technical feasibility.** Even when costs are shared, cooperatives must design bankable projects: realistic generation estimates, strong site selection, and conservative financial planning. Public support programmes can improve feasibility but do not replace rigorous project design.

Fourth, **projects need long-term coordination**. Energy assets require maintenance, monitoring, performance tracking, and periodic decision-making

(reinvestment, upgrades, member changes). Without sustained coordination, the technical system may underperform and member confidence may decline.

Finally, **cooperatives must address seasonality and variability:** solar generation is strong in summer, but demand can peak differently depending on winery operations (harvest/processing) and irrigation schedules. Some regions also experience increasing complexity in wholesale price patterns (including more frequent negative-price hours), which strengthens the case for smart scheduling, demand management, and—where viable—storage or flexible grid integration strategies.

3. Case Studies on Sustainable Viticulture

3.1. Success Stories in Energy Transition and Sustainable Viticulture

The energy transition in viticulture has ceased to be a passing trend and has become a strategic axis that defines the competitiveness and sustainability of the wine sector at a global level. More and more wineries, aware of the impact of climate change and regulatory requirements, are adopting renewable energies, digital solutions for energy efficiency and circular models aimed at reducing their carbon footprint, optimising the use of resources and ensuring their long-term viability (International Organisation of Vine and Wine [OIV], 2021; IWCA, 2022).

This section analyzes real cases in Europe, America and Oceania, as well as the incorporation of **agrivoltaics**, a disruptive technology that combines agricultural production and solar energy generation, redefining vineyard management.

1. Spain: leadership in decarbonisation and agrivoltaics

Familia Torres, one of the most renowned wineries in Catalonia, has established itself as a world leader in the fight against climate change within the wine sector. Through its **Torres & Earth** program, launched in 2008, the company has deployed a comprehensive decarbonization strategy based on three pillars: energy efficiency, renewable energies and ecological soil regeneration. Among its main actions is the installation of **12,000 m^2 of photovoltaic panels** capable of generating **2.5 GWh per year**, which covers approximately **30% of the electricity demand** of its wineries. This generation is complemented by the use of **biomass boilers that take advantage of vine shoots and pruning remains**, creating a circular system that replaces fossil fuels. In addition, Torres has invested in **atmospheric CO_2 capture projects** and in the recovery of degraded soils through regenerative practices, achieving a **cumulative reduction of 34% in its greenhouse gas emissions since 2008**. This commitment has earned them recognition as **Gold members of the International Wineries for Climate Action (IWCA)** and an estimated annual energy saving of **450,000 euros**.

Also in Spain, the century-old González Byass has made a firm commitment to clean energy in its wineries in Jerez de la Frontera (Andalusia). The company has installed **photovoltaic roofs with a capacity of 2 MW**, which supply a significant part of its electricity demand. At the same time, it has carried out comprehensive automation of its air conditioning and ventilation systems, which has led **to a reduction of around 40% in fossil energy consumption** (European Commission, 2022). These measures are part of its corporate strategy to achieve climate neutrality by 2040.

Spain is also emerging as one of the pioneering countries in the application of **Agrovoltaics in vineyards**, thanks to projects promoted by entities such as Repsol, the SMART PVwine project and SOLARWINE. These initiatives combine **bifacial and semi-transparent solar panels installed on the vineyards**, managed by **digital twins and intelligent control systems**. The objectives are ambitious: **to reduce the climate impact on the vineyard, generate additional income from the sale of surplus energy** and **validate agronomic models compatible with climate change** (Ministry of Agriculture, Fisheries and Food, 2023). Preliminary results indicate notable reductions in heat stress

and water consumption in vineyards under panels, which points to a strategic development path for the country.

2. France: carbon neutrality and advanced agricultural technology

Château Larose-Trintaudon, located in the Bordeaux region, is one of the largest vineyards in the area with **190 hectares** and has recently achieved **certified carbon neutrality**. This achievement has been possible thanks to an innovative approach based on the **digital monitoring of energy consumption using IoT sensors integrated into BMS platforms**, the contracting of **100% renewable electricity through PPA (Power Purchase Agreement)** contracts and on-site photovoltaic generation. In addition, agroecological practices reduce the use of chemicals and promote biodiversity in the vineyard. These measures have enabled an **18% decrease in total energy consumption**, largely thanks to the use of artificial intelligence algorithms for thermal **optimization of facilities**, in addition **to the full offsetting of residual emissions through certified forestry projects**.

In the Languedoc region, the Château Maris winery has become an example of eco-friendly architecture and energy efficiency. Its winery, built with natural materials such as **hemp and lime**, works entirely with **solar energy, biomass and electricity from certified renewable sources**. In addition, it has obtained B **Lab (B-Corp) certification** for its environmental, social, and economic performance, and has managed to position itself in **premium markets where it obtains up to 15% more value for its** low-carbon footprint wines (Wine Spectator, 2022).

France has also taken decisive steps in agrivoltaics. In Occitanie, the Domaine de Nidolères vineyard participates in the Sun'Agri program, where **4.5 hectares of vineyards are cultivated under dynamic photovoltaic panels that are automatically oriented according to solar radiation and ambient humidity**. The results are impressive: a **70% reduction in irrigation needs**, yield increases of between **20 and 60%,** and improvements in grape quality thanks to slower and more balanced ripening (INRAE, 2022). This makes France a European benchmark in climate-resilient viticulture.

3. Italy: community energy and agrivoltaic cooperatives

In Tuscany, the historic Cantina Gabbiano has completely modernized its energy system, installing **1.8 MW of solar panels** that provide around **70% of its annual electricity consumption**. This generation is combined with **geothermal heat pumps for air conditioning**, which has reduced **the energy costs related to the temperature of the facilities by 45%.** Thanks to these measures, the winery has managed to avoid the emission of approximately **450 tons of CO_2 each year** and has recovered its investment in just five years, supported by grants from the Piano Nazionale di Ripresa e Resilienza (PNRR).

Further north, the Consorzio Vini del Trentino brings together **more than 3,000 winegrowers in Trentino-Alto Adige** and has become an example of how cooperation can accelerate the energy transition in rural areas. The consortium has promoted the installation **of collective biomass boilers that reuse pomace and vine shoots**, which has

reduced **energy costs by 30%** while **closing the agricultural waste cycle**, transforming waste into clean energy (European Commission, 2021).

Italy is also developing community-based agrivoltaic projects. One of the most emblematic is the **Vigna Agrivoltaica di Comunità – La Svolta** project, in Puglia, where **7,770 thin-film panels with a power of 970 kW have been installed on the vineyards**. This system has made it possible to **delay the harvest by 3 to 4 weeks**, favouring a **slower and more balanced ripening**, as well as reducing the **water stress of the plants by 20%.** The grapes obtained show **higher acidity and lower concentration of sugars**, which allows for **fresher wines suitable for sparkling wines**, opening up new market opportunities in a context of global warming.

4. Chile: digital twins and large-scale energy efficiency

The multinational Concha y Toro, a leader in the wine industry in Latin America, has developed a **comprehensive energy sustainability plan** that combines renewable generation, digitalization and efficiency. The company has installed **solar parks in Maule and Colchagua capable of producing 3 GWh/year**, and has replaced its old boilers with **biomass systems that take advantage of agricultural by-products**. In addition, it has implemented a **digital twin that models the energy and water behaviour of its production plants in real time**, which allows consumption to be optimised and operations to be accurately planned. As a result, it has managed **to reduce electricity consumption per liter of wine produced by 10% and indirect scope 2 emissions by 30%,** being recognized with the **Energy Efficiency Seal of the Government of Chile** (2021). This pioneering approach is being replicated by other wineries in the country.**5. United States: Jackson Family Wines and Smart Solar Energy**

5. United States: Smart Solar and Distributed Storage

In California, Jackson Family Wines has taken energy efficiency to another level by integrating prediction, renewable generation, and smart storage technologies. The company has installed 12 MW of photovoltaic panels, which cover 60% of its energy demand during peak periods (harvest), drastically reducing dependence on the electricity grid. This capacity is complemented by a Tesla Powerpack battery system that stores energy at off-peak hours and releases it during peak demand, while artificial intelligence algorithms dynamically adjust the loads of industrial equipment. These innovations have enabled a reduction of 12,000 tonnes of CO_2 per year and economic savings of 2.5 million dollars per year, reaching its corporate goal of carbon neutrality by 2030 ahead of time (IWCA, 2022).

3.2. Comparative Analysis of Sustainable Models in Viticulture

The comparative analysis of the different sustainability models implemented in viticulture allows us to understand which are the most effective strategies in terms of **cost, environmental impact, return on investment (ROI)** and **social acceptance**. This section presents the main **approaches adopted by internationally renowned wineries**,

comparing their key characteristics: **applied technology, initial investment, savings, emission reduction and co-benefits**.

1. Photovoltaic Energy vs. Biomass: Impact and Viability

Photovoltaic solar energy is the most widespread technology in wineries, thanks to the high radiation in wine-growing regions. Example:

- **Jackson Family Wines (USA)**: 12 MW installed, estimated investment of USD 14 million, with annual savings of USD 2.5 million and reduction of **12,000 t CO_2/year** (IWCA, 2022).

- **Cantina Gabbiano (Italy):** 1.8 MW installed, ROI in 5 years, generation of 70% of energy demand (European Commission, 2021).

In contrast, **wine biomass** takes advantage of by-products such as vine shoots, seeds and pomace, reducing disposal costs and closing the circular cycle. Cases:

- **Torres (Spain):** Biomass boilers that cover cellar heating, reducing **200 t CO_2/year**.

- **Consorzio Vini del Trentino**: Cooperative model that reduces energy bills by **30%.**

Comparative conclusion:

- **Photovoltaic** has a high initial cost but a faster ROI (5-7 years), while biomass is more accessible and provides additional benefits in the circular economy.

- In regions with abundant waste and less solar radiation, biomass is more efficient; In sunny areas, photovoltaics dominate.

2. Hybrid Systems: Combination of Solar + Geothermal + Storage

Hybrid **systems** integrate multiple sources to stabilize supply. Example:

- **Château Maris (France)** combines solar energy, biomass and thermal storage, achieving **energy autonomy of 95%.**

- Incorporation of **Tesla Powerpack batteries in California**, which allows balancing consumption peaks, reducing dependence on the electricity grid.

Proceeds:

- Constant coverage even in periods of low solar radiation.

- High initial cost (investment of more than €500,000 in medium-sized wineries) but total reduction in energy expenditure.

3. Artificial Intelligence (AI) for Energy Efficiency

Digitalisation applied to energy management represents a qualitative leap in sustainability. Cases:

- **Concha y Toro (Chile)** uses **digital twins** to simulate energy scenarios, achieving a **10% reduction in electricity consumption per liter produced**.
- **Torres (Spain)** applies **predictive AI** to manage cooling in tanks, optimizing the use of renewable energy.

Advantages over traditional models:

- Additional energy savings of **10-15%** without large investments in hardware.
- Improved traceability and decision-making to avoid cost overruns.

4. Certifications and Commercial Value: Effect on the Price of Wine

The economic impact of sustainability is not only measured in energy savings, but also in **added value for the consumer**:

- Wineries certified as **Carbon Neutral** (e.g. Château Larose-Trintaudon) have managed to position wines with a **10-15% premium** in premium markets (Wine Spectator, 2022).
- Programs such as **B-Corp** or **IWCA Gold Member** facilitate entry into international chains and increase brand reputation.

5. Comparison of ROI (Return on Investment) and Environmental Benefits

Table 1. Authors' elaboration based on IWCA (2022), Torres (2021), European Commission (2021).

Technology	**Initial Investment (€)**	**ROI**	**CO_2/year reduction**	**Other Benefits**
Photovoltaic (1 MW)	700.000 – 1.000.000	5-7 years	1,000 – 1,500 t	Partial autonomy, green image
Biomass (boiler 500 kW)	250.000 – 400.000	3-4 years	200 – 300 t	Waste recovery
Geothermal (medium winery)	150.000 – 300.000	4-6 years	150 – 250 t	Thermal stability
AI for efficiency	50.000 – 100.000	2 years	50 – 100 t	Digital optimization

Conclusion of the comparative analysis

The most cost-effective model for small and medium-sized wineries is **photovoltaic combined with biomass**, complemented by **AI for energy management**. Large wineries can incorporate **storage and geothermal**, achieving carbon neutrality. The key lies in the **flexibility of the system and access to public aid**, which can reduce investment by **40-60%.**

3.3. Economic and Environmental Impact of the Energy Transition on Wineries

The energy transition in viticulture and winemaking not only involves a technological change, but also a **profound transformation in the cost structure, commercial positioning and environmental footprint of the** sector. This section addresses the main impacts from a double perspective: **economic (costs, savings, return on investment)** and **environmental (emission reduction, resource efficiency),** based on recent studies and case studies.

1. Economic Impact: Costs and Return on Investment (ROI)

The adoption of renewable technologies and energy efficiency represents an **initial financial challenge**, especially for small wineries, where investment can range from **€50,000 to more than €1,000,000**, depending on scale and integrated technologies (European Commission, 2021).

Estimated investment distribution by technology

- **Photovoltaic solar panels (1 MW):** 700,000 – 1,000,000 €
- **Biomass boilers (500 kW):** 250,000 – 400,000 €
- **Geothermal for air conditioning:** 150.000 – 300.000 €
- **Electrical storage (batteries):** 200,000 – 350,000 €
- **AI and energy management systems:** €50,000 – €100,000

The **ROI (return on investment)** depends on the technological mix, energy consumption and available subsidies. According to **International Wineries for Climate Action (IWCA, 2022)** and **Torres (2021):**

- **Photovoltaic:** Return in **5-7 years** thanks to self-consumption and sale of surpluses.
- **Biomass:** ROI in **3-4 years**, in addition to reducing waste management costs.
- **AI and energy optimisation:** Fast return, in **1-2 years**, due to a reduction in electricity consumption (10-15%).

In wineries that combine technologies, **savings of 25-35% in electricity bills** and a **30% reduction in global energy costs** are reported, freeing up capital for innovation and marketing (García et al., 2022).

2. Environmental Impact: Carbon Footprint Reduction

Traditional winemaking has an estimated carbon footprint of between **1.5 and 2.0 kg CO_2 per bottle of wine** (Delmotte et al., 2020). The implementation of renewable energies can significantly reduce these emissions:

- **Photovoltaic:** -40% in the electrical energy footprint.
- **Biomass:** -15-20% additional when replacing fossil fuels.
- **Hybrid systems (solar + biomass + storage):** -70-80% in energy emissions.
- **AI and digitalization:** indirect reduction of 10% due to process optimization.

Quantitative example

- A winery with **a production of 500,000 bottles/year** and electricity consumption of **1.2 GWh/year**:
    - Before: Emissions of 550 t CO_2/year from energy.
    - After integrating photovoltaic (70% coverage): Reduction of 385 t CO_2/year.
    - Incorporating biomass for heating: Further reduction of 90 t CO_2/year.
    - Total: Reduction of more than **85%** in the energy footprint.

This level of mitigation allows wineries to opt for **environmental certifications (Carbon Neutral, ISO 14001),** increasing competitiveness and access to premium markets (Wine Spectator, 2022).

3. Impact on Competitiveness and Commercial Value

Energy sustainability not only reduces costs and emissions, but also **generates direct economic value**:

- **Premium pricing:** Wines certified as sustainable are sold **10-20% more expensive**, especially in markets in the US and Northern Europe (Wine Intelligence, 2021).
- **Attracting green investment and financing:** Funds such as **NextGeneration EU** cover up to **40-60% of the initial investment**, accelerating the transition (European Commission, 2021).
- **Consumer loyalty:** 66% of wine buyers in the EU consider sustainability a key purchasing criterion (OIV, 2022).

4. Economic Barriers and Solutions

- **High upfront costs:** Solution: **Energy SaaS** (Energy as a Service) and **PPA (Power Purchase Agreements) models**.
- **Unequal access to finance:** Cooperatives and wine clusters can negotiate collective purchases to reduce costs by **20-30%.**
- **Lack of real return data: Continuous monitoring systems (IoT + AI)** that generate financial and environmental reports to justify investments.

Economic and environmental impact summary table

Measure	**CO_2 Reduction**	**Annual savings (%)**	**Estimated ROI**
Photovoltaic	40 %	20-25 %	5-7 years
Biomass	15-20 %	15 %	3-4 years
AI and digitalization	10% (indirect)	8-12 %	1-2 years
Hybrid systems	70-80 %	30-40 %	7-10 years

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Annex I – Review Issues

Block 1: Green practices in viticulture

1. It explains the role of organic matter in soil fertility and water retention capacity in vineyards.
2. What effects does intensive tillage have on soil structure and microbial biodiversity?
3. Compare advantages and disadvantages of using green covers versus bare soils in Mediterranean climates.
4. How does functional biodiversity contribute to the biological control of pests in vineyards?
5. He cites three practices that increase functional biodiversity in a vineyard and describes how they promote its resilience.

Block 2: Water Efficiency

1. It defines the concept of controlled water deficit (RDI) and its effects on wine quality.
2. Explains the advantages of soil moisture sensors over fixed irrigation scheduling.
3. Briefly describe the AquaCrop model and its usefulness in viticulture.
4. What do Internet of Things (IoT)-based sensor networks contribute to water management?
5. It relates water saving to energy savings in viticulture.

Block 3: Biodiversity in the vineyard

1. It defines the concept of functional biodiversity and its importance in sustainable viticulture.
2. How does intensive monoculture influence the appearance of pests and diseases?
3. Explain the role of hedges and ecological corridors in the conservation of auxiliary fauna.
4. He mentions three direct ecological benefits of implementing green covers in vineyards.
5. What socio-economic barriers can hinder the adoption of biodiversity promotion practices?

Block 4: Sustainable use of energy

1. What is the approximate percentage of energy costs in conventional viticulture according to the International Organisation of Vine and Wine (OIV)?
2. He explains two technologies that improve energy efficiency in vineyard irrigation.
3. It describes the basic operation of a photovoltaic installation and its main advantages in viticulture.
4. What does an energy audit contribute to the transition of a vineyard to renewable energies?
5. Define a hybrid energy system and give an example applied in wineries.

Block 5: Energy transition in the wine industry

1. It identifies the stages of the wine cycle that concentrate the most energy consumption and GHG emissions.
2. It explains the concept of carbon footprint and the difference between scopes 1, 2 and 3 according to the GHG Protocol.
3. He mentions three strategies to reduce a winery's carbon footprint and its environmental impact.
4. What are the advantages of the International Wineries for Climate Action (IWCA) certification?
5. It defines what Agrivoltaics is and describes how it can be applied in vineyards.

Annex II – Didactic Activity: "Design a sustainable vineyard"

You will be part of the technical team of a winery that wants to transform its conventional vineyard into a sustainable, efficient and resilient production system to climate change. To do this, you must design an agroecological and energy transition plan, applying the knowledge studied in the module on soil, water, biodiversity, energy and climate change mitigation.

Initial information of the fictitious vineyard

- **Location:** inland area with a semi-arid Mediterranean climate
- **Area:** 25 hectares of trellised vineyards
- **Soil:** sandy-loam texture, scarce organic matter, signs of erosion
- **Current management:** intensive tillage, without vegetation covers, scarce auxiliary fauna
- **Water:** sprinkler irrigation, without sensors, high consumption and inefficient
- **Fertility:** use of synthetic chemical and phytosanitary fertilizers
- **Energy:** total dependence on mains electricity and diesel for machinery
- **Emissions:** high greenhouse gas (GHG) emissions
- **Costs:** rising energy bills and low resource efficiency

Your mission is to draw up a sustainable transition plan for the vineyard, which must include the following sections:

1. Soil management and fertility

- **Propose strategies to improve soil health and fertility (e.g., vegetation cover, reduction of tillage, compost or biofertilizers).**
- **Explain how each measure improves the properties of the soil and its relationship with the quality of the grape.**

2. Efficient water management

- **Design a new, more efficient irrigation system (e.g., drip, controlled deficit irrigation, humidity sensors, AquaCrop model).**
- **Indicate how your decisions can reduce water consumption and associated energy expenditure.**

3. Functional biodiversity

- **Propose actions to promote biodiversity (e.g.: hedges, green corridors, nest boxes, auxiliary plants).**

- **Explain how these actions contribute to natural pest control and vineyard resilience.**

4. Energy transition

- **Propose measures to reduce energy consumption and replace fossil sources with renewable ones (e.g. photovoltaic, biomass, geothermal, hybrid systems).**
- **Explain how these measures can improve self-sufficiency and reduce GHG emissions.**

5. Climate strategy and market value

- **Indicate how your proposal will help reduce the winery's carbon footprint (taking into account scopes 1, 2 and 3 of the GHG Protocol).**
- **Choose one or two environmental or sustainability certifications (e.g. International Wineries for Climate Action or B Lab) that the winery could obtain, and explain how they would improve their brand image and access to premium markets.**