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Francisco Javier Carroquino Oñate

Sistemas de energía renovable en las áreas rurales: una demostración en el sector vitivinícola

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SISTEMAS DE ENERGÍA RENOVABLE EN LAS ÁREAS RURALES: UNA DEMOSTRACIÓN EN EL SECTOR VITIVINÍCOLA

Autor

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Escuela de Doctorado
Marzo 2019

TESIS DOCTORAL

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Por compendio de publicaciones:

1. Carroquino, J.; Dufo-López, R.; Bernal-Agustín, J. L. Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops. Renewable Energy 2015, 76, 566–574, doi:10.1016/j.renene.2014.11.069.

2. Carroquino, J.; Roda, V.; Mustata, R.; Yago, J.; Valiño, L.; Lozano, A.; Barreras, F. Combined production of electricity and hydrogen from solar energy and its use in the wine sector. Renewable Energy 2018, 122, 251–263, doi:10.1016/j.renene.2018.01.106.

3. Roda, V.; Carroquino, J.; Valiño, L.; Lozano, A.; Barreras, F. Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell. International Journal of Hydrogen Energy 2018, doi:10.1016/j.ijhydene.2017.12.171.

4. Garcia-Casarejos, N.; Gargallo, P.; Carroquino, J. Introduction of renewable energy in the Spanish wine sector. Sustainability 2018, 10, doi:10.3390/su10093157.

5. Carroquino, J.; Bernal-Agustín, J.-L.; Dufo-López, R. Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case. Sustainability 2019, 11, 951, doi:10.3390/SU11040951.

Autor: Fco. Javier Carroquino Oñate

Directores: José Luis Bernal Agustín y Rodolfo Dufo López

Universidad de Zaragoza

A la memoria de mis padres,
a Lola
y a mis hijas

Sistemas de energía renovable en las áreas rurales:
una demostración en el sector vitivinícola

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Sistemas de energía renovable en las áreas rurales: una demostración en el sector vitivinícola

II – INTRODUCCIÓN

Presentación de las publicaciones y temática

El compendio consta de cinco artículos publicados en revistas con índice de impacto JCR:

1. Carroquino, J.; Dufo-López, R.; Bernal-Agustín, J. L. Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops. Renewable Energy 2015, 76, 566–574, doi:10.1016/j.renene.2014.11.069.

   Factor de impacto 2015: 3,404 (Q2) *Subject Category: Energy and Fuels.*

2. Carroquino, J.; Roda, V.; Mustata, R.; Yago, J.; Valiño, L.; Lozano, A.; Barreras, F. Combined production of electricity and hydrogen from solar energy and its use in the wine sector. Renewable Energy 2018, 122, 251–263, doi:10.1016/j.renene.2018.01.106.

   Factor de impacto 2017: 4,900 (Q1) *Subject Category: Energy and Fuels.*

3. Roda, V.; Carroquino, J.; Valiño, L.; Lozano, A.; Barreras, F. Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell. International Journal of Hydrogen Energy 2018, doi:10.1016/j.ijhydene.2017.12.171.

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4. Garcia-Casarejos, N.; Gargallo, P.; Carroquino, J. Introduction of renewable energy in the Spanish wine sector. Sustainability 2018, 10, doi:10.3390/su10093157.

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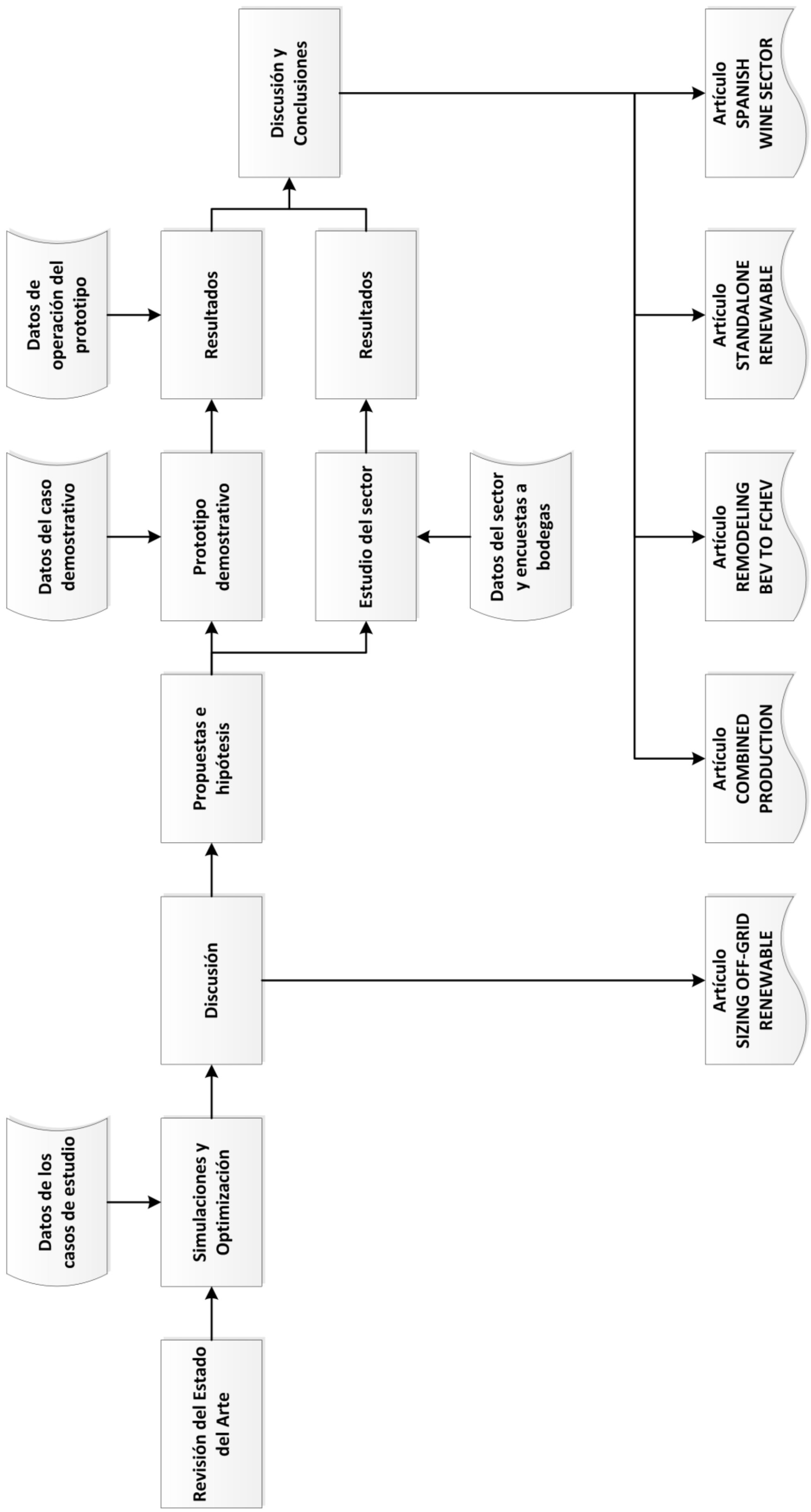
5. Carroquino, J.; Bernal-Agustín, J.-L.; Dufo-López, R. Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case. Sustainability 2019, 11, 951, doi:10.3390/SU11040951.

   Factor de impacto 2017: 2,075 (Q2) *Subject Category: Environmental Sciences.*

El título y temática de la tesis es Sistemas de energía renovable en las áreas rurales: una demostración en el sector vitivinícola. Los artículos del compendio corresponden al desarrollo de la tesis, mostrado en el esquema de la página siguiente. La primera fase de la tesis abordó seis casos de estudio de riego en cultivos mediterráneos de viñedo y olivar, dimensionando los sistemas óptimos de generación renovable. Al término de esa fase, se elaboró el primer artículo *"Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops"*. En la segunda fase, se abordó el diseño de un prototipo de sistema de energía renovable para viñedo. Dicho prototipo incluye la producción de hidrógeno. El diseño y los resultados se abordan en los artículos *"Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case"* y *"Combined production of electricity and hydrogen from solar energy and its use in the wine sector"*. El hidrógeno producido se utilizó en un vehículo eléctrico al que se le incorporó una pila de combustible, cuyo diseño y resultados se abordan en el artículo *"Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell"*. Finalmente, se estudió la disposición del sector del vino español a incorporar sistemas de energía renovable y se identificaron las vías para fomentar su adopción, en el artículo *"Introduction of renewable energy in the Spanish wine sector"*.

Esquema del desarrollo de la tesis



TESIS

Compendio de publicaciones

Sistemas de energía renovable en las áreas rurales: una demostración en el sector vitivinícola

III- COPIAS DE LOS TRABAJOS

Artículo

Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops

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Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops

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ABSTRACT

In the Mediterranean region, there are many drip irrigation systems with pumps that are powered by diesel generator sets (gensets). Although they could be powered by renewable energy produced on-site, technical and economic factors make that difficult. Moreover, the seasonal nature of demand requires an oversizing of energy generation and/or storage, increasing system costs. In this paper, we sought renewable energy systems that were economically optimal. We focused on six farming facility case studies to find the optimal energy generation solution using a simulation and optimization tool based on genetic algorithms. Photovoltaic-diesel hybrids and diesel systems were found to be optimal, with energy costs from 0.13 to 1.08 €/kWh and from 0.32 to 0.52 €/kWh, respectively. The strong effect of demand management was an interesting finding, as it may indicate significant system size and cost reductions. In addition, the optimum photovoltaic fixed tilt angles depended not only on the seasonal profile of the demand, but also on the pumping schedule. Although the difference between market interest rates and the rise of fuel prices strongly influences the advantage of incorporating, or not, renewable generation, this study supports that hybrid photovoltaic-diesel systems can make profitable use of renewable energy in drip irrigation.

1. Introduction

The use of renewable resources to replace fossil fuels brings sustainability, independence, and cleanliness. These advantages are especially remarkable in rural and agricultural areas [1,2]. Additionally, it is not always profitable or convenient to build electrical grid extensions. In fact, diesel gensets are widely used in rural areas because of their simplicity and low purchase price [3]. Drip irrigation, in which water is pumped to reach the proper pressure, is a typical installation that frequently uses gensets, as the electric grid is not often available. In many cases, water is also extracted from underground by pumping, with or without a storage pond.

Vines and olive trees are typical Mediterranean crops that have similar watering needs and for which drip irrigation is usually used [4]. Moreover, these plants' annual watering needs are concentrated in a few months. This very seasonal demand behaviour is an obstacle to the incorporation of renewable generation [5,6]. Power supply continuity and stability are therefore needed, in contrast to the variability of solar and wind resources. These challenges have pushed us to study the economic feasibility of renewable energy integration by searching for systems specially adjusted to this kind of application [7].

A recent work that reviewed the numerous studies in the literature [8] about pumping systems powered by renewable energy also identified their limitations. Among the future research lines suggested, further development of hybrid systems, more advances in the study of technical and economic feasibility, and better knowledge of the influence of photovoltaic tilt angle stand out.

Our main hypothesis was that renewable energy systems may become market-competitive against grid extension or diesel gensets in the agriculture field [9,10]. In this sense, some studies have shown the competitiveness of photovoltaic versus diesel generation in irrigation when agricultural cultivation is shared with household electricity supplies [11]. In fact, many easy and simple options can be applied without electricity storage, such as direct pumping, using wind turbines, photovoltaic panels, or both [12]. Nevertheless, power delivery is not constant in these methods and, particularly for wind energy, can be zero for several consecutive days. This variability is inherently incompatible with drip irrigation.

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Therefore, the need for stable energy sources could mean renewable generation might not be technically and economically feasible [13]. A proposed solution is to achieve the required constant pressure by water accumulation in an elevated tank [14]. This requires a large storage tank to equalize the strong fluctuations in renewable resources. However, because of the large volume of water required, it is hardly feasible and extremely expensive except on very small farms. Under these conditions, it is necessary to consider electric storage to ensure a continuous and stable power supply. Thus, hybrid wind-photovoltaic systems with energy storage [15,16] and renewable-diesel hybridization [17] may be considered potential solutions to the stated problem. Regarding photovoltaic systems, the optimal tilt angle depends on geographic latitude, but it also can be affected by the relationship between solar radiation and energy demand in the period under consideration [18–21]. Indeed, the seasonality of the energy demand for irrigation pumping warrants further research.

To our knowledge, no study has been conducted to ascertain how the characteristics of drip irrigation facilities determine the optimum design and sizing of hybrid renewable energy systems. In our study, we looked for the viability and optimal size of renewable energy systems to power drip irrigation facilities in comparison with existing diesel generation. Moreover, we expanded the search to diesel hybrid systems, taking into account the full range of solutions, from 100% renewable to 100% diesel and various combinations thereof. In addition, we also addressed a highly seasonal demand, this being one of the keys in our research. Our first objective was to demonstrate the technical and economic feasibility of the renewable energy systems for powering drip irrigation facilities that are common in the Mediterranean area. In the same vein, we wanted to determine the characteristics that were economically optimal for that use.

2. Methodology

2.1. Hybrid power system

Fig. 1 shows the actual and usual drip irrigation system with pumps that are powered by diesel generators and the proposed hybrid power system [22] for the study cases analyzed in this paper. In the hybrid power systems, all possible components have been represented, but in several cases only some of them will be part of the system. For example, in a location where the wind is not sufficiently high, the wind turbine should not be present.

The diesel generator is a source of electrical energy that is independent of meteorology. If renewable generation and storage are not considered, the gensets are a widespread solution for isolated

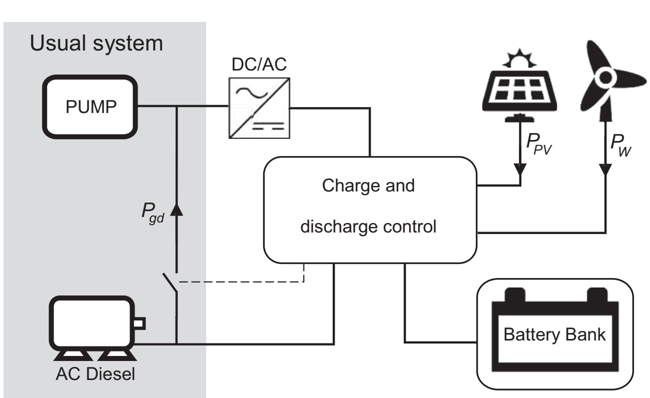

Fig. 1. Proposed hybrid power system.

pumping systems. However, they may also be useful as a backup source in hybrid systems. Simulations in this study considered all those possibilities. Also, considering the life cycle's equivalent CO_2 emissions (the emissions in the manufacturing, transporting, and decommissioning of the PV panels, batteries, and other components), they are high enough in many cases to make the diesel generator a good option to be added in the hybrid system; i.e. hybrid systems with diesel generators in many cases release less life cycle emissions than systems that do not include diesel. Systems without diesel generators must be over-dimensioned (large PV generators, large battery banks, etc.) to supply the whole load during periods of low renewable sources. This implies that their life cycle emissions can be higher than if the system includes a diesel generator (where the PV generator, battery bank, etc. can be much smaller) [23].

The diesel generator can be controlled using the “cycle charging” or “load following” strategy [24]. Using the cycle charging strategy, when the battery state of charge (SOC) is below a given threshold and the renewable sources cannot provide sufficient power to recharge it, the diesel genset is called upon to deliver its maximum power (to supply the net load and charge the batteries until a specific SOC is reached, usually 90 or 95%). With this strategy the diesel genset is operated at close to its optimal load factor, improving the fuel efficiency of the generator and reducing maintenance costs. Using the “load following” strategy, the diesel genset starts in order to generate the power demanded by the pump, but the battery bank is not charged. The diesel genset is used to charge the battery bank only if the user connects the charger manually. With this strategy, if the irradiation is very low for a period of time, then it is habitual for the user to charge the battery bank using the genset.

2.2. Case studies and demand data

To base our study on actual power needs for irrigation pumping, we selected six existing drip irrigation facilities of different sizes and locations. All of them are situated in main viticultural zones of the Aragon region in the Ebro basin, located in the northeast of Spain. This relatively small Spanish region can be considered significant in cultivation of the vine, both for itself and for its proximity to some of the largest vineyard regions in Spain (Castilla La Mancha, La Rioja, Navarra, Ribera del Duero, Catalonia, etc.). They all add up 771,374 ha of crops, a large portion of the total 954,020 ha of vines in Spain. The six pumping systems are powered by diesel fuel and have been operating for several years. In two cases (Pueyez and Tallaqueso), water comes from surface ponds that are filled by gravity. In these, a single surface pump is required to push the water through a pressurized irrigation system. In two cases (Merla and Bancales), a submersible pump extracts water from a well to the surface pond and a surface pump drives it from the pond to the irrigation system. Because of water accumulation in the pond, the management of the submersible pump can be somewhat independent of the management of the irrigation pump. In the other two cases (Masatrigos I and Masatrigos II), a single submersible pump draws water from the well while at the same time activating the irrigation system. In these latter cases, no pond is required. A compendium of characteristics of the irrigation facilities is shown in Table 1. For each case study, six datasets were obtained: solar resource, wind resource, water demand, system size, system management criteria, and power consumption.

The typical year demand was obtained through interviews and questionnaires with agronomists and technicians in charge of the crops. When possible, the data were compared with existing historical records of watering and were found to be consistent. Irrigation decisions were known to be made at specific intervals,

Table 1
General data of the irrigation facilities.

Facility name	Crop type	Water source	Pond	Pumps	Yearly watering (m^3)
Bancales	Vine	Underground	Yes	Submersible + surface	19,332
Masatrigos I	Vine	Underground	No	Submersible	30,000
Masatrigos II	Olive tree	Underground	No	Submersible	155,990
Merla	Vine	Underground	Yes	Submersible + surface	5400
Pueyez	Vine	Surface	Yes	Surface	10,000
Tallaqueso	Vine	Surface	Yes	Surface	17,500

usually weekly, taking into account the rainfall and weather, which can vary from year to year. On average, 1000 m^3/ha were needed on the vineyard annually, and 3000 m^3/ha in the olive grove. In terms of distribution throughout the year, crops are watered mainly in the spring and summer, and watering is very limited or non-existent the rest of the year. Choosing weekly intervals to quantify watering corresponds to the common uses of the studied farms.

There were no historical electricity consumption records available since these facilities are off-grid and without electricity meters. Regarding genset fuel consumption, historical data were insufficiently detailed, as they were limited to dates and amounts of tank refilling. In some cases, daily historical records of irrigation volume and monthly records of the amount of water extracted from groundwater wells were available. In view of this, we chose to calculate the energy demand from the water demand, leaving the limited data of diesel consumption just as a control dataset. The formula used for this calculation was:

$$E_e = E_h \times \left(\frac{100}{\eta}\right) = V \times H \times \left(\frac{\rho \times g}{3,600 \times 10^3}\right) \times \left(\frac{100}{\eta}\right) \tag{1}$$

where

E_e: electrical energy supplied to the pump motor [kWh]
E_h: hydraulic energy [kWh]
V: volume of water pumped [m^3]
H: total pumping head [m]
ρ: density of water [1000 kg m^{-3}]
g: standard gravity [9.8 m s^{-2}]
η: motor-pump efficiency [%].

The relationship between water volume and energy demand was different for each facility. This was mainly due to the different pumping heads, but it was also related to the different motor-pump efficiencies. The motor-pump efficiency was obtained from the manufacturer's technical sheets [25] in accordance with the measured electric and hydraulic parameters. To calculate the total pumping head, we considered suction head, discharge static head, friction head, and discharge pressure at the input of the pressurized irrigation system. In each case they were calculated from parameters of the pumping system (like the piping characteristics and the required pressure input of the drip irrigation system) and from measured parameters (like water flow and the depth of the water level in the well). For the drip irrigation systems studied, an input pressure of about 300 kPa (equivalent to an approximately 30-m water column) was required. The total pumping heads ranged from 30 m to 180 m. The result of multiplying the volume of water pumped by the pump head is called pumping demand, and it is useful for comparing the hydraulic energy requirements in different cases.

In addition to the electrical energy supplied to the pump motor, we considered increased energy requirements to compensate for a 1% power loss in the power line of surface pumps. In the submersible pumps, we raised this figure up to a 3% loss due to the greater length of the feeder line. The amount of fuel needed in order to produce this electricity was obtained from the specification data curves of the genset manufacturer [26]. Yearly pumping demand, fuel consumption, and energy required to replace a diesel genset with electric powering are shown in Table 2.

Finally, the yearly power demand obtained for the six case studies on a weekly basis, accordingly with the yearly irrigation criteria obtained from users, is shown in Fig. 2. Beyond determining the energy demand, we studied the possibilities of managing it. In each irrigation facility, watering is accomplished by pump operation for a variable daily period. The weekly water demand could be satisfied by a few hours of daily watering. Additionally, when more than one pump was available, they could be operated simultaneously or with different schedules. Consequently, demand side management was possible.

2.3. Renewable resources

Sensors for wind speed, wind direction, and solar irradiation were installed in the studied locations. However, these measurements had only been recorded for one year at the time of the writing of this paper. This period is insufficient because of interannual variability. In order to determine a typical year, several years of data are needed. Therefore, available databases were used to obtain the data from renewable resources used in this study. Data measured by sensors were fully consistent with those obtained from external sources. A summary of the average yearly data is presented in Table 3. Solar irradiation data were obtained from the CM-SAF-PVGIS database [27]. The average sum of global irradiation per square metre on the horizontal plane was similar in all the case studies.

Annual irradiation on Masatrigos I and II is shown in Fig. 3. Daytime average temperatures for Masatrigos I and II are shown in Fig. 4. Wind resources were obtained from IDAE [28]. Average wind speeds for Masatrigos I and II are shown in Fig. 5. The other studied locations presented similar climate characteristics.

2.4. Simulation and optimization

Several methods are currently available for off-grid electricity supply analysis [29]. Among the different models and methods for optimization [30–32], we decided to use HOGA (Hybrid Optimization by Genetic Algorithms) software [33,34]. This software works with hourly data of demand and resources. Systems with different combinations of components were tested, simulating their operation for a year as well as their economics along the life cycle. Systems complying with the technical requirements were sorted by cost. The search for optimal solutions was done using genetic algorithms.

The main input data in HOGA were system components, electricity demand, renewable resources, technical parameters, and

Table 2
Pumping, fuel and energy demand.

Case name	Yearly data		
	Pumping demand (m^4)	Fuel consumption (l)	Electric energy (kWh)
Bancales	4,000,110	5692	21,336
Masatrigos I	3,900,000	5400	17,722
Masatrigos II	20,278,700	19,638	79,412
Merla	648,000	1157	3185
Pueyez	300,000	640	1443
Tallaqueso	1,067,500	1956	6394

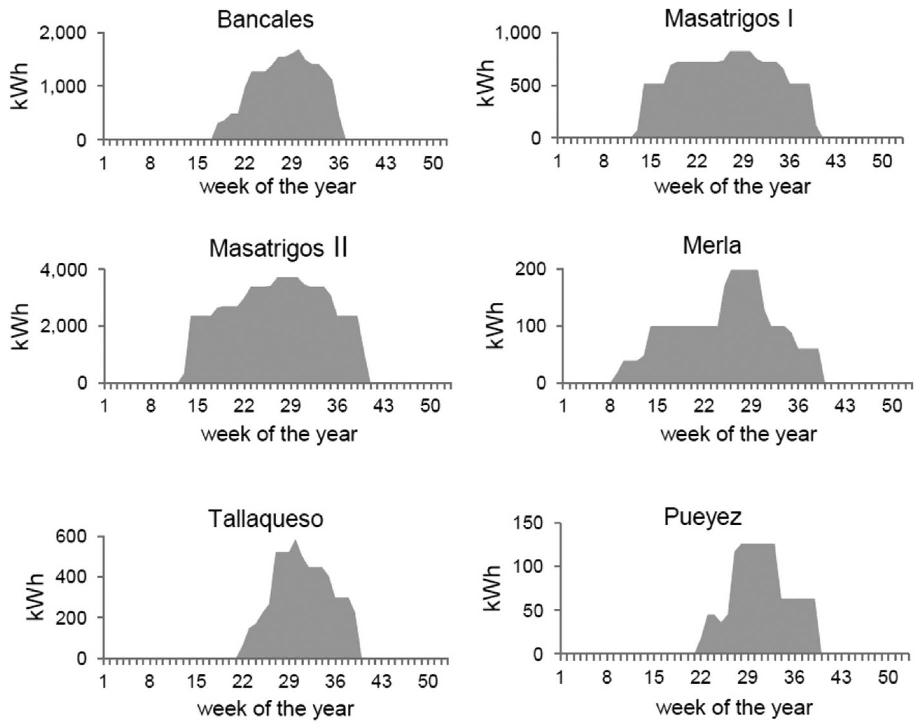

Fig. 2. Yearly electric energy demand for the six case studies.

economic parameters. We considered three types of generation (wind, solar, and diesel) with or without hybridization and electrical storage. For each element type, functional and economic characteristics of several commercially available components were obtained from the manufacturer's datasheets [26,35–40].

As for the batteries, C10 capacity was considered. The minimum allowed state of charge was 20%. Expected battery life was calculated using the Ah model from those available on HOGA. Regarding other components, standard lifetimes were introduced. The genset's output power may be considered one of the sizing parameters to optimize [41]. Component costs are shown in Table 4. The ranges of unit costs were due to the different component sizes, with the lowest unit cost corresponding to the larger size.

Average monthly wind speed and monthly solar radiation were introduced in HOGA for each one of the six case studies. From these monthly data, HOGA software is able to generate annual series of hourly wind speed and solar radiation data [42]. Among the different models available in HOGA for the solar resource, we chose

Table 3
Yearly wind speed and irradiation.

Case name	Average wind speed (30 m high; m s^{-1})	Irradiation on horizontal plane (kWh m^{-2})
Bancales	4.49	1616.95
Masatrigos I	4.57	1671.70
Masatrigos II	4.57	1671.70
Merla	4.77	1675.35
Pueyez	3.28	1708.20
Tallaqueso	3.29	1700.90

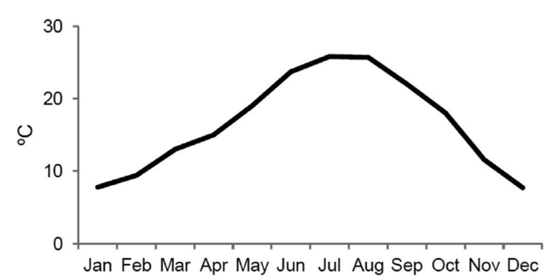

Fig. 4. Average daily temperature for Masatrigos I and II.

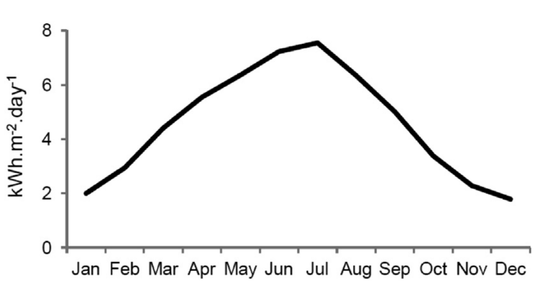

Fig. 3. Average solar irradiation on Masatrigos I and II.

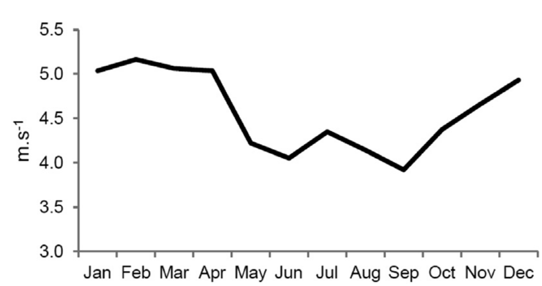

Fig. 5. Average wind speed for Masatrigos I and II.

Table 4
Component costs.

Component	Type	Cost
PV panels (mounted)	Polycrystalline Si	1.20 €/W_p
Wind turbines	6 kW–35 kW	1.71 to 2.00 €/W
Batteries	Lead-acid vented cells	0.23 to 0.47 €/Wh
Inverters	Off-grid hybrid systems	0.62 to 0.95 €/W
Gensets	Oil-cooled	0.12 to 0.40 €/W

the model of Liu and Jordan [43], as we were working with typical years and did not want to introduce statistical variability that could affect the comparisons.

The tilt angle of photovoltaic panels was one of the variables that were optimized. In the simulations, we considered that the azimuth of the PV array was south and the tilt angle was fixed. Simulations were conducted with different fixed tilt angles for a full year to identify optimal tilt angles for each case.

As it was possible to manage the system with different schedules, we carried out two sets of simulations: one with a diurnal operation schedule and the other with a nocturnal operation schedule. In diurnal schedules, energy is consumed during the sun's peak hours. In contrast, with nocturnal operation schedules, consumption occurs in the absence of production. The power consumption and schedules of the six case studies when watering was diurnal are shown in Fig. 6, whereas power consumption and schedules when watering was done at night appear in Fig. 7. In both cases, the schedules shown correspond to the days with the highest demand of the year.

The economic parameters were derived from historical data [44] and correspond to a conservative scenario with a 2.94% discount rate and a 6% increase in diesel fuel prices. Subsidies were not taken into account. The study period was 25 years, and the objective function to be minimized was the Net Present Cost (NPC), given by.

$$NPC = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \quad (2)$$

where

NPC: Net Present Cost [€]
C_n: cost in period n (investment, O&M, replacement, and fuel costs) [€]
N: analysis period
d: annual discount rate

The levelized cost of energy (LCE) was also calculated to compare the energy production costs:

$$LCE = \frac{NPC}{\left\{ \sum_{n=1}^{N} \left[Q_n/(1+d)^n \right] \right\}} \quad (3)$$

where

LCE: Levelized Cost of Energy [€/kWh]
Q_n: energy in year n [kWh]

3. Results and discussion

The results obtained in the optimization process are shown in Table 5. The table is divided in two parts according to the pumping operation schedule (diurnal or nocturnal). For each case study, the best solution is labelled with the number 1. The following solution with different mixes of generation is shown with the number 2. It is noted that all renewable solutions incorporate electric storage to

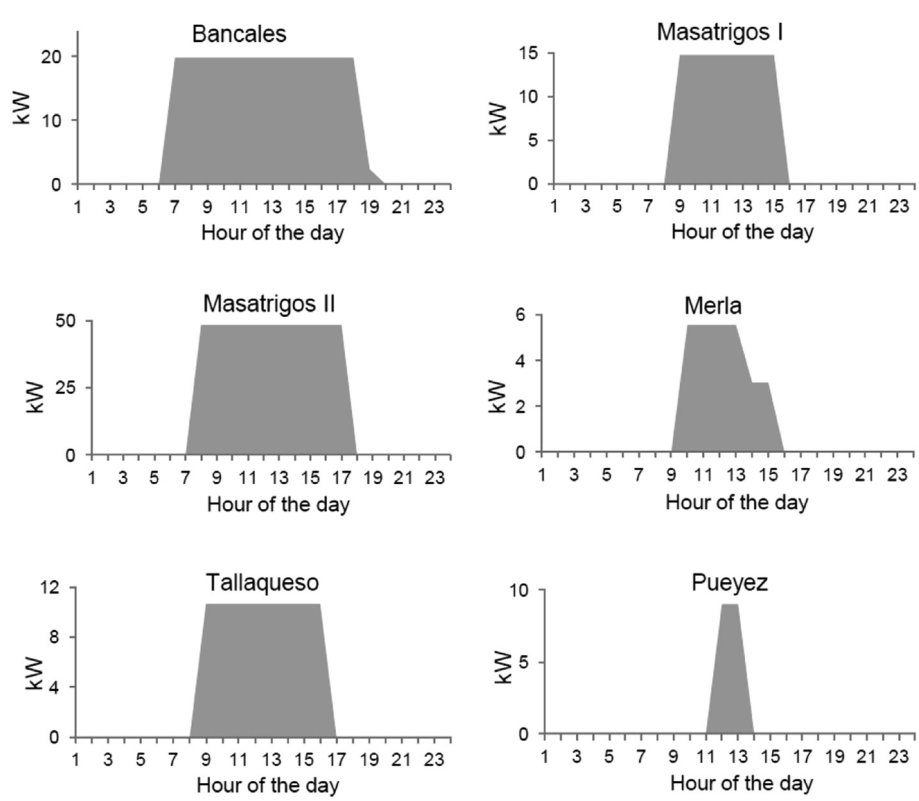

Fig. 6. Graphic of diurnal schedules.

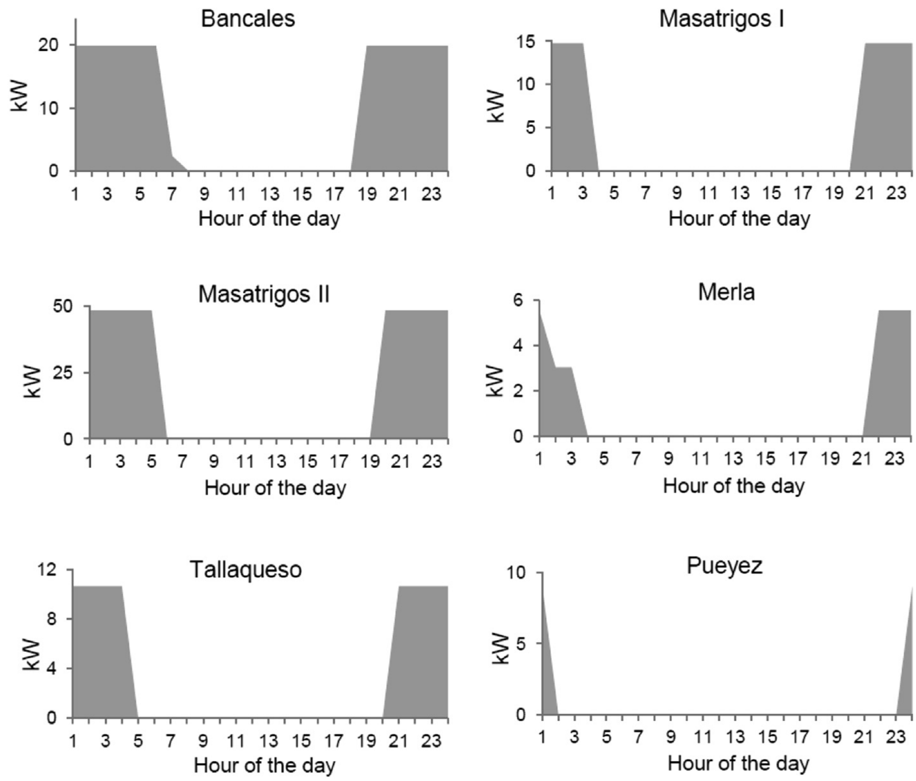

Fig. 7. Graphic of nocturnal schedules.

deliver constant power and even to allow night operation if applicable.

3.1. Hybridization results

In all cases, the optimal solution included a diesel genset. Furthermore, the genset was also present in the second option in five of the six cases. However, the genset alone (i.e. the pre-existing solution) was not the optimal solution in most cases. In contrast, in hybrid solutions the fraction of energy from diesel was low, especially during daylight watering. The simulation results showed that, in hybrid solutions, the diesel genset worked very few hours per year. In fact, the genset typically came into action on days of both high demand and overcast skies. In the studied areas, the high watering season corresponds to sunny weather with generally cloudless skies and intense sunshine. The presence of a diesel genset in the mixed solution allows reaching an unmet load equal to zero, providing continuous supply. The solutions without diesel needed much larger renewable energy, which put them far away from the economic optimum target.

In no cases did the best solution include wind turbines. They only accompanied photovoltaic generation in the second best solutions in three of four locations with average yearly wind speeds greater than 4 m s^{-1} (Masatrigos I, Masatrigos II, and Bancales). In general, the addition of wind generation did not produce a significant increase in the renewable energy fraction, nor did it allow a significant reduction in the power of the photovoltaic generator. In light of previous graphs (Figs. 2, 3 and 5), it is reasonable to conclude that the seasonal pattern of the solar resources is closer to the demand than is the seasonal wind pattern.

3.2. Nocturnal versus diurnal schedules

Obviously, diesel-only generation operates identically in diurnal and nocturnal schedules, running only while the pumping is active. In contrast, photovoltaic generation is greatly conditioned by the schedule of choice. In the nocturnal schedule, diesel alone was more efficient in four of the six case studies, and the best solution was photovoltaic-diesel in only two cases—and even in those cases, the advantage over diesel was very slight. However, in diurnal schedules photovoltaic technology was favoured, becoming part of five of the six best solutions. Simultaneously, the amount of electric storage needed was substantially reduced. This may be related to the fact that the charging and discharging cycle of the battery is typically associated with a loss of about 20%. In the daytime schedule, photovoltaic energy production is relatively concurrent with demand. In contrast, in nocturnal schedules, all the energy is cycled through the batteries, and as a result, increased capacity is needed. Therefore, with nocturnal schedules, the production profile during the day does not matter, only the total amount of energy stored during it. Additionally, with nocturnal schedules, the battery's charge and discharge cycles are deep every day during the irrigation season. Thus, diurnal schedules provide longer battery life, resulting in lower long-term costs. All these facts suggest that diurnal watering schedules are preferred when using renewable energy with this type of irrigation system. If the pumping schedule includes hours of diurnal and nocturnal operation, the technical and economic results prescribe a mixture of both.

3.3. PV tilt angle results

The latitudes of the six case studies' locations are between 41°14′N and 42°05′N. Despite this proximity, we found that optimal tilt angles varied from one case to another. In addition, different tilt angles at each location were obtained depending on daily and nightly energy demand. In general, these optimum tilt angles did not correspond with those obtained by the usual procedures. Usually, the aim is to maximize the incident solar radiation in the long term, either by simple calculations relating to the latitude of

Table 5
Results of the optimization.

		Pumping system		Hybridization				PV		Wind	Diesel		Battery	Renewable	Economic results		
		Power (kW)	Yearly demand (kWh)	Solution	PV	Wind	Diesel	Tilt angle	kW_p	kW	Hours by year	Energy fraction (%)	Capacity C10 (kWh)	energy surplus (%)	Initial investment (€)	NPC (€)	LCE (€/kWh)
Daylight	Bancales	18 + 2	21,336	1	X		X	−4°	38	0	52	2.9	45	59	81,050	127,666	0.24
				2	X	X	X		35	5.76	59	3.2	45	60	89,159	140,703	0.26
	Masatrigos I	15	17,723	1	X		X	21°	25	0	8	0.5	13	56	50,062	81,124	0.18
				2	X	X	X		24	11	7	0.3	13	64	69,408	103,051	0.23
	Masatrigos II	48	79,412	1	X		X	18°	88	0	23	0.9	161	44	187,578	263,558	0.13
				2	X	X	X		81	35	11	0.5	161	58	244,042	324,962	0.16
	Merla	6 + 3	3185	1	X		X	10°	7	0	5	0.6	5	71	17,493	32,722	0.41
				2			X	–	0	0	675	100	0	–	3050	34,049	0.43
	Pueyez	9	1443	1			X	–	0	0	160	100	0	–	4682	18,843	0.52
				2	X			30°	5	0	0	0	26	79	18,799	36,524	1.01
	Tallaqueso	11	6394	1	X		X	15°	15	0	11	1.2	8	75	34,609	57,450	0.36
				2			X	–	0	0	600	100	0	–	4682	63,051	0.39
Nocturnal	Bancales	17 + 2	21,336	1			X	–	0	0	1173	100	0	–	6916	193,901	0.36
				2	X		X	9°	25	0	485	37	200	54	97,492	227,623	0.43
	Masatrigos I	15	17,723	1	X		X	15°	24	0	11	0.6	200	41	89,322	157,647	0.36
				2			X	–	0	0	1200	100	0	–	5692	163,182	0.37
	Masatrigos II	48	79,412	1	X		X	23°	97	0	132	4.9	734	42	324,503	596,396	0.30
				2	X	X	X		77	35	97	4.3	869	52	382,438	601,545	0.30
	Merla	6 + 3	3185	1			X	–	0	0	675	100	0	–	3050	34,049	0.43
				2	X		X	9°	4	0	129	13.6	32	38	18,986	44,864	0.56
	Pueyez	9	1443	1			X	–	0	0	160	100	0	–	4682	18,843	0.52
				2	X			23°	5	0	0	0	32	79	20,231	38,961	1.08
	Tallaqueso	11	6394	1			X	–	0	0	600	100	0	–	4682	63,051	0.39
				2	X		X	13°	11	0	134	18.8	80	63	44,376	85,775	0.54

the site or by methods that are more complex [18,20]. Thus, the maximum energy production is obtained, but it does not take into account the power profile over time. This is suitable for on-grid generation, but not for stand-alone systems. In these, it is important that the production fit as much as possible to the demand over time in order to minimize storage, the associated losses, and surplus energy.

Because of the need to handle large amounts of data such as solar trajectory and the demand curve for a year and for different system configurations, genetic algorithms are a useful tool for finding the optimum tilt angle in this kind of system. By optimizing the tilt angle, the required PV power was slightly reduced by between 6% and 0% depending on each case. The improvement appeared to be related to the adaptation of the generation curve to the power demand curve. If the schedule is nocturnal, daily production should be maximized. However, if the schedule is diurnal, hourly adaptation between production and demand comes into play. The energy that is directly consumed is more efficient than the energy cycled through the batteries, because of the associated losses.

In the Bancales case, in diurnal operation, a slightly negative tilt angle was obtained, which means that panels should be slightly oriented to the north. We did extensive testing to confirm this result. This guidance relates to the fact that in summer the sun rises in the northeast and sets in the northwest. The daily operation time during summer in Bancales (see Fig. 6) is the longest, starting near sunrise and ending near sunset. Thus, the small north-facing tilt has the effect of flattening the daily curve of energy production, favouring the early and late hours to the detriment of the hours around noon. More detailed studies that go beyond the scope of this paper are needed.

3.4. Economic results

The NPC was used to find the economically optimal solution in each case. On the other hand, the levelized cost of energy (LCE) was useful to compare the results of the different cases. These results are also shown in Table 5. Among the various cases studied, there are differences in size, which might cause some economies of scale in favour of larger ones. This happened in both types of generation, photovoltaic and diesel. Another key parameter of each system was the number of pumping hours per year, which varied from a minimum of 160 to a maximum of 1642 h/y. LCE versus pumping hours per year plots are shown in Fig. 8 for the six case studies. For the sake of comparison, LCE results corresponding to diesel generation, i.e. without renewable generation, and hybrid generation, working in both diurnal and nocturnal schedules, are presented. In the case of diesel generation, the differences in LCE ranged from 0.32 to 0.52 €/kWh. In contrast, hybrid photovoltaic-diesel solutions working in a nocturnal schedule exhibited greater differences in LCE, ranging from 0.30 to 1.15 €/kWh. It is remarkable that with few operation hours per year, energy in hybrid solutions was expensive and the left side of the curve moved away from that of diesel. This was due to the increased need for storage. Finally, LCE lay from 0.13 to 1.08 €/kWh for photovoltaic-diesel generation operating during a diurnal schedule. Although the differences in LCE were similar regardless of the operating schedule, in diurnal operation LCE values were shifted down due to the lower cost of energy. This occurs because most of the energy is used without being cycled through the batteries, avoiding the associated losses. The improvement in LCE changing from nocturnal to diurnal operation in Pueyez was only 1.08 €/kWh to 1.01 €/kWh. However, the improvement in Masatrigos II was much higher, from € 0.30/kWh to 0.13 €/kWh. While it was consistently a lower cost of energy in diurnal pumping for the six cases, the improvement was much

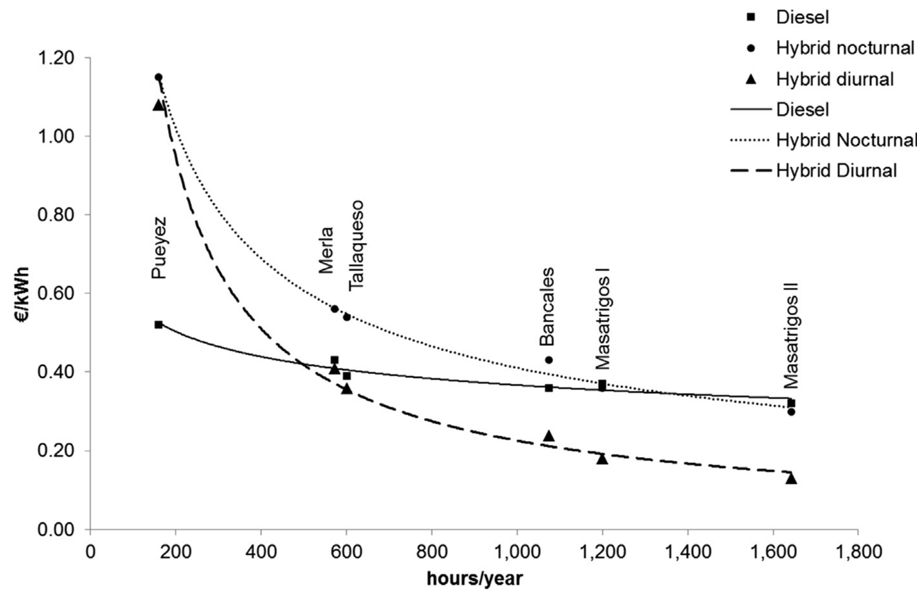

Fig. 8. LCE of diesel, hybrid (nocturnal schedule), and hybrid (diurnal schedule) systems.

larger if the number of pumping hours was high. Again, this was due to the lower need for storage.

The number of operating hours depended on the proportion between the water volume needed and the flow rate delivered by the pumps. When comparing the LCEs of the different facilities, the best results were obtained for those facilities incorporating relatively smaller pumps, as they corresponded to a high number of operating hours. This is due to energy loss reductions associated to energy cycling, as were size and cost reductions of batteries and inverters.

3.5. Sensitivity results

Sensitivity analyses regarding average yearly wind speed, discount rate, photovoltaic panel prices, and inflation of fuel prices were performed. We did not perform sensitivity analyses on the cost of small wind turbines, inverters, or other equipment, since they have reached a relative stability in the European market. Obviously, if the price of panels decreases, photovoltaic hybrid systems solutions will be favoured in comparison with 100% diesel solutions. We also did no sensitivity analysis regarding the magnitude of the solar resource, as it is similar in the studied area. However, wind resources vary widely. In the agricultural areas studied, the average yearly wind speeds at 10–30 m height (the hub height of the wind turbines suitable for these systems) are not very high, rarely more than 5 m/s. The analysis result was that even with a higher average wind speed, the improvement was not large enough, and therefore wind turbines were not considered among the best solutions.

There was a high sensitivity to changes in the discount rate. Renewable generation disappeared from the optimal solutions if the discount rate increased between 2 and 4 points, according to each case. This occurred because renewable generation requires a large initial investment, while fuel has an annual cost that is reduced when translated to the starting point for the calculation of the NPC. The same happens if the inflation rate of fuel price is reduced between 2 and 4 points, depending on each case. In fact, one of the parameters clearly influencing the advantage of incorporating renewable generation was the difference between the discount rate and the inflation of fuel prices. If the first one decreases and/or the second one increases, renewable energy is favoured versus diesel.

4. Conclusions

In the present study, we addressed the economic feasibility of incorporating renewable energy systems into pumping for drip irrigation facilities in the Mediterranean area. These facilities exhibit characteristic demands that have not been previously studied in terms of their influence on the design and the sizing of hybrid renewable energy systems. In the six case studies, we identified that their energy demand had a seasonal pattern relatively similar to that of the solar resource throughout the year. The watering season matched the months of maximum solar radiation. In contrast, the seasonal behaviour of the wind resource was the opposite, with minimums during the watering season. Therefore, wind turbines were not present in the best solutions. The optimal economic solutions to incorporate renewable energy were photovoltaic-diesel hybrid systems. The LCE obtained with the economic parameters considered ranged from 0.13 to 1.01 €/kWh, depending on each case study. The presence of diesel gensets in renewable energy hybrid systems eliminated the need for oversizing renewable generation. In hybrid solutions, the genset had only a few hours of operation per year, and the fraction of renewable energy was very high. The low investment cost of a diesel genset made it the best solution to avoid oversizing the renewable generation and the associated budget overruns.

Additionally, irrigation systems with proportionally smaller pumps and more pumping hours happened to be more cost-effective.

Regarding photovoltaic generation, significant differences were found between diurnal and nocturnal pumping schedules. If the schedule is diurnal, most of the energy does not pass through the battery, avoiding its associated loss. Therefore, if the irrigation requirements allow it, systems designed for diurnal watering are preferred.

As for the photovoltaic tilt angle in the economically optimal systems, results did not correspond to what could be expected by usual procedures of sizing. In addition, significant differences were found between the angles of the various case studies and also between diurnal and nocturnal schedules. This finding seems to be related to the relationship between the generation curves and the power demand curves.

In all the case studies, the use of renewable generation would involve a high percentage of surplus energy outside the irrigation season. With lead-acid batteries, it is not feasible to store the energy produced for several months without demand, so alternative uses for the stored energy should be considered.

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Artículo

Combined production of electricity and hydrogen from solar energy and its use in the wine sector

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Combined production of electricity and hydrogen from solar energy and its use in the wine sector

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A B S T R A C T

In the present research, the energy demanded by the wastewater treatment plant of a winery and the pumping station of the irrigation system of a vineyard is supplied by a stand-alone renewable energy system formed by three photovoltaic arrays connected to a microgrid. A relatively small battery maintains the stability and quality of the energy supply acting as a short-term energy storage. Hydrogen is generated in a production and refueling plant specifically designed for this project, and it is eventually used in a plug-in BEV properly modified as a hybrid vehicle by adding a PEM fuel cell. On the one hand, the technical and economic feasibility of the on-site electricity production for the winery and vineyard, compared to the commercial electricity from the grid and diesel gensets, is demonstrated. On the other hand, the diesel savings by the hydrogen generated on site are assessed. The electricity (72 MWh) and hydrogen (1214 m^3) produced in the first year have saved the emission of around 27 tons of equivalent CO_2.

1. Introduction

Increasing the use of renewable energy sources (RES) in the energy mix has become a challenge for power engineers and scientists all over the world. Even when hybrid power systems based on RES (HRES) have attracted the attention of the sustainable energy market, the optimal use of either solar photovoltaic (PV) or wind power is difficult, specifically in local power grids. This is because of their fluctuating and intermittent nature, due to the dependence on meteorological conditions. Thus, standalone renewable energy sources cannot guarantee a reliable power supply. A typical solution to this problem is the use of HRES combining both short-term energy storage options (batteries, capacitors, flywheels, or compressed air) and long-term ones with hydrogen as energy storage. Hydrogen is considered the energy vector of the future, especially if it is produced from RES [1–5]. Different energy storage systems have been used to optimize the energy management of power systems based on single or multiple RES in the household sector, in applications such as plug-in battery electric vehicles (BEV) [6] or fuel cells [7–10].

In remote rural areas, the energy demand can be actually satisfied using HRES, but their introduction has been limited by the lack of economic viability and technical adaptation. Aerial power lines, which are very expensive, are normally extended in natural areas to distribute commercial electricity to the consumers. These infrastructures have a severe environmental impact affecting the skyline and, what is more important, killing both native and migratory birds, something especially serious in the case of endangered species. In the particular case of the wine industry, energy demands (irrigation, farming machinery, thermal processes, mobility, etc.) present strong seasonal cycles not only throughout the year but also during the day. Besides, fossil fuels are massively used both in transportation and on-site power generation, emitting CO_2 and other pollutants. Thus, in order to achieve standalone HRES with high reliability, which would contribute to their massive use in the wine sector, both short-term and long-term energy management systems must be considered [11,12].

In this research, a part of the energy demanded in a winery is supplied by the power produced from a PV energy system.

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Nomenclature

Acronyms

ATEX	Anti-explosion elements
BEV	Battery electric vehicles
CO_2-e	equivalent CO_2
ECU	Electronic control unit
EM	Electric machine of the BEV
EMS	Energy Management System
FC	Fuel cell
FCHEV	Fuel cell hybrid electric vehicles
GSS	Gas storage system
HEV	Hybrid electric vehicle
HPP	Hybrid power plant
HRES	Hybrid renewable energy systems
IRR	Internal rate of return (%)
NI	National Instruments
NPV	Net present value (€)
OS	Operative system
PEM	Polymer electrolyte membrane
PLC	Programmable logic controller
PV	Solar photovoltaic
PWM	Pulse-width modulation
RES	Renewable energy sources
SOC	State of charge of the battery
TAC	Total annual costs
WWTP + IS	Waste water treatment plant and irrigation system

Latin symbols

AE	Annual expenses (€)
C	Cash-flow
CoE	Energy cost (€)
CoL	Cost due to lifetime (€)
CoP	Power cost (€)
E	Energy consumed (kWh)
I_o	Initial investment costs (€)
Inf	Inflation (%)
K	Discount rate
P	Power consumed (kW)

Subscript

Bat	Battery system
CE	Commercial energy
DG	Diesel generation set
Gen	General
Inv	Inverters
PV	PV solar plant

Specifically, it includes the power consumed by the wastewater treatment plant (aerators), the pumping system for sludge, filtering and irrigation processes, a hydrogen production and refueling station, and the recharge of the battery system of an electric vehicle. To the authors' knowledge, this is the first time that such challenge is assumed in this specific sector, which is very relevant for the European countries of the Mediterranean area (Italy, France, Greece, Spain, Portugal, etc.). The research describes in depth the design and operational tests performed during the demonstration period of the PV system and the hydrogen production and refueling station. Besides, the performance of a BEV suitable modified into a hybrid electric vehicle (FCHEV) equipped with a polymer electrolyte membrane fuel cell (PEMFC) is also discussed.

2. Description of the different facilities

This research is part of the project "*Profitable Small Scale Renewable Energy Systems in Agrifood Industry and Rural Areas: Demonstration in the Wine Sector*" [13], funded by the European Union under the LIFE program.

The project facility is placed at Viñas del Vero winery, which is located in the Somontano region, in the north of Aragon (Spain). As depicted in Fig. 1, this power-to-gas power plant is formed by two main facilities: the electricity production section (upper row) and the hydrogen production and storage units (lower row). They are interconnected by a main cabinet where all the control and safety software are installed. The surplus electricity produced by a solar PV plant is converted into hydrogen by water electrolysis. The hydrogen produced is stored in pressure cylinders and is further reconverted into electricity in a PEMFC that is the secondary power source of the hybrid power plant of a FCHEV.

2.1. The electrical facility

The energy consumed by the wastewater treatment plant and the irrigation system (WWTP + IS), which was originally connected to the main winery electric grid, has been replaced by a solar PV plant and a microgrid formed by battery storage system. As depicted in Fig. 1, the stand-alone electrical facility is formed by the PV plant, a battery that acts as the short-term energy storage system, different inverters to properly use the electricity, and the consumer elements. The water used for irrigation is recycled from the wine production processes. The wastewater is accumulated in an aeration pond where it is treated, and is sequentially moved using centrifugal pumps to the filtration sandbox and to the irrigation pond. The vineyards to be irrigated have an area of 10 ha, and the annual water volume used for this purpose reaches 10,000 m^3 [14]. The power consumed and tasks performed by the different consumers are summarized in Table 1.

Among the different possible RES, only solar and wind power were initially considered, since there are no other reliable resources in the area. However, wind power was discarded due to the small average air velocity (1.66 $m\,s^{-1}$) measured during on-site measurement campaigns [15]. On the contrary, solar power is a very reliable option due to the high average solar irradiance in Spain [16]. The average value corresponding to the exact location of the winery, obtained from the Photovoltaic Geographical Information System (PVGIS) of the European Union [17], is 4.73 kWh m^{-2} day^{-1}, as can be observed in Fig. 2. The maximum value takes place in Summer, concurring with the irrigation season, and it is well above 7.5 kWh m^{-2} day^{-1}. In addition, optimal inclination according to PVGIS varies between 9° in June and 66° in December, with an annual average value of 37°.

2.1.1. The solar photovoltaic system

The use of solar energy within the energy mix is common in many countries all over the world [18–23]. However, the indisputable role of solar energy in the Twenty-first Century is overshadowed by the intermittent nature of its power production. This problem can be addressed by the use of both short-term and long-term energy storage systems [24–29]. Although conventional stand-alone solar systems often use a DC bus architecture, it was

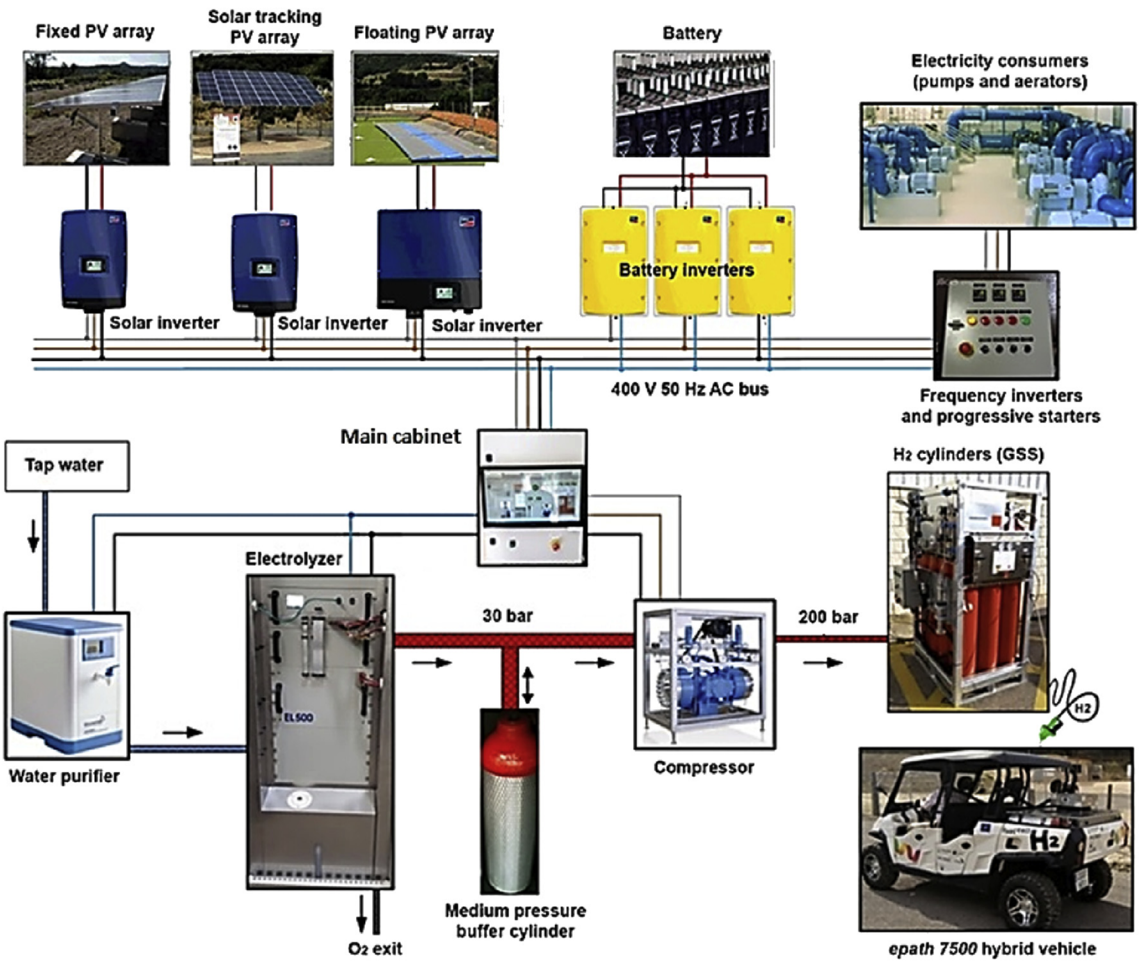

Fig. 1. General scheme of the power-to-gas plant of this project.

Table 1
Summary of the electrical loads of the WWTP + IS.

Consumers	Qty	Tasks	Total Power (kW)
Aerators	2	Injecting air bubbles to activate the biodegradation of the waste water	28
Elevation pumps	2	Moving the treated water from the different ponds	9.8
Irrigation pump	1	Irrigating the vineyard during the irrigation season (123 days)	11
Sludge pumps	2	Moving the sludge from aeration pond to the sludge one	3.6

decided to design a system with an AC bus, to which both PV inverters and power consumers are connected. So, the electric power produced by the PV panels can be directly used by the different AC consumers using DC/AC solar power inverters, increasing the efficiency of the electric system, and reducing the battery size.

There are several computational tools to assist the design and analysis of HRES and microgrids, such as the Hybrid Optimization Model for Electric Renewables (HOMER), improved Hybrid Optimization by Genetic Algorithm (iHOGA), and Hybrid2, which implement quantitative methods. In the present research, to optimize the design and performance of the system in terms of efficiency and reliability, iHOGA was used. In essence, this software tool incorporates the Ah ageing model to optimize the HRES, and takes advantage of genetic algorithm characteristics to enhance the whole optimization process, giving good results in a short computational time [30]. The power plant includes three sets of PV panels, in order to show different assembling options and to carry out comparative studies: a fixed structure located on the sandbox, a solar tracker, and a floating set placed on the surface of the aeration pond. The location of all PV arrays in the WWTP + IS area is indicated in Fig. 3. All of them are commercial (multicrystaline) polysilicon TP 265/275 Wp model PV panels manufactured by REC, which have a conversion efficiency of 16.1% and 16.7%, respectively. A summary of the main data of the three technologies is presented in Table 2. Regarding to the fixed structure, the tilt of the PV panels can be set to 5° or 30° in order to adapt the profile of the incident solar irradiation to the different energy seasonal profiles. With respect to the floating PV array, it should be noted that a remarkable advantage of the decision to place it over the surface of the aeration pond is that the performance of the panels is increased when its working temperature is decreased. In addition, both evaporation of water and proliferation of algae in the pond are also reduced. In summary, the total solar power installed reaches 43.2 kWp.

The variable voltage and intensity DC produced by the PV panels is converted to three-phase AC (400 V, 50 Hz) using three DC/AC Sunny Tripower (STP) PV solar inverters from SMA. Their electrical connection to the main AC bus is depicted in Fig. 1.

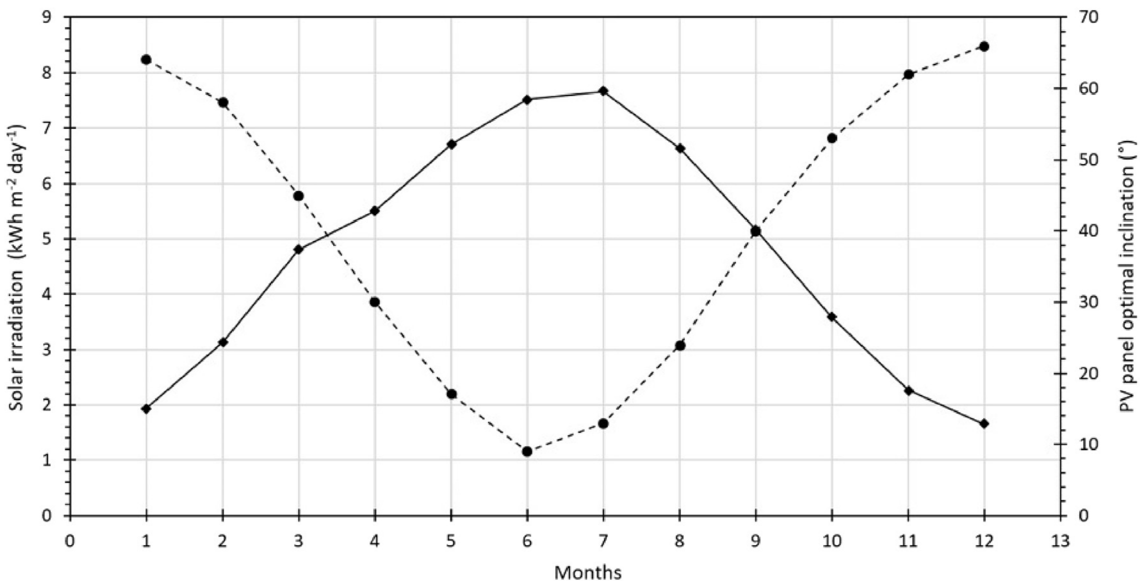

Fig. 2. Estimated values of solar irradiation (solid line) and optimal panel inclination (dashed line) for each month at the winery area [25].

Fig. 3. Assembling of the different solar arrays and main project booth at the WWTP + IS area.

Table 2
Main characteristics of the different arrays forming the solar PV plant.

Array	Supporting structure	Tilt	PV power (kWp)
Fixed	Metallic structure on the ground	5° or 30°	10.8
Tracking	Two-axis solar tracker	–	10.8
Floating	Structure designed for this application	5°	21.6

2.1.2. The battery storage system

The total energy produced by the solar PV facility normally exceeds the needs of the WWTP + IS. A short-term storage system allows energy to be available at any time of the day and at night, regardless of the generator instantaneous production. It consists in a lead-acid battery bank with 24 solar.power OPzS 3610 cells manufactured by Hoppecke, with a capacity of 2680 Ah (128.64 kWh). They are formed by tubular plates with liquid electrolyte, suitable for this application since ultra-fast discharge regimes are not expected. Three Sunny Island SI-8.0H battery inverters from SMA (one for each phase) are used to produce a 400 V 50 Hz microgrid and to correctly manage the battery charge and discharge processes. Their electrical connection to the main AC bus can be observed in Fig. 1. The battery storage system provides flexibility to the facility by storing the excess energy to be consumed later during the periods of lack and/or low renewable energy production.

There are several factors that affect the initial investment and maintenance costs of the battery. The variability of the solar PV system and the operating philosophy can impose stress conditions that eventually reduce its lifetime. On the one hand, the smaller the size of the battery bank the higher the cost effectiveness of the whole system. On the other hand, the lifetime of lead-acid batteries depends on the depth of discharge and the number of cycles. Lowering a state of charge (SOC) below 20% can be very harmful. For this reason, a key point when designing this HRES was to reduce the amount of energy to be stored in the battery bank. It is for this reason that in this system the capacity of the battery bank was not calculated to provide a large autonomy, but to match the production and consumption in an intraday regime, with a small depth of discharge. On the contrary, on days with low PV production, a deeper discharge cycle is possible, but this situation is very uncommon. The actual SOC of the battery is calculated by the charge controller with an accuracy of 95% by combining the direct measurement of the in-flowing and out-flowing current with a current voltage model.

2.1.3. Energy management system and control strategy

The implementation of an energy management system (EMS) is required both to avoid failures due to the lack of available energy and to minimize losses when it cannot be used nor stored [29]. It is noteworthy that much of the consumption of the system can be deferred. Consequently, the loads can be activated when there is PV energy production and deactivated when the battery has a low state of charge. To maximize the output power from the PV modules to the direct consumers, the maximum power point (MPP) control unit is employed [31]. To this end, a fuzzy logic control is used for the solution of the different options of the nonlinear system. The system is managed in such a way that the energy is consumed, if possible, when it is generated, avoiding its cycling in the battery. As a result, the energy stored is largely reduced, minimizing the inherent losses for AC to DC to AC conversion in the battery inverters and those for the battery charge and discharge processes.

The EMS designed in this project optimizes the match between the load demand and the energy generated by the RES at every time. For this purpose, several decisions were adopted in order to establish the priorities between the use of the different consumers and the production of hydrogen during each day, taking into account the different seasons of the year. Different sensors measure the solar irradiation, the energy production, and the SOC of the battery, among other variables. With all of them, the EMS activates or deactivates the different loads. Finally, as far as energy efficiency is concerned, the electric motors of the different loads are driven by commercial variable frequency drivers. Thus, the aerators and the pumps not only work at the optimum working point of their load curve, but also current peaks are avoided, smoothing their mechanical and electrical operation and enlarging its useful lifetime.

The control and safety software is loaded in a computer inside the main cabinet that interconnects the electrical and hydrogen facilities. Two pictures of the inner and outer sides of this cabinet are depicted in Fig. 4. All the decisions adopted are included in the NI LabView® control software that runs on an industrial computer with Windows 7 OS. It is an ultracompact Epatec IPC computer (number 1 in Fig. 4) with a fast Intel Celeron 1.8 GHz Quad Core processor. The Arduino PLC automata (number 2 in Fig. 4) is a M-duino 57 R with an ATmega2560 microcontroller and a clock speed of 16 MHz. It has 18 input ports (12 for analog/digital signals, and 6 interrupt switches), as well as 39 output points (8 analog signals, 23 digital ones, and 8 PWM isolated 8 bit). Users can interact with the control and supervision system through a commercial touch screen. The visualization software shows the status of the installation using different windows that can be easily displayed. Remote access via internet is also possible.

2.2. The hydrogen facility

In addition to the short-term energy storage battery, in the present project hydrogen is used as a long-term storage system. It should be noted that here, contrary to the most common solution where the stored energy is reverted to the same system, hydrogen energy is used to refuel a plug-in BEV properly modified to a hybrid one using a PEM fuel cell. The hydrogen facility is formed by a production and refueling plant and the FCHEV that is the end-user of the produced hydrogen.

2.2.1. The hydrogen production and refueling plant

The hydrogen generation and refueling station (see Fig. 5) has been specifically designed for this research. The system is mainly composed by a compact water purification system (1), an alkaline electrolyzer (2), a metal diaphragm compressor (3), and a stationary gas storage system (4), and a medium-pressure buffer aluminum cylinder from Luxfer with a water volume of 10 L (5) which is placed just in between the electrolyzer and the compressor. The main characteristics of these equipment are summarized in Table 3.

All equipment, devices and elements for the hydrogen production plant are installed in an isolated room inside the project booth, while those corresponding to the storage and refueling station are placed outside. To avoid possible accidents, all elements and

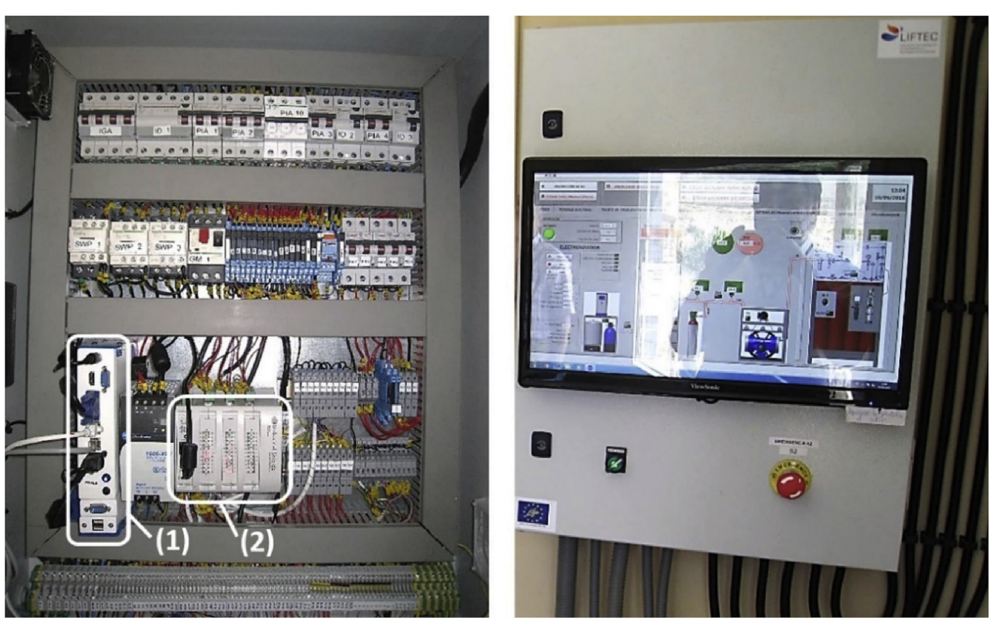

Fig. 4. Inside (left) and outside (right) images of the main control cabinet.

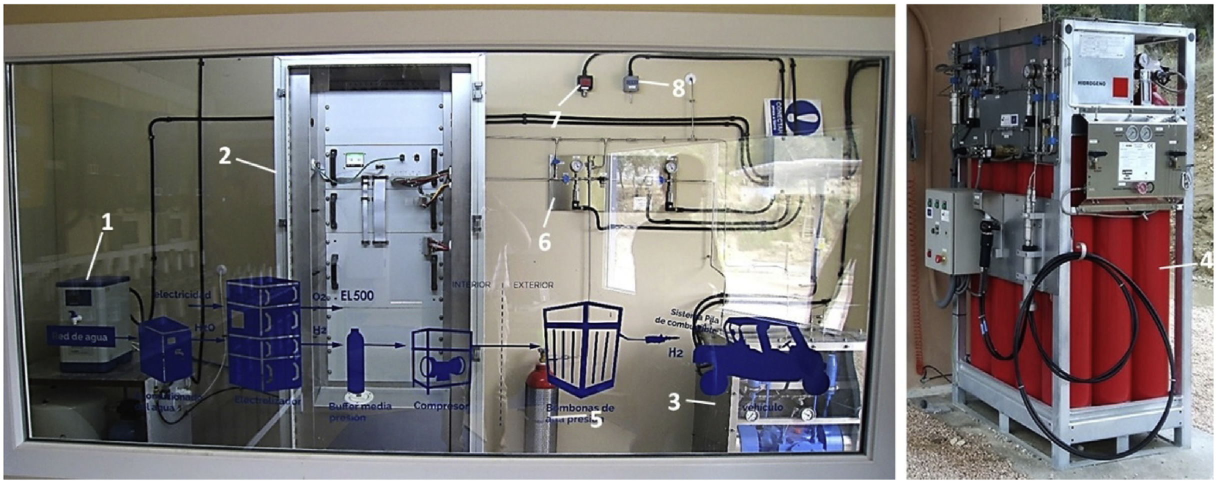

Fig. 5. Hydrogen production and refueling plant. Pictures of the production devices assembled inside the booth and the stationary GSS placed outside (right).

Table 3
Equipment of the hydrogen production plant.

Equipment	Manufacturer	Technology	Characteristics
Ecomatic water purification system	Wasserlab	Reverse osmosis	Flow: 3 l h^{-1}; Conductivity: < 5 μS cm^{-1}
Electrolyzer EL-500	Heliocentris	Alkaline Exchange Membrane (KOH)	Flow: 500 Nl h^{-1} @ 30 bar; Purity: 99.999%
Compressor MV6208	Sera	Metal-diaphragm, double-stage	Flow: 500 Nl h^{-1} @ 200 bar

devices fulfill the anti-explosion (ATEX) regulations required for any hydrogen facility. A detector for hydrogen leaks (7), and a temperature sensor (8) are also assembled to ensure the safe operation of the facility.

The flow diagram of the control panel (number 6 in Fig. 5) can be observed in Fig. 6. It is formed by two check-valves (ChV1, ChV2) for the correct circulation of hydrogen, two manometers (M1, M2) to visualize the pressure just after the electrolyzer and before the compressor, respectively, and three manual valves (MV1, MV2, MV3) that are assembled for security.

The safe operation of the compressor is controlled by the electrical signal provided by the solenoid valve SV1 that takes the pressure reference from pressure transducers P1 and P2. It is turned on when the pressure at P2 raises to 29.5 bar and turns off when it falls below 15 bar. The panel also includes an automatic hydrogen release valve (RV1) that is activated when the pressure at the inlet point (P1) is above 45 bar.

The hydrogen plant also includes a stationary gas storage system (GSS) formed by a rack with 12 cylinders, with a water volume of 50 l each. Thus, it can store 106 m^3 (9.53 kg) of hydrogen at 200 bar. The H_2 stored at the stationary GSS is automatically supplied to the FCHEV with a commercial WEH® refueling system. It is formed by a TK-16 nozzle and a TN-1 receptacle, and integrates a high-flow check valve and a 20 μm self-cleaning particle filter. The WEH system has also a breakaway coupling that cuts off the hydrogen

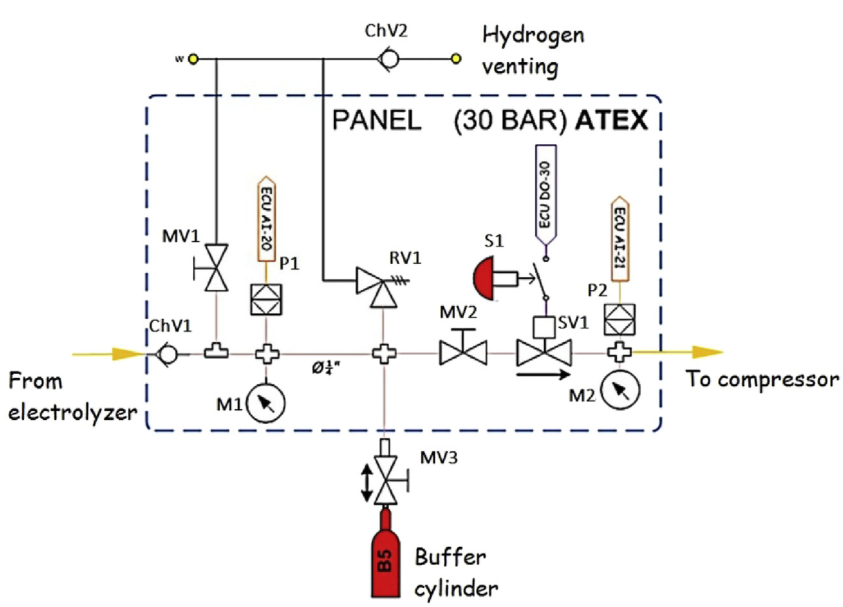

Fig. 6. Panel used to control the correct performance of the compression stage.

flow if a force greater than 300 N is exerted on the hose, preventing it for breaking. A connection panel with its corresponding control electronics was specifically designed and built for this application. It is placed on one side of the GSS, and a photo and the corresponding flow diagram is depicted in Fig. 7. It is formed by a coalescent filter (F1), and different check (ChV3, ChV4) and release valves (RV2, RV3, RV4). As a novelty, it has been designed both to refill the stationary GSS with hydrogen from the compressor (red lines) and to discharge it to refuel the GSS of the FCHEV (blue lines). Thus, some pipes of this panel are indistinctly used both for charge and discharge processes. The correct circulation of the gas is controlled by the solenoid valve SV2. The electrical signal to activate SV2 when refueling comes from the supplying switch placed at the control panel. The overflow valve, OV1, cuts off the hydrogen flow if an unexpected high value is detected providing an extra safety to the facility. This valve also moderates the flowrate when the solenoid valve SV2 is opened to refuel hydrogen to the GSS of the FCHEV.

2.2.2. The PEMFC hybrid electric vehicle (FCHEV)

The end-user of the hydrogen system is a commercial ePath-7500 electric car manufactured by EMC (see Fig. 8a), suitably modified to be powered by a hybrid powertrain based on PEM fuel cell and batteries. This is an all-wheel drive 4-seat vehicle designed to travel on bumpy and irregular terrain, ideal for agricultural or industrial tasks. Originally, the 7.5 kW 72 V electric motor of the car was powered by a set of 12 gel-type 6 V 225 A-h batteries. The EM is connected to the main DC bus through a DC/AC booster electronic converter. The PEM fuel cell stack with its corresponding GSS, and the electronic devices used for hybridization were assembled at the tilting rear load platform, as shown in Fig. 8b).

A commercial Horizon H-3000 PEMFC stack, with a rated power of 3 kW, was included as the second power source in the HPP. This is an open-cathode stack formed by 72 cells and graphite bipolar plates that includes 4 axial fans that supply the air flow needed for both the electrochemical reactions and to cool the stack down to the working temperature (50–65 °C). At the rated power (70 A,

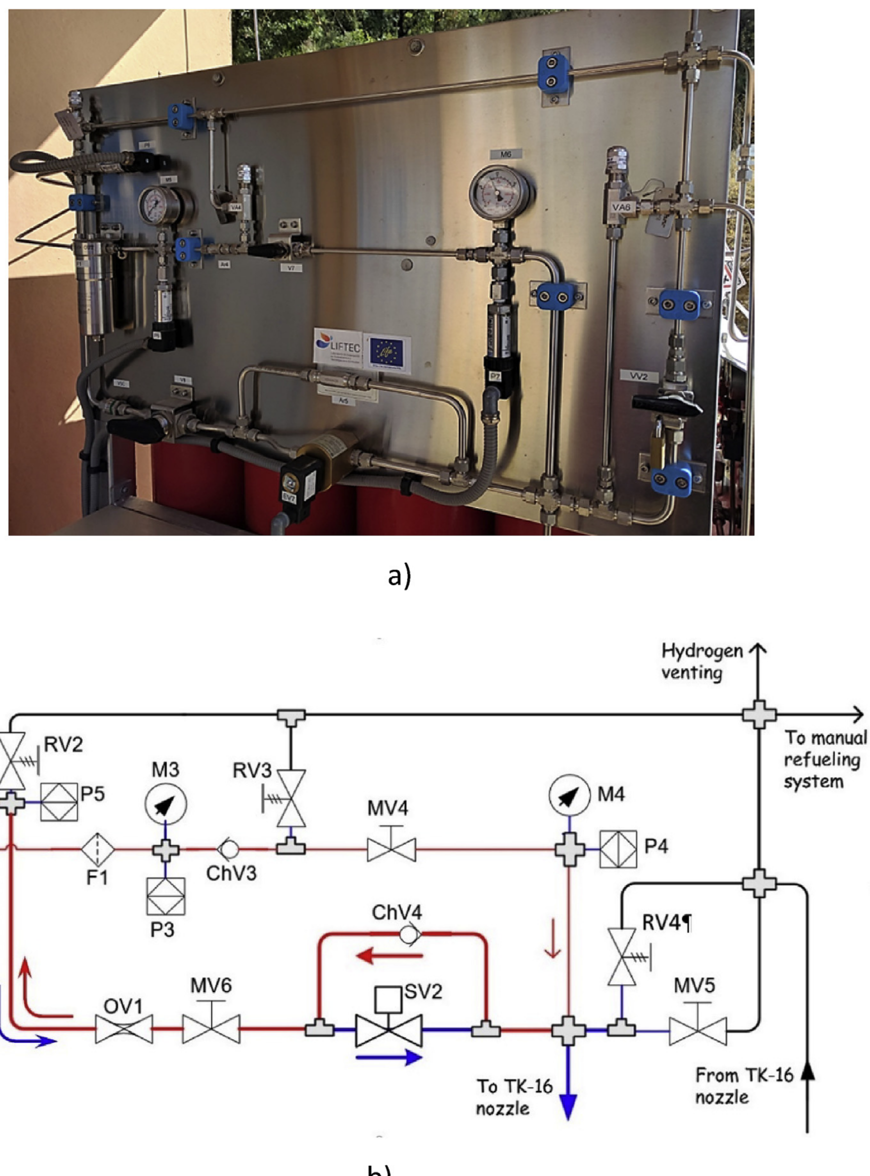

Fig. 7. Panel used to refill the stationary GSS and to refuel hydrogen to the FCHEV.

a) b)

Fig. 8. The original ePath 7500 BEV (a), and the remodeled FCHEV (b).

43.2 V), the gross efficiency is 47.4%, which decreases to 41.8% (net) when power consumed by the ancillary systems are considered. The GSS of the FCHEV is formed by four 10 l Luxfer aluminum cylinders, which can store 0.64 kg (7.12 Nm^3) of hydrogen when compressed at 200 bar. The supplying system includes a recirculation system formed by a proportional solenoid valve and an ejector that allows to recirculate part of the unreacted hydrogen from the anode sides.

The active HPP of the FCHEV is formed by a booster DC/DC power converter that supplies the electric power from the PEMFC stack to the main DC bus, and two other DC/DC converters that deliver power to the different elements of the ancillary systems at 12 V and 24 V. To control and monitor the different electrical parameters of the H_2+PEMFC system, a NI roboRIO microcontroller with a sampling frequency of 800 Hz was used as the central electronic control unit (ECU). The control system includes as a novelty in fuel cells, a discrete state machine model programmed in LabVIEW with LINUX realtime operating system, which was embedded into the ECU microcontroller [32]. Basically, there are two main operation states. When the vehicle operates in a low consumption rate and the SoC of the battery is below 95%, the stack is switched to CHARGING mode. In this case, the excess of energy produced by the stack is sent to recharge the battery. On the contrary, if the power demanded at the main DC bus increases, it is shifted to the SUPPLY POWER mode, providing around 30% of the total power demanded by the EM of the FCHEV. To check the correct operation of the stack, a typical polarization curve was also recorded into the ECU. If the PEMFC stack works properly, it alternates between CHARGING and SUPPLY POWER modes. But, if for a given current it is detected that the voltage delivered by the stack differs by 10% from the value of the recorded polarization curve, it is moved to the REHABILITATION mode. In this case a purging sequence is activated in order to remove the water accumulated inside the stack since the commercial H-3000 operates in anode dead-end mode. Usually, after the purging sequence the performance of the stack is recovered and it is again moved to SUPPLY POWER or CHARGING modes, depending on the total power demanded by the vehicle. Otherwise, the stack is eventually shifted to the FINISH mode, stopping the hybrid control sequence.

3. Results

The system described in this paper was fully installed by the end of May 2016, and the main results obtained in this year are discussed below.

3.1. Performance of the electric system

The performance of the PV/electric system for two typical sunny days, one out of the irrigation season, and another within it, are depicted in Figs. 9 and 10, respectively.

On the one hand, out of the irrigation season, virtually all loads are managed by the system automatically. Thus, the loads are connected during the day, obtaining the maximum simultaneity between generation and consumption of energy, as shown in Fig. 9. It is verified that the energy demand is suitably adapted to the energy production. Only the area not shared by both the production and consumption curves corresponds to the energy charged or discharged from the battery. This represents a very small fraction of the total, minimizing the energy cycled in the battery and the associated AC/DC and DC/AC conversions, avoiding their corresponding losses. The battery absorbs the small intra-day differences of production and consumption, with SOC variations less than 18%, and also maintains its high level of charge which allows the system to work in cloudy days. The average level of SOC (73%) has not been set too high, since no night consumption is expected and in anticipation of being able to store energy if the loads are disconnected part of the day for some reason.

On the other hand, during the irrigation season, the irrigation is scheduled by the vineyard managers, depending on the needs of vine growing. The control system prioritizes these consumptions and adapts the other ones according to the availability of energy. The system manages the other loads automatically. In Fig. 10, the main nocturnal consumption corresponds to the irrigation system. During the first few hours of sunshine in the morning, a part of the energy produced is used to recharge the battery, compensating for the nighttime consumption. The rest of the day, once the SOC of the battery is reestablished, the demand is again well-matched to the production of energy. The SOC variations are less than 35%, and the level of charge is high, which allows the system to work during the night or in cloudy days. The average level of SOC (76%) is similar to that obtained outside the irrigation season, but at sunset it is above 90%, waiting for the night consumption.

During the first year the actual electricity produced by the PV system was 71.9 MWh. Part of that energy was used for the different consumers of the WWTP + IS (62.15 MWh), and 6.4 MWh was employed to produce hydrogen. The energy losses in the system, including those caused by the charge and discharge of the battery bank, have been only 4.76%. This is a very good performance, due to the optimized management strategy. To estimate the amount of equivalent CO_2 saved, the energy mix in the Aragon region has to be

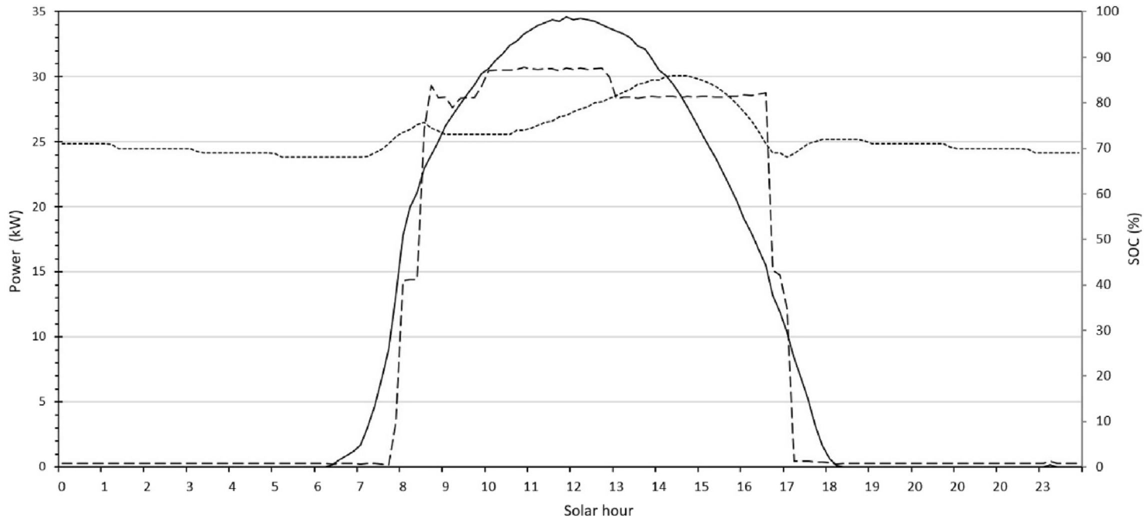

Fig. 9. Electric performance during March 19th· 2017, a day out of the irrigation season. Solid line for power production, dashed for consumption, and dotted one for the SOC of the battery bank.

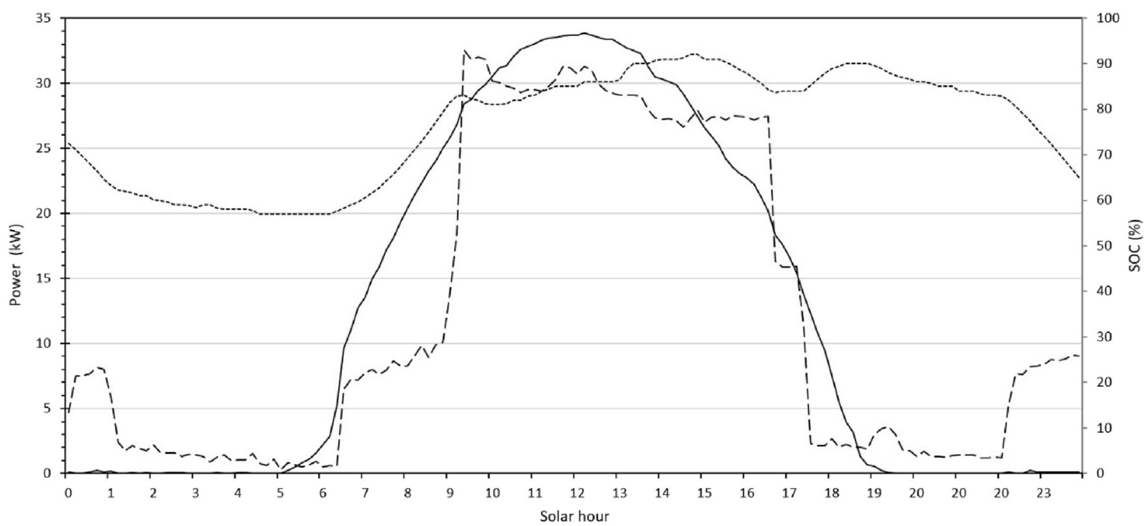

Fig. 10. Electric performance during July 28th, 2017, a day within the irrigation season. The legend is the same as in Fig. 9.

considered. Thus, considering an emission factor of 0.385 kg of CO_2-e per kWh of electricity [33], the emission to the atmosphere of around 27 tons of CO_2 has been avoided. Besides, during this period, 1214 Nm^3 of hydrogen have been produced. As the average consumption of hydrogen when moving at 15.6 km h^{-1} is around 12 Nl min^{-1} (3.6 Nm^3 day^{-1}), considering a diesel specific rate of 15 l per 100 km in a typical agricultural car, and including the energy supplied by the battery when working in hybrid mode that needs to be recharged every day, the use of hydrogen in the FCHEV has saved the consumption of around 1010 l of diesel. Considering a production factor of 2.539 kg of CO_2-e per liter of diesel [34], the emission of 3 tons of CO_2-e has been avoided.

Taking into account the efficiency of the different elements of the power-to-gas plant, the overall efficiency for the electricity conversion, from the PV panels to the vehicle wheels, can be estimated. It was obtained that, depending on the electricity used to produce the hydrogen, it ranges from 24.6% to 30.5%. The upper limit is reached when the electricity to produce hydrogen is directly obtained from the PV panels (the conversion efficiency of the DC/AC STP inverters is 98.4%), while the lower one corresponds to hydrogen produced from energy previously stored in the battery. In the last case, the efficiency of the battery inverters (95%) and that of the charge and discharge processes (85%) have to be included in the analysis.

3.2. Performance of the hydrogen production and refueling plant

The behavior of two pressure transducers, P2 (at the compressor inlet) and P5 (at the stationary GSS) of the hydrogen production and refueling plant, is shown in Fig. 11 a). The data correspond to a period of 3 h (from 10:00 to 13:00) that includes the refilling of the stationary GSS with hydrogen produced by the electrolyzer and the refueling of the GSS of the hybrid electric vehicle.

As it can be observed, the period of each charging cycle is around 24 min, and the pressure at the inlet of the compressor changes from 15 bar to 29.5 bar, which is the set point fixed at the control system to prevent failures. The compressor operates during the descent ramp, while it remains off when this pressure increases. Close to 700 l of hydrogen were stored at the stationary GSS during this test, increasing its pressure from 168 bar to 176 bar. The fast

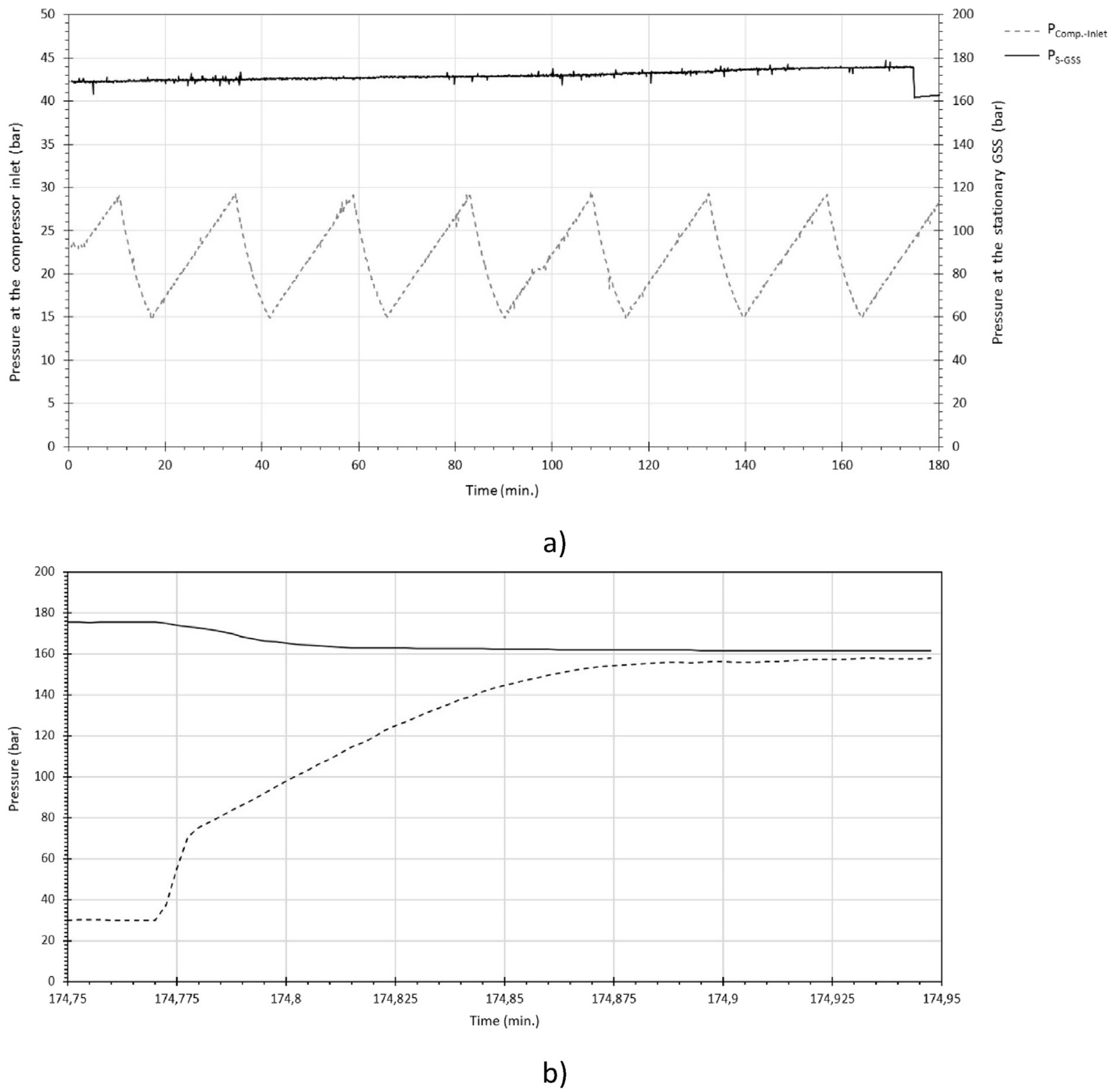

Fig. 11. Performance of both the system to refill hydrogen to the stationary GSS (a), and that to refuel hydrogen to the GSS of the FCHEV (b).

decrease in the pressure at the stationary GSS between minutes 174 to 175 is due to the refueling of the GSS of the FCHEV. A zoom for this time window is observed in Fig. 11b) where this performance is clearly depicted. In the different tests performed, the fast refueling time of the WEH system was demonstrated. In this specific test, the GSS of the FCHEV is refilled from 30 bar to 157 bar in less than 20 s (dashed line), and the pressure at the stationary GSS of the hydrogen production station change in less than 14 bar, from 175.5 bar to 161.6 bar (solid line). From the tests performed, it was shown that the refilling frequency of the GSS of the FCHEV is every 1.5 days, while 11.5 h are needed to refuel the used hydrogen in the stationary GSS.

3.3. *Performance of the hybrid electric car*

Different field tests of the FCHEV were performed in real operating conditions at the winery. The results obtained during a real driving test are depicted in Fig. 12. It consisted in a round trip of 6 km that lasted around 24 min, from the parking of the winery to the vineyards, climbing two small hills. The average velocity of the FCHEV during the whole test was 15.2 km h^{-1}, reaching a maximum of 45 km h^{-1} with an average power demanded by the EM of the vehicle of 4.19 kW. However, as can be observed in Fig. 12a), the peak power demanded by the EM (solid black line) when ascending the hills or during a fast acceleration exceeds, by far, the rated power of the electric motor (7.5 kW). For the high demand range, the power is mainly supplied by the battery (dashed line), while for the low power demand range the CHARGING mode at the H-3000 stack is activated and part of the energy is used to recharge the battery. This situation corresponds to the different zones in Fig. 12a) where the power of the battery is negative. When working in hybrid mode, 74.8% of the total energy demanded by the vehicle was supplied by the battery and 25.2% by the PEMFC.

On the other hand, the PEMFC stack works in a quasi-steady state (solid bold grey line), with an average power of 1.05 kW and a net efficiency of 51.4%. This result shows the excellent

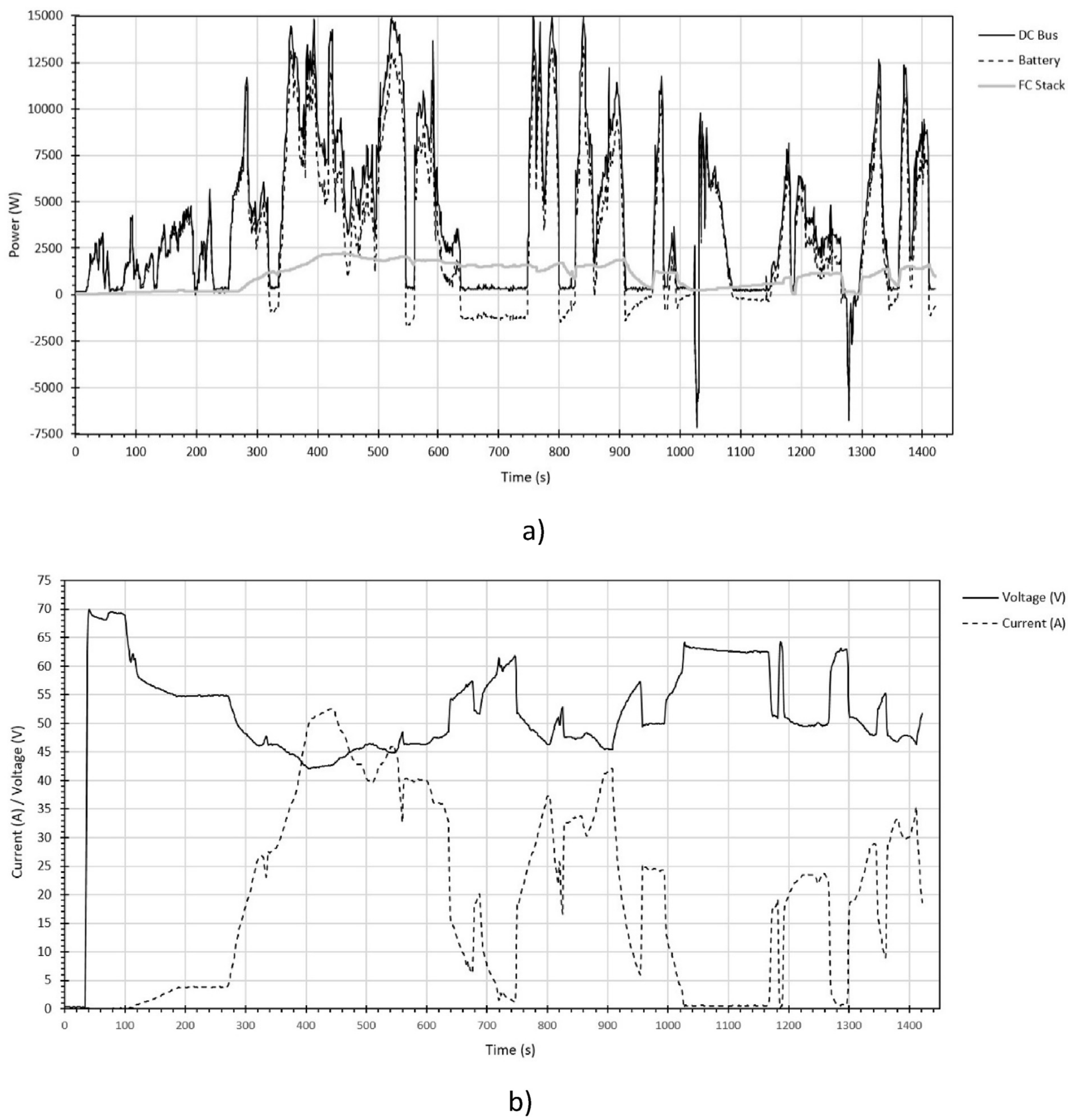

Fig. 12. Results of the real driving test in the winery: a) power of the different sources, and b) electric performance of the stack.

performance of the stack control system, avoiding sudden changes in load that can damage the device due to its slow dynamics. The average voltage of the H-3000 PEMFC stack in this test is 51.8 V, and the average current reaches 20.3 A, which corresponds to a current density of around 0.1 A cm^{-2} (see Fig. 12b). An interesting result was to confirm that part of the kinetic energy of the FCHEV is recovered when braking, corresponding with the two narrow negative peaks of power in times 1028 s and 1280 s. This unexpected performance, not indicated by the manufacturer in the vehicle manual, occurs when the car is moving at a fast velocity (descending the second hill) and the traction system is shifted to the lowest gear. Under this condition, the DC/AC booster electronic converter of the EM can also work as a generator. Finally, it was also confirmed that the actual range of the vehicle was almost doubled, from 2.7 h for the pure BEV to 4.8 h of the hybrid one.

3.4. Cost analysis of the electricity production

Based on the publications of the Solar Energy Industry Association, the average price of a complete PV system has dropped by more than 70% since the beginning of 2011 [35]. It is important to highlight that the PV plant of this project is not a typical commercial facility, but it is a “demonstrative prototype”. Obviously, the replication of the proposed solutions is cheaper than the prototype. In most cases a fixed array, which is the conventional technology, should only be considered. The inclusion of the tracking array and the floating panels increases the final cost, but it allowed showing and testing the performance of the three systems under the same operating conditions. The same demonstration purposes justified the incorporation of the hydrogen production facility and the fuel-cell-powered vehicle despite their high cost, but the production and use of hydrogen is not considered for this economic comparison.

In the cost analysis, the three technologies that are commonly used to supply electric power to the WWTP and to the pumping system for irrigation in the wine industry are compared. These are, namely, the commercial electric grid, a diesel-based generation set (genset), and the PV solar plant. It is noteworthy that the aim of the calculations is to compare the three solutions, because the supply of energy is needed in any case. The cost of all the equipment and the increase in fuel prices have been considered, using the data from the last 15 years. In the case of the PV facility, the costs inherent to the building work for the three arrays, the air conditioning system of the technical room, and the assembling of the whole plant are also included. Besides, a degradation rate of 1% is considered for the solar panels. To calculate the annual costs of the three technologies, the following equations are used,

$$TAC_{PV} = I_{O-PV} + \left[\sum\nolimits_{Year=1}^{n} AE_{Year}\left(1 + Inf_{gen}\right)^{Year}\right] + CoL_{Bat} + CoL_{Inv}, \quad (1)$$

$$TAC_{DG} = I_{O-DG} + \left[\sum\nolimits_{Year=1}^{n} AE_{Year}\left(1 + Inf_{gen}\right)^{Year} + Co_{DG}\left(1 + Inf_{DG}\right)^{Year} + CoL_{DG}\right], \quad (2)$$

$$TAC_{CE} = I_{O-DG} + [(CoE \cdot E_{cons}) + (CoP \cdot P_{cons}) + Taxes](1 + Inf_{CE})^{Year}, \quad (3)$$

where TAC is the total annual costs (€), I_o the initial investment costs (€), AE the annual expenses (€), Inf the inflation (%), CoL the cost due to lifetime (€), CoE the energy cost (€), CoP the power cost (€), E the energy consumed (kWh), and P the power consumed (kW). Subscript PV refers to the solar PV plant, DG to the diesel genset, CE to the electricity from the commercial grid, gen to general, Bat to the battery bank, and Inv to the inverters. Besides, the net present value (NPV) is calculated according to

$$NPV = \sum\nolimits_{Year=1}^{n} \frac{C_{Year}}{(1+k)^{Year}} - I_O, \quad (4)$$

in which C is the yearly cash-flow, and k is the annual discount rate considered (10%). A summary of the main parameter used in the analysis is listed in Table 4.

The evolution of the annual costs of the three systems for the values considered in the study is presented in Fig. 13. The total cost of the PV solar system is almost constant because it is mainly affected by the initial investment cost (181,854.00 €). Nevertheless, the maintenance cost, as well as the costs related to the lifetime of both the battery bank (12 years) and the inverters (15 years) have also been included in the analysis. A lifetime of 15 years, and its corresponding cost, was also considered for the diesel genset. As can be observed, from years 9.5 and 13 the costs of both the

Table 4
Main parameters used in the cost analysis.

Parameters	Diesel genset	Electricity grid	PV solar plant
Annual energy consumption (kWh)		75,000.00	
Total electric power (kW)		50	
Fuel oil price (€ l^{-1})		0.60	
Initial investments (all costs included)	18,500.00	25,000.00	181,854.00
Annual costs:			
Maintenance (€)	1846.63		250.00
Fuel oil (€)	11,079.00		
Electric energy index (€ kWh^{-1})		0.11245	
Electric power index (€ kW^{-1})		45.7245	
Renting devices (€)		343.35	
Taxes in Spain (€)		526.70	
Inflation			
General (%)	3.00	3.00	3.00
Diesel (%)	3.20		
Electricity (%)		3.20	

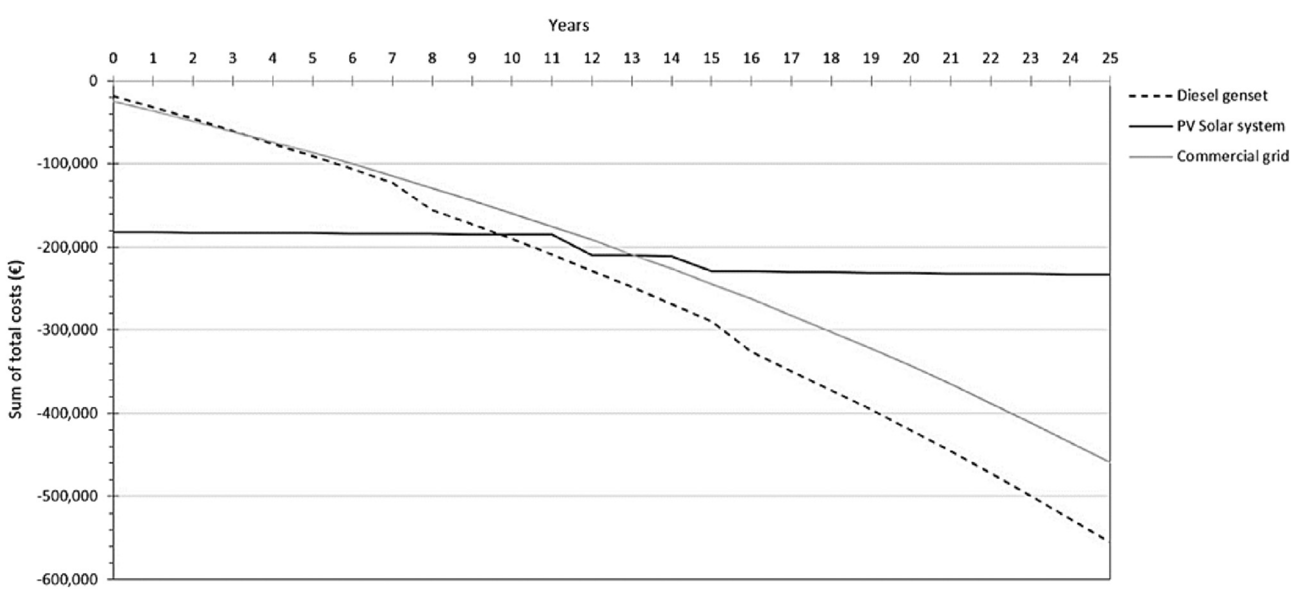

Fig. 13. Cost analysis for the three technologies commonly used to produce electricity in the wine industry.

diesel-based generation system and the commercial electricity, respectively, are greater than the PV solar power system. A positive result of the NPV (58,086.31 €) was only obtained for the PV solar power system, with an internal rate of return (IRR) of 13.44%. The NPV values obtained for the diesel system and for conventional electricity are −187,819.93 € and −161,121.15 €, respectively. So, the profitability of the PV solar power system is clearly demonstrated.

4. Conclusions

The technical and economic feasibility of an isolated electrical plant from PV solar energy that eliminates both local diesel-based generation equipment and aerial power lines has been demonstrated in Viñas del Vero winery. With the facility developed in the present research, during the first year around 72 MWh of electricity were produced, saving the emission of around 24 tons of CO_2-e to the atmosphere. Besides, 6.4 MWh have been employed to produce hydrogen in a generation and refueling station specifically designed and manufactured for this project. During the first year, 1214 Nm^3 of hydrogen have been produced, avoiding the emission of close to 3 tons of CO_2-e. Field tests performed to the FCHEV proved that when working in hybrid mode around 30% of the total energy demanded was supplied by the PEMFC stack, which notably extend the original range. The excellent performance of the commercial WEH refueling system was also demonstrated.

Considering the efficiency of the different elements of the system, the overall efficiency for the electricity conversion of the power-to-gas-to-power plant (from the PV panels to the vehicle wheels) ranges from 24.6% (when the electricity to produce hydrogen is directly obtained from the PV panels) to 30.5% (when the electricity is previously stored in the battery bank). Even when the present PV power plant is a demonstrative prototype, a positive result has been obtained for both the NPV and the IRR, demonstrating the profitability of the investment. This is a very important result to encourage the investment of private capital in the renewable energy sector.

Acknowledgements

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Artículo

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Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell

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ABSTRACT

In the present research, a commercial battery-powered pure electric vehicle was suitably modified to convert it into a hybrid one integrating a PEMFC stack. The hydrogen supply system to the stack included a passive recirculation system based on a Ventury-type ejector. Besides, in order to achieve an optimum operation of the PEMFC stack, a discrete state machine model was considered in its control system. The inclusion of a rehabilitation operating mode prevented the stack from possible failures, increasing its lifetime. It was verified that for the rated operating point when supplying power to the vehicle (2.5 kW) the hydrogen consumption decreased, and the actual efficiency (47.9%) PEMFC was increased close to 1%. Field tests performed demonstrate that the range of the hybrid electric vehicle was increased by 78% when compared to the one of the original battery electric car. Also, under the tested experimental conditions in hybrid mode, 34% of the total energy demanded by the electric machine of the vehicle was supplied by the PEMFC stack.

Introduction

Today, about 60 million internal combustion engine vehicles (ICEV) are manufactured every year, and about a billion ICEV are circulating on the roads of our planet, representing one car for each seven people [1]. They are responsible for the emission of a very large part of the total amount of pollutants (solid particles, CO_2, NOx, CO, SO_2, etc.) contained in the air. The very nature of the combustion process impedes a significant reduction of these emissions in today's advanced ICEV. Modern societies are aware of the necessity of a cleaner air, which reflects in increasingly stricter emission legislations for both pollutants and greenhouse effect gases [2–4]. So, the development of new zero-emission vehicles (ZEV) to gradually substitute the ICEV in transportation is becoming urgent.

Most of the commercially available ZEV that are today accepted and promoted by the Governments of European Countries are pure electric vehicles powered with batteries (BEV). Ideally, the electricity which feeds this kind of vehicles should be obtained from renewable sources. Even if produced in large powerplants where heavy fuel oil is combusted, at

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Acronyms

AWD	All-wheel-drive traction system
ATEX	Anti-explosion regulations
BEV	Battery electric vehicles
ECU	Electronic control unit
EM	Electric machine of the BEV
EMS	Energy Management Strategy
ESD	Energy storage device
FCHV	Fuel Cell Hybrid Vehicles
FPGA	Field-programmable gate array
GSS	Gas storage system
HPP	Hybrid powerplant
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicles
LED	Light emission diodes
MEA	Membrane electrode assembly
NI	National Instruments
PEMFC	Polymer electrolyte membrane fuel cell
PLC	Programmable logic controller
PV	Photovoltaic panel arrays
PWM	Pulse-width modulation
SOC	State of charge of the battery system
ZEV	Zero-emission vehicles

least pollutants are emitted in basically much less populated areas, diminishing the negative health effect on human population. In any case, the main drawback of BEV is their limited range. A very interesting solution is to combine different power sources that can be connected either in serial, parallel, or serial-parallel configurations. This strategy is known as hybridization, and its implementation ensures high values of both energy and specific power [5]. The first hybrid powerplants (HPP) were based on ICEs, and achieved a significant reduction in fuel-oil consumption rates. As combustion products are still emitted, this configuration can only be considered as an intermediate stage towards the final ZEV objective. However, the optimal selection between BEV, hybrid ones or conventional ICEV, considering economic and environmental aspects is mainly dependent on the electricity cost and, into a lesser extent, on how clean it is produced [6–8].

Other solutions are based on hybrid electric architectures (real ZEVs), which are fed by an energy storage device (batteries or capacitors) and a fuel cell stack, which are usually called fuel cell hybrid vehicles (FCHV). The use of polymer electrolyte membrane fuel cells (PEMFC) in HPP offers a high efficiency and zero emissions (if the hydrogen is produced using energy from renewable sources) when compared to an ICE. It has the advantage of using hydrogen, which is the most efficient alternative to long-term energy storage of renewable production. Besides, due to the characteristics of batteries in terms of high energy density, compact size and reliability, these have been widely used in hybrid vehicles [9–11]. This is why FCHEV can be considered a solution for the increasing interest of car manufacturers, also extending the range of BEV. Nevertheless, to make this technology more profitable and affordable, some issues associated to hydrogen economy (production, distribution, storage, and refueling), PEMFC cost and lifetime, have to be improved [12,13].

In this paper, a commercial plug-in electric car was suitably modified to be powered by a hybrid powertrain based on PEMFC and batteries. The major drawback of PEMFC in transportation, the load handling capability during transients, is overcome by the existing battery set. This combination provides a good dynamic, increasing the lifetime of the stack and keeping the battery State of charge (SOC) within the safe limits [14,15]. It should also be noted that, as the electricity used to recharge the battery was produced using energy from renewable sources and the green-hydrogen was generated by water electrolysis, it can be actually considered a “real” ZEV.

The electric vehicle

This research is part of a project funded by the European Union under the LIFE program entitled “Profitable Small Scale Renewable Energy Systems in Agrifood Industry and Rural Areas: Demonstration in the Wine Sector” [16]. The surplus electricity produced by a stand-alone solar PV plant is eventually used to generate hydrogen in a production and refueling plant specifically assembled. According to the NREL [17], electrolysis is probably the most expensive method to produce hydrogen from a renewable source, especially when compared to biomass processing. Nevertheless, it was selected in this project due to the available excess electricity. The end-user of the resultant hydrogen is a commercial electric car, which was suitably modified to be powered by a hybrid powertrain based on a PEM fuel cell.

The original battery electric vehicle (BEV)

The commercial *ePath-7500* car used in this project is an all-wheel drive (AWD) 4-seat plug-in BEV designed to travel on bumpy and irregular terrain, ideal for agricultural or industrial work regimes. A photo of this car is depicted in (Fig. 1a). Originally, its 7.5 kW 72 V AC-electric motor was powered by a series of 12 gel-type 6 V, 225 A-h, battery bank. A 12 V battery block supplies energy to the ancillary systems, just as in conventional cars. The set of batteries is located under the rear seats of the vehicle. As specified by the manufacturer, when moving at a constant velocity of 30 km/h over a flat and asphalted road, the car range is around 100 km. An electric socket placed at the front side of the car allows recharging the batteries from the green-electric network. The total recharge time is around 8 h. The BEV has a tilting load platform at the rear side where the fuel cell system (PEMFC stack, hydrogen storage and supply system, electric, electronic and control devices) was assembled.

Concerning the powerplant of the original BEV (see Fig. 1b), the power from the battery set is supplied to the wheels by an electric machine (EM) through the differential. The EM is connected to the main DC bus through a DC/AC booster electronic converter. This device can also work as a generator, recovering energy when braking. The vehicle has three gears with manual shift, and the regenerative braking only works in the lowest gear.

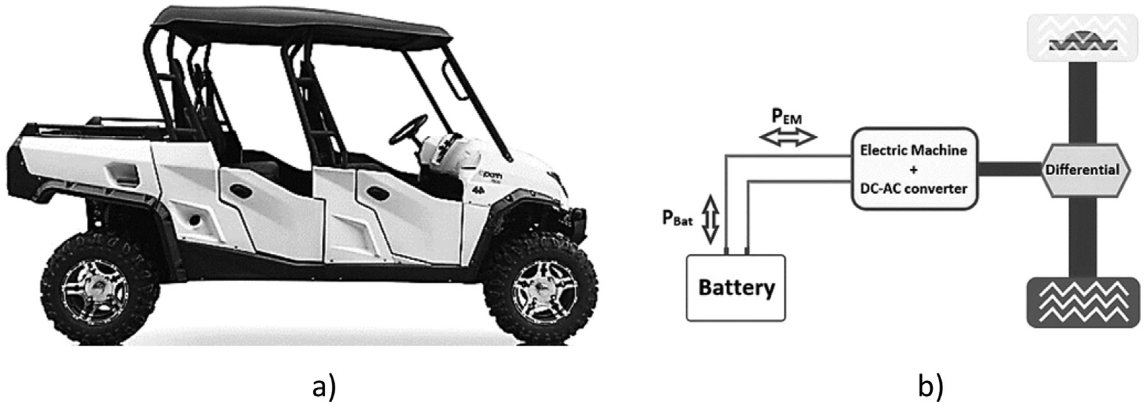

Fig. 1 – The original *ePath 7500* pure electric car (a) and its powertrain (b).

The hybrid electric vehicle (FCHEV)

The commercial *ePath-7500* BEV was suitably modified to be powered by a hybrid powertrain based on a PEM fuel cell and the original gel-type batteries. Several modifications were performed to adapt both the pure electric battery powertrain and the tilting rear load platform to include the commercial PEM fuel cell stack with its corresponding gas storage and supply system, as well as the electronic devices used for the hybridization. A picture of the modified vehicle is shown in Fig. 2.

The PEMFC stack

A commercial *H-3000* PEMFC stack, manufactured by Horizon and with a rated power of 3 kW, was included as the second power source in the HPP. This is an open-cathode stack formed by 72 cells with Nafion® membrane-electrode assemblies (MEAs) and graphite bipolar plates, which includes 4 axial fans to move the air needed both to ensure the oxygen for the electrochemical reactions and to cool the stack down to the working temperature (50–65 °C). Dry hydrogen with a purity of 99.999% coming from the electrolyzer was supplied at a working pressure of 0.5 bar. Its total weight is 15 kg and its volume is 26 L, yielding a specific nominal power of 200 W kg^{-1} and a nominal power density of 115.38 W l^{-1}. As reported by the manufacturer, at the rated power (70 A, 43.2 V), the H_2 consumption at a pressure of 1.5 bar (abs.) is 39 Nl/min, with a gross efficiency of 47.04%, which decreases to 40% when the power consumed by the control system and the ventilation system are considered. On the other hand, the start-up time, at room temperature, is below 30 s. Two polarization curves of the stack obtained in the test bench can be observed in Fig. 4, one for increasing current (lower) and the other decreasing from the maximum value (upper). To avoid damaging the stack, the manufacturer recommends that it should never work below 36 V or generate more than 90 A. Accordingly, an optimal current density of 285 mA cm^{-2} has been considered. At this point, marked in Fig. 3, the stack will generate 56.2 A at 44.5 V, corresponding to a power yield of 2500 W (or a power density of 12.54 W cm^{-2}), and a measured hydrogen consumption of 32 Nl min^{-1}. It has also been established that the current produced by the stack will never exceed 65 A (45.8 V), which translates into a maximum power of 2977 W (14.93 W cm^{-2}), and a consumption of 36.7 Nl min^{-1}.

The hydrogen supply system of the FCHEV

The hydrogen to be used by the PEMFC stack in the HPP is stored in four aluminum cylinders with a geometric volume of 10 L and a weight of 12.75 kg each. Therefore, the total volume of hydrogen that can be stored at 200 bar considering a compression factor of 1.132 is 7.06 m^3, which corresponds to 0.64 kg or, in energy terms, to 21.3 kWh. All the elements and devices of the gas supply system have been assembled in two panels placed at the modified rear tilting platform. Different solenoid valves control both the supply of hydrogen to the stack and its refueling to the GSS, as depicted in the piping and

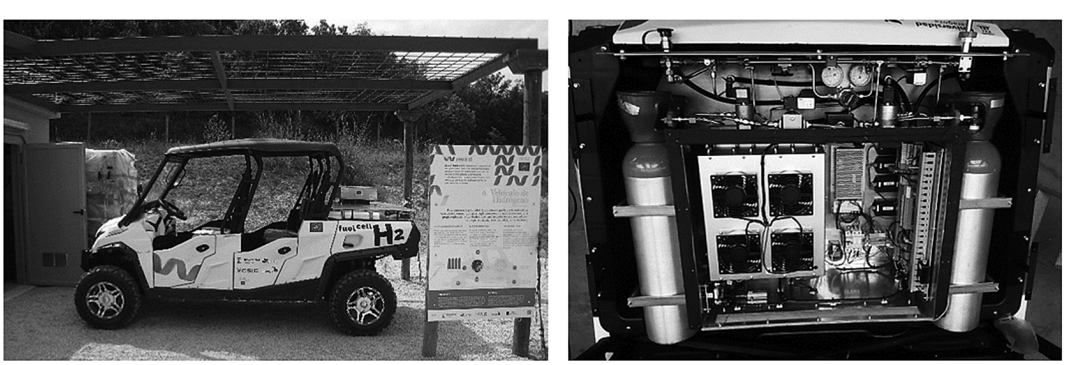

Fig. 2 – Two photos of the modified electric car with the H_2+PEMFC system assembled at the rear platform.

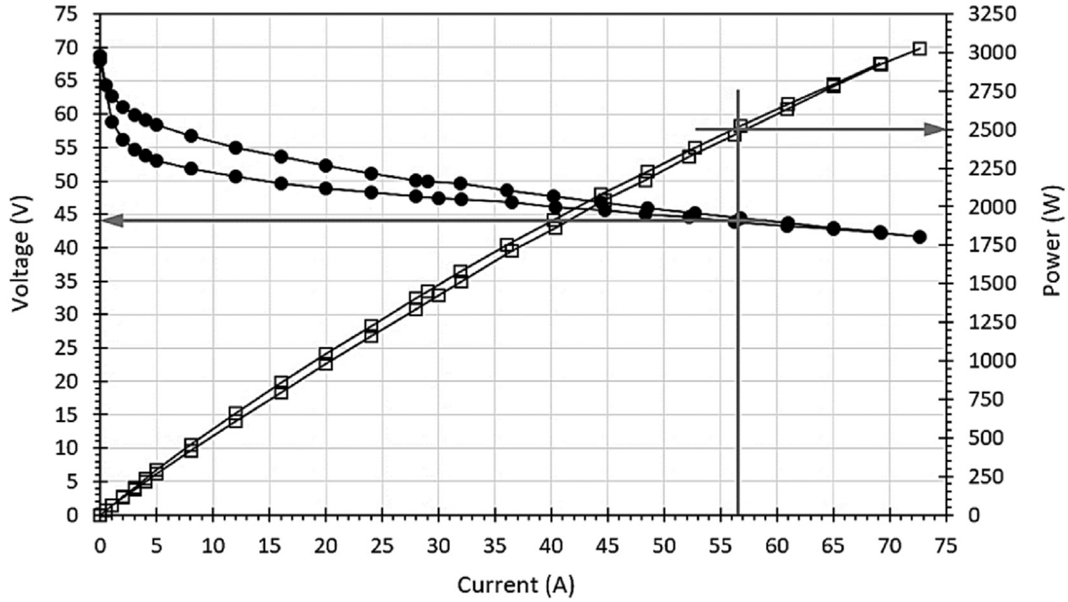

Fig. 3 – Initial polarization curve obtained for the H-3000 in the test bench.

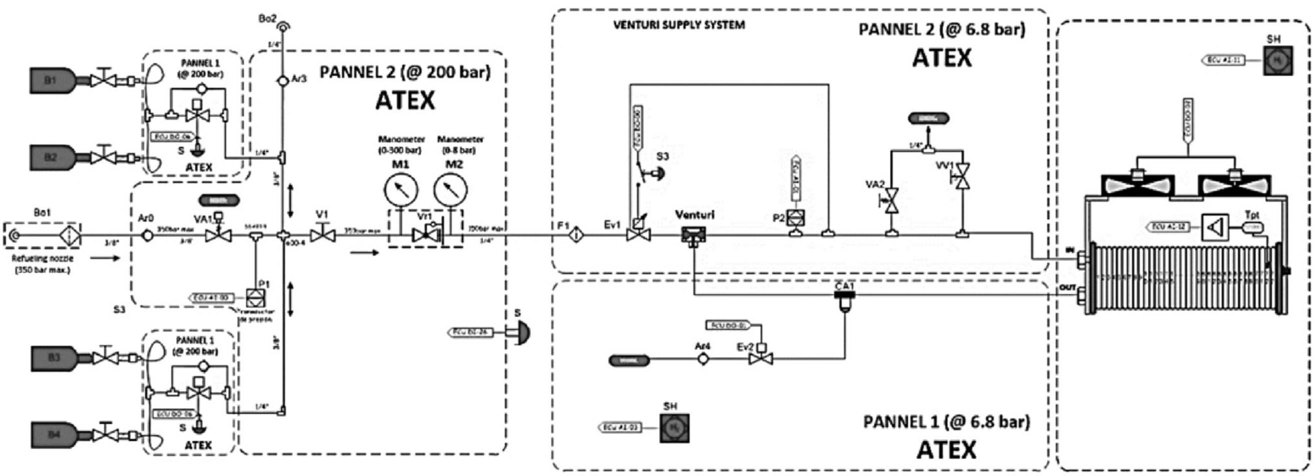

Fig. 4 – Piping and elements diagram of the hydrogen storage and supply system.

elements diagram of Fig. 4. Instruments and devices that fulfill anti-explosion (ATEX) requirements are also identified.

Hydrogen is refueled to the GSS of the FCHEV with a simple and innovative system either automatically through nozzle Bo1 (commercial WEH® system) or manually using connector Bo2. All elements and devices of the hydrogen supply system to the PEMFC stack fulfill ATEX regulations as is mandatory for these facilities. In the present research, two unidirectional solenoid valves (one for each two bottles, as depicted in Fig. 4) of small internal diameter, capable of supporting high pressures, have been placed in parallel with non-return valves, instead of the bidirectional large opening solenoid valves that are commonly used. The solenoid valve is only used to supply the hydrogen to the PEMFC stack (i.e. to discharge the GSS). The refilling of the bottles is carried out through the non-return valves that have a very high flow rate (large internal diameter). They are automatically opened by simple pressure difference. In this way, the refilling time of the GSS is very short and the whole process is very efficient. The commercial refueling WEH® system is formed by the TK-16 nozzle and the TN-1 receptacle, and integrates a high-flow check valve and a self-cleaning particle filter (20 μm).

To supply hydrogen to the PEMFC stack, the system includes a 0.5 μm particulate filter (F1) and a recirculation system formed by a proportional solenoid valve (Ev1) and a Venturi-type ejector. This element allows the recirculation of part of the unreacted hydrogen from the anode sides and to reintroduce it into the stack. Passive or active hydrogen recovery schemes have been used previously in both constant hydrogen bleed or hydrogen purge strategies [18–24]. To this end, hydrogen blowers, recirculation pumps or Ventury-type ejectors are included at the anode gas line. In the ejector, the velocity of the inlet gas increases as it passes through the nozzle while its pressure decreases, allowing the suctioning of the recirculated gas. When the hydrogen is consumed in the stack, the inlet pressure tends to decrease below the set point (0.5 bar). Then, the proportional solenoid valve, which is controlled by the pressure measured at the Venturi outlet, causes a proportional increase in the gas, keeping a constant hydrogen pressure of 0.5 bar at the stack. To ensure a stable operation of the PEMFC for all working conditions, the pressure of Ev1 varies from 0 to 4.4 bar. Another filter (CA1) was also placed in the line in order to collect the impurities dragged by the recirculated gas. Impurities (water and nitrogen) are eventually eliminated from this filter by purges performed at a given frequency depending on the current demanded to the stack [25–28]. The recirculation system is passive, and does not imply any power consumption.

The active hybrid powertrain

The H_2+PEMFC powerplant was added to the original electric one included in the vehicle forming the HPP. This corresponds to the elements enclosed in the dashed square of the final configuration diagram depicted in (Fig. 5 a). The electrical layout with the different elements is shown in (Fig. 5 b).

The aim of the active hybrid system is to safely supply the electric power produced in the PEMFC stack to the main DC bus of the BEV (Busbar) using a booster DC/DC power converter (CP1). Two other DC/DC converters are used to supply power at 12 V and 24 V to the different electric and electronic elements of the ancillary systems of the H_2+PEMFC system. In the hybrid system, the voltage at the Busbar is fixed by the battery, varying from 78.3 V (when the battery set is fully charged) to 69 V (when the SoC is around 30%). Therefore, the booster DC/DC converter (CP1) is current controlled, a different strategy from the one used in Ref. [29] where the device was voltage controlled, meaning that it can only supply power to the Busbar when the SoC of the battery is below 95% (75.9 V). As can be observed in Fig. 5 b), different switches, fuses and protection diodes are included, in order to ensure the safe operation of the hybrid powerplant. If a problem occurs during the PEMFC stack operation, the power switch (Sw1) opens, and the relay Sw5 that powers the resistor (R1) is activated, preventing the degradation of the stack when operating at open circuit voltage [30]. R1 is also used to

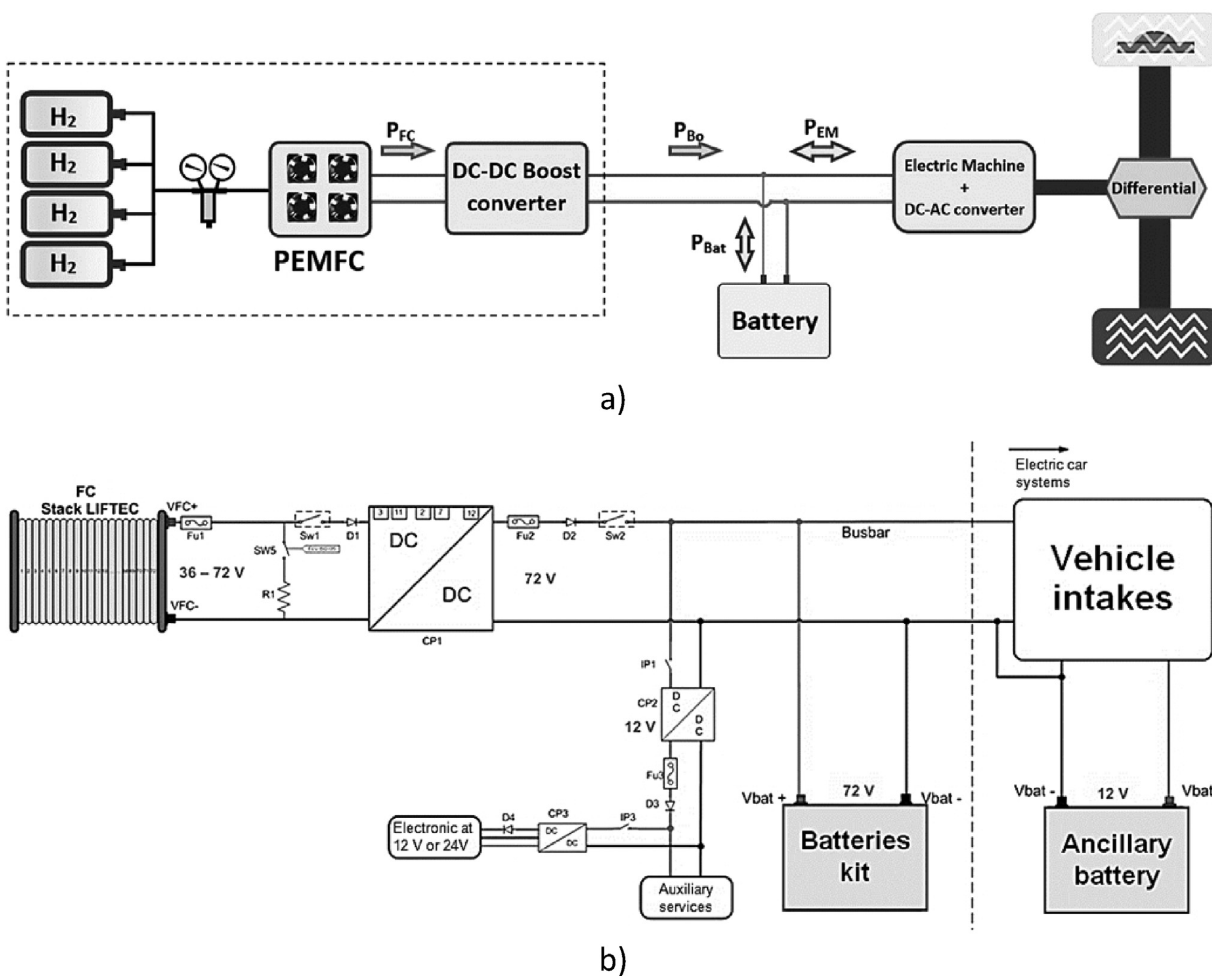

Fig. 5 – Hybrid powerplant of the FCHEV: (a) diagram of the final configuration with the added H_2+PEMFC system (dashed square); (b) electrical layout.

consume all the hydrogen remaining in the stack during the stop protocol of the PEMFC stack.

The control system and energy management strategy

In general, designing an efficient control system for a PEMFC is challenging due to its sluggish dynamics, nonlinearity and strict operating constraints. A sudden change in power load causes a significant drop in the stack hydrogen partial pressure (starvation), which rapidly decreases the cell voltage, shortening the lifetime of the device. Thus, the control system has to be capable of ensuring that the PEMFC satisfies the dynamic load with the maximum operating efficiency. Many of the degradation mechanisms that occur in both PEMFC and batteries are strongly linked to the operating conditions and therefore can be mitigated by optimizing the Energy Management Strategy (EMS). In this way, the overall efficiency of the system is also maximized [31–33]. The commercial H-3000 stack is supplied with its own control system. However, due to the specificities of this application (e.g. the inclusion of the hydrogen recirculating system) and to increase as much as possible the lifetime of the stack, it was decided to replace the commercial electronic control by one accordingly designed. To control and monitor the different electrical parameters of the H_2+PEMFC system, a central electronic control unit (ECU) was used. It consists in an embedded control and acquisition NI roboRIO microcontroller with a real-time dual-core ARM Cortex-A9 processor and a Xilinx Z-7020 FPGA. It is a reconfigurable robotic controller that meets industrial shock and vibration standards. This ECU includes built-in ports for inter-integrated circuits (I^2C), serial peripheral interface (SPI), RS232, USB, Ethernet, PWM and relays. It features LEDs, buttons, an onboard accelerometer and a custom electronics port. The LabVIEW control software regulates the sampling frequency to 800 Hz.

The control system of the stack includes, as a novelty in PEMFC applications, a discrete state machine model programmed in LabVIEW code with LINUX realtime operating system, which was embedded into the ECU microcontroller. The control model, as can be observed in the diagram of Fig. 6, follows a ruled-based approach where the transition among the different operating modes, such as STAND-BY, SUPPLY POWER, CHARGING, etc., is decided by a state machine that is based on vehicle operating conditions, change in driver demand, and any system fault that can be detected [34,35]. The initial mode, START (0), is a transient state where all operating parameters are reset. After that, the stack immediately goes into the IDLE mode (1), waiting until the "fuel cell ON" button is pressed (START FC mode). If, due to a problem, either the stack cannot be turned-on or it does not work properly, it will return to IDLE, and some visual alerts (LEDs) are lighted up. If the fuel cell is switched on correctly, it jumps to STAND-BY mode (3), where the stack only generates the power consumed by the control electronics and the ancillary systems. Once in this state, the stack is ready to either supply power to the EM of the vehicle or to recharge the battery system.

Three different situations are considered. On the one hand, when the vehicle operates in a low consumption rate and the

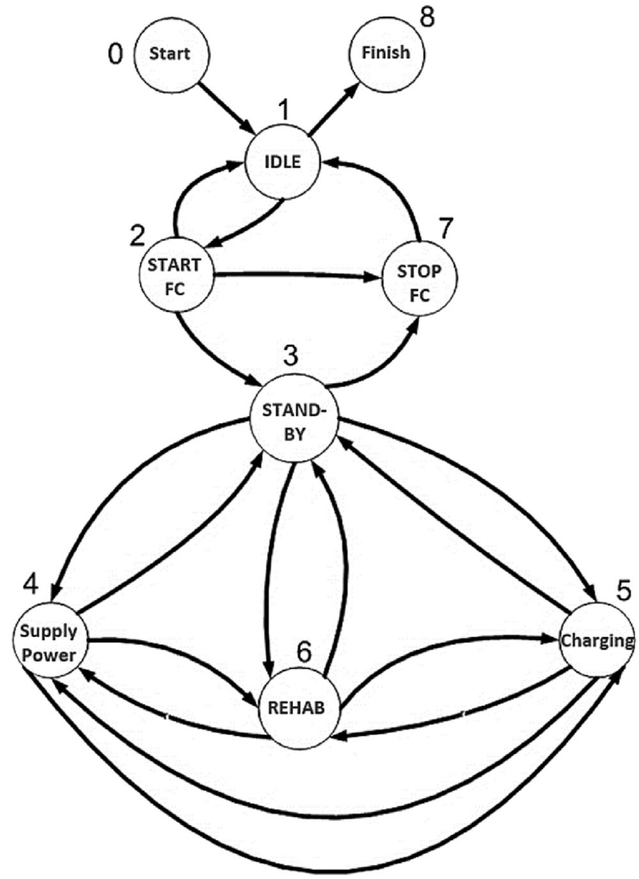

Fig. 6 – Diagram of the operating modes of the state machine used to control the stack performance.

SoC of the battery is below 95%, the stack is switched to CHARGING mode (5). On the contrary, if the power demanded at the main DC bus increases, it is shifted to the SUPPLY POWER state (4). The control system was designed to ensure an almost constant power delivered by the PEMFC, while the battery system provides the additional power required for acceleration. So, the H_2+PEMFC system acts as a range extender of the original BEV. When the PEMFC stack works properly, it alternates between CHARGING and SUPPLY POWER modes. In order to check the correct operation of the stack, a typical polarization curve was also recorded into the microcontroller. Nevertheless, if it is observed that for a given current the voltage delivered by the PEMFC departs 10% from the one corresponding to that of the recorded polarization curve, it enters in the rehabilitation (REHAB) mode (6). The aim of this mode is to improve (or recuperate) the correct performance of the PEMFC, eliminating the water and nitrogen accumulated inside the stack activating the purging strategy, since the commercial H-3000 operates in dead-end mode. Usually, after the purging sequence the performance of the stack is recovered and it is again moved to SUPPLY POWER or CHARGING modes, depending of the total power demanded by the vehicle. On the contrary, if after the purging sequence the performance of the stack is not improved, the alarm LEDs are lighted up again, and the stack is sequentially moved to

STAND-BY, STOP FC (7) and IDLE states. Eventually, it is shifted to the FINISH mode (8), stopping the hybrid control sequence.

Additionally, the internal 3-axis accelerometer of the NI roboRIO is used either to calculate the inclination of the vehicle, or to identify if it has undergone a sudden acceleration or an abrupt deceleration caused by an accident. In that case, the electrical signal produced by this device cuts off the main hydrogen supply system.

Results

The results discussed in this section were obtained in different field tests performed during the use of the FCHEV in real operating conditions at Viñas del Vero winery.

Performance of the PEMFC stack

Once the hydrogen system (GSS, H_2 supply system, PEMFC stack, and control electronics) was fully assembled in the vehicle, the performance of the H_2 recirculation system was verified. The polarization curve and the hydrogen consumption directly measured are depicted in Fig. 7. As can be observed, the use of the Venturi recirculating system slightly improves the performance of the FC. If this performance is compared with that initially obtained in the test bench (see Fig. 3), it is observed that a lower current is needed to supply the power corresponding to the rated operating point (2.5 kW). Then, hydrogen consumption also decreases, and the actual efficiency (47.9%) of the H-3000 is increased close to 1%. It is also important to note that a better performance is also obtained when the stack works in the CHARGING operating

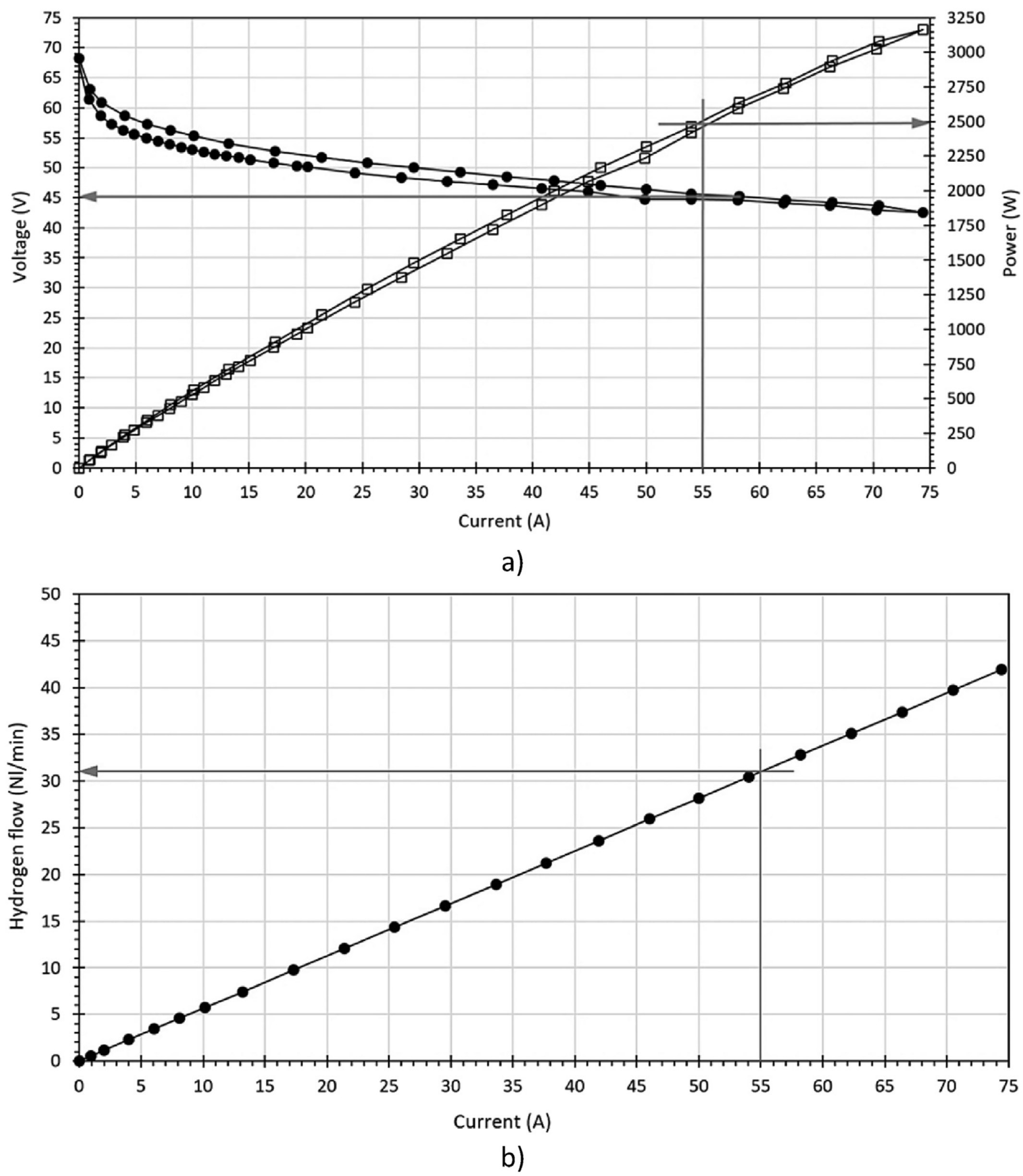

Fig. 7 – Polarization curve (a) and hydrogen consumption (b) of the H-3000 with the hydrogen recirculating system for the nominal operating point (2.5 kW).

mode. For this mode, the current delivered by the stack with the Venturi system for the demanded power (1.4 kW) is 27.5 A, and the hydrogen flowrate is 15.3 Nl/min, yielding an efficiency of 55.51%. On the contrary, for the original system, for the same operating point the current provided is 29 A, the hydrogen consumption is 16.34 Nl/min., and the efficiency falls down to 51.98%.

In the present research, the importance of the passive hydrogen recirculating has been demonstrated. During dead-end anode operation, impurities (liquid water and nitrogen gas) are transported through the membrane from the cathode to the anode side. This accumulation causes a decrease in the hydrogen partial pressure and also may block hydrogen gas from reaching the anode catalyst layers. This, in turn, leads to local hydrogen starvation that can result in corrosion of the carbon support, a decrease in cell performance, and finally, irreversible cell degradation [36–39]. With the purge strategy, the water and nitrogen accumulated are swept out and replaced by fresh dry hydrogen improving the fuel utilization rate. This system also helps to control the cell voltage. This is very important, especially in the low current density range, avoiding the irreversible corrosion damage of the carbon support due to an uncontrolled voltage increase. Finally, this system also allows the self-humidification of the stack, avoiding the use of an external humidifier.

In the field tests performed at the winery, it was verified that there are some factors that affect the behavior of the PEMFC stack. The most relevant ones are the position in which stack is assembled, the head losses in the air circuit, and the ambient temperature. It was also demonstrated that the influence of the pressure losses introduced at the hydrogen supply system is very low and can be neglected. For the assembling position, the manufacturer recommends to place the stack vertically in order to facilitate the extraction of the water produced in the electrochemical reactions. Regarding the air circuit, a filtering material with low pore size was placed at the air inlet port, to prevent the entry of dust into the cathode channels, which could seriously damage the MEAs. To overcome the added pressure loss, the working voltage of the axial fans was carefully optimized. Finally, in tests performed during winter, it was noted that when the ambient temperature was close to 5 °C, which is usual in the winery, the stack temperature during the operation was in the lowest limit established by the manufacturer.

In Fig. 8, the performance of the stack registered at the winery after 1000 h (empty symbols) and the initial polarization curve obtained at the test bench (solid symbols) are compared. As it can be observed, the power difference for the same operating point (50 A) with respect to the value obtained in the test bench is about 110 W (4.8%). The main part is attributed to the different operating conditions between both the laboratory and the field tests. When the polarization curve was obtained at the test bench, the stack voltage was stabilized for each demanded current. On the contrary, in the field tests the stack reacts dynamically to the power demand of the vehicle user, as it happens in real life. Besides, as the field tests were performed in May with an optimal ambient temperature (25 °C), the low performance can only be attributed to the assembling position, and to the head losses at the air circuit.

Performance of the hybrid electric car

The results obtained during a real driving test are depicted in Fig. 9. It consisted in a round trip from the parking of the winery to the closest vineyards at a distance of 3.5 km, climbing two small hills (40 m), as can be observed in the altitude profile (solid line) in Fig. 9 a). The velocity profile is also plotted with the dotted line. The average velocity of the FCHEV during the whole test was 15.6 km/h, reaching a maximum of 43 km/h. It was calculated that the average power demanded by the EM of the vehicle was 3.75 kW. However, as can be observed in (Fig. 9 b), the peak power demanded by the vehicle (solid black line) exceeds, by far, the EM rated power (horizontal dashed grey line). This corresponds to the ascension of the hills or when a fast acceleration is demanded. In this situation, the control systems limited the

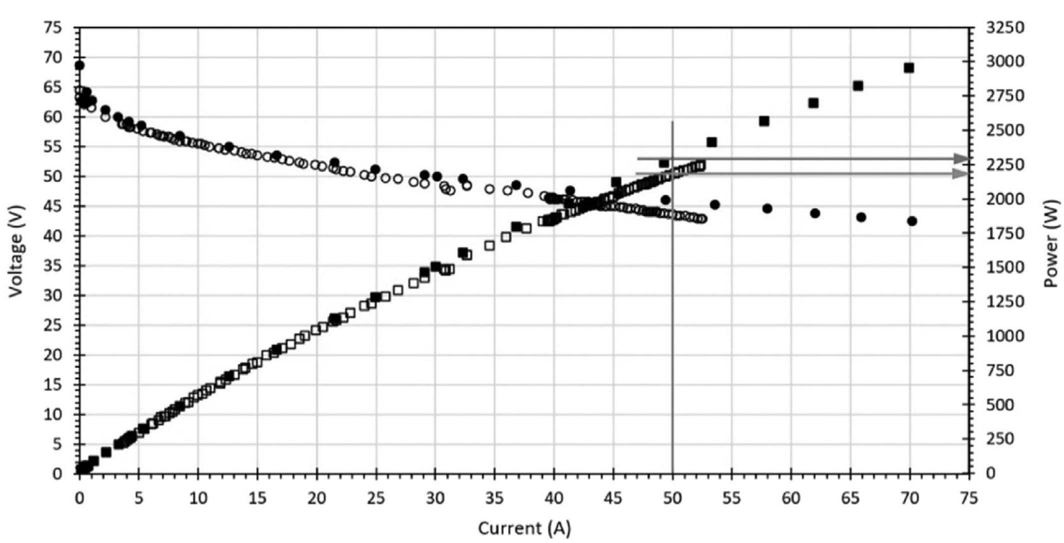

Fig. 8 – Comparison of the performance of the PEMFC stack: Initial (solid symbols) vs. 1000 h at the winery operating conditions (empty symbols).

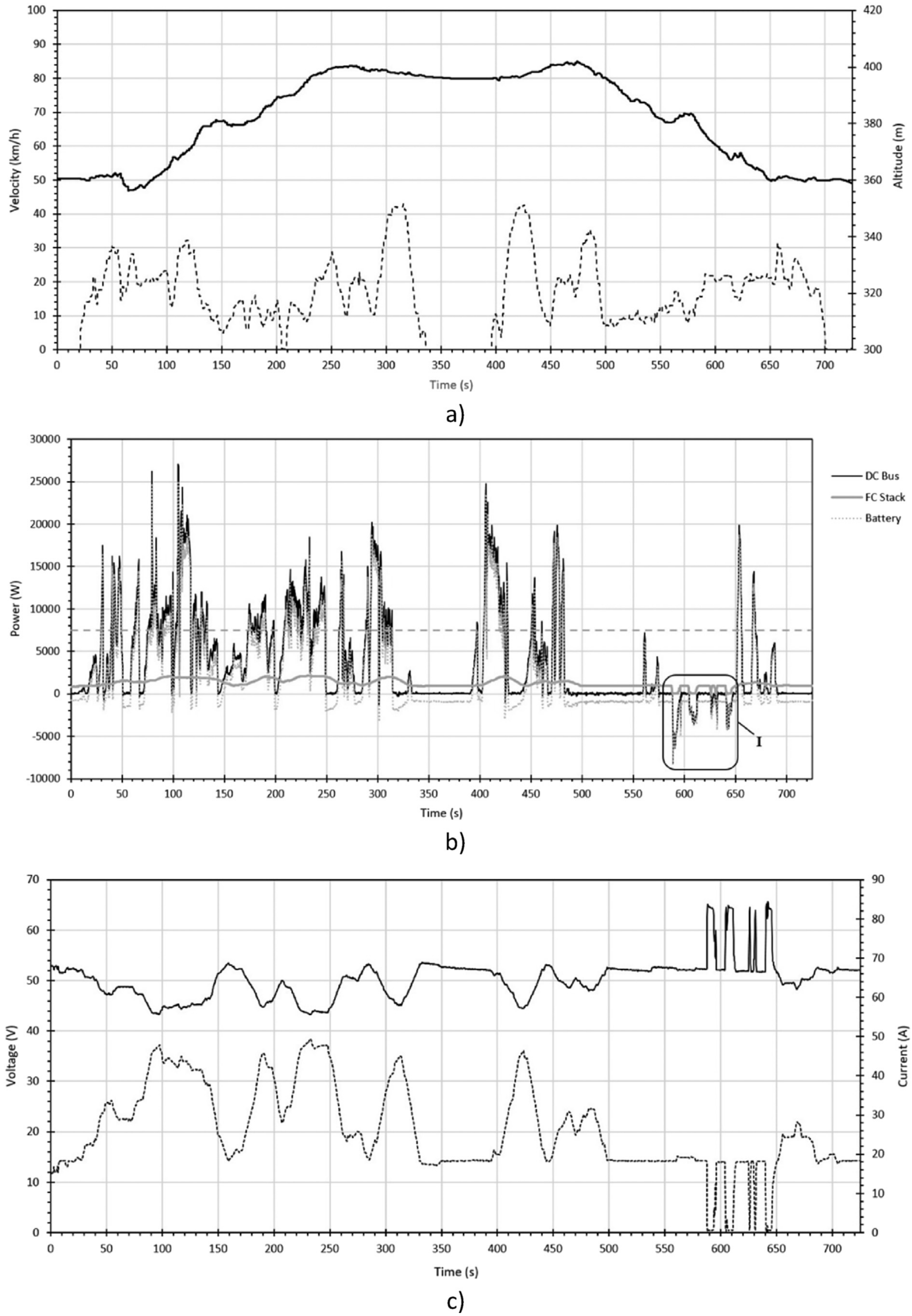

Fig. 9 – Results of the real driving test in the winery: (a) Altitude (solid line) and velocity profiles (dotted line), b) Power of the different sources, and c) Electric performance of the stack (voltage in solid line and current in dotted one).

power supplied by the PEMFC stack to the EM of the vehicle to a maximum of 30% (2.5 kW) of the rated one (7.5 kW). It was also verified that for the high demand range, the power is mainly supplied by the battery (dotted grey line), while for the low power demand range the CHARGING mode at the H-3000 stack is activated and part of the energy is used to recharge the battery. This situation corresponds to the zones in Fig. 9 b) where the power of the battery is negative. In this case, the stack supplies 1.4 kW (power density of 7.02 W cm^{-2}) to the DC-DC converter; 1.14 kW (5.72 W cm^{-2}) of them are used to recharge the battery, due to the efficiency of the electronic elements for the operating point (92.8%) and the low power needed for the ancillary systems (160 W). The rest of the power of the stack is used in the control electronic devices. Besides, it is also important to highlight that during both start-up and before stopping the vehicle, the total energy demanded by the EM is supplied by the PEMFC stack.

On the other hand, the PEMFC stack operates in a quasi-steady state (solid bold grey line), with an average power of 1.27 kW and a net efficiency of 52.02%. As depicted in (Fig. 9 c), very low variations of both voltage and current delivered by the stack were detected, except for the region "I" surrounded by the square in (Fig. 9 b), which corresponds to the running time between 590 s and 645 s. This behavior coincides with the recovery of electric energy from braking that took place (in this test) when descending the second hill and the vehicle traction system was shifted to the lowest gear. It was also confirmed that, when working in hybrid mode, 66% of the total energy demanded by the vehicle was supplied by the battery, and 34% by the PEMFC.

When running in the bumpy and irregular terrain of the winery, the operating time of the pure electric vehicle (without the use of the hybrid powerplant) was verified to be close to 2.7 h until the minimum SoC of the battery set was achieved (below 25%). As recommended by the manufacturer the state of charge of the battery should never be less this limit because it can be very harmful, and its lifetime is drastically reduced. This means that the actual range of the BEV is lower than 80 km. On the contrary, when the hybrid system was used, to the energy stored in the set of batteries (40.9 MJ), a net energy of 30.88 MJ (actual energy output from the booster DC/DC converter) was added by the PEMFC stack, and the FCHEV was able to run during 4.8 h. So, the actual range of the vehicle when using the hybrid powerplant is extended 78% compared to the original BEV. This is very important because the range of the hybrid vehicle does meet the requirements of daily range imposed by the winery, which, according to the tasks assigned, should be more than 4 h. The possibility to perform an electric recharge during the day to meet this requirement was neglected because the commercial charger of the vehicle is very slow. Actually, the time needed to complete a full electrical recharge is above 8 h. However, the hybrid system increases the autonomy up to 4.8 h with the hydrogen contained in the GSS of the vehicle. However, if for any reason the working time needs to be further extended, the hydrogen refueling system allows to refill the GSS of the vehicle in less than 20 s.

It should also be highlighted that the significant increase in the autonomy of the FCHEV verified in the actual field tests has been possible by the implementation of the stack control system and energy management strategy. The transition among the different operating modes (STAND-BY, SUPPLY POWER, CHARGING, etc.) is decided depending on the vehicle working conditions, change in driver demand, and on any system fault that can be detected. The operation strategy imposed by the designed control system, ensures that the PEMFC stack always works in a range very close to the maximum efficiency and minimum fuel consumption operating point. The inclusion of the rehabilitation mode (REHAB) in the control system has allowed to improve the performance of the stack and to increase its lifetime. All the improvements incorporated to the hybrid vehicle have allowed its operation for more than 1000 h during the first year of the project without a noticeable loss of performance. So the validity of the EMS implemented in the control system has also been demonstrated.

Finally, the energy management strategy of the hybrid powerplant also allows to increasing the useful lifetime of the batteries. In general, as already discussed, the PEMFC stack supplies 30% of the power demanded by the EM if it is close to the rated one (7.5 kW), and all of the total when it is lower than 2 kW. This situation enables to establish a less aggressive operating strategy for the batteries, allowing prolonged inactive intervals that help to cool them down, avoiding deep energy discharge, and reducing its degradation.

Conclusions

A commercial plug-in *ePath-7500* BEV has been suitably modified to be powered by a hybrid powertrain formed by a commercial H-3000 PEMFC stack that increases 78% the initial range of the BEV. The PEMFC system (electric and electronic control, hydrogen storage, and the stack) was assembled at the original tilting rear load platform. The hydrogen supply system includes a proportional solenoid valve and a Ventury-type ejector that allows the recirculation of part of the unreacted hydrogen from the anode sides. Polarization curves of the stack show that its performance slightly improves when the hydrogen recirculation system is used. It is verified that for the rated operating point (2.5 kW) the hydrogen consumption decreases, and the actual efficiency (47.9%) PEMFC is increased close to 1% when compared to the results obtained in the test bench. Besides, an optimum state machine model has been integrated in the control system of the PEMFC stack. The inclusion of a rehabilitation operating mode ensures the safe operation of the stack, enlarging its lifetime. A better performance of the stack is also obtained when the stack works in the CHARGING operating mode. For this mode, the current delivered by the stack for the demanded power (1.4 kW) is 27.5 A, and the hydrogen flowrate is 15.3 Nl/min, yielding an efficiency of 55.51%.

Field tests performed proved that when working in hybrid mode 34% of the total energy demanded by the vehicle was supplied by the PEMFC stack. During the demonstration period (237 day) the vehicle has efficiently operated in hybrid mode for more than 1000 h, confirming the validity of the EMS implemented in the control system, which also extends the lifetime of the battery set. The excellent performance of the refueling system was also verified, refilling the GSS of the FCHEV in a very short time.

Acknowledgements

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Artículo

Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case

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Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case

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Abstract: Standalone renewable energy is widely used to power irrigation systems. However, in agricultural facilities, electricity from the grid and diesel are also consumed. The design and sizing of renewable generation involves difficulties derived from the different seasonal profiles of production and demand. If the generation is 100% renewable, a considerable energy surplus is usually included. This paper is focused on a renewable energy system, which has been installed in a vineyard, located in the northeast of Spain. With energy from the photovoltaic fields, the wastewater treatment plant of the winery, a drip irrigation system and other ancillary consumptions are fed. The favourable effect of combining consumptions with different seasonal profiles is shown. The existence of some deferrable loads and the energy management strategy result in an aggregate consumption curve that is well suited to production. Besides, the required energy storage is relatively small. The surplus energy is used for the on-site production of hydrogen by the electrolysis of water. The hydrogen refuels a hybrid fuel cell electric vehicle, used for the mobility of workers in the vineyard. In summary, electricity and hydrogen are produced on-site (to meet the energy needs) from 100% renewable sources and without operating emissions.

Keywords: photovoltaics; energy management strategy; hydrogen; fuel cells; irrigation; off-grid; Mediterranean crops; vineyard

1. Introduction

On the one hand, the transition to a low-carbon economy is a process that requires the use of energy produced from renewable resources. In fact, the renewable fraction of the grid's electricity mix is increasing. On the other hand, the ubiquity of some renewable resources, especially solar irradiation, allows electricity to be generated in any location, that is, the so-called distributed generation (DG). Therefore, renewable generators can be connected to the distribution network, preferably at the points where it provides stability to the network parameters, such as voltage and frequency [1]. Despite these favourable effects, the variability of renewable resources may require measures to improve the behaviour of the generators in the face of instabilities [2].

Instead of grid-connected generation, standalone photovoltaic generation is especially well suited to rural and natural areas, where the costs and environmental impacts of power lines are higher. In this way, the on-site production of renewable energy for agricultural uses is a subject widely studied [3], especially photovoltaics in relation to pumping and irrigation [4]. Regarding off-grid renewable energy systems, the variability of solar and wind resources makes it difficult to ensure the satisfaction of the energy demand. To address this, various techniques can be applied, which mainly incorporate short-term or long-term storage [5], hybridize several energy sources [6], and manage the energy demand in the short term [7] and in the long term [8]. As a result, the sizing of an off-grid renewable generation system is not a trivial matter [9,10]. In fact, the systems usually proposed have high fractions of surplus energy or a non-negligible fraction of non-renewable energy.

A simple application is direct coupled solar pumping [11]. In it, the pump is activated according to the solar radiation incident on the photovoltaic panels. Below a certain irradiation threshold, the pump does not work, and the power is lost. Above this threshold, the speed of the pump is a function of the solar irradiation. Consequently, the flow of water is not constant. The limitations are obvious. On the one hand, there is no guarantee regarding the volume of water that is pumped every hour or every day, since this varies according to the weather. On the other hand, this solution is not suitable for pressurized irrigation systems, which require constant flows and pressures. Consequently, direct solar pumping is adequate in several specific cases, such as the filling of accumulation ponds or reservoirs.

The incorporation of storage in batteries allows some of the aforementioned limitations to be overcome [5]. In this way, a stable supply is obtained, which can meet the demand independently of the instantaneous production of energy. In the systems endowed with renewable generation and storage in batteries, the difficulty is that the variability of the production (and in many cases of the demand) requires oversizing the system, as a greater guarantee of supply is required. Moreover, storage in batteries is only feasible in the short term (several days) due to technical and economic limitations.

Solar and wind resources are not only variable in the short term, but also have a strong seasonal variation. The demand for energy can also have a seasonal profile, especially in agricultural activities. Consequently, if the size of the energy system is adequate for the most unfavourable period, for the rest of the year, there will be a considerable energy surplus [12]. This can be alleviated by the long-term storage (months) of surplus energy, for example, in hydrogen. However, the cost of the long-term storage can exceed the savings obtained by not oversizing the system, even if the surplus energy is lost.

A technique to avoid the generation of energy presenting the same variability as the renewable resource is the hybridization of two or more types of generation [6]. The hybridization of photovoltaic panels with wind turbines has been widely proposed. However, both resources are very variable, and in the case of the wind, it is not very predictable and can present long periods, even weeks, of calm. Therefore, for irrigation in various locations of Mediterranean crops, photovoltaic generation is more suitable than photovoltaic-wind hybridization and much better than wind alone. On the other hand, the hybridization of photovoltaic panels with a diesel generator set obtains excellent results and is frequently the optimal solution from the economic point of view [13]. This is because diesel generation is manageable and can provide the necessary power when the photovoltaic generator cannot do it or the battery is empty. However, the price to pay is that a fraction of the energy comes from a non-renewable origin and the supply of fuel to the system must be maintained, even a relatively small amount.

Beyond the supply of energy for pumping or irrigation, RES (renewable energy systems) can be widely applied in rural areas, livestock farms, agro-food industries, housing, rural hotels or even villages. For the sizing of these standalone systems, it is necessary to know the profile of the demand and that of the renewable resource, which are often not well suited to one another.

For the aforementioned facts, at least three very different options exist for the supply of energy for activities in rural areas: A diesel genset, the construction of a power line to the electric grid, or a standalone renewable energy system. Among these three alternatives, the first intensively uses fossil fuels, and the second presents environmental and landscape impacts. As for its profitability, usually the first has a high operating cost, and the second, a high investment cost. Regarding the third solution, standalone renewable generation systems require a specific dimensioning for each case, which does not allow for prior generalizations about their viability or profitability. For this reason, it is interesting to address different types of activities and study their energy demands and other relevant characteristics in order to design and size their renewable generation systems.

One of the relevant economic activities taking place in rural areas is the production of wine. This combines viniculture and winemaking, including various processes with different energy demands, allowing for a more elaborate approach than, for example, only an irrigation system. That is why, in this work and other related works, the wine sector has been taken as a case study. According to data from the OIV (International Organization of Vine and Wine) [14], in 2017, the total world area under vines was 7.534 million ha, and the production of wine was 248 million hl. Regarding the emissions associated with wine production, a study [15] assigned between 0.41 kg and 1.6 kg of CO_2 per bottle of standard wine. According to the Methodological recommendations for accounting for GHG (Greenhouse gases) balance in the vitivinicultural sector [16] (p.47), glass, fuel and electricity are by far the major contributors to GHG emission in a winery. As a result, the substitution of the energies used for others of a renewable origin would considerably reduce the emissions associated with the activity of wine production.

The introduction of renewable energies in the wine sector, as in other sectors of activity, is still relatively slow. To facilitate this, it is necessary to adapt the generation systems to the needs of the activity, as well as to increase the information available to the decision-makers, the suppliers of energy systems and other stakeholders [17]. The European project, LIFE REWIND [18], has addressed the incorporation of renewable energy, generated on-site, in the wine industry. Among other actions, a standalone RES has been installed in a Spanish vineyard. This prototype meets two objectives that are difficult to combine in a standalone RES: all the energy comes from renewable sources, specifically photovoltaics, and all of it is harnessed, that is, there is no surplus energy. The purpose of this article is to show the context, configuration and results of the prototype. Some of its characteristics, such as the EMS (Energy management strategy) and the on-site production of hydrogen for use in an agricultural FCHEV (fuel cell hybrid electric vehicle) in the farm itself, are, to the extent of the knowledge of the authors, completely novel.

2. Materials and Methods

The Viñas del Vero winery is located near the town of Barbastro, in the northeast of Spain. In its vineyard, the European project LIFE REWIND has installed a prototype of RES to comply with a demonstrative function: On the one hand, to show and disseminate innovative applications of renewable energy in the wine sector; on the other hand, to carry out tests and studies, including the environmental impact.

The project has followed a process of building a prototype appropriate to a real case, which could be a representative in the wine sector. For this purpose, a series of data were collected (Table 1), to be used to size and design the prototype and determine the possibilities of replication in other cases.

Two ambits with different energy needs have been identified: vineyard and winery. In the vineyards, energy is used for mobility, agricultural machinery and, if necessary, irrigation pumping. The supply of this energy is usually provided by refuelling diesel and, in some cases, by the power grid. As for wineries, energy is used in many processes, both in winemaking and in the business office, if it is located there. This energy is usually supplied by the power grid, except for thermal processes, which are frequently fed by fuels, such as gas and biomass. The demonstrative scope of the prototype of the LIFE REWIND project is limited to electricity for wineries and electricity and diesel for vineyards. The objective is to introduce renewable energy, replacing non-renewable energy sources. For this reason, the objective is not to design an RES for a specific process that requires energy, but for a whole set of applications in wine production activities. The characterization of the demand in different cases of vineyards (irrigation, agricultural machinery and mobility) and wineries has allowed us to identify their profiles, which have a strong seasonal pattern, related to the seasonality of the cropping and winemaking processes. The purpose chosen for the prototype is to provide renewable energy for three uses: the WWTP (wastewater treatment plant) of the winery, a drip irrigation system that uses purified water and an off-road agricultural vehicle. This mix includes several of the most representative processes of vineyard activity, addressing both electricity and diesel. In order to determine the size of the RES, a series of simulation and optimization processes have been carried out, using the iHOGA (Improved Hybrid Optimization by Genetic Algorithms) software [19]. However, some of the design decisions have been made in a different way, that is, to fulfil the aims of the prototype: demonstration and testing. Among other things, this means that the system has not been designed for the economic optimum. In fact, when the LIFE REWIND project was studied in relation to the profitability of the incorporation of renewable energy, models of RES found to be simpler than the prototype were taken into account. For this reason, the present article does not include an economic study of the prototype. The following subsections describe the existing facilities in the vineyard (Section 2.1), the loads and their energy demands (Section 2.2), the criteria followed to configure the prototype (Section 2.3), and finally, the assembled RES (Section 2.4).

Table 1. Types and sources of the data.

Data Sources	Data Sets
Electricity Bills	Historical Electricity Consumption
	Electricity Prices
	Seasonality of the Demand
Fuel delivery Notes and User Annotations	Historical Fuel Consumption
	Maintenance Costs
Market Prices	Investment Cost
Interviews and Surveys	Demand Side Manageability
	Needs and Criteria for Operation
	Attitude about Sustainability
On-Site Measurements	Powers and Consumptions
Photovoltaic Geographic Information Systems	Solar Resource
Bibliographic Databases	Wind Resource
On-Site Measurement Campaigns	Solar Resource
	Wind Resource
	Temperatures

2.1. The Existing Facility

The water used by the Viñas del Vero winery is not discarded. All the water used for the processes taking place in the winery is transferred to a WWTP. Finally, the water is used for irrigation in the vineyard. An aerial view of the facility is shown in Figure 1.

First, the effluent water from the winery is collected in a pond, with a capacity of 10,000 m^3, where a biological process, which requires oxygen for its activation, degrades the organic content. Two aerators introduce air into the water to increase its oxygen level. Each of them is driven by an electric motor. The presence of oxygen in the water is measured periodically to prevent it from falling below a certain level. The process produces sludge sediment at the bottom of the pond, which is occasionally evacuated by two small electric pumps.

Secondly, the water is pumped (Pump A) to a sand filter that removes much of the residual suspended matter. The filtration is gradual, and at the outlet of the filter, another pump (Pump B) moves the water to an accumulation pond, with a capacity of 900 m^3, for irrigation.

Finally, another pump (Pump C) pressurizes the water from the irrigation pond and supplies it to the drip irrigation system. The total annual volume of purified water used for irrigation is 10,000 m^3, with little variations every year. Before the implantation of the prototype of the standalone renewable energy system, the power was supplied from non-renewable sources.

The control of aerators and pumps was conducted manually. The irrigation pump had an irrigation timer, whose programming was manually entered on a daily basis.

Regarding agricultural machinery, in the vineyard, there are some tractors and, during the vintage, some grape-harvesting machines. All-terrain vehicles are used for the mobility of workers in the vineyard and from there to the winery. Both the machinery and existing vehicles are powered by diesel.

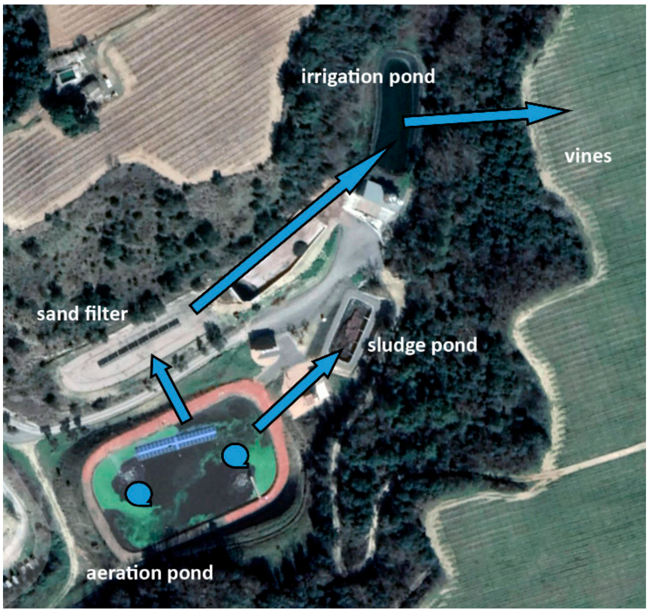

Figure 1. Aerial view of the facility, indicating the aerators and pumping.

2.2. The Energy Consumptions and Their Manageability

To analyse the total electricity consumption of the facility, the loads have been grouped into two sets due to their dependence on the water treatment and irrigation processes. One of them includes the loads whose operation is determined by the irrigation demand. The other set includes the loads that maintain the process that takes place in the aeration pond. In addition, the energy demand of an all-terrain vehicle for mobility in the vineyard is considered.

2.2.1. Irrigation and Pumping Loads

From the aeration pond to the irrigation pond, two pumps drive the water successively: A (from the aeration pond to the sand filter) and B (from the sand filter to the irrigation pond). Finally, Pump C pressurizes the water to the drip irrigation system. Therefore, each of the pumps annually moves 10,000 m^3 of water, which comes from the aeration pond to be used in irrigation. The drip irrigation system requires a constant flow and pressure. One of the first decisions was to incorporate frequency converters in the pumps. On the one hand, this avoids the high starting current, which the inverters could not support. On the other hand, this ensures that the pumps work at the desired point of their performance curves. As a result, their water flow and power consumption are constant. Therefore, knowing the annual volume of water, the pumping rate, and the power, the annual energy demand of each pump is easily obtained (Table 2). The total yearly electricity demand for pumping and irrigation is 8473 kWh.

By contrast, the seasonal profile of the demand and its manageability is not so obvious, because of its dependency on agricultural criteria for irrigation. The vine, like other Mediterranean crops, has traditionally been cultivated with rainfall as the only source of water. Some decades ago, drip irrigation was introduced in the vineyards of Spain and other countries. This trend is increasing, partly because the effects of climate change. In the Viñas del Vero vineyard, the volume of water needed is calculated each week, depending on the evolution of the crop, evapotranspiration, rainfall, etc. To know the profile of the irrigation demand throughout the year, historical data were used. The graph of an average year is shown in Figure 2. It is shown that the irrigation season begins in May and ends in September, with its maximum in August. For more than half of the year, the demand is zero.

Table 2. Operating data of the pumps.

Pump	Power (kW)	Volume of Water (m^3/year)	Pumping Rate (m^3/h)	Operating Time (h/year)	Energy Demand (kWh/year)
A	7	10,000	22	455	3185
B	2.8	10,000	23	435	1218
C	11	10,000	27	370	4070
Sum	20.8	-	-	-	8473

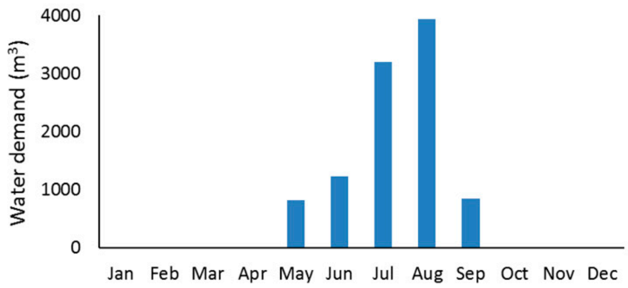

Figure 2. Graph of the irrigation by month over an average year.

Regarding demand manageability, since the irrigation decision is made weekly, it is possible to manage it only within this period. That is, the irrigation planned for a week can be divided among the seven days, with some flexibility. In the month of the greatest demand (August), 146 hours of Pump C operation (irrigation) are required, with an average of 4.7 hours a day. Some agricultural studies [20] suggest that, for field crops, such as grapevines, the drip irrigation efficiency is not affected by the time of day of watering, although the manager of the vineyard indicated his preference for operating irrigation at night. Many farmers share this preference, so it is necessary to take it into account.

Pump A is operated to replenish water in the irrigation pond. Therefore, it can be activated at any time while the pond is not full. Pump B is activated automatically when the water driven by Pump A passes through the sand filter.

2.2.2. Aerators and Sludge Pumps

The biological process that takes place in the aeration pond requires the oxygen level in the water to be above a certain limit. Below this level, the process stops. Above this level, the process accelerates to a certain limit. The aerators are responsible for maintaining or increasing the oxygen level. Since the oxygen loss in the pond is relatively slow, the operation of the aerators is not critical. This allows them to be considered deferrable loads, which are not critical in a period of several days, depending on the level of oxygen previously reached. Throughout the day, one or the other, or both, of the aerators can be activated with flexibility. However, according to historical data, to complete the treatment of 10,000 m^3 of water, the working time of the aerators must be approximately 3400 h in total. In summary, the annual demand of the aerators is 47,600 kWh, and they can be used with any daily schedule or can even be stopped on some days.

The biological process produces a very slow sedimentation of sludge at the bottom of the aeration pond. During the treatment of 10,000 m^3 of water, according to historical data, the working time of the sludge pumps is approximately 150 h each. The evacuation of the sediment is not at all critical, so its activation can be done almost at any time.

The power, operating time and energy demand of each load are shown in Table 3. Regarding the demand manageability, the intra-day flexibility is total. In fact, the aerators are short-term deferrable loads. However, the maintenance of the minimum level of oxygen in the aeration pond limits the long-term deferability. Unfortunately, the available historical data contained only the total number of hours of operation in a year, not on a daily or monthly basis. Consequently, the profile of demand was not available. However, the largest contribution of water from the winery to the aeration pond occurs every year after the vintage, that is, when the irrigation season has ended.

Table 3. Operating data of the aerators and sludge pumps.

Load	Power (kW)	Volume of Water treated (m^3/year)	Operating Time (h/year)	Energy Demand (kWh/year)
Aerator 1	14	-	3400 [1]	47,600 [1]
Aerator 2	14			
Sludge pump 1	1.8	-	150	270
Sludge pump 2	1.8	-	150	270
Sum	31.6	10,000	-	48,140

[1] Sum of both aerators.

2.2.3. All-Terrain Vehicle

The initial idea of replacing the diesel in mobility by replacing some of the vehicles or agricultural machinery used in the vineyard by others that have electric traction. Because agricultural machinery, such as tractors, is not currently available, an all-terrain diesel car has been chosen, to be replaced by an electric one. After incorporating a fuel cell in order to convert it into a FCHEV, it could be supplied with energy from the RES, either in the form of electricity, or in the form of hydrogen.

In the previous situation, an all-terrain diesel vehicle was being used for the movements of workers from the winery to the vineyard, and within the vineyard. The cycle of operation of the vehicle in a day included short trips at a low or moderate speed and multiple stopping periods. The available historical data only included the refuelling quantities. The users provided additional information to estimate the number of days they use the vehicle. Finally, an average consumption of 6 L of diesel per day and 225 workdays per year was estimated, which totals 1350 L of diesel per year.

2.2.4. Ancillary Loads

In the RES, a lead-acid battery will be in charge of the short-term storage. In addition, there will be a hydrogen production system. Both elements are sensitive to extreme temperatures and especially to freezing. Given its location in a cabin, with a limited thermal insulation, in a countryside where the external temperature varies from −10 °C, on winter nights, to 40 °C in summer, it has been considered necessary to incorporate a heating and cooling system by means of a heat pump. This will prevent the freezing of the water in the electrolyser and will preserve the useful life of the battery and the power electronics. Small water heating resistances will also be incorporated as a safety measure against the risk of freezing in the most critical water pipes. The power of the heat pump is 2 kW. Its estimated energy consumption is 3200 kWh/year, obviously with a very seasonal profile.

The RES will also incorporate a control system. Its functions will be the control of the loads according to the EMS, the control of the system of production of hydrogen, the reception of orders from the operator, the communications, and the storage of data from the sensors. This system will work at all times, with a stable power of approximately 0.22 kW, and therefore, its estimated consumption is 1927 kWh/year.

2.3. Configuration of the Renewable Energy System

The next sub-subsections describe, in a non-exhaustive way, the criteria followed in the configuration and sizing of the RES.

2.3.1. Renewable Resources and Energy Generation

For the seasonal irrigation of Mediterranean crops, previous studies have shown, as in this case, that the ideal renewable generation is photovoltaics [13]. Data of the solar resource at the location (42°03′36″ N 0°05′42″ E) have been obtained from the Photovoltaic Geographical Information System (PVGIS) [21]. In addition, on-site measurements, before and after the installation of the prototypes, have confirmed the validity of these data. The solar irradiation on the horizontal plane is shown in Figure 3. Regarding the wind resource, the available data and measurements showed that it was scarce, with long periods of calm, even during several successive weeks. It also had strong variations from one year to the next. As a result, the solar resource suits the profile of the energy demand a lot better than the wind resource, resulting in a generation mix, with 100% of photovoltaic. For all these reasons, photovoltaics is the only kind of renewable generation used in the standalone RES of the present case study.

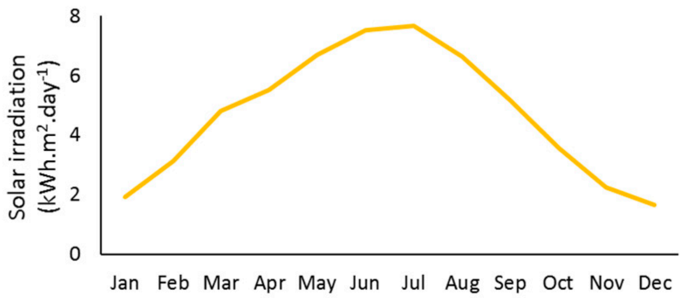

Figure 3. Solar irradiation on horizontal plane.

2.3.2. Objectives and Sizing Criteria

The role of the prototypes in the whole LIFE REWIND project conditioned the design objectives. For example, its demonstration character is the reason for incorporating three different kinds of photovoltaic assemblies, as explained in Section 2.4.1. Furthermore, in the design of the standalone RES, three main objectives were taken into account:

(1) All the energy coming from renewable sources.
(2) Taking advantage of the synergies that may appear when combining consumptions with different seasonality.
(3) The harnessing of all the energy produced.

The first condition excludes hybridization with diesel and, to obtain a stable supply, requires an oversized generation and storage. The increase in generation produces an excess of energy, which must be used in some way to achieve the third objective. Short-term storage can be achieved simply and efficiently using batteries. On the contrary, long-term storage in a standalone RES requires expensive and inefficient solutions. In both cases, in the short and long term, a large storage capacity can reduce the efficiency of the system, both in relation to the economic costs and the energy losses. Thanks to the fact that several loads are deferrable in the short term, an adequate management strategy can reduce the need for short-term storage, that is, the size of the battery. Regarding long-term storage, the option of producing hydrogen, storing it and then returning the energy to the system through a fuel cell was considered. The use of an alkaline membrane electrolyser [22] and a proton exchange membrane fuel cell (PEMFC) [23] would be indicated, although the efficiency of the electricity-hydrogen-electricity conversion is relatively low. For this reason, it was decided to produce hydrogen in the system and extract it for use in the electric vehicle. In this way, efficiency is not a critical factor, because that of the fuel cell and electric powertrain are equal to or better than that of the diesel powertrain.

Likewise, the production of hydrogen to replace diesel is a way of extracting and subsequently harnessing the energy surplus from the RES. That is why, in relation to the sizing of the RES, no demand for the production of hydrogen has been taken into account. The considered demand (Table 4) includes all the already described loads of water aeration in the WWTP, pumping and irrigation, as well as the auxiliary consumption of the heat pump and the control system.

Table 4. Data of energy demand used for sizing the RES.

Load	Energy Demand (kWh/year)	Deferrable Load	Seasonality
Aerators and sludge pumps	48,140	Yes [1]	Low
Water supply pumps [2]	4403	Intra-week	High
Irrigation pump [3]	4070	One day	High
Control system	1927	No	No
Heat pump	3200	No	High
Sum	61,740	-	-

[1] Limited by the minimum level of oxygen in the aeration pond. [2] Pumps A and B. [3] Pump C.

Multiple simulations have been carried out, with different scenarios of seasonality and manageability, looking for sizes of the photovoltaic generation and the battery that could satisfy the demand. In each of these cases, an amount of surplus energy appeared, which could be used to produce hydrogen. Finally, one of the possible solutions was chosen. In it, the size of the battery only ensured night-time operation and the intraday compensation of consumption and production, thus giving up long-term storage. Under these conditions, the size of photovoltaic generation ensures a supply, in the worst case, on a weekly basis.

2.4. The Standalone RES

The following subsections describe the RES that has been assembled and is working in the vineyard.

2.4.1. The Photovoltaic Field

Three photovoltaic sets in the prototype, mounted on different supports, have been installed in order to show them to the project stakeholders and compare their performances.

A first array is mounted on a fixed metal structure on the ground. It is fixed to the ground by prefabricated counterweights, which are easy to place and remove without leaving residue. This set on a fixed support represents the most common solution for farms due to its simplicity and reliability. The tilt of the panels can be manually adjusted in two positions, one of which is better for the irrigation season and the other for maximizing the annual production. This set includes 40 photovoltaic panels, with a total power of 10.8 kWp.

A second array is mounted on a two-axis solar tracker (Figure 4). A set of sensors and two motors allow for the continuous orientation of the panels according to the plane of maximum incident radiation, obtaining more production on any day and season than with any fixed orientation. This set can produce a more stable power throughout the day, and its purpose is to obtain enough power in the first and last diurnal hours. The solar tracker includes 40 photovoltaic panels, with a total nominal power of 10.8 kWp.

The third array is mounted on a floating structure on the aeration pond (Figure 4). The floating system has been designed specifically for its placement in irrigation ponds. Among other things, this includes the ability to adapt to frequent changes in level due to the filling and emptying of the pond. The panel tilt is fixed and is close to the optimum for June, according to the seasonality of irrigation. This floating support is itself a prototype, and its purpose is to offer an innovative solution for irrigation facilities and test its performance. This set includes 80 photovoltaic panels, with a total nominal power of 21.6 kWp.

In summary, the total nominal power of the photovoltaic field is 43.2 kWp, but with different types of azimuth and tilt. Each of the three sets incorporates three sensors: environmental temperature, panel temperature, and irradiation on the plane of the panels. In addition, two other sensors were installed: irradiation on the horizontal plane and wind speed. All of them will be used to study comparatively the three photovoltaic sets.

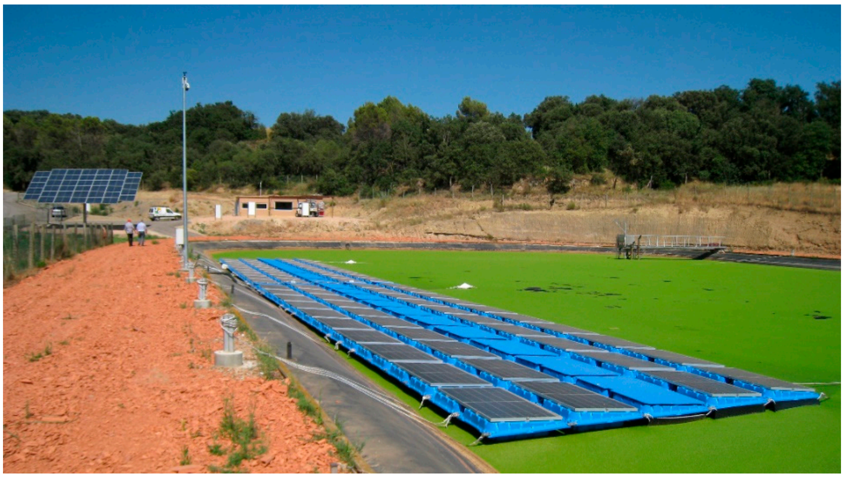

Figure 4. View of the floating set and the solar tracker.

2.4.2. The Inverters and the Energy Bus

The room of the inverters, batteries and control devices is shown in Figure 5. The pumps and aerators require a supply of three-phase AC 400 V 50 Hz. In addition, one of the design criteria was the use of energy simultaneously with its production, avoiding its storage whenever possible. For these reasons, it was decided to use an AC bus, to which both solar inverters and battery inverters are connected (Figure 6). In this way, the alternating current from the solar inverters can go directly to the loads, reducing conversion losses. Another advantage is that solar inverters have a higher performance than solar chargers. Each of the three photovoltaic assemblies has its own three-phase solar inverter, with a total power of 44 kW.

Figure 5. The room of the inverters, batteries and control devices.

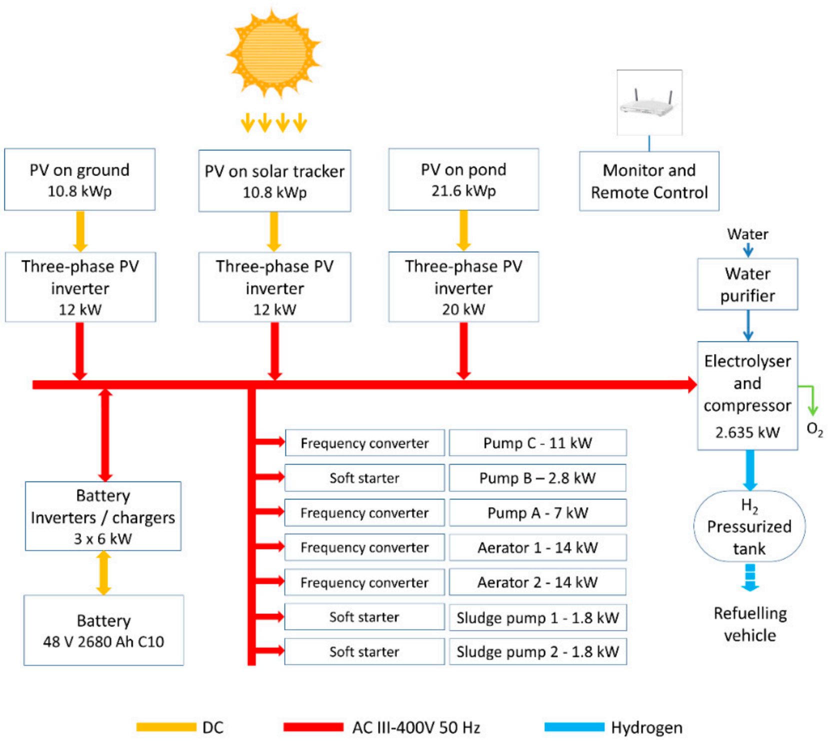

Figure 6. Block diagram of the RES (excluding the ancillary loads).

Regarding the battery inverters, a set of three units maintains the three-phase bus at 400 V 50 Hz. They are also responsible for managing the battery. Its power will determine the loads that can be activated in the absence of photovoltaic production, for example, at night. These are the irrigation pump (Pump C), the heat pump, the control system, and in some instances, Pump B, which totals a maximum of 16.02 kW. The total continuous power of the selected battery inverters is 18 kW, although they can maintain a higher power for a limited time. In the opposite direction, the set of the three battery inverters cannot charge the battery to a power greater than approximately 20 kW. That is, although solar inverters can produce up to 44 kW, no more than 20 kW can be dispatched to charge the battery. This is due to the under sizing of the battery, following the strategy in which the energy goes from the solar inverters to the loads in the largest possible proportion. Consequently, to avoid overcharging the battery inverters, when the solar production rises above 20 kW, one or more loads (for example, an aerator) must be activated to consume this excess. This is one of the criteria incorporated into EMS. In a conventional RES with the same photovoltaic power, it would be appropriate to incorporate a set of battery inverters of more than twice the power chosen here. In fact, the chosen sizing does not respect the recommendations of the manufacturer of the inverters, but this has been done intentionally to show how it is possible to drastically reduce the size and the cost of the short-term storage subsystem.

2.4.3. The Short-Term Storage

Regarding the battery capacity, it should be sufficient to allow for nocturnal irrigation, as well as to maintain the operation of the ancillary loads, especially the control system and the heat pump. In the month of the maximum irrigation demand (August), the irrigation pump is activated for, on average, 4.7 hours a day. If, for some reason, the weekly watering was conducted in just six days, each activation would last 5.5 hours. Since the irrigation pump consumes 11 kW, the energy extracted from the battery is, in the worst case, 60.5 kWh. Adding 3.3 kWh of the nightly consumption of the ancillary loads, the maximum discharge during a night is 63.8 kWh. A battery of twice the capacity of this figure has been chosen, that is, a series of 24 OPzS lead-acid cells of 2 V 2680 Ah C10, which make a total of 48 V and 128.64 kWh. Consequently, the maximum reduction of the SOC (state of charge) during the night is, in worst cases, 50%. Since deep discharges cause damage and shorten the life of lead-acid batteries, a minimum permissible SOC of 20% has been adopted as a design condition. As a result, the SOC level at sunset should be at least 70%. Finally, this figure was increased to 85%, which increases the safety margin for the operation of the system controller, even on days with very low solar radiation.

A battery of this size is relatively small and does not meet the minimum recommended by the inverter manufacturer, which was 100 Ah per kWp of the photovoltaic panels. That is, for the 43.2 kWp of the photovoltaic set, a minimum of 4320 Ah would be appropriate, rather than the 2680 Ah that was chosen. This recommendation seems to be designed to avoid charge rates above C5. However, in the design of the prototype, it was decided not to comply with this manufacturer's recommendation. That is, the battery incorporated into the prototype is 2680 Ah C10, which corresponds to 128.64 kWh. To limit the charge current of the battery, the difference between the power produced and consumed has been limited as explained in Section 2.4.2.

It is remarkable that the battery was dimensioned to compensate the intra-day deviations of the generation and demand curves, as well as to allow watering at night. It was not designed to provide days of autonomy to the loads.

2.4.4. The Production of Hydrogen

Certainly, one of the main challenges to avoid the use of diesel in agricultural machinery is the limited energy density of the batteries. Taking into account the demonstrative function of the prototypes, it was decided to use not only electricity, but also hydrogen as an energy vector, to extract the surplus energy from the RES and supply it to an off-road vehicle. For this purpose, a hydrogen production system (Figures 7 and 8) was added to the RES, including a water purifier, an electrolyser, a compressor, a storage tank and a refuelling mechanism. A specific article focusses on this system [24].

Figure 7. The hydrogen production enclosure.

The electrolyser can produce hydrogen at a pressure of 30 bar. The compressor increases the hydrogen pressure to a maximum of 200 bar and stores it in a 600 litres tank. Every hour of operation of the set, 0.5 Nm^3 of hydrogen are produced, consuming 2.635 kWh of electricity. This is a deferrable consumption, to the extent that the hydrogen can be stored in tanks in the production and refuelling system.

Figure 8. The hydrogen tank and the refuelling system.

2.4.5. The FCHEV

An electric all-terrain vehicle was modified to be an FCHEV (Figure 9), incorporating a fuel cell and the corresponding hydrogen tanks. The whole process is explained in depth in a previous article [25]. This vehicle is refuelled from the prototype's tank to its own tanks, consisting of four aluminium cylinders, with a volume of 10 L and a weight of 12.75 kg each. Working at 200 bar pressure, the hydrogen that can be stored is 0.64 kg. The fuel cell, a Horizon H-3000 stack, reverses the electrolysis, combining hydrogen with oxygen to form water and produce electricity (Figure 10). This does not mean that the vehicle's battery cannot also be charged from other sources, such as electricity from the grid in the winery, which is the base of the vehicle when it is not being used. Using 100% renewable energy and 100% clean hydrogen production and use processes, the operation of the vehicle can be classified as zero emissions. The vehicle is used to move around the vineyard and winery, avoiding the use of a conventional vehicle, with an internal combustion engine driven by diesel.

Figure 9. The fuel cell hybrid electric vehicle (FCHEV).

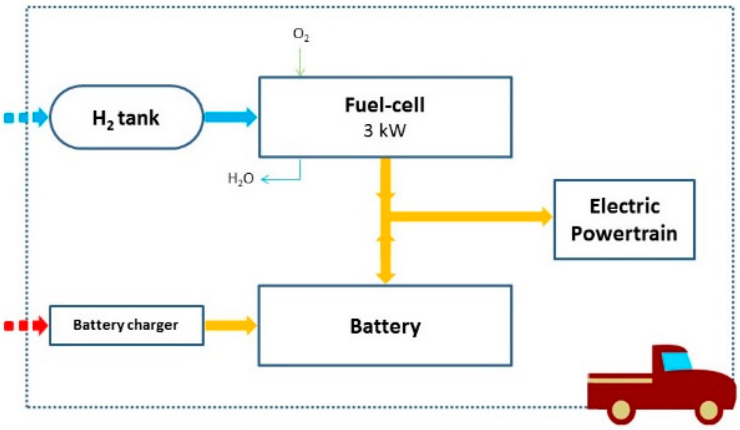

Figure 10. Block diagram of the FCHEV.

2.4.6. The EMS

The total installed power is the sum of all the loads, that is, 57.255 kW. However, not all of them can work simultaneously. The operation of the aerators clouds the water in the aeration pond. As a consequence, Pump A must not extract water from the start of the aerators until three hours after they stop. This reduces the maximum simultaneous load to 50.255 kW. On the one hand, this power is greater than the maximum output (44 kW) of the solar inverters. On the other hand, it is not necessary to activate all those charges at the same time. Consequently, the management strategy is based on activating the deferrable charges according to the power produced at each moment. In this way, we attempt to make the consumption curve approximate the generation curve. The direct and instantaneous use of the energy produced reduces the losses associated with the cycling of energy in the battery.

However, it was not possible to use photovoltaic production as a control variable. This is because if the system consumption, including the battery charge, exceeds the photovoltaic production, the solar inverters reduce their power to maintain the stability and frequency of the micro-grid. When that happens, the power delivered by the solar inverters is lower than what would correspond to the incident radiation. For this reason, it was decided that the first control variable was solar irradiation, since it is directly related to the power that the inverters can deliver. To do this, the correspondence between the irradiation and the power obtained from the solar inverters was established.

The second control variable is the SOC of the battery. The purpose is that, at the end of the day, the battery has enough energy stored to ensure night-time operation (heat pump, control system and, if applicable, irrigation).

For the purposes of the management strategy, the charges were divided into four groups:

(1) Loads whose operation is permanent: their operation is independent of the EMS. They are the control system and the heat pump. Their operation is guaranteed, except if the battery inverters stop the micro-grid to protect the battery below the minimum allowed SOC.

(2) Loads that the operator of the facility activates directly or by programming: their operation is allowed only above a certain SOC, which is different for each one. They are irrigation (Pump C), water pumping (Pump A), and sludge pumps. Pump B, which is activated automatically, also belongs to this group. Each of these loads has a minimum SOC assigned, below which it cannot be active. The higher priority, the lower the SOC allowed. Therefore, as the stored energy decreases, lower priority loads stop. The parameters, finally adjusted for these loads, are shown in Table 5.

(3) Deferrable loads that are activated depending on the irradiation: the aerators. They also have an assigned minimum SOC, below which they are not activated, irrespective of irradiation. These loads take advantage of the power available at each moment, and its management allows the battery to recharge in the morning and reach the sunset with a level high enough for the

maintenance of the system. The parameters, finally adjusted for these loads, are shown in Table 6. It should be noted that the irradiation level for start-up is higher than that for the stop level, which facilitates the recovery of the battery SOC in the morning. This hysteresis also introduces stability into its operation. Moreover, the operator of the installation periodically measures the level of oxygen in the water in the aeration pond to check that it does not fall below the minimum level allowed.

(4) Extraction of surplus energy from the system. This energy drainage from the RES to the FCHEV can be conducted either in the form of hydrogen or by recharging the vehicle's battery. On the one hand, the production of hydrogen is allowed under the condition that the battery has reached a very high SOC (90%). On the other hand, charging the vehicle's battery requires the presence of the vehicle parked next to the RES, which is infrequent.

Table 5. Loads of group 2, in order of priority.

Load	Minimum SOC
Pump B	30
Pump C (irrigation)	40
Pump A	45
Sludge pumps	50

Table 6. Conditions to enable aerators.

Load	SOC Minimum (%)	Irradiation to Start (W/m^2)	Irradiation to Stop (W/m^2)	Hysteresis of Irradiation (W/m^2)
Aerator 1	85	150	100	50
Aerator 2	40	330	290	40

All the aforementioned parameters have previously been estimated and subsequently checked and adjusted during the tests of the RES.

3. Results

The prototypes, once installed, are used in real working conditions. In addition to the observations of and approval by the workers and managers of the winery, a series of data have been collected to carry out various studies. The following subsections present the results of the short-term operation of the RES (Section 3.1), the long-term (a year) operation of the RES (Section 3.2), the hydrogen production (Section 3.3), the FCHEV (Section 3.4), and the avoided emissions (Section 3.5).

3.1. Short-Term Operation

The Figure 11 is the graph of irradiation on horizontal plane, measured at the location, over two consecutive days, specifically 5 and 6 May 2017. The first day the weather was cloudy, while the second day was sunny. This period includes different events, useful in checking the behaviour of the system in various situations.

The Figure 12 shows the performance of the RES over the same days. During this period, the production of hydrogen was not allowed, in order to observe the behaviour in the absence of long-term storage.

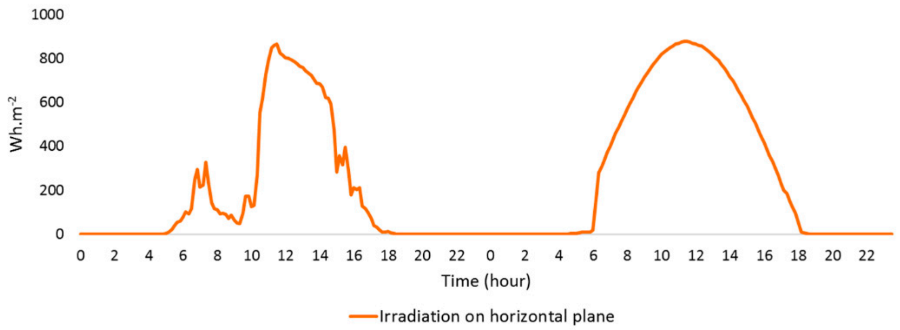

Figure 11. Irradiation on horizontal plane over 5 and 6 May 2017.

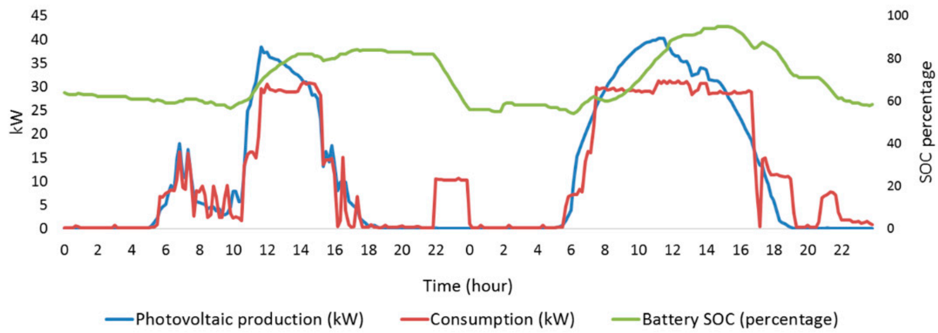

Figure 12. Performance of the RES over 5 and 6 May 2017.

The first day, the production is irregular due to the cloudy weather in the morning. The EMS operates the loads in such a way that the consumption curve is adjusted according to the available power (as explained in Section 2.4.6). Some of the energy is diverted to the battery to recover its SOC. At night, the irrigation was activated for two hours, fulfilling the schedule programmed by the user. In consequence, the SOC of the battery decreases. The small jump of the SOC around 02:00 h the following night does not correspond to an increase of energy, but to the daily recalibration of the SOC measurement.

The second day, the weather is clear and the production is in accordance with the solar trajectory. However, after 11:40 h, the production is disturbed. This is because there are no more charges available to be activated and the battery is almost fully charged. In this situation, the solar inverters reduce their power output in order to maintain the voltage and frequency of the RES. When this happens, the production follows the variations in the consumption. If the production of hydrogen had not been deactivated, it would not have been necessary to reduce production, because the surplus of energy could have been deviated to long-term storage.

In summary, the EMS worked as desired. The system made moderate use of the battery, cycling a small fraction of the managed energy. As a result, the losses associated with the charge and discharge processes were slight. In addition, the SOC remained at conservative levels, benefiting the health of the battery.

3.2. Long-Term Operation

The consumption of the different sets of loads, excluding the hydrogen production, over a year of operation, is shown in Table 7. Their graphs, on a monthly basis, are shown in Figure 11.

Table 7. Yearly consumption by set of loads.

Set of loads	Consumption (kWh/year)
Irrigation (Pumps A, B, and C)	8759
Aeration (aerators and sludge pumps)	49,100
Heat pump	3507
Control system	2060
Sum	**63,426**

3.2.1. Irrigation and Water Pumping

The consumption for irrigation and water pumping, that is, Pumps A, B, and C, is shown in Figure 13a. Its profile is similar to that taken into account during the design phase (Section 2.2.1.), although the irrigation started in March and the maximum has been moved to July, instead of August. Slight variations like this are common, depending on the different evolution of the conditions of the crop from one year to the next. There were very small consumptions, barely visible in the graph, during the months when there was no irrigation, because of the automatic activation of Pump B to drain the rainfall in the sand filter of the WWTP.

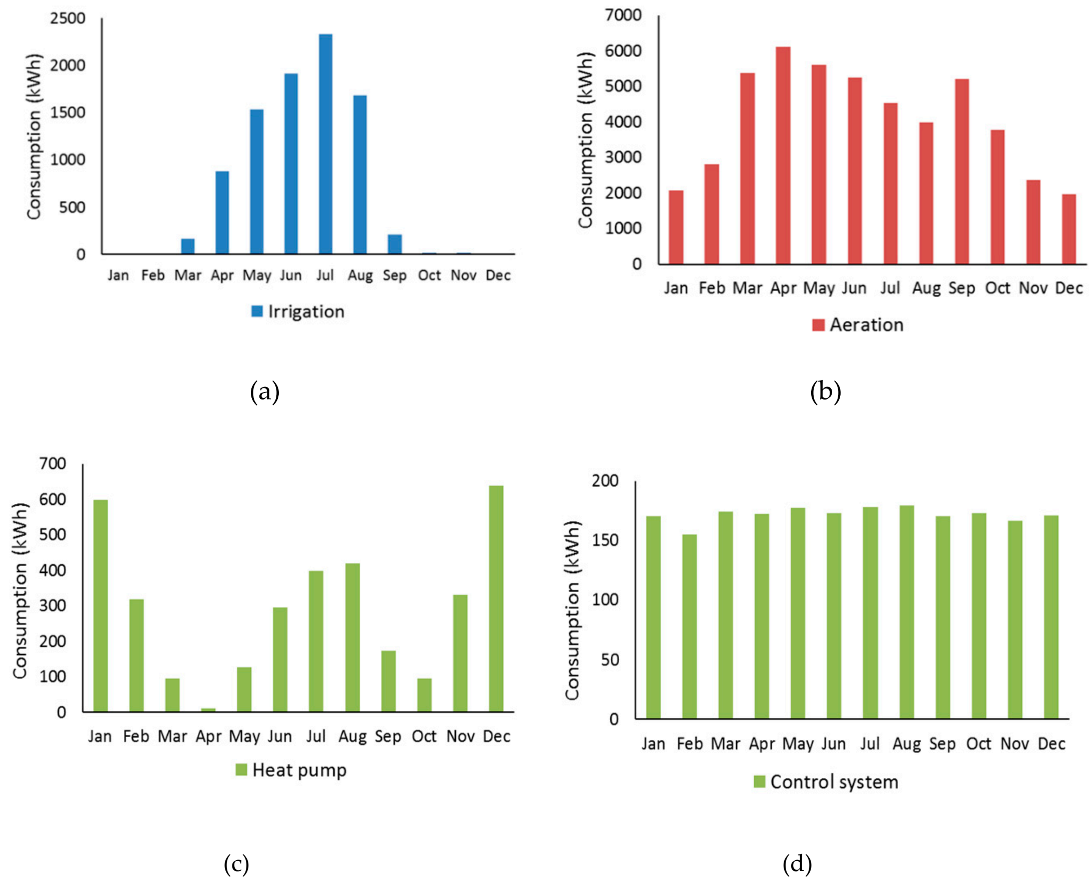

Figure 13. Consumption over a year of operation: (**a**) Irrigation and water pumps; (**b**) Aerators and sludge pumps; (**c**) Heat pump; (**d**) Control system.

As indicated in Section 2.2.1, the manageability of irrigation (Pump C) is limited. If on some days there is not enough energy available for the scheduled irrigation, it can be deferred to the days immediately following. In fact, because the sunny weather during the irrigation season in the Mediterranean climate, this has happened on just a few days. In summary, during the period of operation studied, the irrigation program that was established on a weekly basis has been fulfilled. Regarding the pumping of water by Pumps A and C, the capacity of the irrigation pond

(900 m^3) allows for a margin of several days of irrigation, so that its refilling has been done without management difficulties.

3.2.2. Aerators and Sludge Pumps

The consumption of the two aerators and the two sludge pumps is shown in Figure 13b. As indicated in Section 2.2.2, the aerators are deferrable loads. Their operation has been controlled according to the EMS, as indicated in Section 2.4.6. The profile of the measured consumption shows a seasonal profile, with maximums in April and September. On the one hand, this profile is partly caused by the availability of energy for the activation of the aerators, that is, by the difference between the energy produced and the consumption of the priority loads. On the other hand, the maximums coincide with the start of the irrigation season (April) and its end (September). In April, the extraction of the water from the aeration basin—to be used in irrigation—begins, so it must be sufficiently purified. In September, the irrigation ends and the vintage begins, and with it, the discharge of the new wastewater from the winery.

Regarding the result of the aeration, the process was correct and all irrigation water was of adequate quality. The oxygen levels in the aeration pond remained above the minimum necessary and increased when more energy was sent to the aerators, accelerating the process.

3.2.3. Ancillary Loads: Heat Pump and Control System

The consumption of the heat pump is shown in Figure 13c. Its maximum consumption occurs in winter and its relative maximum in summer due to the temperatures of the external environment. This seasonality is very different from those of irrigation and aeration. The consumption of the control system, which is practically constant and of a small magnitude, is shown in Figure 13d.

3.2.4. Production Versus Aggregate Consumption

The photovoltaic production over the studied year is shown in Figure 14a. The closer the graph of consumption to production, the lower the surplus energy. None of the individual loads, shown in Figure 13, have a profile similar to those of production.

Graphs of the aggregate consumption of the loads have been obtained, which are to be compared with photovoltaic production. The irrigation and heat pump have different seasonality. Both consumptions are priorities, and none of them has been deferred in the medium or long term. On the one hand, the maximum of the heat pump occurs in winter, when the demand for irrigation is zero. On the other hand, the maximum of the irrigation coincides with a relative maximum of the heat pump, but also with the maximum of photovoltaic production. The aggregate consumption of both is shown in Figure 14b. This combination approaches the profile of production better than the loads considered individually.

The aggregate consumption, including all loads, except the production of hydrogen, which is fed by the surplus energy, is shown in Figure 14c. This presents a very similar profile to that of photovoltaic production. The seasonal profile of the aerators is a consequence of the management carried out by the control system, according to the EMS, as explained in Section 2.4.6, adapting the consumption to the available energy. As a result, the consumption is well suited to the demand, taking advantage of the available energy and adopting a very similar annual profile, as shown in the Figure 14d.

Regarding the annual energy balance, the annual totals of production, consumption, energy used to produce hydrogen, and the electrical losses in the RES, are shown in Table 8. All energy measurements have been made at the connection of each element (solar inverters, loads, battery inverters, hydrogen production, etc.) to the AC bus. As a result, it can be stated that the measured losses occur in the cycling of energy in the battery. This is in the AC-DC and DC-AC conversions as well as in the battery itself. One of the criteria incorporated in the EMS is the reduction of energy cycled in the battery in order to avoid the associated losses. In fact, the measured losses correspond to the cycling of energy for nightly consumption (Pump C, heat pump and control system) and the intraday adjustment of a small portion of the daily consumption. It is remarkable that the lost energy represents 3.4% of the produced energy, which is an excellent figure for an RES with battery storage.

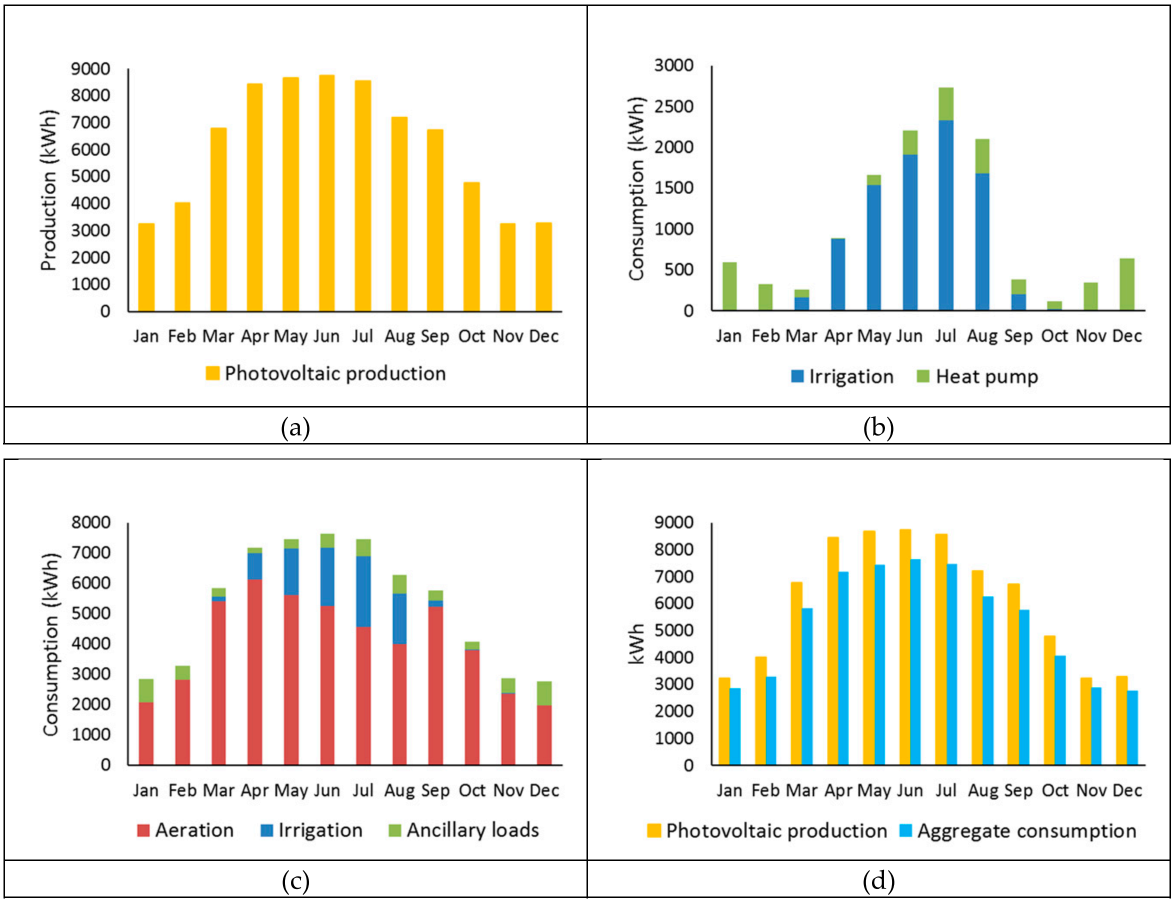

Figure 14. Photovoltaic production vs aggregate consumption: (**a**) Photovoltaic production; (**b**) Aggregate consumption of the aerators, sludge pumps, and heat pump; (**c**) Aggregate consumption of all loads, excluding the hydrogen production; (**d**) Photovoltaic production vs aggregate consumption, excluding the hydrogen production.

Table 8. Energy balance.

Concept	Energy (kWh/year)
Photovoltaic production [1]	73,648
Consumption of the loads [2]	63,426
Energy for hydrogen production	6797
Electrical losses	3425

[1] Measured at the output of solar inverters; [2] Excluding hydrogen production.

3.3. Hydrogen Production

The energy that is not used simultaneously with the production is stored in the battery. Once the SOC is very high, the control system dispatches the surplus energy to produce hydrogen. Some parameters of the hydrogen production system are shown in Table 9. As a result, over the year studied, the system produced 1290 Nm^3 of hydrogen, which incorporates 3870 kWh of energy. The volume of hydrogen production, by month, is shown in Figure 15.

Table 9. Hydrogen production system.

Power consumption [1]	2.635 kW
H_2 production rate	0.5 Nm^3/h
H_2 energy [2]	3 kWh/Nm^3
Energy efficiency	0.569

[1] Including average power consumption of the compressor; [2] based on Lower Heating Value.

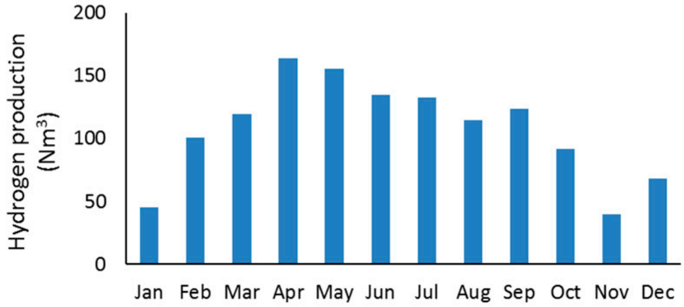

Figure 15. Production of hydrogen.

3.4. Operation of the FCHEV

The FCHEV can be powered by hydrogen or by charging its battery. In the period studied, the supply from the RES has been made only by refuelling hydrogen. This power supply has been complemented by occasional battery recharges, using electricity from the grid during vehicle stops in the winery. As indicated in Section 2.2.3, the substituted diesel vehicle would have consumed approximately 1350 litres of diesel. Equation (1) obtains the equivalence between the quantity of hydrogen refuelled and the diesel avoided, according to the energy densities of diesel and hydrogen and the efficiencies of the process.

$$D\ (l) \times 10.28\ (kWh/l) \times \eta_d, = H\ (Nm^3) \times 3\ (kWh/Nm^3) \times \eta_f \times \eta_e \quad (1)$$

where D is the diesel fuel avoided; H is the volume of hydrogen supplied; η_f is the efficiency of the electricity production in the fuel cell; η_e is the efficiency of the electric vehicle powertrain; and η_d is the efficiency of the diesel vehicle powertrain. The efficiency values obtained during the operation of the prototypes [25] were $\eta_f = 0.48$, $\eta_e = 0.90$ and $\eta_d = 0.15$. It is probable that the reduced value of the latter is a consequence of the work cycle of the vehicle, with frequent starts, stops, and standby periods. As a result, 1290 Nm^3 H_2 have avoided the consumption of 1084 l of diesel. The rest of the diesel fuel can be considered to have been replaced by electricity from the grid. More explanations on the performance of the hydrogen subsystem and the FCHEV are published in previous articles [24,25].

3.5. Emmissions Avoided

To analyse the CO_2 emissions and high-level radioactive waste prevented by the operation of the prototypes, the initial situation has been compared with the new situation:

(1) The starting situation for the WWTP was grid connected. Once the prototypes were implanted, the WWTP was disconnected from the grid and supplied by photovoltaic generation. According to the emission rates of the generation mix of the Spanish electricity grid in 2017 [26], a savings of 49,100 kWh prevented the emission of 15,221 kg CO_2 and 27 g of high-level radioactive waste.

(2) The starting situation considered for irrigation is the supply from a diesel generator set with a consumption of 2621 litres of diesel. According to the emission rates of diesel vehicles [27], the fuel savings has prevented the emission of 7517 kg CO_2.

(3) The starting situation for the agricultural off-road vehicle is the use of a conventional model, with a diesel engine. Once implanted, the diesel vehicle has been replaced by an FCHEV, avoiding the consumption of 1084 litres diesel. According to the emission rates of stationary diesel [27], the fuel savings has prevented the emission of 2732 kg CO_2. The other 266 litres of diesel has been replaced by electricity from the grid. This change has not been taken into account, because this electricity is not produced by the RES.

In summary, the operation of the RES over a year has prevented the emission of 25,470 kg CO_2 and 27 g of high-level radioactive waste.

4. Discussion

The LIFE REWIND project aims to reduce the CO_2 emissions from agriculture in general and the wine sector in particular, by replacing the energy they use with another from renewable origin. Modifications of the working processes are intentionally excluded, which is left to other initiatives. This facilitates the adoption of change [28] in existing facilities or in front of professionals reluctant to modify their work criteria. In fact, in winemaking, innovations have to coexist with respect for traditional uses and with subtle personal touches in the preparation of well-differentiated products [17,29]. In order to comply with this principle of non-intervention, in the case of the prototype, it was ruled out to modify the existing WWTP [30,31] or automate the irrigation decisions of the vineyard [7,32]. Therefore, the pumping schedule has been kept in the user's hands, either by direct or remote activation or by time programming. Consequently, different degrees of priority have been established for the loads. The loads activated by the user have a higher priority than the deferrable loads, but less than the control and communication devices. Besides, unlike the energy management of systems hybridized with diesel [8], in a RES like this, whose only source of energy is photovoltaic, it is also necessary to avoid system crashes due to the lack of energy. To make all this compatible with an off-grid 100% renewable supply, the demand has been studied.

First, some energy demands present high seasonality, because of crop or climate cycles. The energy supply to various loads from the same RES can offer advantages. In this case, both the photovoltaic production and the irrigation consumption present seasonal profiles. In addition, the demand for the heat pump has a very different profile, which contributes to a better suit between the profile of the aggregate demand to that of generation. This opens the possibility of combining two or more loads, whose aggregate demand can be more similar to the profile of the photovoltaic resource, in the same RES. Obviously, this is not always possible, since each case needs a detailed study. A line of possible future work is the study of the consumption of activities that are usually carried out in the same agricultural or industrial context, from the point of view of their seasonal complementarity.

Secondly, deferrable consumption can be managed to follow the variations of available production. This is already widely known, with the name of DSM (demand side management), but it is mainly used in the context of smart grids [33]. The standalone RES prototype has incorporated an EMS to fulfil this function. On the one hand, the annual profile of consumption was well suited to that of production. As a result, long-term storage is unnecessary. On the other hand, the daytime consumption profile has also been adapted to the available production [24] (pp. 258–259), allowing for a small-size short-term storage. To be widely applied in standalone RES, dimensioning tools that take into account load management parameters are necessary. Likewise, the EMS must be considered one of the elements to be designed. Moreover, the incorporation into the EMS of smart energy system techniques could further reduce the cost of irrigation [34]. The team of the authors of this paper is preparing a work on the EMS used in the prototype and on a predictive control.

Finally, a standalone RES usually cannot take advantage of all available production. One solution is that part of the energy comes from non-renewable generation, such as diesel, configuring a hybrid system. In them, the diesel generation is managed to supply more energy when needed. The prototype of the case study shows another strategy, which assumes the existence of surplus energy and extracts it from the system, for use in another application. On the one hand, the sizing of the system has been made, taking into account the most unfavourable periods of the relationship between energy demand and renewable resources. On the other hand, the surplus energy has been transferred to an application that can use it in a flexible way, without needing a supply in rigidly determined quantities and times. In the case study, the FCHEV fulfils this function, since it does not depend exclusively on the energy from the RES. The extraction of surplus energy in the form of electricity requires the presence of the vehicle next to the RES for a relatively long period, as well as an adequate management [35]. By contrast, the use of hydrogen as an energy vector allows the vehicle to be refuelled in only 20 s [24] (p. 260). Besides, the vehicle does not only feed on the surplus energy of the RES. It can be powered by either refuelling hydrogen or charging its batteries. The fraction of the demand that cannot be satisfied by the energy coming from the renewable generation system, which it is usually outside of its service hours, is met by the electric charge in the winery. In this way, the amount of energy transferred from the RES can be matched to the available surplus. The vehicle incorporates a hybrid supply, from the RES and from the grid, but the use of diesel has been completely avoided. If the electricity that is recharged in the winery is of a renewable origin, the condition of a 100% renewable supply is also fulfilled. In the context of the incorporation of hydrogen in agricultural machinery [36], the production and refuelling of hydrogen in the farm itself, coming from renewable sources, can be studied.

One of the distinctive features of the prototype is the incorporation of a hydrogen production subsystem. The hydrogen technologies are candidates to provide long-term storage in standalone photovoltaic systems, avoiding the need for hybridization with diesel [6,37,38]. However, there are relatively few studies proposing specific off-grid applications, for example, remote base stations [39]. With regard to hydrogen, this work proposes some novelties. On the one hand, the production and use of hydrogen take place in an agricultural context, including irrigation and mobility. On the other hand, the hydrogen produced is extracted from the system, avoiding the need for a big hydrogen storage tank. The prototypes, including the FCHEV, have been operating on the farm for more than two years.

As explained in Section 2, the present article does not include an economic study of the prototype. Nevertheless, it is appropriate to make some observations on the current feasibility of replicating the proposed solutions. Given the high cost of the components of the hydrogen technologies [38,39], it is worth asking if this investment is justified, beyond the demonstration prototype presented. In many off-grid cases, the economically optimal solution is a hybrid photovoltaic-diesel system [6,13,37]. In this case, the polluting emissions depend on the fraction of energy supplied by diesel. This impact on some locations in the natural environment may be undesirable. The economic result would depend, among other things, on the cost of fuel throughout the lifecycle of the system, including its transport to the location. Further research is needed that incorporates current costs and future scenarios.

In the prototype, the use of hydrogen is justified. Certainly, in the absence of the hydrogen subsystem, the RES could transfer energy in the form of electricity, by recharging the battery of an electric vehicle. However, the recharge should be allowed only when the surplus occurs. Additionally, in order not to waste a part of the surplus, the supply would be mandatory when the battery of the RES was full. In addition, the demonstration purpose of the prototype is a reason to show both ways to refuel a vehicle with zero emissions, with hydrogen or electricity produced from renewable sources on the farm itself.

Regarding photovoltaics, the prototype collected data that will be the subject of further studies. One of them will focus on the performance of the three types of support for the photovoltaic fields: a floating structure on the pond, fixed structure on the ground, and two-axis solar tracker. Especially, its different thermal behaviour and its effect on production will be taken into account. Since floating photovoltaic plants are expected to offer better thermal performance than other mounting supports [40], this is an opportunity for study. Other research will address the relationship between the daily and seasonal profiles of consumption and the optimal angles of orientation and inclination of the photovoltaic panels.

5. Conclusions

In the context of renewable energies in the wine sector, the LIFE REWIND project has designed and assembled a demonstrative prototype of RES in a Spanish vineyard. It addresses on-site, off-grid renewable generation for the energy supply for water purification and irrigation. The approach includes two objectives that are difficult to combine in a standalone RES: a supply, 100% of which is from renewable sources, and the harnessing of surplus energy. In the prototype, several strategies have been used to achieve these objectives. One of them is an EMS that manages the loads. On the one hand, it operates the deferrable loads, based on the instantaneous production and energy status. As a result, the use of the battery and its associated losses is minimized. On the other hand, an adequate level of the battery is maintained, preventing system crashes.

To harness the energy surplus of the RES, hydrogen is used as an energy vector. For this purpose, a hydrogen production system was added, which includes a water purifier, an electrolyser, a compressor, a storage tank and a refuelling mechanism. An electric all-terrain vehicle was modified to be a FCHEV, incorporating a fuel cell and the corresponding hydrogen tanks. This vehicle is refuelled from the prototype's tank. Using 100% renewable energy and 100% clean hydrogen, the operation of the vehicle can be classified as zero emissions. The FCHEV is used to move around the vineyard and winery, avoiding the use of a conventional diesel vehicle.

In summary, the prototype of the LIFE REWIND project has shown the technical feasibility of on-site production of photovoltaic energy to supply exclusively various consumptions in the farm. Furthermore, it has shown the possibility to replace diesel with hydrogen produced at the same location.

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Abbreviations

AC	Alternating current
DC	Direct current
DG	Distributed generation
DSM	Demand side management
EMS	Energy management strategy
FCHEV	Fuel cell hybrid electric vehicle
GHG	Greenhouse gasses
iHOGA	Improved Hybrid Optimization by Genetic Algorithms software
OIV	International Organization of Vine and Wine
PEMFC	Proton exchange membrane fuel cell
PVGIS	Photovoltaic Geographical Information System
RES	Renewable energy system
SOC	State of Charge
WWTP	Wastewater treatment plant

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Artículo

Introduction of renewable energy in the Spanish wine sector

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Introduction of Renewable Energy in the Spanish Wine Sector

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Abstract: The wine sector is very sensitive to the effects of climate change. Despite this, there is little use of renewable energy in the wine sector. In fact, the adoption of mitigation measures by companies depends on their own attitudes and interests. The objective of this work was to understand the use and disposition of Spanish wineries to incorporate renewable energy. In addition, subjective obstacles to and motivations for adoption could be identified. First, a survey was conducted on the Spanish wine sector. Second, the multivariate statistical technique of factor analysis was applied. Third, a set of indicators to describe the determinant factors that influence a winery's decision to adopt renewable energy was obtained. Finally, a cluster analysis provided three different profiles. The first group comprised wineries that did not trust on the maturity of renewable energy. The second one comprised wineries that were not convinced about introducing renewable energy, either for environmental or reputational reasons. The third group comprised wineries convinced of the benefits of incorporating renewable energy. This work was done as a part of the European project: Renewable Energy in the Wine Industry (LIFE REWIND).

Keywords: renewable energy; sustainability; wine sector; viticulture; wineries; survey; CO_2 emissions; cluster analysis

1. Introduction

1.1. Energy and Climate Change

Energy production from fossil fuels is the biggest source of greenhouse gases, which contribute to climate change and global warming. This damage is continuous but silent, and the responsibility is widely distributed and little assumed. In addition, the fact that energy production is external to the business seems to avoid the concern of companies in nonenergy economic sectors. Therefore, it is very desirable that companies be concerned not only with reducing their energy consumption, but also about the source of that energy. Thus, a sectoral approach to the use and source of energy could be useful.

The effects of climate change are predicted to impact the agricultural sector in coming decades [1], affecting this sector and all of its associated industries. Meanwhile, most agricultural tools and equipment are driven by fossil fuels, which are the main source of greenhouse gases (GHGs) accelerating global warming [2]. The use of fossil fuels, either mobile or at fixed locations, produces pollutant emissions, such as carbon dioxide (CO_2), carbon monoxide (CO), sulphur oxides (SOx), nitrogen oxides (NOx), volatile hydrocarbons (HC), and solid particles (C+). Moreover, by accident or by mismanagement, losses of fuel, lubricants, and other substances and polluting residues (filters of air and fuel, etc.) occur. At the same time, engines are a source of noise pollution. As one of the main sources, agricultural systems contribute between 19% and 29% of global anthropogenic GHG emissions [3].

1.2. The Wine Sector and Its Energy Use

Agribusiness is one sector with high energy consumption; in fact, its consumption accounted for 26% of the EU total in 2013, and 28% of this consumption came directly from industrial processes [4]. This means that 7.3% of all the energy consumed in the EU goes toward the production of food and beverages. In addition, Spain is among the five European countries with a larger food and beverage industry (the others are Germany, France, Italy, and the United Kingdom), and therefore is among the countries with higher energy consumption. In this way, the introduction of renewable energy would be associated with cost reduction and environmental improvement.

The wine industry is at risk for substantial climate-related threats [5]. Global warming has many effects on wine [6,7]. First, high temperatures during vine growing exert a negative effect on grape composition and wine quality. Second, ripening is accelerated, leading in turn to excessive sugar accumulation in grapes and an increase of 50% in alcohol level in the wines. Finally, there is faster depletion of organic acids in the grape juice, which increases pH value. As a result, the general flavor profile may undergo an atypical change toward overmatured. For these reasons, important adaptation measures might have to be implemented [8,9].

Additional risks are related to the consequences to revenues and production costs throughout the supply chain [10]. Modifying production processes due to climate variability and extreme events, may lead to additional socioeconomic impacts for the whole sector and its related activities [11]. Some studies [12,13] address the main areas of environmental concern, currently facing wine organizations. These authors agree that the most relevant environmental aspects, include but are not limited to the following: water use and management, organic and inorganic solid waste, energy use and greenhouse gas emissions, air quality, agrochemicals, land use issues, and biodiversity.

This paper is focused on the perception of sustainability and the use of renewable energy in the wine sector. In fact, climate change and energy are now two sides of the same coin, i.e., most of the greenhouse gas emissions come from the use of energy. This is due to the presence of nonrenewable resources in the current generation mix.

Although this fact is not usually taken into account, the wine sector consumes large amounts of energy in the different phases of winemaking: grape growing, vinification, bottling, and distribution [14]. As a result, the industry is responsible for the emission of a large quantity of CO_2. Nowadays, most of the energy used in the wine sector (mainly electricity and diesel) is produced from nonrenewable energy sources. Therefore, reducing CO_2 emissions requires a change in the energy system, with a greater proportion of renewables in the energy mix. In fact, evidence suggests that it takes approximately 2618 GJ of energy to process one ton of grapes into the finished product, and for every standard bottle of wine produced, between 0.41 kg and 1.6 kg of CO_2 is released into the atmosphere [15]. Wine distribution and postproduction logistics are also carbon intensive, due in part to the reliance on heavy and bulky forms of packaging [16].

According to the necessary reduction of greenhouse gas emissions, the European Union has promoted the use of renewable energy sources through several directives, establishing a common framework for the production and promotion of renewable energy. In this sense, three key targets have been set for the year 2020, i.e., 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables, and 20% improvement in energy efficiency. Moreover, the 2030 climate and energy framework sets higher targets for the year 2030, i.e., at least a 40% cut in greenhouse gas emissions (from 1990 levels), 27% share of renewable energy, and 27% improvement in energy efficiency [17].

1.3. The Spanish Wine Sector

The wine sector has great importance due to its economic, social, cultural, and environmental value throughout the world and across Europe, as well as in Spain. In fact, according to data from the International Organization of Vine and Wine (OIV), in 2016 the total world area under vines reached 7.52 million ha; European vineyards occupy an area of 3.3 million ha, and Spain has 975,000 hectares under vines [18]. Spain is the country with the largest wine area (i.e., 13% of global and 30% of European vineyard area) (Figure 1). Out of the 975,000 hectares, 95.4% goes to the production of wine grapes; 33% of Spanish vineyards are irrigated (333,459 ha) and occupy 10% of the total agricultural area nationwide.

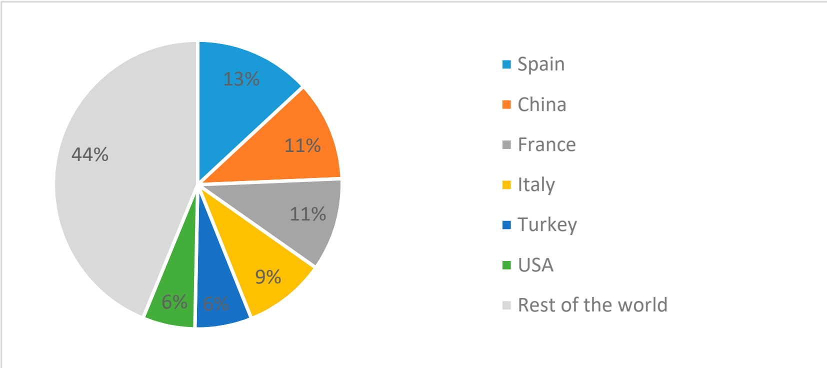

Figure 1. World area under vines by country.

Global wine production (excluding juice and must) is 267 million hl, and the EU vinified production is likely to reach 162 million hl. Spain, with 39.4 million hl, is the third-largest wine producing country in the world (Figure 2).

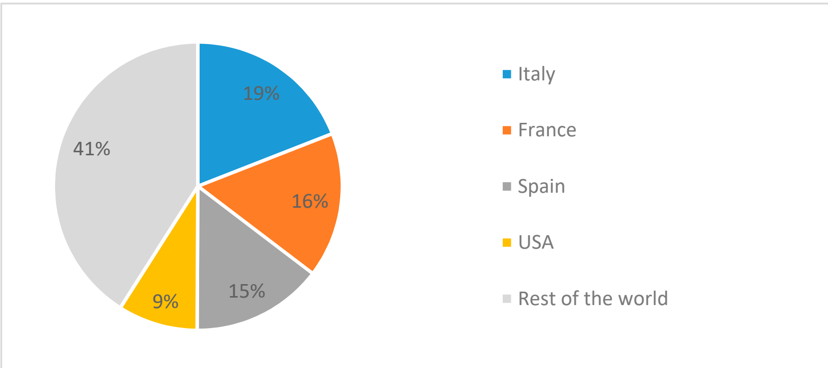

Figure 2. World wine production by country.

Despite the importance of this industry in Spain, it also should be mentioned that the wine sector has been shrinking in recent years in favor of countries from the "new world" (in the vitivinicultural context). These include the United States, Australia, New Zealand, China, Argentina, Chile, etc. Therefore, Spain has to be in a constant search for alternatives to stay at the elite level of international trade. Along these lines, the origin denominations have been a key factor in giving greater popularity to those countries' wines. In addition, diversification of the sector with activities of restoration, recreation, etc., are intended to promote the variety of their wines, as well as to look for new ways to expand their products in the market. In this context of searching for new business alternatives, Spanish wineries and vineyards must integrate sustainable development and eco-efficiency. Building construction may include the concepts of sustainable development associated with energy and water management aspects, i.e., thermal insulation, renewable energy, and water-saving technologies.

1.4. Penetration of Renewable Energy in the Spanish Wine Sector

Several barriers have hindered the widespread adoption of renewable energy [19]. One barrier is the relatively high initial investment. However, profitability must be analyzed in the medium and long term. Conventional energy sources become more expensive over time, due to the cost of purchasing electricity or fuel. In contrast, renewables become less expensive, because once the infrastructure is built, the sun and wind provide free resources. Furthermore, renewable energy technologies are being rapidly improved by continuously increasing their cost efficiency. As a result, at vineyards or wineries, renewable energy could be economically competitive [20], even more so in locations far from electricity grids [21]. In fact, public subsidies for renewable energy are declining and will gradually disappear. Despite this, it is almost certain that the policy will continue to favor a transition to renewable energy. In summary, the economic difficulty will be limited to obtaining financing for an investment, which will be amortized over a few years.

As far as energy independence and security of supply is concerned, Spain has a very high dependence on imported oil, gas, and nuclear fuel [22]. In general, energy security requires a confident supply, at a stable and competitive price over time. In rural areas where the wine activities are carried out, quality of supply by the power grid is not always guaranteed and is always very expensive.

1.5. From Attitudes to Innovations in the Wine Sector

The decision-making process for incorporating innovations in companies is not obvious [23]. In addition to mandatory rules, there are many other factors that can play a role in inducing change [24], including the attitudes of managers and stakeholders [25]. Managers' perception refers to their subjective personal evaluation of the attributes of innovation. This perception is used to assess whether an innovation offers increased benefits over the technology that one intends to replace.

On the one hand, adopting innovations that provide environmental improvements is a process strongly influenced by profitability. While some may be profitable, others are not, although they may be necessary from a social and environmental point of view. Adoption depends on a range of personal, social, cultural, and economic factors, as well as on characteristics of the innovation itself [26]. Understanding the factors of adopting innovations is important to design programs which favor it. This also helps in finding out why other programs have not worked as well as expected [27]. A study carried out among dairy farmers showed that their decisions about the environmental practices they used on their farms were based on a pragmatic evaluation of the production context, that is, the decisions of farmers about adopting these practices were not strongly influenced by their attitudes on sustainability and the environment [28].

On the other hand, a factor of interest to wineries regarding the environment is market demand [29,30]. The environmental awareness of customers is increasing, and more wine consumers have an environmentally friendly lifestyle. In this sense, the image of a sustainable product with a small carbon footprint can be appreciated. The perception of sustainability in other countries has been addressed [31,32], but this work is especially focused on the use of renewable energy. In another direction, there are studies [33] which question whether innovations in wine are well received by consumers, as they can break from the traditional product image associated with wines from the old world. This doubt does not affect the case that concerns us, namely, the substitution of fossil fuel-based energy for renewable energy, given that this does not change the winemaking process or the quality of wine. Depending on the market niche that the winery wants to reach, it may or may not incorporate this innovation in the image of its wines.

With all that said, the objective of this work was to understand the disposition of the Spanish wine sector to incorporate renewable energy. Our aim was to know which of the mentioned determinant factors influence wineries in Spain, to adopt or not adopt, renewable energy.

The adoption of innovations for sustainability by the wine sector has been addressed by multiple studies [27,34–36]. In general, the energy part has been limited to reducing consumption involved in the production of wine. In contrast, this work focused on a specific action: replacing conventional energy with energy of renewable origin. In this sense, it is a work that can be seen from two different angles. On the one hand, from the vitivini cultural point of view, it tackles a concrete way of reducing the carbon footprint, without intervening in the winemaking process. On the other hand, from the energy point of view, it shows a path to advance the transition to renewables through a specific production sector.

This work is framed within the European project Renewable Energy in the Wine Industry (LIFE REWIND), which addresses the technical and economic feasibility of using renewable energy produced on site in agricultural activities. It also shows that it is possible to use hydrogen in transport and agricultural machinery [37], including producing hydrogen from renewable energy on the farm itself [38]. The scope of that project is very broad, including technical, economic, energy, environmental, and socioeconomic approaches. From the multidisciplinary LIFE REWIND project, and from other works in the energy field, the feasibility and profitability of incorporating renewable energy in wineries and vineyards has been addressed. The purpose of this work was to know the point of view of companies in the sector, to identify actions that can facilitate this change.

2. Materials and Methods

Statistical Methodology: First, a survey was conducted in the Spanish wine sector. Second, the multivariate statistical technique of factor analysis was applied. Third, a set of indicators was obtained to describe the decision factors. Finally, a cluster analysis provided 3 different profiles.

2.1. Sample of Wineries

According to the System of Analysis of Iberian Balances (SABI) [39], an online database that contains financial information on 940,000 Spanish and 100,000 Portuguese companies, the Spanish wine map in 2016 was formed by 3894 wineries. To have a photo of the Spanish wine sector, we decided to use a simple random sample of 87 wineries, stratified by region, corresponding to a confidence level of 94% and an error rate of 10%. Table 1 presents the final sample of wineries, and Figure 3 their geographic locations.

Table 1. Number of wineries and sample size by Spanish region.

Spanish Regions	Number of Wineries	Sample Wineries
Andalucía	287	7
Aragón	144	3
Asturias	19	0
Baleares	57	1
Canarias	84	2
Cantabria	5	0
Castilla-León	597	13
Castilla-La Mancha	445	10
Cataluña	603	13
Extremadura	118	3
Galicia	342	8
La Rioja	326	7
Madrid	195	4
Murcia	87	2
Navarra	116	3
País Vasco	261	6
Valencia	208	5
Total	3894	87

Figure 3. Locations of surveyed wineries.

2.2. Questionnaire

According to the usual practice of creating a questionnaire, several winery owners were asked to identify the key aspects and the most relevant characteristics of this sector. This process involved semi-structured and in-depth interviews. The definitive questionnaire includes various blocks, as shown in Table 2.

Table 2. Questionnaire blocks.

Block	Topic
I	Identification and location
II	Company activity
III	Company's environmental policy
IV	Attitude on climate change
V	Renewable energy use and attitude
VI	Use and consumption of nonrenewable energy

I. The first block of questions identified and located the wineries by name, municipality, and province; the wine area they belong to, the year they were established, the majority shareholders, and the legal form of the company.

II. The second block of questions were about the company's activity. This involved questions on the number of employees, turnover volume, and gross floor area, to establish whether it was a large or small winery. Wineries were also questioned on the percentage of different qualities of wine they produced and of the foreign market sales out of their total sales. Another important issue was establishing whether they performed additional activities, and what percentage these represent of their total turnover. Furthermore, of interest was learning where the grapes used in producing their wine came from; in other words, whether the grapes were their own, or they came from vine growers with or without a contract, or from cooperatives. It was obviously important to discover how many hectares were involved, and whether they participated in their management whilst the crop was growing.

III. The third block of questions focused on environmental responsibility and policy. Wineries were asked if they had any organic winemaking certification, if they had calculated the carbon footprint of their activity or products, if they conducted energy audits, and if they had their own resources to manage the company's environmental policy.

IV. The fourth block of questions was aimed at analyzing wineries' attitudes on climate change. The purpose was to know whether the wineries were convinced that the climate had changed, and what their level of willingness was to reduce their CO_2 emissions. We were interested in finding out, which measures they had already adopted.

V. The fifth block included questions on renewable energy. The companies were asked about the type of energy they used, whether they were convinced of the need to use renewables, their opinion on the outlay for implementing them, and the aspects they valued to adopt their use, such as reliability, environmental sustainability, grants, and the impact on their image.

VI. The last block of questions was aimed at knowing whether the use of renewable energy was technically and economically viable. Consequently, questions were included on the use and consumption of non-renewables, especially electricity, diesel, and gas. Wineries were asked about their consumption trend throughout the year, their level of concern for energy costs, and whether they had reviewed invoices and the power usage stated in their contract, with a view to reducing it.

Given that our objective was to discover the penetration of renewable energy in the Spanish wine sector, this paper was focused on the questions of block V. The relevant questions were related to the opinions of wineries about using renewable energy, the cost of implementing it, and the motivations to adopt it.

2.3. Descriptions of the Variables

To create a concise and easy-to-answer questionnaire, very few questions were asked, specifically, conviction of using renewable energy; opinion on the cost of renewable energy implementation (i.e., investment, maintenance, and operational costs); and motivations to adopt the use of renewable energy (i.e., reliability, environmental sustainability, existence of subsidies, and corporate image). The variables were as follows:

- **Convinced use:** This variable measured, on a 0–10 scale, the degree of agreement of the winery with the need to use renewable energy. A score of 0 indicated that the winery strongly disagreed, and 10 that it strongly agreed.
- **Investment:** This variable measured, on a 0–10 scale, the winery's perception of the importance of the investment associated with implementing renewable energy. A score of 0 indicated that the winery thinks it is a very small expense, and 10 that the expense is very high.
- **Operational costs:** This variable measured, on a 0–10 scale, the winery's perception of the dimension of operational costs associated with adopting renewable energies. A score of 0 indicated that the winery thinks it is a very small expense, and 10 that the expense is very high.
- **Maintenance costs:** This variable measured, on a 0–10 scale, the winery's perception of the dimension of maintenance costs associated with adopting renewable energy. A score of 0 indicated that the winery thinks it is a very small expense, and 10 that the expense is very high.
- **Grants:** This variable measured, on a 0–10 scale, the importance the winery gives to the existence of subsidies for adopting renewable energy. A score of 0 indicated that the winery considered the existence of subsidies unimportant, and 10 that it was very important.
- **Image:** This variable measured, on a 0–10 scale, the importance of the effect on the corporate image of adopting renewable energy. A score of 0 indicated that the winery considered the impact unimportant, and 10 that it was very important.
- **Reliability:** This variable measured, on a 0–10 scale, the importance that the winery gives to the reliability of renewable energy at the time of deciding on its adoption. A score of 0 indicated that the winery considered it unimportant, and 10 that it was very important.
- **Sustainability:** This variable measured, on a 0–10 scale, the importance that the winery gives to sustainability in its decision to implement renewable energy. A score of 0 indicated that the winery considered it unimportant, and 10 that it was very important.

The mean values and standard deviations obtained, for each of these variables in the sample of selected wineries, are shown in Section 3.2.

The answers provided by the wineries were manually coded and processed using the Statistical Package for Social Sciences (SPSS). Applying the multivariate statistical technique of factor analysis, a set of indicators which allowed us to describe the determinant factors influencing the implementation of renewable energy was constructed. Factor analysis is one of the most commonly used interdependency techniques. It is utilized when the relevant set of variables shows a systematic interdependence, and the objective is to find the underlying latent factors, permitting a reduction of the set of variables. In the case of the present work, this technique allowed a reduction from the previous 8 variables to 4 factors. The estimation method used was principal components, together with an orthogonal varimax rotation. The main 4 factors explained 77.4% of the total variability of the 8 variables, as shown in Section 3.3.

3. Results

3.1. Description of the Sample

3.1.1. Company Activity

Winery staff size is very varied, with an average of 15 people. Fifty percent of wineries have more than seven employees. The average turnover volume is € 5,358,365, and 50% of wineries have a volume above € 1 million. The average wine production is 206,120.88 hl, and 50% of the analyzed wineries had production over 2800 hl. Approximately 51% of wineries obtain their income only from the wine they produce, and the remaining 49% obtain additional income from other activities. Nevertheless, their revenue for additional activities represents less than 10% of turnover in 71% of the cases, which means these activities are peripheral to the winery's main business.

Of the wineries in the sample, 43% had relationships with external vine growers. As a result, 82% of these wineries participated in management of the viniculture. On average, the vineyard area providing grapes to wineries is 29.18 ha. The survey also allowed analysis of the characteristics and activities of the vineyards, because 81% of the wineries owned them. In addition to vines, 33% of the land included some other crops.

Regarding the vineyards, 85% were rain-fed; for 16% of these, their owners intended to incorporate irrigation systems. These companies gave several reasons for transforming rain-fed vineyards into irrigated ones, as shown in Table 3. Reasons given by companies that did not plan to incorporate irrigation are shown in Table 4.

Table 3. Reasons given by companies that plan to incorporate irrigation.

Reason to Incorporate Irrigation	Percentage (%)
Assure/improve grape quality	80
Compensate for rainfall variations	40
Increase grape production	40

Table 4. Reasons given by companies that do not plan to incorporate irrigation.

Reason to Not Incorporate Irrigation	Percentage (%)
Type of wine produced	53
Maintain traditions	30
Respect the microclimate of the vineyard	25
Lack of water	20
Administrative difficulties	8
No electricity available	3
Other (including appellation of origin rules)	15

3.1.2. The Company's Environmental Policy

Only 28% of wineries in the sample had any kind organic or ecologic certification or labelling (ecologic cropping, organic wine, etc.). Sixteen percent of wineries have calculated their carbon footprint or have been subjected to energy audits. These data are consistent with the resources that the wineries in the sample assigned to environmental management (Figure 4). It should be noted that, almost half of the wineries did not have internal resources assigned to it.

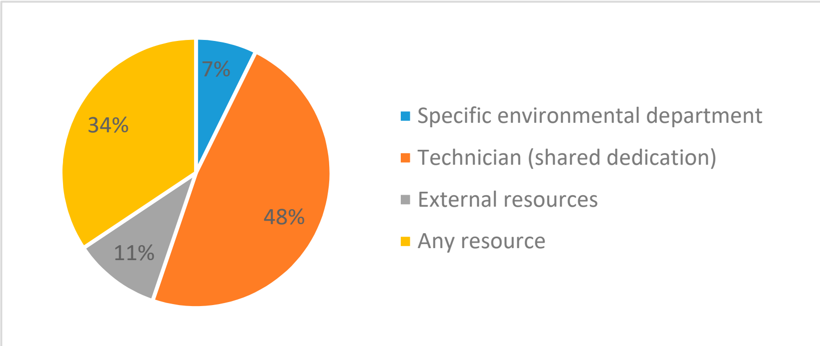

Figure 4. Resources that wineries in the sample assigned to environmental management.

3.1.3. Attitudes on Climate Change

The wineries seemed highly aware of the climate change problem, with an average rating of 7.83 points about the statement "The climate has changed." Similarly, the willingness of sampled wineries to decrease their CO_2 emissions presented an average of 7.83. Despite the limited use of personnel specialized in environmental management, the wineries had already adopted several measures of energy efficiency and general climate change mitigation (Table 5).

Table 5. Energy efficiency and mitigation measures adopted by wineries in the sample.

Climate Change Mitigation Measure	Percentage (%)
Recycling	93
Efficient consumption management	69
Improve thermal insulation	64
Purchase low consumption equipment	51
Reduce weight of packaging	44
New types of containers	35
Estimation and reduction of emissions	15
Other	13

The vineyards' average commitment level to adapting to climate change was high at 7.12, and 50% of the companies had a commitment level above 8. The measures of climate change adaptation that they carried out are shown in Table 6.

Table 6. Climate change adaptation measures adopted by wineries in the sample.

Climate Change Adaptation Measure	Percentage (%)
Advance the vintage date	47
Introduce or increase irrigation	28
Vegetal ground cover	25
Introduce new grape varieties	21
Transfer to higher altitude vineyards	21
Change the architecture of the vineyard	13
Other	4

3.1.4. Renewable Energy: Use and Attitude

The declared use of renewable energy did not represent more than 10% of winery consumption, in any case. The three most common renewable energy types are biomass (11%), photovoltaic power (11%), and solar thermal power (9.3%). Regarding the vineyards, the use of renewables was very limited. Only 5% of vineyards used them, of which 50% used photovoltaics for pumping and 50% produce biomass. For instance, the exploitation of vineyard biomass was very limited (Figure 5).

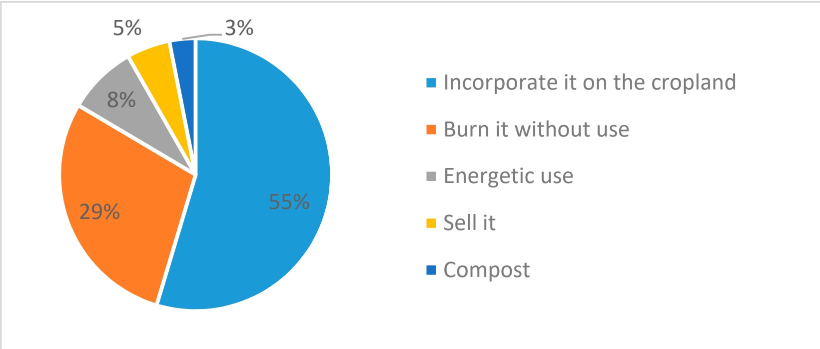

Figure 5. Destination of vineyard pruning waste.

Despite the low level of use of renewables, the wineries were convinced of the need to use them, with an average score of 7.28, and 50% of wineries rated it with more than 8 points. This gap is likely related to the wineries rating the investment involved in implementing renewable energy as high, with 8.33 points, on average. They considered that operating and maintenance costs were lower, and they rated them, on average 5.5 and 5.4, respectively. The aspects that wineries believed favored the adoption of renewable energy, are shown in Table 7.

Table 7. Aspects that favor the adoption of renewables.

Aspect Favoring the Adoption of Renewables	Mean	Median
Environmental sustainability	8.60	8
Impact on image	7.84	8
Reliability	7.24	7
Existence of grants	7.12	7

3.1.5. Use of Conventional Energy

Increased electricity costs have motivated wineries to check their electricity bills. Of the wineries in the sample, 62.7% reduced their reactive power and 66.7% reduced their contracted power. The wineries were asked about their heating and air-conditioning systems; 50% had a heating system and 67% had one or more air-conditioners.

Regarding the vineyards, energy consumption takes place in pumping for irrigation, fed by the power grid or diesel generators. Tractors, grape harvesters, and personnel transport vehicles are fed in all cases with diesel. The average consumption of diesel in the vineyards was € 14,092, although with large deviations; 50% of the vineyards had consumption less than € 5000, of which 82.7% corresponded to agricultural machinery and 7.3% to irrigation pumping, on average.

3.2. Descriptive Statistics of the Variables

Table 8 shows, for the sample of wineries, the mean values and standard deviations of the variables described in Section 2.3.

Table 8. Descriptive statistics of the variables.

Variable	Mean	Standard Deviation
Convinced use	7.28	2.57
Investment	8.33	1.29
Operational cost	5.48	2.41
Maintenance cost	5.44	2.30
Reliability	7.24	2.19
Sustainability	8.57	1.32
Grants	7.12	2.43
Image	7.84	1.80

3.3. Determinant Factors

With the information provided by the respondent wineries, the multivariate statistical technique of factor analysis was applied. A set of indicators was constructed to describe the determinant factors, which influence the implementation of renewable energy. Principal components and orthogonal varimax rotation, were used to obtain the main four factors explaining 77.4% of the total variability. Table 9 presents the rotated components matrix, with correlations between factors and original variables.

Table 9. Rotated components matrix.

	Cost Factor	Conviction Factor	Investment Factor	Sustainability Factor
Operational cost	0.943	–	–	–
Maintenance cost	0.936	–	–	–
Convinced use	–	0.863	–	–
Image	–	0.797	–	–
Grants	–	–	0.840	–
Investment	–	–	0.728	–
Reliability	–	–	–	0.825
Sustainability	–	–	–	0.785

From this matrix, it is possible to name and interpret each factor as follows:

- **Cost factor:** This factor is positively related to operational and maintenance costs. That is, if a winery considers that the costs associated with renewable energy are high, then it has a high score in the cost factor.
- **Conviction factor:** This factor is positively related to the conviction of using renewable energy and reputational image. That is, if a winery is convinced of using renewables and gives great importance to perceived image, then it has a high score in the conviction factor.
- **Investment factor:** This factor is positively related to investment. That is, if a winery considers the investment in renewable energy to be too high, then it has a high score in the investment factor. Therefore, it probably prefers to adopt other measures to mitigate climate change. This factor also includes companies with high scores in the subsidies variable, which means that companies would see subsidies as a way to compensate for the high amount of investment.
- **Sustainability factor:** This factor is positively related to motivations that can lead a winery to adopt renewable energy, such as the importance of sustainability and reliability. That is, if a winery considers that sustainability and reliability are decisive for implementing renewables, then it has a high score in the motivation factor.

3.4. Types of Wineries

A multivariate cluster analysis technique was used on the four indicators to classify the wineries. This procedure is an exploration tool, designed to discover natural groupings of a set of data. It allows categorical and continuous variables to be treated jointly, using the likelihood provided by the probability distribution between the variables as a measure of distance between two individuals. A normal distribution is assumed for continuous variables, and multinomial distributions for categorical variables. The first stage consists of a pre-classification that sequentially builds a tree, where its nodes represent groups. The previous solution is refined in the second stage through an agglomerative hierarchical procedure. The final algorithm automatically selects the number of clusters, using a model selection criterion for different grouping solutions. In our case, the four indicators were continuous variables and the selection criteria used was the Bayesian information criterion (BIC), implemented with SPSS 22 software. This analysis identified three groups (Figures 6 and 7), including 40%, 40% and 20% of the wineries. The characteristics are explained and discussed in the next section.

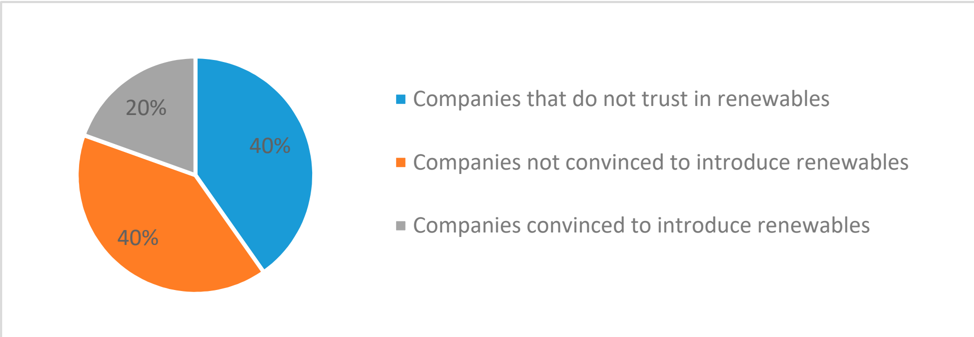

Figure 6. Winery groups.

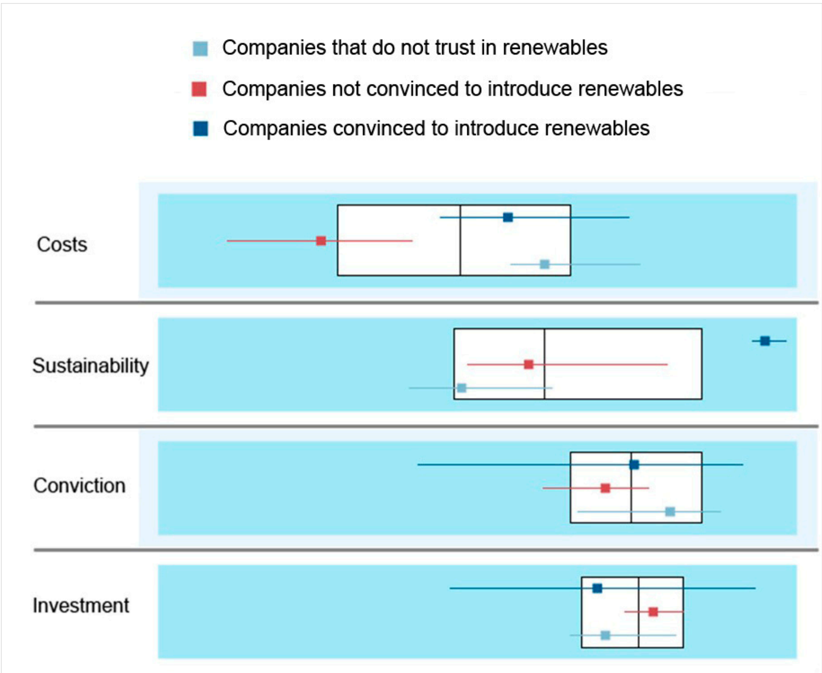

Figure 7. Comparison among winery groups.

4. Discussion

The three groups of wineries presented characteristics that allowed us to interpret different dispositions of companies in the wine sector to incorporate renewable energy:

1. **Companies that do not trust renewable energy.** This group comprised 40% of the sample. These companies were not convinced of the environmental importance of introducing renewable energy.

They did not believe that renewables were sufficiently developed to be a reliable energy supply. The main driver they considered for incorporating them, is the impact on image and reputation. They were not worried about the investment, and consequently they did not feel the need to establish a subsidy system.

2. **Companies that are not convinced to introduce renewable energy.** This group comprised 40% of the sample. These companies were not convinced to introduce renewable energy. Neither environmental nor reputation points were sufficient to motivate them. They did not consider that in their case, starting up renewable energy will give them an image improvement or significant CO_2 savings. They considered that the investment costs were high, and the environmental improvement to their image would not compensate them. However, they were not worried about the maintenance costs.
3. **Companies that are convinced to introduce renewable energy.** This group comprised 20% of the sample. These companies wanted to reduce CO_2 emissions. Their interest in sustainability was the main driver, above factors such as obtaining a clean company image. For these companies, reliable supply and environmental improvement were the most outstanding aspects. They were not worried about the investment costs. In contrast, they considered that the maintenance costs are high.

Beyond the existence of a wide spectrum of individual cases, the three groups had characteristics that agree with practical experience. A large number of wineries (group 1) are not yet considering investing in renewables, although they do not rule out doing so in the future. This attitude may be related to the novelty of renewable energy technologies. In the case of Spain, the administrative obstacles and lack of public promotion in recent years, may also play against it. Another large number of wineries (group 2), seemed to be completely absorbed by the core of their business, without worrying about the sustainability of their input, and especially without knowing the large share of energy in the carbon footprint of their activity. Some wineries, not a majority, but a considerable number, are already willing to make the investment to incorporate renewable energy.

The results obtained may indicate some ways to encourage the transition to renewable energy in the wine sector.

First, the number of companies that are already willing to incorporate renewable energy (group 3) is sufficient to initiate this transition in the sector. However, that market has not yet been activated in significant quantity. It is important to keep in mind that companies in the wine sector do not know about energy technologies. For instance, the belief of many companies that the costs of operation and maintenance of renewables are high is completely wrong. This lack of information is likely related to the fact that 34% of wineries in the sample did not assign resources to environmental management, as indicated in Section 3.1.2. Increased information and technical and economic offers for the decision-makers of the sector, would probably increase the demand for renewable facilities. Nevertheless, the possible existence of subsidies, by itself, is not enough motivation. Even for the most willing group, the largest investment required to incorporate renewables represents a disadvantage, compared to traditional energy options. For this reason, an excellent measure would be to facilitate access to financing.

Second, a large group of companies believed that it was not yet time to switch to renewable energy (group 1). This perception is no longer correct, since renewable energy technologies have reached a sufficient degree of maturity. However, many stakeholders still do not know their feasibility. Therefore, the same measure proposed for the first group is necessary here, that is, an increase in information and technical and economic offers.

Finally, a big group of wineries were not interested in renewables (group 2). This is not strange, given the novelty of this technology and its distance from the core of the wineries' activities. Again, the limited resources dedicated to environmental management by the wineries may be behind this lack of interest. It is reasonable to expect that future introduction of renewables in the sector, led by companies in group 3 and supported by group 1, will modify the perceptions of this group. In addition, the foreseeable environmental and energy policy, as well as the evolution of the market, will end up pushing the transition, even in the absence of other convictions.

The results obtained were in agreement with other studies related to the incorporation of renewable energy [40]. It has been identified that the highest economic barrier is the high initial investment. In contrast, a lack of subsidies is the lowest economic barrier. The lack of a sufficient market base and of political commitment, have also been reported as high barriers.

Regarding the wine sector, some studies [31,32,34,41] have shown limited adoption of environmental innovations, although with some regional differences. This coincides with the low adoption of renewable energy observed by the present study. However, many Spanish wineries have incorporated other mitigation practices (different to renewable energy) to increase sustainability, as shown in Table 5.

To introduce sustainability in the wine sector, one study [42] shows the successful case of the Sustainable Winegrowing New Zealand program [43]. The process shown is interesting, although it differs from the Spanish case, because it belongs to the new world, where, in its export market, sustainability of products is a very valued factor. In addition, the energy standard of this program is based on reducing the amount of energy used, whilst the present study focused on substituting renewable energy sources. Although Spanish wineries export a large part of their production, in the survey they indicated that only part of their market demands wines with an image of sustainability, and in any case, this was not their competitive advantage. Consequently, it is not expected that market pressure will push the Spanish wine sector toward sustainability in the short term, and generally. Other studies [33,35] agree with this assessment, especially in the old world.

In this study, an important mismatch was found between the favorable perception of decision-makers regarding renewable energy, and its actual implementation. According to other studies [25], the social norms perceived by decision-makers could be more directly associated with their decisions, than the managers' attitudes themselves. In fact, the positions held during the last decade by the government and the energy companies in Spain, and the situation of paralysis, were generally regarded as negative [44]. This has caused a climate of doubt about the opportunity to change toward renewable energy sources. Moreover, sociopolitical and community acceptance are important to understand the apparent contradictions, between general public support for renewable energy and the difficulty in realizing specific projects [45]. For the aforementioned reasons, the attitude of waiting for better times before investing in renewable energy can be widespread, especially in the wineries of group 1. Nevertheless, information and perceptions are modifiable, adding more weight to the likelihood of adoption [46]. For this purpose, carefully tailored information on the use of renewables for wineries should be made available to winemakers. Regarding the dissemination of innovations [23], information is the key.

5. Conclusions

The wine industry consumes significant amounts of energy. Climate change affects the winemaking process severely, especially in the vineyard. In addition, both the commercial interest and the social responsibility of the companies point the same way. For these reasons, beyond adaptation measures, it is essential that the sector actively contributes to mitigation. Incorporating renewable energies in their processes can considerably reduce the CO_2 emissions associated with the activity and the product. The technical and economic feasibility of this change has been demonstrated. However, implementation depends on the stakeholders. In addition, the attitudes of the wineries are far from unanimous in that direction.

Although the study was carried out with a representative sample of Spanish wineries, it would have been desirable to work with a larger sample. However, it was difficult to obtain a large number of responses to the questionnaire. With the available data, the confidence level was 94%, with an error rate of 10%.

This work identified the existence of three groups of Spanish wineries, with different attitudes. First, 20% of Spanish wineries are willing to incorporate renewable energy. Second, 40% are favorable, but do not believe that it is time to invest in it. Finally, 40% of wineries are not interested in incorporating renewables. Despite the favorable attitude of a significant group of wineries, it must be considered that the willingness to implement renewable energy is not enough, nor is it the only factor for its real implementation. The results suggest two main measures to encourage an energy transition in the Spanish wine sector: (i) Increasing the information provided to decision-makers in the sector, including technical and economic offers; and (ii) Facilitating access to financing.

Regarding future research, a study of the three identified groups can be addressed through representative case studies. Moreover, statistical models could be proposed and tested to determine which characteristics of the wineries are related to their implementation of renewable energy. A comparison of the Spanish case with the results obtained in other regions, both in the old world and in the new world, could be interesting. In the same way, similar studies could be carried out on the incorporation of renewable energy in other sectors, especially in agricultural farms.

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TESIS

Sistemas de energía renovable en las áreas rurales: una demostración en el sector vitivinícola

IV- MEMORIA

ÍNDICE DE LA MEMORIA

1 Introducción

1.1 Premisas

De entre los planteamientos posibles para un trabajo de tesis en el programa de Doctorado en Energías Renovables y Eficiencia Energética, la elección del tema ha incluido tres premisas. En primer lugar, se ha elegido la rama eléctrica. En segundo lugar, se busca una aportación a la descarbonización de la economía, mediante la sustitución de energía procedente de recursos fósiles por otra de origen renovable. Finalmente, se aborda la aplicación en actividades económicas concretas.

1.2 Descripción del contexto

La revisión detallada de la literatura científica se aborda de forma específica en las secciones de introducción de los artículos del compendio. En esta Memoria se presenta sumariamente el contexto general de la tesis como un conjunto.

1.2.1 Vientos de cambio en el sistema eléctrico

La energía eléctrica se ha desarrollado principalmente en el marco del sistema eléctrico centralizado. Mientras los consumidores están geográficamente dispersos en casi cualquier ubicación, la generación se ha localizado de forma concentrada en un número relativamente reducido de instalaciones de alta potencia y casi siempre alejadas del consumo. Esto guarda relación con dos factores:

- La existencia de economías de escala en la generación [1], lo que aconseja la construcción de grandes centrales.
- El alto impacto en su entorno de los sistemas de generación nuclear, térmico y gran hidráulico [2].

En consecuencia, se ha construido una enorme red de transporte y distribución [3]. En ella se producen pérdidas de energía, y sus costes de operación trasladan una importante carga económica al precio de la electricidad para el consumidor. La red también produce considerables impactos ambientales y paisajísticos [4]. Además, en muchos países, incluida España, parte de la red de transporte se encuentra al límite de su capacidad [5,6], lo que combinado con la existencia de cierto rechazo social al tendido de nuevas líneas supone un problema para el futuro próximo [7].

El modelo del sistema centralizado está presente en todos los países desarrollados, donde ha llegado a alcanzar altos niveles de complejidad y calidad. Mientras tanto, en los países en desarrollo, el sistema eléctrico frecuentemente no ha ofrecido calidad ni servicio a toda la población [8,9]. En consecuencia, la generación in situ ha sido la forma de suministro en ubicaciones donde no llega la red, recurriendo mayoritariamente a generadores movidos por motores de combustión interna, alimentados por combustibles fósiles.

Una primera reducción de los costes de generación desde fuentes renovables, especialmente la fotovoltaica, le ha permitido pasar de ser usada solamente en casos muy especiales, como los satélites artificiales o las sondas y naves espaciales, a plantearse como una posible alternativa en ubicaciones remotas [10,11]. La existencia de dificultades técnicas y económicas ha sido afrontada por infinidad de estudios. El resultado es la paulatina introducción de generación renovable, en aquellos lugares donde las opciones convencionales (red eléctrica o generadores con motor de combustión interna) resultan inviables o comparativamente más costosas. En muchos casos, la elección óptima puede ser una combinación híbrida fotovoltaica-diésel [12]. En cuanto a la generación renovable que hasta hace poco tiempo se ha conectado al sistema centralizado, se ha apoyado en el auxilio de subvenciones o primas públicas, a la espera de alcanzar la paridad de red [13].

En este camino, un nuevo factor se ha introducido en la toma de decisiones estratégicas sobre energía. Las evidencias de cambio climático y los modelos de calentamiento global prevén escenarios de futuro dramáticos [14], lo que ha obligado a replantear las actividades que liberan gases de efecto invernadero a la atmósfera. De entre ellas la energía es, por mucho, la mayor [15]. Esto ha puesto en el foco mundial la transición desde una economía basada en los combustibles fósiles a otra basada en los recursos renovables.

Mención aparte merece la generación nuclear ya que, aunque su recurso no es renovable, su operación no produce emisiones de CO_2. Sin embargo, no está libre de otros problemas, como las externalidades [4] derivadas de la gestión a largo plazo de los residuos radioactivos y de los poco frecuentes pero gravísimos y costosísimos accidentes. A ello se suma el rechazo social del que es objeto por buena parte de la población. Nuevas tecnologías nucleares, como la fusión controlada, llevan décadas incumpliendo sus propias expectativas y, en el mejor de los casos, tardarán cuatro décadas más en estar comercialmente disponibles [16].

Ya en el presente, las tecnologías de generación eólica y fotovoltaica han devenido económicamente competitivas ante la generación convencional. Puede afirmarse que en algunos contextos la paridad de red respecto al precio minorista está muy próxima o ya se ha alcanzado [17,18]. Además, en el marco de la mitigación del cambio climático, las administraciones públicas, especialmente la Comunidad Europea, han adoptado ambiciosos objetivos para la descarbonización de la economía [19]. Ambas cosas han impulsado la penetración cada vez mayor de la generación renovable en el mix energético de la red.

El sistema eléctrico centralizado también está sufriendo cambios y siendo objeto de propuestas para su actualización. Como consecuencia de la variabilidad de los recursos eólico y solar, se necesitan soluciones para la continuidad, estabilidad y calidad del suministro [20,21]. Otro componente de la transición energética en curso va a ser la sustitución de los vehículos con motor de combustión por otros eléctricos, lo que supondrá un impacto considerable en la red eléctrica [22]. En el marco de la denominada red inteligente [23,24], se incorporarán otras técnicas como la gestión de la demanda, el autoconsumo, la acumulación y la generación distribuida [25]. Además, la evolución de la tecnología no sólo permite, sino que incluso aconseja la utilización de redes eléctricas de relativamente pequeño tamaño, las microrredes [26,27], que pueden estar conectadas, o no, al sistema centralizado. De hecho, si la red general falla, una microrred puede seguir funcionando de forma autónoma. La posibilidad de obtener la estabilidad del suministro de esta forma convive con otra tendencia, que busca aumentar las conexiones internacionales para crear una macrorred europea. Sin embargo, no hay evidencias de que esas interconexiones mejoren la estabilidad, mientras que por el contrario, los apagones pueden propagarse de forma inesperada a larga distancia [28,29]. Eso sí, podrían crear un mercado eléctrico de mayor tamaño. No cabe olvidar que el suministro de energía no sólo es un servicio público, sino también un negocio.

En el contexto descrito, cabe hacerse una pregunta. ¿Hasta qué punto el sistema centralizado va a seguir siendo la mejor solución para el suministro eléctrico? Una forma de abordar la cuestión es plantearse en qué casos las novedades juegan o no en su contra. Sin ánimo de ser exhaustivos, pueden apuntarse enfoques tecnológicos, económicos y sociales.

Enfoque tecnológico

El mix de generación está sufriendo importantes cambios. De entre las diferentes clases de generación renovable, algunas casan bien con el esquema de generación concentrada. Por ejemplo, la eólica presenta mucho mejores rendimientos en ubicaciones muy concretas, incluso off-shore, y con aerogeneradores de gran tamaño [30]. Otras tecnologías propias para su centralización son la solar de concentración, la termosolar, las energías marinas y la geotermia profunda. La biomasa puede ser objeto de planteamientos diversos, centralizados o no.

La generación fotovoltaica pone más en cuestión el statu quo. En primer lugar, el recurso solar es ubicuo [31]. En segundo lugar, la generación fotovoltaica no produce emisiones durante su operación. En tercer lugar, es plenamente escalable y las economías de escala son limitadas [32]. Puede afirmarse que no es necesario centralizar la generación fotovoltaica. Sin embargo, la variabilidad del recurso solar y su inexistencia durante la noche constituyen un inconveniente. En conexión a red, esto deviene en problema menor, ya que hay otras clases de generación conectadas. Por el contrario, en uso aislado requiere sobredimensionamiento de la generación y acumulación o hibridación [33,34].

Enfoque económico

Por una parte, la conexión de generación fotovoltaica en la ubicación del consumo evita las pérdidas asociadas al transporte y la distribución. En consecuencia, la fotovoltaica es idónea para autoconsumo conectado a la red [18]. Esto no supone abandonar el sistema centralizado, sino introducir en él generación distribuida.

Por otra parte, el óptimo económico de un suministro puede cambiar drásticamente si la conexión a la red es muy costosa, lo que es común en ubicaciones del entorno rural o natural [35]. En este caso, el coste de sobredimensionar la generación e incorporar almacenamiento en un sistema aislado puede estar justificado.

En resumen, en entornos urbanizados donde la red está presente y hay consumos próximos, es viable la generación fotovoltaica conectada a la red, mientras que en ubicaciones rurales hay consumidores cuyo coste de suministro pude ser menor mediante un sistema de generación renovable aislada.

Enfoque social

Un tercer aspecto a tener en cuenta es el cambio económico y social. En España se ha desmantelado, aunque en realidad sólo parcialmente, el monopolio territorial del suministro eléctrico [36]. Han entrado en el mercado nuevos y pequeños productores y comercializadores. Y, sobre todo, se ha abierto la puerta al autoconsumo eléctrico, tanto para el consumidor particular como para las empresas. Ante ello, los grandes actores del sistema centralizado, no sólo eléctrico sino también petrolero, estos últimos ante la perspectiva del vehículo eléctrico, velan por sus intereses y buscan su reposicionamiento en este entorno cambiante. Finalmente, las actitudes sociales ante la energía [37] se han convertido en muy relevantes, tanto en el ámbito de decisión de los particulares como de las empresas.

1.2.2 Los sectores difusos

Los llamados sectores difusos, tales como el residencial, transporte, agrícola y ganadero, y la gestión de residuos, no están sometidos al comercio de derechos de emisión [38]. En muchos de ellos no sería viable elaborar un inventario de las instalaciones emisoras, ya que son numerosísimas y corresponden a numerosísimos propietarios y usuarios. Así, la transición energética en estos sectores no se limita a la posible imposición normativa, sino que la implicación de las partes interesadas (propietarios, profesionales, proveedores, clientes, autoridades, organizaciones, etc.) resulta necesaria para la adopción de estas innovaciones [39]. Así, la búsqueda de sostenibilidad en las actividades económicas es un asunto tan tecnológico como social.

Ante la diversidad de factores que condicionan la transición energética y la adopción de generación renovable, el enfoque multidisciplinar está justificado. Una hipótesis subyacente es la siguiente:

> El estudio, con enfoque holístico, de las necesidades energéticas de una actividad o sector económico concreto, permite hallar sinergias y establecer diseños de sistemas de energía renovable idóneos para esa actividad.

La tesis busca aportar nuevas propuestas para facilitar el uso de generación fotovoltaica, no conectada a la red eléctrica, para la satisfacción de la demanda de energía in situ. En consecuencia, la tesis se aplica a un sector de actividad concreto. De entre los sectores difusos, se han elegido las actividades agrícolas. Las razones para ello son las siguientes:

- Las actividades agrícolas se desarrollan en el medio rural, donde no siempre está presente o cercana la red eléctrica.
- El entorno natural, a menudo de alto valor, es especialmente sensible al impacto paisajístico de las líneas eléctricas de distribución y de las emisiones de los motores de combustión.

1.2.3 El sector del vino

De entre las actividades agrícolas, se ha seleccionado para la demostración la actividad vitivinícola. El sector del vino reúne características muy adecuadas para ello:

- La industria del vino está implantada en numerosos países desarrollados [40].
- España tiene la mayor superficie de viñedo del mundo [40].
- La vid y por lo tanto la producción de vino es muy sensible al cambio climático [41].
- La tendencia actual es el aumento de la superficie de regadío [42].
- Se trata de un sector a la vez tradicional e innovador, con abundancia de profesionales cualificados, así como organizaciones sectoriales e intergubernamentales activas.
- Existe mucha literatura científica sobre la actividad vitivinícola, pero escasa sobre mitigación y escasísima sobre el uso de energía en el sector.

La aplicación al sector del vino se aborda en los dos últimos párrafos de la sección Introducción del artículo del compendio *Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case* [43]. El enfoque sectorial se aborda más detalladamente en el artículo del compendio *Introduction of Renewable Energy in the Spanish Wine Sector* [44]. Concretamente, en las secciones 1.1. *"Energy and Climate Change"*, 1.2. *"The Wine Sector and Its Energy Use"*, 1.3. *"The Spanish Wine Sector"*, 1.4. *"Penetration of Renewable Energy in the Spanish Wine Sector"* y 1.5. *"From Attitudes to Innovations in the Wine Sector"*.

Hasta aquí la determinación del ámbito de la tesis, esto es, el suministro de energía de origen fotovoltaico, sin conexión a la red, aplicada a la industria agrícola y tomando como demostrador el sector del vino.

1.2.4 La generación renovable aislada

En la revisión inicial de la literatura científica existente, la generación fotovoltaica aislada se ha encontrado mayoritariamente circunscrita al suministro de electricidad en países en desarrollo, siendo el riego la aplicación, con mucho, más abordada. Entre los otros tipos de generación renovable, la eólica ha sido también propuesta, y utilizada en la práctica, para alimentar bombeos de riego. Mientras, en la práctica, el suministro de electricidad en áreas rurales en los países desarrollados ha tenido como primera opción la construcción de una línea para su conexión a la red. Ante dificultades económicas o de otro tipo, la generación diésel in situ ha sido la segunda opción.

Los estudios para el uso de fotovoltaica aislada en aplicaciones industriales o agrícolas, más allá del riego, han sido relativamente escasos. Una primera aproximación a los sistemas fotovoltaicos para riego ha mostrado entre otras cosas lo siguiente:

1. La demanda de energía para riego en los cultivos mediterráneos presenta una fuerte estacionalidad [45], que casa relativamente bien el perfil anual de la irradiación solar. Esto facilita usar generación fotovoltaica.
2. En los cultivos mediterráneos, más de la mitad del año no hay demanda de riego [45], por lo que la energía de ese período no puede utilizarse, ni almacenarse de manera eficiente en el largo plazo.
3. En los países desarrollados, el riego de los cultivos mediterráneos se hace casi exclusivamente mediante sistemas presurizados, como el goteo [46,47]. Para ello, se necesita un suministro estable en potencia. Esto apunta a la conveniencia de incorporar acumulación a corto plazo, en baterías.
4. En muchos casos los profesionales agrícolas prefieren el riego nocturno [48]. Para ello, las baterías son necesarias.
5. Si se necesita cierta seguridad de suministro, o bien se ha de sobredimensionar la generación fotovoltaica o bien se ha de hibridar con diésel.
6. Si la generación es 100% fotovoltaica o incluso fotovoltaica-eólica, existe una cantidad considerable de energía excedente, que no llega a aprovecharse.

El contexto de aplicación de la generación renovable aislada se aborda más detalladamente en las secciones de introducción de los artículos del compendio:

- *Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops* [49]
- *Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case* [43].
- *Combined production of electricity and hydrogen from solar energy and its use in the wine sector* [50].

En cuanto a la utilización de hidrógeno en movilidad, se aborda en el artículo del compendio *"Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell"* [51].

1.3 Objetivos de la investigación

La investigación ha tenido como objetivo elaborar una propuesta novedosa para el suministro de energía de origen 100% renovable en el medio rural, en modo no conectado a la red y aplicado a la satisfacción de consumos concretos del sector vitivinícola (viñedo).

Se ha buscado la innovación en la aplicación de tecnologías existentes, que antes no se hubieran utilizado de forma conjunta para estos fines. Entre los objetivos no está analizar la viabilidad económica en lo que afecta a tecnologías que aún no han alcanzado un grado suficiente de madurez comercial, como las de producción y uso de hidrógeno, ya que su validez sería muy probablemente efímera.

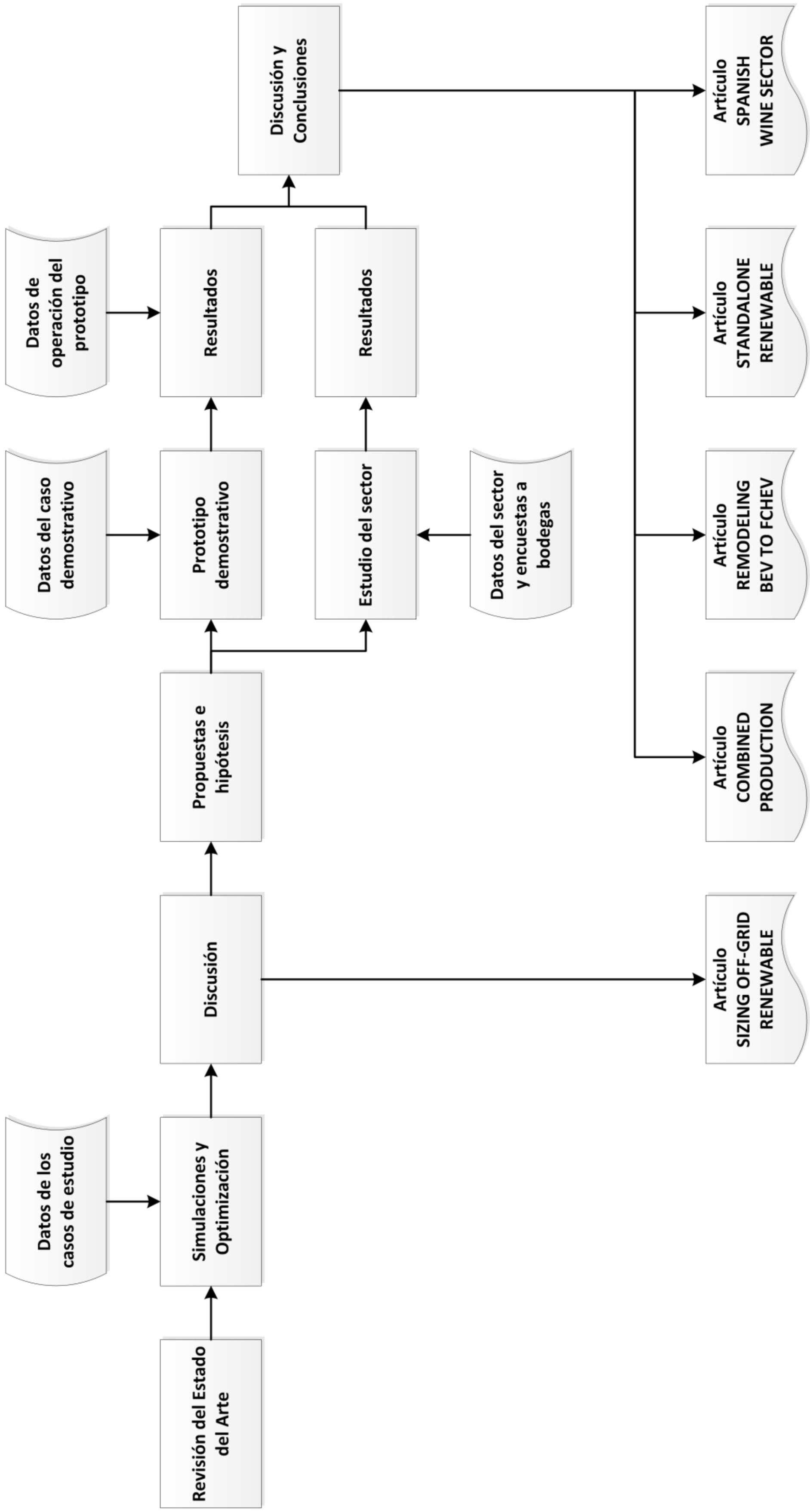
Por el contrario, entre los objetivos sí se ha incluido el estudio del sector de aplicación (la industria del vino) en cuanto a su disposición a la adopción de las tecnologías comercialmente maduras, como la generación renovable para riego y otras medidas de mitigación.

2 Metodología

2.1 Esquema general

La tesis tiene entre sus precedentes el Trabajo Fin de Máster, previamente realizado por el doctorando en el Máster de Energías Renovables y Eficiencia Energética, titulado “INTEGRACIÓN DE ENERGÍA RENOVABLE EN EL PROCESO VITIVINÍCOLA”, así como el artículo del mismo autor *“Introducing Off-Grid Renewable Energy Systems for Irrigation in Mediterranean Crops”* [45]. A partir de ahí, se hizo una primera fase de revisión del estado del arte, con la finalidad de determinar los objetivos y el alcance del trabajo a realizar. El trabajo se planteó con enfoque multidisciplinar (energético, agrícola y empresarial), buscando la innovación por combinación [52]. La figura siguiente muestra el esquema del desarrollo de la tesis.

Esquema del desarrollo de la tesis



2.2 Revisión del estado del arte

A lo largo de todo el trabajo, se ha revisado la literatura científica existente. Las herramientas empleadas principalmente para la búsqueda han sido:

- Alcorze, el metabuscador de la Universidad de Zaragoza http://alcorze.unizar.es/
- Scopus https://www.scopus.com/ y ScienceDirect https://www.sciencedirect.com/

De forma secundaria, también se han utilizado:

- Web of Science http://www.webofknowledge.com/
- Ieeexplore https://ieeexplore.ieee.org/Xplore/home.jsp
- Google scholar https://scholar.google.es/

La búsqueda se hizo en diferentes fases:

1. Revisión inicial, para explorar el ámbito de la tesis y poder determinar los objetivos.
2. Temas específicos, como las diversas tecnologías empleadas, aplicaciones, casos de estudio, metodología, etc.
3. Búsquedas de actualización, al menos una vez al año.
4. Además de las búsquedas realizadas, se configuraron alertas para recibir información nueva a lo largo del tiempo.
5. Búsquedas para posicionar los resultados en el contexto.

La gestión de referencias se hizo con la herramienta Mendeley y su incorporación a los textos de los artículos con la correspondiente extensión para Microsoft Word.

La revisión del estado del arte se refleja en las citas a las referencias seleccionadas e incorporadas en los diferentes artículos publicados.

2.3 Obtención de datos de los casos de estudio

2.3.1 Datos de recursos renovables

Por una parte, se utilizaron bases de datos de recursos renovables. El recurso eólico se consultó en el Atlas Eólico de España, del Instituto para la Diversificación y Ahorro de la Energía (IDAE), entre otros. El recurso solar se consultó principalmente en el *Photovoltaic Geographical Information System* (PVGIS) [31].

Por otra parte, se instalaron estaciones de medida en las ubicaciones de los diversos casos de estudio y del caso demostrativo. Estas estaciones incluían anemómetros, veleta y piranómetro.

La obtención de datos de recursos renovables se menciona en los artículos del compendio:

- *Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops* [49], sección 2.3 *Renewable resources.*
- *Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case* [43], sección 2.3.1. *Renewable Resources and Energy Generation*.

2.3.2 Datos de las instalaciones

Los casos de estudio fueron seleccionados mediante contactos con las organizaciones vitivinícolas de las diferentes zonas de Aragón (Consejos Reguladores y Asociaciones de las Indicaciones

Geográficas Protegidas) Se utilizaron datos del Portal de Infraestructura de datos Espaciales del Ministerio de Agricultura, Pesca y Alimentación (MAPA) [53]. Se efectuaron visitas técnicas a las instalaciones, especialmente a los sistemas de riego de los viñedos. Durante ellas se tomaron datos de su configuración y se efectuaron medidas, principalmente eléctricas y de caudal de agua. Se buscaron los datos técnicos de las bombas, en especial las curvas características, en la documentación de sus fabricantes. También se mantuvieron entrevistas presenciales para conocer la gestión de los sistemas de riego. Como herramienta de apoyo, se utilizó un cuestionario que se acompaña como Anexo 1 a esta memoria.

La obtención de datos de las instalaciones se menciona en el artículo del compendio "*Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops"* [49], sección 2.2. "*Case studies and demand data"*.

2.4 Simulaciones y optimizaciones

Con los datos obtenidos de los casos de estudio, se llevaron a cabo diversos procesos de simulación y optimización de sistemas de energía renovable para riego en viñedo y olivar, utilizando el software iHOGA (improved Hybrid Optimization by Genetic Algorithms) [54]. Se realizaron búsquedas mono-objetivo de óptimos económicos, de óptimos ambientales, así como multiobjetivo combinando ambos. Se identificaron, entre otras cosas, los mix óptimos de generación, los costes de la energía, los ángulos de inclinación de los paneles fotovoltaicos, etc.

El artículo del compendio "*Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops"* [49], en su sección 2.4, describe este proceso.

2.5 El proyecto LIFE REWIND

En el marco de la tesis, se aplicó a la convocatoria del programa LIFE de la Comisión Europea, con la propuesta de un proyecto al que se puso por acrónimo REWIND *(Renewable Energy in the Wine Industry)* [55]. Además de la Universidad de Zaragoza, formaron parte del consorcio el CSIC, a través del Laboratorio de Investigación en Fluidodinámica y Tecnologías de la Combustión (LIFTEC), la empresa Viñas del Vero S.A. y la empresa Intergia S.L. La propuesta fue aceptada, con un presupuesto total de 1.562.994 € y una duración de 37 meses.

Durante la ejecución del proyecto, el investigador principal fue J.L. Bernal (codirector de la tesis), mientras que el coordinador fue el doctorando. El equipo de investigación del proyecto incorporó 13 doctores. De ellos, nueve profesores de UNIZAR, de ingeniería industrial ramas eléctrica y mecánica, ingeniería agrónoma y economía y empresa. Del CSIC, cuatro investigadores de la línea de hidrógeno. El equipo también incorporaba personal técnico de Viñas del Vero e Intergia, así como personal administrativo.

2.6 El prototipo

El prototipo se instaló en un viñedo de la bodega Viñas del Vero, en Barbastro (Huesca). Para su diseño y dimensionado, se realizó una toma de datos de recursos eólico y solar, de las instalaciones y de los criterios de los operadores, de forma similar a la indicada en la sección 2.3. El dimensionado se hizo con ayuda de la herramienta iHOGA. Se buscó una generación aislada 100% renovable, para alimentar diversos consumos del viñedo y bodega, incluyendo el suministro de hidrógeno para uso en movilidad en el viñedo.

El prototipo se aborda como sistema de energía renovable aislado en el artículo del compendio *"Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case"* [43]. Concretamente en su sección 2, "*Materials and Methods"*, el proceso completo de obtención de datos, descripción de las instalaciones, datos de demanda energética, configuración y dimensionado del sistema de energía renovable, estrategias de gestión de la energía y descripción del prototipo.

Un enfoque más orientado a la utilización de hidrógeno en el sistema del prototipo se presenta en el artículo "*Combined production of electricity and hydrogen from solar energy and its use in the wine sector"* [50].

Finalmente, el vehículo con pila de combustible se aborda en *"Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell"* [51].

2.6.1 Revisión de la tecnología comercialmente disponible

Se realizó la búsqueda de los productos disponibles en el mercado, para elegir aquellos que podrían incorporarse en el prototipo demostrativo. Para ello se utilizaron los buscadores generalistas y la información técnica y comercial disponible. También se establecieron contactos a nivel técnico con fabricantes y proveedores.

Cabe mencionar en especial varios aspectos concretos:

- La colaboración establecida para la fabricación y primera instalación, en el prototipo demostrativo, del prototipo de un nuevo sistema de soportes flotantes para paneles fotovoltaicos, actualmente comercializados https://isifloatingcom.wordpress.com/.
- Los contactos con el departamento técnico del fabricante de inversores SMA, tras los cuáles se optó por no cumplir sus recomendaciones de sobredimensionado de la batería, en línea con los objetivos de la tesis de reducción de acumulación a corto plazo.
- La inmadurez comercial observada en la tecnología del hidrógeno, con escasa oferta comercial, elevados precios y largos plazos de entrega.

Una vez identificadas las opciones comercialmente disponibles, se seleccionaron las que iban a ser incorporadas al prototipo. En los artículos del compendio se describe la composición del prototipo.

2.6.2 Montaje

El montaje del prototipo se realizó en la finca de Viñas del Vero, en Barbastro, entre la estación depuradora de aguas residuales de la bodega y el viñedo. Su energía alimenta dicha depuradora, los bombeos del agua depurada hasta una balsa de riego y el bombeo de riego propiamente dicho. El subsistema de producción de hidrógeno se ensambló y probó previamente en el laboratorio del LIFTEC. También allí se realizó la transformación del vehículo eléctrico incorporándole la pila de combustible, los depósitos de hidrógeno y los sistemas de control. Fotografías de la ubicación, el proceso de montaje y el prototipo terminado se acompañan como Anexo 2 a esta Memoria.

2.6.3 Operación

El prototipo operó en condiciones normales de trabajo desde su puesta en marcha y ajuste. Se formó a los operarios en la gestión y mantenimiento de los sistemas, especialmente el control presencial y remoto, así como la recarga de hidrógeno al vehículo. Se mantuvieron frecuentes contactos para conocer las posibles incidencias y el grado de satisfacción de los usuarios. El período inicial de operación del prototipo previsto en el proyecto era de un año. No obstante, dado su satisfactorio funcionamiento, sigue prestando servicio actualmente.

2.7 Datos de operación del prototipo

En el prototipo se incluyó un ordenador que, además de su función de control, almacena de forma diezminutal hasta 160 parámetros. Parte de ellos son mediciones de sensores y estados de los subsistemas (inversores, cargas, batería, hidrógeno, etc.).

Además de los datos capturados del propio sistema, el prototipo incluye cuatro piranómetros, para la medición de la irradiación solar incidente en los tres conjuntos de paneles (paneles fijos en suelo, fijos flotantes y sobre seguidor solar a dos ejes), así como la irradiación incidente sobre plano horizontal. También incorpora un anemómetro, así como seis sensores térmicos para la medición de la temperatura ambiente y la de los paneles en cada uno de los tres conjuntos.

2.8 Datos del sector

El método utilizado para estos trabajos se describe en la sección *“Materials and Methods”* del artículo del compendio *“Introduction of Renewable Energy in the Spanish Wine Sector”* [44]. Se resume en esta memoria en las dos subsecciones siguientes.

2.8.1 Datos acumulados

Se recopilaron datos cualitativos y cuantitativos del sector agrario en general y del sector del vino en particular. Para ello se utilizaron las bases de datos de la Oficina de Estadística Europea - EUROSTAT [56], la Organización Internacional de la Viña y el Vino - OIV [57], el Ministerio de Agricultura, Pesca y Alimentación - MAPA [58] y el Sistema de Análisis de Balances Ibéricos - SABI [59].

2.8.2 Encuestas a bodegas

La transformación del sector vitivinícola hacia una mayor sostenibilidad de sus procesos y actividades se ve influida por varios factores. En ese sentido, una de las acciones llevadas a cabo ha sido un estudio para conocer la penetración de las energías renovables dentro del sector vitivinícola español. La metodología de este estudio ha constado de tres etapas:

1. En una primera fase, de carácter exploratorio, se eligieron diez propietarios o gestores de viñedos y bodegas de diferentes regiones españolas, para identificar los aspectos clave y las características del sector analizado. Esto se realizó mediante entrevistas en profundidad, semiestructuradas y dirigidas, como prueba del cuestionario o pre-test.
2. En la segunda etapa se elaboró el cuestionario definitivo, se diseñó la muestra y se seleccionó el tipo de muestreo aleatorio simple, estratificado por comunidad autónoma. Se obtuvieron 92 cuestionarios respondidos. Dicho cuestionario contenía cuatro bloques de preguntas: I-Identificación y localización, II-Actividad de la empresa, III-Política medioambiental de la empresa y IV-Actitud ante el cambio climático.
3. La tercera y última fase consistió en el análisis de los datos proporcionados por la encuesta, con el fin de extraer conclusiones. Las respuestas obtenidas se procesaron mediante el software *Statistical Package for Social Sciences* (SPSS) [60].

El cuestionario utilizado se incluye como Anexo 3 a esta Memoria.

3 Aportaciones del doctorando

La relación, no exhaustiva, de las aportaciones del doctorando en la realización de la tesis, es:

a) Elaboró la propuesta inicial para la tesis, así como el plan de investigación. Ambos fueron consultados con los codirectores y posteriormente perfeccionados a lo largo de los primeros cursos.
b) Propuso el método a seguir.
c) Efectuó la revisión del estado del arte, en todas sus etapas.
d) Identificó los casos de estudio y recopiló los datos técnicos de las instalaciones de riego existentes, así como los datos históricos de consumo energético.
e) Recopiló datos de recurso eólico y solar, mediante sensores instalados en las explotaciones aragonesas de viñedo y olivar.
f) Llevó a cabo los procesos de simulación y optimización, así como el análisis de sus resultados.
g) Preparó y redactó el primero de los artículos del compendio, titulado *"Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops"* [49], publicado en la revista *Renewable Energy*.
h) Con la finalidad de construir el consorcio del proyecto LIFE REWIND, estableció contactos con el LIFTEC (Laboratorio de Investigación en Fluidodinámica y Tecnologías de la Combustión), con la empresa Viñas del Vero S.A. y con la empresa Intergia S.L., de la cual el doctorando es socio fundador.
i) Redactó la propuesta del proyecto LIFE REWIND, coordinadamente con los codirectores de la tesis y los representantes de las otras entidades del consorcio (CSIC, Viñas del Vero e Intergia).
j) Fue coordinador del proyecto y del consorcio durante los 37 meses de su duración.
k) A lo largo del proyecto, participó en prácticamente todas las actividades, especialmente en:
    - Obtuvo datos del sector vitivinícola, mediante revisión bibliográfica.
    - Realizó visitas técnicas y encuestas a profesionales del sector en decenas de bodegas en toda España.
    - Analizó los resultados del estudio estadístico de las encuestas, en colaboración con las dos profesoras de la Facultad de Economía y Empresa participantes en el proyecto.
    - Obtuvo los datos de las instalaciones de riego, depuración de agua y maquinaria agrícola en la bodega y viñedo de Viñas del Vero.
    - Revisó la tecnología disponible para su incorporación en el prototipo.
    - Diseño y dimensionó la parte eléctrica de los prototipos.
    - Se coordinó con los investigadores del CSIC (LIFTEC) para el dimensionado de la parte hidrógeno de los prototipos y su integración en el sistema.
    - Diseñó el subsistema de comunicaciones del prototipo.
    - Definió la estrategia de gestión de la energía y ajustó sus parámetros.
    - Solucionó los problemas causados por los armónicos y las interferencias electromagnéticas debidas a la conmutación en los inversores y variadores de frecuencia, que provocaban errores en el bus de datos y caídas del subsistema de control y de las comunicaciones.
    - Procesó y analizó los datos (diezminutales y horarios) almacenados en el sistema durante dos años de operación.

- Presentó el trabajo y sus resultados en seis congresos, incluida la presentación oral del proyecto en el 40º Congreso Mundial de la OIV (Organización Internacional de la Vid y el Vino), la intergubernamental del sector.
- Presentó el proyecto en las universidades de Zaragoza (3 presentaciones), Politécnica de Madrid y Politécnica de Valencia, así como en el Centro Nacional del Hidrógeno.
- Fue ponente invitado en el III Foro Solar Español
- Desarrolló múltiples acciones de difusión y divulgación en revistas especializadas, radio, prensa, TV y asociaciones del sector (Federación Española del Vino, consejos reguladores de denominaciones de origen, sindicatos agrarios, etc.).
- Preparó, en colaboración con el investigador principal y apoyado por el resto del equipo, los informes del proyecto: el *"Inception Report"*, el *"Midterm Report"*, el *"Final Report"*, el *"Layman Report"* y diversos entregables para la Comisión Europea.
- Coordinó las reuniones de gestión del proyecto.

l) Participó en la preparación del segundo y tercer artículos del compendio en colaboración con investigadores del CSIC (LIFTEC): *"Combined production of electricity and hydrogen from solar energy and its use in the wine sector"* [50], publicado en la revista *Renewable Energy* y *"Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell"* [51], publicado en la revista *International Journal of Hydrogen Energy*.

m) Redactó el cuarto artículo del convenio en colaboración con una profesora del departamento de Dirección y Organización de Empresas y otra del área de Métodos Cuantitativos para la Economía y la Empresa, de la Universidad de Zaragoza, titulado *"Introduction of Renewable Energy in the Spanish Wine Sector"* [44] y publicado en la revista *Sustainability*. En la sección *"Author Contributions*" del propio artículo se recoge su detalle.

n) Preparó y redactó el quinto artículo del compendio, titulado *"Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case"* [43], publicado en la revista *Sustainability*. En la sección *"Author Contributions*" del propio artículo se recoge su detalle.

o) En las últimas fases de los estudios de doctorado, revisó artículos para las revistas *Science of the Total Environment*, *Journal of Cleaner Production*, *Energy Conversion and Management* y *International Journal of Hydrogen Energy*, todas ellas de la editorial Elsevier.

4 Resultados

Los resultados obtenidos se muestran de forma específica en los artículos del compendio. En esta Memoria se presentan los más relevantes en el contexto general de la tesis en su conjunto, enmarcados en cinco líneas:

- Dimensionado de sistemas aislados de generación para riego de viñedo, olivar y otros cultivos mediterráneos.
- Prototipo de generación aislada 100% renovable con producción de hidrógeno.
- Introducción de energía renovable en el sector del vino.
- Publicaciones.

- Otras vías de difusión.
- reconocimientos.

4.1 Sistemas óptimos para riego estacional

La primera oleada de resultados deriva del trabajo realizado sobre seis casos de estudio de riego en viñedo y olivar. Se trata de cultivos mediterráneos, regados mediante sistemas presurizados, concretamente riego por goteo. El ciclo anual de este tipo de cultivos provoca que la demanda de energía para riego presente una elevada estacionalidad, cuyos máximos corresponden en buena medida a los meses de máxima irradiación.

Los procesos de simulación y optimización han ofrecido diversos resultados relevantes:

- En todos los casos, la solución económicamente óptima incluye un generador diésel, sólo o hibridado con fotovoltaica. Esto es, ninguna de las soluciones óptimas es 100% generación renovable [49] (sección 3.1).
- La generación eólica no entra en ninguna de las soluciones económicamente óptimas [49] (sección 3.1 y Tabla 5). Además, el análisis de sensibilidad muestra que esta ausencia se mantendría incluso en escenarios con un recurso eólico de considerablemente mayor magnitud [49] (sección 3.5).
- En riego nocturno, la generación fotovoltaica sólo entra en el mix óptimo en dos de los seis casos estudiados [49] (sección 3.2 y Tabla 5). Si el riego es diurno, la generación fotovoltaica está presente en cinco de los seis casos y, además, el tamaño de la batería se ve reducido. La diferencia entre que el riego sea nocturno o diurno afecta fuertemente a la presencia en el sistema óptimo de la generación fotovoltaica. En este sentido, lo idóneo es regar durante las horas centrales del día, cuando la irradiación y por tanto la producción fotovoltaica es máxima. De esta forma se reduce el tamaño de la acumulación necesaria y se minimizan las pérdidas derivadas de la carga y descarga de la batería (por resistencia interna, eficiencia de la conversión, etc.). Ante esta simultaneidad entre producción y consumo, la arquitectura de bus en alterna resulta más eficiente, ya que la energía puede ir directamente de los inversores solares de red (de mayor eficiencia que los cargadores solares) a los motores de las bombas (alimentados en alterna trifásica).
- A pesar de la relativa cercanía de los casos de estudio, todos ellos ubicados en Aragón, se obtuvieron muy diferentes ángulos fijos óptimos de inclinación de los paneles fotovoltaicos [49] (sección 3.3). Estos ángulos óptimos también resultaron ser diferentes si el riego era diurno o nocturno. Como era de esperar, las fechas y duración de la temporada de riego afectan al ángulo óptimo. Sin embargo, aparecen otras influencias, en relación con el horario de actividad del riego. En caso de riego nocturno, prima maximizar la producción diaria. En caso de riego diurno, la mayor eficiencia obtenida cuando consumo y generación son simultáneos produce resultados en algunos casos sorprendentes (como -4º en el caso Bancales), que fueron exhaustivamente comprobados.
- Se observó una relación inversa entre el número de horas anuales de operación del riego y el coste de la energía. Mientras que en los sistemas 100% diésel la proporcionalidad era ligera, en los sistemas híbridos fotovoltaica-diésel era mucho mayor. Resulta más económica la energía si el sistema de riego ha sido dimensionado con un caudal tal que el volumen de riego diario se complete a lo largo de las horas del día con producción fotovoltaica [49] (sección 3.4 y Figura 8).
- Los resultados económicos mostraron la viabilidad de incorporar generación fotovoltaica a los riegos estudiados, siendo a menudo los sistemas híbridos fotovoltaica-diésel la

solución óptima, aunque con diferencias relevantes en el dimensionado de cada caso concreto [49] (sección 3.4 y Tabla 5).

Estos y otros resultados se presentan en el artículo del compendio *“Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops”* [49].

4.2 El prototipo

El prototipo se diseñó con la intención de ofrecer un suministro de energía 100% de origen renovable, producida in situ para alimentar diversos consumos de viñedo y bodega. Este tipo de sistemas aislados requieren un sobredimensionado debido a la variabilidad, no controlable, de la producción. Por lo tanto, considerando el balance anual, presentan un excedente de energía. En el prototipo se optó por extraer ese excedente en forma de hidrógeno para su utilización en un vehículo para uso agrícola con pila de combustible. También se incorporó al conjunto una estrategia de gestión de la energía. El Anexo 4 muestra imágenes del prototipo.

Los resultados obtenidos con el prototipo, en cuanto a la gestión de la energía, se muestran en la sección 3 del artículo del compendio *“Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case”* [43] y en la sección 3.1 del artículo *“Combined production of electricity and hydrogen from solar energy and its use in the wine sector”* [50]. Entre ellos pueden mencionarse:

- La combinación de demandas energéticas, con perfiles estacionales diferentes, ha dado como resultado una demanda agregada mejor adaptada a la estacionalidad del recurso solar que cada una de ellas considerada individualmente [43] (sección 3.2).
- La estrategia de gestión de las cargas diferibles ha permitido una adaptación adicional, obteniendo una curva de la demanda agregada muy cercana a la de la producción fotovoltaica [43] (sección 3.1) [50] (sección 3.1).
- La estrategia de prioridad de cargas y de consumos diferibles ha reducido el uso de la batería, ha evitado descargas profundas y caídas del sistema [43] (sección 3.1) [50] (sección 3.1).
- Desde su puesta en marcha, el prototipo ha suministrado toda la energía necesaria para el funcionamiento de la estación depuradora de aguas residuales de la bodega, los bombeos de elevación y de riego, y los consumos auxiliares (climatización, control y comunicaciones [43] (sección 3.2).
- La producción de energía en un año, de origen únicamente fotovoltaico, ascendió a 73.648 kWh. Las pérdidas debidas al ciclado de energía en la batería (incluidas las de los cargadores e inversores) representan tan sólo el 3,4% de la energía producida [43] (sección 3.2.4).
- La totalidad de la energía excedente de un año (6.797 kWh) se ha podido utilizar para la producción de 1.290 Nm^3 de hidrógeno [43] (sección 3.3).
- La operación del prototipo evitó en un año la emisión de 25.470 kg de CO2 y 27 g de residuos radioactivos de alto nivel, procedentes de la combustión de gasóleo y de electricidad de la red [43] (sección 3.5).

En cuanto a los resultados específicos del funcionamiento del subsistema de producción de hidrógeno, se muestran en la sección 3.2 del artículo del compendio *“Combined production of electricity and hydrogen from solar energy and its use in the wine sector”* [50]. Los resultados del vehículo con pila de combustible, se muestran en la sección "3.3 del artículo del compendio

"Combined production of electricity and hydrogen from solar energy and its use in the wine sector" [50] y en la sección *"Results"* del artículo*"Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell"* [51]. Es remarcable que:

- La recarga de los depósitos de hidrógeno del vehículo desde la hidrogenera del sistema se completa en menos de un minuto (por ejemplo, de 30 a 157 bar en 20 segundos). Para el ciclo de trabajo considerado habitual del vehículo, se requiere recargarlo cada 1,5 días [50] (sección 3.2. *Performance of the hydrogen production and refueling plant*).
- Durante el funcionamiento del vehículo, la pila de combustible trabaja en un estado cuasi estable, actuando la batería como nivelador para absorber o ceder la potencia necesaria en cada instante. Esto redunda en un buen rendimiento de la pila y en la protección de su vida útil [50] (sección 3.3. *Performance of the hybrid electric car*).
- El test de funcionamiento de la pila de combustible y los criterios incorporados en su sistema de control se muestran en [51] (sección *Performance of the PEMFC stack)*.
- Se llevó a cabo un test real de conducción del vehículo, monitorizando los parámetros de funcionamiento, cuyos resultados se describen en [51] (sección *Performance of the hybrid electric car*).

4.3 Introducción de energía renovable en el sector del vino

Como ya se ha indicado, el trabajo realizado aborda también la adopción de energía renovable por las empresas del sector. Los resultados obtenidos en este aspecto se recogen en la sección 3 del artículo del compendio *"Introduction of Renewable Energy in the Spanish Wine Sector"* [44]. Entre ellos pueden mencionarse:

El análisis estadístico unidimensional ofrece algunos resultados interesantes, por ejemplo:

- Recursos destinados por las bodegas a la gestión medioambiental: en el 33 % de las bodegas no se asigna ningún recurso a estas tareas; en el 46 % se encargan a técnicos generalistas junto con otras funciones asignadas; y solamente en el 7 % se dispone de un técnico o departamento exclusivo de medioambiente.

- Existe un muy bajo nivel de uso de energías renovables.

Las bodegas que componen la muestra están muy centradas en lo que constituye su *core business*, que es la producción y venta de vino. También se observa un alto grado de vinculación entre la propiedad de la bodega y la propiedad de la explotación vitícola.

A continuación, el análisis factorial aborda las variables que muestran, para cada bodega, su grado de acuerdo con que el clima ha cambiado, su disposición a reducir las emisiones de CO_2, su convencimiento del uso de energías renovables, su opinión del gasto que supone su implantación en cuanto a inversión, costes de operación y de mantenimiento; también la importancia que atribuyen a la sostenibilidad ambiental, la fiabilidad, la existencia de subvenciones y el impacto de la imagen en la adopción de energías renovables. Se obtuvieron cuatro factores con dichas variables:

a) Factor de costo: relacionado con la importancia dada a los costos de operación y mantenimiento.

b) Factor de convicción: relacionado con la convicción de usar energía renovable y una imagen de reputación.

c) Factor de inversión: relacionado con la importancia dada a la inversión necesaria.

d) Factor de sostenibilidad: relacionado con la importancia dada a la sostenibilidad y fiabilidad.

A partir de estos cuatro factores, se ha utilizado la técnica multivariante del análisis clúster para realizar una clasificación de las bodegas en tres grupos bien diferenciados:

I. Bodegas que están convencidas de introducir energías renovables (20% de la muestra). Su interés en la sostenibilidad es el principal impulsor. Estas bodegas ya están dispuestas a incorporar energía renovable.

II. Bodegas que aún no confían en las energías renovables (40% de la muestra). No creen que las energías renovables estén lo suficientemente desarrolladas para ser un suministro confiable. Esta actitud puede estar relacionada con la novedad de las tecnologías de energías renovables. En España, los obstáculos administrativos y la falta de promoción pública en los últimos años también pueden haber jugado en contra.

III. Bodegas que no están convencidas de introducir energías renovables. (40% de la muestra). Ni los puntos ambientales ni de reputación son suficientes para motivarlos. Parecen estar completamente absorbidas por el núcleo de su negocio, sin tiempo para preocuparse por la sostenibilidad y sin saber la gran participación de la energía en la huella de carbono de su actividad.

4.4 Publicaciones

4.4.1 Artículos en revistas JCR

Los cinco artículos publicados hasta ahora en revistas con índice de impacto JCR, en orden cronológico, son:

1. Carroquino, J.; Dufo-López, R.; Bernal-Agustín, J. L. Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops. Renewable Energy 2015, 76, 566–574, doi:10.1016/j.renene.2014.11.069.

   Factor de impacto 2015: 3,404 (Q2)
   Factor de impacto 5 años: 4,982
   Citas a 28/02/2019 (Web of Knowledge): 25

2. Carroquino, J.; Roda, V.; Mustata, R.; Yago, J.; Valiño, L.; Lozano, A.; Barreras, F. Combined production of electricity and hydrogen from solar energy and its use in the wine sector. Renewable Energy 2018, 122, 251–263, doi:10.1016/j.renene.2018.01.106.

   Factor de impacto 2017: 4,900 (Q1)
   Factor de impacto 5 años: 4,982
   Citas a 28/02/2019 (Web of Knowledge): 3

3. Roda, V.; Carroquino, J.; Valiño, L.; Lozano, A.; Barreras, F. Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell. International Journal of Hydrogen Energy 2018, doi:10.1016/j.ijhydene.2017.12.171.

Factor de impacto 2017: 4,229 (Q1)
Factor de impacto 5 años: 4,064
Citas a 28/02/2019 (Web of Knowledge): 2

4. Garcia-Casarejos, N.; Gargallo, P.; Carroquino, J. Introduction of renewable energy in the Spanish wine sector. Sustainability 2018, 10, doi:10.3390/su10093157.

   Factor de impacto 2017: 2,075 (Q2)
   Factor de impacto 5 años: 2,177

5. Carroquino, J.; Bernal-Agustín, J.-L.; Dufo-López, R. Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case. Sustainability 2019, 11, 951, doi:10.3390/SU11040951.

   Factor de impacto 2017: 2,075 (Q2)
   Factor de impacto 5 años: 2,177

4.4.2 Capítulo de libro

Por invitación de los coordinadores del libro "El sector vitivinícola frente al desafío del cambio climático", monografía editada en la colección ADN Agro de Cajamar Caja Rural y con participación de relevantes autores del sector, el doctorando redactó el capítulo "La sostenibilidad de las bodegas españolas. Oportunidades de mitigación en materia energética":

> Carroquino, J. La sostenibilidad de las bodegas españolas. Oportunidades de mitigación en materia energética. In *El sector vitivinícola frente al desafío del cambio climático*; Compés López, R., Sotés Ruiz, V., Eds.; Cajamar Caja Rural, 2019 ISBN 978-84-95531-92-6.

4.4.3 Publicaciones sectoriales

Artículo publicado en revista "Wine Studies", revisada por pares, pero no incluida en JCR:

> Carroquino, J.; García Casarejos, N.; Gargallo, P. Introducing renewable energy in vineyards and agricultural machinery: A way to reduce emissions and provide sustainability. Wine Studies 2017, 6, 5–9, doi:10.4081/ws.2017.6975.

Artículo invitado en revista revista "FuturEnergy":

> Carroquino, J. FuturEnergy. Madrid. Febraury 2017, pp. 63–66.

Artículo invitado en revista del Consejo Regulador de la denominación de origen Somontano:

> Carroquino, J. Revista D.O. Somontano. Barbastro July 2017, pp. 4–5.

Artículo invitado en revista on-line Feed in the World, también publicado en la revista on-line Euroganadería:

> Carroquino, J. Proyecto LIFE REWIND Available online: http://www.feedingtheworld.es/proyecto/reportajes/proyecto-life-rewind_409_36_478_0_1_in.html (accessed on Feb 23, 2019).

4.4.4 Ponencias publicadas

Se han publicado siete ponencias que fueron previamente presentadas en congresos. Las numeradas como 2 y 3 fueron presentadas en el 40º Congreso Mundial de la OIV (Organización Internacional de la Vid y el Vino), la intergubernamental del sector.

1. Mustata, R.; Roda, V.; Nueno, A.; Valiño, L.; Lozano, A.; Barreras, F.; Bernal-Agustín, J. L.; Carroquino, J. Small scale demonstration project for the production and use of hydrogen from renewable energy sources in the wine sector. In WHEC 2016 - 21st World Hydrogen Energy Conference 2016, Proceedings; 2016.
2. Carroquino, J.; García-Casarejos, N.; Gargallo, P.; García-Ramos, F.-J.; Yago, y J. Energía renovable e hidrógeno generados in situ para riego y movilidad en viñedos. In BIO Web of Conferences; 2017; Vol. 9, p. 01005.
3. Gargallo, P.; Garcia-Casarejos, N.; Carroquino, J. La sostenibilidad como medio para conseguir el posicionamiento de mercado de una bodega. In BIO Web of Conferences; 2017; Vol. 9, p. 03010.
4. Carroquino, J.; García-Casarejos, N.; Gargallo, P.; Yago, J. The LIFE REWIND project : renewable electricity for the wine industry , with hydrogen production to replace diesel in agricultural machinery / Producción de hidrógeno para sustituir al gasóleo en maquinaria agrícola. In Proceedings from the 21st International Congress on Project Management and Engineering; 2017; pp. 1537–1549.
5. Gargallo, P.; Carroquino, J. Renewable Energy in the Wine Sector and its Socioeconomic and Environmental Effects. In Proceedings of SEEP; 2017; pp. 27–30.
6. García-Casarejos, N.; Gargallo, P.; Carroquino, J. Attitude survey of wine sector toward renewables for reducing GHG. Energy Procedia 2018, 153, 438–443, doi:10.1016/J.EGYPRO.2018.10.040.

4.5 Otras vías de difusión

Los trabajos y sus resultados han sido ampliamente difundidos. Las presentaciones más relevantes han sido:

- Dos presentaciones orales (una sobre los resultados del prototipo y otra sobre el estudio del sector), ante delegados científicos, de las organizaciones empresariales y gubernamentales, en el 40º Congreso Mundial de la OIV (Organización Internacional de la Vid y el Vino), la intergubernamental del sector.
- Presentación ante el Grupo de Trabajo de Medioambiente e Innovación de la Federación Española del Vino (FEV) con presencia de los directivos de las principales empresas y grupos vinícolas españoles.
- Tres presentaciones en la Universidad de Zaragoza, una en la Politécnica de Madrid y otra en la Politécnica de Valencia, así como en el Centro Nacional del Hidrógeno.
- Ponencia invitada en el III Foro Solar Español, organizado por la Unión Española Fotovoltaica (UNEF), ante más de 400 personas, con participación entre otras autoridades del Comisario Europeo de Acción por el Clima y Energía.
- Múltiples presentaciones divulgativas en radio, prensa, TV y asociaciones del sector (consejos reguladores de denominaciones de origen, sindicatos agrarios, etc.).

- Publicación del *"Layman Report"* del proyecto LIFE REWIND.
- Video de difusión, con versiones en español, inglés y francés, del proyecto LIFE REWIND.

4.6 Reconocimientos obtenidos

Los reconocimientos y premios obtenidos hasta la fecha son:

- Accésit del premio Jaime Blasco a la Innovación 2017, de la Asociación Española de Dirección e Ingeniería de Proyectos (AEIPRO), por la comunicación "El interés de las bodegas españolas por la eficiencia energética a través de las energías renovables", en el XXI Congreso Internacional de Dirección e Ingeniería de Proyectos.
- Primer premio en sesión de posters del WAC 2017, organizado por la Cátedra UNESCO de la Universidad de Borgoña, por el trabajo *"The interest of the renewable energy for the Spanish wine sector"*.
- El proyecto LIFE REWIND resultó finalista del premio Tercer Milenio 2017 de Heraldo de Aragón.
- El proyecto LIFE REWIND, presentado por Viñas del Vero, obtuvo el premio Expansión 2018 i + emprendedor sostenible, que fue entregado por la ministra de agricultura.

5 Discusión

5.1 Implicaciones tecnológicas

La discusión, respecto a los sistemas de generación in situ de energía renovable no conectada a la red, se recoge en forma detallada en la sección 3 del artículo del compendio *"Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops"* [49]. En este documento se mencionan las implicaciones más generales.

Se han identificado características distintivas para el suministro energético al riego de cultivos mediterráneos, como la vid y el olivo. En primer lugar, se utilizan habitualmente sistemas de riego presurizados, como el riego por goteo, lo que requiere un suministro estable de potencia durante el funcionamiento de las bombas. Esto casi descarta el riego solar directo y aconseja disponer en el sistema de acumulación de energía a corto plazo, para la nivelación intradiaria.

En segundo lugar, la demanda de energía presenta un muy marcado perfil estacional, centrado en los meses de mayor irradiación solar. En consecuencia, la generación fotovoltaica resulta ser idónea, mientras que la eólica no lo es.

En tercer lugar, en los sistemas de riego con generación fotovoltaica, es muy relevante el horario de accionamiento del riego:

- Existe una considerable diferencia en la eficiencia del suministro fotovoltaico entre el riego diurno y el nocturno. En el diurno se necesita un menor tamaño de la batería y se producen menores pérdidas asociadas a su carga y descarga. En esa misma línea, la arquitectura con bus de alterna resulta ser la más eficiente para el sistema eléctrico.
- Se ha observado una relación inversa entre el número de horas de funcionamiento del bombeo de riego y el coste de la energía. Si esto se tuviera en cuenta al dimensionar el sistema de riego, la viabilidad económica del suministro fotovoltaico aumentaría.

- En función del horario de riego a lo largo del año, el ángulo de inclinación fijo óptimo de los paneles fotovoltaicos puede variar ampliamente. Una nueva línea de investigación podría abordar el efecto del perfil horario y estacional de la demanda en la inclinación fija óptima de los paneles.

Consecuentemente a todo lo anterior, en las nuevas instalaciones es conveniente efectuar el dimensionado conjunto del sistema de riego y la generación renovable. En caso de incorporar generación fotovoltaica en instalaciones de riego prexistentes, es conveniente conocer los horarios de funcionamiento.

La discusión relativa a las soluciones propuestas en el prototipo y sus resultados se recoge de forma detallada en la sección 4 del artículo del compendio *"Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case"* [43], así como en el artículo "*Combined production of electricity and hydrogen from solar energy and its use in the wine sector"* [50].

El conjunto de datos obtenido durante la operación de los prototipos permitirá abordar un nuevo estudio comparativo de los tres campos fotovoltaicos (estructura fija en suelo, seguidor solar y flotante en balsa), teniendo en cuenta el efecto de la temperatura debido a sus diferentes comportamientos térmicos.

En cuanto a la gestión de la energía en sistemas aislados de generación fotovoltaica, se han obtenido buenos resultados de la estrategia empleada.

Se ha mostrado la utilidad de combinar diversos consumos, obteniendo un perfil de la demanda agregada más cercano al perfil del recurso solar que los consumos considerados independientemente. No se puede inducir que esto suceda en todos los casos, pero resulta una posibilidad que merece ser estudiada durante el dimensionado en cada caso concreto. También ha resultado útil conocer las posibilidades de gestión de las diferentes cargas, tanto desde el punto de vista objetivo como desde los criterios de los usuarios. Esto confirma la utilidad de enfocar las necesidades energéticas de una actividad o sector económico concreto de forma holística, lo que permite hallar sinergias y establecer diseños de sistemas de energía renovable idóneos. En esta dirección, nuevos trabajos pueden abordar la incorporación de un modelo de control predictivo.

Uno de los avances obtenidos es la reducción de la acumulación necesaria en el corto plazo. En cuanto a la acumulación a largo plazo, dado que en este tipo de sistemas aislados existe energía excedentaria, la producción de hidrógeno permite derivar el excedente fuera del sistema para su aprovechamiento. El empleo de baterías de flujo como almacenamiento a largo plazo en sistemas aislados también es una opción a ser estudiada.

Finalmente, la discusión relativa al vehículo con pila de combustible se aborda en *"Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell"* [51].

Es de reseñar que el aprovechamiento de la energía excedentaria, en forma de hidrógeno, en un vehículo agrícola para transporte de personal, puede ser el antecedente de su futuro uso en maquinaria agrícola. Esto permitiría el suministro de energía de origen renovable y generada in situ a la maquinaria agrícola.

5.2 Implicaciones sectoriales

La discusión, en lo relativo al sector del vino, se recoge de forma detallada en la sección 4 del artículo del compendio *"Introduction of Renewable Energy in the Spanish Wine Sector"* [44]. En el presente documento únicamente se exponen sumariamente.

Más allá de la existencia de un amplio espectro de casos individuales, los tres grupos identificados presentan características que concuerdan con la experiencia práctica. En este estudio, se ha encontrado un desajuste importante entre la percepción favorable de los tomadores de decisiones con respecto a la energía renovable y su implementación real. Sin embargo, los resultados obtenidos pueden indicar algunas formas de fomentar la transición a las energías renovables en el sector del vino.

Primero, hay un porcentaje significativo de empresas (el Grupo I) que ya están dispuestas a incorporar energía renovable. Sin embargo, ese mercado aún no se ha activado en cantidad significativa. Muchas empresas consideran erróneamente que los costos de operación y mantenimiento de las energías renovables son altos. Además, incluso para el grupo más dispuesto, la inversión requerida representa una desventaja en comparación con las opciones de energía tradicionales.

En segundo lugar, un gran grupo de empresas (el Grupo II) cree que aún no es hora de cambiar a energía renovable y suponen que las tecnologías de energía renovable no han alcanzado un grado suficiente de madurez.

Por último, otro gran grupo de bodegas (el grupo III) no está interesado en las energías renovables. Esto no es extraño, dada la novedad de estas tecnologías y su distancia del núcleo de actividades y conocimiento de las bodegas.

Se ha identificado que la mayor barrera económica es la alta inversión inicial. En contraste, la falta de subsidios es la barrera económica más baja. La falta de una base de mercado suficiente y de un compromiso político, también se han reportado como altas barreras. Es razonable esperar que la innovación que supone la introducción de renovables en el sector sea liderada por las bodegas del primer grupo y termine modifique las percepciones de los otros dos. Además, la política ambiental y energética europea, así como la evolución del mercado, terminarán impulsando la transición incluso en ausencia de otras convicciones.

En resumen, puede afirmarse que, a pesar de que tanto en bodegas como en viñedos la transición a las energías renovables todavía no se ha producido, ya existen las condiciones para ello. Los principales frenos son la carencia de información y la financiación.

El conjunto de datos obtenido en las encuestas permitirá abordar nuevos estudios sobre la adopción por las bodegas españolas de medidas de mitigación y adaptación al cambio climático.

5.3 Futuras líneas de investigación

Tal como se ha indicado en las anteriores secciones 5.1 y 5.2, de los trabajos de la tesis derivan posibles futuros trabajos de investigación, que se presentan aquí agrupados:

- Efecto del perfil horario y estacional de la demanda en la inclinación fija óptima de los paneles fotovoltaicos.
- Estudio comparativo del rendimiento de los tres campos fotovoltaicos (estructura fija en suelo, seguidor solar y flotante en balsa) en relación a su diferente comportamiento térmico.
- Incorporación a la estrategia de gestión de la energía de un modelo de control predictivo.
- Empleo de baterías de flujo como almacenamiento a largo plazo en sistemas aislados.
- Suministro de energía de origen renovable y generada in situ a la maquinaria agrícola.

- La adopción por las bodegas españolas de medidas de mitigación y adaptación al cambio climático.

6 Conclusiones

La tesis ha abordado el suministro de energía renovable en áreas rurales, para actividades concretas en entornos no conectados a la red eléctrica. El estudio se ha desarrollado en el sector vitivinícola.

En una primera fase, se ha trabajado con seis casos de estudio de sistemas de riego de cultivos mediterráneos de viñedo y olivar. Mediante procesos de simulación y optimización, se han identificado los sistemas de generación económicamente óptimos. Se ha comprobado la idoneidad de la generación fotovoltaica y del diésel, solas o hibridadas. Por el contrario, la generación eólica no está presente en los mix óptimos. Se ha identificado la influencia del horario de accionamiento del riego y la conveniencia de utilizar la arquitectura de bus de alterna y de simultanear en lo posible la producción fotovoltaica y el consumo, reduciendo el tamaño de la acumulación y las pérdidas a ella asociadas. Se ha revelado la necesidad de efectuar un diseño individualizado para cada caso concreto, incluyendo el horario de riego. También se ha comprobado la influencia del horario de riego en la inclinación fija óptima de los paneles fotovoltaicos, lo que abre una nueva vía de investigación.

Ante la dificultad del suministro eficiente con generación aislada 100% renovable, en una segunda fase se ha propuesto un sistema de generación avanzado con enfoques novedosos. En este sentido, se ha abordado la integración de diversos consumos, la seguridad de suministro, la necesidad de sobredimensionado y el aprovechamiento de la energía excedentaria. Se ha diseñado, montado y operado un prototipo de sistema aislado de generación 100% fotovoltaica como caso demostrativo en un viñedo en el noreste de España (Barbastro, provincia de Huesca). El sistema alimenta de electricidad a la estación depuradora de aguas residuales de la bodega, los bombeos de elevación y riego y otros consumos auxiliares. Por una parte, la combinación de consumos cuya demanda presenta perfiles estacionales diferentes contribuye a acercar el perfil de la demanda agregada al del recurso solar. Por otra parte, se ha incorporado una estrategia de gestión de la energía que consigue un seguimiento fiel de la producción disponible, minimiza la necesidad de acumulación y sus pérdidas asociadas, y evita caídas del sistema por falta de energía. Adicionalmente, el prototipo utiliza la energía excedentaria para producir hidrógeno, mediante electrolisis del agua, que se almacena a alta presión para su extracción del sistema a través de una estación de repostaje. Para su utilización, se ha modificado un vehículo agrícola de transporte de personal, inicialmente eléctrico a batería, incorporándole una pila de combustible, depósitos de hidrógeno y el correspondiente sistema de control. Todo el conjunto ha sido operado durante más de un año a plena satisfacción de los usuarios. En el alcance del conocimiento del autor, se trata del primer sistema de producción in situ, aislado de la red, de energía renovable e hidrógeno para su uso en la propia explotación agrícola, tanto en usos estacionarios como en movilidad, en este caso en un viñedo. También se han recogido datos de funcionamiento que han permitido su análisis y su utilización en actuales y futuras investigaciones.

Adicionalmente, se ha llevado a cabo un estudio de la situación, perspectivas y actitudes de incorporación de energía renovable en el sector del vino español, que actualmente es escasa. Mediante encuestas a las empresas y su posterior tratamiento y análisis, se han identificado tres grupos de bodegas con diferentes actitudes ante la incorporación de energía renovable. También se han identificado las principales barreras y los posibles medios de acelerar dicha incorporación.

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Anexo 1 Cuestionario de sistemas de riego

Cuestionario sobre sistemas de bombeo para riego de vid

Fecha ________________________________

Nombre de la finca ____

Provincia _____________________________

Ubicación SIGPAC ____

Número de hectáreas regadas ____________ ha

Producción de Kg de uva por hectárea __________ kg/ha

Tipo de riego:

- □ Goteo
- □ Aspersión
- □ Manta
- □ Otros __________________

Procedencia del agua:

- □ Superficie por gravedad
- □ Superficie con bombeo (para salvar desnivel)
- □ Subterránea (pozo con bombeo)
- □ Otras __________________

Volumen anual de agua consumida en m^3/hectárea_____________ m^3/ha

Horario de riego (*posible respuesta múltiple)*

- □ Diurno
- □ Nocturno

En caso de marcar la opción nocturno. Si obtuviera la energía más barata por el día, ¿admitiría realizar riego diurno?

SI □   NO □

En general, programa las decisiones de riego:

- □ Diariamente
- □ Semanalmente
- □ Mensualmente
- □ Otras __________________

¿Puede indicar, de forma aproximada, cómo varía el riego a lo largo del año? Ponga una cruz en la casilla correspondiente a la columna de cada mes)

	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic
Máximo												
Medio												
Mínimo												
Nulo												

La energía para el bombeo la obtiene de:

- □ Red eléctrica
- □ Generador diésel
- □ Bomba diésel
- □ Desde el tractor
- □ Otras ___________________

Si utiliza suministro eléctrico a la red:

¿Ha revisado la facturación de energía reactiva con el fin de reducirla?

SI □

NO □

¿Ha revisado su potencia contratada con el fin de reducirla?

SI □

NO □

Si es posible, se ruega aportar copias de las facturas de electricidad del año 2013

Sí se aportan □

No se aportan □

¿Se suministra en baja tensión (230/400 V) o en alta tensión (> 1.000 V)?

BT □

AT □

¿Se llevó la línea eléctrica hasta allí expresamente para el bombeo?

SI □

NO □

Si es afirmativo ¿En qué año? _______________

¿Recuerda cuánto costó la extensión de red? _____________ €

Si utiliza generador diésel:

Potencia del generador _______ kVA

Consumo de gasóleo por hora ________ litros/hora

Consumo anual de gasóleo ______ litros o bien horas de funcionamiento anual _______ h

Otros costes de mantenimiento y averías ______________ €/año

Si utiliza bomba diésel:

Potencia de la bomba _______ CV

Consumo de gasóleo por hora _______ litros/hora

Consumo anual de gasóleo _______ litros o bien horas de funcionamiento anual ______ h

Otros costes de mantenimiento y averías ______________ €/año

¿De cuántas bombas se compone la instalación? _______________

Bomba nº______ *(repetir para tantas bombas como existan en la misma instalación de riego)*

Marque una cruz el tipo de bombeo y responda a las casillas blancas de la fila correspondiente:

Marca X	Tipo de bombeo	Desnivel (m)	Capacidad de la Balsa (m^3)	Profundidad de extracción (m)	Presión de descarga
	Superficie a				
	Pozo a balsa				
	Pozo a riego				
	Balsa a riego				

Potencia ______________ CV

Caudal de agua de la bomba ______________ m^3/hora

Tiene instalado variador de frecuencia SI □ NO □

Horas de funcionamiento al año __________________

Se acciona *(posible respuesta múltiple)* □ Día

□ Noche

Bomba nº______ *(repetir para tantas bombas como existan en la misma instalación de riego)*

Marque una cruz el tipo de bombeo y responda a las casillas blancas de la fila correspondiente:

Marca X	Tipo de bombeo	Desnivel (m)	Capacidad de la Balsa (m^3)	Profundidad de extracción (m)	Presión de descarga
	Superficie a				
	Pozo a balsa				
	Pozo a riego				
	Balsa a riego				

Potencia ______________ CV

Caudal de agua de la bomba ______________ m^3/hora

Tiene instalado variador de frecuencia SI □ NO □

Horas de funcionamiento al año __________________ horas

Se acciona *(posible respuesta múltiple)* □ Día

□ Noche

Anexo 2 Fotografías del prototipo

Figura 1. Vista aérea de la zona antes de la instalación del prototipo e indicación de los bombeos.

Figura 2. Vista aérea de la zona, después de la instalación de los prototipos. Se aprecian el conjunto de paneles solares flotante sobre la balsa, el conjunto fijo sobre el filtro de arena y el seguidor solar.

Figura 3. Zona de la balsa de aireación, antes de la instalación del prototipo.

Figura 4. Zona de la balsa de aireación, después de la instalación del prototipo.

Figura 5. Zona de la balsa de aireación, después de la instalación del prototipo.

Figura 6. Primer prototipo del soporte flotante para paneles fotovoltaicos.

Figura 7. Fase de montaje del conjunto flotante de paneles fotovoltaicos.

Figura 8. Vista cercana del conjunto de paneles flotantes.

Figura 9. Conjunto de paneles sobre suelo, antes de su conexión.

Figura 10. Fase de montaje del seguidor solar.

Figura 11. Fase de montaje de la caseta para los cuartos técnicos.

Figura 12.Balsa con paneles flotantes y aireador 2 en marcha.

Figura 13. Seguidor solar, vehículo y balsa con aireador 1 en marcha.

Figura 14. Cuarto técnico visto desde la cámara de vigilancia. Se aprecian los tres inversores solares (azules), los tres inversores de batería (amarillos), la batería, la ventana a la zona de producción de hidrógeno y el armario de control con pantalla táctil.

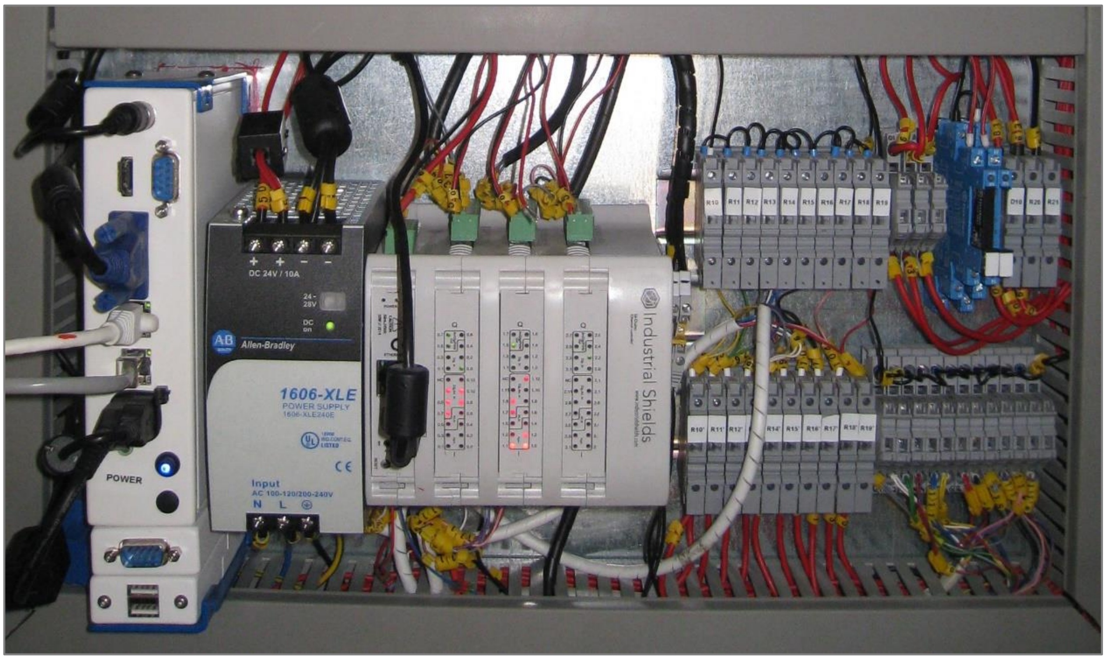

Figura 15.. De izquierda a derecha: Ordenador de control, fuente de alimentación, controlador lógico programable basado en Arduino.

Figura 16. Armario con variadores de frecuencia para los aireadores y las bombas de elevación y riego.

Figura 17. La zona de producción de hidrógeno. De izquierda a derecha: depurador de agua, electrolizador alcalino, depósito buffer a 20 bar, compresor hasta 200 bar.

Figura 18. Zona de repostaje para el vehículo: Depósito de hidrógeno hasta 200 bar y sistema de repostaje.

Figura 19. El vehículo eléctrico a batería, antes de su transformación

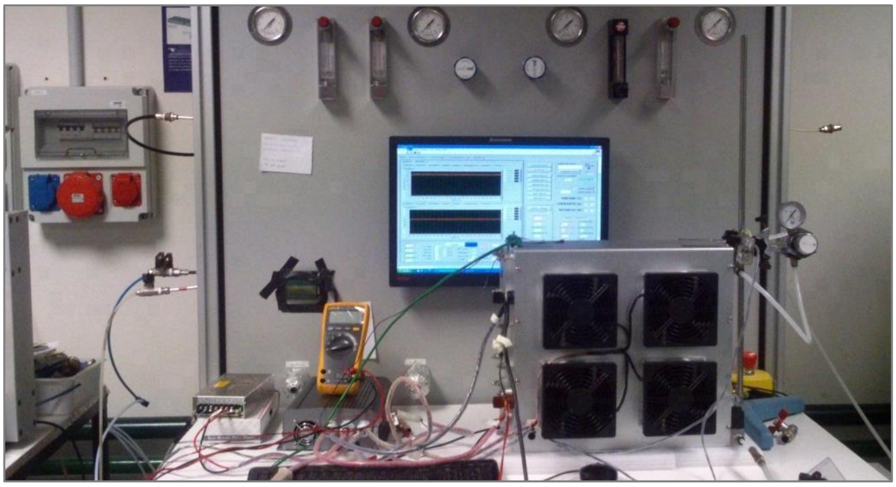

Figura 20. Pila de combustible en el banco de pruebas

Figura 21. El vehículo operativo en campo, una vez incorporada la alimentación por hidrógeno y pila de combustible

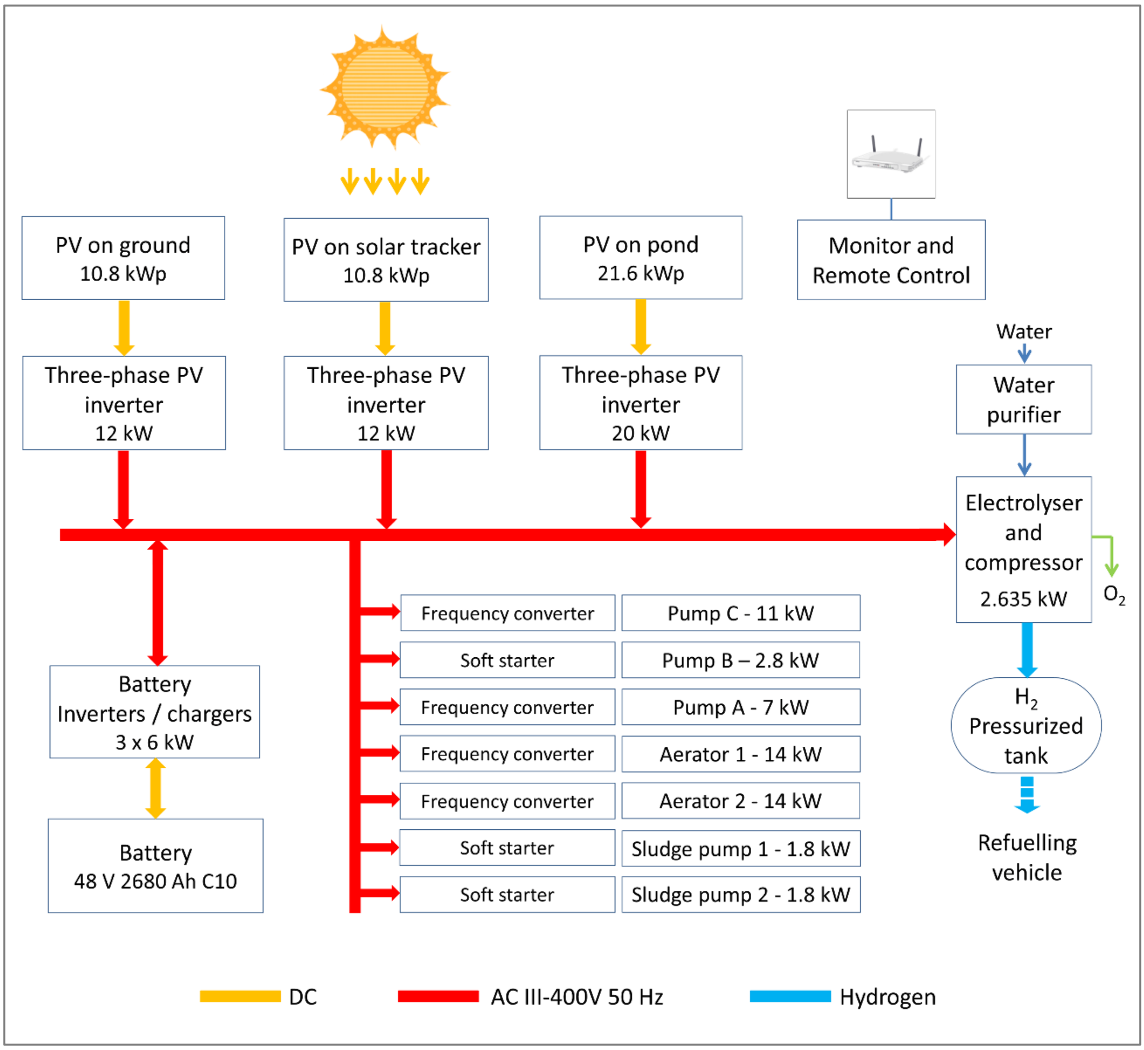

Figura 22. Esquema del sistema de energía

Figura 23. Vista general el día de la inauguración.

Anexo 3 Cuestionario de encuesta a bodegas

Cuestionario para la bodega

Este cuestionario forma parte de las acciones preparatorias del Proyecto LIFE+ REWIND, cofinanciado por la Unión Europea y coordinado por la Universidad de Zaragoza.

Los datos proporcionados se tratarán de forma confidencial por el personal de la Universidad de Zaragoza adscrito al proyecto, mediante análisis estadísticos agregados con fines de investigación.

Gracias por su colaboración.

*Obligatorio

Proyecto cofinanciado por la Unión Europea

Datos de identificación de la bodega

Nombre o razón social *

....

Municipio

....

Provincia *

....

Zona vitivinícola (nombre de la DO, IGP,...)

....

Año de constitución de la empresa

....

El accionista mayoritario es
Marque solo un óvalo.

- ◯ Una empresa
- ◯ Una persona física

Forma Jurídica

Marque solo un óvalo.

- S.L.
- S.A.
- Cooperativa
- Empresario individual
- S.A.T.
- Otro: ____________

Actividad de la bodega

1. Número de empleados (excluidos contratos eventuales)

____

2. Volumen de facturación anual de la bodega (euros)

____

3. Superficie construida total de la bodega (m2)

____

4. Indique el porcentaje que representa sobre el total de sus ventas, las distintas calidades diferenciadas del vino que produce y/o elabora

Denominación de Origen Protegida (D.O.P.) (%)

____

Indicación Geográfica Protegida (I.G.P.) (%)

____

Otros vinos embotellados (%)

____

Vino a granel (%)

____

5. Indique qué % de las ventas de la bodega se destina al mercado exterior

____

Actividad de la bodega

6. Indique si la bodega realiza otras actividades complementarias en las que utiliza sus recursos (superficie, edificios, máquinas, productos…) *

Marque solo un óvalo.

- Si
- No

Si ha contestado que realiza otras actividades complementarias

6.1. Señale las actividades complementarias realizadas (respuesta múltiple)
Seleccione todos los que correspondan.

- [ ] Turismo, alojamiento y otras actividades recreativas
- [ ] Artesanía
- [ ] Transformación y/o ventas de otros productos agrícolas (queso, conservas...)
- [ ] Producción de energía renovable para la venta (eólica, biogás, solar...)
- [ ] Otro: ....

6.2. Indique el % que representan estas actividades en el total de la facturación de la bodega en 2013
Marque solo un óvalo.

- ( ) Menos del 10%
- ( ) Entre 10% y 50%
- ( ) Más del 50%

Actividad de la bodega

7. Indique la producción total de vino, en hectolitros

....

8. Indique si la bodega utiliza uva procedente de viticultores con contrato estable, para elaborar su vino *

Marque solo un óvalo.

- ( ) Sí
- ( ) No

Si ha contestado que utiliza uva procedente de viticultores con contrato estable

8.1. Indique el número de hectáreas que proporcionan uva a la bodega vinculadas a viticultores con contrato

....

8.2. Indique si la bodega participa en su gestión durante el cultivo
Marque solo un óvalo.

- ( ) Sí
- ( ) No

Actividad de la bodega

9. Indique si la bodega utiliza uva procedente de una cooperativa *
Marque solo un óvalo.

- ( ) Sí
- ( ) No

Si ha contestado que utiliza uva procedente de una cooperativa

9.1. Indique el número de hectáreas que proporcionan uva a la bodega vinculadas a cooperativas

....

9.2. Indique si la bodega participa en su gestión durante el cultivo
Marque solo un óvalo.

- Sí
- No

Actividad de la bodega

10. Si la bodega compra uva, a viticultores sin contrato, indique el número de kilogramos que adquiere

....

11. Si la bodega compra mosto, indique el número de hectolitros que adquiere

....

12. Si la bodega compra vino, indique el número de hectolitros que adquiere

....

Política medioambiental

13. Indique si la bodega dispone de alguna certificación de vinificación ecológica
Marque solo un óvalo.

- Sí
- No

En caso de respuesta afirmativa, escriba cuál/es

....

14. Indique si la bodega tiene calculada la huella de carbono de su actividad o de sus productos

Marque solo un óvalo.

- Sí
- No

15. Indique si la bodega realiza auditorias energéticas
Marque solo un óvalo.

- Sí
- No

16. Para gestionar la política medioambiental, la empresa dispone de:
Seleccione todos los que correspondan.

- [ ] Un departamento de medio ambiente propio o del grupo empresarial
- [ ] Un técnico interno, propio o del grupo empresarial, dedicado a esta gestión
- [ ] Un técnico interno con otras funciones, pero que también se ocupa de la gestión medioambiental
- [ ] Un técnico externo/consultor
- [ ] Ningún recurso destinado a política medioambiental
- [ ] Otro: ______________________

Respecto a su actitud ante el cambio climático

17. El clima ha cambiado *
Valore en una escala de 0 a 10 su grado de acuerdo con esta afirmación
Marque solo un óvalo.

	0	1	2	3	4	5	6	7	8	9	10	
Totalmente en desacuerdo	○	○	○	○	○	○	○	○	○	○	○	Totalmente de acuerdo

18. Reducción de las emisiones de de CO2 *
Valore en una escala de 0 a 10 el grado de disposición de la bodega a reducir las emisiones de CO2 Marque solo un óvalo.

	0	1	2	3	4	5	6	7	8	9	10	
Ninguna disposición	○	○	○	○	○	○	○	○	○	○	○	Disposición total

19. Señale las medidas de mitigación del cambio climático o eficiencia energética YA ADOPTADAS por la bodega

Seleccione todos los que correspondan.

- [ ] Reciclaje
- [ ] Mejora de los aislamientos térmicos
- [ ] Reducción del peso (cajas, botellas, envases, embalajes…)
- [ ] Nuevos envases (bag-in-box….)
- [ ] Gestión más eficiente de los consumos (agua, electricidad, gasóleo…)
- [ ] Reducción de emisiones de los procesos
- [ ] Adquisición de maquinaria, instalaciones, vehiculos,…de bajo consumo
- [ ] Otro: ______________________

20. Señale las energías renovables que utiliza la bodega
Seleccione todos los que correspondan.

- [ ] Solar térmica
- [ ] Fotovoltaica para venta a red
- [ ] Fotovoltaica en autoconsumo
- [ ] Fotovoltaica aislada
- [ ] Eólica
- [ ] Biomasa producida en la propia explotación
- [ ] Biomasa comprada (pellets, etc.)
- [ ] Geotérmica
- [ ] Hidroenergía
- [ ] Otro: ....

21. La bodega está convencida de la necesidad de utilizar las energías renovables *
Valore en una escala de 0 a 10 su grado de acuerdo con esta afirmación
Marque solo un óvalo.

	0	1	2	3	4	5	6	7	8	9	10	
Totalmente en desacuerdo	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Totalmente de acuerdo

22. Valore en una escala de 0 a 10 su opinión sobre el gasto que supone implantar energías renovables*

Donde 0 es "Gasto muy reducido" y 10 es "Gasto muy elevado"
Marque solo un óvalo por fila.

	0	1	2	3	4	5	6	7	8	9	10
La inversión inicial	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Costes de operación	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Costes de mantenimiento	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

23. Valore en una escala de 0 a 10 su opinión sobre la importancia que tienen los siguientes aspectos para favorecer la adopción de energías renovables por parte de la bodega *
Donde 0 es "Nada importante" y 10 es "Absolutamente determinante"
Marca solo un óvalo por fila.

	0	1	2	3	4	5	6	7	8	9	10
Fiabilidad	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Sostenibilidad ambiental	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Existencia de subvenciones	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Impacto en la imagen	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Uso de energías no renovables

24. Indique el coste anual en 2013 en LA BODEGA de:

Electricidad (euros)

....

Gasóleo (diesel/gasoil) (euros)

....

Gas (euros)

....

25. Conocimiento de los costes energéticos asociados a la actividad *

Valore en una escala de 0 a 10 el grado de conocimiento de la bodega de sus costes energéticos

Marque solo un óvalo.

	0	1	2	3	4	5	6	7	8	9	10	
Desconocimiento absoluto	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Conocimiento exacto

26. Valore en una escala de 0 a 10 el grado de preocupación por los costes energéticos asociados a la actividad de la bodega

Donde 0 es "Totalmente despreocupado" y 10 es "Totalmente preocupado"

Marque solo un óvalo por fila.

	0	1	2	3	4	5	6	7	8	9	10
Evolución del coste de la electricidad	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Evolución del coste del gasóleo (diésel/gasoil)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Evolución del coste del gas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

27. Valore en una escala de 0 a 10 el grado de satisfacción respecto al uso de los siguientes tipos de energía para el desempeño de la actividad de la bodega (pueden entrar aspectos tales como: la fiabilidad del suministro, averias, atención de la empresa suministradora, problemas derivados de su uso, etc.)

Donde 0 es "Totalmente insatisfecho" y 10 es "Totalmente satisfecho".

Marque solo un óvalo por fila.

	0	1	2	3	4	5	6	7	8	9	10
Utilización de la energía eléctrica	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Utilización de gasóleo (diésel/gasoil)	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Utilización de gas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Uso y consumo de energía eléctrica

28. Indique de forma aproximada cómo varía el consumo de la bodega en electricidad a lo largo del año

Marque para cada mes la casilla que corresponda

Marque solo un óvalo por fila.

	Bajo	Medio	Alto
Ene	◯	◯	◯
Feb	◯	◯	◯
Mar	◯	◯	◯
Abr	◯	◯	◯
May	◯	◯	◯
Jun	◯	◯	◯
Jul	◯	◯	◯
Ago	◯	◯	◯
Sep	◯	◯	◯
Oct	◯	◯	◯
Nov	◯	◯	◯
Dic	◯	◯	◯

29. Indique si la bodega ha revisado su facturación de energia reactiva con el fin de reducirla
Marque solo un óvalo.

- Sí
- No

30. Indique si la bodega ha revisado su potencia contratada con la finalidad de reducirla
Marque solo un óvalo.

- Sí
- No

31. Indique si el contrato de suministro eléctrico de la bodega es en baja o en alta tensión
Marque solo un óvalo.

- En baja tensión (230/400 V)
- En alta tensión (>1.000 V)

32. Indique si la linea eléctrica se llevó hasta allí expresamente para alimentar la bodega
Marque solo un óvalo.

- Sí
- No

Calefacción y aire acondicionado

33. Indique si la bodega dispone de sistema de calefacción
Marque solo un óvalo.

- Sí
- No

34. Si dispone de sistema de calefacción, marque el tipo de energía que utiliza
Seleccione todos los que correspondan.

- [ ] Electricidad
- [ ] Gasóleo
- [ ] Gas
- [ ] Biomasa
- [ ] Otro: ____________________

35. Indique si la bodega dispone de aire acondicionado
Marque solo un óvalo.

- Si
- No

36. ¿La bodega tiene viñedos propios? *
Si la respuesta es afirmativa, usted seguirá con un cuestionario referido únicamente a la explotación vitícola
Marque solo un óvalo.

- Si
- No

Actividad de la explotación vitícola

37. Indique la producción anual de uva para vinificación (kg)

38. Indique la fecha de comienzo del periodo habitual de vendimia

Ejemplo: 15 de diciembre

39. Indique la fecha de finalización del periodo habitual de vendimia

Ejemplo: 15 de diciembre

40. Indique el número de hectáreas que posee de viñedos propios (ha)

41. Indique cuántas de esas hectáreas son de REGADÍO (ha)

Por regadío se entiende la existencia de un sistema de riego instalado de forma permanente

42. Indique si tiene algún otro cultivo diferente de la vid en 2013 *

Marque solo un óvalo.

- Sí
- No

Si ha contestado que tiene otro/s cultivo/s diferente de la vid

42.1. Indique el número de hectáreas totales que posee en otros cultivos

42.2. Indique, de las hectáreas dedicadas a otros cultivos, las que son de REGADIO

Actividad de la explotación vitícola

43. Indique los meses en los que riega
Seleccione todos los que correspondan.

- [ ] Enero
- [ ] Febrero
- [ ] Marzo
- [ ] Abril
- [ ] Mayo
- [ ] Junio
- [ ] Julio
- [ ] Agosto
- [ ] Septiembre
- [ ] Octubre
- [ ] Noviembre
- [ ] Diciembre

44. En caso de tener hectáreas de vid para vinificación de secano, indique si planea transformarlas en regadío *
Marque solo un óvalo.

- Sí
- No
- No tengo hectáreas de secano

Si ha contestado Sí, señale con las principales razones por las transformaría en REGADÍO sus hectáreas de secano

Razones por las que transformaría
Seleccione todos los que correspondan.

- [ ] Aumento de la producción de la uva
- [ ] Compensación de las variaciones anuales del clima y pluviosidad
- [ ] Mejora de la calidad de la uva
- [ ] Otro: ____________________

Si ha contestado No, señale con las principales razones por las que NO transformaría en REGADÍO sus hectáreas de secano

Razones por las que NO transformaría
Seleccione todos los que correspondan.

- [ ] Carencia de agua
- [ ] Costes energéticos elevados
- [ ] Ausencia de suministro eléctrico
- [ ] Microclima del viñedo
- [ ] Tipo de vino producido
- [ ] Problemas administrativos
- [ ] Conservación de tradiciones
- [ ] Otro: ....

Responsabilidad medioambiental

45. Indique si la explotación utiliza métodos de agricultura ecológica *
Marque solo un óvalo.

- ( ) Si
- ( ) No

Responsabilidad medioambiental

45.1. Indique si la explotación dispone de alguna certificación de agricultura ecológica*
Marque solo un óvalo.

- ( ) Sí
- ( ) No

En caso de respuesta afirmativa, escriba el nombre/es de la/s certificación/es

....

Responsabilidad medioambiental

46. Acciones para adaptarse al cambio climático *
valore en una escala de 0 a 10 el nivel de compromiso a medio plazo de la bodega para adaptarse al cambio climático
Marque solo un óvalo.

	0	1	2	3	4	5	6	7	8	9	10	
Ningún compromiso	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	Compromiso total

47. Señale las medidas de adaptación del cambio climático o eficiencia energética YA ADOPTADAS por la explotación vitícola

Seleccione todos los que correspondan.

- ☐ Puesta en regadío o aumento de los riegos
- ☐ Adelanto de las fechas de vendimia respecto a lo habitual
- ☐ Nuevas variedades de uva
- ☐ Cultivos en terrenos a mayor altitud
- ☐ Cambios en la arquitectura del cultivo
- ☐ Cubierta vegetal
- ☐ Otro: ....

48. Señale las energías renovables que utiliza la explotación vitícola

Seleccione todos los que correspondan.

- ☐ Biocombustible
- ☐ Fotovoltaica para bombeo
- ☐ Eólica para bombeo
- ☐ Produce Biomasa en la propia explotación
- ☐ Otro: ....

49. Indique qué hace la explotación con los restos de poda

Seleccione todos los que correspondan.

- ☐ Los incorpora al terreno
- ☐ Los quema
- ☐ Los recoge para utilizarlos como biomasa
- ☐ Los vende
- ☐ Otro: ....

Consumos de la explotación vitícola

50. Indique el número de sistemas de bombeo de riego independientes que posee la explotación

....

51. Indique el número de tractores que posee

....

52. Indique el número de vendimiadoras que posee

....

53. Indique el número de vehículos de transporte de personal que posee

....

54. Indique el número de calentadores y/o ventiladores contra heladas

....

55. Indique de forma aproximada cómo varía su consumo de gasóleo en maquinaria y vehículos a lo largo del año

Marque para cada mes la casilla que corresponda
Marque solo un óvalo por fila.

	Nulo	Bajo	Medio	Alto
Ene				
Feb				
Mar				
Abr				
May				
Jun				
Jul				
Ago				
Sep				
Oct				
Nov				
Dic				

56. Indique el consumo de gasóleo total de la explotación (euros)

57. De ese consumo total, indique qué porcentaje (%) corresponde a

Maquinaria agrícola

Bombeos de riego

58. Indique de dónde obtiene la energía para los bombeos (respuesta múltiple)

Seleccione todos los que correspondan.

- [ ] Red eléctrica
- [ ] Generador diésel
- [ ] Bomba diésel
- [ ] Desde el tractor
- [ ] Otro:

59. Indique si la explotación vitícola utiliza suministro eléctrico a la red *

Marque solo un óvalo.

- Si
- No

Consumos de la explotación vitícola

60. Indique si la línea eléctrica se llevó hasta allí expresamente para alimentar algún bombeo *

Marque solo un óvalo.

- Si
- No

Datos de la persona que rellena el cuestionario

Sexo
Marque solo un óvalo.

- ◯ Mujer
- ◯ Hombre

Edad

....

Cargo o función *

....

Años de experiencia en el sector

....

Formación
Marque solo un óvalo.

- ◯ Estudios primarios
- ◯ Estudios secundarios / FP
- ◯ Estudios universitarios

Formación agraria
Marque solo un óvalo.

- ◯ Experiencia agraria exclusivamente
- ◯ Estudios profesionales agrarios
- ◯ Estudios universitarios agrarios
- ◯ Otra formación agraria o cursos agrarios

Email de contacto *

....

Anexo 4 Pantallas del control y de datos

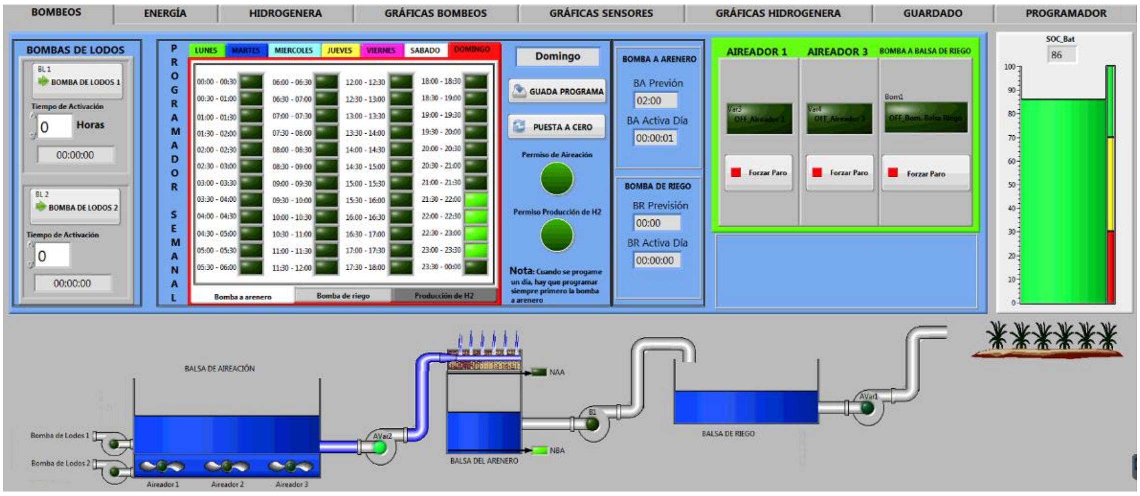

Figura 24. Pantalla de bombeos

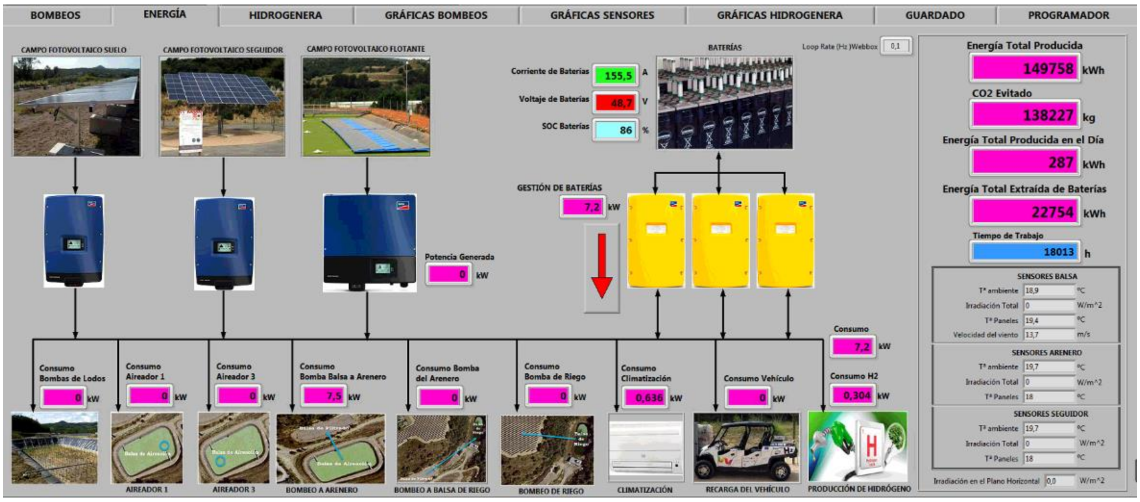

Figura 25. Pantalla de energía

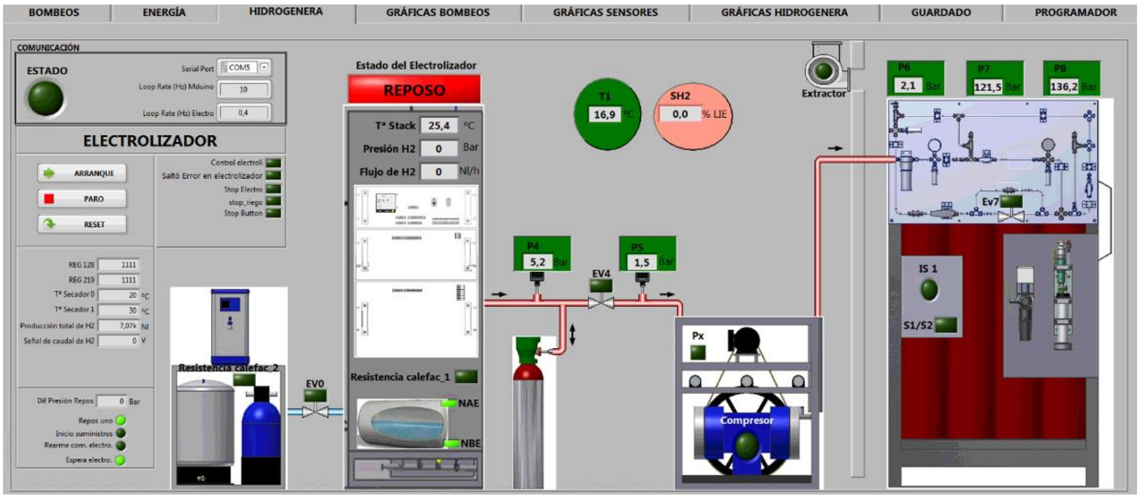

Figura 26. pantalla de la hidrogenera

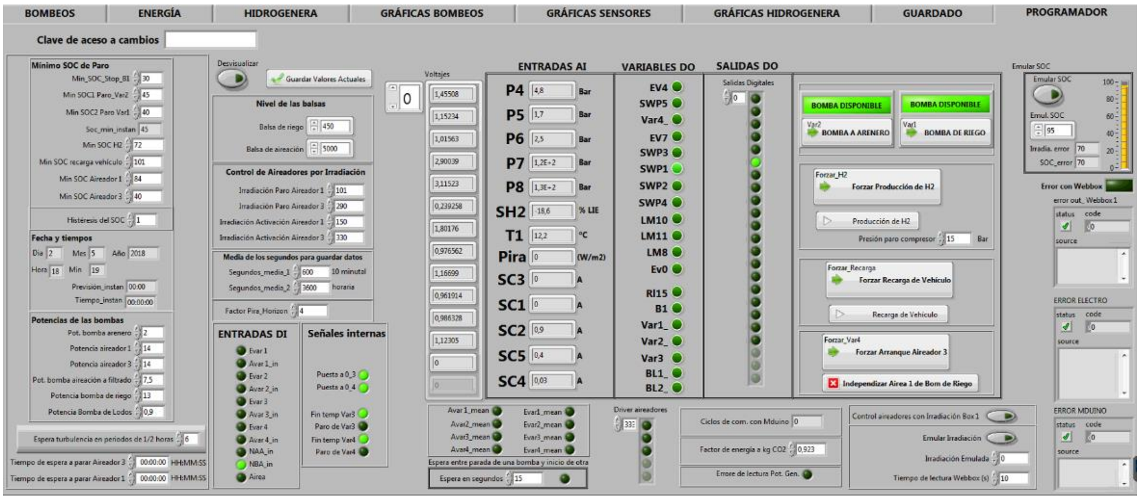

Figura 27. Pantalla del programador

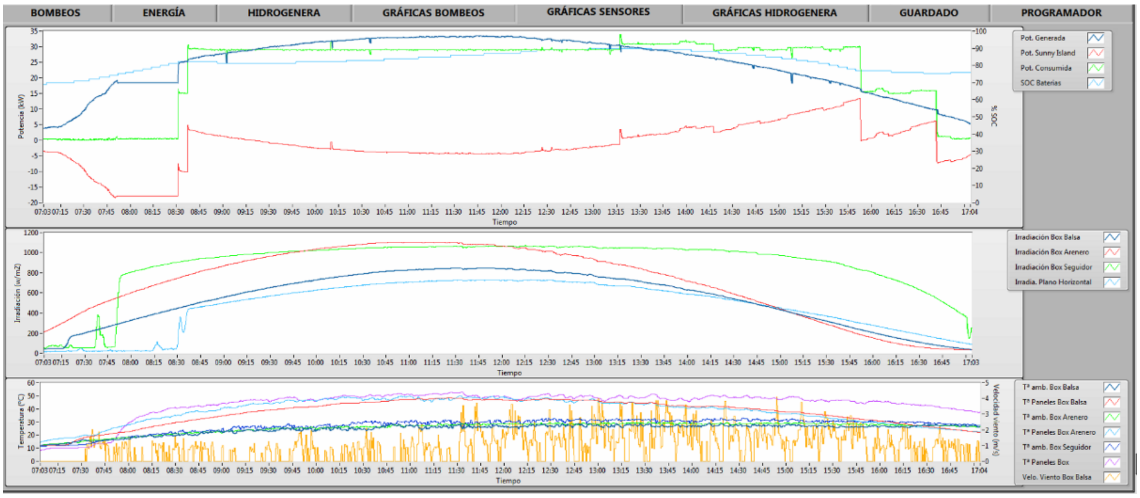

Figura 28. Pantalla de sensores (configurable)

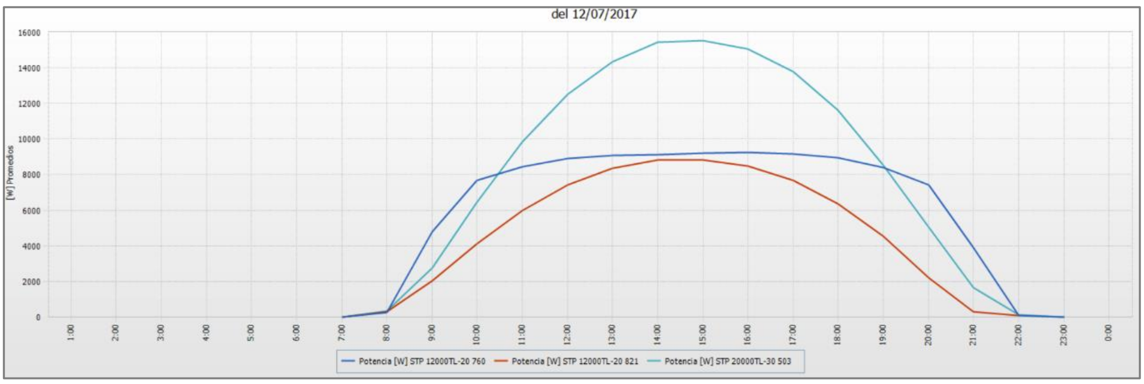

Figura 29. Gráficas de producción durante un día soleado (12/07/2017) de los tres campos fotovoltaicos: suelo (10 kWp), seguidor 10 (kWp) y flotante (20 kWp)

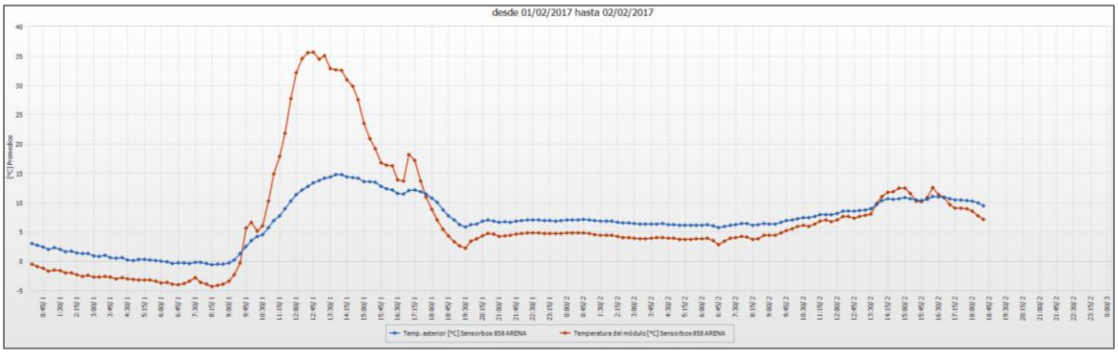

Figura 30. Gráfica de temperaturas ambiente y de los paneles de la estructura fija sobre el suelo

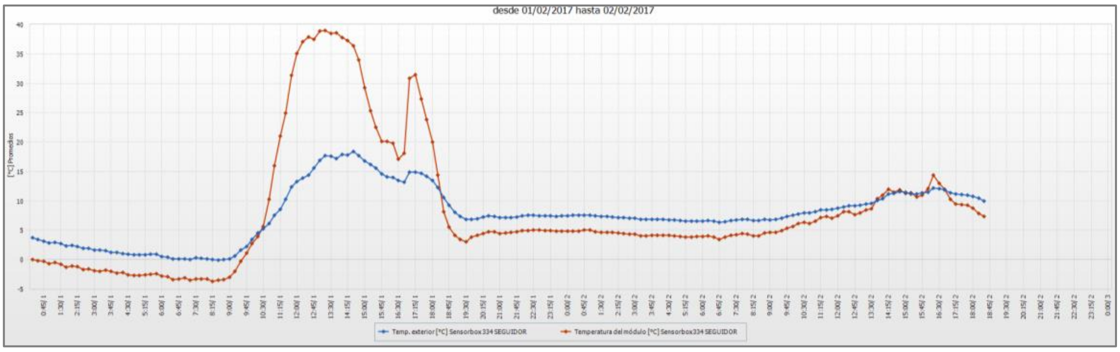

Figura 31. Gráfica de temperaturas ambiente y de los paneles del seguidor solar

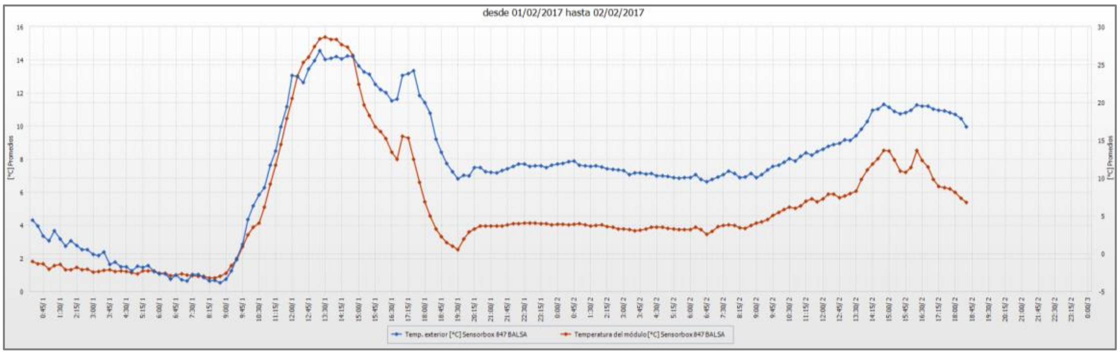

Figura 32. Gráfica de temperaturas ambiente y de los paneles flotantes sobre la balsa

TESIS

Sistemas de energía renovable en las áreas rurales: una demostración en el sector vitivinícola

V – APÉNDICE

Factor de impacto de las revistas

El compendio de publicaciones consta de cinco artículos publicados en revistas con índice de impacto JCR:

1. Carroquino, J.; Dufo-López, R.; Bernal-Agustín, J. L. Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops. Renewable Energy 2015, 76, 566–574, doi:10.1016/j.renene.2014.11.069.

   Revista: RENEWABLE ENERGY
   Factor de impacto 2015: 3,404 (Q2) *Subject Category: Energy and Fuels.*

2. Carroquino, J.; Roda, V.; Mustata, R.; Yago, J.; Valiño, L.; Lozano, A.; Barreras, F. Combined production of electricity and hydrogen from solar energy and its use in the wine sector. Renewable Energy 2018, 122, 251–263, doi:10.1016/j.renene.2018.01.106.

   Revista: RENEWABLE ENERGY
   Factor de impacto 2017: 4,900 (Q1) *Subject Category: Energy and Fuels.*

3. Roda, V.; Carroquino, J.; Valiño, L.; Lozano, A.; Barreras, F. Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell. International Journal of Hydrogen Energy 2018, doi:10.1016/j.ijhydene.2017.12.171.

   Revista: INTERMATIONAL JOURNAL OF HYDROGEN ENERGY
   Factor de impacto 2017: 4,229 (Q1) *Subject Category: Energy and Fuels.*

4. Garcia-Casarejos, N.; Gargallo, P.; Carroquino, J. Introduction of renewable energy in the Spanish wine sector. Sustainability 2018, 10, doi:10.3390/su10093157.

   Revista: SUSTAINABILITY
   Factor de impacto 2017: 2,075 (Q2) *Subject Category: Environmental Sciences.*

5. Carroquino, J.; Bernal-Agustín, J.-L.; Dufo-López, R. Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case. Sustainability 2019, 11, 951, doi:10.3390/SU11040951.

   Revista: SUSTAINABILITY
   Factor de impacto 2017: 2,075 (Q2) *Subject Category: Environmental Sciences.*

Contribución del doctorando

Contribución del doctorando en las publicaciones, conforme a *Contributor Roles Taxonomy* (CRediT) https://casrai.org/credit/ :

	Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops	Combined production of electricity and hydrogen from solar energy and its use in the wine sector	Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell	Introduction of renewable energy in the Spanish wine sector	Standalone Renewable Energy and Hydrogen in an Agricultural Context: A Demonstrative Case
Número del artículo	1	2	3	4	5
Conceptualization	Sí	Parcial			Sí
Data curation	Sí	Parcial		Sí	Sí
Formal analysis	Sí	Parcial			Sí
Funding acquisition	Sí	Sí	Sí	Sí	Sí
Investigation	Sí	Parcial		Sí	Sí
Methodology	Parcial	Parcial	Parcial		Sí
Project administration	Sí			Sí	Sí
Resources	Sí	Sí	Sí	Sí	Sí
Software					
Supervision	Sí			Sí	Sí
Validation					Sí
Visualization	Sí	Parcial			Sí
Writing - original draft	Sí	Parcial	Parcial	Sí	Sí
Writing - review & editing	Parcial	Parcial	Parcial	Sí	Sí