

UNIVERSIDAD POLITÉCNICA DE MADRID
ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA Y SISTEMAS DE
TELECOMUNICACIÓN



Development of a dehydration technical solution using photovoltaic heat pumps

DOCTORAL THESIS

Submitted for the degree of Doctor by:

Antonio Quijano González

Agricultural Engineer

Madrid, 2025



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**Doctoral Degree in Systems and Services Engineering for the
Information Society**

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Under the supervision of:
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To my family

Acknowledgement

I would like to especially thank my parents, who can witness how I continue the education they initiated and the passion for learning they instilled in me. I also want to thank my family for their support and for enduring the time I have taken away from them to work on this thesis. Lastly, I am deeply grateful to my advisors for their dedication, as they have been the driving force and support I needed to bring this work to completion.

Abstract

Work has been conducted on the design and implementation of a forage drying prototype for cold and humid climates, where spring and autumn cuts take longer to dry naturally, resulting in reduced product quality and delayed growth of the subsequent cut. The goal is to accelerate the drying process at the lowest possible cost. To date, industrial drying equipment relies on expensive fossil fuels, which contribute to pollution and decrease the profitability of the crop.

An economic evaluation has been conducted comparing three drying systems with different configurations: diesel-powered (DDS), grid-powered (GDS), and photovoltaic-powered (PVDS). The latter introduces significant technological innovations, including a standalone photovoltaic system (operating without batteries or grid support) and heat pump technology optimized to dry recirculated air, reducing electricity consumption by 52% compared to a diesel air heater or an electric resistance heater. Key performance indicators such as Profitability Index (PI), Internal Rate of Return (IRR), Payback Period (PBP), and Levelized Cost of Energy (LCOE) have been calculated. All indicators demonstrate good profitability across the three technologies (PI values range from 6.78 to 10.11, IRR values from 24% to 37%, and PBP between 3 and 4 years). However, PVDS offers clear economic advantages: its PI and IRR are over 40% higher, PBP is 25% shorter, and LCOE savings range from 40% to 47% compared to the other configurations.

The drying process has been characterized in terms of time and energy consumption. The PV system performance ratio (PR_{PV}), which evaluates the photovoltaic system's efficiency during periods when PV energy can be utilized by the heat pump unit, showed values of 0.82 and 0.85—comparable to a grid-connected PV system with good performance. Drying times ranged from 1 to 5 hours, and specific energy consumption per liter of water removed was between 0.7 and 1.46 kWh/l, comparable to traditional systems powered by diesel or grid electricity.

Overall, the PVHP drying technology has proven effective for drying alfalfa bales in a region with warm and humid climatic conditions, using 100% renewable energy and without the need for batteries. This technology offers economic savings of up to 40% in terms of LCOE compared to diesel-powered systems.

Resumen

Se ha estado trabajando en el diseño e implementación de un prototipo de secado de forrajes en climas fríos y húmedos, dónde los cortes de primavera y otoño, tardan en secarse de modo natural, reduciéndose la calidad del producto y retrasando del crecimiento del siguiente corte. Se busca acelerar el secado, con el menor coste. Hasta hoy, los equipos industriales de secado funcionan con costosos combustibles fósiles, contaminando y reduciendo la rentabilidad del cultivo.

Se ha realizado una evaluación económica comparando los tres sistemas de secado con diferentes configuraciones: diésel (DDS), red eléctrica (GDS) y alimentado por energía fotovoltaica (PVDS). Esta última, introduce importantes innovaciones tecnológicas (sistema fotovoltaico autónomo, sin baterías ni soporte de red) y con la tecnología de bomba de calor utilizada (optimizada para secar el aire recirculado, lo que reduce el consumo eléctrico un 52%, comparado con un calentador de aire a diésel o una resistencia eléctrica). Se ha calculado el Índice de Rentabilidad (PI), la Tasa Interna de Retorno (IRR), el Periodo de Recuperación de la Inversión (PBP) y el Costo Nivelado de Energía (LCOE). Todos los indicadores muestran buenas rentabilidades para las tres tecnologías (los valores de PI varían entre 6.78 y 10.11, los de IRR entre 24% y 37%, y los PBP están entre 3 y 4 años), pero el PVDS ofrece claras ventajas económicas: su PI y IRR son más de un 40% superiores, el PBP es un 25% más corto y los ahorros en LCOE, en comparación con las otras dos configuraciones, representan entre un 40% y un 47%.

Se ha caracterizado el proceso de secado en términos de tiempo y consumo de energía. El PR_{PV} , que evalúa el rendimiento del sistema fotovoltaico únicamente durante los periodos en los que la energía PV puede ser utilizada por la unidad HP, presentó valores de 0.82 y 0.85, comparables a los de un sistema fotovoltaico conectado a la red con buen rendimiento. Los tiempos de secado variaron entre 1 y 5 horas, y el consumo específico de energía por litro de agua extraída estuvo entre 0.7 y 1.46 kWh/l, comparables a los sistemas tradicionales alimentados por diésel y electricidad de red.

En términos generales, esta tecnología de secado PVHP ha demostrado ser efectiva para secar fardos de alfalfa en una región con condiciones climáticas cálidas y húmedas, utilizando energía 100% renovable y sin necesidad de baterías. Generando ahorros económicos de hasta un 40% en términos de LCOE en comparación con los sistemas alimentados por diésel.

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Abbreviations and Acronyms

Table 1: Nomenclature used in this document for referring to technical terms and variables (units are in brackets).

AM_n	Annual Amortization Cost [€/year]
CF_n	Annual Cash Flow [€/year]
$CAGR$	Compound Annual Growth Rate
COP	Coefficient of Performance of the Entire System [%]
DDS	Diesel-powered Drying System with air heater
D_p	Drying period
E_{AC}	AC energy delivered by the PV generator [kWh]
EUR	Energy Utilization Ratio [kWh/kg]
FC	Frequency Converter
$G(t)$	Global solar irradiance in the plane of the generator at a given moment [W/m ²]
G^*	Global solar irradiance in the plane of the generator at Standard Test Conditions [W/m ²]
G_{used}	G considering only the periods of time when the compressor is functioning [W/m ²]
G_{useful}	G considering only the periods of time when the PV power is within the power range of operation of the compressor [W/m ²]
Gd	Total daily irradiation received in the plane of the PV generator [Wh/m ²]
GDS	Grid-Powered Drying System with electric resistance
HP	Heat Pump
i	Interest rate [%]

<i>IEA</i>	International Energy Agency
<i>IIC</i>	Initial Investment Cost [€]
<i>IRR</i>	Internal Rate of Return [%]
<i>KPIs</i>	Key Performance Indicators
<i>LCOE</i>	Levelized Cost of Energy [€/kWh]
MER	Mean Drying Rate [gwater kg ⁻¹ h ⁻¹]
MPP	Maximum Power Point of the PV generator
<i>OM_n</i>	Annual Operation and Maintenance Cost [€/year]
<i>PBP</i>	Payback Period [years]
<i>P_{DC}</i>	DC power delivered by the PV generator [kW]
PLC	Programable Logic Controller
<i>P_{MPP}</i>	DC power of the PV generator at the MPP [kW]
<i>P_{MPP}*</i>	DC power of the PV generator at the MPP at STC [kW]
<i>P_n</i>	Annual Profit [€/year]
<i>PI</i>	Profitability Index [€/€]
<i>PR</i>	Performance Ratio [kWh/kWh]
<i>PR_{MPP}*</i>	Maximum PV Power Point at Standard Test Conditions [kWh/kWh]
<i>PR_{PV}</i>	<i>PR</i> considering only losses strictly associated to the PV generator itself (i.e., actual versus nominal peak power, dirtiness, thermal and DC/AC conversion losses) [kWh/kWh]
<i>PR_{PV,STC}</i>	<i>PR_{PV}</i> corrected to Standart Test Conditions [Wh/Wh]
PV	Photovoltaic
PVDS	Photovoltaic-powered Drying System with HP
<i>RH</i>	Relative Humidity [%]
<i>RH_i</i>	Initial relative humidity (before drying) [%]
<i>RH_f</i>	Final relative humidity (after drying) [%]
SAHP	Solar-assisted heat pump drying systems

SMER	Specific Moisture Extraction Rate [kg/kW h]
STC	Standard Test Conditions ($G^*=1,000$ W/m ² , $T_c=25^\circ\text{C}$)
t	Corporate tax rate [%]
T_c	Cell temperature of the PV generator [$^\circ\text{C}$]
T_c^*	Cell temperature of the PV generator at STC [$^\circ\text{C}$]
UR	Utilization Ratio of the PV system [kWh/kWh]
UR_{Dp}	UR that reflects the energy losses associated to the Dp [kWh/kWh]
UR_{PV-HP}	UR that reflects the energy losses associated to the operating power ranges of the drying system [kWh/kWh]
UR_{EF}	UR that reflects the energy losses associated to the behaviour of the end-user of the system [kWh/kWh]
USD	<i>United States Dollar</i>
V_{MPP}	DC voltage of the PV generator at the MPP [V]
V_{MPP}^*	DC voltage of the PV generator at the MPP at STC [V]
Vol_W	Volume of water extracted during the drying test [l]
β	Coefficient of variation of the open circuit voltage of the PV module with T_c [$\text{V}/^\circ\text{C}$]
γ	Coefficient of variation of the maximum power of the PV module with T_c [$\text{W}/^\circ\text{C}$]
$\eta(G)$	Efficiency of the PV generator at the given G [W/W]
η^*	Efficiency of the PV generator at STC [W/W]
μ	Average Thermal Efficiency [%]

1. Introduction

1.1. The Industrial and Agricultural Drying Market

The drying market, both in agricultural and industrial fields, plays a crucial role in the preservation, processing, and transportation of a wide variety of products such as grains, fruits, vegetables, wood, industrial materials, and pharmaceuticals. Drying is a key step in many production chains, particularly in sectors like food, pharmaceuticals, chemicals, and energy, making it a vital economic and strategic activity.

In the food sector, examples include drying grains and cereals to prevent mold growth, drying fruits like apples and grapes to produce dehydrated fruits, and dehydrating products like powdered milk in the dairy industry. In industrial manufacturing, drying materials such as plastics, paper, and chemicals are critical to ensuring their stability and final quality. In the chemical industry, drying pharmaceuticals and industrial catalysts is essential for productive efficiency.

It is estimated that the industrial drying market accounts for approximately 15% of the total energy consumption of the global manufacturing industry. In specific sectors like food and beverages, this figure can reach up to 20% due to the need for prolonged thermal processes [1].

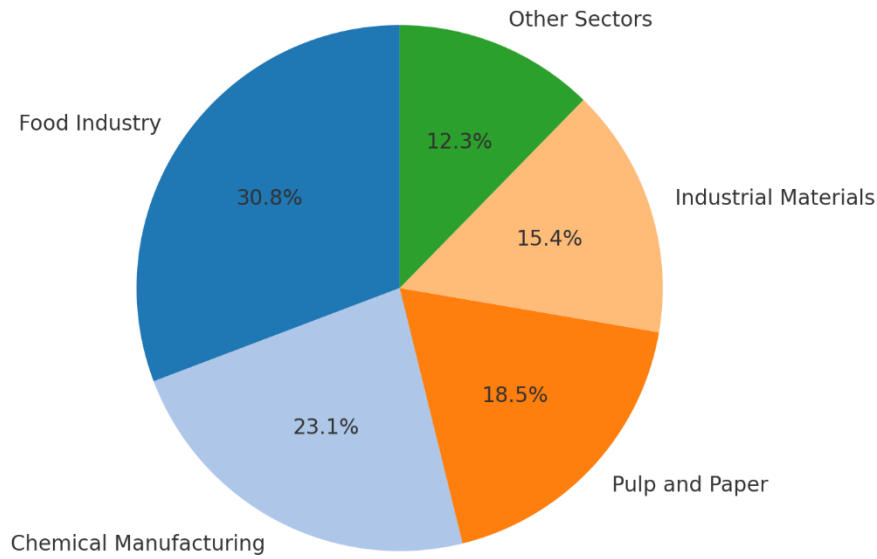


Figure 1: Percentage of energy consumption associated with drying processes in various industries [1].

The global industrial drying market has been growing for several decades. Recent reports suggest that the global market for drying equipment is expected to reach USD 7 billion by 2025, with a compound annual growth rate (CAGR) of 4.2% [2]. This demand is driven by the need to optimize production and reduce product losses in various industries. Particularly, the global agrifood industry dedicates a significant portion of its budget to drying processes to prevent the spoilage of perishable products and maintain quality.

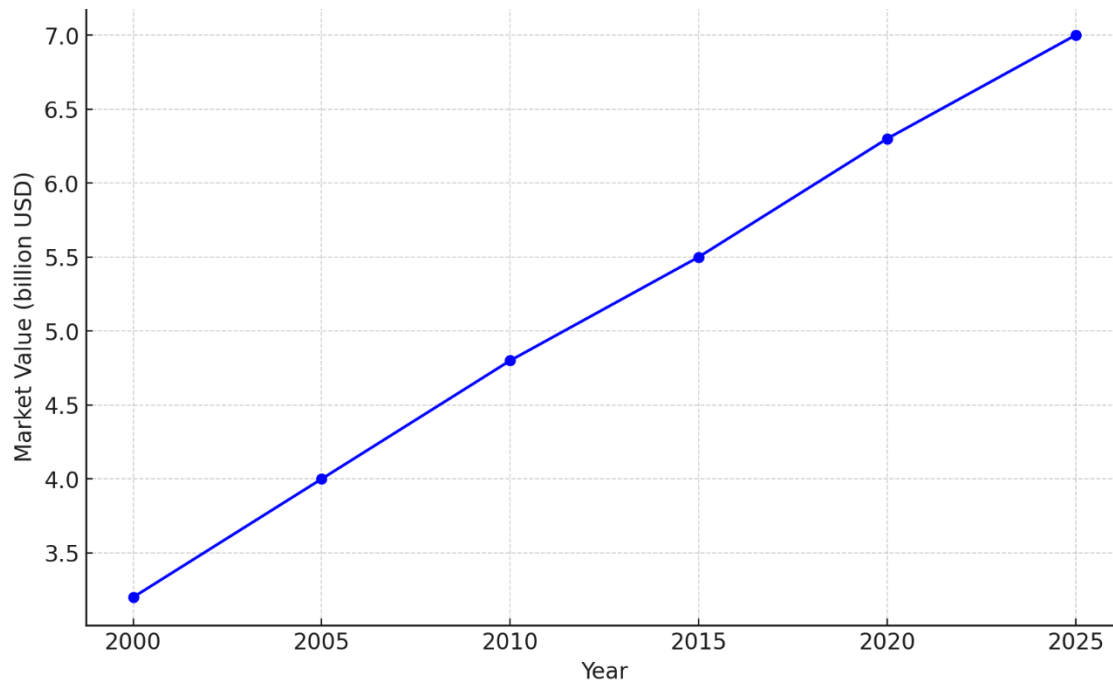


Figure 2: Growth of the global drying market (2000–2025) [2].

Major players in the drying market are concentrated in industrialized countries with strong agrifood production. The United States leads the global market with approximately 25% market share due to its robust presence in the agrifood and manufacturing industries [3]. China, with a 20% share, has experienced rapid growth due to its industrial and agricultural expansion. In Europe, Germany and France jointly account for 15% of the European drying market thanks to their technological development and innovations in energy-efficient systems. Spain plays a significant role in sectors such as agrifood and ceramics, contributing approximately 5% to the European market. Finally, regions like Latin America and Southeast Asia are gaining importance due to increased production capacity and greater demand for efficient and sustainable drying systems.

However, one of the greatest challenges of the drying market is the high energy consumption associated with the process. It is estimated that 10% to 25% of global industrial energy consumption corresponds to drying operations, representing a significant cost both economically and environmentally (Source: IEA, 2022). For example, in food drying processes, the required thermal energy can account for up to 15% of total operational costs. The predominant use of fossil fuels for heat generation (estimated at 75% of the thermal energy used in industrial processes) exacerbates energy dependency and contributes to greenhouse gas emissions. According to the International Energy Agency (IEA), the industry emits approximately 8.4 billion tons of CO₂ annually, of which 20%

to 30% comes from industrial thermal processes, including drying. This highlights the urgency of implementing innovative solutions to reduce greenhouse gas emissions.

1.2. The Case of La Rioja and the Potential of Alfalfa Cultivation

La Rioja, one of Spain's smallest autonomous communities (but ranked seventh in terms of GDP per capita), has experienced significant changes in the use of its agricultural land over recent decades. These changes have been driven by economic, technological, and political factors that have transformed both traditional crops and the adoption of new farming practices. Specifically, irrigated crops have expanded considerably thanks to favorable climatic conditions and improved irrigation infrastructure, largely funded by European public financing.

Historically, La Rioja's agricultural landscape has been dominated by vineyards, which enjoy worldwide renown for producing high-quality wines. However, in irrigated areas, crops like sugar beet and maize have played a key role in diversifying the agricultural economy. During the 20th century, irrigation became a decisive factor in improving the productivity of these plants, especially in the Ebro Valley regions, where climatic and soil conditions favor the development of intensive crops.

However, some of these crops have become less economically viable in recent years, limiting their production. Sugar beet, primarily grown for sugar production, peaked in the second half of the 20th century. During this period, the cultivated area reached 4,000 hectares in La Rioja. However, this figure has drastically decreased to less than 1,000 hectares by 2020 due to the liberalization of the European sugar market and competition from other producing countries [4]. Similarly, maize, which was once considered a profitable crop due to high demand for animal feed and biofuels, reached a peak cultivated area of 3,500 hectares in the 1990s. Currently, this figure has dropped to less than 1,200 hectares due to rising production costs, intensive water consumption, and the volatility of international prices [5].

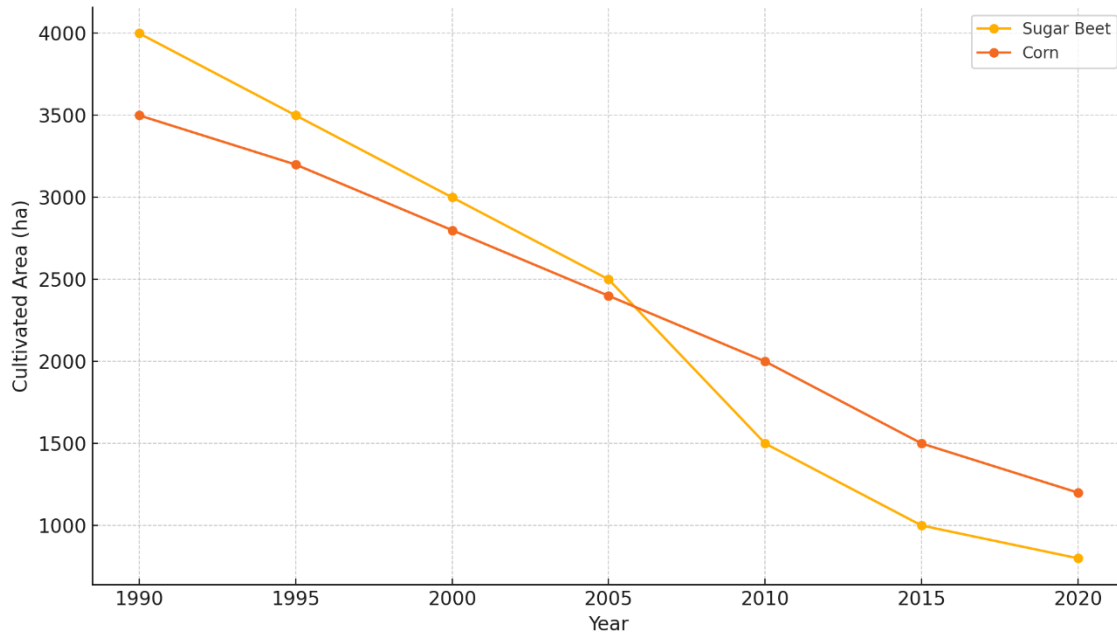


Figure 3: Evolution of sugar beet and maize cultivation areas in La Rioja (2000–2025) [5].

Faced with this scenario, some farmers are exploring alternatives like alfalfa, an irrigated crop with significant potential for profitability and sustainability. Alfalfa, being a perennial crop, requires less soil tillage and can help improve soil fertility due to its ability to fix nitrogen. Additionally, its demand is growing both in domestic and international markets due to its use as high-quality forage in livestock farming [6].

Alfalfa is highly valued for feeding racehorses and livestock farms, particularly in milk and meat production, where it is an essential feed due to its high protein content and its ability to improve animal health. In Spain, dehydrated alfalfa exports have increased considerably in recent years, reaching nearly 1.5 million tons annually, with an average annual growth rate of 10%. The main international destinations include Saudi Arabia, the United Arab Emirates, and China, where demand has surged due to the expansion of their livestock sectors and the need for high-quality forage. This increase in exports has positioned Spain as the world's second-largest exporter of alfalfa, accounting for approximately 15% of the global market, with a total value of €400 million annually (with a selling price ranging from €200 to €250 per ton) [7].

Alfalfa cultivation is not only a profitable option but also offers high added value for farmers, as it allows them to diversify their income, reduce costs associated with fertilizer use, and contribute to the sustainability of their farms. In this

regard, focusing on alfalfa could position La Rioja as a key region in the production of quality forage, meeting both national market demands and the growing requirements of the international market.

1.3. The Problem of Dehydration

Dehydration of alfalfa is an essential process for its large-scale commercialization due to its numerous benefits. Alfalfa, as forage, is highly nutritious and constitutes one of the main feed sources for livestock worldwide. However, its high natural moisture content presents serious logistical and economic challenges for transportation and storage for two main reasons: the significant weight of the product and the risk of fermentation, which can cause temperature increases. Such temperature rises may lead to fires, which are extremely difficult to extinguish once they start. For example, in 2023, a fire in an alfalfa warehouse in Zaragoza, Spain, resulted in the loss of approximately 400 tons of product. With a selling price ranging from €200 to €250 per ton, it is easy to deduce that these accidents represent a serious economic problem.

Dehydrating alfalfa before storage and transportation emerges as an effective solution to these challenges but also brings certain drawbacks that must be considered.

Beyond the safety considerations related to fermentation, one of the main benefits of dehydrating alfalfa is the extension of its shelf life. By reducing its moisture content, the risk of microorganism growth, such as mold and bacteria, which could degrade the product, is minimized. Additionally, the process concentrates nutrients, resulting in a more compact product that is easier to transport. This is particularly advantageous for export markets and for meeting international demands where dehydrated alfalfa is used as an ingredient in balanced rations for high-performance animals.

Another significant advantage is the uniformity of the final product. Industrial dehydration allows standardization of moisture levels and forage quality, ensuring buyers receive a homogeneous product, which facilitates commercialization and increases its market value.

However, this process also has drawbacks. Firstly, dehydration costs can be high. The use of specialized equipment and energy consumption represents a significant investment, potentially limiting accessibility for small-scale producers. According to the European Commission, the average cost of

dehydrating one ton of alfalfa ranges between €50 and €70, depending on the technology used and energy prices [8]. Additionally, energy consumption is considerable: industrial dehydration processes may require up to 1,000 kWh per ton of processed product.

Indeed, among the main processes required for alfalfa commercialization—primarily baling, drying, and pellet processing (for sales in this format)—drying is the most expensive in both energy and economic terms [9].

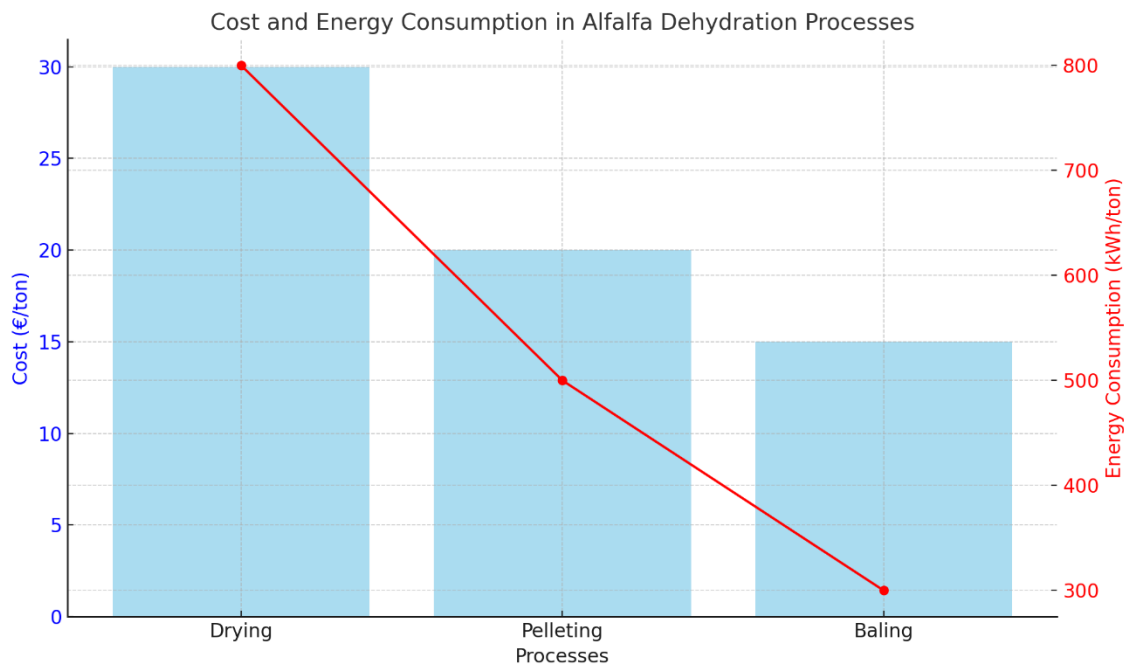


Figure 4: Economic cost and energy consumption of the main processes for alfalfa dehydration [9].

Another aspect to consider is the environmental impact. Large-scale alfalfa dehydration requires significant energy, often derived from fossil fuels, contributing to greenhouse gas emissions. This has raised questions about the sustainability of the process and the need to explore more environmentally friendly alternatives. For example, CO₂ emissions associated with dehydration can reach up to 300 kg per ton of processed product [10].

In conclusion, alfalfa dehydration is a key tool for optimizing its commercialization, especially in international markets. However, the economic and environmental costs associated with this process must be carefully managed to ensure the benefits outweigh the drawbacks. The search for more sustainable

and efficient technologies will be crucial for the future of the dehydrated alfalfa industry.

1.4. Objectives and Motivation of the Doctoral Thesis

Given the context described in this introduction, this doctoral thesis aims to solve the specific problem of alfalfa dehydration (its high energy and economic costs) by developing innovative technology. The goal is to encourage its production in regions like La Rioja, where other irrigated crops are losing profitability, and alfalfa substitution offers significant added value for producers. Finally, the market potential of the solution developed extends beyond alfalfa dehydration, addressing the broader drying market, a major energy consumer with a high environmental impact.

The dominant dehydration technology today is the use of high-temperature drum dryers powered by diesel or biomass generators. This technology is highly energy-intensive, leading to high operating costs. As an alternative, this doctoral thesis proposes a dehydration technology based on heat pumps powered exclusively by photovoltaic generators, without relying on the grid or batteries. Heat pumps, leveraging the characteristics of the thermodynamic cycle, utilize ambient thermal energy, reducing electrical consumption by a factor of 3 to 6, depending on the system's COP. Additionally, the heat pump technology used in this work is not the standard type aimed at cooling/heating air but is optimized specifically to dry air (removing relative humidity) with low electrical consumption. Furthermore, photovoltaic technology has demonstrated cost reductions in electricity supply of between 60% and 80% in its application to water pumps. Here, it will be applied to heat pumps, reducing electricity costs and enabling alfalfa drying to be 100% renewable.

Therefore, the general objective of this thesis is the development of a photovoltaic-powered heat pump dehydrator prototype for validating its technical feasibility and exploring its economic viability. This general objective is broken down into the following specific objectives:

- **Development of alfalfa dehydrators** that combine heat pump technology with photovoltaic technology for 100% renewable dehydration. This aims to address the specific problem of alfalfa dehydration.

- **Making alfalfa cultivation viable** by integrating the added value of dehydration, commercialization, and export through the installation of photovoltaic dehydrators. This seeks to boost the economy of farmers in regions like La Rioja, where other irrigated crops have lost profitability and can be replaced with high-value-added alfalfa.
- **Demonstration and widespread dissemination of this innovative technology** by installing a prototype in real operating conditions. This aims to extend its use to other regions and applications requiring some type of drying, not just forage dehydration.

2. State of the art

2.1. Classification of systems

In Figure 5, a diagram is presented in which drying systems are classified based on the energy source and the technology they utilize:

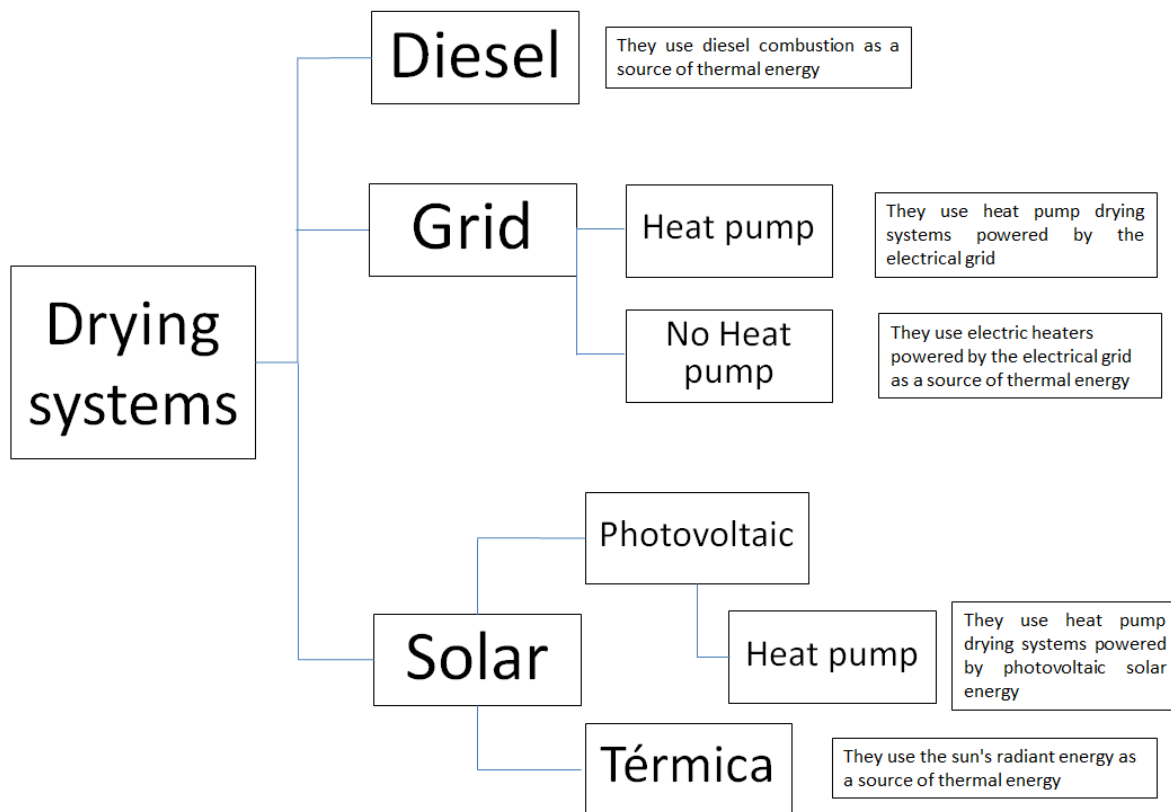


Figure 5: Diagram of drying systems by energy source and technology.

Diesel drying systems

The most commonly used configuration for forage drying relies exclusively on diesel as the energy source to heat the drying air and simultaneously power an electricity generator for the turbine, as well as the process control and monitoring components. This system is particularly viable in areas with limited access to the electrical grid or in facilities without sufficient contracted power to operate the turbine. The cost of contracted power is significant and annual, whereas drying

needs are typically seasonal or intermittent. Figure 6 show a diagram of this drying system with a diesel power source:

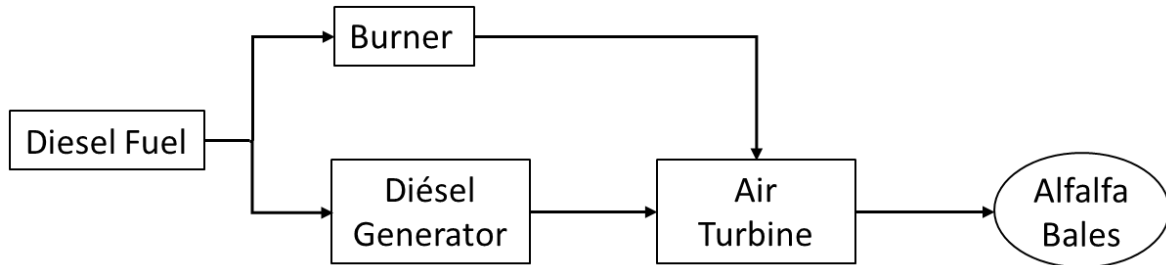


Figure 6: Diagram of drying systems with exclusive diesel energy source.

A variation of this configuration is to power the turbine using the electrical grid, with diesel being used exclusively to heat the air for drying. Figure 7 shows the diagram of a drying system in which the air is heated with diesel and propelled using electrical grid energy:

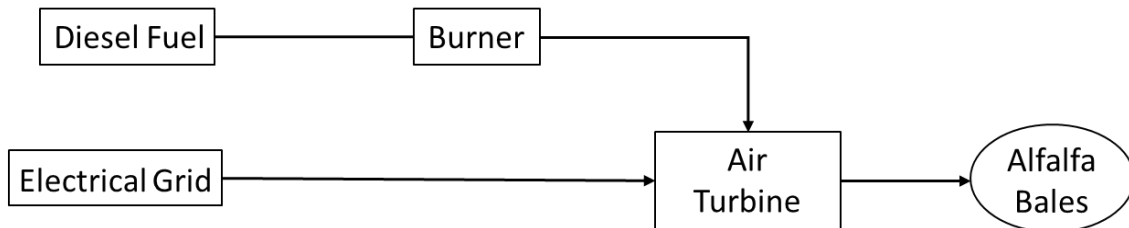


Figure 7: Diagram of drying systems with diesel power source for generating hot/dry air and electrical grid for air propulsion.

In drying systems powered by diesel energy sources, items are selected based on their use of heat energy derived from diesel combustion, either through direct heating of the fluid or by using heat exchangers to transfer thermal energy to the fluid that comes into contact with the product being dried. This study does not consider systems that utilize heat released by the exhaust gases of diesel engines used for other processes, as these are cogeneration supplements whose primary purpose is not drying.

Drying Systems Connected to the Grid

These systems use the electrical grid to power electric resistances and heat pumps, which heat/dry the air that is then propelled by a turbine, also powered by the electrical grid. Figure 8 and Figure 9 show that in the case of heat pumps, the air may be recirculated or not.

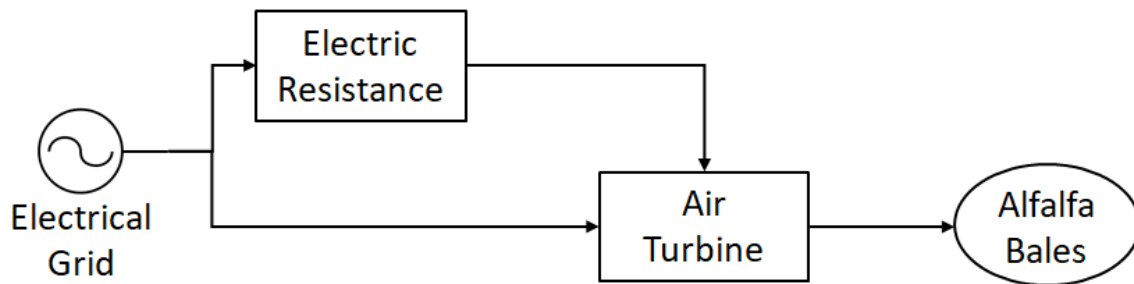


Figure 8: Diagram of drying systems exclusively powered by the electrical grid, using electric resistance.

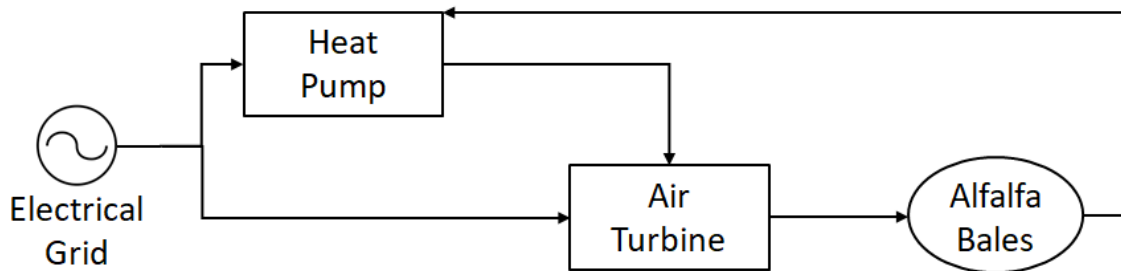


Figure 9: Diagram of drying systems powered by the electrical grid to generate hot/dry air with a heat pump and to propel the air using grid electricity.

These systems benefit from the stability of the energy source, allowing continuous drying processes. However, they are subject to fluctuations in energy prices and variations based on tariff periods. Additionally, they require a contracted power reserve, which incurs a fixed cost for equipment amortization. The significant price fluctuations in electricity in recent times have disrupted amortization projections. Another advantage of this system is that electricity does not generate waste in the facility, making the drying process clean and free from contaminants during operation. Furthermore, automation is simpler since sensors and controllers require a continuous and stable energy source, and standardized solutions are readily available with grid electricity.

Solar-Powered Drying Systems

The oldest drying systems used solar thermal energy, employing convection to circulate air through the product being dried, releasing moisture-laden air afterward. Simultaneously, the solarization of the product prevented spoilage during the process. To improve air circulation, turbines were added, which could force the air through the products. These turbines can be powered by various energy sources. Figure 10, Figure 11, and Figure 12 illustrate the studied systems that use solar thermal and photovoltaic energy as power sources.

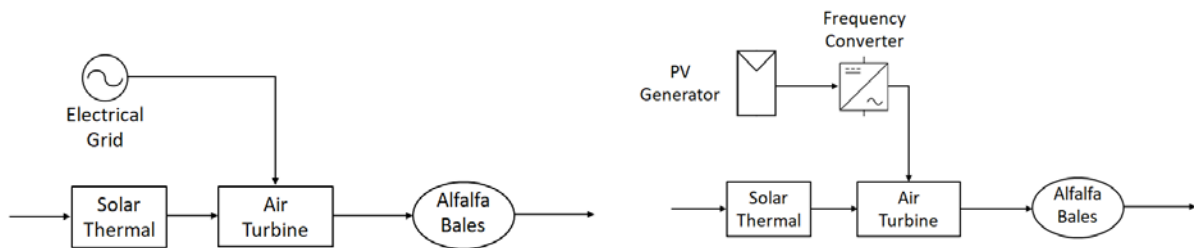


Figure 10: Diagram of drying systems powered by solar thermal energy and supplemented by the electrical grid or photovoltaic solar energy.

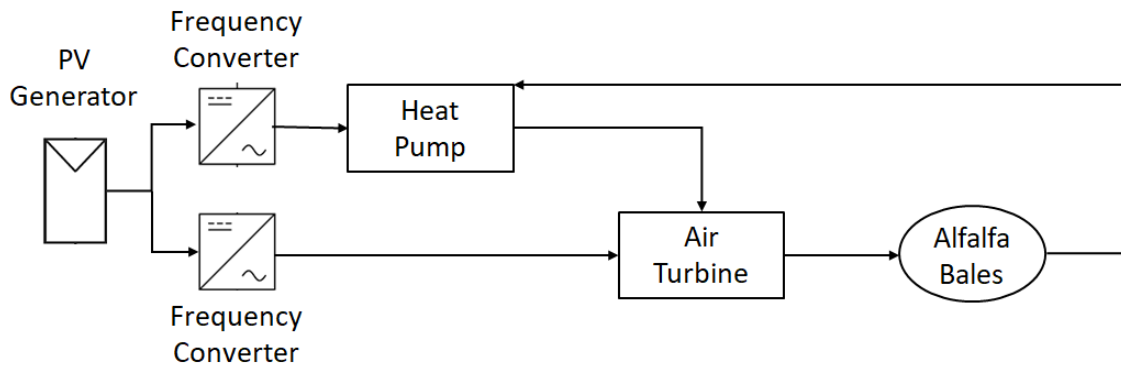


Figure 11: Diagram of drying systems exclusively powered by photovoltaic energy.

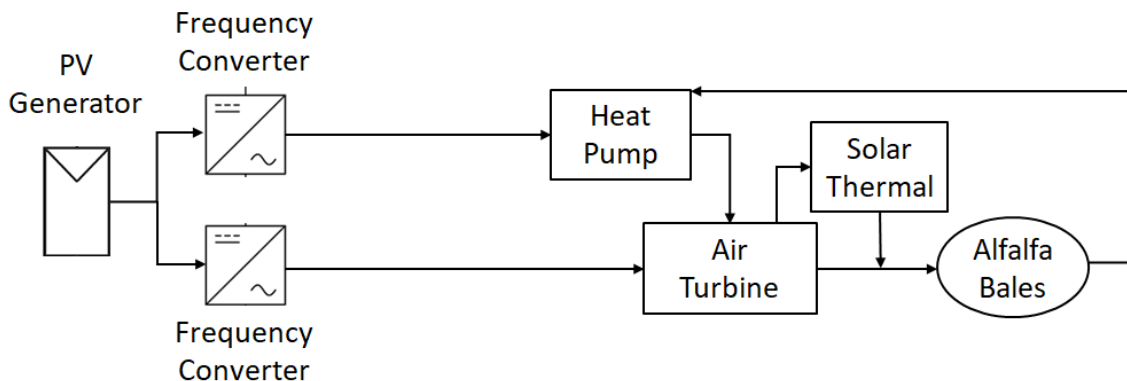


Figure 12: Diagram of drying systems powered by solar thermal and photovoltaic energy.

In Figure 12, systems are schematized that power the heat pump and air turbine using photovoltaic energy while complementing the fluid (air) temperature increase with a solar thermal collector. This collector contributes heat when sufficient solar radiation is available. When the photovoltaic generator's size and solar radiation provide the minimum power required to start the drying equipment, the drying process begins and stops when this power falls below the defined minimum threshold.

One improvement introduced to this system in this thesis is the regulation of the power demand based on available solar radiation, allowing adaptation to the available radiation. This optimization reduces the necessary photovoltaic generator size and lowers implementation costs by designing a generator tailored to drying power requirements. A second improvement is that the system has been made independent of other energy sources or storage systems, making it highly versatile with low implementation and operational costs.

This thesis explores a technological solution enabling drying systems with heat pumps to operate autonomously using photovoltaic energy without batteries. The literature review found no existing technological solutions that enable autonomous operation without batteries or thermal energy storage, with self-regulation according to energy availability and drying demand. Reported benefits include higher energy efficiency, independence from other energy sources requiring investment and contracted power, and cost stability since it depends only on equipment amortization, maintenance costs, and workload.

The primary contribution of this study is the synergy that this autonomous system offers for drying needs and surplus photovoltaic energy in agricultural environments, where photovoltaic energy is already used for irrigation water pumping.

2.2. Definition of KPIs

Definition of the Key Performance Indicators (KPIs) identified:

- **Coefficient of Performance of the Entire System (COP):** This is the ratio between the thermal power output and the total power input of the equipment. Units: % or per unit.

$$COP = \frac{\sum Q}{\sum W}$$

Where Q is the power output from the heat pump as heat or cooling, and W is the electrical power supplied to the equipment.

- **Average Thermal Efficiency (μ):** Refers to the amount of heat transferred from one fluid to another compared to the amount of heat/cooling that would have been achieved under perfect transfer conditions.
Effectiveness = (Actual Heat Transferred) / (Maximum Heat Transfer).
Units: % or per unit [1].

$$\mu t = \frac{\int_{t_1}^{t_2} Q}{\int_{t_1}^{t_2} Es} \times 100\%$$

Where t_1 and t_2 are the operation times, Q is the total useful output energy, and Es is the total energy received.

- **Specific Moisture Extraction Rate (SMER):** This is the amount of moisture removed per unit of energy consumed. Units: kg/kW h.

$$SMER = \frac{m}{\sum W}$$

Where m is the mass of water extracted.

- **Energy Utilization Ratio (EUR):** The amount of electrical energy consumed per unit of water obtained. Units: kWh/kg or per unit.

$$EUR = \frac{\sum W}{m}$$

- **Payback Period (PBP):** The time required to recover the initial investment.
Units: years.
PBP = Initial Investment / Average Cash Flow Outcome.
- **Mean Drying Rate (MER):** This is the rate at which each unit of water is extracted relative to the total product. Units: gwater kg⁻¹ h⁻¹ or kgwater kg⁻¹ h⁻¹.

2.3. Selected articles

The articles identified that address the thesis topic have been categorized in the following table based on the framework in Figure 5, considering their energy sources, whether they involve an experiment or a simulation, the drying duration, and the system's size based on its power.

<u>ARTICLE</u>	<u>ENERGY SOURCE</u>	<u>EXPERIMENTAL / SIMULATED</u>	<u>STUDY TIME</u>	<u>SYSTEM SIZE</u>	<u>OBSERVATIONS</u>
[11]	Diesel	Experimental	72 h	4220 MJ G	
[12]	Thermal S. / Diesel	Experimental	24 h	sd P	
[13]	Thermal S.	Experimental	24.5-40.5 h	sd P	
[14]	Thermal S. / Photovoltaic S.	Experimental	24 h	sd P	
[15]	Thermal S.	Experimental	3 h	sd P	
[16]	Thermal and Photovoltaic S. / Heat Pump Grid	Experimental	12 h	sd P	
[17]	Thermal S. / Grid	Experimental	24 h	sd P	
[18]	Thermal S. / Photovoltaic S.	Experimental	6 h	sd P	
[19]	Thermal S. / Photovoltaic S.	Experimental	6.5 h	sd P	
[20]	S. / Heat pump Grid	Experimental	24 h	sd P 1hp	
[21]	Thermal S. / Photovoltaic S.	Experimental	7 h	sd P	Refrigerated panel
[22]	Thermal S. / Heat Pump Grid	Experimental		sd P	Bibliographic Review
[23]	Heat Pump Grid	Simulated	18 h	sd P	
[24]	Heat Pump Grid / Thermal System	Experimental	34 h	24 kW medium	
[25]	Heat Pump Grid	Experimental		sd P	Bibliographic Review
[26]	Heat Pump Grid / Thermal System	Experimental	16 h	sd P	
[27]	Heat Pump Grid	Experimental	7.5 h	3.89 kW small	

[28]	Heat Pump Grid	Experimental		64.14kWE. 244.5kWT.	
[29]	Heat Pump Grid / Thermal System	Experimental	5.5 h	sd P	
[30]	Heat Pump Grid	Experimental		16 kW M	
[31]	Heat Pump Grid / Thermal System	Experimental	9 h	sd P	
[32]	Heat Pump Grid	Simulated	8 h	sd P	
[33]	Heat Pump Grid / Thermal System	Experimental	1 h	sd P	
[34]	Heat Pump Grid	Experimental	11 h	sd P	Gasoline generator
[35]	Heat Pump Grid / Thermal System	Experimental	11 h	130.2 kW thermal	
[36]	Heat Pump Grid / Thermal System	Experimental	11 h	sd P	
[18]	Thermal S. / Photovoltaic S.	Experimental	7 h	sd P	
[37]	Thermal S. / Heat Pump Grid	Experimental	216 h	4.12 kW T 1.2 kW E	
[38]	Thermal S. / Heat Pump Grid	Experimental	1 h	10 kW M	Support with wind energy
[39]	S. Photovoltaic / Heat Pump	Experimental	720 h	10 kW M	Support with wind energy
[40]	Thermal S. / Heat Pump Grid	Experimental	132 h	sd P	
[41]	Thermal S.	Simulation	3 h	sd P	Exhaust gases
[42]	Thermal System / Photovoltaic System / Heat Pump				Bibliographic Review
[43]	S. Photovoltaic / Heat Pump	Experimental	144 hours	sd P	

Table 2: Selected items with their technology, experimental or simulated nature, drying duration, and power. sd = not determined, P = small power, M = medium power, G = large power, S = Solar (power), E = Electric (power).

ARTICLE	(COP)	average thermal efficiency(μ)	(SMER)	(EUR)	Payback period (PBP)	Average Drying Rate (MER)
[11]						219.54 g water kg ⁻¹ h ⁻¹
[13]		66.79 to 96.09%				
[14]		53.51 %				
[15]	12.5	73.7%				2.53-102 g water/g dry matter.min
[16]		68-84%,				
[18]			0.275 kg/kW h			
[19]		43.75%				
[20]	1.96-2.28	16%-79%	0.03 kg/kW h- 0.46 kg/kW h	0.19 - 0.48		
[21]	4.18	56.37%				
[22]						Bibliographic Review
[23]	5.5summer 4.5winter				1.22 years	
[24]					7.5 years	
[25]	1.94 and 5.338		0.156 to 9.25 kg/kWh		1.6 and 3.6 years	
[26]			14.68 ± 0.02 to 0.13 (g/g)		3.67 SD, 4.95 SCD and 2.98 HPD, years,	
[27]			1.63 kg/kWh			
[28]	4.54		4.25 kg/kWh	4.69kWh/kg	1.5 years	
[29]		29.1%	0.44 kg/kWh	4.69kWh/kg		8.34 kg/s
[30]			3.07 kg/kWh			43.8 kg/h.
[31]	3.26	39.3%				
[32]			2.15-2.27 kg/kWh			0.66 - 0.75 kg/h
[33]			0.19 - 0.24kg/kWh	8.85, 5.81 and 3.04kWh/kg		
[34]			1.19 kg/kWh, 1.18 kg/kWh 1.05 kg/kWh			
[35]	5.03		1,934 kg/kWh			
[18]			0.275 kg/kW h			
[37]	4.77-8.34	51-74%				2.62-3.08 kg/h
[38]					12.9 years	71.42 kg/h
[39]			2.2 kg water/kWh			
[40]	3.91 and 7.2		4.24-8 kg/kWh			11.23-14.32 kg/h
[43]	5,338		0.041- 16.4kg/kWh			

Table 3: Selected articles with their most representative KPIs.

2.4. Discussion of results

Most representative KPI coefficients

The most commonly used coefficient is the **Coefficient of Performance of the Entire System (COP)**, which generally indicates the efficiency of energy conversion in the equipment. It is used in eleven articles, with values ranging from 1.94 [15] to 12.5 [15], with the most typical values being between four and five units. This coefficient allows for the comparison of equipment that converts electrical energy into thermal or cooling energy and is widely standardized among manufacturers and installers of such systems. However, for drying or dehumidification processes, it needs to be complemented with the **SMER** (Specific Moisture Extraction Rate) to specify the level of efficiency or energy consumption of the drying equipment.

SMER was reported in sixteen articles, with values ranging from 0.03 kg/kWh [20] to 16.4 kg/kWh [43]. However, the latter value decreases significantly in the first hour of drying to 3.077 kg/kWh and in the second hour to 0.52 kg/kWh, rapidly dropping to levels similar to those obtained in the experiments conducted in this thesis. The most characteristic values are 1–2 kg/kWh. The experiments reported higher values during periods of higher outdoor air temperatures, such as summer [21], or when a thermal storage unit was included [13]. The **EUR** (Energy Utilization Ratio) is also valid in this context, as it considers efficiency in the inverse sense but allows for similar evaluations. EUR values range from 0.19 kWh/kg [20] to 8.85 kWh/kg [33], with the four reports found averaging 4–5 kWh/kg. The highest value corresponds to a solar dryer with biomass, while the lowest is for heat pump equipment.

It is noteworthy that articles utilizing solar thermal energy as the primary or auxiliary energy source report the highest COP values: 12.5, 8.34, and 7.2 in [44], [37], [40], respectively. This is because the solar energy contribution is not considered as energy consumed by the equipment in the COP calculation.

In articles using heat pumps, COP values of approximately 4 or 5 are reported [21] [28] [35], which is expected for this technology. However, other articles report lower values, between 1 and 2 [20], [25] associated with different locations and ambient temperatures.

A parameter useful for the preliminary sizing of drying systems is the Mean Drying Rate (MER), which indicates the drying speed without considering

equipment efficiency, power, or energy consumption. Eight reports were found in the selected articles, with values ranging from 0.66 kg/h [22] to 8.34 kg/s [45]. This parameter is heavily influenced by the size and technology of the drying system, providing an idea of drying potential but not enabling direct comparisons between different studies.

The highest drying rate is observed in a system capable of drying 420 kg of product in 6 hours, using outdoor equipment supplemented with a biomass furnace, heat pump, solar collector, air blower, and product handling equipment. The lowest drying rate corresponds to a laboratory setup with a maximum capacity of 20 kg of static product to dry, featuring a 279 W compressor and 2.2 kW fans. In summary, MER is not a comparable parameter across different dimensions or drying technologies.

To assess the efficiency of the equipment, the Average Thermal Efficiency (μ) is used. Eleven reports were found, with values ranging from 16% [10] to 96.09% [13], with typical values of 50–60%. Alongside this coefficient, the Payback Period (PBP) is used to evaluate investment feasibility. The reported PBPs range from 1.22 years [23] for a simulated serial dryer using heat pumps, to 12 years [38], which involves a high moisture removal rate using renewable energy but with high implementation costs, resulting in a longer PBP.

The reported **Average Thermal Efficiency (μ)** ranges from 16% [20] to 96.09% [13], with an average of 55%, highlighting the importance of standardizing coefficients. The minimum efficiency values (16%) correspond to drying products with a small specific surface area in contact with the airflow (e.g., tomatoes and strawberries) in a winter trial conducted in Turkey, under low irradiance and with minimal energy contribution from the photovoltaic generator (below expected standard conditions) [20]. The maximum values, on the other hand, are from a trial with thermal energy storage, enabling continuous drying, conducted under summer conditions in Morocco [13].

Solar energy equipment

Studies on drying equipment utilizing solar thermal energy are more abundant, as this is a long-standing system and a renewable energy source. Nowadays, these systems have become significantly more advanced due to improvements in solar thermal energy collectors, fluid drivers, and overall system efficiency. Additionally, the rising costs of fossil fuels and electricity have increased the

demand for renewable energy solutions. These drying systems typically consist of either sun-exposed chambers or thermal collectors that heat a fluid—usually air—which is then brought into contact with the product to be dried. In some cases, the air is released to the exterior (open chamber), partially released (semi-open chambers), or dehumidified and recirculated in a closed-loop cycle.

Solar systems are generally classified into photovoltaic and thermal categories. In some cases, solar drying is supplemented by heat pumps [46] [47] [48]. Typically, experimental drying equipment includes a solar collector, a drying chamber, and a fan to force air circulation. The heat pump cools the air in the evaporator, causing water extracted from the product to condense from the recirculating or external air. The air is then reheated in the condenser, enhancing its moisture absorption capacity before being exposed to the product for drying.

In other studies, photovoltaic generators are used to supply electricity to the fans. In other studies, photovoltaic generators are used to supply electricity to the [44] [49] [50] [19] [51] [52] [53] [54], aiming to make drying equipment independent of the electrical grid. A few studies investigate powering the entire drying system with photovoltaic energy. In one case, a dryer with electric resistances supported by solar thermal energy and powered by photovoltaics was studied, achieving a drying time reduction to one-third of what it would have been using only solar thermal energy [55]. In another case, air was heated using electric resistances, and a dehumidifier was added to the closed-cycle air, allowing for air recirculation. This system was patented in Taiwan in 2005 [17].

Regarding photovoltaic systems, the focus is on heat pump-based drying equipment. Among approximately 45 recent articles, around 15 are relevant to this study as they involve food and plant leaf drying. However, no experimental studies were found on heat pump drying systems that exclusively use photovoltaic energy or battery storage. One possible challenge in developing this technology without a backup energy source could be the difficulty of modulating the equipment to adapt to variations in solar radiation.

One study conducted a mathematical simulation of a heat pump drying system powered by photovoltaic energy [41], emphasizing key parameters that enhance efficiency, such as air velocity, drying temperature, and relative humidity [56]. Another study focused on the optimal compressor frequency and heat exchanger dimensions to optimize drying parameters [57].

Grid-Connected Equipment

In the published articles on drying equipment powered by grid electricity, few focus on systems using electric resistances to heat the fluid in contact with the product to be dried [58]. Most of the articles, however, describe systems employing heat pumps to reduce the water content in the fluid. All of these systems use electricity to power fans that drive air toward the drying products. Energy studies on alfalfa cultivation highlight that the highest energy consumption occurs in the use of electricity [59], concluding that the largest potential savings also lie in reducing electrical consumption [60]. While the past two decades have seen a prolific number of publications, only 1% of the 463 articles reviewed addressed topics related to drying forages or food using grid-connected equipment other than heat pumps. In one case, a study examined a grid-connected infrared-assisted drying system [61], finding that the hybrid solar-infrared system was approximately 11% more efficient than a purely solar system. It also achieved better acceptability of samples in terms of color and texture. Among these studies, the most commonly used performance coefficient is the average thermal efficiency, with values ranging from 53% [62] to 84% [15].

Comparative studies between drying systems using electric resistances and heat pumps [63], document that heat pump drying is more efficient, reducing energy consumption by almost two-thirds (2.76 times lower).

In grid-connected heat pump systems, numerous studies investigate drying performance across various heat pump configurations and types. This includes examining the effect of having an open, semi-open, or closed drying chamber [64] [65], with findings indicating that an open system is more efficient in Tanzania. Other studies focus on the temperature difference between the evaporator and the condenser, recommending minimizing this difference [66]. The feasibility of adding an auxiliary condenser has also been explored, demonstrating that this can help increase the air flow temperature [67].

Research on the type of refrigerant used [68] [69], concluded that R717 offers the best energy performance, whereas R1234yf results in the shortest drying time and the lowest product drying cost. Some studies examine the combination of solar energy and heat pumps for drying, evaluating improvements in performance and reductions in electrical consumption [70]. Solar-assisted heat

pump drying systems (SAHP) are now considered a well-established solution [71] [22].

In-depth reviews on the use of heat pumps for drying agricultural products [25] show that the coefficients of performance range from 1.94 to 5.34, while the specific moisture extraction rate varies from 0.156 to 9.25 kg/kWh. These systems significantly reduce energy consumption by up to 80%. Nutritional composition and color analysis reveal that heat pump dryers retain maximum nutrient content while enhancing product color.

The expansion valve has the lowest exergoeconomic factor (a measure of the relative contribution of fixed costs to the total cost overruns in the equipment [72]) among all components of heat pump dryers. In contrast, the compressor has the highest exergy destruction cost overall. Technical and economic analyses show that most heat pump dryers have short payback periods, ranging from 1.6 to 3.6 years.

Diesel Drying Equipment

The forage drying equipment found in industrial and private facilities primarily operates on diesel or petroleum derivatives. However, there are few articles discussing systems using fuel burners to transfer calorific power directly to the drying fluid [11]. Instead, combustion is often used for other purposes, with the residual combustion heat repurposed for parallel drying processes [73]. This can be described as a cogeneration process, where surplus heat is utilized for drying. Similarly, the application of forage drying with photovoltaics in this thesis stems from the anticipated surplus energy outside the photovoltaic water-pumping season.

The forage drying equipment observed in the field primarily uses diesel burners that combust hydrocarbons directly into the air stream, which is then brought into contact with the forage. As a result, the calorific power transfers directly to the air and subsequently to the forage. Over the past 25 years, approximately 162 articles have been published on this topic. However, after excluding studies focused on residual heat from diesel engine exhausts and those using biofuels to power engines, fewer than 10% of the articles are relevant to this study. These relevant studies involve products similar to alfalfa or food items or use solar energy to support diesel or gas drying systems [62].

In conclusion, conventional diesel drying for forages, where diesel directly heats and dries the air used to extract moisture, has not been extensively studied. This is likely due to its low efficiency and high cost, which has increased significantly in recent years. This is paradoxical because large-scale forage dehydration plants often use "drum dryers" and diesel burners. However, there are no notable studies examining this process, likely because the expected profit margins in food dehydration are insufficient to justify the direct combustion of diesel. Additionally, the smoke contamination from diesel combustion poses a problem for certain dried products. In recent years, as diesel prices have surged, other petroleum derivatives have been used for forage drying.

Studies on direct hydrocarbon combustion into the fluid indicate that the air flow rate is approximately 283.2 m³/min, with diesel atomized at 488 kPa. Three flow rates—7.6, 53, and 87 l/h—were tested [11], providing a reference point for understanding the high energy consumption and costs associated with this method. The diesel-powered drying equipment referenced in this thesis consumes approximately 50 l/h during the drying of 10 tons of product. Comparative studies on drying with different energy sources reveal that diesel has lower drying efficiencies compared to propane and solar energy, as well as inferior quality results in terms of chlorophyll retention and product color [74].

Despite these drawbacks, diesel drying is competitive in terms of drying speed because it can act on a larger specific surface area of the product. However, the quality of the dried product is lower compared to solar thermal energy or heat pump drying.

The most commonly used performance coefficients in this category include drying efficiency [11], system-wide performance coefficients (COP) [75], average thermal efficiency (ranging from 66.79% to 96.09%) [75], specific moisture extraction rate for the entire system (SMER, approximately 3 kg/(kWh)) [75], and average drying rate (219 gwater kg⁻¹ h⁻¹) [12].

In two operational forage dryers, one industrial [76] and the other operated by a farmer, it was observed that air is preheated using biomass combustion (straw) to improve efficiency and reduce diesel consumption. Figure 13 shows the biomass boiler installed at the air intake of the drying system.



Figure 13: Biomass air preheating systems in forage dryers (Odarpi and Villafranca [76])

2.5. Conclusions

In this review of the state of the art, as in other studies on this subject, it has been concluded that different KPIs are used, and those that are identical or similar have not been obtained under the same measurement conditions or variables. As a result, they are not perfectly comparable and do not provide precise information on the reliability of the obtained data. As indicated in [77], there are several limitations associated with the coefficients used, which are caused by:

- The influence of local climatic conditions on performance due to the average ambient temperature. This makes comparisons between different climatic regions difficult.
- The influence of the study duration. Operating conditions may vary throughout the year. This effect is mitigated over prolonged periods, as coefficients are influenced by average values.
- The different technologies used, which necessitate focusing only on electricity consumption and the energy source from which it is derived.

Some coefficients that are widely used due to their effectiveness in characterizing the process are not acquired under similar conditions, making direct comparisons between them impossible. To enable comparability, additional variables should be recorded, and the coefficient adjusted accordingly.

To compare the different studies in this review, they have been classified and parameterized following the guidelines in [77], based on factors such as study duration, whether they involve simulations or experiments, system size, energy source, and the technology used. It was found that this information is not clearly indicated or standardized in units. In some cases, studies are complemented by other energy sources, which should be accounted for in both consumption and performance metrics. Additionally, the study locations should be included to evaluate the external conditions of the experiments, such as outdoor temperature, relative humidity, and solar radiation—parameters that allow for the comparison of KPIs and the assessment of how these conditions influence the results.

The difficulty in accounting for energy derived from renewable sources diminishes their significance in terms of efficiency and performance. Similarly, costs associated with other energy sources are not fully considered, such as the

increased expenses due to contracted grid power availability, equipment rental and maintenance costs, supply expenses, etc.

It is also considered that studies should account for the availability of the energy source and price fluctuations over time, even within a single drying interval. Under the current tariff and variable pricing scenario, certain energy sources may be more cost-effective than others. The current energy landscape means that, within the same drying experiment, energy prices fluctuate similarly to how solar radiation does. Therefore, it is necessary to consider this cost variability, just as the variation in solar radiation has always been seen as a disadvantage of this energy source.

3. Economic Assessment of a PV-HP System for Drying Alfalfa in The North of Spain

3.1. Introduction

The objective of this chapter is to evaluate the economic feasibility of this innovative PVDS, compared to two traditional drying systems: diesel and grid-powered, respectively. This assessment includes:

- A comparative economic viability analysis of the monetary investment required to install a Diesel-powered Drying System (DDS), a Grid-powered Drying System (GDS) and a PVDS. The return of the investment is compared for these three options, where the main difference is the operational costs associated to the energy generation. The results are expressed in terms of the Profitability Index (PI), the Internal Rate of Return (IRR) and the Payback Period (PBP).
- An estimation of the savings in terms of the Levelized Cost of Energy (LCOE), comparing the PVDS solution to the diesel and grid-powered ones.
- An estimation of the CO₂ savings with PVDS, comparing to the other systems.

The rest of the chapter is structured as follows: section 3.2 describes the methodology for the economic assessment, section 3.3 presents and discusses the base-case results, section 3.4 is a sensitivity analysis and section 3.5 summarizes the main conclusions of this chapter.

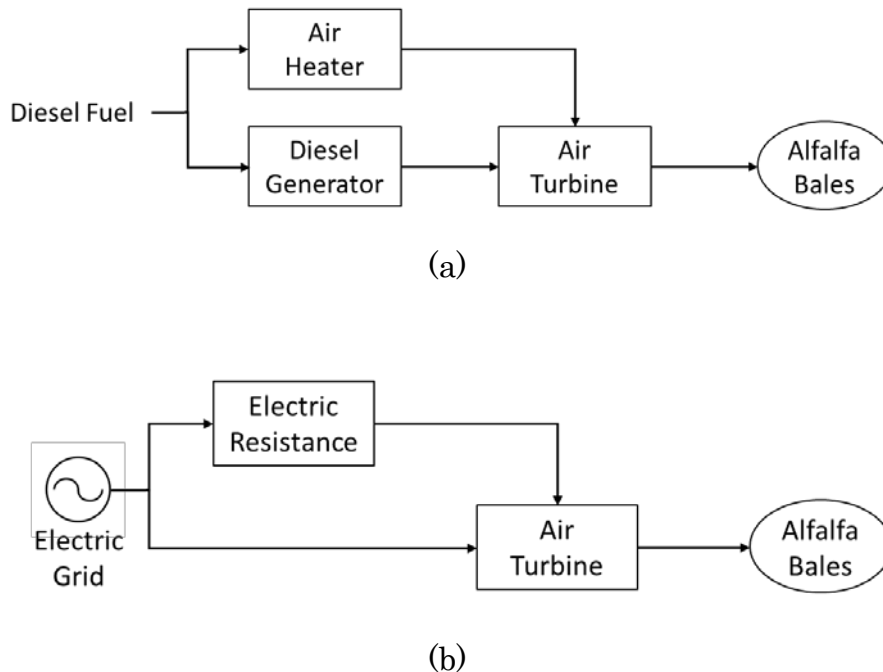
3.2. Methodology

This chapter compares the economic profitability and environmental impact of three different drying systems: a Diesel-powered Drying System (DDS), a Grid-powered Drying System (GDS) -both composed of an air heater and an electric turbine-, and a PV-powered Drying System (PVDS) -composed of an air-drying HP unit exclusively fed by a PV system-. The methodology used for this evaluation is described in the following sections. Firstly, the energy consumption required for drying a certain number of bales per year is estimated for the three

systems, as well as the corresponding CO₂ emissions. Secondly, the sizing of the PV generator for the PVDS is established based on the estimated energy consumption, considering some energy losses that are inherent of these type of applications (as opposed to grid-connected PV systems). Finally, this section describes in detail the methodology used for the economic viability analysis and for the LCOE of the three systems.

3.2.1. Energy consumption and CO₂ emissions

Figure 14 presents the schematic of the three systems under study: the DDS (a) is composed of an air heater and a diesel generator that powers a turbine, that impulses the hot air through the alfalfa bales; the GDS (b) is composed of an electric resistance that acts as the air heater, and an air turbine that is now powered by the grid; the PVDS (c) is composed of an air-drying HP unit and an air turbine, both powered just by a PV generator through seldom frequency converters.



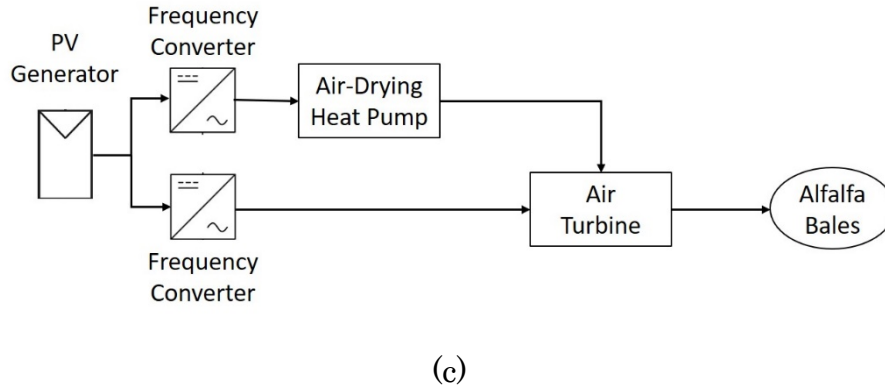


Figure 14: Schematic of the Diesel-powered Drying System (a), of the Grid-powered Drying System (b) and of the PV-powered Drying System (c).

According to different interviews with farmers [76], a DDS consumes 50 l/h (for powering both the air heater and the air turbine) and dries approximately 2.5 tons/h of alfalfa (dry matter). From this information, the hourly energy consumptions of the three systems (DDS, GDS and PVDS) were estimated. Finally, the results were scaled-up for drying 60 tons of alfalfa (dry matter) per year, under the hypothesis that the consumption increases linearly with the volume of dried product:

- **DDS:** from the 50 l/h of diesel, 37 l/h are consumed by the air heater [76] (considering 9.85 kWh/l as the inferior caloric value of the diesel fuel and an average efficiency of 90.6% [79], the hourly consumption of the air heater is 330.3 kWh) and 13 l/h are consumed by the diesel generator for powering the air turbine (assuming an average energy output per diesel fuel consumption 3.5 kWh/l [80], this corresponds to an hourly consumption of 45.5 kWh). In total, the DDS system consumes 375.8 kWh for drying 2.5 tons; for drying 60 tons per year, it would consume **9,019.2 kWh/year**. Assuming an average CO₂ emissions intensity of 2,790 gCO₂/kWh [80], this consumption generates **25.16 metric tons CO₂/year**.
- **GDS:** the electric resistance must generate the same thermal energy as the air heater of the DDS (for generating 330.3 kWh with an efficiency of 99% [82], it consumes 333.6 kWh) and the air turbine consumes the same 45.5 kWh. In total, the GDS system consumes 379.1 kWh for drying 2.5 tons; for drying 60 tons per year, it would consume **9,099.4 kWh/year**. For a conversion factor of 259 gCO₂/kWh of electric grid [80], this consumption generates **2.35 metric tons CO₂/year**.

- **PVDS:** the HP dryer has an average drying capacity of 21 liters of water per hour [83], which corresponds to an electric consumption of 0.20 kWh per liter of water. Assuming that the alfalfa bales have an initial relative humidity of 27.5% and that they need a final humidity of 12% [76], the HP needs to extract 96 l of water per bale. Each bale weights 396 kg (dry matter), so the annual consumption required for drying 60 tons of alfalfa is **4,715.66 kWh/year**. Note that this represents less than 52% of the energy consumption, if compared to the DDS and GDS. Additionally, this energy consumption does not generate CO₂ emissions (for the PV energy, the emissions are associated only to the manufacturing and transport of the system components, not considered in this work).

Table 4 summarizes the values of electricity consumption and CO₂ emissions given in the previous paragraphs for easily comparing the three systems under study (numbers between parenthesis are the savings in energy consumption, comparing the DDS and GDS to the PVDS).

Table 4: Values of yearly electricity consumption and CO₂ emissions estimated for the three systems under study. Values between parenthesis are the savings in terms of electricity consumption if a PVDS was used instead of a DDS or GDS.

	<i>Electricity Consumption (kWh/year)</i>	<i>CO₂ emissions (metric tons/year)</i>
DDS	9,019.2 (47.7%)	25.16
GDS	9,099.4 (48.2%)	2.35
PVDS	4,715.66	0

3.2.2. Sizing of the PV generator for the PVDS system

The Performance Ratio (PR) of a PV system is the total AC energy obtained along a certain period of time, divided by the DC energy that could have been generated in ideal conditions. For an expected PR value, it is easy to calculate the peak power (i.e., installed power) of the PV generator, P_{MPP}^* , that is required for a certain AC energy demand, according to the following expression [84]:

$$PR = \frac{E_{AC}}{\frac{P_{MPP}^*}{G^*} \int G(t) dt} \quad (1)$$

where E_{AC} is the AC energy delivered by the PV generator, P_{MPP}^* is the maximum power of the PV generator at Standard Test Conditions (STC), G^* is the global solar irradiance in the plane of the generator at STC (1,000 W/m²) and $G(t)$ is the global solar irradiance on the plane of the generator.

Grid-connected PV systems usually present high PR values, between 0.75 and 0.9 [[85], [86], [87]], because they can theoretically inject all of the PV electricity produced into the grid. However, when the PV generator is connected to an intermittent load, such as the drying system here described, it is almost impossible to reach such high PR values. There are three main causes of additional energy losses: the drying period might not be the whole year, but only several months, the operating power ranges of the drying system components (even if they admit variable speed, they can only be turned on when a certain threshold of power is available) and the decisions made by the final user (that can choose to dry during some hours of the day and not others, depending for example on the alfalfa availability). In previous works, the IES-UPM has developed a methodology for considering the energy losses associated to this application (and not to the quality of the PV system itself), based on the factorization of the traditional PR [88]:

$$PR = PR_{PV} \times UR_{Dp} \times UR_{PV-HP} \times UR_{EF} \quad (2)$$

where PR_{PV} is the PR considering only losses strictly associated to the PV generator itself (i.e., actual versus nominal peak power, dirtiness, thermal and DC/AC conversion losses), UR_{Dp} is the Utilization Ratio (UR) that reflects the energy losses associated to the Drying Period (Dp), UR_{PV-HP} is the UR that reflects the energy losses associated to the operating power ranges of the drying system and UR_{EF} is the UR that reflects the energy losses associated to the end user of the system.

By combining equations (1) and (2), if the designer of the PV system knows the AC energy demand of the drying process, the total yearly solar irradiation on the plane of the PV generator at the system location $\int G(t) dt$ and the expected energy losses, the calculation of the required PV peak power is immediate. The

AC energy demand was estimated in section 3.1 and the monthly and yearly solar irradiation was obtained using the simulator of PV systems SISIFO [89], for a PV generator on a static structure, South oriented and tilted 30°, located at Zarratón (Spain). This simulator takes the Typical Meteorological Year (hourly irradiance and temperature series of data that best represent median weather conditions) generated by the PVGIS database [90] for a given location. Then, it uses the correlations of Erbs [91] for splitting horizontal global irradiation into its direct and diffuse components, and the Perez model [92] for the transposition from horizontal to the plane of the generator. The D_p for the alfalfa is from May to September, which means a UR_{Dp} value of 0.52. Unfortunately, there are no experimental records for this specific application that permit to estimate the remaining expected energy losses. For partially solving this barrier, the authors have remitted to the values obtained for real PV-powered irrigation systems that have been designed and monitored by the IES-UPM [93]. Irrigation systems and heat pump drying systems have in common that their main electric loads (i.e the water pump and the refrigerant compressor) can operate at variable speed, so the causes for the energy losses reflected in the PR factorization are the same.

Table 5: presents the input values used for the sizing of the PV generator, as well as the corresponding value of value of P_{MPP}^* according to equations (1) and (2):

E_{AC} (kWh)	4715.66
G^* (kW/m ²)	1
$\int G(t)dt$ (kWh/m ²)	2102.96
PR_{PV}	0.8
UR_{Dp}	0.52
UR_{PV-HP}	0.8
UR_{EF}	1
P_{MPP}^* (kW _p)	7

3.2.3. Methodology of Economic viability analysis

The viability of the monetary Initial Investment Cost (IIC) required for installing each of the Drying Systems is expressed in terms of the PI , the IRR and the PBP .

The values of these indicators are determined by the annual Cash Flows (CF_n) during the lifetime of the system (25 years), defined as the difference between the annual profits and costs [94]. The annual profits (P_n) match the revenue from selling the alfalfa bales and are the same for the three systems, while the annual costs, consisting of the Operation and Maintenance (OM_n) and Amortization Costs (AM_n), will differ in each case. In general, the annual CF s are given by the following equation:

$$CF_n = \begin{cases} -IIC & (if\ n = 0) \\ (P_n - OM_n - AM_n) \times (1 - t) + AM_n & (if\ n \neq 0) \end{cases} \quad (3)$$

where P_n is 18,000 € (assuming a selling price of 300 €/t [95], AM_n was calculated assuming a constant amortization linear coefficient of 7% of the IIC [96] and t , the corporate tax rate in Spain, is 25% [96]. Table 6 shows the input values given to the remaining variables for the three drying systems:

Table 6: Initial Investment Cost (IIC) and Annual Operation and Maintenance Cost (OMn) considered for the Diesel-powered Drying System (DDS), Grid-powered Drying System (GDS) and Photovoltaic Drying System (PVDS). All the costs include a Value Added Tax or VAT of 21% for Spain.

	DDS	GDS	PVDS
IIC (€)	49,579 ⁽¹⁾	49,579 ⁽¹⁾	42,955 ⁽²⁾
OM_n (€/year)	1,848.88 ⁽³⁾	2,311.96 ⁽⁴⁾	859 ⁽⁵⁾

⁽¹⁾ The IIC for both the DDS and GDS are considered to be similar, assuming that the electric resistance is equivalent to the diesel generator in terms of cost and that both use an equivalent air turbine [76].

⁽²⁾ Considering a unit cost or CAPEX of 1.5 €/kW_p for the PV system [98], including the Frequency Converter, and a total cost of 25,000 € for the Heat-Pump dryer.

⁽³⁾ Calculated for a unit price of 86.7 c€/l [99], considering an average diesel fuel consumption per energy unit of 3.5 kWh/L [80]. This cost was assumed to increase by 3% annually [100].

⁽⁴⁾ Determined according to tariff 2.0 in Spain for access power and energy consumption [101] and tax rate on electricity costs is 5.11% of 15% of the total costs [102]. This cost was assumed to increase by 3% annually [100].

⁽⁵⁾ 2% of the IIC for the PVDS [80].

Finally, the three economic viability indicators are calculated from the CFs according to equations (4), (5), (6). The PI is defined as the present value of future cash flows divided by the IIC , the IRR is the interest rate at which the IIC is returned at the end of the lifetime of the project and the PBP is the period of time needed for the IIC to be returned with the present value of CFs :

$$PI = \frac{\sum_{n=1}^{25} \frac{CF_n}{(1+i)^n}}{IIC} \quad (4)$$

$$IIC = \sum_{n=1}^{25} \frac{CF_n}{(1+IRR)^n} \quad (5)$$

$$IIC = \sum_{n=1}^{PBP} CF_n \quad (6)$$

where i is the interest rate, which has been given the value 0.8% (the average in the last 10 years in Spain [96]).

3.2.4. Methodology of Levelized Cost of Energy (LCOE)

$LCOE$ is defined as the lifetime cost of a certain energy generation system (including the IIC and OM costs), divided by the total Energy Production (EP) during this lifetime [103]. The resulting $LCOEs$ are given by the following equations:

$$LCOE_{DDS} = \frac{IIC_{DDS} + \sum_{n=1}^{25} \frac{OM_{n,DDS}}{(1+i)^n}}{\sum_{n=1}^{25} \frac{EP_{n,DDS}}{(1+i)^n}} \quad (7)$$

$$LCOE_{GDS} = \frac{IIC_{GDS} + \sum_{n=1}^{25} \frac{OM_{n,GDS}}{(1+i)^n}}{\sum_{n=1}^{25} \frac{EP_{n,GDS}}{(1+i)^n}} \quad (8)$$

$$LCOE_{PVDS} = \frac{IIC_{PVDS} + \sum_{n=1}^{25} \frac{OM_{n,PVDS}}{(1+i)^n}}{\sum_{n=1}^{25} \frac{EP_{n,PVDS}}{(1+i)^n}} \quad (9)$$

where $EP_{n,DDS} = 9.017,92$ kWh, $EP_{n,GDS} = 9.098,00$ kWh and $EP_{n,PVDS} = 4.715,66$ kWh (see section 3.1) and the rest of the input values are taken from Table 6

3.3. Results and discussion

3.3.1. Result and discussion of Economic viability analysis

The installation of a drying system, whether it powered by a diesel generator, the electric grid or a PV system, is economically viable if the PI is bigger than 1, the IRR is higher than the national interest rate and the PBP is significantly lower than the lifetime of the system [94]. shows the PI , IRR and PBP values of the economic investment required for installing a DDS, a GDS and a PVDS. It can be observed that such an investment is profitable in any case: the PI values are 7.03, 6.78 and 10.11, the IRR values are 25.7%, 24.9% and 37.1% (much higher than the interest rate considered as reference, 0.8 %) and the PBP values are 4 and 3 years, less than a quarter of the lifetime of the system. The profitability is significantly better for the PVDS (the PI and the IRR are more than 40% higher), because not only the IIC is lower for this system, but (and specially) also the OM costs. If comparing the two other systems, the DDS is slightly more profitable than the GDS because the unit cost of the diesel fuel is lower than the electricity costs. However, the difference is not really significant (the PI and the IRR are only 3% higher) and this situation could easily be reversed in the current landscape of fossil fuels scarcity.

Table 7: Profitability Index (PI), Internal Rate of Return (IRR) and Payback Period (PBP) of the economic investment required for installing a Diesel-powered Drying System (DDS), a Grid-powered Drying System (GDS) and a PV-powered Drying System (PVDS).

	$PI(\text{€}/\text{€})$	$IRR(\%)$	$PBP(\text{years})$
DDS	7.03	25.7%	4
GDS	6.78	24.9%	4

PVDS	10.11	37.1%	3
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3.3.2. Result and discussion of Levelized Cost of Energy (LCOE)

Table 8 presents the *LCOE* of the three systems under study (DDS, GDS and PVDS), as well as the savings in terms of *LCOE* of the PVDS compared with the two other systems. These savings are bigger than 40% in both cases, indicating that the cost per unit energy consumption is lower if using a PVDS. As well as with the economic profitability, the results are better for the DDS than for the GDS. The electricity costs (including energy and power costs) are higher than the diesel costs (including the fuel and *OM*), resulting into a bigger *LCOE* (and smaller *LCOE* savings).

Table 8: Levelized Cost of Energy (LCOE) of the Diesel-powered Drying System (DDS), the Grid-powered Drying System (GDS) and the PV-powered Drying System (PVDS), and savings of the PVDS system compared to the DDS and GDS.

	<i>LCOE</i> (€/kWh)	<i>LCOE</i> Savings (%)
DDS	0.52	40.5%
GDS	0.59	47.3%
PVDS	0.31	-

3.3.3. General discussion

Considering the economic viability results and the LCOE values obtained in this assessment, it can be stated that the PVDS solution presents significant advantages over the DDS and the GDS. The economic investment required for installing the PV system and the heat pump dryer is around 40% more profitable than for installing diesel or grid-powered configurations. The monetary costs of generating the energy required for the drying process are also more than 40% smaller with the PVDS solution. Besides, these results are not likely to be reversed in the short term, considering the current energetic landscape of fossil-fuels scarcity. Diesel fuel costs are expected to slightly decrease in the very short term, but to start slowly increasing after 2-3 years, while electricity prices are expected to fluctuate around current values, but also slowly increasing in average [103]

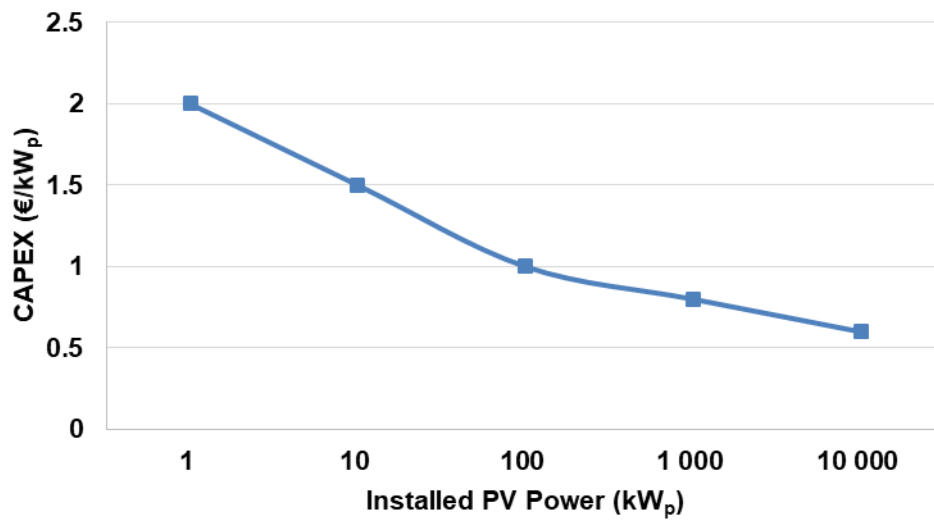
Furthermore, it should be taken into account that the PV solution is not only more economic, but also consumes less energy (around 52% of the energy consumption of the DDS and GDS) and less pollutant (although the life cycle assessment of the three systems in terms of CO₂ emissions is not considered in this work, the PVDS solution does not emit greenhouse gasses during its operation, while the DDS and the GDS emit 25.16 and 2.33 metric tons CO₂/year, respectively). This is especially relevant for mitigating the climatic change, one of the cornerstones of the European energy policies.

Finally, there is an additional benefit of using PV-powered systems that is not reflected in an economic assessment, but should be considered when considering different options: it is an independent and reliable power supply, that does not depend on any generation and/or transportation infrastructure. If combined with electricity storage systems, it can be more reliable than the electric grid, especially in remote locations. This additional advantage is becoming more and more relevant in market assessments, due to the increasing fear of electric and/or diesel fuel supply deficiencies.

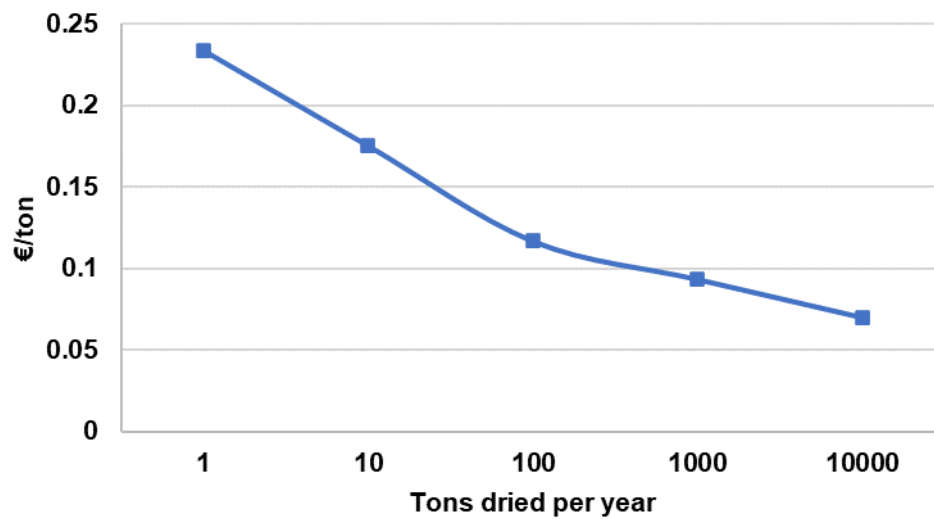
3.3.4. Discussion on the Initial Investment Cost for the PVDS

As already discussed, the use of PV energy for drying applications presents important economic, energetic and environmental advantages, as well as offering a reliable electric supply. This chapter intends to be useful for farmers that are considering new investments in drying infrastructures. In the light of this objective, the authors include in this section a short discussion on the *IIC*, or CAPEX (as usually named in the PV sector) of the PV system that would be necessary for drying a certain volume of alfalfa per year. It should be highlighted that the volume of alfalfa considered for the base case of this analysis requires of a small PV system, of only 7 kW_p. The CAPEX for bigger PV systems is much smaller, both in terms of installed PV peak power and of tons of dried alfalfa per year, as shown in Figure 15 [98]. A PV system of 1 kW_p would permit to dry around 9 tons of alfalfa per year, at a unit cost of 0.23 €/ton; with a PV system of 10 MW_p, more than 85,000 tons of alfalfa could be dried at a unit cost of 0.07 €/ton. The selling price of the alfalfa would be the same as the one considered for

the base case, so the economic profit of using PV energy could be significantly higher for bigger-scaled systems.



(a)



(b)

Figure 15: Unit cost per unit of installed PV power (a) and per ton of dried alfalfa (b) for different system sizes, from a small scale (1 kW_p) to a large scale (10 MW_p).

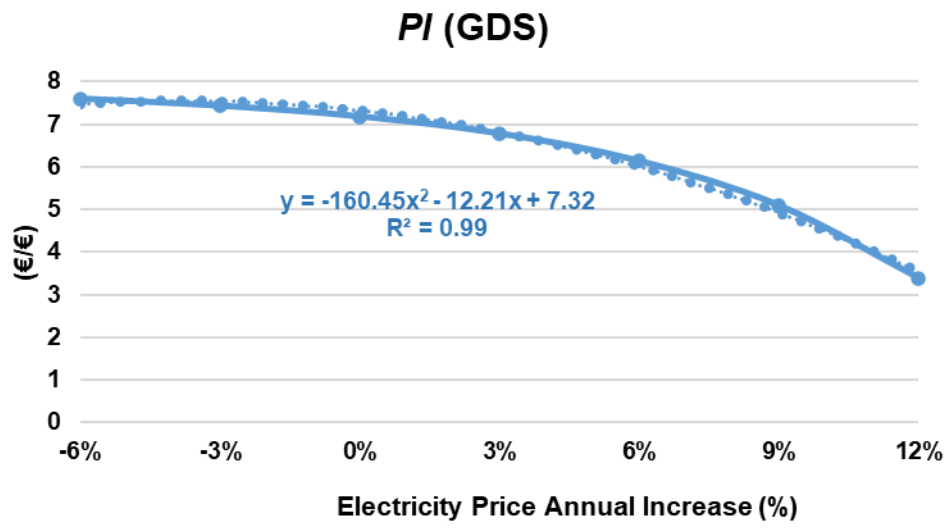
3.4. Sensitivity analysis

The results previously presented are obviously conditioned by the inputs introduced into the model, some of which are currently subject to significant variations. For example, a diesel price of 0.85€/l has been considered, which is conservative as recent geopolitical events have increased fossil fuel costs in Europe up to historical values. Therefore, in order to generalize these results, it is necessary to carry out a sensitivity analysis with respect to the most important input variables. This section presents the variability of the final results for the most relevant variables of the model.

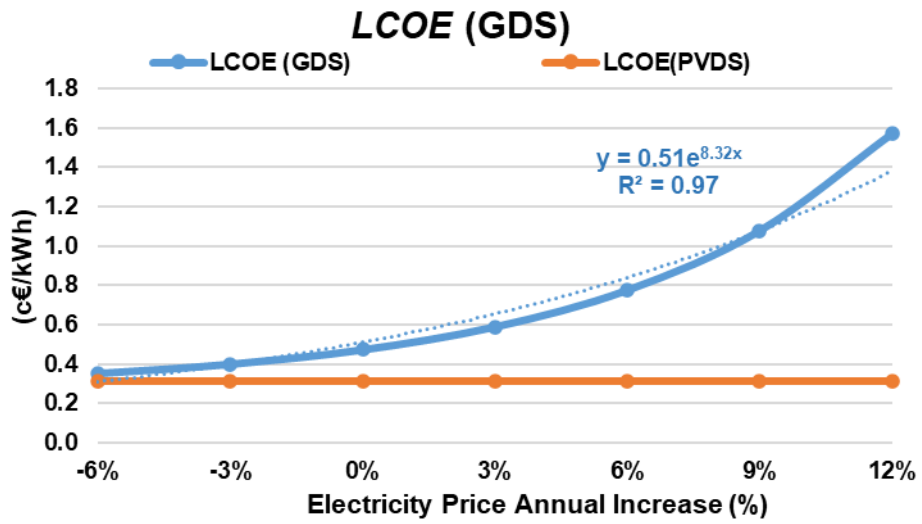
3.4.1. Annual variation of Electricity Prices

For the base case of this assessment, the electricity costs have been assumed to increase by 3% annually. Figure 16 shows the *PI* of the GDS (a), the *LCOE* (b) and the *LCOE* savings -comparing the PVDS with the GDS- (c) obtained for an annual variation of electricity prices between -6% and +12%. The *PI* follows a polynomial trend and the *LCOE* follows an exponential trend, tending to 7.18 (€/€) and 0.51 (c€/kWh) if there was no annual variation of the electricity prices. The *LCOE* savings of the PVDS follow a linear trend.

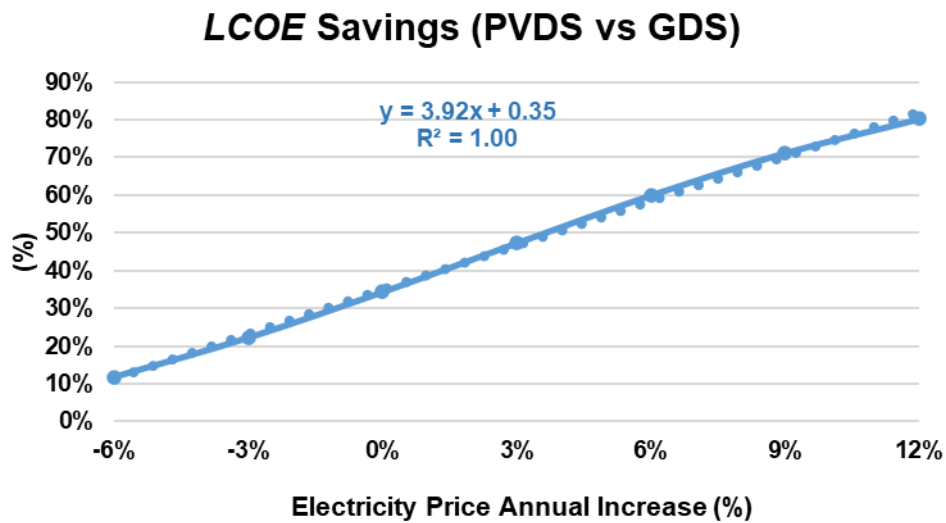
The *IRR* and *PBP* values are also sensible to this variable, but it is easier to visually identify when an investment stops being profitable ($PI < 1$) just by looking at the *PI*. In this case, the investment required for the GDS would cease to be profitable if the electricity prices increased more than 16.40% annually. The *LCOE* of the GDS increases very rapidly with the increase in the price of energy, to the point that it quadruples when going from -6% to 12%. The *LCOE* of the GDS would be lower than the one of the PVDS (hence *LCOE* savings would become *LCOE* losses) if the prices decreased by at least 9% annually. In any case, the current energetic and geopolitical landscape is already inflating electricity prices above 3% annually in Europe, suggesting that the actual results could benefit the PVDS even more than the base case here considered.



(a)



(b)



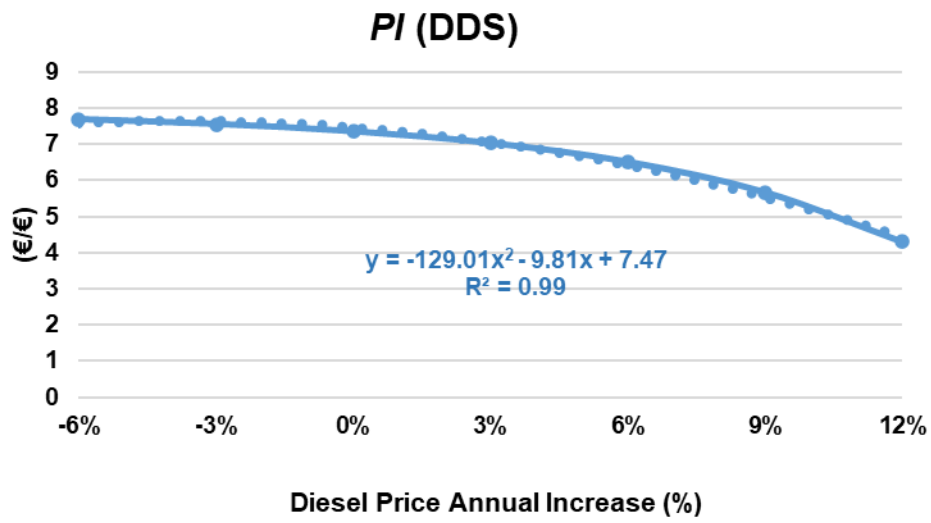
(c)

Figure 16: Profitability Index (a), Levelized Cost of Energy (b) and LCOE savings compared to the Grid-powered Drying System (c), obtained for an annual variation of electricity prices between -6% and +12%.

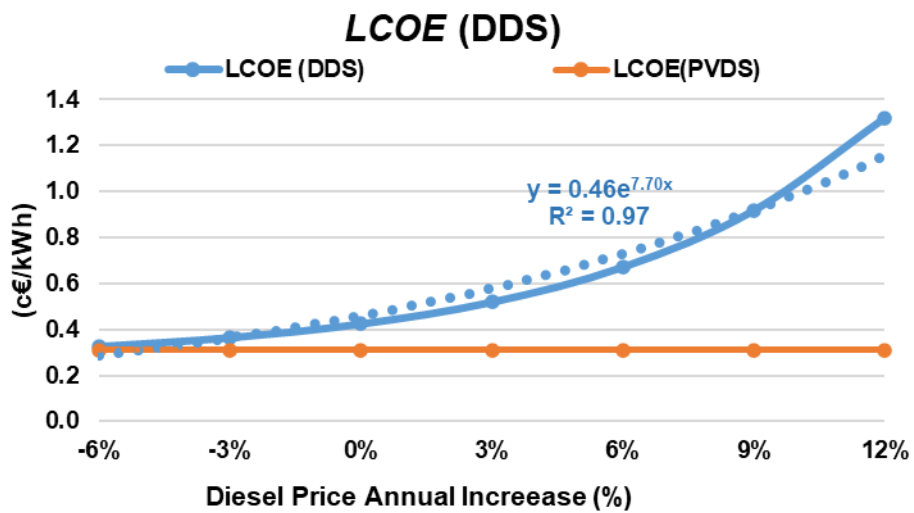
3.4.2. Annual variation of Diesel Fuel Price

For the base case of this assessment, the diesel fuel costs have been assumed to increase by 3% annually. Figure 17 shows the *PI* of the DDS (a), the *LCOE* (b) and the *LCOE* savings -comparing the PVDS with the DDS- (c) obtained for an annual variation of diesel fuel costs between -6% and +12%. The *PI* follows an exponential trend and the *LCOE* an exponential trend, tending to 7.35 (€/€) and 0.46 (c€/kWh) if there was no annual variation of the diesel prices. The *LCOE* savings, on the other hand, follows a linear trend.

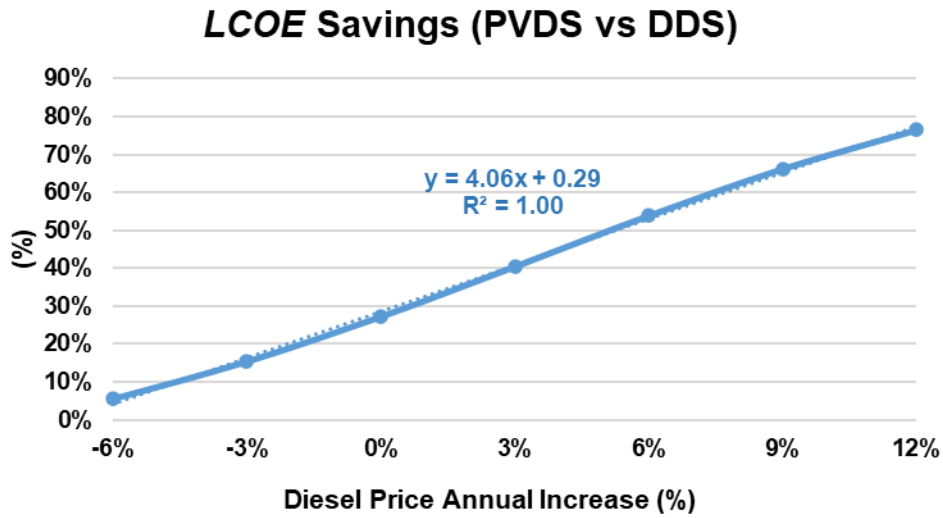
In this case, looking again at the *PI*, the investment required for the DDS would remain profitable until annual diesel prices rise by more than 18.89%. Similarly, the *LCOE* of the DDS increases rapidly with the increase in the price of diesel. *LCOE* savings would become *LCOE* losses if the diesel prices decreased by at least 7% annually. As with electricity costs, current diesel fuel prices are increasing at a higher rate than in the base case of this study, so higher returns from PV solutions can be expected.



(a)



(b)



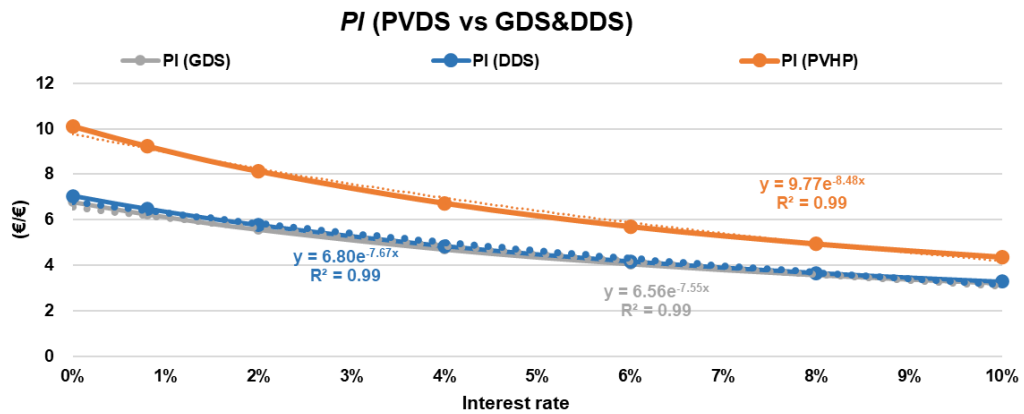
(c)

Figure 17: Profitability Index (a), Levelized Cost of Energy (b) and LCOE savings compared to the Diesel-powered Drying System (c), obtained for an annual variation of diesel fuel costs between -6% and +12%.

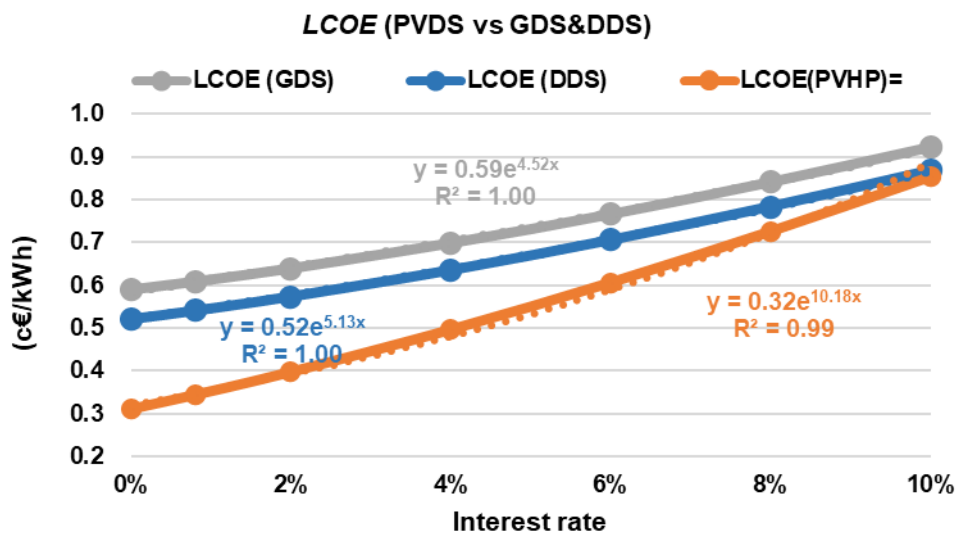
3.4.3. Interest rate

For the base case of this assessment, the interest rate has been given an average value of 0.8%. Figure 18 shows the *PI* (a), the *LCOE* (b) and the *LCOE* savings (c) obtained for interest rate between 0% and 10%. The *PI* and the *LCOE* follow an exponential trend tending to 6.78, 7.03 and 10.11(€/€) for GDS, DDS and PVDS respectively, and 0.59, 0.52 and 0.31 (c€/ kWh) for GDS, DDS and PVDS respectively when the interest rate is zero. *LCOE* savings, on the other hand, follow a linear trend.

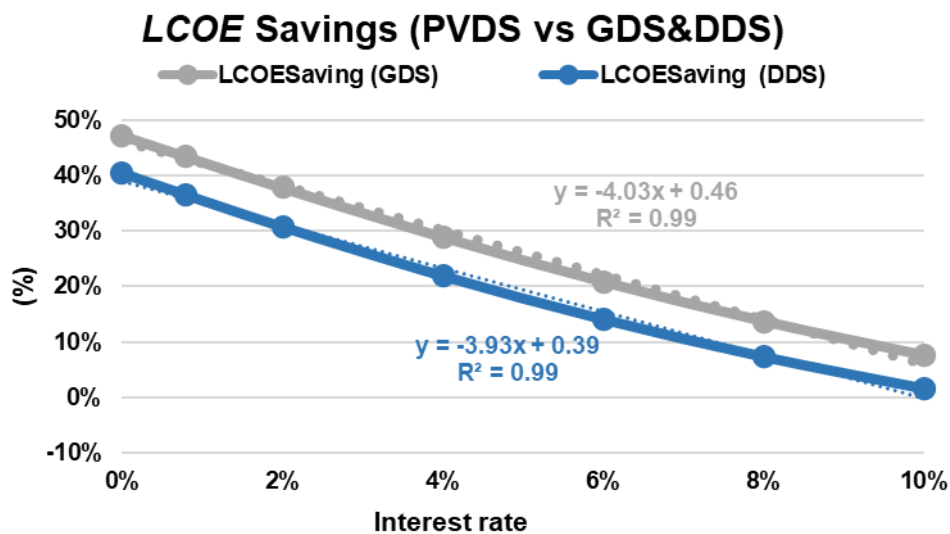
The investments required to install a GDS, a DDS or a PVDS would still be profitable even if the interest rate increased to 10%. In European countries, economic disturbances of this magnitude are extremely rare. The *LCOE* of the GDS and DDS systems increase with the interest rate, but the *LCOE* of the PVDS increases faster. Consequently, the *LCOE* savings decrease, reaching almost 0% in the case of PVDS vs DDS when $i=10\%$.



(a)



(b)



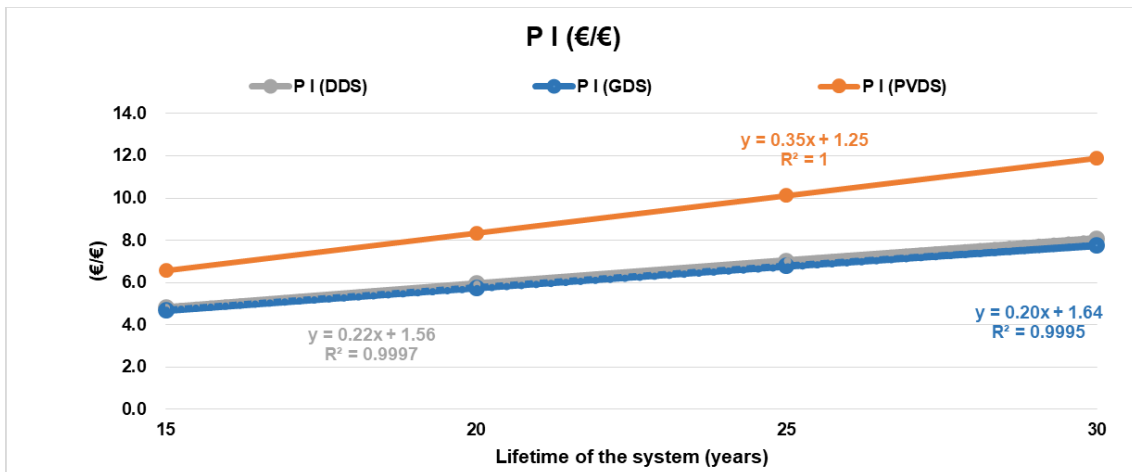
(c)

Figure 18: Profitability Index (a), Levelized Cost of Energy (b) and LCOE savings (c), obtained for an interest rate between 0% and 10%, for the cases PVDS vs DDS and PVDS vs GDS.

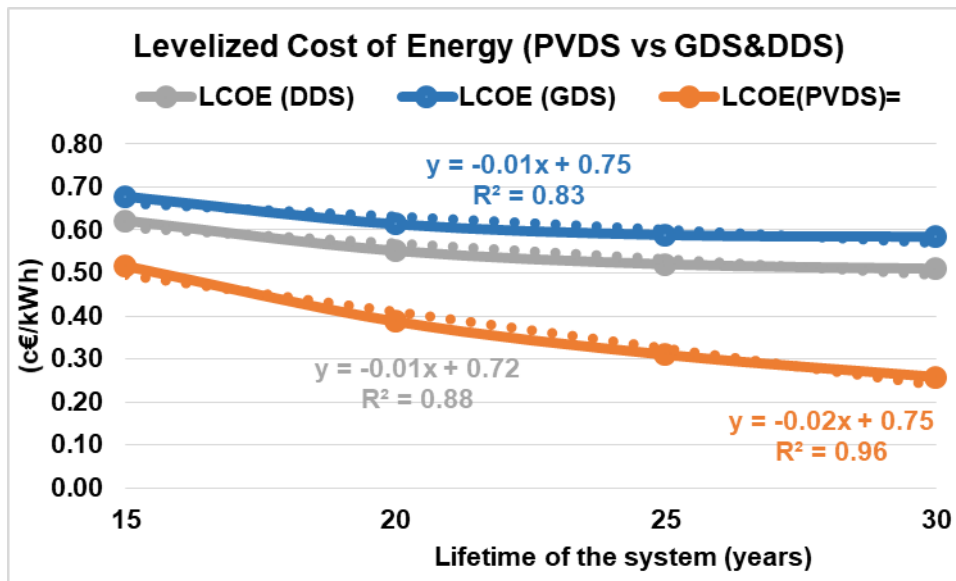
3.4.4. Lifetime of the system

For the base case of this evaluation, the useful life of the system is 25 years. However, this can change if for example the PV array experiences annual degradation rates other than 0.8% (as assumed for this analysis). Figure 19 shows the *PI* (a), *LCOE* (b) and *LCOE* savings (c) obtained for a system life of between 15 and 30 years. The *PI* and the *LCOE* follow a linear trend, increasing by 0.20, 0.22 and 0.35 €/€ for each additional year of useful life of the GDS, DDS and PVDS, respectively. *LCOE* savings also follow a linear trend.

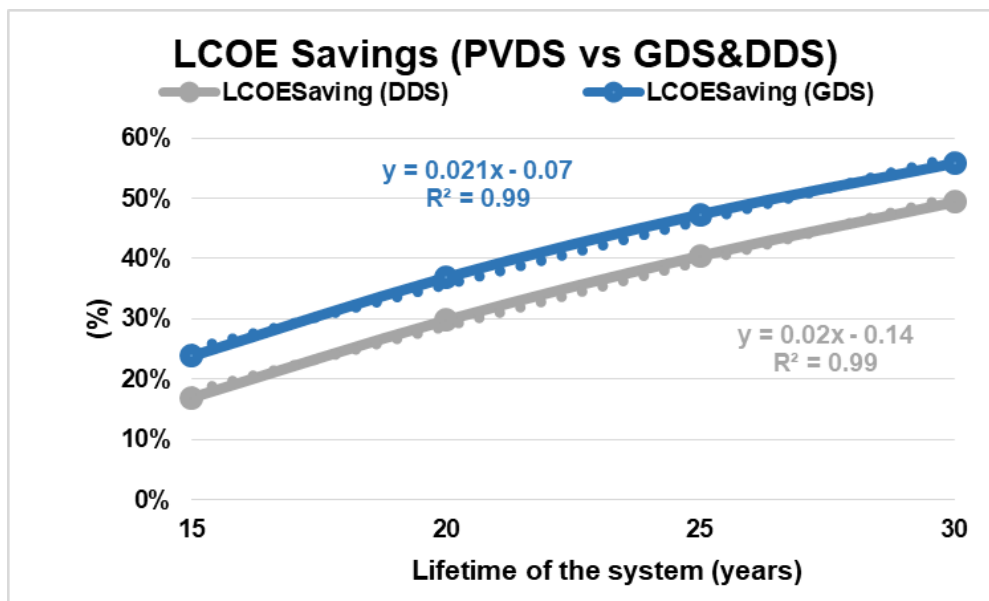
The investments required to install a GDS, a DDS or a PVDS would still be profitable even if the useful life of the system were 15 years. Today's manufacturing techniques and quality control procedures make PV systems very robust, so nowadays warranties typically cover periods of more than 15 years. The *LCOE* of all three systems decrease with system life, but to a lesser extent for PVDS. Consequently, the *LCOE* savings also increase for longer lives. If the system lasted only 15 years, PVDS would have a lower *LCOE* than DDS and GDS (*LCOE* savings would be positive).



(a)



(b)



(c)

Figure 19: Profitability Index (a), Levelized Cost of Energy (b) and LCOE savings (c), obtained for a lifetime of the system between 15 and 30 years, for the cases PVDS vs DDS and PVDS vs GDS.

3.5. Conclusions

The substitution of irrigated crops like potato or beetroot with alfalfa is a good alternative for farmers in the North region of Spain. However, the drying of the alfalfa for its conservation during transportation is currently an expensive and polluting process, whether it is Diesel-powered (DDS) or Grid-powered (GDS). This chapter evaluates and compares the economic benefits of installing the traditional drying systems, DDS and GDS, with the profitability of installing a PV-powered one (PVDS), mainly composed of a PV system and an air-drying heat pump. An economic viability assessment has been performed, obtaining the Profitability Index (PI), Internal Rate of Return (IRR) and Payback Period (PBP), the $LCOE$ of the three drying technologies have been estimated and a sensitivity analysis has been included for testing the robustness of the base case results.

- Regardless of the economic benefits of the PVDS solution, it reduces by at least 52% the energy consumed, and the CO₂ emitted is virtually zero. This helps to mitigate the current energetic crisis and climatic change, a pressing need in Europe and worldwide.
- PI values are bigger than 1 (indicating that the investment is profitable) whether a DDS, GDS or PVDS is installed. The profitability is higher for PVDS ($PI=10.11$), followed by DDS ($PI=7.03$) and lastly that of GDS ($PI=6.78$), mainly due to the high prices of electricity (especially the costs of energy).
- IRR values are much higher than the Spanish interest rate (with an average value of 0.8%), showing good profitability. Again, the best IRR is obtained for PVDS ($IRR=37.16\%$), followed by DDS ($IRR=25.66\%$) and finally by GDS ($IRR=24.85\%$). PVDS is better from the economic point of view.
- PBP periods are one eighth to one sixth of the lifetime of the system (4 years for DDS, 4 years GDS and 3 years for PVDS, compared to a 25-year useful life). This means that after these 3, 4 years of life, there are only financial benefits and no losses.
- The three drying configurations present $LCOE$ of 0.59€/kWh (GDS), 0.52€/kWh (DDS) and 0.31€/kWh (PVDS). This implies that installing a photovoltaic generator and an HP dryer implies an $LCOE$ saving of 47.34% compared to GDS and 40.45% compared to DDS.
- The results of the economic evaluation are sensitive to electricity prices, diesel fuel costs, the interest rate and the useful life of the system. The scenarios where there would be no $LCOE$ savings with the PVDS are the following: annual variation in electricity or diesel costs at -7% or more,

interest rates greater than 10%, or a system life of less than 9 years. However, it is unlikely that energy prices will not continue to rise, albeit at a slow pace. Finally, photovoltaic systems are already a very mature technology, and all of the manufacturers offer guarantees of more than 15 years for their products.

The economic viability indicators (the *PI*, *IRR* and *PBP*) reflect the profitability of a monetary investment. In other words, how much money can be earned for a certain initial capital investment. The *LCOE*, on the other hand, reflects the economic cost of generating a certain amount of energy. The first indicators are useful for possible investors; the second, for policy makers. In any case, the results presented in this chapter show that the PVDS solution is beneficial from both points of view.

In any case, the study here presented is a starting point and is limited to a region and to certain conditions, but it can be extended in the future by means of more detailed considerations:

- Only locations with very high annual irradiances have been considered, but it would be useful to estimate the profitabilities of PV irrigation systems in regions with fewer solar resources available.
- Only PV configurations in stand-alone operation without batteries have been simulated. However, there are many applications where hybrid configurations, whether with the local grid or with other energy sources, are not only possible but also very beneficial (or even the only solution if drying during the night is necessary). The analysis of the feasibility of these solutions would be a very interesting future work.
- As mentioned in section 4, the bankability of PV projects is often evaluated through the Performance Ratio of the system, which in drying applications can be affected by external factors that do not depend on the quality of the PV system itself (i.e., the PV system is underused during periods where there is no need to dry). It is recommended that future works include information related to the drying necessities of the crop (alfalfa or other agricultural products) in order to perform more accurate and site-specific economic evaluations.

The growth in the market of PV drying systems should be accompanied by an effort in policy aspects related to administrative permissions and ad-hoc financing schemes. These are the main barriers for the market uptake of these systems once their technical and economic viability have been proven.

4. Technical evaluation of a stand-alone photovoltaic heat pump dryer without batteries.

4.1. Introduction

This chapter presents the first results of the technical validation of a PVHP dryer prototype for drying alfalfa bales, based on a PV generator and a HP unit, but without the need of a grid or batteries. With this stand-alone configuration, it could be possible to achieve economic savings of more than 40% in terms of LCOE if compared to diesel-powered systems [105]. This solution introduces three relevant innovations with respect to the current state of the art:

- The control algorithm developed at the IES-UPM allows for the management of the PV power fluctuations due to cloud-passing (characterized by very abrupt fluctuations of the solar irradiance) without external support. This way, all the energy required for the drying process is provided by the PV generator, allowing for energetic independence and reducing the investment and operational costs.
- The HP unit installed does not work with the standard inverter technology (where the target is a certain temperature of the air), but with an advanced algorithm that reaches the dew point of the air to condense its humidity [83]. This way, the HP unit generates very dry air, with a high capacity of absorbing the humidity from the alfalfa, potentially reducing the drying time and energy consumption.
- Contrary to the traditional diesel-powered dryers, where the humid air is released into the ambient, this prototype recirculates the air in a closed loop: once it has absorbed the humidity from the alfalfa, it is reintroduced into the HP unit. The HP dries it by condensation, and the water extracted can be reused for several applications, such as irrigation, or even human consumption. This leads to a more efficient use of the solar resource, enabling the drying of the alfalfa and the simultaneous production of water.

The validation results are presented in terms of the performance of the PV control algorithm (that needs to maximize the usage of the solar resource and manage the PV power fluctuations due to cloud-passing) and in terms of the quality of the drying process (measured through the final relative humidity inside of the bale, the drying time and the specific energy consumption during the process).

The rest of the chapter is structured as follows: section 4.2 describes the methodology for the technical evaluation, section 4.3 presents and discusses the results and section 4.4 summarizes the main conclusions of this chapter and future work.

4.2. Methodology

The PV-HP dryer operated for two consecutive drying campaigns (July–October 2022 and 2023). In 2022, the PV control of the system was validated in terms of the PV energy usage and stability against PV power fluctuations. However, it was not possible to characterize the drying process because of the inadequate design of the air conducts. During the 2023 campaign, the prototype was improved in order to solve the difficulties found in 2022, and the drying process of the alfalfa bales was characterized in terms of time and energy consumption.

This section describes the prototype components and configuration, as well as the KPIs defined to assess the quality of the PV control and the drying process.

4.2.1. System Description

Figure 20 shows the schematic of the PV-HP dryer prototype. It is composed of the following:

HP dryer with an internal PLC1, which indicates an external PLC2 if there is any alarm in the HP unit, and when the user wants to start/stop drying. PLC1 monitors several pressures and temperatures in different points of the refrigerant circuit for regulating the evaporator and condenser fans and the expansion valve.

An external PLC2 that reads the PV operating conditions—global irradiance on the plane of the generator (G) and cell temperature (TC)—from a PV calibrated cell. If the PLC1 allows it, the PLC2 calculates the DC voltage at the Maximum

Power Point (VMPP) and sends it to the Frequency Converter (FC). This setpoint is calculated as follows:

$$V_{MPP} = V_{MPP}^*[1 + \beta(T_C - T_C^*)] \quad (1)$$

where V_{MPP}^* is the V_{MPP} at Standard Test Conditions (STCs), β is the temperature coefficient of the PV voltage, and T_C^* is the cell temperature at STCs (25 °C).

The FC converts the DC power delivered by the PV generator (operating at the setpoint given by PLC2) into AC power for controlling the compressor of the HP dryer.

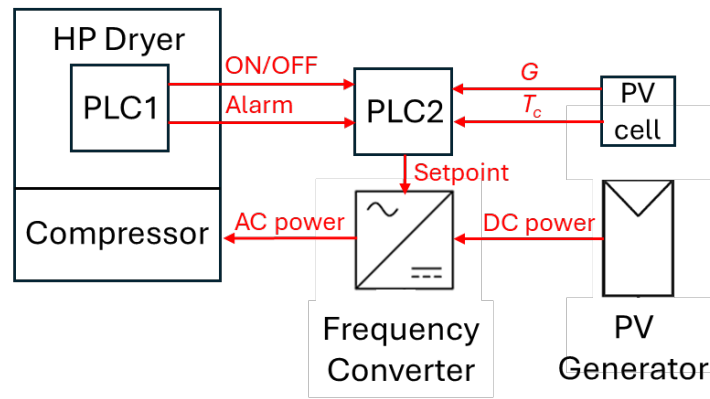


Figure 20: Schematic of the PV-HP dryer prototype. It is composed of a HP dryer with an internal PLC1 (which controls the HP fans and expansion valve), a FC (which controls the compressor of the HP) powered by the PV generator and controlled by an external PLC2 (which reads the PV’s operating conditions from a calibrated PV cell).

The HP dryer is optimized for extracting the humidity from the air, generating a very dry airflow with a high humidity absorption capacity. This air flow is forced through the alfalfa bale (that has been previously introduced in a drying box), absorbs its humidity, and returns to the HP unit in a closed cycle. Figure 21 shows this drying infrastructure as it was installed in 2023. In 2022, the air ducts were made of carbon fiber and could not withstand the pressure of the air impulse: they opened in several points during the drying experiments, allowing some air exchange with the ambient. This did not prevent the alfalfa from being effectively dried but made it impossible to calculate the volume of water extracted in the process (which is needed for the characterization of the drying process, as will be explained in Section 3.3). In 2023, these air ducts were replaced by aluminum ones, as shown in Figure 21, which are much more

resistant to the air pressure. Consequently, the results of 2022 are only effective for evaluating the performance of the PV system, but not for characterizing the drying process. The results for 2023 are valid for both: once the air ducts were replaced and the air moved in a closed circuit without any leaks, it was possible to estimate the water extracted by measuring the weight loss of the alfalfa after the drying test.



Figure 21: Drying infrastructure of the prototype of 2023. It consists of an HP dryer unit (which extracts humidity from the air), the inlet and outlet aluminum air ducts and the drying box (where the alfalfa bale is). The red arrows indicate the air flow direction.

Table 9: Technical specifications of the HP dryer, its compressor, the PV generator and the Frequency Converter.

Heat Pump Dryer	
Manufacturer	GENAQ
Model	Nimbus N500-4.2
Nominal Power	4.1
Moto compressor	
Manufacturer	Frascold
Model	D4-18.1Y
Nominal AC power (kW)	3
PV generator	
Orientation	0° (South oriented)

Inclination	30°
Nominal DC power, P_{MPP} (kW)	6.6
Modules in series per string	14
Strings in parallel	1
Module manufacturer	Solarwatt
Module model	Panel Classic P1.0 pure

Frequency converter

Manufacturer	ABB
Model	ACS310-03E-17A2-4
Nominal AC power (kW)	7.5

4.2.2. Validation of the PV System and Control System

The quality of a PV system is typically assessed in terms of the PR , which is the ratio between the AC energy produced by the PV system during a certain period (E_{AC}) and the DC energy that could have been ideally produced:

$$PR = \frac{E_{AC}}{\frac{P_{MPP}^*}{G^*} \int G(t) dt} \quad (2)$$

where P_{MPP}^* is the maximum power of the PV generator at STCs, and G^* is the global irradiance at STC.

The main limitation of the traditional PR is that it was conceived for grid-connected systems, which, theoretically, can use all the available irradiance to generate AC power. However, when the PV generator powers an intermittent electric load, such as the compressor of a HP, the PR is affected by additional factors, which do not depend on the quality of the system itself (i.e, the drying period may not be the whole year, the compressor only operates within a certain power range). These factors can generate PV losses and lower the PR . In order to separate these intrinsic losses from those caused by a malfunction, the traditional PR has been factorized as follows [77]:

$$PR = PR_{PV} \times UR_{Dp} \times UR_{PVHP} \times UR_{EF} \quad (3)$$

where the three Utilization Ratios (URs) are defined in Table 10 [106]:

Table 10: Definition of the Utilization Ratios (URs) proposed for the factorization of the PR for PV-HP systems [106].

$PR_{PV} = \frac{E_{AC}}{P_{MPP}^*/G^*} \times \frac{1}{\int G_{used} dt}$	<p>This is the PR considering only losses strictly associated with the PV system itself, i.e., actual versus nominal peak power, dirtiness, thermal and DC/AC conversion losses. It is intrinsic to the technical quality of the PV components and its maintenance. G_{used} is the irradiance effectively used by the system, considering only the periods of time when the compressor is functioning.</p>
$UR_{Dp} = \frac{\int_{Dp} G dt}{\int G dt}$	<p>This is the ratio of the total irradiation, which is the integration of the irradiance along a period of time throughout the drying period (Dp), to the total annual irradiation. It is intrinsic to a given crop. Note that it can only be applied to the annual period.</p>
$UR_{PVHP} = \frac{\int G_{useful} dt}{\int_{Dp} G dt}$	<p>This is the ratio of the irradiation necessary to deliver the power required by the compressor to the total irradiation throughout the Dp. It is intrinsic to the drying system design; specifically, it depends on the power range of the operation of the compressor, the ratio between the PV peak power and the PV power demanded by the HP, and the maximum number of starts per hour recommended by the compressor's manufacturer. G_{useful} is the irradiance considered during the periods of time when the PV power is within the power range of operation of the compressor.</p>
$UR_{EF} = \frac{\int G_{used} dt}{\int G_{useful} dt}$	<p>This is the ratio of the irradiation required by the compressor during the drying schedule to the irradiation necessary to deliver the power required by the HP. It is intrinsic to both the availability of product to be dried and to the end user's behavior.</p>

Additionally, the PR_{PV} has been corrected to STCs to obtain an indicator that does not depend on the climatic conditions of a certain location or period:

$$PR_{PV,STC} = \frac{E_{AC}}{\frac{P_{MPP}^*}{G^*} \int G_{used}(t) [1 - \gamma(T_c(t) - T_c^*)]^{\frac{\eta(G)}{\eta^*}} dt} \quad (4)$$

where γ is the coefficient of variation of P_{MPP} with T_c , $\eta(G)$ is the efficiency of the PV generator at the given G , and η^* is the efficiency at STCs. Note that the $PR_{PV,STC}$ allows for the comparison of different systems regardless of the system size, the drying schedule and the location.

The G and T_c measurements required for these calculations were given by a calibrated PV cell installed on the plane of the PV generator. The voltage and current were monitored at both the input and output of the FC to estimate DC and AC energy consumption. The monitoring frequency was 1 min.

Finally, the control of the system was evaluated in terms of the stability against PV power fluctuations due to cloud passing. These power fluctuations imply a voltage drop at the DC bus of the FC, with two potentially negative consequences:

If the DC voltage drops below a minimum value, there is an undervoltage alarm at the FC and the system stops abruptly. Abrupt stops are undesirable because they reduce the lifetime of the system components, mainly the FC and the compressor. If the operating voltage of the PV generator approaches the minimum value, the PLC orders a controlled (i.e., slow) stop of the FC.

When the DC voltage drops, so does the frequency of the compressor; if it operates below the minimum value specified by the manufacturer for more than 3 s, the PLC orders a controlled stop. Otherwise, there is risk of overheating in the compressor and of damage in the refrigerant circuit due to excessive vibrations.

The control system that must deal with power fluctuations is based on PID control, implemented at the FC, which requires manual tuning [106]. The ability of this control system to deal with power fluctuations was evaluated through the number of undervoltage alarms at the FC and the number of overheating alarms at the HP dryer.

4.2.3. Characterization of the Drying Process

One of the main challenges of this experimental work was to accurately determine the humidity of the alfalfa bales, how it was distributed and at what

rate it was extracted. Bales are greatly heterogeneous in terms of pressure and composition (the leaves do not have the same humidity as the stems), so it is possible to register very different humidity levels even among very close areas. Additionally, the alfalfa is compressed at very high pressures, which makes it difficult to force the air through it homogeneously (the external areas typically offer preferential ways for the airflow, which tends to avoid the core).

To characterize the humidity of the bales before and after each drying test, the relative humidity (RH) was measured in 60 equally distributed points. This allowed for the estimation of the average RH—initial (RH_i) and final (RH_f)—and its distribution. The quality control for deciding whether a bale was satisfactorily dried consisted of assuring that all 60 points had less than 16% of RH. To obtain a more accurate estimation of the volume of water extracted during the drying process, the bale was weighted before and after each test. The weight loss correlates with the volume of water extracted from the alfalfa (Vol_w). The energy consumption per liter of water extracted was calculated dividing the E_{AC} by the Vol_w .

Finally, temperature and humidity sensors were located in the inlet and outlet air ducts to monitor the evolution of the RH during the experiment. The intention was to determine when the 16% goal was reached, in order to characterize the energy consumption up to that point. However, these sensors provided values for the total volume of water extracted that did not match the values indicated by the weight scale. After trying several locations for the sensors, it was concluded that it was very complicated to obtain a representative measurement of the heterogeneous air flow only with two points. More precise ways of monitoring these variables should be explored in future experiments.

4.3. Results and Discussion

This section presents the results of the validation of the PV system and control system, obtained during the 2022 and 2023 experimental campaigns. The results of the characterization of the drying process are also presented, but only for 2023 (as it was already explained, in 2022 the experimental setup presented some deficiencies in the air ducts design, which were solved for the second campaign).

4.3.1. Validation of the PV System and Control System

Table 11 presents the values for the PR, PR_{PV} , $PR_{PV,STC}$ and the URs, together with the daily global irradiation on the plane of the PV generator (G_d) and the average daily T_c for the 2022 and 2023 campaigns. All these parameters, except for the T_c , are obtained by integrating minute values of AC power and solar irradiance (according to the equations shown in Section 3.2) for those days when a drying test was performed. The total values for 2022 and 2023 are the sum of these days. The $PR_{PV,STC}$ is calculated according to Equation 4, using minute values of the T_c , rather than the average value presented in this table. Note that the UR_{Dp} is not reported because all the experiments were performed during the alfalfa season, which is precisely the drying period for this crop (hence, $UR_{Dp} = 1$).

Table 11: Values for the PR, PR_{PV} , $PR_{PV,STC}$ and the URs defined in the methodology section, together with the daily global irradiation on the plane of the PV generator (G_d) and the average daily T_c for the 2022 and 2023 campaigns.

Date	PR	PR_{PV}	UR_{PVHP}	UR_{EF}	$PR_{PV,STC}$	G_d (kWh/m ²)	T_c (°C)
09/07/2022	0.69	0.81	0.88	0.96	0.98	5.37	68.51
10/07/2022	0.51	0.77	0.70	0.94	0.92	5.67	66.88
11/07/2022	0.40	0.82	0.49	1.00	0.98	3.67	69.24
20/07/2022	0.65	0.82	0.80	1.00	0.97	2.53	64.37
21/07/2022	0.54	0.80	0.69	0.99	0.93	5.17	60.24
26/07/2022	0.38	0.87	0.71	0.61	0.98	3.98	49.83
28/07/2022	0.64	0.81	0.85	0.93	0.96	5.66	43.22
29/07/2022	0.28	0.85	0.84	0.39	0.98	6.29	41.37
01/08/2022	0.26	0.80	0.92	0.35	0.97	4.70	68.32
02/08/2022	0.53	0.82	0.95	0.68	0.96	5.54	62.76
17/08/2022	0.32	0.89	0.55	0.66	0.99	3.90	37.41
04/10/2022	0.60	0.81	0.86	0.86	0.96	4.30	46.10
05/10/2022	0.61	0.87	0.81	0.86	0.96	4.90	35.54
Total 2022	0.49	0.82	0.81	0.74	0.96	61.68	54.91
07/08/2023	0.37	0.84	0.79	0.56	0.91	1.76	37.09
10/08/2023	0.26	0.84	0.80	0.38	0.93	5.58	60.96
23/08/2023	0.63	0.81	0.91	0.86	0.94	3.85	65.26

24/08/2023	0.25	0.87	0.85	0.34	0.96	5.61	56.23
25/08/2023	0.49	0.85	0.84	0.68	0.94	4.37	51.19
07/09/2023	0.08	0.85	0.78	0.12	0.93	5.21	41.58
08/09/2023	0.56	0.87	0.70	0.92	0.95	5.18	42.49
09/09/2023	0.63	0.85	0.79	0.94	0.93	5.46	41.22
10/09/2023	0.58	0.83	0.82	0.86	0.96	6.08	44.53
27/09/2023	0.36	0.85	0.45	0.94	0.92	4.35	35.31
28/09/2023	0.41	0.82	0.74	0.68	0.94	5.80	45.47
11/10/2023	0.30	0.84	0.89	0.40	0.94	5.71	42.87
13/10/2023	0.34	0.87	0.45	0.87	0.95	2.60	29.38
Total 2023	0.40	0.85	0.75	0.64	0.94	61.58	45.66

The traditional PR presented values of 0.49 and 0.4 for 2022 and 2023, which could seem too low if compared to what could be expected from grid-connected systems (typically above 0.8 [77, 108]). Without further considerations, this could lead to the believe that the PV system is underperforming. However, the PR_{PV} , that considers only the periods of time when the PV energy can be consumed by the HP drying system, presents values of 0.8 and 0.85, consistent with a good performance of the PV generator and FC. The difference between both PR_s comes from the UR_{PVHP} , which reflects the energy losses associated to the design of the PV-HP Dryer (with values of 0.81 and 0.75 for 2022 and 2023), and from the UR_{EF} , which reflects the energy losses associated to the availability of alfalfa and the end user's behavior (with values of 0.74 and 0.64). In general terms, the second contributed more to reduce the PR than the first.

Regarding only the UR_{PVHP} , all the daily values are bigger than 0.7 except for three days (highlighted in grey in Table 11). These unusually low ratios are a consequence of the control implemented to manage PV power fluctuations. As explained in the methodology section, this control orders the compressor to stop if the available PV power is not enough to reach the minimum frequency of the compressor. The problem is that the manufacturer of the compressor recommends a maximum of 6 starts per hour. For days with a lot of sunny-cloudy intervals, this maximum was eventually reached, and the compressor remained stopped for the rest of the hour, even if the available PV power permitted to restart it. This can be observed in Figure 22, that is discussed further in this section. This could be partially mitigated with an IA-based control, that could

analyze the cloud patterns to estimate the magnitude and duration of the power fluctuation. This way, some unnecessary stops could be avoided. On the other hand, the UR_{PVHP} reached values bigger than 0.7 for the rest of the days and even bigger than 0.9 for very sunny ones. This indicates that the sizing of the system components (mainly PV generator and HP compressor) is quite optimized.

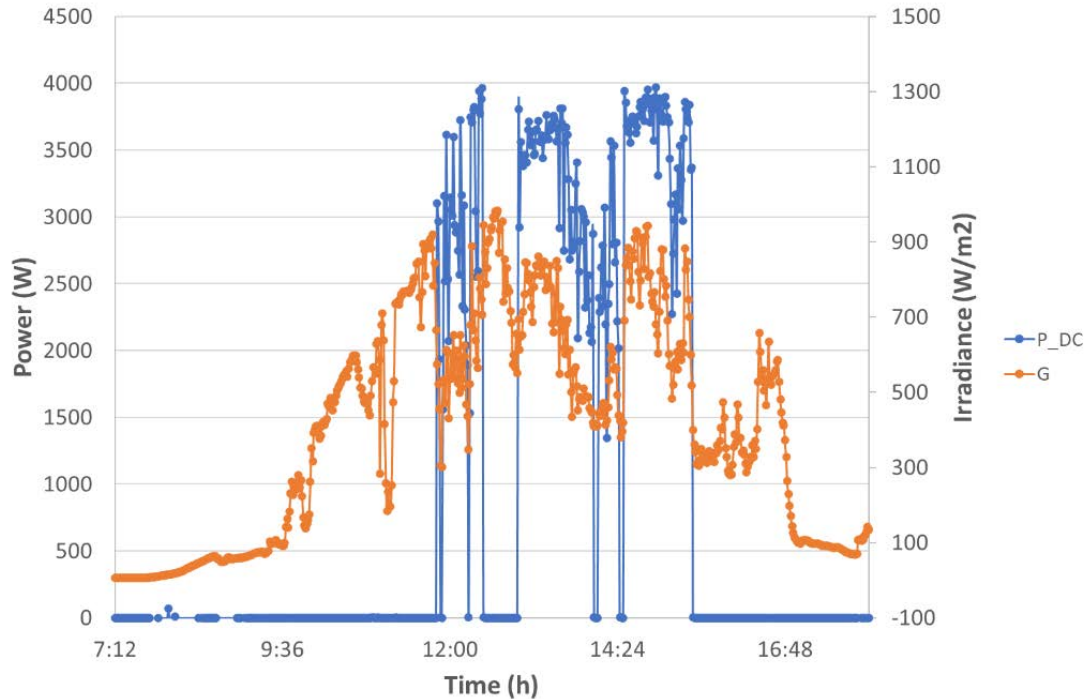


Figure 22: Solar global irradiance on the plane of the PV generator (orange) and DC power consumption of the HP dryer (blue) for a day with many passing clouds (27/09/2023).

The UR_{EF} is the indicator that presents bigger variability, as it responds to external factors that do not depend on the design or the control of the PVHP dryer. In Table 11, there are three values highlighted in grey that are examples of such variability. The minimum value of 0.12 indicates that there was no alfalfa available during most of the day, due to limitations in local production. The maximum value of 1 indicates that the alfalfa was available and already introduced in the drying box when the PV power permitted to turn on the HP. Note that an UR_{EF} of 0.12 leads to a PR of 0.08, a very low value that once again is not caused by the underperformance of the PVHP system (the PR_{PV} for that same day was 0.85). In an industrial installation, the availability of alfalfa would be almost guaranteed during the drying period, so such low UR_{EF} values would not be likely to appear.

The last indicator shown in Table 11 is the $PR_{PV,STC}$, which is the PR_{PV} corrected to STC by eliminating thermal losses and low-irradiance losses. This way, the $PR_{PV,STC}$ reflects the performance of the PV system considering only the irradiance that can be effectively used by the HP dryer, independently of the location and climatic conditions during the experiments. The total values for 2022 and 2023 (0.96 and 0.94, respectively) indicate a very good performance of the system. The efficiency of the FC during the experiments was 0.96 on average, so the $PR_{PV,STC}$ mainly reflects the DC/AC conversion losses.

From these KPIs, the most useful ones in order to compare the performance of this system with the performance of other PV systems are the PR_{PV} (that compares PV systems regardless of the application) and the $PR_{PV,STC}$ (that compares PV systems regardless of the location and climatic conditions). Table 12 presents the mean and standard deviation of the daily values of these two KPIs, considering the 2022 and 2023 campaigns. According to this table, we could expect a PR_{PV} of 0.84 for a PV system operating in summer in a region with similar climatic conditions as La Rioja (Spain), regardless of its application and whether it is grid-connected or stand-alone. For systems operating under climatic conditions, we could expect a $PR_{PV,STC}$ of 0.95. This result is actually very similar to a previous PVHP system validated by the UPM (which accomplished 0.96 for MPPT tests) [93], although the HP technology and application were different.

Table 12: Mean and standard deviation of the daily values of the PR_{PV} and the $PR_{PV,STC}$, considering the 2022 and 2023 campaigns.

	PR_{PV}	$PR_{PV,STC}$
Mean	0.84	0.95
Standard deviation (%)	2.68	2.15

Finally, the PV control system was evaluated for resisting PV power fluctuations without abrupt stops of the system (caused by undervoltage alarms for the FC or overheating alarms for the compressor). At the beginning of the 2022 campaign, the PID control was tuned for allowing a quick start-up of the compressor (so that it reached the minimum frequency in less than 3 s), without undervoltage alarms in the FC. If the start-up is too fast, the DC voltage of the PV generator decreases very abruptly from the open-circuit point, with the risk of falling under the minimum voltage required for the FC. This was achieved with the following PID

parameters: proportional gain of 0.1 (tuned for a correct start-up), integral time of 0.1 s (tuned for fast PV power fluctuations) and a derivative time of 0 s (as there is too much electrical noise that otherwise would destabilize the control). This tuning of the PID control allowed it to operate during the rest of the 2022 and 2023 campaign without any alarm or abrupt stop. Figure 22 shows G and the DC power consumption of the HP dryer (P_{DC}) for a day with many passing clouds (27/09/2023). The HP dryer starts operating around 11:50 h, when the solar PV power allows the compressor to reach its minimum frequency. It can be observed that there are three consecutive start-ups and stops due to irradiance fluctuations, followed by two more stops close to noon. After these five stops (all of them ordered by the PLC, so there was no alarm in the FC), the compressor remains stopped until 13:00 h, due to the limitation of six starts per hour that was already mentioned. This is precisely what decreases the UR_{PVHP} during days with many passing clouds. After this, note that the system continues to operate until 15:30 h with only two more controlled stops, regardless of the abrupt irradiance fluctuations.

4.3.2. Characterization of the Drying Process

Table 13 shows Vol_W (L), the AC drying consumption per liter (kWh/L), RH_i and RH_f (%) and drying times (h) for the drying tests performed in 2023, after the air ducts from the first prototype (which allowed for air-leaks) were replaced by aluminum ones (which are much more resistant to air pressure). The first aspect that was evaluated was whether the RH of the alfalfa bales was less than 16% after the drying test, so it could be considered safe to transport them without risk of fermentation. Note that, from a total of 12 samples on 13 different days, all were satisfactorily dried, except for two samples (highlighted in grey): sample 4 was dried up to 19.4% (most of the 60 measured points actually exhibited RH of less than 16%, but there was a very moist portion of the bale that the air flow was unable to dry); sample 6 was hardly dried during the date 07/09/2023 (its RH went from 28.2% to only 27.2%) because the alfalfa was not available for most of the day (as reflected by the UR_{EF} in Table 11), so it was left inside the drying box for a second test, after which it reached an average RH of 16%.

Table 13: Volume of water extracted (Vol_w), AC drying consumption, initial and final relative humidities (RH_i and RH_f) and drying times for the drying tests performed in 2023.

Sample	Date	RH _i (%)	RH _f (%)	Drying Time (h)	Vol _w (l)	AC Consumption (kWh/L)
1	07/08/2023	18.3%	13.7%	1.0	3.96	0.90
2	10/08/2023	21.1%	6.7%	2.1	11.12	0.70
3	23/08/2023	21.1%	7.3%	3.8	13.60	0.96
4	24/08/2023	28.5%	19.4%	2.3	8.28	0.92
5	25/08/2023	27.1%	10.2%	3.3	14.73	0.79
6	07/09/2023	28.2%	27.2%	0.7	1.03	2.41
6	08/09/2023	27.2%	16.0%	4.6	11.44	1.46
7	09/09/2023	29.6%	1.8%	5.1	20.22	0.99
8	10/09/2023	27.4%	1.0%	5.3	18.26	1.11
9	27/09/2023	20.1%	10.4%	3.0	6.97	1.34
10	28/09/2023	18.6%	0.4%	3.5	11.48	1.16
11	11/10/2023	25.4%	14.5%	2.9	11.50	0.83
12	13/10/2023	17.9%	11.9%	1.7	5.37	1.03

The drying time was calculated considering only the periods when the compressor was operating. Comparing this table with Table 11, it can be observed that this time is correlated with the UR_{EF} (the bigger the UR , the longer the drying test), so it is strongly affected by the alfalfa availability. As a consequence, the tests had a duration between 1 h and 5.3 h, from the moment the alfalfa was introduced in the drying box to the moment when there was not enough solar power available (at the end of the day). The difference between the RH_i and the RH_f depends strongly on this drying time (among other factors such as the bale's homogeneity). For most cases (except for samples 7 and 8), the PVHP dryer was capable of correctly drying the alfalfa bales below 16% of RH in less than 5 h, even when the RH_i was greater than 25%. This seems reasonable if compared to commercial installations (that report drying times of around 3 h).

Figure 23 shows the volume of water extracted during the experiments versus the difference between RH_f and RH_i in the same test. Both variables are linearly

correlated, with $R^2 = 0.98$. This finding implies two things: it validates the method for the RH estimation (if this method was not accurate, there would be more dispersion in this figure) and it opens the possibility of estimating the RH level during the experiments by knowing only the RH_i and measuring the volume of water condensed inside of the HP unit. However, note that the slope of the line that correlates the volume and the RH is specific to a given volume of alfalfa.

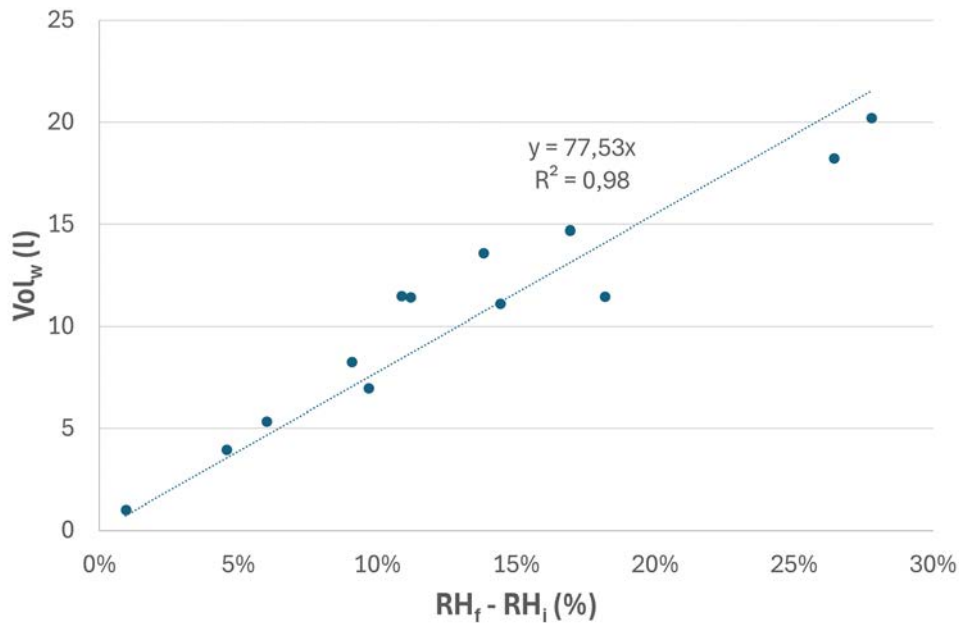


Figure 23: Volume of water extracted (L) versus the difference between the initial and final relative humidities (%) for all the drying tests reported in Table 13.

The third relevant variable for this analysis is the drying AC energy consumption (i.e., the AC energy needed for extracting 1 L of water). Commercial diesel-powered installations report consumptions between 0.5 and 1 kWh/L, while the PVHP dryer moved in the 0.7–2.41 kWh/L range. To understand this significant variability, the authors selected three days when the total volume of water extracted was similar when calculated by weight difference (with values reported in Table 13) and when calculated with the humidity and temperature sensors in the air ducts. When the difference between both values was less than 10%, the measurements from the sensors were considered to be reasonably reliable. The main advantage is that they allow us to see how the consumption per liter varies along the drying process, as shown in Figure 24. This figure leads to the following discussion:

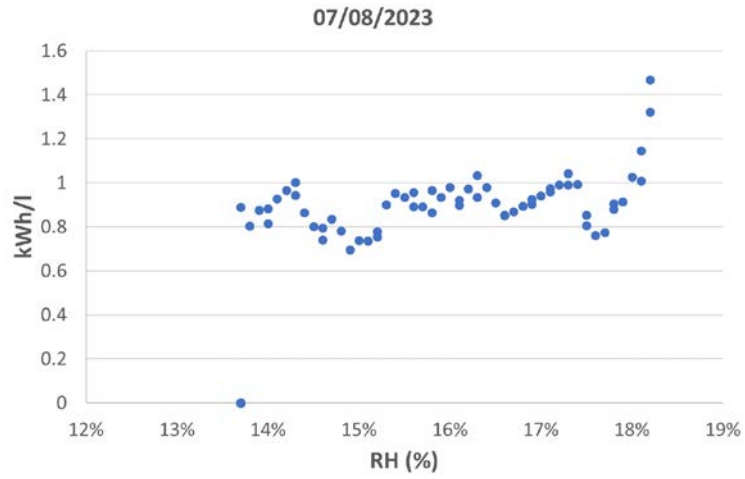
At the beginning of the drying test (i.e., when the RH is higher), the energy consumption is very high but decreases drastically after reducing the RH by approximately 1%. This behavior is observed over the three days. The reason is that, when the HP unit is turned on, the refrigerant temperatures at the evaporator and condenser require a few minutes to stabilize and reach the optimum values for drying the air. During this time, the PVHP dryer does not extract the water efficiently, so the energy consumption increases.

In Figure 24b,c, after the energy consumption reaches a minimum, it increases again, slowly at first, and then quite abruptly. This abrupt increase occurs at different RH levels and has different causes. In Figure 24b, the RH reaches lower values than 10%, so, at the end of the experiment, the alfalfa was very dry. In this situation, the air flow absorbs little water during each recirculation (mainly because there is little water to extract), which increases the specific energy consumption. In Figure 24c, on the other hand, the increase in energy consumption occurs at RH levels higher than 20%, and the target value of 16% is never reached. In this case, the reason is an incorrect fit of the alfalfa bale inside of the drying box, which left open spaces for the air to pass through, instead of flowing through the alfalfa. These spaces increase when the alfalfa loses water and, consequently, the volume, which explains the increase in the specific energy consumption at the end of the experiment. Finally, Figure 24a does not present this abrupt increase at the end because the experiment stopped at a medium RH level, and there was a proper fit inside the drying box.

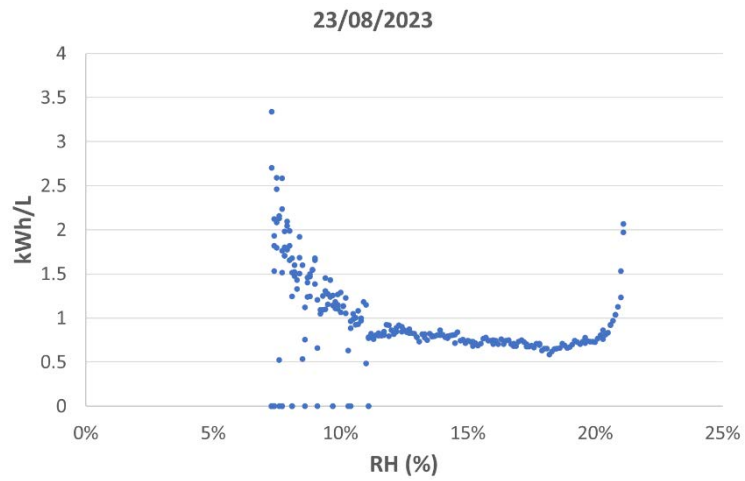
This allows us to identify the main sources of the variability observed in the energy consumption per liter of water extracted, which are as follows:

The RH levels during the drying process, specially the RH_f . There are two possibilities for reducing this uncertainty: by using a more accurate monitoring system for the humidity and temperature of the air flow, which allows us to know the RH at any moment, or by directly measuring the volume of water condensed inside the HP unit. If the RH_i is well known, it is possible to know how many liters of water must be extracted for reaching the optimum 16% (as seen in Figure 23).

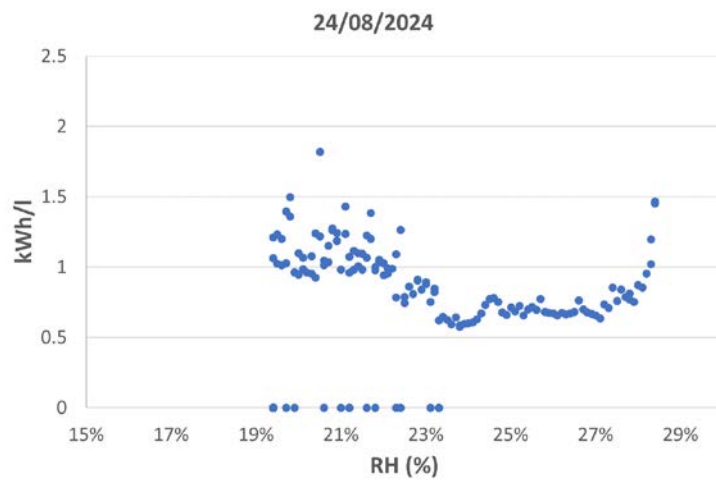
The correct or incorrect fit of the alfalfa bale inside of the drying box conditions the efficiency of the air flow to absorb water. This could be mitigated with an advanced design of the drying infrastructure, by changing the orientation of the box so that the weight of the alfalfa ensures a good fit by gravity.



(a)



(b)



(c)

Figure 24: AC energy consumption per liter of water extracted (kWh/L) versus the relative humidity of the alfalfa (%) for three drying tests when the bale was dried up to 14% (a), 7% (b) and 19% (c) of relative humidity

If we now go back to Table 13, we can assume that the highest energy consumption (2.41 kWh/L the day 07/09/2024) was an anomaly. That day, the test begun late (because there was no alfalfa available) and lasted less than 1 h. Therefore, it was strongly affected by the high energy consumption at the beginning of the experiments (as shown in Figure 24). If we disregard this day, the range of energy consumption per liter spans from 0.7 to 1.46 kWh/L for the rest of the experiments. These values are much closer to those reported by diesel-powered systems and can be further lowered with the improvements described for the monitoring system and the drying box.

4.4. Conclusions and Future Work

This work presents the results of the technical validation of a PVHP drying system for alfalfa bales, a high-value agricultural product that is traditionally dried with diesel-powered systems. The high operational costs of these driers have put the economic viability of the alfalfa crop at risk, making it necessary to explore other alternatives. The PVHP technology proposed here is based on a HP unit that optimizes air drying (instead of simply heating the air) and is powered only by a PV generator (without grid or battery support, which complicates the economic feasibility of the solution). This technology offers several advantages: energetic independence, modularity, low operational costs and low environmental impact. An initial demonstrator was validated in real operating conditions for two consecutive drying campaigns (2022 and 2023) in La Rioja, a region in the North of Spain. The results were promising, showing that the drying of alfalfa bales using this technology is technically feasible.

First, the quality of the PV system control was evaluated in terms of the utilization of the solar resource (a factorization of the traditional PR is proposed to differentiate among different types of energy losses). The PR_{PV} , which considers only the irradiance that could be used by the HP unit, presented an average value of 0.85, comparable to that of a well-performing grid-connected PV system. The $PR_{PV,STC}$, which is the PR_{PV} corrected to STCs and is independent of the climatic conditions during the experiments, showed an average value of 0.95. This is representative of what could be expected from future PVHP dryers. The

UR_{PVHP} and the UR_{EF} , which quantify the solar energy losses, indicated proper sizing of the system components and that the main cause of energy losses was the availability of alfalfa.

There were no abrupt stops of the system caused by PV power fluctuations due to cloud-passing, demonstrating that batteries are not necessary for this application. They could of course increase the operating time, but this is not critical for drying alfalfa (as this crop is only harvested over 3–4 months per year). In fact, in the region where this work was validated, there are plans to install a PVHP dryer that consumes the PV surplus of a large PV generator mainly devoted to irrigation.

As for the quality of the drying, all the samples, except for one, were satisfactorily dried, reaching RH_f of less than 16%, which is the critical value for avoiding fermentation. The drying times (1–5 h) were reasonable if compared to current diesel-powered systems. The specific energy consumption (0.7–1.46 kWh/L) was in some cases higher than that of diesel-powered systems (0.5–1 kWh/L) but is susceptible to being reduced with a better design of the drying box.

In order to make this PVHP drying technology commercially feasible, the following improvements should be explored and implemented:

- An accurate monitoring system for the humidity and temperature of the air flow, which allows for the determination of the RH at any moment. If this is not possible due to the heterogeneity of the air flow, a simpler solution would be to directly measure the volume of water condensed inside of the HP unit. This would allow for determining the optimum RH_i and RH_f to reduce the energy consumption.
- Designing a drying box that ensures a better fit of the alfalfa bale, forcing the air flow through the core and reducing both energy consumption and drying times. For this, a better understanding of the fluid dynamic inside of the box would be needed, in order to evaluate the pressure and temperature gradients.
- Integrating an AI-based control system for minimizing the number of stops per hour during cloudy days, reducing the UR_{PVHP} losses by improving the use of the solar resource and extending the lifetime of the compressor.
- The solution proposed should be validated in different seasons and climatic conditions to generalize the results. Specially, the cloud-passing control

algorithm could need different tuning, depending on the local cloud-patterns. There are already two previous works by the IES-UPM that validated the cloud-passing control algorithm for long term operation in PV irrigation systems [93] and a stand-alone PVHP system for cooling applications [106].

In general terms, this PVHP dryer technology has proven effective for drying alfalfa bales in a region with warm and humid climatic conditions, using 100% renewable energy and without the need of battery support. This could lead to economic savings of up to 40% in terms of *LCOE*, if compared to diesel-powered systems [105]. Additionally, this technology is complementary to PV irrigation systems: the same PV generator can be used for both applications, using the PV surplus from irrigation for the HP drier and improving the energetic and economic efficiency of the whole. Finally, note that the combo HP dryer + PV generator, with the cloud-passing control algorithm, is valid for any low-temperature drying application, independent of the drying infrastructure that is needed.

5. Conclusions

The general objective of this thesis is the development of a prototype alfalfa dehydrator powered by a photovoltaic heat pump, to validate its technical feasibility and explore its economic viability. This general objective is broken down into the following specific objectives:

- **Development of alfalfa dehydrators** that combine heat pump technology with photovoltaic technology for 100% renewable dehydration.
- **Making alfalfa cultivation viable** by integrating the added value of dehydration, commercialization, and export through the installation of photovoltaic dehydrators.
- **Demonstration and widespread dissemination of this innovative technology** by installing a prototype in real operating conditions.

The main contributions of this thesis to these objectives have been:

- No abrupt system stops were caused by PV power fluctuations due to cloud cover, proving that batteries are not necessary for this application.
- The PR_{PV} , which considers only the irradiance that could be used by the HP unit, presented an average value of 0.85, comparable to that of a well-performing grid-connected PV system. The $PR_{PV,STC}$, which is the PR_{PV} corrected to STCs and is independent of the climatic conditions during the experiments, showed an average value of 0.95. This is representative of what could be expected from future PVHP dryers. The UR_{PVHP} and the UR_{EF} , which quantify the solar energy losses, indicated proper sizing of the system components and that the main cause of energy losses was the availability of alfalfa.
- The drying times (1–5 h) were reasonable if compared to current diesel-powered systems. The specific energy consumption (0.7–1.46 kWh/L) was in some cases higher than that of diesel-powered systems (0.5–1 kWh/L) but is susceptible to being reduced with a better design of the drying box.
- The main economic indicators: $PI > 1$, $IRR > 0.8\%$, $PBP = 3\text{-}4$ years, and $LCOE = 0.31\text{-}0.59\text{€}/\text{kWh}$, indicate the feasibility of the investment and cost

savings over the drying equipment's lifetime. The sensitivity analysis reveals that it is not affected by the expected short-term economic trends.

- The PVDS solution could reduce energy consumption by at least 52%, with CO₂ emissions virtually eliminated. This contributes to mitigating the current energy crisis and climate change, which are urgent global challenges, particularly in Europe.

In general terms, the technical feasibility of a stand-alone PVHP drying system has been demonstrated, showing a good performance of the PV system, a good sizing of the system components and good stability against PV power fluctuations. However, the economic potential of the solution is still to be fully exploited to reach the results shown in the economic evaluation. For that, the specific energy consumption must be lowered. In any case, the technology is already competitive in terms of drying times, and its energy consumption costs virtually nothing (once the system is installed).

Future lines of work

In order to make this PVHP drying technology commercially feasible, the following improvements should be explored and implemented:

- **Enhanced Monitoring:** Improve the monitoring of airflow humidity and temperature to determine optimal initial and final relative humidity levels (HR_i and HR_f), reducing energy consumption.
- **Drying Box Design:** Develop a drying box design that optimizes the fit of alfalfa bales and airflow through the core, reducing both energy consumption and drying times.
- **AI-Based Control Integration:** Incorporate AI-based control systems to minimize stops per hour during cloudy days, reducing UR_{PVHP} losses by better utilizing solar resources and extending compressor lifespan. The cloud-passing control algorithm may require fine-tuning to adapt to local cloud patterns. Previous studies by IES-UPM have validated this algorithm for long-term use in PV irrigation systems [106] and standalone PV_{HP} cooling systems [92].

- It is necessary to standardize and regulate the KPIs to enable the comparison of different technologies and climatic conditions, with the aim of improving the process and equipment efficiency.

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