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Review Paper

Main indicators evaluating the performance of Solar Dryers

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Abstract

This article presents a concise review of thirty (30) key performance indicators used to evaluate and optimize the efficiency of solar dryers during the design phase. Solar dryers play a crucial role in food preservation, food safety, and the promotion of sustainable practices. By examining these indicators, the study provides a solid basis for the design, optimization, and assessment of sustainable solar drying systems. The identified indicators are classified according to their relevance in energy, exergy, environmental, and economic analyses. From an energy perspective, drying energy efficiency (η_d) *is the most commonly used parameter. At the environmental level,* CO_2 *emissions dominate performance assessment, while the discounted payback period (PBP) is the most widely applied economic indicator. However, the study emphasizes that relying on a combination of indicators leads to more robust decision-making. For example, in agro-food processing units, both the discounted payback period and net present value are critical economic metrics. Furthermore, the review highlights the exergo-economic indicator (Rex) as essential for optimal solar dryer design. This parameter integrates technical and economic considerations and identifies potential performance improvements at the component level. Consequently, minimizing Rexshould be a primary objective in solar dryer design.*

Keywords: Solar dryers; Performance indicators; Energy efficiency; Environmental impact; Economic analysis.

Introduction

The global challenge of food insecurity remains a pressing concern. The Food and Agriculture Organization of the United Nations (FAO) estimates that between 691 and 783 million people suffered from hunger worldwide in 2022 [1] while nearly 1.3 billion tonnes of food for human consumption are lost every year worldwide[2]. Inappropriate and less efficient preservation methods are essentially the reasons for these food losses along the food value chain. However, drying is known to be one of the best methods for preserving crops, fruit, vegetables and herbs, reducing not only the volume of the raw material but also its weight[3–5].

Product drying is a well-known means of preserving foodstuffs and can make a significant contribution to reducing food losses and, by extension, food insecurity. It reduces product moisture, inhibits internal microbial growth, mould and chemical changes during storage, which extends the shelf life of dried products, improves quality and reduces storage and transport costs[3,6,7]. Sun drying is still by far the most common method of drying. It consists of using surfaces such as the ground, roads or tables, to expose the products to be dried directly to the sun in order to remove their moisture. During sun drying, the product surrounding air typically remains at ambient temperature, i.e. low, resulting in prolonged drying times. This extended duration often leads to a decline in the final product quality, manifested by crop discoloration caused by enzymatic and non-enzymatic browning, and an increased likelihood of mold formation[8]. The increasing development of renewable energies in today's world has led to renewed interest in solar technologies, particularly in the field of converting solar energy into heat for applications such as drying[9]. Solar dryers, as devices for the direct conversion of solar energy into heat for the processing of food, agricultural and industrial products, have been widely studied and deployed in various parts of the world. In comparison to sun drying, solar dryers generally experience elevated temperatures, leading to a reduction in drying time and often resulting in enhanced final product quality. However, to ensure their efficiency and reliability, it is imperative to assess and understand the key performance indicators that govern their operation.

Nomenclature			
UE_d	Minimum useful energy required for drying unit amount of product (kJ/kg)	E_e	Energy embodied (kWh)
x_i	Initial moisture content in % (wet basis)	E_{out_a}	Useful annual energy output of solar dryer

			(kWh/year)
x_f	Final moisture content in % (wet basis)	E_d	Daily thermal output of the dryer (J)
$C_{p_{produ}}$	Specific heat of the product (kJ/kg.°K)	N_d	Number of days within a year during which the solar dryer is in operation or actively utilized
T_d	Drying temperature (°C)	L	Lifetime of the system (in year)
T_a	Ambient temperature (°C)	L_a	Transmission power loss (%)
T	Time required (in days) for drying of a single batch of the product	L_{td}	Transmission and distribution loss (%)
ξ	Fraction of the sensible heating requirement of the product on the first day that is required for sensible heating on other days of drying	EF_{elec}	Emission factor of electricity consumption (kg CO_2/kWh)
l_v	Water evaporation latent heat (J/kg)	CCE	Earned carbon credit ($)
η_d	Overall efficiency of a drying system (%)	D	Exchange rate of carbon credit based international policy ($/tons of CO_2 mitigation)
$M_{pro\ d_i}$	Initial mass of fresh product to be dried (kg),	LCC	Life cycle cost
T_s	Evaporation temperature of moisture inside the product (°C)	CAPE	Initial cost (Capital Expenditure) or initial Investment
T_i	Initial temperature of the product (°C)	OPEX	Cost of labour (operational expenditure), operation, and maintenance
m_w	Mass of water evaporated from the product (kg)	SV	Salvage value of the dryer at the end of its life
t_d	Gross time used for drying samples (h)	LCB	Life cycle benefit
A_d	Dryer-collector surface exposed to the incident solar energy (m^2)	R	Annual benefit
I	Global solar irradiance or incident insolation in (W/m^2)	e	Annual escalation in cost (%)
P_f	Power of the fan used in active mode (W)	d	Interest or discount rate (%)
C_{LPG}	Calorific power of LPG (kJ/kg)	PBP_o	Payback period (basic/ undiscounted)
$\dot{m}_{LPG}$	Flow of consumed LPG (kg/s)	PBP	Payback period (discounted)
t_1, t_2	The start and end dates of drying respectively	S_{annua}	Annual net undiscounted benefits
SMER	Specific moisture extraction rate (kg/kWh)	B_t	Benefit in each year
SEC	Specific energy consumption (kWh/kg)	C_t	Cost in each year
HUF	Heat utilization factor (-)	IRR	Internal Rate of Return (%)
COP	Coefficient of Performance (-)		
T_i	Air temperature at the inlet of the drying chamber (°C)	CRF	Capital recovery factor (-)
T_o	Air temperatures at the outlet of the drying chamber (°C)	UAC	Uniform annualized cost
C_{pa}	Specific heat of the air at constant pressure (kJ/kg °C)	SMF	sinking fund method (-)
DE	Drying effectiveness (-)	NPV	Net present value
RH_o	Relative humidity of air at outlet (%)	R_{en}	Energoeconomic indicator
RH_i	Relative humidity of air at inlet (%)	L_{en}	Energy loss rates (kWh)
η_{ex}	Exergetic efficiency (%)	R_{ex}	Exergoeconomic indicator
Ex_{dco}	Exergy outflow (kW)	Ex_{Loss}	Exergy loss (kW or MJ)
Ex_{dci}	Exergy inflow (kW)	P_{ec}	Cost of equipment purchased
$\dot{m}_a$	Mass airflow rate in the dryer (kg/s)	Z_{CO_2}	Enviroeconomic parameter ($)
Ex_{Loss}	Exergy loss (kW)	ϕ_{CO_2}	Amount of CO_2 reduction (ton)
EPBT	Energy payback time (year)	z_{CO_2}	Price of carbon ($/ton CO_2)

Most studies on solar dryers report thermal performance-related parameters, especially ambient temperature, drying time/drying rate, and drying air temperature[10]. Moreover, physical features of dryers are also frequently reported, mainly the size and shape of solar dryers, collector areas, and solar apertures. However, performance indicators related to economics and environments are rarely reported. Hence, the evaluation procedures of solar dryers generally neglect financial feasibility. Out of a total of six indicators related to the quality of dried food, the moisture content is the only indicator generally measured.

This article aims to provide a comprehensive examination, delving not only into the performance indicators of solar dryers but also on the main parameters that influence these performance metrics.

In the rest of the paper, we will first recall the typology of solar systems. Then, a summary of technical, economic, exergy and environmental performance indicators will be presented. The last part will be devoted to a comparative analysis of these parameters which sheds light on the limits and strengths of these indicators.

Typology of solar dryers: Based on the works of some authors[11–13], solar dryers can be classified according to the operating mode, operation air circulation method, and energy source.

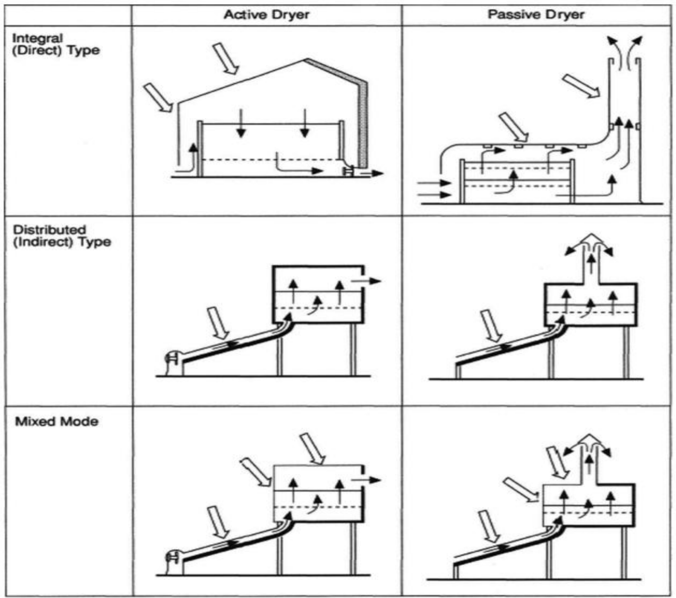


Figure-1: Typology of solar dryers[14].

To compensate for the intermittent nature and diurnal variation of solar energy, storage systems can be integrated into solar dryers[15]. The main features of the above-mentioned solar dryers are described in the following sections.

Classification based on operation mode: Direct solar dryers: Direct solar dryers, known as natural convection dryers, are fairly simple to build and inexpensive. They generally consist of an insulated box with inlet and outlet holes and a transparent sheet of glass/ polyethylene/ polycarbonate[16,17]. The products to be dried are placed in the drying chamber[18]. The heat required for drying is generated by absorbing solar radiation from the product itself and from the internal surfaces of the drying chamber.

Indirect solar dryers: Indirect dryers are characterised by a drying chamber detached from the solar collector, and made up of three main elements: the solar collector, the drying chamber and an air duct for circulation. As the air passes through the solar collector, it is heated and then passed through air ducts into the drying chamber and onto the drying trays. The humid air is evacuated through vents or a chimney at the top of the chamber[19–21].

Mixed solar dryers: Mixed solar dryers are a combination of direct and indirect solar dryers. In these dryers, solar energy is collected both by flat solar collectors and by the roof of the drying chamber[11,22]. They combine both the advantages and disadvantages of direct and indirect solar dryers.

Classification based on operation air circulation method: Natural-circulation or passive solar dryers: Natural-circulation solar-energy dryers operate solely on solar thermal energy. In these systems, air heated by solar thermal energy circulates through the product due to thermosiphon effect or wind pressure[12]. Natural convection solar dryers require minimal expenditure to control drying temperature.

Forced-circulation or active solar dryers: An active solar dryer, in contrast to passive solar dryers, is a system that utilizes fans to circulate air through the crop for the drying process[12]. Forced convection solar dryers necessitate the use of electrically powered fans to achieve enhanced drying rates. However, in many developing countries, limited access to electricity in rural areas or the high costs associated with electricity generation render these dryers impractical for widespread adoption[23].

Classification based on energy source: Conventional solar dryers: They rely solely on solar energy without combining it with other external energy sources.

Hybrid solar dryers: Hybrid solar dryers integrate thermal solar energy with another energy source, such as the public grid, PV solar, gas or biomass, to enhance overall drying efficiency and reliability. In a hybrid solar dryer, drying may continue outside the hours of sunlight thanks to auxiliary energy or energy storage. As a result, drying continues and the product is protected from any deterioration caused by microbial infestation[4,24–26].

The main performance indicators for solar dryers' evaluation: Performance analysis in drying studies is often conducted using four key indicators, referred as to the 4E evaluation (Energy, Exergy, Environmental, Economic)[6,27–29]. Susanto et al.[27] proposes the addition of three (3) other levels of analysis to improve the evaluation of solar dryers. These are energoeconomic, exergo economic, and enviroeconomic analysisas shown in Figure-2. In addition, some studies considered the quality of dried products and physical features as performance indicators for solar dryers[27,30].

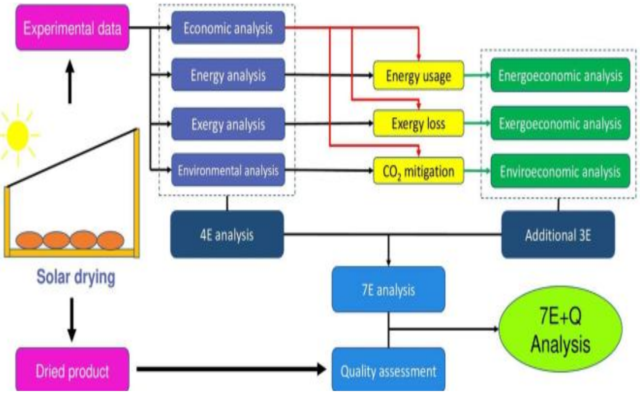


Figure-1: 7E+Q Analysis: A new multi-dimensional assessment tool of solar dryers for food and agricultural products[27].

The performance indicators of these studies are summarized in Table-1. These parameters will be discussed in more detail in the following sections.

Energy indicators: Energy efficiency: The minimum useful energy required for drying unit amount of product ($\boldsymbol{UE_d}$) can be defined as the sum of the energy required for sensible heating of the product ($\boldsymbol{q_{sens}}$) and the energy required for evaporating moisture inthe product ($\boldsymbol{q_{evap}}$)[31,32] as illustrated by the following equations:

$$UE_d = q_{sens} + q_{evap} \tag{1}$$

This equation can be rewritten as follows:

$$UE_d = \left[\left\{\left(\frac{1-x_f}{1-x_i}\right) C_{p_{product}} \left(T_d - T_a\right)\right\} \times \{1 + (\tau - 1)\xi\} + \left\{\frac{x_i - x_f}{1-x_i}\right\} l_v\right] \tag{2}$$

With x_i,x_f the initial and final moisture content in % (wet basis) respectively, $C_{p_{product}}$: specific heat of the product (kJ/kg/°K), T_d: drying temperature (°C), T_a: ambient temperature (°C), τ : time required (in days) for drying of a singlebatch of the product, ξ :fraction of the sensible heating requirement of the product on the first day thatis required for sensible heating on otherdays of drying, l_v : latent heat of evaporation of water (kJ/kg).

Sensible heat is associated with the temperature variation of the product without a change in state, while latent heat is linked to the evaporation of moisture from the product. In many solar drying processes, a substantial portion of energy is used for water vaporization, corresponding to latent heat. Consequently, sensible heat is often neglected compared to latent heat.

Table-1: Summary on solar dryers performance indicators.

Analysis	Indicator/parameter	Observation
Energy	Energy or thermal efficiency (%)	It reflects improved efficiency when its value is closest to 1.
	Specific moisture extraction rate (SMER)(kg/kWh)	A higher SMER indicates that the solar dryer is able to extract more moisture with lower energy consumption.
	Specific energy consumption (SEC)(kWh/kg)	The lower the SEC, the more energy-efficient the dryer, as it uses less energy to evaporate a given quantity of water.
	Heat Utilization Factor (HUF)	The higher the heat utilization factor, the more efficient the drying process is
	Coefficient of Performance (COP)	It is a measure of how efficiently a heat-pump dryer converts energy into useful heat for drying.
	Drying Effectiveness (DE)	High values of DE, are desirable. It is calculated by comparing the amount of moisture removed from the material to the amount of energy used in the drying process
Exergy	Exergetic efficiency (%)	It helps forecast how the system will perform thermally.
Environmental	Embodied energy (kWh)	It refers to the amount of energy used to manufacture a solar dryer. It is considered an indicator of the solar dryer overall environmental footprint.
	Energy Payback Time (EPBT)(year)	EPBT represents the period it takes to recover the initial embodied energy invested in items.
	CO_2 emissions (kg of CO_2/year)	The amount of annual CO_2 emissions from a solar dryer
	Net CO_2 mitigation (kg CO_2)	This indicator represents the dryer's potential to reduce CO_2 emissions over its lifetime.
	Earned Carbon Credit ($)	This environmental performance parameters indicates the contribution of the solar drying system developed to global climate change and the environment.
Economic	Life cycle costs ($)	LCC is the total cost involved over the lifetime of the dryer.
	Life Cycle Benefit (LCB) (in $)	LCB is the total profit that can be obtained over the lifetime of the solar dryer.
	The payback period (PBP) (in year)	It is the time required for the system developed to recover the amount equivalent to that spent on its manufacture.

Analysis	Indicator/parameter	Observation
	Benefit - Cost (B/C) Ratio	A dryer is accepted as suitable provided Benefit-Cost ratio > 1, and the dryer is rejected if Benefit-Cost ratio < 1.
	Net Present Value (NPV) ($)	The calculation of Net Present Value (NPV) serves the purpose of assessing the project's profitability.
	Internal Rate of Return (IRR) (%)	It is utilized to determine the discount rate that makes the present value of benefits equal to the present value of costs in a project.
	Capital recovery factor (CRF)	It represents the constant annuity received from the solar dryer over its lifespan.
	Uniform annualized cost (UAC)	UAC is the annualized total cost of the solar dryer throughout its entire lifespan.
	Sinking fund Method (SFM)	The sinking fund method is used for depreciating a solar dryer, simultaneously generating revenue to facilitate its replacement at the end of its lifespan
	Energoeconomic indicator	A lower R_{en} value is favourable, indicating improved thermal efficiency and reduced energy loss.
	Exergoeconomic indicator	It estimates the overall cost of system inefficiencies.
	Enviroeconomic indicator	It quantifies the system's cost savings due to CO_2 mitigation.
Quality	Color, Texture, shrinkage, Flavour and odor, water activity, nutritional content	The degradation of these indicators can lead to quality degradation of products.

The efficiency of the drying system η_d is defined as the ratio between the energy required to evaporate the moisture and the heat supplied to the dryer[33]. Drying system efficiency also called energy efficiency, is a measure of the overall efficiency of a drying system [6,29,34–39]. It can be calculated using equation (3):

$$\eta_d = \frac{M_{pro\,d_i} \cdot C_{p_{product}} \cdot (T_s - T_i) + m_w\, l_v}{A_d \int_{t_1}^{t_2} I\,dt + C_{LPG} \int_{t_1}^{t_2} \dot{m}_{LPG}\, dt + \int_{t_1}^{t_2} P_f\, dt} \tag{3}$$

Where $M_{pro\,d_i}$: initial mass of fresh product to be dried (kg), $T_i(°C)$: the initial temperatures of the product, $T_s(°C)$: evaporation temperature of moisture inside the product, $C_{p_{product}}$: the specific heat of the product (kJ/kg.°C), m_w: mass of water evaporated from the product (kg), l_v: latent heat of evaporation of water (kJ/kg), A_d : dryer-collector surface exposed to the incident solar irradiance (m^2) (in general, we consider the area of transparent cover. This consideration is valid for direct, indirect and mixed dryers[22,40]) , I: global solar irradiance or incident insolation in (W/m^2) measured by the Pyranometer[41] (It concerns both direct and diffuse solar radiation that strikes a surface), P_f : power of the fan used in active mode (W) (in passive mode, $P_f = 0$), C_{LPG} : calorific power of LPG (kJ/kg), $\dot{m}_{LPG}$: flow of consumed LPG (kg/s) for solar gas hybrid mode, $t_1 and\, t_2$ the start and end dates of drying.

As mentioned above, sensible heat is usually negligible as compared to the latent one. The previous equation can therefore be rewritten as follows:

$$\eta_d = \frac{m_w \cdot L_v}{\int_{t_1}^{t_2} (A_d \cdot I + C_{LPG} \cdot \dot{m}_{LPG} + P_f)\, dt} \tag{4}$$

This indicator reflects improved efficiency when its value is closest to 1. Table-2 shows orders of magnitude of energy efficiency for five solar dryers inventoried by Boroze et al.[11] in West Africa.

Specific moisture extraction rate (SMER): The specific moisture extraction rate (SMER) is an indicator that can be defined as the amount of water evaporated per unit of energy consumption[29,42–46]. The following equation is used to calculate SMER for solar dryer in active mode:

$$SMER = \frac{m_w}{E_{in}} = \frac{m_w}{\int_0^{t_d} (A_d I + P_f) \cdot dt} \tag{5}$$

Table-2: Estimated energy efficiency of some dryers reported by Boroze et al.[11]

Type of solar dryer	Products to be dried	Estimated energy efficiency (η_d)
Traditional drying on a protective sheet (cover dryer)	Maize	8%
Direct cupboard	Tomato	15%
Shell dryer	Tomato	19%
Chamber	Rice	23%
Geho	Cassava pasta	25%

It could be noticed that, when assuming the latent heat constant during the whole drying process, SMER may be directly linked to the energy efficiency by equation:

$$\eta_d = SMER \times l_v \tag{6}$$

With m_w : mass of water evaporated from the product (kg), E_{in} : total energy input (kWh), t_d the gross time used for drying samples (h), A_d : dryer-collector surface exposed to the incident solar energy (m^2), I: global solar irradiance or incident insolationin (W/m^2),P_f : power of the fan used in active mode (W) (in passive mode, $P_f = 0$).

The masse of water removed can be calculated with equation:

$$m_w = \frac{M_{pro\,d_i}(x_i - x_f)}{100 - x_f} \tag{7}$$

With $M_{pro\,d_i}$: initial mass of fresh product to be dried (kg),x_i and x_f:the initial and final moisture content in % (wet basis), respectively.

Gilago et al.[45] compared the performance of a passive indirect solar dryer for carrots drying when operated with or without a paraffin-based heat storage unit. According to the work carried out, the dryer with heat storage showed the best performance. The SMER is improved by 3.31kg/k-Wh compared to dryer without heat storage.

The authors compared theirs results with those obtained by Gilago and Chandramohan[28], on drying green chili in a passive solar dryer (SMER: 0.6526 kg/kWh).

Specific energy consumption (SEC): The specific energy consumption (SEC) is the inverse of the specific moisture extraction rate[6,29,34,45,47,48] as illustrated in equation:

$$\mathrm{SEC} = \frac{1}{\mathrm{SMER}} \tag{8}$$

With SEC in kWh/kg.

The values obtained for the SEC parameter by Gilago et al. [45] for carrots drying shows that drying with energy storage reduces energy consumption by 92%.

Heat utilization factor (HUF): The heat utilization factor is a measure of how efficiently heat is used in the drying process and is relevant basically for both mixed and indirect dryers. It's calculated as the ratio of the temperature decrease of the air in the drying chamber to the temperature increase of the air in the collector. The higher the heat utilization factor, the more efficient the drying process[29,34,49,50].

However, it may be observed that if the drying chamber is not well insulated, a high utilisation factor may be observed as a result of heat loss through the wall of the drying chamber. HUF is determined as follows:

$$HUF = \frac{heat\ removal\ \ in\ the\ drying\ \ chamber}{heat\ supplied\ \ by\ the\ solar\ \ collector} \tag{9}$$

The equation can be rewritten as:

$$HUF = \frac{\dot{m}_a C_{pa}\,(T_i - T_o)}{\dot{m}_a C_{pa}\,(T_i - T_a)} \tag{10}$$

where T_i, $T_o$and T_a the air temperatures at the inlet and outlet of the drying chamber (in °C), the ambient temperature (°C), respectively. C_{pa}: specific heat of the air at constant pressure (kJ/kg °C) and assumed constant[29].

Simplifying equation, we obtain the following:

$$HUF = \frac{T_i - T_o}{T_i - T_a} \tag{11}$$

Coefficient of Performance (COP): The Coefficient of performance (COP) is the ratio of the remain heat output the dryer, to the energy consumed by the dryer[6,29,34,50] as illustrated by equation:

$$COP = \frac{T_o - T_a}{T_i - T_a} \tag{12}$$

$$COP = 1 - HUF \tag{13}$$

where T_i, T_o and T_a are the air temperatures at the inlet-air, outlet-air temperatures of the drying chamber (in °C) and ambient temperature (°C), respectively. Table-3 presents some COP and HUF values obtained in literature.

Drying effectiveness (DE): Drying effectiveness is the ratio of outlet air relative humidity to inlet relative humidity during the drying process as illustrated in equation:

$$DE = \frac{RH_o}{RH_i} \tag{14}$$

With RH_o: relative humidity of air at outlet (%), RH_i: relative humidity of air at inlet (%).

Since drying is essentially a dehumidification process, higher drying effectiveness is desirable[29].

Exergy indicators: Exergy analysis of drying technology is intimately tied to the concept of sustainability. The problem is that not all energy in the system could be efficiently used for drying. For example, low-quality energy like sensible heat in the saturated vapor does not help with drying but rather negatively affects drying performance. Therefore, the evaluation of the process performance should consider only a fraction of the total energy, which is available for drying, or exergy.

The application of the exergy method in solar dryers allows for a detailed analysis at the component level, facilitating the identification and correction of inefficiencies at their source. This method enables a precise determination of losses, aiding in the design of more efficient thermal systems. In the context of a solar dryer, improved efficiency not only enhances performance but also contributes to environmental sustainability by directly reducing potential irreversibility. The exergy approach proves valuable for maximizing the effective utilization of energy resources, promoting environmentally acceptable practices in the design and operation of solar drying systems[29].

The exergetic efficiency η_{ex} of a solar dryer can be calculated as the ratio of the exergy outflow (Ex_{dco} $in\ kW$) to the exergy inflow (Ex_{dci} in kW) for the drying chamber [6,51,52] as illustrated by equation below:

$$\eta_{ex} = \frac{Ex_{dco}}{Ex_{dci}} \tag{15}$$

$$Ex_{dci} = \dot{m}_a C_{pa}\left[(T_i - T_a) - T_a \ln\frac{T_i}{T_a}\right] \tag{16}$$

$$Ex_{dco} = \dot{m}_a C_{pa}\left[(T_o - T_a) - T_a \ln\frac{T_o}{T_a}\right] \tag{17}$$

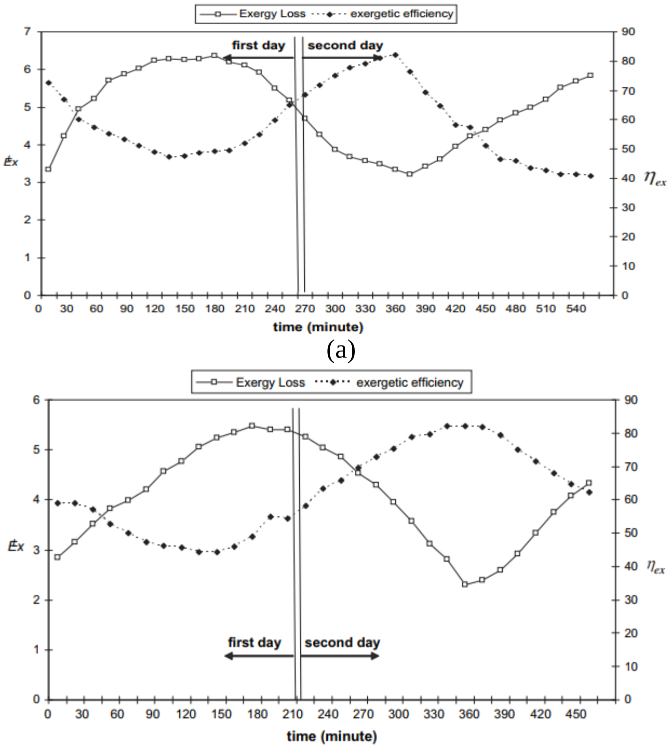
Ex_{dco} can also be estimated as follows:

$$Ex_{dco} = Ex_{dci} - Ex_{Loss} \tag{18}$$

Where $\dot{m}_a$: the mass airflow rate in the dryer (kg/s), C_{pa}: specific heat of the air at constant pressure (kJ/kg°C) and assumed constant[29], T_i, T_o and T_a the air temperatures at the inlet and outlet of the drying chamber (in °C) and the ambient temperature (°C) respectively, Ex_{Loss}: exergy loss (kW).

Figure-2a and 3b, illustrate the evolution of exergetic efficiency during thin-layer drying of mulberry in a forced indirect solar dryer in Elazığ (Turkey), for two different air mass flow rates[51].

In this work, the exergetic efficiency of the drying chamber was evaluated under varying mass flow rates of drying air. For a mass flow rate of 0.014 kg/s, efficiency ranged from 21.3% to 78.7% on the first day and 35.2% to 75.6% on the second day. With a 0.02 kg/s mass flow rate, efficiencies varied from 30% to 61.7% and 38.7% to 83.3% on the first and second days, respectively. At a mass flow rate of 0.026 kg/s, efficiency fluctuated between 40.8% and 82.1%, and for 0.033 kg/s, it ranged from 44.4% to 82.2%. The highest efficiency, 44.4% to 93.3%, was observed at a 0.036 kg/s mass flow rate. It was observed that exergy loss exhibited a decreasing trend with an increase in the drying mass flow rate, while the exergetic efficiency demonstrated an upward trend.



(a)

(b)

Figure-2: The results of the exergy loss and exergetic efficiency for: a) 0.026 kg/s mass flow rateof the drying air, b) 0.033 kg/s mass flow rate of the drying air[51].

Environmental indicators: Environmental performance parameters indicate the contribution of the solar drying system developed to global climate change and the environment.

Table-3: COP and HUF values obtained by some authors[35,50,51].

Type of solar dryer	Products to be dried	HUF Values obtained	COP Values obtained
Modified Greenhouse Dryer (MGD) operating under active mode (AM) and passive mode (PM) with thermal storage[34]	Tomato, capsicum, Potato chips	Active mode: 0.26 – 0.53 Passive mode:0.12 – 0.38	Active mode: 0.58 – 0.73 Passive mode: 0.55 – 0.87
Greenhouse dryer by using insulated north-wall under natural convection mode[49]	tests realized in no load conditions	0.769 (maximum obtained)	0.953 (maximum obtained)
Indirect dryer combined with box solar cooker[50]	Tomato, Fruit, vegetables	0.34	0.66

Embodied energy: Embodied energy is the total energy required to produce any items, goods, or services[53,54]. In the present case, embodied energy refers to the amount of energy used to manufacture a solar dryer. Energy consumption generates carbon dioxide (CO_2), which adds to greenhouse gas (GHG) emissions. As a result, embodied energy is considered an indicator of the overall environmental footprint of items, goods, or services. Table-4 gives embodied energy values for some materials used in the manufacture of solar dryers.

Table-4: Embodied energy of selected materials[6].

Material	Embodied Energy
Aluminum	55.28 (kWh/kg)
Steel	8.89 (kWh/kg)
Galvanized iron	9.67 (kWh/kg)
Copper	19.61 (kWh/kg)
Glass	7.28 (kWh/kg)
Polyvinyl chloride	19.44 (kWh/kg)
Wood	0.31 (kWh/kg)
Wood board	2.89 (kWh/kg)
Black paint	25.11 (kWh/kg)
Polycrystalline cell	1130.5600 (kWh/m^2)
Battery	46.0000 (kWh/m^2)
Solar charge controller	33.0000 (kWh/m^2)
Polycarbonate	10.1974 (kWh/kg)
Rubber gasket	25.64 (kWh/kg)
Silver coating	0.2780 (kWh/m^2)

Energy payback time (EPBT): Energy payback time (EPBT) represents the period it takes to recover the initial embodied energy invested in items, services, or products. It is calculated as follows[55]:

$$EPBT = \frac{E_e}{E_{out\_annual}} \tag{19}$$

Where: E_e: energy embodied (in kWh) and E_{out_annual} useful annual energy output of solar dryer (kWh/year).

The useful annual energy output can be calculated using the following equations[55–57]:

$$E_{out\_annual} = \sum_{d=1}^{N_d} E_d \tag{20}$$

$$E_d = m_w l_v \tag{21}$$

In equation 20, E_d is daily thermal output of the dryer (in J); N_d: the number of days within a year during which the solar dryer is in operation or actively utilized, m_w: mass of water evaporated from the product per day (kg), l_v: water evaporation latent heat (J/kg).

CO_2 emissions: The amount of annual CO_2 emissions from a solar dryer can be calculated using the following equation[6,58,59]:

$$\text{CO}_2 \text{ emission per year} = \frac{E_e}{L} \times \frac{1}{1-L_a} \times \frac{1}{1-L_{td}} \times \text{EF}_{\text{electricity}} \tag{22}$$

With CO_2 emission per year in kg of CO_2/year, E_e: Energy embodied (kWh), L is the lifetime of the system (year), L_a is the transmission power loss (%), L_{td} the transmission and distribution loss (%) and $EF_{electricity}$ the emission factor of electricity consumption (kg CO_2/kWh) which varies according to geographic location/country. For instance, the value of 0.98, is assigned to $EF_{electricity}$, in the works of V. Saini et al.[58] taken place in New Delhi (India). According to the work of A. Jain et al.[55] and P.S. Chauhan et al.[60], emissions for various solar dryers are shown in **Figure-3**.

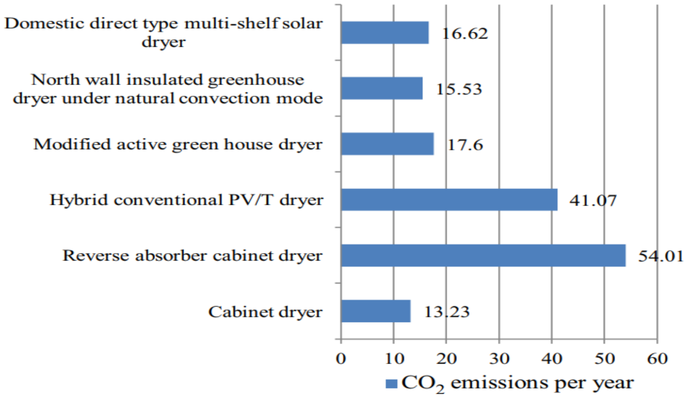


Figure-3: CO_2 emissions (in kg of CO_2 /year) for various solar dryers[55].

Net CO_2 mitigation: This indicator represents the dryer's potential to reduce CO_2 emissions over its lifetime. It can be calculated as follows[6,29,55]:

$$\text{Net CO}_2 \text{ mitigation} = (\text{E}_{\text{out\_annual}} \times \text{L} - \text{E}_\text{e}) \times \frac{1}{1-\text{L}_\text{a}} \times \frac{1}{1-\text{L}_{\text{td}}} \times \text{EF}_{\text{electricity}} \tag{23}$$

Where E_{out_annual} : Annual energy output (kWh/year), L is the life of the system (in year), E_e : Energy embodied (in kWh), L_a is the transmission power loss (%) and L_{td} the transmission and distribution loss (%) and $EF_{electricity}$ the emission factor of electricity consumption (kg CO_2/kWh) which varies according to geographic location/country By combining previous equation, we obtain the following equation between Net CO_2 mitigation and CO_2 emission per year:

$$Net\ CO_2\ mitigation = L \times CO_2\ emission\ per\ year \cdot \left(\frac{E_{out_{annual}} \cdot L}{E_e} - 1\right) \tag{24}$$

This last equation clearly shows that in the case where the energy produced by the dryer is equivalent to the embodied energy, then dryer's potential to reduce CO_2 emissions over its lifetime, is zero.

Earned carbon credit: For international trade in energy systems, particularly renewable energy systems, earned carbon credits are an important indicator of environmental sustainability. This parameter can be expressed as follows[6,34]:

$$\mathrm{CCE} = \mathrm{Net\ CO_2\ mitigation} \times \mathrm{D} \tag{25}$$

With D: Exchange rate of carbon credit based international policy (\$/tons ofCO_2 mitigation).

Economic indicators: Life cycle costs: The life cycle cost LCC is the total cost involved over the lifetime of the dryer and is given as follows[61]:

$$\mathrm{LCC} = \mathrm{CAPEX} + \mathrm{OPEX} - \mathrm{SV} \tag{26}$$

In this expression, CAPEX : initial cost (CA Pital Expenditure), OPEX : cost of labor (Operational Expenditure), operation, and maintenance,SV : salvage value of the dryer at the end of its life.

Life cycle benefit (LCB): This is the total profit that can be obtained over the lifetime of the solar dryer[61] :

$$LCB = R\ \frac{X\,(1-X^L)}{(1-X)} \tag{27}$$

$$X = \frac{1+e}{1+d} \tag{28}$$

In equations (27), (28) R: annual benefit; e: annual escalation in cost (%) and d: interest or discount rate (%), L: lifetime of the solar dryer.

The payback period (PBP): The payback period is the time required for the system developed to recover initial investment. The basic expression used to evaluate the *PBP* of any drying system is given by the next equation[62]:

$$PBP_o = \frac{CAPEX}{S_{annual\ \_Net}} \tag{29}$$

Where: CAPEX: initial cost (CA Pital Expenditure) or initial Investment, $S_{annual\ \_Net}$: annual net undiscounted benefits.

When taking into account the discount rate (time value of money), we obtain the following equation, representing the discount payback time *PBP* [63,64] :

$$PBP = \frac{\ln\left[1 - \frac{CAPEX}{S_1}(d-i)\right]}{\ln\left(\frac{1+i}{1+d}\right)} \tag{30}$$

Where: *CAPEX*: initial cost (Capital Expenditure) or initial Investment; S_1 :savings after the first year; i : annual inflation rate (%); d :interest rate (%).

The following table shows the PBP for different solar dryer technologies from the article by Kamarulzaman et al.[65]:

Table-5: Payback Period of different solar dryer technologies.

Solar Dryer Technologies	PBP (year)
Passive	0.8
Active	2.4
Direct	1.1
Indirect	0.54-3.26
Mixed-mode	0.65-0.75
Hybrid (with biomass)	1.6
Hybrid (with PV/T)	2.3

Benefit - Cost (B/C) Ratio: The methodology employed for dryer selection involves assessing the benefits and drawbacks through the benefit-cost ratio[6,66]. The benefit-cost ratio is obtained by equation:

$$Benefit - Cost\ ratio = \frac{\sum_{t=1}^{t=n} \frac{B_t}{(1+d)^t}}{\sum_{t=1}^{t=n} \frac{C_t}{(1+d)^t}} \tag{31}$$

Where: B_t : is the benefit in each year, C_t: cost in each year t,d: interest or discount rate (%), n: number of annuities.

A dryer is accepted as suitable if value of provided Benefit – Cost ratio is greater than 1, and the dryer is rejected if this value is less than 1.

Net Present Value (NPV): The calculation of Net Present Value (NPV) serves the purpose of assessing the project's profitability. A positive NPV implies that the investor stands to make profits upon undertaking the project, while a negative NPV signifies potential financial losses for the investor if the project is pursued[29]. NPV is given as follows:

$$NPV = \sum_{t=0}^{t=n} \frac{B_t - C_t}{(1+d)^t} \tag{32}$$

With B_t : is the benefit in each year, C_t: cost in each year t,d: interest or discount rate (%).

Internal Rate of Return (IRR)

The internal rate of return (IRR) is a discounted capital budgeting technique that accounts for the time value of money. It is utilized to determine the discount rate that makes the present value of benefits equal to the present value of costs in a project. The IRR is the rate at which the present value of cash inflows matches the present value of cash outflows.

The internal rate of return is the discount rate that sets the net present value, to zero, as illustrated by equation:

$$\sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+IRR)^t} = 0 \quad (33)$$

In equation (33) B_t : is the benefit in each year, C_t: cost in each year t, IPR: internal rate of return (%).

Typically, a trial-and-error approach is employed to identify the IRR that results in a net present value of zero[29].

Capital recovery factor (CRF): The capital recovery factor (CRF) represents the constant annuity received from the solar dryer over its lifespan and is mathematically expressed as follows[6,29]:

$$CRF = \frac{d(1+d)^n}{(1+d)^n - 1} \quad (34)$$

With d : interest rate (%), L : lifetime of the solar dryer (years).

Uniform annualized cost (UAC): Uniform annualized cost (UAC)is the annualized total cost of the solar dryer throughout its entire lifespan. It is calculated using the following equation[6,29]:

$$UAC = \frac{CAPEX\ (1+d)^n}{(1+d)^n - 1} \quad (35)$$

With: $CAPEX$: initial cost (CA Pital Expenditure) or initial Investment, d: interest rate (%).

Sinking fund Method (SFM): The sinking fund method is a technique for depreciating a solar dryer, simultaneously generating revenue to facilitate its replacement at the end of its lifespan. SFM is obtained as follows [6,29]:

$$SFM = \frac{d}{(1+d)^n - 1} \quad (36)$$

Where d is the interest rate (%).

Energoeconomic indicator: This analysis assesses the economic impact of energy usage in thermal systems. The energoeconomic parameter (R_{en}) is defined as the ratio of energy loss rates to capital cost[27,67] as illustrated below:

$$R_{en} = \frac{L_{en}}{CAPEX} \quad (37)$$

Where: L_{en} is the energy loss rates (kWh) and CAPEX: initial cost (CA Pital Expenditure) or initial Investment.

A lower R_{en} value is favourable, indicating improved thermal efficiency and reduced energy loss [27].

Exergoeconomic indicator: Exergoeconomic analysis combines exergy principles with economic constraints to offer a comprehensive perspective not obtainable through conventional exergy or economic assessments. The exergoeconomic parameter R_{ex} is obtained using the following equation[27,46,67]:

$$R_{ex} = \frac{Ex_{Loss}}{P_{ec}} \quad (38)$$

Where: Ex_{Loss}: exergy loss (kW), P_{ec}: the cost of equipment purchased.

Exergoeconomic analysis estimates the overall cost of system inefficiencies. It has been observed that a higher exergy destruction is associated with a decrease in unit cost[27,68,69].

Ozturk and Dincer [67], conducted an exergoeconomic analysis of a solar-assisted tea dryer, defining the exergoeconomic parameter as the ratio between exergy loss and the capital cost, resulting in a parameter value of 72.63 MJ/$. They observed that an increase of inlet air mass flow rate led to a higher exergy loss ratio, while a higher reference temperature had the opposite effect[67]. The exergoeconomic parameter can be also determined as follows:

$$R_{ex} = \frac{Ex_{Loss}}{CAPEX} \quad (39)$$

Where: Ex_{Loss} : exergy loss (MJ), $CAPEX$: initial cost (CAPital EXpenditure) or initial Investment($).

Enviroeconomic indicators: The enviroeconomic parameter (Z_{CO2}, $), which quantifies the system's cost savings due to CO_2 mitigation can be computed by multiplying the amount of CO_2 reduction with the price of carbon as defined by the equation [70,71]:

$$Z_{CO_2} = \phi_{CO_2} z_{CO_2} \quad (40)$$

Where ϕ_{CO_2} : the amount of CO_2 reduction (in ton), z_{CO_2}: the price of carbon (in $/ton CO_2).

The importance of the economic aspect is emphasised for national users and those operating on a smaller scale. Many researchers have focused their efforts on the economic evaluation of solar dryers. For example, the annual cost of a cabinet-type indirect forced convection solar dryer for bitter gourd drying was calculated at Rs. 661.70 (US$1 ≈ Rs. 45) for 52.5 kg of product dried annually. The Cost of drying 1 kg of bitter gourd in the solar dryer was Rs. 17.52. For comparison, the cost of drying 1 kg of bitter gourd in an electric dryer was calculated as Rs. 41.35/kg. Moreover, a payback period of 3.26 years was found, which is relatively short in comparison to the expected lifespan of the dryer, which is 20 years [72].

Table-6 illustrates the thermo-economic investigation done by Boroze et al.[11] on five different types of dryers.

Table-6: Thermo-economic analysis of solar dryers studied by Boroze et al.[11].

Dryer	Geho	Chamber	Shell	Direct cupboard	Cover dryer
Products to be dried	Cassava pasta	Rice	Tomato	Tomato	Maize
Dryer data					
Dryer cost (€)	1220	7630	115	76	6
Life cycle (year)	5	20	10	10	2
Annual maintenance cost (€/year)	15.3	7.6	4.5	0.8	0.3
Number of days of dryer use per year(d/year)	180	284	100	100	90
Operating					
Humid product initial mass per cycle(kg/cycle)	150	2000	5	2	50
Initial moisture content (dry basis)	223%	32%	1718%	1718%	54%
Final moisture content (dry basis)	10%	12%	12%	12%	15%
Raw material cost per day(€/d)	0.31	0.14	0.15	0.15	0.15
Dried product price per kg (€/kg)	3.31	0.92	1.83	1.83	0.27
Drying time (d/cycle)	2	1	3	1.5	5
Theoretical calculation					
Energy received per day by the dryer(kJ/d)	439,900	1452,300	18,200	18,600	67,700
Water mass evaporable by the dryer (kg/d)	196	646	8.1	8.3	30.1
Practical calculation					
Final mass of dried product per day (kg/d)	26	848	0.1	0.1	7.5
Daily evaporated water mass from the product (kg/d)	49.5	152	1.6	1.3	2.5
Evaporated water mass/evaporable water mass	25%	23%	19%	15%	8%
Daily turn-over (€/d)	85	777	0.19	0.15	2.05
Drying cost per kg of evaporated water(€/kg)	0.09	0.01	0.10	0.07	0.01
Daily capital gain (€/d)	54	640	- 0.14	- 0.36	0.53
Part of drying cost in capital gain(%)	9%	0.2%	-	-	7%
Dryer cost/daily evaporated water mass (€d/kg)	25	50	73	61	2.4
Profit per evaporated water mass (€/kg)	1.0	4.2	- 0.2	- 0.4	0.2

Summary and Discussion

Limitations of Single-Metric Approaches: While the various explored indicators provide valuable insights into solar dryer performance, relying solely on a single metric can be misleading. Solar dryers must balance multiple objectives such as drying efficiency, energy consumption, economic viability, and environmental impact. Focusing on a single metric might lead to overlooking other crucial aspects. For example, a dryer with exceptionally high drying efficiency could result in high costs or a significant environmental footprint. Often, there are inherent trade-offs between different performance indicators. For instance, a dryer with a high drying rate (faster drying time) might consume more energy and have a higher initial cost. Similarly, a dryer with low embodied energy (environmentally friendly) and a lower initial cost might have a very low drying rate (excessively long drying time). The relevance of a particular metric may vary depending on the context. In a scenario where drying costs are a major concern, economic indicators such as return on investment or cost-benefit ratio could be more crucial. A single metric might not capture the nuances of these interactions. To overcome these limitations, a multicriteria decision-making approach is recommended. This involves considering a set of relevant performance indicators and applying a weighting system to reflect their relative importance in a specific context. This allows for a more comprehensive evaluation and selection of the most suitable solar dryer technology.

Limitations of mixed indicators: Energy efficiency indicators, such as Ren, Rex and Z_{CO2}, are valuable tools for evaluating the performance of systems and processes. However, it is important to recognize their limitations for judicious use.

Energo economic parameter (Ren): i. Limited Scope: Ren only considers the cost of capital, neglecting other economic factors such as operating and maintenance expenses. ii. Ignorance of Efficiency Gains: A lower Ren value could be achieved by reducing upfront costs by using lower quality materials, which could result inreduced durability and higher maintenance costs in the long run.

Exergoeconomic indicator (Rex): *In addition to the limitation presented by the Ren.* Exergy analysis can be complex, requiring specialized software and expertise for accurate calculations. ii. Challenges in Cost Allocation: Attributing exergy losses to specific components of the dryer can be challenging, making it difficult to identify areas for improvement.

Enviroeconomic indicator (Z_{CO2}): i. Market Volatility: The price of carbon can fluctuate significantly depending on location and policy changes, making Z_{CO2} a dynamic value. ii. Limited Scope: Z_{CO2} only takes into account CO_2 emissions, neglecting other environmental impacts such as water use or potential pollution related to the manufacture of materials.

Quality of dried products: Solar drying induces irreversible changes in the physical, chemical, and nutritional attributes of dried products. Balancing solar dryer performance with product quality is crucial. Mild drying conditions (40 - 60 ºC) are recommended to minimize product degradation. Indirect and mixed-mode solar dryers are preferred for preserving product quality, with the former being suitable for photosensitive materials and the latter allowing rapid drying due to consistent solar radiation collection. Prolonged drying, especially at high temperatures, can lead to quality degradation. In general, the main quality parameters are: sensory attributes (color, flavor, taste, texture, aroma), nutritional attributes, moisture content, rehydration capacity, uniformity of drying, microbial load[30,73].

Table 7 provides a concise summary of the negative effects of solar drying on some quality parameters.

Table-7: Negative effect of solar drying on some quality parameters[27,74].

Property	Impacts of solar drying	Cause
Physical Properties	Increased product color degradation	Higher drying temperatures Enzymatic or non-enzymatic reactions
	Increased brittleness of dried materials Affected Texture	Water Loss
	Presence of cracks on the dried product	Pressure imbalance created inside the material
	Reduction of volume, shape (shrinkage) and possibly cracks	Humidity Reduction
Chemical Properties	Flavour and odour affected	Reduced humidity (resulting in changes in the chemical composition of dried materials)
Nutritional properties	Loss of essential chemical compounds	High drying temperatures (often exceeding 60°C)

Conclusion

This mini review highlights the strengths and weaknesses of 30 solar dryer performance indicators, an area of critical importance in the context of food security, environmental sustainability and energy efficiency. These performance indicators are not only evaluation tools, but also guides for the design, optimization and implementation of efficient solar dryers. Knowledge of the strengths and weaknesses of these indicators is a sine qua non for researchers and designers in order to contribute to the continuous improvement of solar dryer technology. This, with the aim of maximizing energy efficiency, minimizing product quality losses and speeding up the drying process.

This work shows that the most frequently used performance indicators are those relating to energy, economic and environmental analysis. From the energy aspect, the most used parameter is the energy efficiency. On the environmental level, CO_2 emissions indicator is the most used parameter and on the economic level, the discounted payback period (PBP) is identified. It appears that for economic operators (agri-food processing unit for example) the discounted payback period (PBP) and the Net Present value are very important parameters in decision-making.

This paper also turns out that an optimal and comprehensive evaluation of solar dryers needs to take into account a combination of indicators from different types of existing analysis. From this point of view, the exergo-economic indicator (Rex) is recommended. It estimates the remaining room for improvement to improve the performance of each component of a solar dryer. The lower this parameter, the more efficient the dryer is, technically, environmentally and economically.

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