

Modular Solar Drying and Thermal Energy Storage System Configuration Assessment

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Abstract. Solar drying is an effective method for preserving food and enhancing its characteristics by removing moisture using ambient air and elevated temperatures. This technology, made for harnessing solar energy, offers a sustainable alternative to conventional drying methods, reducing the consumption of fossil fuels. This study investigates the configuration of a solar drying system for kiwi slices, based on flat plate collector (FPC) combined with packed bed thermal energy storage (PBTES) using copper slag as the storage medium. The research assesses both unidirectional and bidirectional configurations of the storage unit flow to determine the effect on the drying process. The analysis is supported on experimental validation of the thermal models for the FPC and PBTES unit, along with the calibration of the drying model using existing data. Results indicate that unidirectional flow provides better outcomes with smaller storage volumes, whereas bidirectional flow may offer superior performance with larger storage volumes. The maximum plant factor obtained was 93,3% for the bidirectional configuration with a solar field size of 10 m² and storage volume of 3141 lt. A careful calibration of the thermal system is necessary to avoid suboptimal configurations that either underutilize solar energy or risk overheating the product. The use of a bidirectional configuration with solar heat could lead to a better process performance without the need for external heating.

Keywords: Solar Drying, Thermal Energy Storage, Packed Bed Model

1. Introduction

Food drying is a useful technique to help preserve foods and create new characteristics. By using ambient air and temperatures higher than the environment, the moisture of the media is removed. Solar food drying consists of harvesting solar radiation to increase the drying air temperature, as a way to help preserve foods and create new characteristics, while diminishing the need for additional energy, such as fossil fuels. Solar drying has been applied worldwide, with a huge demand by various foods and agricultural products [1].

Thermal energy storage for enhancing solar energy applications, such as molten salts for CSP is a common practice [2]. Solar food drying is no exception, as the drying periods for some foods could be larger than the hours during the day in which solar resource could be exploited. Examples of TES for food drying are abundant, with better results than systems with open solar drying [3]. Sensible TES has been directly incorporated into the solar air collector using different solid media, such as sand, rocks, bricks, concrete, among other materials [4].

Latent TES, considering a phase change material (PCM), has also been considered, such as using paraffin wax after the solar air collector [5] or with encapsulated PCM in a packed bed reactor [6].

Packed bed TES (PBTES) is a simple yet effective technique to store and recover energy in sensible heat using air as a Heat Transfer Fluid (HTF) [7]. Due to the overlap with the temperature ranges of food drying and the direct use of air in the storage media, PBTES presents high compatibility with food drying processes [8]. Due to the natural thermal stratification of PBTES systems, an inversion of the flow in the storage unit could allow the higher temperatures near the inlet to be exploited, in what is called a bidirectional configuration [9]. Nevertheless, the configuration of solar air collector and storage unit could directly impact the efficiency of the drying process. The temperature of the air must be kept in a range to ensure that the drying process is effective. Too cold, and the evaporation of moisture could be too slow, and too hot could cook, or even burn the product. A thorough assessment of the configuration of the thermal system could ensure that the process could work during intermittent solar availability.

This study proposes a model for a solar drying system for kiwi slices with a modular and bidirectional configuration for the storage unit, to assess the configurations of solar collector and storage unit that allow the maximum exploitation of the available solar resource. An experimental test bench is used to validate the mathematical models of the solar air collector and PBTES unit, using copper slag as storage media. An available regression for the effective diffusivity is used to calibrate the drying model. A parametric analysis is proposed for the collector area, storage volume and the hour of the flow inversion in the storage unit. The proposed methodology could lead the way for a thorough assessment of the thermal system configuration, to enhance clean industrial processes.

2. Methodology

2.1 Experimental Setup

The system is composed by an air flat plate collector by GRAMMER Solar, model TwinTop 2.0. The collector is coupled with a 0,08 m³ cylindrical packed-bed TES (see Fig. 1).

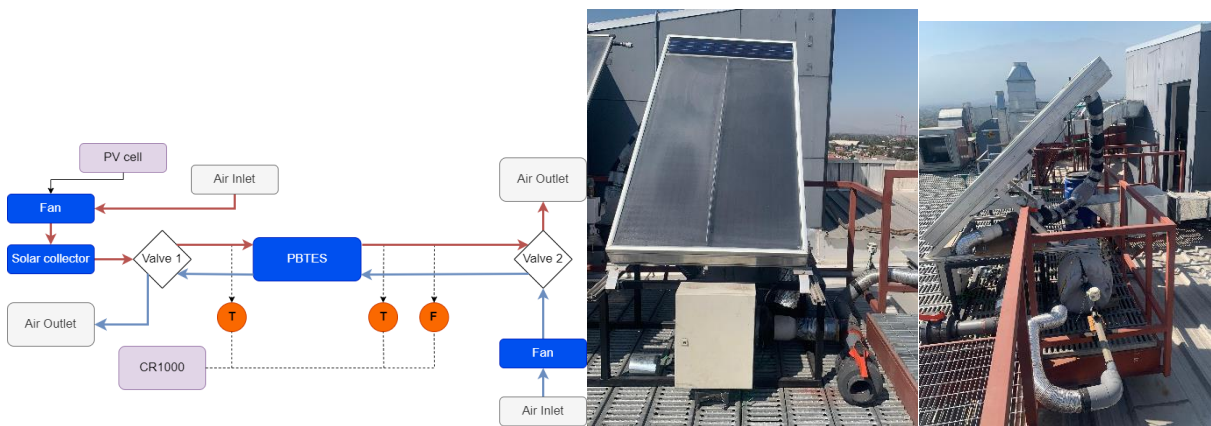


Figure 1. Experimental layout (Left) and Test bench (Right)

The components are installed on a rooftop of a building in Santiago, Chile. Regarding the operation of the system, air is taken from the surroundings and through the internal fan of the FPC. When heated, the air is transported to the TES which is disposed horizontally. The experimental bench has temperature sensors for ambient air, FPC outlet TES outlet, 3 internal TES sensors and an air velocity sensor. This experimental system is proposed for the validation of the numerical model proposed. The outlet temperature from the flat plate collector is

calculated by performing an energy balance on that component and considering an instantaneous efficiency model. The outlet temperatures of the packed bed are calculated by experimentally fitting a heat balance model. The FPC and PBTES experimental parameters can be seen in Table 1.

Table 1. Experiment Parameters

Parameter	Value
FPC Area	2 m ²
FPC Surface Tilt	45°
FPC Efficiency at zero losses	0,834
FPC Linear efficiency coefficient	3,197 W/m ² K
FPC Quadratic efficiency coefficient	0,00034 W/m ² K ²
FPC Irradiation angle correction factor	0,96
PBTES Tank Length	0,74 m
PBTES Tank Diameter	0,394 m
PBTES Particle Diameter	0,02 m
PBTES Void Fraction	0,4
Copper Slag Density	3500 kg/m ³
Copper Slag Specific Heat	968 J/kgK
Copper Slag Conductivity	1,6 W/mK

2.2 Collector Model

The mathematical model for the FPC is obtained from the global efficiency for a solar collector [10]. With two ways to obtain the efficiency, shown in Eq. 1 and 2, the collector outlet temperature T_{out} can be obtained.

$$\eta = \eta_0 K - \frac{a_1}{G_T} (T_m - T_{amb}) - \frac{a_2}{G_T} (T_m - T_{amb})^2 \quad (1)$$

$$\eta = \frac{m c p_f (T_{in} - T_{out})}{A_T G_T} \quad (2)$$

where η_0 is the FPC base efficiency, a_1 and a_2 are the collector linear and quadratic efficiency coefficients, K is the irradiation angle correction factor, T_m is the FPC average temperature, T_{amb} is the ambient temperature, η is the FPC efficiency, m is the Air Mass flow, A_T is the FPC area and G_T is the Incident radiation.

2.3 Packed Bed Model

The dynamics of the PBTES are described through a 1-phase formulation. The assumptions to obtain the general 1-phase approach were based on [11] the general simplifications of the system's behavior were proposed by [9], and the analytical solution of the 1-phase 1D heat transfer equation (see Eq. 3) was developed by [12] through the integral transform technique.

$$(\rho c_p)_{eq} \frac{\partial T}{\partial t} + \varepsilon (\rho c_p)_f u \frac{\partial T}{\partial z} = k_{eff} \frac{\partial^2 T}{\partial z^2} - h_w \beta_w (T - T_\infty) \quad (3)$$

where T is the fluid-solid temperature, z the axial coordinate of the tank, and t the time. $(\rho c_p)_{eq} = \varepsilon (\rho c_p)_f + (1 - \varepsilon) (\rho c_p)_s$ is the equivalent thermal capacitance by volume-averaging the fluid (f) and solid (s) phase with the PBTES void's fraction (ε). The fluid flows through the rocks in a plug-flow condition with a mean interstitial velocity, u . The effective thermal conductivity (k_{eff}) is calculated with the contribution of the fluid and the solid's conductivity (k_f and k_s), and an additional term that integrates the thermal front spread within the solid matrix.

$$k_{eff} = \varepsilon k_f + (1 - \varepsilon) k_s + \frac{(w (1 - \varepsilon) (\rho c_p)_s)^2}{h a_p} \quad (4)$$

On Eq. 4, h is the fluid-to-solid heat transfer coefficient, $a_p = 6 (1 - \varepsilon)/d_p$ the surface-to-bed volume factor, with d_p the particle diameter. $w = (\dot{m} c_{p,f})/(\rho c_p)_{eq}$ is the thermal front velocity, considering $\dot{m}$ the fluid's mass flow rate. Finally, the thermal losses to the environment at T_∞ is calculated with an overall heat transfer coefficient h_w between the storage medium and the surroundings, and the shape factor $\beta_w = 4/D$ with D the tank diameter.

2.4 Drying Model

For the drying model, an effective diffusivity model is used, based on the work of Pailahueque et al. [5]. The Moisture Ratio is obtained from Eq. 5.

$$MR = \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (5)$$

where D_{eff} is the effective diffusivity, t is time and L is the characteristic length of the fruit.

Then, the moisture content is obtained from Eq. 6.

$$X(t) = MR(X_i - X_{eq}) \quad (6)$$

where $X(t)$ is the moisture content, X_i is the initial moisture and X_{eq} is the equilibrium moisture.

The D_{eff} value is obtained from a regression obtained from an experimental work for kiwi slices [13], and can be seen in Eq. 7. The temperature ranges for these results are between 40°C and 70°C.

$$-Ln(D_{eff}) = \frac{3038,37}{T} + 12,62 \quad (7)$$

The drying chamber is modelled as a trail drying, set to dry 1 kg of fruit per daily batch, and with a set mass flow of $m = 0,0111$ kg/s.

The drying plant factor is defined as the number of days in which the humidity at the end of the day reaches the drying goal of 10% of the initial humidity, over the total days the system is drying.

2.5 Simulation

All simulations were performed in Python 3.7, using the mathematical models proposed in this section. The solution of each module is solved sequentially, from the solar collector, fan, TES and drying module. The selected time step is 3600 seconds, and the simulation is performed for 90 days, starting from January 1st. The data for solar resource and ambient temperature for the experimental validation was obtained through a SOLYS station in a building in Santiago, Chile. The data for solar resource and ambient temperature for the parametric analysis was obtained through a TMY file for Santiago, Chile [14].

The experimental validation is performed for the collector and PBTES models. The validation is performed by measuring the RMSE of the temperature profiles for a daily operation for each model, for a Unidirectional operation day and a Bidirectional operation day.

The control logic applied for both configurations considered that the outlet flow temperature, used for the drying process, could not be over 70°C and below 30°C, otherwise there would be no flow going into the drying chamber (The air would be released into the environ-

ment). Furthermore, when flow is passing through the air collector, the internal fan of the collector would be used, which is powered through the PV module attached to the collector. This implies that the collector fan could only work if the incident irradiation is above 200 W/m^2 . For the unidirectional configuration, the control logic assumed that the daily drying batch could only start after 8 AM. For the bidirectional configuration, the control logic assumed that the drying batch would start with the flow switch.

The dimensions used for the parametric analysis are the storage volume, FPC area and, for only the bidirectional configuration, the hour for the flow switch.

3. Results

3.1 Experimental Validation

The experimental validation is performed for a clear day with high radiation (above 900 W/m^2), for both unidirectional and bidirectional configurations. The models for the FPC and PBTES are contrasted with the experimental data collected for the day, using the RMSE. Results are shown in Table 2.

Table 2. Experimental validation RMSE

Model	Unidirectional	Bidirectional
FPC	3,815 K	5,890 K
PBTES	3,233 K	3,240 K

With a working temperature range of 70 K, the measured RMSE shown is up to 8,4% of error, which is considered to be acceptable for the simulation conditions.

3.2 Simulation Results

Figure 2 show the results of the simulation for the unidirectional and bidirectional configurations, respectively. The results are shown for 5 consecutive days, starting from January 1st, and for a specific set of parameters (FPC area, TES volume and hour for flow switch). Each graph is divided into sections, for temperature and irradiance profile, and a moisture profile.

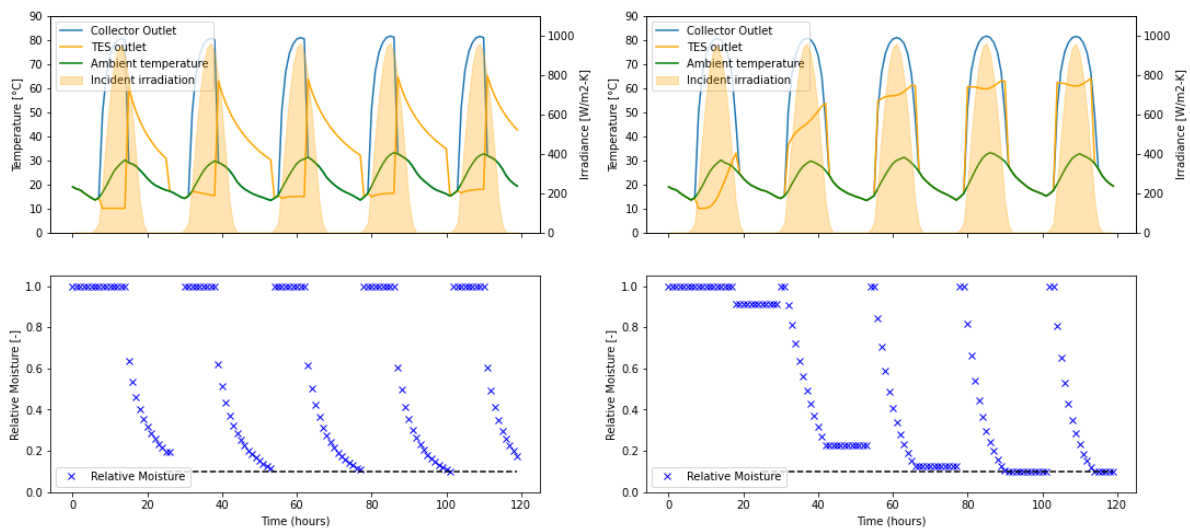


Figure 2. Unidirectional Results, Collector area 6 m², TES volume 221 lt (Left). Bidirectional Results, Collector area 6 m², TES volume 3142 lt, switch hour at 15 hrs (Right).

3.3 Parametric Analysis

In Figure 3 are shown the parametric analysis results for the drying plant factor of the unidirectional configurations, and bidirectional configuration for the hour of flow switch.

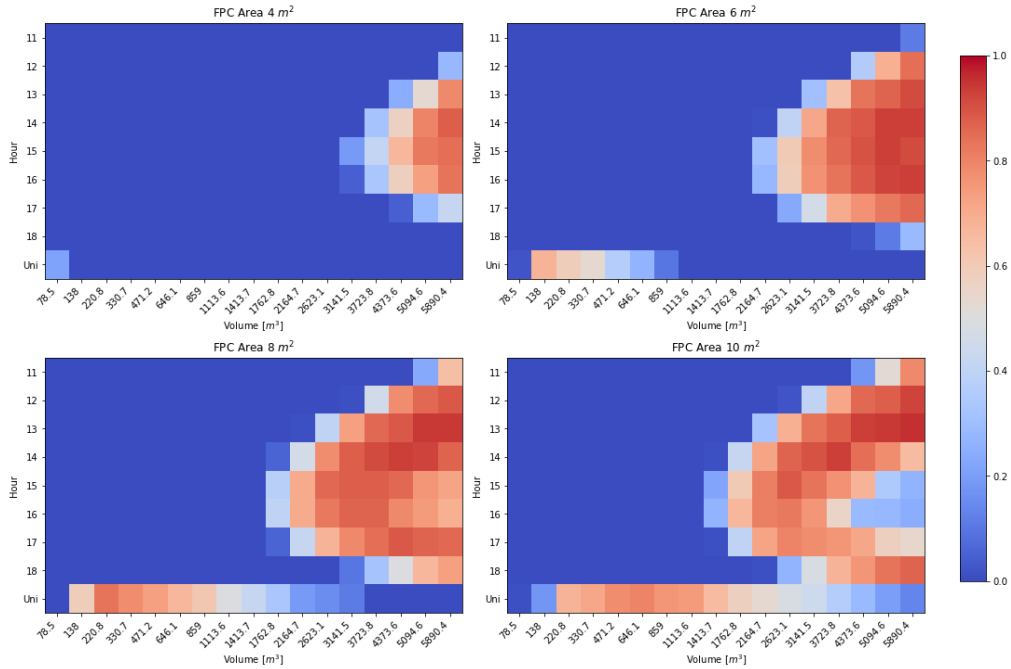


Figure 3. Drying plant factor, unidirectional and bidirectional results

Results of this analysis for the unidirectional configuration, showed that the FPC and PBTES dimensions directly affects the drying plant factor, with different possible results. Due to the high temperature restriction, a medium storage volume compared to a large collector area is not an effective configuration, as it results in many days above the temperature operating range for the drying process. Similar case is for the low temperature restriction with a small storage volume, as the PBTES cannot act as a damper for the high temperature peaks provided by the FPC. A maximum for the drying plant factor of 83,3% is obtained for a FPC area of 8 m² and a storage volume of 220,9 lt. Near this maximum, a tendency of increasing the storage volume in relation to the FPC area, to provide a mitigation of the temperature peaks that delivers air flow inside the drying ranges.

The parametric analysis results shows that the bidirectional configuration is benefited from large storage volume, in comparison with the unidirectional configuration. For the same FPC area, a bidirectional flow could present a plant drying factor up to 10% higher, if the storage volume is increased. The maximum of plant factor is 93,3% for a storage volume of 3131,5 lt. This configuration also present results according to the temperature peak mitigating effect of the PBTES. Increasing FPC area led to an increase in thermal energy collected, however it could lead to surpassing the maximum temperature range of the drying process. Furthermore, the hour of the flow switch adds another relevant variable, as it determines the hour of the day at which the solar resource collection stops, but also determines the hours of drying, as per the control logic, the drying process begins when discharging the PBTES. A zone of high drying plant factor can be seen from 14 PM to 16 PM, especially for small FPC areas. When increasing the collector size, once again we can see that the plant factor is reduced, as the temperature to the process is often above the allowed range.

4. Conclusions

Solar food drying is a sustainable method for food preservation, offering an energy-efficient alternative to conventional heat sources. The use of an experimental test bench was crucial in validating the mathematical models of the solar air collector and PBTES unit. Copper slag, chosen as the storage media due to its favorable thermal properties, is beneficial to the thermal energy storage capacity of the system. This choice of material not only contributes to the overall efficiency of the drying process but also demonstrates the potential for using industrial by-products in sustainable energy applications. The defined metric, drying plant factor, proved to be useful in assessing the system configurations.

The analysis of the unidirectional configuration revealed that the dimensions of the FPC and the PBTES system significantly influence the drying plant factor, with varying outcomes depending on the chosen configuration. Results show that a medium storage volume paired with a large collector area is not effective, as it often results in temperatures exceeding the operational range for drying. Similarly, a small storage volume fails to adequately dampen high-temperature peaks, reducing the system's plant factor. The analysis suggests that increasing the storage volume relative to the FPC area is beneficial for mitigating temperature peaks and maintaining airflow within the desired temperature range. In contrast, the bidirectional configuration demonstrated a greater benefit from larger storage volumes compared to the unidirectional setup. For the same FPC area, the bidirectional flow could achieve a drying plant factor up to 10% higher with an increased storage volume, highlighting the benefits of the PBTES in mitigating temperature peaks. While increasing the FPC area results in more thermal energy collected, it also risks exceeding the maximum temperature range required for the drying process. The timing of the flow switch is also critical, as it affects both the duration of solar resource collection and the drying period. Overall, the study highlights the importance of carefully balancing the FPC area and PBTES volume, as well as optimizing the flow switch timing.

In conclusion, solar drying presents a viable, clean alternative for food processing, with the potential to reduce energy consumption and fossil fuel usage. The study highlights the importance of assessing the system configuration, to increase drying performance. Copper slag as a storage medium offers a promising option for improving thermal storage efficiency, making it a valuable component in the design of future solar drying systems.

Data availability statement

All data used to create this study is available on the article.

Author contributions

IW: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing – review & editing. MM: Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – review & editing. ICV: Methodology, Software, Writing - original draft, Writing – review & editing. NP: Methodology, Supervision, Writing – review & editing. JMC: Funding acquisition, Methodology, Supervision, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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