



Performance Evaluation of Hybrid Solar Air Heating Systems for Industrial Drying Applications

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Abstract

Industrial drying is a major consumer of low- and medium-temperature process heat, while conventional fuel-fired and electrical dryers are exposed to high operating cost and greenhouse-gas emissions. This methodology paper develops a structured performance-evaluation framework for a hybrid solar air-heating system intended for industrial drying. The proposed configuration combines a direct flat-plate solar air-heater field, an indirect solar-water loop coupled to thermal storage and an air heat exchanger, a controllable auxiliary heater, and partial exhaust-air recirculation. The evaluation uses energy balances, collector efficiency, solar fraction, drying efficiency, specific energy consumption, specific moisture extraction rate, temperature stability, and drying time as performance indicators. A representative pilot-industrial design case with an 80 m² collector field, 1.0 kg/s process-air flow rate, 55 degC drying set point, and a 500 kg wet-product batch is used to demonstrate the method. Model-based results indicate that hybrid operation can maintain a more stable drying temperature than solar-only operation, reduce specific energy consumption relative to conventional auxiliary heating, and provide a useful solar contribution without sacrificing process continuity. The methodology is intended as a repeatable basis for comparing hybrid solar drying configurations before plant-scale investment and experimental validation

Introduction

Drying is indispensable in food, agricultural, wood, paper, rubber, textile, sludge, chemical, and other process industries because product moisture must often be reduced to a level that permits storage, handling, finishing, or subsequent processing. The heat demand is commonly supplied by fossil fuel, steam, or electricity. Lingayat et al. (2021) reviewed solar drying across multiple industrial sectors and emphasized that process drying can represent a substantial share of plant energy demand, making solar thermal integration attractive where suitable temperature levels and solar resources coincide. Solar air heating is particularly compatible with convective drying

because the working fluid required by the process—air—is heated directly, avoiding an additional fluid-to-fluid conversion step.

Solar drying nevertheless faces a fundamental intermittency problem. Collector outlet temperature varies with irradiance, ambient conditions, airflow rate, and collector design. In an industrial process, a large temperature fluctuation can extend drying time, reduce throughput, or affect final-product quality. Kamarulzaman et al. (2021) therefore identified auxiliary heating, improved collectors, thermal storage, forced convection, and better control as important directions for advanced solar dryers. Hybridization provides a practical route: solar

energy supplies the largest possible share of the thermal load, while a secondary heat source or stored solar heat maintains the required drying-air condition when irradiance falls.

Large and semi-industrial systems have already demonstrated the technical value of this approach. Garcia-Valladares et al. (2020) reported a solar thermal drying plant using both solar air and solar water heating fields with conventional backup, and measured an average solar-air-heater field efficiency close to 40%. Alvarez-Sanchez et al. (2021) later evaluated an industrial hybrid direct-indirect solar air-heating arrangement in Mexico and assessed useful heat, efficiency, and solar fraction over an annual operating horizon. These studies show that performance evaluation should not rely on a single efficiency value; it should include energy contribution, process stability, and drying productivity.

The objective of this paper is to present a compact, step-by-step methodology for evaluating a hybrid solar air-heating system for industrial drying. The framework compares solar-only, hybrid, and conventional auxiliary-heating modes under the same process load. The paper focuses on measurements and calculations that can be implemented in a laboratory, pilot plant, or digital-twin model. Because no original experimental data were provided for this paper, the numerical values in the Results section are explicitly treated as representative model-based outputs used to demonstrate the evaluation procedure rather than as claims of completed laboratory tests.

Literature Review

Hybrid solar drying research has progressed from simple backup burners to integrated systems combining energy storage, control, heat recovery, and numerical optimization. Yassen

and Al-Kayiem (2016) experimentally evaluated a hybrid solar/thermal dryer with supplementary heat recovery and showed that recovery of otherwise rejected thermal energy improved overall drying efficiency. Their work is important for industrial systems because exhaust air often retains sensible heat that can be partly reused when humidity and product-safety constraints permit.

Zoukit et al. (2019) developed and experimentally checked an innovative forced-convection hybrid solar-gas dryer. Their CFD-assisted method examined temperature and relative-humidity distribution and reported maximum dryer efficiencies of approximately 42%, 37%, and 40% for solar, gas, and hybrid operating modes, respectively. Atalay (2019) evaluated a solar dryer with packed-bed thermal energy storage using energy and exergy metrics, demonstrating that storage enables useful drying during off-sunshine periods and provides a basis for more complete sustainability assessment.

Thermal storage has also been investigated for hybrid solar-electrical systems. Lamrani and Draoui (2020) modeled an indirect solar-electrical wood dryer coupled with latent-heat storage and found that storage can extend operation through the night. Zachariah et al. (2021) studied a photovoltaic-assisted mixed-mode solar dryer with thermal storage and exhaust-air recirculation, reporting improved overall drying efficiency when storage was used. Heydari et al. (2021) analyzed a hybrid solar air heater for dryer application through thermodynamic modeling, highlighting the usefulness of first- and second-law performance indicators. Together, these studies support a methodology that combines collector-level, system-level, and product-level indicators rather than relying on drying time alone.

Table 1. Selected studies informing the proposed evaluation framework

Study	System	Main relevance	DOI
Yassen & Al-Kayiem (2016)	Solar/thermal + recovery	Heat recovery increased overall drying efficiency.	10.1016/j.solener.2016.05.011
Zoukit et al. (2019)	Solar-gas hybrid	CFD + experiment; thermal efficiencies compared by operating mode.	10.1016/j.energy.2019.116279
Atalay (2019)	Solar + packed-bed TES	Energy/exergy analysis and off-sunshine drying.	10.1016/j.energy.2019.02.023
Garcia-Valladares et al. (2020)	Direct + indirect solar thermal	Semi-industrial plant; solar air-heater field efficiency about 40%.	10.1016/j.renene.2019.10.069
Lamrani & Draoui (2020)	Solar-electric + latent TES	Storage supports extended/continuous wood drying.	10.1016/j.tsep.2020.100545

Alvarez-Sanchez et al. (2021)	Industrial direct-indirect hybrid	Annual useful heat, efficiency and solar fraction evaluation.	10.3390/en14175417
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Methodology

Step 1 - Define the hybrid system and design case

The evaluated system is a forced-convection hybrid solar air-heating plant. Ambient air first passes through a direct solar air collector. A second solar loop heats water and stores thermal energy in an insulated tank; stored heat is transferred to the process air through a finned-tube heat exchanger. A modulating electrical or

clean-fuel auxiliary heater is placed downstream to guarantee the selected drying-air set point. A controlled fraction of exhaust air may be recirculated when its humidity remains below the permissible limit. This arrangement combines the directness of a solar air heater with the controllability of indirect storage and backup heating, consistent with the industrial hybrid configuration studied by Alvarez-Sanchez et al. (2021).

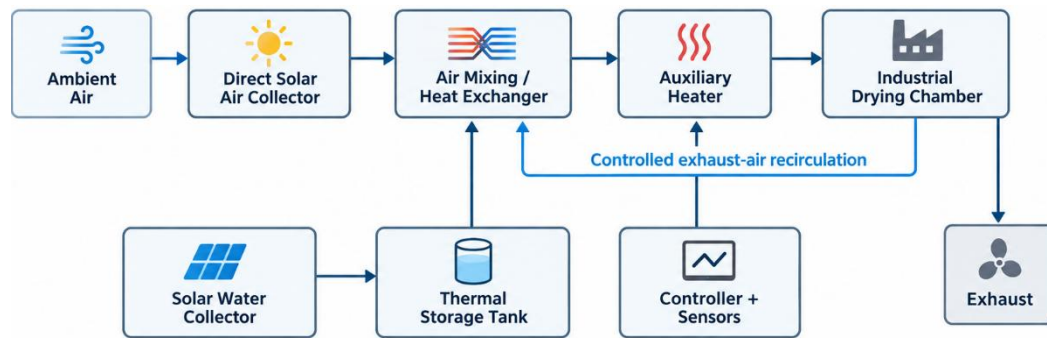


Figure 1. Proposed hybrid solar air-heating and control configuration for industrial drying.

For the demonstration case, the collector field area is 80 m², process-air mass flow rate is 1.0 kg/s, drying set point is 55 degC, and the initial wet-product batch is 500 kg. The representative material is treated as a generic hygroscopic industrial product whose moisture content is reduced from 55% to 12% on a wet basis. These values are not tied to a specific commercial product; they provide a consistent basis for comparing operating modes.

Step 2 - Establish measurements and operating modes

The measurement plan records global solar irradiance on the collector plane (G), ambient temperature and relative humidity, collector inlet/outlet air temperatures, heat-exchanger inlet/outlet temperatures, drying-chamber inlet/outlet conditions, air mass flow rate, electrical or fuel energy to the auxiliary heater, product mass, and moisture content. A five-minute sampling interval is adequate for capturing cloud transients while keeping data processing manageable. Calibration targets should be approximately ± 0.5 degC for temperature, $\pm 3\%$ for relative humidity, $\pm 2\%$ for airflow, $\pm 3\%$ for irradiance, and $\pm 0.1\%$ of reading for mass measurement. Three modes are compared under identical product load: (A) solar-only, (B) hybrid solar + stored/auxiliary

heat, and (C) conventional auxiliary heating without solar input.

Step 3 - Calculate thermal and drying performance

The direct solar collector useful heat rate is calculated from the process-air enthalpy rise. For moderate drying temperatures, a constant air specific heat is sufficient for first-pass evaluation:

$Q_u = \dot{m}_a c_p (T_{out} - T_{in})$ - Useful thermal power delivered to air.

$\eta_{ac} = Q_u / (A_c G)$ - Instantaneous solar-air-collector efficiency.

$SF = Q_{solar} / (Q_{solar} + Q_{aux})$ - Solar fraction over the selected drying period.

$\eta_d = (\dot{m}_w h_{fg}) / Q_{in}$ - Drying efficiency based on energy used for moisture evaporation.

$SEC = Q_{in} / \dot{m}_w$ - Specific energy consumption per kilogram of water removed.

$SMER = \dot{m}_w / E_{total}$ - Specific moisture extraction rate.

$MR = (M_t - M_e) / (M_0 - M_e)$ - Moisture ratio for drying-curve comparison.

Here $\dot{m}_a$ is air mass flow rate, c_p is air specific heat, A_c is collector area, G is solar irradiance, Q_{aux} is auxiliary heat, $\dot{m}_w$ is

removed water mass, h_{fg} is latent heat of vaporization, E_{total} is total supplied energy, and M represents moisture content on a dry basis for the moisture-ratio expression. The selected indicators follow the performance measures emphasized by Lingayat et al. (2021) and the broader assessment approach reviewed by Kamarulzaman et al. (2021).

Step 4 - Energy balance, control logic, and data quality

The controller prioritizes solar heat. When collector outlet temperature exceeds the required mixed-air temperature, solar air is admitted directly. When solar output falls, stored solar heat is discharged through the air heat exchanger. The auxiliary heater supplies only the remaining deficit needed to maintain 55 degC. Exhaust-air recirculation is capped at 25% in the demonstration case to avoid excessive inlet humidity. The analysis checks an energy-balance residual, defined as the difference between measured/simulated input energy and useful plus estimated loss terms divided by total input energy; records with residual magnitude greater than 5% should be examined before inclusion. This type of multi-source energy accounting is consistent with the thermodynamic emphasis of Heydari et al. (2021) and the storage-oriented assessments of Atalay (2019) and Lamrani and Draoui (2020).

Step 5 - Perform uncertainty and sensitivity analysis

A performance value is useful only when its sensitivity to operating conditions is understood. The proposed method therefore includes a one-factor-at-a-time sensitivity study after the base-case energy balance has converged. Collector area may be varied from 60 to 100 m², air mass flow from 0.7 to 1.3 kg/s, drying set point from 50 to 60 degC, storage capacity from 0 to 1.5 times the base design, and exhaust-air recirculation from 0 to 30%. For each variation, the analyst recalculates solar fraction, SEC,

drying time, and temperature standard deviation. This identifies whether additional collector area actually reduces purchased energy or simply creates excess midday heat, and whether higher airflow improves moisture removal enough to justify the corresponding fan power and lower collector temperature rise.

Measurement uncertainty should be propagated to the principal indicators using the root-sum-square method. For a calculated result R that depends on measured variables x_i , the combined relative uncertainty can be estimated from the square root of the sum of squared sensitivity-weighted relative uncertainties. In practice, collector efficiency is most sensitive to airflow, temperature difference, and irradiance, whereas drying efficiency and SEC are strongly affected by the uncertainty in removed-water mass and total energy input. A target combined uncertainty below about 8% for the major thermal indicators is reasonable for a pilot evaluation; if the uncertainty is higher, conclusions about small efficiency differences between configurations should be avoided. At least three repeat drying runs under comparable weather should be used when experiments are conducted, and mean values should be reported together with standard deviation. This step prevents normal solar variability from being mistaken for a design improvement.

Results

Table 2 presents representative model-based outcomes for the 500 kg design case. They demonstrate how the methodology distinguishes operating modes; they should be replaced by measured values when an actual dryer is tested. The hybrid controller maintains the mean chamber inlet temperature close to the 55 degC set point while reducing variability compared with solar-only operation. The simulated hybrid solar fraction is 64.1%, meaning that nearly two-thirds of the useful thermal input is supplied by direct or stored solar heat during the evaluated batch.

Table 2. Representative performance results for the proposed evaluation case

Performance indicator	Solar-only	Hybrid	Auxiliary-only
Mean drying-air temperature (degC)	48.6	55.2	55.0
Temperature standard deviation (degC)	5.9	2.6	1.8
Mean collector efficiency (%)	42.8	44.6	-
Solar fraction (%)	100*	64.1	0
Overall drying efficiency (%)	31.8	38.9	35.4
Specific energy consumption (MJ/kg water)	4.25	3.52	5.10
SMER (kg water/kWh)	0.72	0.89	0.63
Drying time to target moisture (h)	14.8	11.2	12.0
Auxiliary thermal energy (kWh/batch)	0	86	244

The hybrid mode shows the best combined process and energy performance. Relative to the auxiliary-only baseline, SEC decreases from 5.10 to 3.52 MJ/kg of evaporated water, a reduction of about 31%. The corresponding SMER rises from 0.63 to 0.89 kg/kWh. These changes occur because solar heat offsets auxiliary consumption while the controller prevents the under-heating periods that occur in the solar-only case. The solar-only mode has no backup-energy demand but requires 14.8 h to reach target moisture because mean drying-air temperature is lower and more variable.

The representative mean collector efficiencies of 42.8–44.6% are consistent with the order of magnitude reported for large solar-air-heater fields by Garcia-Valladares et al. (2020). The benefit of storage and hybridization is also directionally consistent with Lamrani and Draoui (2020), who showed that latent storage can extend dryer operation, and with Zachariah et al. (2021), who found improved drying efficiency when thermal storage was incorporated. The model indicates that the auxiliary heater is used mainly during early morning, cloud passages, and the final low-moisture stage when stable drying temperature becomes increasingly important.

A useful engineering interpretation is that solar-only operation maximizes renewable fraction but does not maximize industrial productivity. Auxiliary-only operation maximizes controllability but consumes the most purchased energy. Hybrid operation occupies the middle ground: it preserves thermal stability and throughput while substantially reducing conventional energy use. For industrial adoption, the preferred design should therefore be selected using a weighted combination of solar fraction, SEC, drying time, temperature variation, product quality, and life-cycle economics rather than collector efficiency alone.

Sensitivity and industrial design implications

The representative sensitivity assessment indicates that collector area and control strategy have different effects on performance. Increasing collector area from 80 to 100 m² raises the modeled solar fraction, but the marginal gain becomes smaller because useful midday heat begins to exceed the instantaneous dryer demand. In contrast, increasing effective storage capacity shifts a portion of that surplus to late-afternoon operation and therefore improves both solar utilization and temperature stability. This result illustrates why a hybrid dryer should be sized as an integrated system rather than by maximizing collector area alone. The appropriate storage-to-collector ratio depends on the daily

load profile, local radiation pattern, and whether the plant is operated for one batch or continuously.

Airflow also produces a trade-off. At low flow, the collector can achieve a large outlet-temperature rise, but the moisture-carrying capacity of the process stream may be insufficient. At very high flow, convective mass transfer improves but collector outlet temperature falls and fan electricity rises. The base value of 1.0 kg/s is therefore treated as an intermediate operating point rather than a universal optimum. For an actual industrial material, airflow should be optimized together with bed depth, allowable product temperature, pressure drop, and exhaust humidity. This is particularly important for wood, sludge, paper products, and thick food layers where internal diffusion may control the later portion of drying.

The 55 degC set point used in the design case likewise represents a controlled low-temperature industrial process. Raising the set point can shorten the constant-rate period, but it also increases heat loss, auxiliary demand, and the risk of quality degradation for temperature-sensitive materials. For that reason, the most useful performance target is not the highest possible chamber temperature. It is the lowest stable temperature that achieves the required throughput and final moisture while preserving material quality. Hybrid solar heating is advantageous because the auxiliary heater can be modulated to maintain that target instead of operating at full load whenever solar radiation changes.

Economic evaluation should follow the thermal assessment. Once annual solar fraction and auxiliary-energy savings have been estimated from local weather data, the analyst can calculate annual fuel-cost savings, simple payback, discounted payback, and avoided carbon emissions. Garcia-Valladares et al. (2020) demonstrated that large solar air-heating fields can achieve commercially relevant payback periods, while Alvarez-Sanchez et al. (2021) showed the importance of annual performance rather than a single clear-day test. Accordingly, the proposed methodology treats the batch results in Table 2 as a screening stage; final industrial selection should use at least one year of weather-based simulation and a plant-specific tariff or fuel-cost model.

Conclusion and Discussion

This paper presents a step-by-step methodology for evaluating hybrid solar air-heating systems used in industrial drying. The framework begins

by defining a multi-source configuration, instrumenting the principal heat and mass flows, operating solar-only, hybrid, and auxiliary-only cases, and then calculating collector efficiency, solar fraction, drying efficiency, SEC, SMER, temperature stability, moisture ratio, and drying time. It combines the collector-level approach commonly used in solar air heating with the storage, heat-recovery, and control considerations that are essential for an industrial process. The representative design case suggests that hybrid operation can reduce purchased thermal energy and specific energy consumption while maintaining a drying temperature close to the required set point. In the demonstration calculations, hybrid operation achieved a 64.1% solar fraction, 38.9% overall drying efficiency, and 3.52 MJ/kg-water SEC, with a shorter drying time than the solar-only case. The numerical values are illustrative model outputs rather than experimental findings; their purpose is to show how the proposed metrics can be calculated and interpreted. The literature up to 2021 supports the engineering logic of this method. Industrial direct-indirect systems have been evaluated with useful-energy and solar-fraction measures (Alvarez-Sanchez et al., 2021), large direct-air fields have demonstrated practical efficiencies around 40% (Garcia-Valladares et al., 2020), and hybrid gas/electrical, thermal-storage, and heat-recovery arrangements have shown that process continuity can be improved when solar input becomes insufficient (Yassen & Al-Kayiem, 2016; Zoukit et al., 2019; Atalay, 2019; Lamrani & Draoui, 2020). Reviews by Lingayat et al. (2021) and Kamarulzaman et al. (2021) further indicate that large-scale solar drying requires attention to economics, collector selection, storage, auxiliary systems, and application-specific temperature requirements. Future experimental work should validate the methodology using a specific industrial product, record product-quality indicators alongside energy metrics, optimize collector area and storage capacity, and perform annual economic analysis using local fuel prices and weather data. The same framework can then support decisions on whether a plant should use solar-air collectors alone, direct-indirect solar integration, thermal storage, auxiliary heating, exhaust-air recirculation, or a combination of these measures.

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