Energetic And Exergetic Investigations of an Integrated Heat Pump System for Drying Applications

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ABSTRACT

The main aim of this study is to conduct energetic and exergetic investigations of a dual stage heat pump for drying applications in order to evaluate the performance of the overall system. The integrated system consists of two processes, namely a drying unit and a dual stage heat pump. In the heat pump process, R-134A is used as the thermodynamic fluid and the drying unit is used to reduce the moisture content of the air. There are two evaporators used in the dual stage heat pump process: the first evaporator works at high pressures and the second evaporator works at lower pressures. The second evaporator provides supplementary cooling and drying effect for the air used in the drying unit. In the integrated system, there are two sub-coolers which provide additional heating to R-134A after the condenser. In this study, the energy and exergy efficiencies and exergy destruction rates of the overall integrated system, and each component and subprocess are calculated and discussed in detail. Exergetic performance of each component and subprocess are further investigated to identify where the highest exergy destructions occur in order to minimize irreversibilities within the integrated system and hence enhance the overall exergetic efficiency of the integrated system. The impact of environmental conditions on exergetic efficiency and exergy destruction is investigated via parametric studies. In addition, the coefficient of performance (COP) of the whole system and the effect of operating conditions are examined. The highest energy and exergy efficiencies occur when the drying unit's inlet air mass flow rate is 0.5 kg/s and the environmental pressure and temperature are at 101 kPa and 298K which are 62% and 35%, respectively. The overall integrated system has a COP of around 3.8.

Keywords:

INTRODUCTION

As the world faces unprecedented energy challenges, many countries are looking to include smart solutions to energy consuming processes as an effort to reach a sustainable future. Drying is a major energy-intensive process used in a wide variety of industrial applications. The main reason for the wide use of drying as a popular industrial application is drying reduces overall product weight and size for easier transportation which also decreases the space requirements and fuel consumption. Drying also increases the storage time of foods and industrial products. However, drying is the main reason of high energy consumption of many industries, for instance, the energy consumption during the drying process is equal to almost 50% and 70% of the overall energy consumption in the textile and forestry industries,

respectively [1]. The most commonly utilized primary energy resources in air conductive industrial dryers are fossil fuels, electricity, and biomass. Reducing the high energy consumption of drying processes can be done by increasing system efficiencies which essentially decreases the harmful greenhouse gas emissions during drying. In heat pump integrated drying processes, significant amounts of energy can be recovered, energy loss and harmful wastes can be minimized, and, as a result, up to 50% of the primary energy sources can be saved [2, 3].

The core aim of a drying system is to provide its output at a preferred moisture content and quality at a lowest possible cost and environmental impact and highest possible efficiency by optimizing the system para-

Table 1. Technical comparison of heat pump dryers with selected drying technologies

Parameter	Freeze drying	Hot air drying	Vacuum drying	Heat pump drying
SMER, kg water/kWh	< 0.4	0.1–1.3	0.7–1.2	1.0–4.0
Operating temperature range, °C	-35-50	40–90	30–60	-10–80
Operating relative humidity range, %	Low	Variable	Low	10–80
Drying efficiency, %	Very low	35–40	< 70	<95
Drying rate	Very low	Average	Very low	Faster
Capital cost	Very high	Low	High	Moderate
Running cost		High	Very high	Low
Control	Good	Moderate	Good	Very good

Source: Erbay and Hepbasli [8].

meters. Drying has very high energy demand. For example, 15% of the entire industrial energy use is caused by drying applications. What is more important is the fact that a significant amount of energy is wasted in industrial dryers. More specifically, here are some examples of the contribution of drying in different industrial operations:

- 70% of the energy use in forestry

- 50% of the energy use in the textile industry

- More than 60% of the energy use in farms

In developed countries, 9-25% of the energy demand is caused by the drying processes. As a consequence, to decrease the energy demand of the drying processes, it is essential to inspect alternative and innovative technologies to enhance the performance of dryers. For example, compared to traditional dryers, heat pump drying processes can reduce energy consumption significantly. In addition, heat pump dryers can lower CO_2, NO_x, and other GHG emissions considerably. In addition, the literature shows that heat pump dryers enhance the quality of the final product.

Heat pump assisted drying processes to have significant advantages such as reduced greenhouse gas emissions, less energy loss, and better control of drying gas temperature and moisture content [4, 5]. In some industrial applications, the moisture content and temperature of the product and the overall product quality are especially important, therefore, this critical requirement makes heat pump assisted drying processes very promising options when it comes to better control and monitoring of all key drying process parameters [6, 7]. Furthermore, regardless of their primary energy source requirement, any conventional dryer can be integrated into any type of heat pump, and this is another major advantage. In heat pump integrated drying processes, latent heat can be converted to sensible heat, and therefore these systems are considered as outstanding alternatives when recovering heat in a drying unit is a critical require-

ment [8, 9]. Table 1 summarizes some of the technical characteristics of three drying options: (i) freeze drying, (ii) hot air drying, (iii) vacuum drying, and (iv) heat pump drying. Table 1 shows some of the most important benefits of using heat pump driers, which are namely enhanced SMER (Specific Moisture Extraction Ratio), better drying quality and rate at lower operating temperatures, applicability in a wide range of drying operating conditions, enhanced operation control when delivering high quality and critical end-use products, and less energy consumption and waste. Potential benefits of heat pump dying systems are illustrated in Fig. 1.

The idea of heat pump integrated drying systems is becoming more popular in the literature. First, Perry [10] have suggested an integrated system which utilizes a heat pump with two evaporators. In their system, the first evaporator has operated at higher pressures and the second one has operated at lower pressures. This dual stage heat pump has been integrated with a drying unit. In Perry's design, the high-pressure evaporator has delivered cooling via sensible heat transfer and the second evaporator has been utilized to deliver cooling via latent heat transfer. In the beginning, Perry's proposal has not been acknowledged widely because
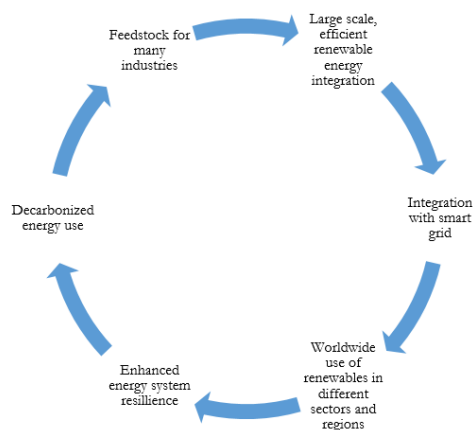

Figure 1. Potential benefits of heat pump drying systems as a smart energy solution.

controlling a system with one evaporator had been considered a lot easier. Therefore, Perry's proposed integrated system has been assumed to be a complex idea. Following Perry's work, Chua and Chou have designed, constructed, and verified Perry's proposed system, primarily for agricultural product drying purposes [2, 11, 12]. Then, a refrigeration process with two evaporators has shown higher efficiencies compared to the ones with one evaporator only [13]. These aforementioned previous studies on double evaporator processes show that from the thermodynamic perspective, a dual evaporator process can offer enhanced surface areas for better heat transfer rates, as a result, these systems can minimize the compressor load of the entire system.

Heat pump drying systems have the potential to become a part of a clean, reliable, affordable, safe, and sustainable portfolio of smart energy solutions. Heat pump dryers can be used to provide high-quality products cleanly and efficiently in a wide range of operating conditions and for different applications. Widespread deployment of heat pump drying systems offers a broad range of benefits for the environment, for our energy security, for our domestic economy, and for end-users. Heat pump dryers are smart solutions for the sustainability of future energy systems. They offer many sustainable end use options for small scale, large scale, and mobile and stationary applications. Many different industries such as pharmaceutical, forestry, textile, agriculture, food, etc. highly benefit from heat pump dryers. Globally, heat pump drying systems have been getting more popular among end users. Heat pump dryers work with a wide range of locally available, abundant, clean, and efficient resources. They can smartly link these resources to end users via a diverse set of industrial and residential applications.

We live in an era where everything we use and everything we interact with in our daily lives has to be smart. Therefore, it is safe to say that future energy solutions, including heat pump dryers, have to be smart as well. In regards to future heat pump drying systems, we need to make it in line with these under smart energy solutions. With the developed cutting-edge technologies and artificial intelligence applications, we need to change the course of action in dealing with energy matters, covering the entire energy spectrum under five categories, as energy fundamentals and concepts, energy materials, energy production, energy conversion, and energy management.

With the global energy crisis and climate change concerns, it is becoming more and more obvious that we need to change the course of action and switch from conventional methods, approaches, systems, solutions to a smart energy portfolio where the smart solutions are targeted. Switching to smart energy solutions does not mean that we can ignore the concepts and fundamentals which should be treated like a building cannot stand without pillars. Energy solutions cannot survive without concepts and fundamentals.

The primary aim of the present research is to perform a complete investigation of the energetic and exergetic performance of a dual-step integrated heat pump drying system formerly designed by Chua and Chou [2]. In this study, R134A is selected instead of R22 used by [2] due to the environmental benefits of R134A. In addition, the literature including [2] lacks the comprehensive exergetic investigation of the proposed heat pump-drying system, and a better understanding of any energy system can be accomplished only with a thorough exergy analysis [14], which is the main motivation behind this study. The performance investigation of the overall integrated system is conducted according to comprehensive energy and exergy assessments of each and every constituent, unit, and subprocess of the entire integrated system. Overall system performance and the component based efficiency analysis are conducted by changing a variety of key parameters such as environmental temperature via parametric studies. In the last part of this study, suggestions for enhanced system performance are presented for less environmental impact and better sustainability in the future directions section.

HEAT PUMP DRYING PERFORMANCE CHARACTERISTICS

The performance characteristics of a heat pump drying system can be classified in four groups as follows: (i) thermodynamic performance, (ii) economic performance, (iii) environmental impact, and (iii) final product quality. Compared to other drying alternatives, heat pump drying systems are environmentally benign since they do not emit harmful gases and at the drying site [15]. In heat pump dryers, the condensate can be recovered and disposed of properly and the valuable volatiles can be recovered from the condensate [16]. In this section, the quality aspects of heat pump dried products are discussed in detail.

Quality of the Final Product

The key expectations from effective heat pump drying systems with high-quality final products are the ability to [17]:

•   operate at an absolute humidity less than that of the environment

•   select the operating temperature to be less than or above the environmental temperature

•   provide drying in a non-vented chamber using a

modified drying atmosphere

The quality of dried products as enhanced by heat pump drying is comprised of a number of physical, chemical and sensory characteristics are discussed in this section.

Microbial safety

Quality deterioration caused by microorganisms is undesirable commercially because they limit the shelf life and lower the quality of the final product. Drying helps in reducing or overcoming potential microbial damages. With heat pump drying, microbial safety is minimized by ensuring that all raw materials conform to recognized standards of preparation [18]. Heat pump dryers are able to enhance microbial safety in the final product by maintaining the relative humidity at reasonably low levels. Also, the operating temperature of heat pump dryers is not limited by the environmental humidity.

Color

Color degradation is a major cause of loss in the quality of the final product. Especially in the food industry, the color of food is an important indicator of the final product quality. Although sulfating agents prevent the browning reactions in the final product, their use is restricted due to several health and safety concerns. On the other hand, enzymatic browning in food drying can be reduced without the use of sulfates by increasing the air velocity at low relative humidity (<20%) and high moisture content (~2kg/kg dry matter) [19]. This strategy is applicable in heat pump dryers because the humidity can be controlled independently by the environmental conditions. Also, drying under nitrogen has been found to be effective in inhibiting browning during the critical initial drying period when the moisture content is high [20]. This shows that there is the possibility of using heat pump drying processes to produce high-quality final products. Another way constrain browning in dried products is utilizing heat pump dryers to produce specific temperature-humidity conditions [21].

Ascorbic acid (AA) and volatile compound content and preservation of active ingredients

The impact of constant temperature drying on product quality is well recorded in the literature [22]. As the drying temperature increases, the browning of the final product accelerates and the AA content of the final product decreases. With proper selection of the drying temperature, the AA content of the final product can be kept at desired levels without significant enhancement in drying time. In addition, using reduced air temperatures

at the onset of drying as in the case of heat pump drying followed by temperature elevation as drying proceeds yield a better quality product [23]. The volatile component concentration usually increases, especially in low-temperature heat pump drying systems. Therefore, heat pump dryers are seen as the best systems for the preservation of volatile compounds in the final product. Also, the preservation of total chlorophyll and ascorbic acid content in fried fruits can be accomplished in heat pump dryers with higher rehydration ratios and sensory scores than hot air dryers [24].

Aroma and flavor loss

Drying methods that employ lower temperatures provide a higher concentration of key aroma compounds [25]. Therefore, heat pump dryers can effectively retain the aroma content of the final products and minimize the degradation of the aromatic compounds by keeping the drying operation at low temperatures. Furthermore, since heat pump drying occurs in a closed chamber, any compound that volatilizes remain inside the drying unit. As the partial pressure of the volatile compound gradually builds up within the chamber, further volatilization from the product slows down [26]. Therefore, it can be said that the color and aroma of the final products can be better preserved with heat pump dryers.

Viability

When drying oxygen-sensitive materials such as flavor compounds and fatty acids, the product can undergo oxidation, causing poor flavor, color, and rehydration properties of the final product. Heat pump dryers have the advantage of drying without unacceptable deterioration of viability and activity. This could be accomplished by freeze-drying too, however, heat pump dryers are cheaper, which makes them more favorable [27].

Rehydration

During drying, important changes in structural properties can be observed as water is removed from the moist material. Rehydration is a process of moistening the dried product. For example, in most cases, dried foods are soaked in water before cooking or consumption, therefore rehydration is a very important quality criterion. Factors affecting the rehydration process include:

- porosity, capillarity, and a cavity near the product surface

- temperature, trapped air bubbles, amorphous crystalline state, soluble solids, and pH of soaking water

Using heat pump dryers can accelerate the rehydration times and enhance the rehydration ratios of the final product [28].

Shrinkage

Heating produces major changes in the structure of the dried products. Shrinkage occurs because the dried product's structure cannot support their weight and, therefore, collapse under gravitational force in the absence of moisture. Shrinkage occurs first at the surface and gradually moves to the bottom with increasing drying times. When the drying process occurs at higher temperatures, cracks are formed in the final product. With their lower drying times and temperatures, heat pump dryers minimize shrinkage problems and offer products which have less structural damage and deformation [29].

Drying Efficiency

The performance of a drying system is characterized by various indices, including energy efficiency, thermal efficiency, volumetric evaporation rate, specific heat consumption, surface heat losses, unit steam consumption, and others which have been defined to reflect the requirements of various drying technologies [30]. Energy efficiency is critical because energy consumption strongly affects the drying costs [31]. Efficiency calculations are useful when assessing the system performance, identifying potential improvements, and selecting the optimum drying system and conditions [32]. Energy efficiencies are meant for providing an objective comparison between different dryers and drying processes. There are three groups of factors affecting drying efficiency [33]:

- Environmental conditions

- Current and desired moisture content of the product

- Operating conditions

For heat pump drying systems, drying efficiency is a measure of the quantity of energy used to remove one unit mass of water from the product, normally measured in kJ/kg water or kWh/kg water. In general, drying efficiency, η can be defined by:

$$\eta = \frac{T_{in} - T_{out}}{T_1 - T_0} \tag{1}$$

where T_{in} is the inlet temperature of the dryer, T_{out} is the outlet temperature of the dryer, and T_0 is the environmental temperature. The numerator of Equation 1 is a major factor in determining the efficiency of a dryer [34]. Energy efficiency is also the ratio of the latent heat of evaporation of the moisture removed to the drying air heat input.

Coefficient of Performance (COP)

COP can be used to evaluate the amount of work converted into heat for two different system operations: for cooling and for heating. For a heat pump, the heat transfer Q_{out} from the system to the hot body is desired, and the coefficient of performance is expressed in Equation 2, where W_{comp} is the electrical power input of the compressor.

$$COP = \frac{Desired\ output}{Required\ input} = \frac{Heat\ added}{Work\ required} = \frac{Q_{out}}{W_{comp}} \tag{2}$$

Specific Moisture Extraction Ratio (SMER)

An alternative indicator of the energy efficiency for heat pump dryers is the specific moisture extraction ratio which is calculated as

$$SMER = \frac{Amount\ of\ water\ evaporated\ (kg)}{Energy\ use\ (kWh)} \tag{3}$$

The SMER can be calculated either as an instantaneous value or as an average value during drying [35]. During the drying process, the SMER value decreases as the removal of moisture become more difficult due to smaller water vapor deficits at the surface of the product. For heat pump dryers, the SMER value can be above the theoretical maximum value. The energy efficiency of heat pump dryers can be reflected by their higher SMER values and drying efficiency when compared to other drying systems as shown in Table 1. Consequently, higher SMER would then be translated to lower operating cost, making the payback period for initial capital considerably shorter. The following are some suggestions for maximizing the capacity and efficiency of a heat pump dryer:

- use of continuous operation instead of batch drying so that the system can be operated at stable optimal conditions

- air flow should be counter current instead of cross-flow or co-current relative to the product movement to maximize the relative humidity at the dryer outlet and to match the drying characteristics of the product

- the inlet temperature of the dryer should be maximized in accordance with the product requirement,

- the refrigeration capacity should not be oversized so as not to reduce the relative humidity and a consequent

reduced SMER

• if possible, evaporating and condensing temperatures should be selected to optimize the COP and the thermal efficiency

Exergy

Exergy analysis is a useful tool that can be successfully used in the design of an energy system and provides the information necessary to choose the appropriate component design and operating procedure [36]. Exergy efficiency has been used rather than the energy efficiency in the performance analysis of heat pump dryers, particularly to indicate the possibilities for thermodynamic improvement [37]. It is defined as the maximum amount of work that can be produced by a stream of matter, heat, or work as it comes to equilibrium with its reference environment [38]. Information on exergy is effective in determining the processing plant and operating cost as well as energy conservation, fuel versatility, and pollution associated with the process [39]. Using an exergy analysis method, the magnitudes and locations of exergy destructions (i.e., irreversibilities) in the whole system can be identified [40].

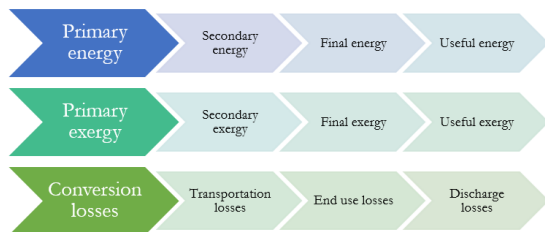Due to the definition of the first law of thermodyna-

Figure 2. 3S (system-source-service) approach from energy and exergy perspectives, including losses.

mics, energy is already conserved, therefore, instead of energy conservation, exergy conservation must be accomplished via exergization. Exergization should be applied to every component of heat pump drying systems from source, to the system, to service. With this approach, both energy and exergy losses in each step of a heat pump drying process such as conversion transportation, end use, and discharge losses as shown in Fig. 2 can be identified and addressed. Exergization is a useful smart energy solution to properly evaluate and point out which step in a process requires the highest attention to modifying for the better management of the "quality of energy".

DETAILED INFORMATION ON THE SYSTEM

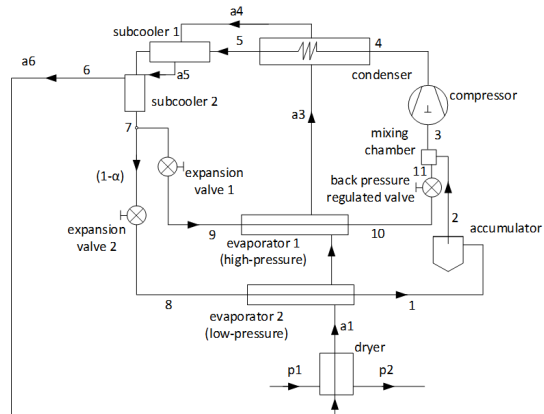The integrated heat pump drying process examined in

Figure 3. Graphic illustration of the dual stage integrated heat pump drying process (modified from [2]).

the present research is given in Fig. 3. The system is developed according to Chua and Chou's proposal [2]. Overall, the integrated system is different than most of the heat pumps since it has two evaporators instead of one. Other components are schematically presented in Fig. 3.

The review of every stream, together with their matching stream numbers, constituents, stream flow rates (kg/s), temperatures (°C), pressures (kPa), and states are shown in detail in Table 2. The comprehensive energetic and exergetic performance investigation of the integrated dual stage heat pump drying system is carried out by using the data presented in Table 2. In this study, R–134A is carefully chosen for the heat pump and the air is used in the drying unit. More detailed information on mass, energy, entropy, and exergy balance equations, in addition to energy and exergy efficiency, COP, relative irreversibility, and sustainability index equations, are presented in the following segment entitled "System Analysis". And the thermodynamic evaluation results are presented in the upcoming section, along with detailed discussion and suggestions for better system performance.

SYSTEM ANALYSIS

Quantitative and comprehensive approach to the first and second laws of thermodynamics is conducted in this research in order to comprehensively investigate the thermodynamic performance of the integrated dual stage heat pump integrated dryer. The thermodynamic evaluation criteria used in this study are energetic and exergetic efficiencies, exergy destruction rates, relative irreversibilities, and sustainability indexes. For the performance analysis part, the EES software is utilized in order to find the thermodynamic properties of each stream and solve the mass, energy, entropy, and exergy balance equations.

The integrated dual stage heat pump drying system

Table 2. Thermodynamic properties of each stream of the selected system.

Stream Number	Component	State	Temperature (°C)	Pressure (kPa)	Mass flow rate, $\dot{m}$ (kg/s)
1	R-134A	Gas	7.45	500	0.0429
2	R-134A	Gas	7.45	500	0.0429
3	R-134A	Gas	7.45	500	0.066
4	R-134A	Liquid	83.48	2500	0.066
5	R-134A	Liquid	61.35	2500	0.066
6	R-134A	Liquid	56.35	2500	0.066
7	R-134A	Liquid	51.35	2500	0.066
8	R-134A	VLE*	0.1148	500	0.0429
9	R-134A	VLE*	23.4	1000	0.0231
10	R-134A	Gas	23.4	1000	0.0231
11	R-134A	Gas	7.45	500	0.0231
a1	air	Gas	28.05	101.3	0.5
a2	air	Gas	25.27	101.3	0.5
a3	air	Gas	23.6	101.3	0.5
a4	air	Gas	44.21	101.3	0.5
a5	air	Gas	45.17	101.3	0.5
a6	air	Gas	46.08	101.3	0.5

VLE: Vapor-liquid equilibrium

operates at steady state steady flow and the changes in kinetic and potential energy in all streams and components are neglected. There are no chemical reactions in any components and streams within the entire system, therefore, chemical exergies are not taken into account. All auxiliary components such as tubing, pipes, valves, etc. are assumed to be very well insulated and there are no heat losses or pressure drops within these components. The compressor's isentropic efficiency is presumed to be 95%. The energy efficiency of the condenser and expansion valve are taken as 100%. Specific heat capacity and density of air, water, and R-134A are assumed to be constant within the selected operating temperature interval. All equipment is assumed to be adiabatic except the evaporators, sub-coolers, condenser, and drying unit. The general mass balance equation within a given control volume (cv) can be written as in the following form:

$$\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} \tag{4}$$

Here, m and $\dot{m}$ specify the mass and mass flow rate, and the subscripts "cv", "in" and "out" mean the control volume and the inlet and outlet streams to/from the control volume, respectively. When a system operates in steady state steady flow conditions, the general mass balance equation (Equation 1) becomes:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{5}$$

The steady state steady flow energy, entropy, and exergy balance equations are developed in a similar fashion to Equation 2 such as

Energy Balance Equation (EBE):

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{6}$$

Entropy Balance Equation (EnBE):

$$\sum \dot{S}_{in} + \dot{S}_{gen} = \sum \dot{S}_{out} \tag{7}$$

Exergy Balance Equation (ExBE):

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \dot{E}x_{dest} \tag{8}$$

where $\dot{E}_i$ shows the energy input/output rate and "in" and "out" point out the inlet and outlet streams to/from the selected control volume, respectively. The energy flow rate ($\dot{E}$) is either in heat form ($\dot{Q}$), or work form ($\dot{W}$), as the inlet or outlet stream. The energy flow rate is calculated by using the following equation:

$$\dot{E}_i = \dot{m}_i h_i \tag{9}$$

The subscript i signifies the "stream i" and h_i denotes the specific enthalpy (kJ/kg) of that stream. In the same way, $\dot{S}$ in Equation 4 implies the entropy input rate ($\dot{S}_{in}$), entropy output rate ($\dot{S}_{out}$), or entropy generation rate ($\dot{S}_{gen}$). The entropy flow rate within a stream is calculated by using

its specific entropy content s_i according to:

$$\dot{S}_i = \dot{m}_i s_i \tag{10}$$

The term ($\dot{Ex}$) in Equation 5 represents the exergy flow rate and the subscript dest denotes the exergy destruction rate. The exergy destruction rate is an important indicator of potential system irreversibilities. The main goal is to enhance exergetic system performance by lowering exergy destruction rates. The mode specific steady state exergy balance equation is given in the following equation as

$$\sum \dot{m}_{in} ex_{in} + \sum \dot{Ex}_{\dot{Q}_{in}} + \sum \dot{Ex}_{\dot{W}_{in}}$$
$$= \sum \dot{m}_{out} ex_{out} + \sum \dot{Ex}_{\dot{Q}_{out}} + \sum \dot{Ex}_{\dot{W}_{out}} + \dot{Ex}_{dest} \tag{11}$$

The exergy content of work ($\dot{Ex}_W$) is equal to its energy content ($\dot{W}$). For the energy content of heat input or output ($\dot{Q}$), the maximum amount of useful work which could be obtained from the heat source is called thermal exergy flow. And the thermal exergy flow rate ($\dot{Ex}_Q$) can be calculated by using the following equation

$$\dot{Ex}_Q = \dot{Q}\left(1 - \frac{T_0}{T}\right) \tag{12}$$

In equation (9), (1-T0⁄T) is the Carnot efficiency, which is also called as the dimensionless exergetic temperature. The Carnot efficiency of a system is calculated based on its operating temperature (T) and the environmental temperature (T_0).Exergy content of an energy or matter flow is the maximum amount of useful work which could be obtained from that particular energy or matter flow. When a matter or system is in complete equilibrium with its environment, its exergy content reaches zero. Therefore, the environment's state is also referred to as "dead state". When calculating the specific exergy content of matter, the physical (ex^{ph}), chemical (ex^{ch}), kinetic (ex^{ke}) and potential (ex^{pe}) exergy components are all taken into account. Here, the chemical, kinetic, and potential exergies are not taken into account because the kinetic and potential energy changes are neglected and no chemical reactions occur within the system. Hence, the exergy amount stored in the matter can be calculated based on its specific enthalpy and entropy at the environmental temperature (T_0) and pressure (P_0), which is given in the following equation as

$$ex = (h - h_0) - T_0(s - s_0) \tag{13}$$

Here, h and h_0 are specific enthalpies at system temperature and pressure (T, P) and environmental (T_0, P_0), respectively. Similarly, s and s_0 are specific enthalpies at system temperature and pressure (T, P) and environmental (T_0, P_0), respectively.

The total exergy output rate of a process is always less than the total exergy input rate due to exergy destruction. The exergy destruction rate is shown as $\dot{Ex}_{dest}$ in this study and it can be calculated from the entropy generation rate by

using the following equation:

$$\dot{Ex}_{dest} = T_0 \dot{S}_{gen} \tag{14}$$

Energy analysis alone is not enough to understand system irreversibilities and identify points for improvement. Energy conservation is misleading because due to the first law of thermodynamics, energy is conserved. However, the second law of energy states that the quality of energy (exergy) decreases. Therefore, our aim must be conserving exergy as much as possible by eliminating or minimizing exergy destructions (i.e., irreversibilities) [14]. The energy and exergy efficiency equations of each component are presented in detail in Table 3.

The following equations are used to calculate the relative irreversibility (RI) and sustainability index (SI) of each system component:

$$RI_i = \frac{\dot{Ex}_{dest,i}}{\dot{Ex}_{dest}} \tag{15}$$

$$SI_i = \frac{1}{1 - \psi_i} \tag{16}$$

The COP and energy and exergy efficiency equations of the overall system are estimated via the subsequent equ-

Table 3. Efficiency equations of the main components of the integrated design.

	Units	Energetic Efficiency	Exergetic Efficiency
1	Compressor	$\eta_1 = \dfrac{\dot{E}_4 - \dot{E}_3}{\dot{W}_1}$	$\psi_1 = \dfrac{\dot{Ex}_4 - \dot{Ex}_3}{\dot{W}_1}$
2	Condenser	$\eta_2 = \dfrac{\dot{E}_{a4} - \dot{E}_{a3}}{\dot{E}_4 - \dot{E}_5}$	$\psi_2 = \dfrac{\dot{Ex}_{a4} - \dot{Ex}_{a3}}{\dot{Ex}_4 - \dot{Ex}_5}$
3	Sub-cooler 1	$\eta_3 = \dfrac{\dot{E}_{a5} - \dot{E}_{a4}}{\dot{E}_5 - \dot{E}_6}$	$\psi_3 = \dfrac{\dot{Ex}_{a5} - \dot{Ex}_{a6}}{\dot{Ex}_5 - \dot{Ex}_6}$
4	Sub-cooler 2	$\eta_4 = \dfrac{\dot{E}_{a6} - \dot{E}_{a5}}{\dot{E}_6 - \dot{E}_7}$	$\psi_4 = \dfrac{\dot{Ex}_{a6} - \dot{Ex}_{a5}}{\dot{Ex}_6 - \dot{Ex}_7}$
5	Expansion Valve 1	$\eta_5 = \dfrac{\dot{E}_9}{\dot{E}_{a7}\alpha}$	$\psi_5 = \dfrac{\dot{Ex}_9}{\dot{Ex}_7\alpha}$
6	Expansion Valve 2	$\eta_6 = \dfrac{\dot{E}_8}{\dot{E}_7(1-\alpha)}$	$\psi_6 = \dfrac{\dot{Ex}_8}{\dot{Ex}_7(1-\alpha)}$
7	Low-Pressure Evaporator	$\eta_7 = \dfrac{\dot{E}_1 - \dot{E}_8}{\dot{E}_{a1} - \dot{E}_{a2}}$	$\psi_7 = \dfrac{\dot{Ex}_1 - \dot{Ex}_8}{\dot{Ex}_{a1} - \dot{Ex}_{a2}}$
8	High-Pressure Evaporator	$\eta_8 = \dfrac{\dot{E}_{10} - \dot{E}_9}{\dot{E}_{a2} - \dot{E}_{a3}}$	$\psi_8 = \dfrac{\dot{Ex}_{10} - \dot{Ex}_9}{\dot{Ex}_{a2} - \dot{Ex}_{a3}}$
9	Back Pressure Regulated Valve	$\eta_9 = \dfrac{\dot{E}_{11}}{\dot{E}_{10}}$	$\psi_9 = \dfrac{\dot{Ex}_{11}}{\dot{Ex}_{10}}$
10	Accumulator	$\eta_{10} = \dfrac{\dot{E}_2}{\dot{E}_1}$	$\psi_{10} = \dfrac{\dot{Ex}_2}{\dot{Ex}_1}$
11	Mixing Chamber	$\eta_{11} = \dfrac{\dot{E}_3}{\dot{E}_2 + \dot{E}_{11}}$	$\psi_{11} = \dfrac{\dot{Ex}_3}{\dot{Ex}_2 + \dot{Ex}_{11}}$

Table 4. Input data of the integrated dual stage heat pump drying system.

$\dot{m}_r$	Mass flow rate of the refrigerant (kg/s)	0.066
$\dot{m}_a$	Mass flow rate of the air used in the dryer (kg/s)	0.5
α	Mass ratio of the refrigerant used in the HP evaporator	0.35
T_3	Compressor inlet stream's refrigerant temperature (K)	280.6
P_3	Compressor inlet stream's refrigerant pressure (kPa)	500
ΔT_{SC1}	Sub-cooling degree in Sub-cooler 1 (K)	5
ΔT_{SC2}	Sub-cooling degree in Sub-cooler 2 (K)	5
T_0	Environmental temperature (K)	278.15
P_0	Environmental pressure (kPa)	101.33

ations:

$$COP = \frac{Condenser\ Load\left(\dot{E}_3 - \dot{E}_4\right)}{Compressor\left(\dot{W}_1\right)} \tag{17}$$

$$\eta = \frac{\dot{Q}_2}{\dot{W}_1} \tag{18}$$

$$\psi = \frac{\dot{Q}_2\left(1 - \dfrac{T_0}{T}\right)}{\dot{W}_1} \tag{19}$$

RESULTS AND DISCUSSION

When conducting the comprehensive energetic and exergetic investigations of the integrated dual stage heat pump drying system, the very first step is to define each and every stream along with their state, composition, temperature, and pressure. In the next step, after all, streams are clearly identified, the specific enthalpy, entropy, and exergy flow rates and the total energy and exergy flow rates of all streams are computed. This calculation is conducted by using the input data listed in Table 4 together with balance equations (shown in the equations provided in Section 4) and the Engineering Equation Solver (EES) software package.

The inlet conditions of the system are selected by taking the model previously introduced by [2] into account. The environmental temperature and pressure are considered to be 20°C and 101.3 kPa, respectively. The thermodynamic properties of each stream are obtained via the EES software package. In this section, the results of the exergetic and exergetic performance analyses, including RI, and SI, COP, and efficiencies of all components and the entire system are given and these results are discussed in detail.

Table 5 sums up the major findings of this study such as the energy inputs and outputs, exergy efficiencies, exergy destruction rates, RI and SI of all components of the integrated dual stage heat pump system.

From Table 5, it can be understood that the high-pressure evaporator has the lowest exergy efficiency within the entire system (37%), followed by the low-pressure evaporator (41%), and the condenser (59%). By the same token, the largest rate of exergy destruction occurs in the low-pressure evaporator (0.9 kW), followed by the condenser (0.8 kW), and the high-pressure evaporator (0.7 kW). The electrical energy input to the compressor is around 2.8 kW. Taken as a whole, the overall energy and the exergy efficiencies are 62% and 35%, respectively. The overall exergy destruction rate in the entire system is almost 4 kW and the overall sustainability index is around 1.5.

In Fig. 4, the relative irreversibilities of the process components (compressor, condenser, sub-coolers, expan-

Table 5. Thermodynamic performance results of the main system units.

	Unit	Exergy efficiency	Heat (kW)	Work (kW)	Exergy destruction rate (kW)	Relative irreversibility	Sustainability index
1	Compressor	84%		2.808	0.37	10%	6.2
2	Condenser	59%	10.73*		0.83	22%	2.42
3	Sub-cooler 1	79%	0.5*		0.02	0%	4.78
4	Sub-cooler 2	87%	0.48*		0.01	0%	7.49
5	Expansion Valve 1	94%			0.06	2%	17.51
6	Expansion Valve 2	85%			0.07	2%	6.61
7	Low-Pressure Evaporator	41%	6.24**		0.9	24%	1.68
8	High-Pressure Evaporator	37%	3.42**		0.7	19%	1.58
9	Back Pressure Regulated Valve	72%			0.17	5%	3.51
10	Dryer (D)	66%	8.52**		0.42	11%	2.9

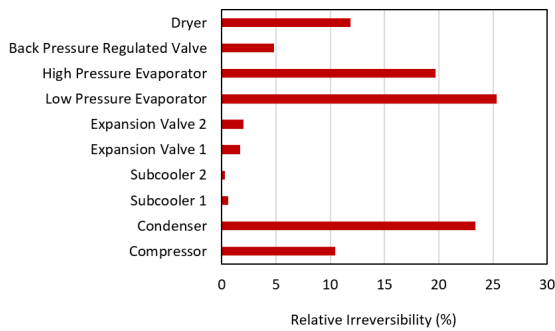*Heat rejected   **Heat input

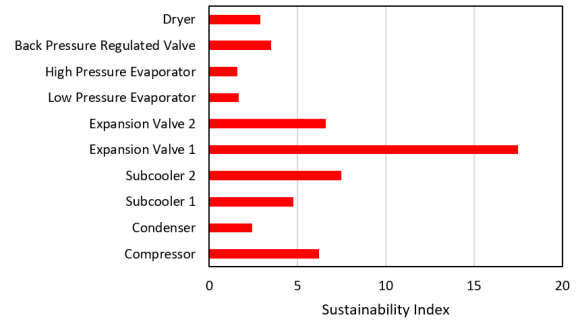**Figure 4.** RI of the selected components of the system

Figure 5. SI of the selected components of the system

sion valves, evaporators, regulation valve, and the dryer) are shown. The low-pressure evaporator (Unit 7) has the greatest irreversibility (24%) because of the elevated exergy destruction rate within this unit, which is mentioned earlier in this section. Following the low-pressure evaporator, the condenser (Unit 2) has the second highest irreversibility (22%). Third highest irreversibility occurs in the high-pressure evaporator (Unit 8) which is also quite high (19%). Combined together, the low-pressure evaporator, condenser, and the high-pressure evaporator account for more than half of the irreversibilities within the entire system, which is 64%.

The primary reasons of the in the evaporator and the condenser irreversibilities can be listed as the (i) temperature difference between the two heat exchanging fluids within these components; (ii) changes in stream pressures; (iii) flow imbalances; and (iv) heat transfer between the system and the environment. In view of the fact that compressor energy requirements depend firmly on the pressures of inlet and outlet streams, any improvements in heat exchanger operation which could lower the temperature difference can potentially significantly lower the compressor energy requirements by bringing the condensation and evaporation temperatures closer to each other.

From an innovative system development point of view, compressor irreversibilities could potentially be lowered independently from the other system components. For instance, modern improvements in the heat pump system design have pointed out the importance of scroll compressors in such systems. The overall system cooling efficiencies can be significantly enhanced by substituting the reciprocating compressor with novel scroll compressors. There is only one technique to minimize or completely get rid of the throttling losses which is to substitute the expansion devices with isentropic expanders. This way, some of the shaft work can be recovered from the pressure drop within the tubes and expanders. Another possible reason for compressor irreversibilities is because of the significant amounts of superheat emissions as a result of the compression process. This excess superheat leads to big temperature differences between the

inlet and outlet streams of the compressors, causing high exergy destruction rates and irreversibilities. The main reasons for mechanical and electrical losses within this process can be the imperfect electrical and mechanical conditions and low isentropic efficiencies. Therefore, there is a significant need for careful material selection for this equipment, since components with low-quality materials could potentially lower overall system efficiencies significantly.

In Fig. 5, the sustainability indexes of the key components of the integrated dual stage heat pump drying system (compressor, condenser, sub-coolers, expansion valves, evaporators, regulation valve, and the dryer) are presented. The average sustainability index values of the sub-coolers (Units 3 and 4) and expansion valves (Units 5 and 6) are considered as the base values while preparing the data shown in Fig. 5 Here, it is important to note that the accumulator (Unit 10) and the mixing chamber (Unit 11) are considered to have hundred percent energy efficiencies. For that reason, these components' sustainability indexes are not calculated and presented here. Because the auxiliary system components (such as the regulators, tubing, etc.) are presumed to be completely reversible and all the exergetic losses within these components are ignored, that is why the expansion valves have very high sustainability indexes (which means these components have high exergetic efficiencies) with respect to other system components. The high exergy destruction and losses within the condenser (Unit 2), the low-pressure evaporator (Unit 7) and high-pressure evaporator (Unit 8) cause their poor sustainability indexes. Sustainability index of the overall integrated dual stage heat pump system is 1.54.

The exergetic performance of the integrated dual stage heat pump system is evaluated when the environmental temperature is 5°C first. In the next step, in order to investigate the impact of the environmental temperature on the exergetic performance of the integrated system, several parametric investigations are performed. In this part, the impact of the environmental temperature on the exergy destruction rates and exergy efficiencies of the individual system components and the overall system is studied and the results are presented in Fig. 4–6.
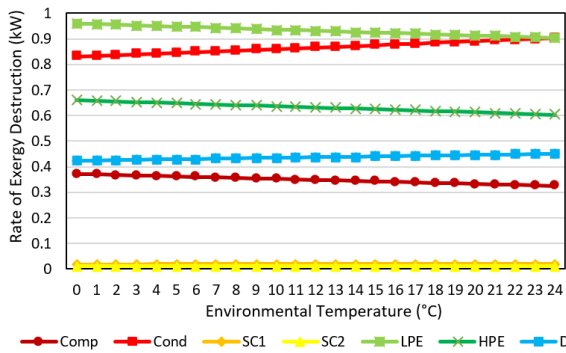
Figure 6. Impact of the environmental temperature on the exergy destruction rates of the main components

Figure 7. Impact of the environmental temperature on exergy efficiencies of the selected system components

Fig. 6 shows that when the environmental temperature is varied between 0°C and 25°C, the exergy destruction rate of the compressor (Unit 1) decreases by around 0.05 kW as the environmental temperature increases. Within the same environmental temperature interval, the rate of exergy destruction within low-pressure evaporator (Unit 7) and high-pressure evaporator (Unit 8) decrease by about 0.06 kW as the environmental temperature is increased. As a result, it can be said that the environmental temperature has a similar impact on the exergy destruction rates of the compressor and the evaporators. Contrariwise, when the environmental temperature is raised from 0°C to 25°C, the condenser (Unit 2)'s exergy destruction rate increases by about 0.07 kW, the exergy destruction rate of the drying unit (Unit 12) increases by around 0.03 kW. This reason behind this tendency could be rationalized by the change in temperatures and pressures within the corresponding components. When the stream's exergy flow rate decreases, it means the stream is getting closer to the environmental conditions. Therefore, higher environmental temperatures affect each stream in different ways; several streams' exergy flow rates increase with increasing environmental temperatures and in contrast, other streams' exergy content could decrease by increasing environmental temperatures.

Fig. 7 shows the change in exergy efficiencies of the major components of the integrated dual stage heat pump drying system with respect to increasing environmental temperatures from 0 to 25°C. The effect of environmental temperature on exergy efficiencies of the components is similar to the effect of the environmental temperature on exergy destruction rates. When the environmental temperature is raised within the selected environmental temperature interval from 0°C to 25°C, the exergetic effectiveness of the compressor (Unit 1) increases by around 1.6%, and the exergetic effectiveness of the low-pressure evaporator (Unit 7) and the high-pressure evaporator (Unit 8) increase by about 1.7%. Oppositely, within the when the environmental temperature is raised within the same selected interval, the exergetic effectiveness of the condenser (Unit 2) and the drying unit (Unit 12) decrease by around 10%. As discus-
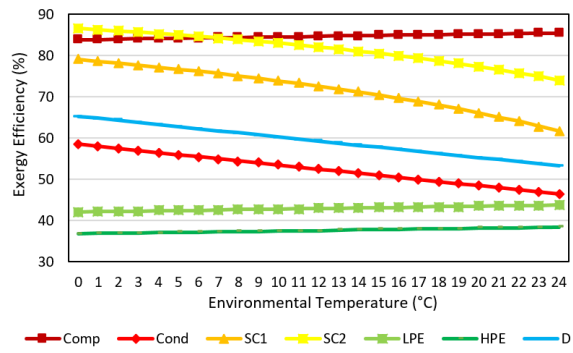
sed before, higher environmental temperatures affect each stream in a different way; several streams' exergy flow rates increase with increasing environmental temperatures and in contrast, other streams' exergy content could decrease by increasing environmental temperatures.

Fig. 8 represents the impact of the environmental temperature on the exergetic effectiveness of the overall system. As the environmental temperature increases within the selected interval from 0°C to 25°C, the overall system's exergy destruction rate increases from about 3.7 kW to around 6.8 kW. In contrast, the exergetic effectiveness of the system decreases from about 35% to around 10%. The change in the exergetic effectiveness based on the variation in the environmental temperature is parallel to the change in the exergetic performance of the condenser and the drying unit.

This study is the comprehensive energy and exergy performance analysis of the system proposed in [2]. The study is strengthened with parametric studies to have a comprehensive understanding of the impact of some key parameters on the system performance. The mass flow rate, temperature, and pressure of each stream within the integrated dual stage heat pump system are given in Table 2. Here, the reason for selecting 0.5 kg/s as the dryer's inlet air mass flow rate is because this amount is selected in [2]. The COP of the system and all initial energy and exergy investigations are conducted based on the input values provided in Table 4. Under
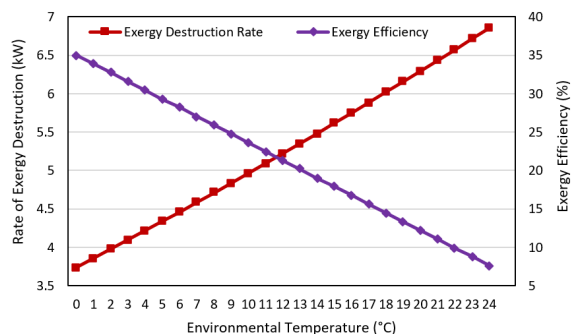

Figure 8. Impact of the environmental temperature on the overall system's exergy efficiency and destruction rate
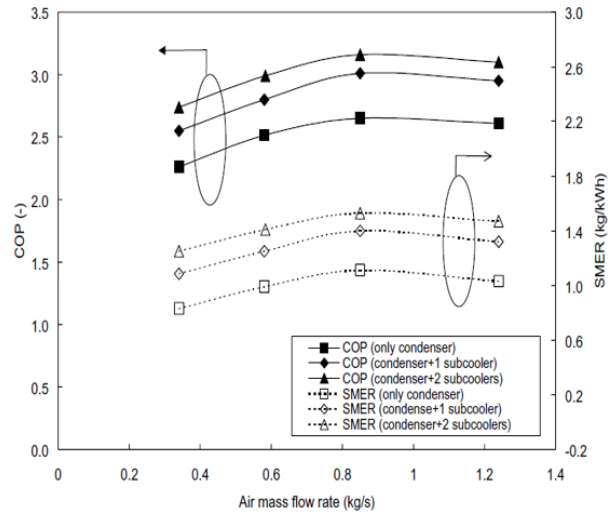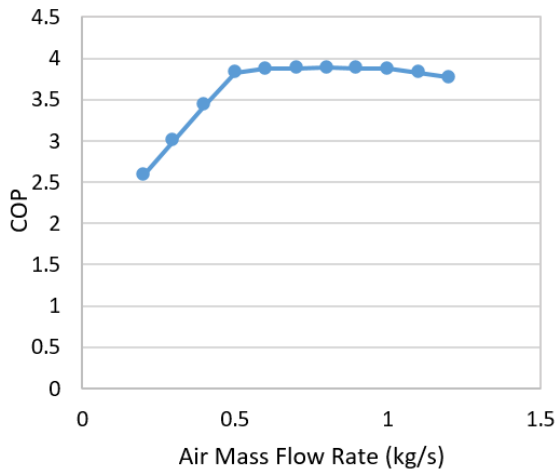
Figure 9. Overall COP with respect to the air mass flow rate (left) and the results from the literature [2] (right)

these conditions, the COP of the integrated dual stage heat pump drying system is estimated to be about 3.82. In the next step, the impact of the dryer's inlet air mass flow rate on the overall COP of the system is examined and the parametric study findings are given in comparison with the data published in the literature [2] in Fig. 9. From Fig. 9, it can be seen that the results of this study show significant similarities to the originally published work, in terms of COP calculations. The small differences can be justified by the assumptions taken into account when conducting the comprehensive energetic and exergetic investigations of the integrated dual stage heat pump drying system. One major reason is ignoring the heat losses within the system components which increase the overall system's energy efficiency quite significantly. Furthermore, the supplementary units are assumed to perfectly insulated with zero mechanical and heat energy losses. As a result, any losses within these components are ignored and most of the auxiliary components are assumed to be isenthalpic. In addition, all heat losses and pressure drops within the pipes, tubes, connecting components, and valves are ignored. When these assumptions are taken into consideration, and when these assumptions are eliminated, the COP and energetic and exergetic efficiencies of the overall system could further decrease.

In this study, an existing model of an integrated dual stage heat pump based drying process is modified and thoroughly investigated from energy and exergy perspectives, which has not been done before. Below, there is a list of results presented in this study which makes it unique and different than the previously published studies in the literature, including [2] based on which the design parameters of the integrated heat pump-drying system is selected:

- Technical comparison of heat pump dryers with other drying technologies

- Potential benefits of heat pump drying systems as a smart energy solution

- 3S (system-source-service) approach from energy and exergy perspectives, including losses

- Energy and exergy efficiency equations of each component of the heat pump-drying system

- Results are presented for each component of the heat pump-drying system including:

  o Exergy destruction rates

  o Relative irreversibilities

  o Energy and exergy efficiencies

  o Sustainability indexes

- Parametric studies are conducted to understand the effect of environmental temperature on:

  o Exergy destruction rates of each component and the overall system

  o Exergy efficiencies of each component and the overall system

The comprehensive energy and exergy analyses performed in this study have not been conducted and presented in the literature before, including the basis study [2]. By taking exergy into account and by conducting parametric studies on key factors, a better insight into system performance is obtained and solid future directions are provided for enhanced performance of heat pump-drying systems. The results

of this study could further be utilized to design optimum operating parameters for integrated dual stage heat pump drying systems.

FUTURE DIRECTIONS

Heat pump dryers are recognized as smart solutions for sustainable drying since they have many advantages as presented in Table 1. However, in order to be considered as 100% sustainable, the smart energy solutions criteria should be followed when developing heat pump dryers [41]. And a crucial challenge is to use renewable resources in a cost competitive, emission-free, and efficient manner in heat pump dryers. This section aims to present the future directions of heat pump drying processes to guide students, researchers, policy makers, and industry members.

To reduce overall system cost, research is focused on improving the efficiency of heat pump drying technologies as well as reducing the cost of capital equipment, operations, and maintenance while minimizing the overall environmental impact of the process.

In the literature, there are many conventional and novel heat pump dryer process designs. Each one of these processes is at different stages of research and development. Among these alternatives, the ones that are already commercially available such as fossil fuel powered systems can be used as near-term solutions as the renewable based and sustainable technologies are being developed and commercialized. Another research focus is on minimizing and/or eliminating the emissions of these technologies. Future directions of heat pump drying systems in light of smart energy solutions is shown in Fig. 10.

The first step in Fig. 10 is "exergization", meaning including the concept of exergy and exergy analysis when evaluating the performance of heat pump dryers. Efficient use of exergy, or minimization of exergy losses, is the key smart energy solution for a sustainable future [42]. The se-
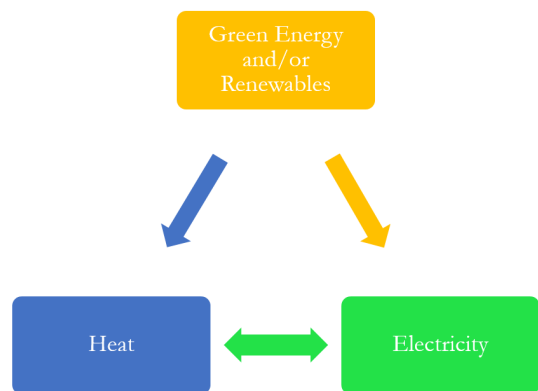

Figure 11. Green and renewable energy integration options with heat pump drying systems

cond step is "greenization" which means using green energy and material resources in heat pump drying systems which include carbon capture and storage technologies, taking advantage of waste and loss of energy, etc. From the source, system, and service approach; all components of heat pump drying systems must be greenized [43]. One example of greenization is the growing interest in green electricity as a means of utilizing renewable electrical energy based heat pump drying systems. This relationship is illustrated in Fig. 11. The third step is "renewabilization", which goes one step beyond "greenization" and suggests all steps in heat pump drying systems must use renewable energy and material resources. Since sustainability is widely defined as "providing for today without harming tomorrow", using renewable resources certainly is a smart solution for a sustainable future. The fourth step is "integration", which includes a variety of future directions from the integration of different methods for a more efficient and comprehensive energy system. "Integration" also means integrating heat pump drying systems with different sustainable energy systems such as hydrogen production, desalination, heating, cooling, water purification, etc. The fifth step is "multigeneration" which is essential in smart energy systems. Heat pump drying systems must operate in a multigeneration mode in order to minimize system losses and enhance desirable process outputs, which increases system efficiencies and as a result, costs and negative environmental impacts decrease. This is certainly a key step toward sustainability. The sixth step is "storagization" as effective heat storage is still one of the most challenging aspects of energy systems. And lastly, the seventh step is "intelligization" which means making every step of heat pump drying systems intelligent, with smart control devices, better forecasting, and effective information, material, and energy flow.

Reducing the cost of heat pump drying systems is the key challenge of the emerging technologies. Cost reduction especially becomes more challenging when renewable resources and novel technologies come into the picture. The
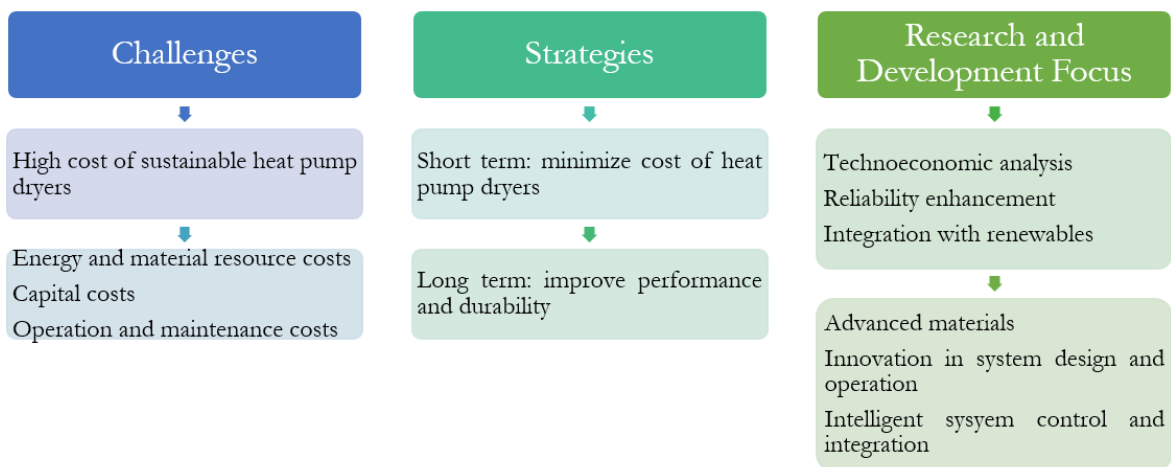

Figure 10. Future directions of heat pump drying systems in light of smart energy solutions

| Challenges | Strategies | Research and Development Focus |

Figure 12. Challenges, strategies, and R&D focus of heat pump drying systems for a sustainable future

challenges, strategies, and research and development suggestions for future heat pump drying systems are shown in Fig. 12.

Another important future direction for understanding and therefore enhancing heat pump drying systems' performance is proper and comprehensive life cycle analysis (LCA). With the cradle-to-grave type of LCA approach, the cost, emissions, and efficiency of a heat pump dryer can be calculated in the most accurate manner. This also allows consumers, policymakers, scientists, industry, academia, and governments choose the smart energy option among different alternatives. As a result, heat pump drying systems can get truly exergized, greenized, renewabilized, integrated, and intelligent with multigeneration options. And heat pump dryers could become the most sustainable drying option for end users of all types.

CONCLUSION

Heat pumps are very well known technologies in terms of delivering efficient heating and cooling with the lowest possible electrical energy consumption. Here, it is shown that heat pump dryers have significant advantages compared to other available drying technologies. Heat pump drying systems can become more sustainable when green, clean, and eventually 100% renewable energy and material resources are used instead of fossil fuels. Enhancing the COP of heat pump dryers is essential. However, in the next steps. SMER must also be taken into account. When developing a sustainable energy system; capital, operating, and maintenance cost and other financial factors, energetic and exergetic performance, and environmental impact must all be taken into account together simultaneously. Hybrid technologies could potentially enhance energetic and exergetic efficiencies. On the other, further research is required to lower their capital, operating, and maintenance cost and environmental impact.

The main aim of this study is to conduct energetic and exergetic investigations of an integrated heat pump drying process in order to evaluate the performance of the overall system. For that reason, exergy efficiencies and exergy destruction rates of each system component along with the overall system are carefully calculated. Here, this analysis is done in order to take all process irreversibilities into account to tackle the end results the loss of the quality of energy. By calculating the overall exergetic performance of the entire process along with all of its components, it is aimed to identify where there is a loss in the quality of energy. In addition, the location of these quality losses within major components is investigated at different environmental temperatures. In order to provide a straight advantage to the society and industry, it is essential to take advantage of the possible profits of exergy. Also, it should be noted that, unlike the assumptions in this study, it is not possible in reality to perfectly insulate the components of the heat pump system, not with the current material science and engineering technologies. On the other hand, appropriate insulating materials and technologies for the overall system including all components, auxiliary units, and monitoring devices could potentially enhance the system COP and energetic and exergetic efficiencies significantly. Imperfections because of the component and material inefficiencies can be increased to further increase system COP and energy and exergy efficiencies. The careful material, equipment, and technology selection could further enhance the system COP and energy and exergy efficiencies. The following items are the summary of some of the major particular results of this study:

• At the selected environmental temperature and pressure, the integrated heat pump drying system has overall energetic and exergetic efficiencies around 62% and 35%, respectively.

• At the selected environmental temperature and pressure, the integrated heat pump drying system's exergy

destruction rate is 3.96 kW.

• The components where the highest exergy destruction occurs are the low-pressure evaporator (0.9 kW), the condenser (0.83 kW), and the high-pressure evaporator (0.7 kW).

• As the environmental temperature increases, the overall exergy destruction rate increases and the exergy efficiency decreases.

In this study, the primary aim is to improve the exergy efficiency of the proposed integrated dual stage heat pump based drying process by identification of where the irreversibilities occur and developing strategies to minimize these irreversibilities. There are several reasons behind high irreversibilities (exergy destruction) in a process, some of these reasons can be listed as: (i) temperature difference between the inlet and outlet streams of a system component, (ii) pressure difference between the inlet and outlet streams of a system component, (iii) any other flow imbalances between the inlet and outlet streams of a system component, and (iv) not being able to recover the latent heat in heat exchangers which is caused by high temperature differences. Lowering the inlet and outlet streams' temperature variance also lowers the difference between the condensing and evaporating temperatures. And as a result, enhances the amount of heat recovery per unit of energy input to a system or component.

TERMINOLOGY

E	Energy (kJ)
$\dot{E}$	Energy flow rate (kW)
ex	Specific exergy (kJ/kg)
Ex	Exergy (kJ)
$\dot{Ex}$	Exergy (kJ)
h	Specific enthalpy (kJ/kg)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa)
Q	Heat (kJ)
$\dot{Q}$	Heat transfer rate (kW)

s	Specific entropy (kJ/kg-K)
S	Entropy (kJ/K)
$\dot{S}$	Entropy flow rate (kW/K)
t	Time (s)
T	Temperature (K)
W	Work (kJ)
$\dot{W}$	Work transfer rate (kW)

Greek Letters

α	Mass ratio of the refrigerant sent to HPE
Δ	Change
η	Energy efficiency
ψ	Exergy efficiency

Subscript and Superscripts

a	Air
ch	Chemical
$comp$	Compressor
$cond$	Condenser
cv	Control volume
$dest$	Destruction
en	Energy
ex	Exergy
gen	Generation
in	Inlet stream
ke	Kinetic energy
out	Outlet stream
pe	Potential energy
ph	Physical

r	Refrigerant
°	Standard state
0	Environmental state

Abbreviations

AA	Ascorbic Acid
BPRV	Back Pressure Regulated Valve
COP	Coefficient of Performance
D	Dryer
EES	Engineering Equation Solver
EV	Expansion Valve
GHG	Greenhouse Gas
HPE	High-Pressure Evaporator
LCA	Life Cycle Analysis
LPE	Low-Pressure Evaporator
RH	Relative Humidity
RI	Relative Irreversibility
SC	Sub-cooler
SI	Sustainability Index
SMER	Specific Moisture Extraction Ratio
VLE	Vapor-liquid Equilibrium

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