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Current state and future projections of drying processes in the US food and pulp and paper sectors: Energy, economic, and environmental assessment

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ABSTRACT

The pulp and paper (P/P) and food sectors are the third- and fifth-largest industrial energy consumers in the United States, with total on-site energy consumption of 2,039 TBtu and 1,144 TBtu, respectively. Thermal drying processes for moisture removal, which are energy-intensive, play a critical role in both industries. This study is the first to evaluate state- and national-level US drying energy demand for these sectors from 2020 to 2050. To complete this evaluation, we developed a thermodynamic modeling framework integrated with economic and environmental models to compute product-specific drying energy intensity and estimate the sector-specific costs and emissions profiles associated with drying operations. The model-predicted energy intensity was validated against the literature. Using current and projected annual production volumes in these sectors, we estimated total drying energy use. Results indicate that drying accounts for 22 % of total energy consumption in the P/P sector and 10 % in the food sector. The estimated annual energy cost (2020) to operate thermal dryers is $919 M in the P/P sector and $417 M in the food sector. Additionally, drying contributes to 25 % of total CO_2e emissions in the P/P sector (including biogenic) and 15 % of emissions in the food sector. Regional performance shows that the Southern US is the leading energy consumer for P/P drying, whereas the Midwest leads in food drying. This study presents both potential solutions to enhance drying efficiency and barriers to implementation. Energy efficiency improvements, low-carbon fuels, and electrification are discussed as key pathways for reducing costs and optimizing industrial drying processes.

Introduction

The US industrial sector is a substantial energy consumer and carbon dioxide equivalent (CO_2e) emitter, accounting for 32 % (19,436 TBtu) of total economy-wide energy consumption in 2018 and 1,903 MMT of CO_2e emissions in 2022 [1,2]. Within the industrial sector, two subsectors are the third- and fifth-largest industrial energy consumers in the United States—the pulp and paper (P/P) and food sectors consumed 2,039 and 1,144 TBtu of on-site fuel, respectively, in 2018 [3]. Process heating and indirect boiler combined use account for 45.3 % and 39.0 % of the total natural gas consumption in the food and P/P subsectors, respectively [3], demonstrating the importance of these processes in these sectors' total energy consumption. Currently, natural gas, biomass, and coal are the primary fuel sources for the food sector, whereas the P/P sector relies on a mix of black liquor, natural gas, and biomass [4].

Industrial drying—an integral part of products manufacturing in both the food and P/P sectors—is a process heating operation aimed at removing volatile substances and moisture to yield a desired dried solid product. In the food industry, drying is essential for preservation because it inhibits the growth of bacteria, molds, and yeasts, thereby enhancing supply chain efficiency, product quality, and shelf life and enabling diverse product offerings [5,6]. In the P/P industry, drying is crucial for achieving the mechanical properties required for paper usability and stability [7] and for market pulp production.

The global market value for industrial drying, estimated at approximately $12.5 billion as of 2024, is driven by the growing demand for efficient drying solutions that specifically meet strict product quality standards and extend shelf life [8]. In the US, the industrial dryer market exceeded $1.8 billion in 2024 and is projected to grow at a compound

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Nomenclature

Symbols and Units

a_w	Water activity [-]
CI	Carbon intensity [CO_2e/Btu]
CO_{2e} *emissions*	CO_2e emissions [MT CO_2e]
$c_{p,P}$	Specific heat of the product [kJ/kg-K]
$c_{p,P,d}$	Specific heat of the product on a dry basis [kJ/kg-K]
$c_{p,P,w}$	Specific heat of the product on a wet basis [kJ/kg-K]
$c_{p,w}$	Specific heat of water [kJ/kg-K]
EC	Energy mix [%]
E_{Lw}	Latent heat of water [Btu]
E_{min}	Minimum energy to evaporate the moisture [Btu]
EP	Energy price [$/Btu]
E_{sp}	Sensible heat of the product [Btu]
E_{sw}	Sensible heat of the water [Btu]
E_T	Total energy consumption [Btu]
E_U	Energy consumption [Btu]
h_{gw}	Specific latent heat of water [kJ/kg-K]
m_p	Mass of the dry product [lb]
m_T	Total mass of the product [lb]
m_w	Mass of water [lb_w]
n	Number of fuel types [-]
ns	Total number of states [-]
SEC	Specific energy consumption [Btu/lb or Btu/lb_w]
TEC	Total energy cost [$]
X_{db}	Moisture content on a dry basis [-]
X_{wb}	Moisture content on a wet basis [-]
Δm_w	Mass of water evaporated [lb_w]
ΔT	Difference between the inlet and outlet of the charged material [°C]
η_D	Drying efficiency [-]

Subscription

f	Final
i	Initial
m_p	Based on the mass of moisture removed during the drying process
m_w	Based on the mass of the dry product
w	Water

Abbreviations

CO_2e	carbon dioxide equivalent
DOE	US Department of Energy
FDA	US Food and Drug Administration
NAICS	North American Industry Classification System
P/P	pulp and paper

annual growth rate of about 5.6 % from 2025 to 2034 [9].

Thermal dryers—the primary technology employed in the food and P/P sectors—use heat to evaporate moisture from products. In the P/P sector, contact multicylinder dryers, which use steam as the primary energy source, are predominant [7]. Conversely, the food sector employs a variety of dryer types tailored to the specific requirements of each subsector, with convective and contact dryers most commonly used [10].

Convective dryers, which rely on convection as the primary heat transfer mechanism, can operate as either continuous or batch systems. Common types of convective dryers include rotary drum, tunnel, fluidized bed, pneumatic, spouted, spray, and chamber; most of these use hot air or flue gases as the heat transfer medium. In contrast, indirect or contact dryers use hot water or steam to heat a material, transferring heat through a surface to dry the charged material via conduction. The primary types of contact dryers—drum and belt—are continuous systems [10].

Several studies have reviewed current drying technologies and highlighted their advantages, disadvantages, and future potential [10–13]. For the food sector, Routray et al. [13] explored both conventional and emerging drying technologies, and Calín-Sánchez et al. [12] provided a critical comparison of traditional and novel methods. Li et al. [11] analyzed various dryer types—including convective, rotary, and infrared—and found energy consumption ranges from 142 to 4,841 Btu/lb_w, depending on dryer type, temperature gradients, and pre- and post-treatment steps. High exergy losses were associated with systems involving large temperature differences, such as combustion.

Other studies tied to the food sector focused on grain and fluidized bed drying. Chojnacka et al. [5] and Mondal and Sarker [14] assessed energy use and emissions in grain drying. Sivakumar et al. [15] and Majumder et al. [16] examined fluidized bed dryers for crops like tea and rice, discussing sustainability and quality impacts. Spray drying also was evaluated, with Woo and Bhandari [17], Moejes et al. [18], and Lisboa et al. [19] emphasizing energy efficiency and system optimization.

In the P/P sector, which involves fewer materials and specificities than those of the food sector, the volume of literature is smaller but still significant. Stenström [20] reviewed major studies from 2000 to 2018 related to paper dryers, including condebelt, heated cylinders, impulse drying, and infrared drying; review topics included operational aspects such as energy consumption and heat and mass transfer phenomena. Laurijssen et al. [21] highlighted the prevalence of different dryer types in the P/P sector, showing that 85 %–90 % of dryers used are multicylinder models, followed by Yankee (4 %–5%), infrared (3 %–4%), and impingement dryers (2 %–3%). Multicylinder dryers are common in major subsectors such as paper, paperboard, and pulp, whereas Yankee dryers are predominantly used for tissue products, which are not covered in this paper.

Numerous studies have used mathematical and numerical models to quantify energy use in drying processes for various foods and the P/P sector. Perazzini et al. [22] created an instantaneous energy and exergy model for wheat drying., based on heat and mass balances. Tripathy et al. [23] and Akpinar et al. [24] applied similar methods to potatoes and pumpkins, respectively. Tripathy and Kumar [25] used a general approach to predict food temperatures during drying. Lisboa et al. [19] mathematically modeled spray drying of milk, coffee, and juice. Dincer and Sahin [26] developed a novel exergy model for drying in general, while Kinstrey and White [27] estimated minimum energy needs for P/P drying systems.

The US Department of Energy (DOE) has reported briefly on energy consumption estimations for drying processes in the US [28,29]. In 2017, DOE analyzed energy use in the food sector, providing energy intensity data for dryers in major subsectors (e.g., dairy, animal slaughter and processing, fruits and vegetables processing, sugar manufacturing, and grain and oilseed milling) [29]. The report detailed production levels and on– and off-site energy consumption, presenting scenarios for energy reduction using state-of-the-art, practical minimum, and thermodynamic minimum technologies. Similarly, in 2015, DOE conducted a study on the P/P manufacturing sector, estimating an annual energy consumption of approximately 430 TBtu for industrial dryers [28]. The report also provided state-level production and identified energy intensity reduction opportunities.

Additional studies have further explored the energy intensity of drying processes [30–32]. For example, Thirumaran et al. [33] reported energy use in the paper and paperboard industry, estimating an energy intensity of 4.05 MMBtu/ton and total energy consumption of 219.71

TBtu/year. Subsector-specific analyses have also been conducted, such as a study on wet corn milling by Galitsky et al. [34], which examined energy consumption for a facility producing 100,000 bushels per day. This study, which specified electricity, steam, and fuel use, detailed energy intensities for several processes (e.g., germ dewatering and drying, starch drying, fiber washing/drying, gluten thickening and drying, and gluten feed drying). Brown et al. [35] further investigated energy intensities across various industries, including corn milling, animal slaughter and processing, dairy, cane sugar, soybeans, beet sugar, and P/P sectors. These studies collectively provide a comprehensive understanding of energy usage and opportunities for efficiency improvements in drying processes across diverse applications.

Despite the broad availability of sources describing the energy intensity of some subsectors covered in this study, many of these sources are outdated, lack comprehensive data on total energy consumption for specific drying processes or subsectors, or present widely divergent results. A major limitation in the literature is the lack of standardized methodologies for estimating drying energy demand, which is often influenced by variability in operational parameters, fuel mix, and drying technologies across facilities. Moreover, there is no focused analysis on how energy consumption for drying processes in the food and P/P sectors is expected to evolve over the coming decades. Such analysis is crucial, given the significance of these industries to US energy consumption. Additionally, the complexity and scale of the US necessitates a state-level understanding of these processes to assess how local policies, energy demand, and other regional factors (e.g., fuel costs) might influence future changes in drying technologies.

The objective of this study is to provide a comprehensive analysis of national and state-level energy, environmental, and economic effects associated with drying processes in the US food and P/P sectors. Using publicly available data (literature and industry) and assuming the continued use of currently deployed drying technologies, we project energy demand, CO_2e emissions, and costs from 2020 to 2050 to establish a baseline scenario. These two sectors were chosen because they account for a significant portion of drying energy use in the US manufacturing sector, based on Cresko et al. [29]. The present study focuses exclusively on dedicated dryers and did not attempt to estimate drying energy use that may have occurred as part of other processes (e.g., baking and frying). To the best of the authors' knowledge, the current study is the first to present a detailed breakdown of energy usage across specific subsectors at the state level, incorporating critical parameters to develop a framework that calculates the energy consumption of drying processes.

This analysis is valuable for both industry and academia, serving as a foundational tool for future research and decision-making. Projections are used to evaluate the effects of drying processes and to identify trends and opportunities for improvement. Additionally, this study explores energy efficiency pathways, including their barriers, solutions, and policies to enable these transitions.

Methodology

This section outlines the data collection strategy, the energy, economic, and environmental models proposed in this study, and the validation procedures employed.

The Excel-based framework used to estimate state- and national-level energy consumption, cost, and CO_2e emissions is illustrated in the flow diagram in Fig. 1. As shown in the figure, the process begins with data collection (see Section 2.1). Next, the specific energy consumption (SEC) is calculated for all products (see Section 2.2.1). By using production data for each state (see Section 2 of the Supplementary Material [SM]), the state-level energy consumption is then determined. Subsequently, state-level energy costs and CO_2e emissions are calculated based on energy mix, state-specific energy prices and the carbon intensity of each energy source (see SM, Section 2), as detailed in this paper in Sections 2.2.2 and 2.2.3, respectively. Finally, national-level energy consumption, costs, and CO_2e emissions are obtained by aggregating the results across all states.

Data collection

To calculate the SEC for each subsector categorized by the North American Industry Classification System (NAICS), we collected the inputs in Fig. 1 and the parameters outlined in Table 1. Data presented in Table 1 include reported average values (in bold and italics) and the corresponding most common minimum and maximum input values to capture the typical range of variability.

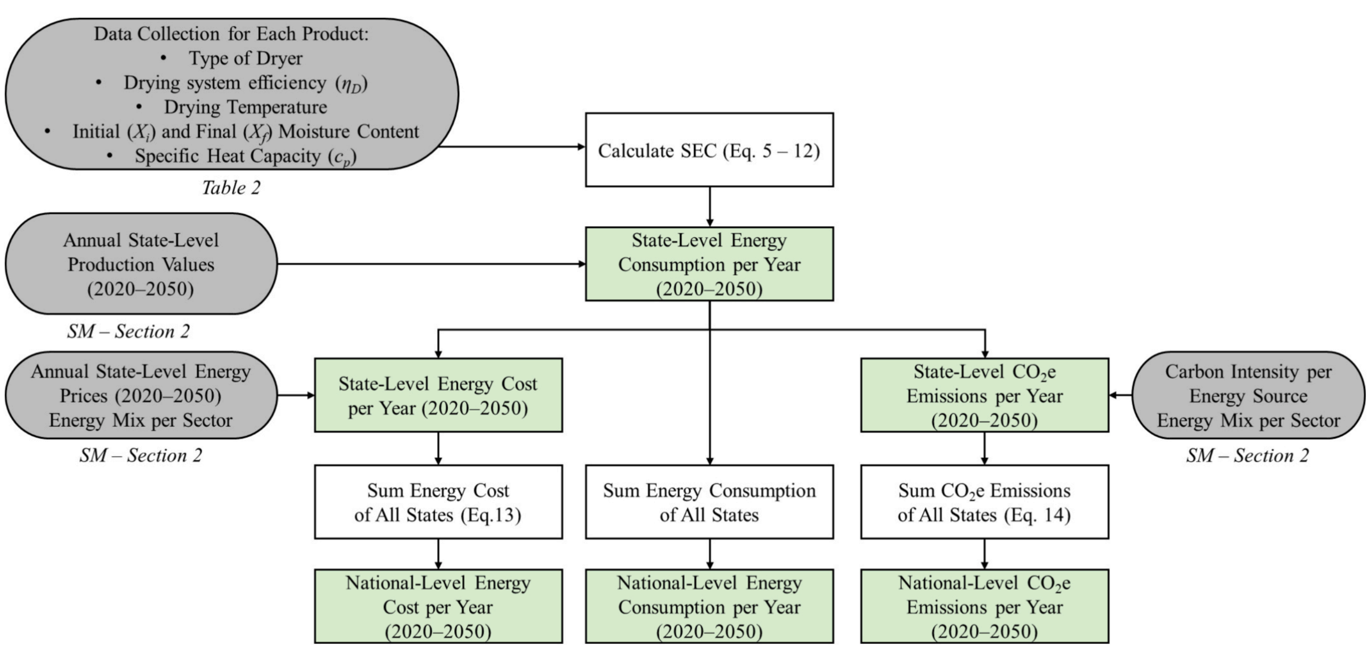


Fig. 1. Framework for estimating state- and national-level energy use, costs, and CO_2e emissions.

Table 1
Average drying efficiency; the minimum, average (in bold and italic type), and maximum initial and final moisture content; specific heat; and the minimum, average (in bold and italic type), and maximum drying temperature for the most typical dryer types used in each subsector and in that subsector's products.

NAICS Class.	Subsector	Main Product	Subproduct	Type of Dryer	Drying Efficiency (%)	Initial Moisture Content (%)	Final Moisture Content (%)	Specific Heat (kJ/[kg•K])	Temperature (°C)*
3112	**Grain and Oil Seed Milling**	Soybean	Soybean Flake	Rotary Indirect	52	18 | ***20*** | 22 [36]	***12*** [36,37]	$c_{p,P} = 1.444 + (1 + 4.06x10^{-2}X_{db})$ [38]	50 | ***70*** | 80 [39]
			Soybean Oil	Fluidized Bed	48	15 | ***17.5*** | 20 [10,36,40–47]	10 | ***11.5*** | 13 [10,36,40–47]	$c_{p,P} = 1.444 + (1 + 4.06x10^{-2}X_{db})$ [38]	30 | ***45*** | 60 [42–47]
		Corn	Corn Starch	Flash	50	33 | ***37.5*** | 42 [48,49]	3 | ***4*** | 5 [48,49]	$c_{p,P} = 1.64 - 1.91xX_{wb}$ [50]	54 | ***77*** | 100 [35,51]
			Corn Germ	Rotary Indirect	52	45 | ***52*** | 60 [52,53]	1.5 | ***3*** | 4 [34,53,54]	$c_{p,P} = 1.470 + 0.036X_{wb}$, $1 < X_{wb} < 30\ \%\ (X_{wb})$ [10]	95 | ***105*** | 115 [35,54]
			Gluten Thickening and Drying	Flash	50	14 | ***17*** | 20 [55,56]	10 | ***11*** | 12 [55,56]	$c_{p,P} = 1.470 + 0.036X_{wb}$, $1 < X_{wb} < 30\ \%\ (X_{wb})$ [10]	50 | ***55*** | 60 [57]
			Fiber Drying	Rotary Indirect	52	***10.0*** [34]	3.4 | ***6.2*** | 9 [58]	$c_{p,P} = 1.470 + 0.036X_{wb}$, $1 < X_{wb} < 30\ \%\ (X_{wb})$ [10]	30 | ***45*** | 60 [59]
			Gluten Feed	Flash	50	40 | ***50*** | 60 [56,60]	10 | ***11*** | 12 [61,62]	$c_{p,P} = 1.470 + 0.036X_{wb}$, $1 < X_{wb} < 30\ \%\ (X_{wb})$ [10]	50 | ***55*** | 60 [57]
			Dextrose Drying	Fluidized Bed	48	15 | ***18.5*** | 22 [63]	7.5 | ***8.5*** | 9.5 [63–65]	$c_{p,P} = 1.470 + 0.036X_{wb}$, $1 < X_{wb} < 30\ \%\ (X_{wb})$ [10]	50 | ***77*** | 105 [35]
		Breakfast Cereal	Breakfast Cereal (Pre-Dryer)*	Rotary Indirect	52	28 | ***32*** | 36 [66–69]	12 | ***17*** | 22 [66–69]	2.28 [70]	65 | ***80*** | 95 [66–69]
			Breakfast Cereal (Main Dryer)*	Conveyor	40	12 | ***15*** | 18 [66–69]	1 | ***2.5*** | 4 [66–69]	1.70 [70]	120 | ***148*** | 175 [66–69]
		Rice	Rice	Fluidized Bed	48	20 | ***22.5*** | 25 [14,71–73]	9 | ***11.5*** | 14 [14,71–73]	$c_{p,P} = 1.197 + 0.038X_{wb}$ [74]	40 | ***43*** | 45 [71,72]
		Malt	Malt (for Beer)**	Drum	47	***45*** [75]	3 | ***4*** | 5 [75]	2.16 [75]	125 | ***153*** | 180 [75]
3113	**Sugar**	Cane Sugar	Cane Sugar	Spray Dryer	46	2 | ***2.5*** | 3 [76]	0.02 | ***0.3*** | 1.1 [76,77]	$c_{p,P} = 0.491 + 0.501X_{db} + 0.025X_{db}^2$ [78]	70 | ***85*** | 105 [77]
		Beet Sugar	Beet Sugar (Granulator)	Spray Dryer	46	2 | ***2.5*** | 3 [76]	0.02 | ***0.3*** | 1.1 [76,77]	$c_{p,P} = 0.491 + 0.501X_{db} + 0.025X_{db}^2$ [78]	70 | ***85*** | 105 [77]
			Beet Sugar (Pulp)	Drum	47	70 | ***76*** | 82 [79–81]	10 | ***11*** | 12 [81–83]	$c_{p,P} = 1.5 + 4.18X_{wb}$ [84]	60 | ***105*** | 150 [80,81,83,85]
3115	**Dairy**	Milk	Powdered Dry Milk	Spray Dryer	46	45 | ***50*** | 55 [86,87]	2 | ***3*** | 4 [86,87]	1.50 [88]	100 | ***150*** | 200 [87,89]
			Powdered Whey	Spray Dryer	46	40 | ***45*** | 50 [90]	2 | ***3*** | 4 [86,87]	1.50 [88]	100 | ***150*** | 200 [87,89]
		Cheese	Cheese Powder**	Spray Dryer	46	45 | ***52.5*** | 60 [91]	3 | ***4*** | 5 [92]	3.00	60 | ***125*** | 190 [93]
3116	**Slaughtering and Processing**	Red Meat	Meal Blood	Spray Dryer	46	60 | ***62*** | 63 [94,95]	2% | ***6*** | 10 [10,95–98]	1.50 [88,99]	80 | ***100*** | 120 [95,97,98,100]
			Jerky**	Conveyor	40	***60*** [101,102]	15 | ***20*** | 25 [102–104]	3.00 [105]	54 | ***57*** | 60 [101,104]
3114	**Fruits and Vegetables**	Apple	Apple	Conveyor	40	***80*** [106]	***24*** [106]	2.00 [84]	50 | ***55*** | 60 [10]
		Grape	Grape	Conveyor	40	70 | ***75*** | 80 [106]	15 | ***18*** | 20 [106]	2.00 [84]	50 | ***55*** | 60 [10]
		Other Noncitrus	Other Noncitrus	Conveyor	40	***75****	***15****	2.00 [84]	***65*** [10]
		Potato	Potato	Conveyor	40	75 | ***80*** | 85 [10]	10 | ***12*** | 14 [10]	2.00 [84]	***70*** [10]
		Onion	Onion	Conveyor	40	80 | ***83*** | 85 [10]	***8*** [10]	2.00 [84]	***50*** [10]

(continued on next page)

Table 1 (*continued*)

NAICS Class.	Subsector	Main Product	Subproduct	Type of Dryer	Drying Efficiency (%)	Initial Moisture Content (%)	Final Moisture Content (%)	Specific Heat (kJ/[kg•K])	Temperature (°C)*
		Juice	Juice Powder**	Spray Dryer	46	25 | ***27.5*** | 30 [107]	2 | ***3*** | 4 [107]	2.83 [108]	80 | ***130*** | 180 [107]
3111	**Dog and Cat Food Manufacturing**	Pet Food	Dry Pet Food*	Conveyor	40	25 | ***27.5*** | 30 [109,110]	10 | ***11*** | 12 [109,110]	*2.00* [111]	***121*** [110,112]
3117	**Seafood Product Preparation and Packaging**	Fish Meal	Fish Meal**	Rotary Indirect	52	***50*** [113]	7 | ***9.5*** | 12 [113]	*2.03* [113]	***90*** [113]
3118	**Bakeries, Tortilla, Dry Pasta**	Pasta*	Dry Pasta*	Conveyor	40	29 | ***30*** | 31 [114]	12 | ***12.5*** | 13 [114]	$c_{p,P} = 1.44 + 2.74X_{wb}$ [115]	60 | ***83*** | 105 [116]
3119	**Coffee and Tea**	Coffee*	Ground Coffee**	Spray Dryer	46	60 | ***65*** | 70 [117]	2.5 | ***3.25*** | 4 [117]	$c_{p,P} = 0.248 + 8.14X_{wb}$ [118]	88 | ***99*** | 110 [117]
	Coffee and Tea	Tea	Tea**	Conveyor	40	40 | ***45*** | 50 [10,119,120]	4 | ***5*** | 6 [10,119,120]	*3.50* [121]	60 | ***110*** | 160 [10]
	All Other Miscellaneous Food Manufacturing	Yeast	Yeast**	Fluidized Bed	48	65 | ***70*** | 75 [122]	4 | ***5*** | 6 [122]	*1.4* | *1.80*	50 | ***55*** | 60 [122]
322	**P/P**	Pulp	Pulp Mill	Multicylinder	43.5	82 | ***100*** | 122 [21,123–125]	***11*** [126,127]	1.25 [27]	***75*** [10]
		Paper	Paper Mill	Multicylinder	43.5	82 | ***100*** | 122 [21,123–125]	5 | ***8*** | 10 [10,21,124]	1.25 [27]	***115*** [27]
		Paperboard	Paperboard Mill	Multicylinder	43.5	82 | ***100*** | 122 [21,123–125]	8 | ***9*** | 11 [128,129]	1.25 [27]	***115*** [27]

*Owing to a lack of state-level data and future production projections, these products will be included only in the current national-level 3E analysis.
**Owing to limited available production data, these products are excluded from the scope of this study.

Mathematical models

Energy model

The minimum energy (E_{min}) required to dry the charged material from initial to final moisture content can be expressed as follows:

$$E_{min} = E_{sp} + E_{sw} + E_{Lw} = m_P c_{p,P} \Delta T + m_{w,i} c_{p,w} \Delta T + \left(m_{w,i} - m_{w,f}\right) h_{gw} \quad (1)$$

where E_{sp}, E_{sw}, and E_{Lw} represent the sensible heat of the product, the sensible heat of the water, and the latent heat of water, respectively. The term m_p is the mass of the dry product; $c_{p,P}$ and $c_{p,w}$ are the specific heat capacity of the product and water, respectively; $m_{w,i}$ and $m_{w,f}$ are the initial and final mass of water in the charged material, respectively; h_{gw} is the specific latent heat of water (assumed to be constant at 2,260 kJ/kg); and ΔT is the difference between the inlet and outlet temperatures of the charged material.

The energy consumption, considering the distinct types of dryers, is given by Eq. (2):

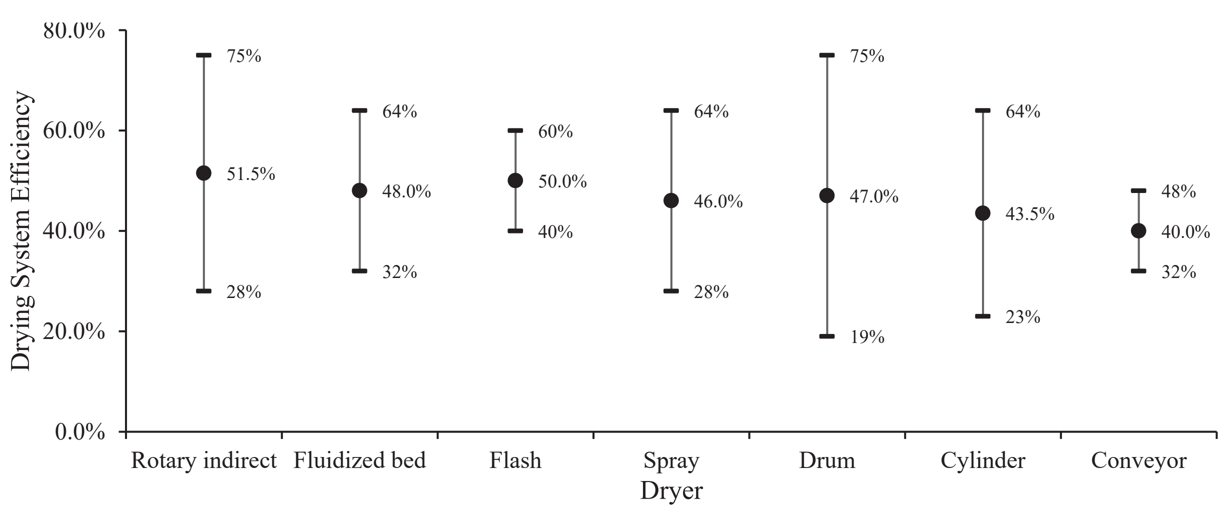


Fig. 2. Drying system efficiency of the most common dryers used in the food and P/P sectors.

$$E_U = \frac{E_{min}}{\eta_D} \quad (2)$$

where E_U is the energy consumption, and η_D is the drying system efficiency.

Fig. 2 illustrates the range of drying system efficiency for the most used conventional thermal dryers in the food and P/P sectors, as reported in the literature [10,14,125]. Drying system efficiency can be defined in various ways depending on its intended use. Some definitions include only dryer losses, whereas others also account for upstream systems and distribution losses. This study uses system-level energy efficiency, which captures losses at the dryer (e.g., exhaust and wall losses) and generation (e.g. boiler) and distribution. Using system-level energy efficiency provides a more accurate estimate of actual energy required relative to the theoretical minimum. Reported literature values were adjusted to reflect this approach, and the system efficiency ranges applied for each dryer type are shown in Fig. 2.

SEC is defined as the ratio of energy consumption (E_U) to the mass of moisture removed during the drying process ($m_{w,i} - m_{w,f}$) or the mass of the dry product (m_p). In this case, the units of evaluation will be Btu/lb$_w$ or Btu/lb, respectively. The following equations illustrate how to compute SEC, whether based on the water of moisture evaporated [Eq. (3)] or the dry product mass [Eq. (4)] [130]:

$$SEC_{mw} = \frac{E_U}{m_{w,i} - m_{w,f}} \quad (3)$$

$$SEC_{mp} = \frac{E_U}{m_p} \quad (4)$$

Given the diverse range of products and their varying calculation methods, this study proposes a framework for estimating the SEC based on available input data. Depending on the reference, product, and sector, the moisture content may be reported on a dry (X_{db}) or wet (X_{wb}) basis, and the SEC can be expressed per unit of evaporated water mass or dry product mass. Additionally, users may have access to specific heat data as a function of moisture content ($c_{p,P,w}$) or as fixed values ($c_{p,P,d}$).

Fig. 3 illustrates the decision-making process for calculating the SEC of drying processes based on different moisture content bases (wet or dry), specific heat capacities ($c_{p,P}$), and mass considerations. The framework begins with input parameters: initial and final moisture content on different basis ($X_{wb,i}$, $X_{wb,f}$ or $X_{db,i}$, $X_{db,f}$), specific heat capacities of the product ($c_{p,P,w}$ or $c_{p,P,d}$ for the wet basis and the dried product, respectively), specific heat capacity of water ($c_{p,w}$), specific latent heat of water (h_{gw}), and inlet and outlet charged material temperatures (T_{in} and T_{out}).

The flowchart in Fig. 3 determines the drying energy calculation method to be used depending on the availability of the specific heat capacity of the product on either a wet ($c_{p,P,w}$) or dry ($c_{p,P,d}$) basis. Last, the resulting equation (SEC) is tailored to per-dry mass (SEC_{mp}) or total evaporated water mass (SEC_{mw}).

For cases where the $c_{p,P,w}$ is used, the sensible heat of the product (E_{sp}) already accounts for the sensible heat of the water (E_{sw}). Table 2 summarizes the eight proposed equations, detailing how each can be used depending on the inputs available.

The total drying energy consumption for a specific product (E_T) is calculated by multiplying the SEC and the total mass of the product. Because dedicated drying operations typically occur at the final stage of product processing, the mass of the final product is assumed to equal the

Table 2
Energy equations depending on available inputs.

Variable	Equation	Eq.
$SEC_{m_p,X_{wb},C_{p,P,w}}$	$\left(1+\frac{X_{wb,i}}{1-X_{wb,i}}\right)c_{p,Pw}\Delta T + \left(\frac{X_{wb,i}}{1-X_{wb,i}}-\frac{X_{wb,f}}{1-X_{wb,f}}\right)h_{gw}$	(5)
$SEC_{m_w,X_{wb},C_{p,P,w}}$	$\frac{\left(1+\frac{X_{wb,i}}{1-X_{wb,i}}\right)c_{p,Pw}\Delta T}{\left(\frac{X_{wb,i}}{1-X_{wb,i}}-\frac{X_{wb,f}}{1-X_{wb,f}}\right)} + h_{gw}$	(6)
$SEC_{m_p,X_{db},C_{p,P,w}}$	$(1+X_{db,i})c_{p,Pw}\Delta T + (X_{db,i}-X_{db,f})h_{gw}$	(7)
$SEC_{m_w,X_{db},C_{p,P,w}}$	$\frac{(1+X_{db,i})c_{p,Pw}\Delta T}{(X_{db,i}-X_{db,f})} + h_{gw}$	(8)
$SEC_{m_p,X_{wb},C_{p,P,d}}$	$\left(c_{p,P}+\left(\frac{X_{wb,i}}{1-X_{wb,i}}\right)c_{p,w}\right)\Delta T + \left(\frac{X_{wb,i}}{1-X_{wb,i}}-\frac{X_{wb,f}}{1-X_{wb,f}}\right)h_{gw}$	(9)
$SEC_{m_w,X_{wb},C_{p,P,d}}$	$\left[c_{p,P}+\left(\frac{X_{wb,i}}{1-X_{wb,i}}\right)c_{p,w}\right]\frac{\Delta T}{\left(\frac{X_{wb,i}}{1-X_{wb,i}}-\frac{X_{wb,f}}{1-X_{wb,f}}\right)} + h_{gw}$	(10)
$SEC_{m_p,X_{db},C_{p,P,d}}$	$(c_{p,P}+X_{db,i}c_{p,w})\Delta T + (X_{db,i}-X_{db,f})h_{gw}$	(11)
$SEC_{m_w,X_{db},C_{p,P,d}}$	$[c_{p,P}+X_{db,i}c_{p,w}]\frac{\Delta T}{(X_{db,i}-X_{db,f})} + h_{gw}$	(12)

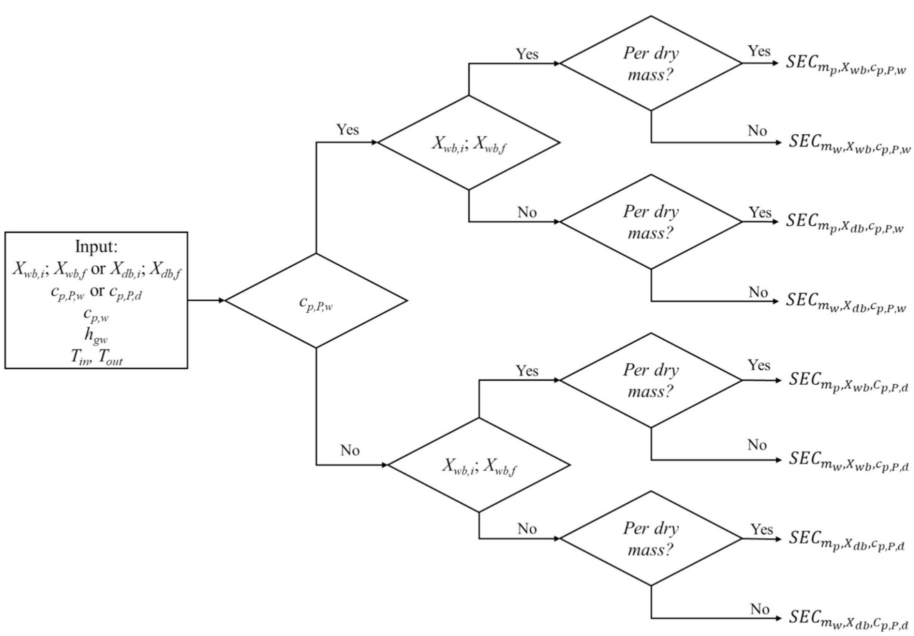


Fig. 3. Proposed framework for energy equation selection based on (1) specific heat ($c_{p,P,w}$ or $c_{p,P,d}$), (2) moisture content ($X_{wb,i}$, $X_{wb,f}$ or $X_{db,i}$, $X_{db,f}$), and (3) SEC (SEC_{mp} or SEC_{mw}).

mass of the dried product.

To estimate energy consumption at state and national level for drying processes, the analysis begins with the total national production for each product. When state-level distribution data are available, the national production is allocated across U.S. states using percentage shares from the literature [28,131–138] (see Section 2 of the SM). Multiplying these shares by the national production yields state-level production values. The SEC for drying is then multiplied by each state's production, and summing across all states provides the national total. For some products—specifically dry pet food, breakfast cereal, and dry pasta—state-level distribution data are not available, so only national-level estimates are used. Production projections are available through 2033 [139,140], and are linearly extrapolated to 2050, following the US Department of Agriculture [140] approach. The analysis assumes that SEC values, and therefore drying technologies, remain constant throughout the projection period.

Economic model

The total energy cost for drying is calculated as the sum of the costs associated with each energy source across all states, as defined in Eq. (13). Because natural gas and coal prices vary by region, local energy costs significantly influence overall expenditures. Byproducts such as biomass and black liquor are also excluded from this calculation because they incur no direct cost to the facility.

$$\mathrm{TEC} = \sum_{i=1}^{n} \sum_{j=1}^{ns} \mathrm{E}_{\mathrm{T_j}} \times \mathrm{EC_i} \times \mathrm{EP_{i,j}} \tag{13}$$

where *TEC* is the total energy cost for drying, E_{T_j} is the energy consumption in the jth state (the value varies depending on the year and the specific subsector analyzed), EC_i is the energy mix of the i th energy source, $EP_{i,j}$ is the energy price for the i th energy source in the jth state, n is the number of fuel types for a specific sector, and *ns* is the total number of states. The $EP_{i,j}$ values are provided in Section 2 of the SM. Additionally, the values of EC_i can be found in Section 1.3 of the SM. According to DOE [4], the food and beverage sector derives 83 % of its fuel energy from natural gas, 7 % from biomass, 5 % from coal, and 5 % from miscellaneous sources.

Within the P/P sector, we categorized the products into market pulp, virgin paper/paperboard, and recycled paper/paperboard based on mill types: integrated, pulp, and recycled mills. Fuel energy is obtained in integrated and pulp mills as follows: 40 % from black liquor, 30 % from natural gas, 25 % from biomass, and 5 % from miscellaneous sources. To simplify the analysis, the 5 % miscellaneous share in both sectors was excluded, and the remaining values were proportionally adjusted to the key energy sources. Meanwhile, in recycled mill, 100 % of the fuel's energy is assumed to come from natural gas.

Overall, this analysis assumes that all drying operations rely exclusively on on-site fuel combustion, with no contribution from electricity-generated or purchased steam (either direct or indirect).

Environmental model

To assess the unintended consequences of drying energy consumption, the environmental model aids in computing the emissions associated with fuel use. The model accounts for CO_2e emissions associated with combustion of a specific type of fuel for drying operation. This study considers only Scope 1 emissions and does not include upstream emissions of each fuel delivered.

The calculation of total CO_2e emissions (in MT CO_2e) per year was conducted for each sector ($CO_{2e\ emissions}$), as detailed in Eq. (14):

$$\mathrm{CO_{2e\ emissons}} = \sum_{i=1}^{n} \sum_{j=1}^{ns} \mathrm{E}_{\mathrm{T_j}} \times \mathrm{EC_i} \times \mathrm{CI_i} \tag{14}$$

where CI_i is the carbon intensity for the i th energy source. The values of EC_i and CI_i can be seen in Section 1.3 of the SM. Note that E_{T_j} varies based on the year and subsector analyzed.

Validation

Table 3 presents input data used to validate the energy model. Note that a value of 100 % for drying system efficiency is considered for studies reporting the minimum SEC for drying.

Results

This section provides an overview of the results of this research effort, including model validation, SEC estimations by subsectors of the food and P/P sectors, and both the current state of and future projections for drying processes in the US food and P/P sectors.

Model validation

Fig. 4 compares the proposed model-calculated SEC values with their corresponding reported values, indicating a ± 20 % deviation range. For food products, the analysis indicates an average error of 15 %, with absolute differences ranging from 1 % to 31 %. For wood products, the agreement is notably better, with a maximum difference of only 14 %.

Several factors may contribute to the higher discrepancies observed for food products, including inaccurate values for specific heat capacity and unaccounted irreversibilities inherent in combustion processes and temperature gradients. Section 3 of the SM parametrically analyzed the equations presented in Table 2, showing how moisture content differences and thermal properties affect the SEC.

SEC Estimation by subsector

Food subsectors

Fig. 5 presents typical SEC ranges for the food sector, with values standardized to the SEC per unit of dry product to ensure an accurate, meaningful comparison. The results reflect how typical maximum and minimum moisture content differences and drying temperatures affect the SEC of selected food products, while average values are used for drying efficiencies.

The figure compares calculated values with benchmarks from Brown et al. [35], Cresko et al. [29], manufacturing partner communication, and others [10,34]. The comparisons reveal differences in the estimated SEC of charged material. Notably, the SEC range calculated by our framework in most cases aligns with all literature references except that of Brown et al. [35]. The reason behind the higher reported SEC value in Brown et al. [35] is unclear but could be attributed to design specificity, use of an older system, higher inlet moisture content, or a combination of factors. Details about the various food subsectors follow the figure.

The average calculated SECs for soybeans and soybean flakes are 216 and 152 Btu/lb, respectively. The SEC ranges for soybeans (149–270 Btu/lb) and soybean flakes (48–257 Btu/lb) reflect typical operational variability in drying processes. These values align closely with results from Brown et al. [35], which reported SEC values of 157 and 145 Btu/lb, respectively.

Corn starch drying exhibits an SEC range of 599–908 Btu/lb, similar to values from Cresko et al. [29] (530 Btu/lb) and Galitsky et al. [34] (629 Btu/lb). However, Brown et al. [35] reports a significantly higher SEC of 1,351 Btu/lb, likely because of outdated system efficiencies.

With a calculated SEC range of 899–1,282 Btu/lb, corn germ drying exhibits considerable variability among references. The range represents a midpoint relative to reported values. Cresko et al. [29] and Galitsky et al. [34] report values of 129 and 145 Btu/lb, respectively, whereas Brown et al. [35] exceeds the maximum range with a significantly higher value of 1,620 Btu/lb. As shown in Fig. 2 and Table 1, input variations can lead to a wider range of SEC values. For example, initial moisture reduction is achieved mechanically, typically via screw pressing, before final thermal drying to 1.5 %–4 % moisture content. The

Table 3
Input values used for validation of the energy model.

Product	Drying Efficiency (η_D), %	Initial Moisture Content ($X_{db,i}$), %	Final Moisture Content ($X_{db,f}$), %	Specific Heat ($C_{p,P}$), kJ/[kg•K]	Drying Temperature, °C	Ambient Temperature (T_{amb}), °C	Ref.
Corn[a]	30.0	33.33	17.65	1.48	110	25	[141]
Corn[b]	100.0	20.48	17.65	1.48	90	20	[142]
Corn[b]	100.0	25.00	17.65	1.48	90	20	[142]
Soybean[a]	40.0	33.30	23.50	1.64	110	30	[41]
Soybean[a]	33.7	24.50	12.91	1.38	100	30	[143]
Soybean[a]	44.1	24.50	12.91	1.38	100	30	[143]
Soybean[a]	60.1	24.50	12.91	1.38	100	30	[143]
Soybean[a]	62.9	24.50	12.91	1.38	100	30	[143]
Soybean[a]	66.0	24.50	12.91	1.38	100	30	[143]
Wood[c]	100.0	138.00	5.00	1.25	100	50	[27]
Wood[c]	100.0	100.00	5.00	1.25	100	50	[27]
Wood[c]	100.0	42.90	5.00	1.25	100	50	[27]
Wood[c]	51.2	65.00	15.00	1.70	80	2.2	[144]
Wood[b]	53.0	50.00	8.00	1.70	80	25	[145]
Dewatered digestate[a]	46.5	316.70	9.41	3.00	60	25	[146]

[a] Method: $SEC\text{m}_{w}$, X_{wb}, $C_{p,P,w}$.
[b] Method: $SEC\text{m}_{w}$, X_{db}, $C_{p,P,w}$.
[c] Method: $SEC\text{m}_{p}$, X_{db}, $C_{p,P,d}$.

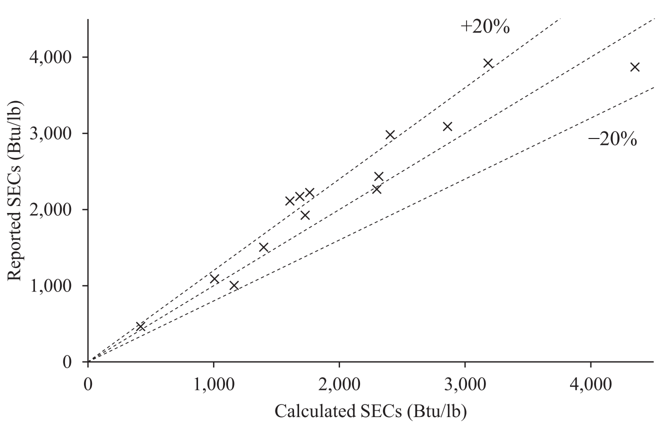


Fig. 4. Comparison of calculated and reported SECs.

efficiency of this process depends on factors such as dryer type, manufacturer specifications, equipment age, and technological advancements [34].

For gluten meal (26–171 Btu/lb) and fiber drying (26–171 Btu/lb), Cresko et al. [29] and Galitsky et al. [34] align with the lower portion of the calculated ranges. In the case of gluten feed (589–1,043 Btu/lb), the reference values are on average 26 % lower than the lower bound of the calculated range, but they remain within the same order of magnitude, which indicates reasonable consistency. And finally, for dextrose drying, Brown et al. [35] reported a value of 150 Btu/lb, which is near the lower value of the calculated spectrum (149–422 Btu/lb).

Manufacturing partners communication reported an average SEC of 1,020 Btu/lb for breakfast cereal drying, closely aligned with the average SEC calculated in this study (982 Btu/lb). The range presented in Fig. 5 (599–1,370 Btu/lb) represents the combined SEC of both the pre-dryer and the main dryer, as detailed in Table 1.

SEC results for the cane sugar dryer and beet sugar granulator demonstrate that Brown et al. [35] values fall between the minimum and average calculated results. These dryers exhibit relatively narrow SEC ranges, with beet sugar granulator differences reaching a maximum of 61 Btu/lb. In contrast, beet sugar pulp drying shows significant variability, ranging from 1,374 to 2,201 Btu/lb.

Section 3 of the SM presents a parametric analysis to evaluate the influence of various parameters on each component of Eq. (1), including moisture content variations on SEC.

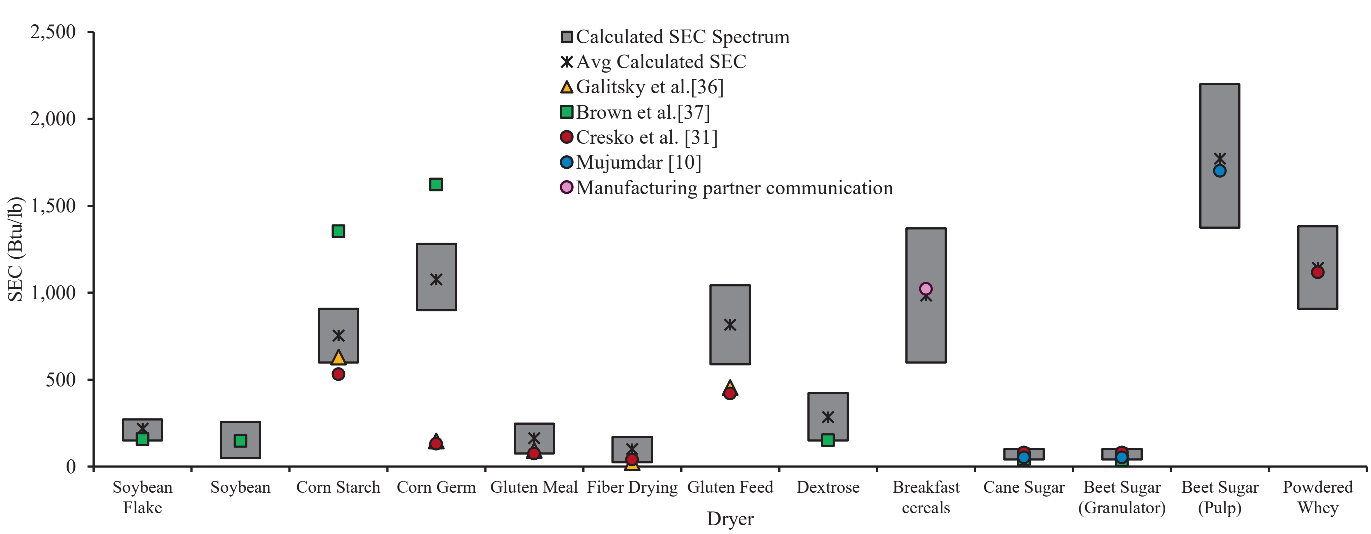


Fig. 5. SEC ranges for drying processes in the food sector compared with values found in the literature.

P/P subsectors

For the P/P industry, Fig. 6 presents the minimum, mean, and maximum SEC values calculated using average drying efficiency and typical moisture content ranges. These results are compared with data from Theresa Miller [28], Kramer et al. [147], and others [27,125,148]. Most of the values exhibit similar magnitudes—ranging from 1,865 to 3,150 Btu/lb—thus underscoring the validity of the model and its alignment with existing literature. However, values from Theresa Miller [28] for pulp drying and Devki Energy Consultancy Pvt. Ltd. [125] for paper drying are relatively lower than expected.

Current state of drying processes in the US food and P/P sectors

Energy analysis

Energy consumption for various drying processes was calculated as a product of the average SEC results from Section 3.2 and the production volumes for 2020 of final products, provided in SM Section 2.

Fig. 7 illustrates drying energy consumption for the food and P/P sectors in the US, highlighting the contributions of key subsectors to overall energy use in the manufacturing sector [10,74,119,120]. The food sector, shown on the left in Fig. 7, consumed nearly 112.1 TBtu of drying energy in 2020. Soybean processing at 33 % of total energy use emerged as the sector's most energy-intensive drying process, followed by corn processing (21 %), fruits and vegetables (12 %), dry pet food (10 %), sugar production (8 %), dairy (5 %), rice (4 %), breakfast cereal (3 %), dry pasta (2 %), and animal slaughter (2 %). The total energy consumption by the food sector in 2018 was 1,144 TBtu [3], of which 10 % was related to the thermal drying process. When considering process heating energy demand, drying operations account for about 22 % of energy consumption in the food sector.

In 2020, the P/P sector accounted for approximately 442 TBtu of energy consumption for drying processes. Of this total, 57 % was attributed to paperboard (250 TBtu), 32 % to paper (139.8 TBtu), and 12 % to pulp (52.3 TBtu). Of total paper production, 96 % was virgin (116.7 TBtu) and 4 % was recycled (23.1 TBtu). For paperboard, 81 % was virgin (202.4 TBtu) and 19 % was recycled (47.7 TBtu).

Energy consumption for the drying process in the P/P sector was 480.6 TBtu in 2002 [27] and 430 TBtu in 2010 [28]. These figures reflect a 2.8 % increase since 2010 but an 8.0 % decrease compared with 2002. In 2018, the P/P sector consumed 2,039 TBtu of energy [3], with approximately 21.7 %—a significant percentage—allocated to thermal drying processes. This share aligns with findings from Theresa Miller [28], which indicate that around 20 % of the sector's energy consumption is dedicated to drying operations. For process heating in the P/P sector, drying operations account for approximately 58 % of energy use.

Fig. 8 shows the energy distribution of drying processes for specific products within the food sector. In the soybean subsector, soybean meal drying accounts for 58 % of total energy use (21.3 TBtu). In the corn subsector, 41 % of drying energy is used for corn starch (9.9 TBtu), followed by 27 % for gluten feed (6.4 TBtu) and 26 % for corn germ (6.1 TBtu). In the fruits and vegetables subsector, potato drying leads with 54 % of energy consumption (7.3 TBtu), followed by grape drying at 22 % (2.9 TBtu). In the sugar subsector, beet sugar pulp drying dominates with 86 % of energy use (8.0 TBtu). Finally, in the dairy subsector, powdered dry milk dryers account for 72 % of drying energy (3.9 TBtu).

For the assessment of state-level production effects, the distribution of energy consumption for drying across the examined sectors is shown in Fig. 9.

For the food sector, Illinois leads with an energy consumption of 9.83 TBtu (10.4 %), followed closely by Iowa at 9.79 TBtu (10.3 %), California at 5.86 TBtu (6.2 %), and Minnesota at 5.80 TBtu (6.1 %). The high energy usage in Illinois, Iowa, and Minnesota is driven primarily by grain drying processes (specifically soybeans and corn, which dominate production in these states). California, although not a major grain producer, stands out because of its substantial fruits and vegetables drying activities—93 % of grape production [149], 24.5 % of onion production [150], 2.1 % of potato production [132], 2 % of apple production [151], and 34.2 % of other noncitrus fruits [133].

For the P/P sector, the southern region dominates energy consumption, with Georgia consuming 52.6 TBtu (11.9 %), followed by Alabama at 43.7 TBtu (9.9 %), Florida at 27.1 TBtu (6.1 %), and Louisiana at 26.3 TBtu (6.0 %). These states host a significant concentration of paperboard, paper, and pulp mills, which contribute to this high energy demand. Outside the southern region, Wisconsin also exhibits notable energy consumption levels at 28.8 TBtu (6.5 %).

Economic analysis

Estimated drying energy costs for both sectors, based on 2020 production volumes and state-level energy prices (see SM, Section 2), are shown in Fig. 10. The total drying energy cost for the P/P sector is estimated at $919 M, whereas the food sector accounts for $417 M.

In the food sector, the cost distribution across subsectors follows the same rankings as those of energy consumption. The soybean subsector accounts for the largest share of drying costs at 30 %, followed by corn (19 %), fruits and vegetables (17 %), sugar (9 %), dry pet food (8 %), dairy (7 %), rice (5 %), breakfast cereal (3 %), dry pasta (2 %), and animal slaughter (2 %). Owing to variations in state energy prices, the percentage contribution to total cost differs from the energy consumption breakdown (see Fig. 7). For instance, the fruits and vegetables subsector has a greater effect on total drying costs compared with its energy consumption share, primarily because of the concentration of production in California, where energy prices are well above the national average.

In the P/P sector, the pulp and virgin paper/paperboard subsectors notably obtain approximately 68 % of their energy from waste biomass and black liquor—byproducts of the production process; this approach helps lower overall energy costs by offsetting the use of purchased fuels.

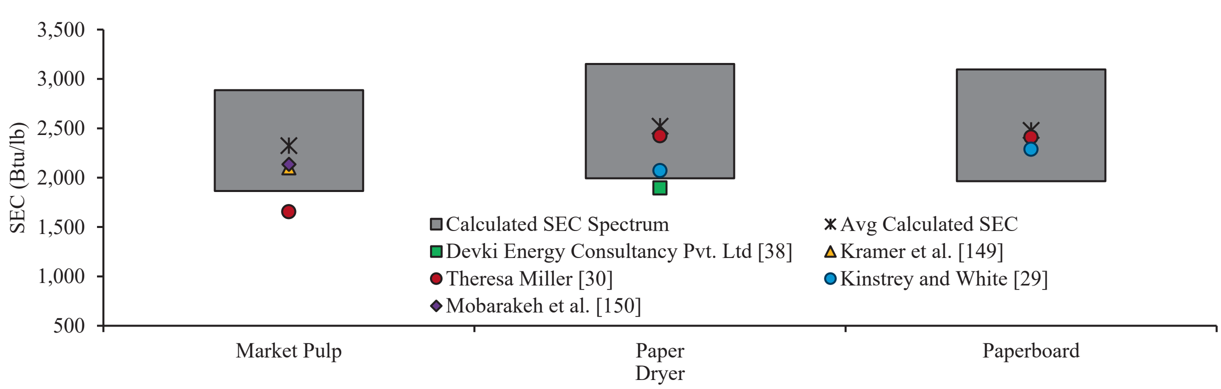


Fig. 6. SEC ranges for drying processes in the P/P sector compared with values found in the literature.

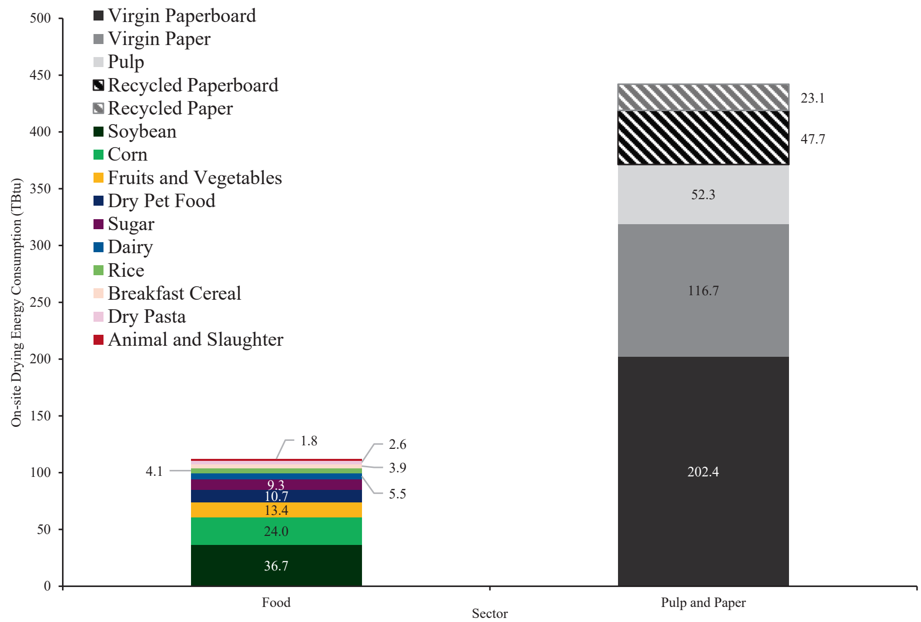


Fig. 7. Total drying energy consumption in 2020 for the food and P/P sectors, further broken down into energy use of the various subsectors.

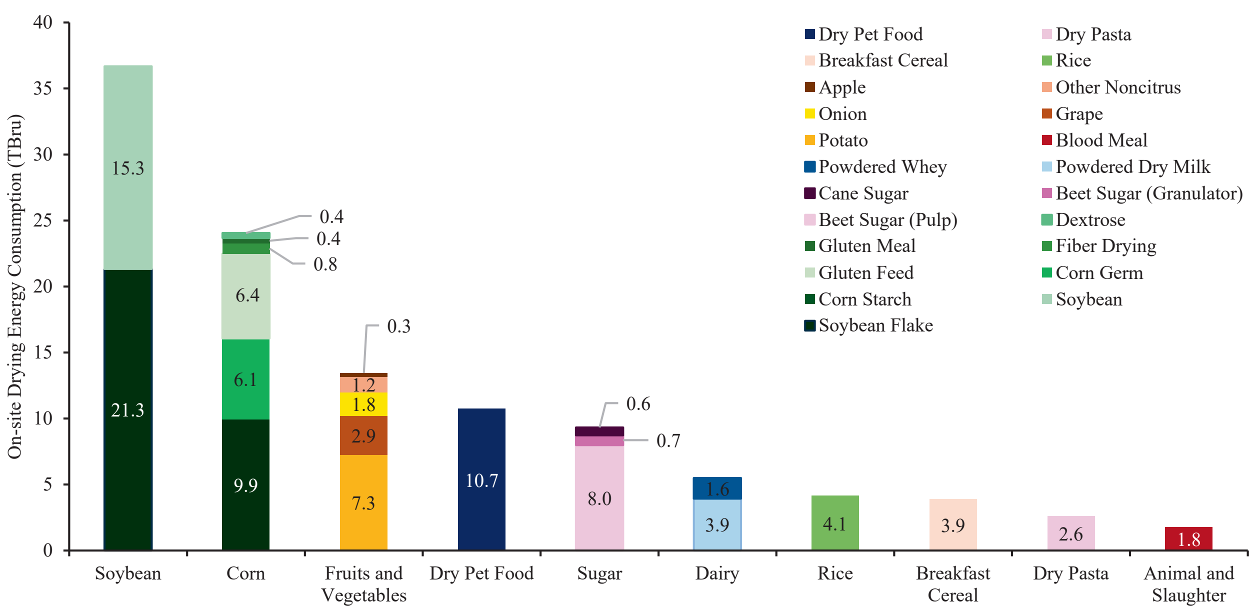


Fig. 8. Food sector drying energy consumption for the drying process in 2020 for each subsector and products within those subsectors.

Conversely, recycled paper and paperboard production require primary fuels (i.e., natural gas), resulting in 12 % and 25 % contributions, respectively, to the sector's total drying energy costs. Virgin paperboard remained the highest contributor, with approximately $310 M spent on drying, followed by recycled paperboard, which incurred about $231 M in drying-related costs.

Fig. 11 illustrates the energy cost associated with drying each product in the food sector. The contribution of each product remains roughly consistent with the trends observed in the energy analysis section, except for the sugar subsector, which is now in fourth place. Notable differences emerge within the fruits and vegetables subsector: dried potatoes account for the largest share of energy costs at 44 %, followed by grapes at 29 %, and onions at 14 %. These variations are primarily driven by regional energy prices.

Fig. 12 presents state-level energy costs associated with drying processes in the food and P/P sectors. The figure highlights the influence of regional energy prices, particularly that of natural gas, which accounts for 87.4 % of energy use in the food sector and 74 % of energy use in the P/P sector.

In the food sector, California has a high relative energy cost of $40.5 M (11.1 %) due to elevated energy prices, despite ranking lower in total energy consumption. Iowa is the second with an energy cost of $40.3 M (11.1 %). Illinois, the most energy-intensive state, ranks third in economic terms at $38.8 M (10.6 %). Notably, Florida also plays a significant role in energy costs, contributing $25.3 M (6.7 %).

In the P/P sector, Georgia leads in drying energy costs, reaching $86.3 M (9.4 %) because of high production volumes. Pennsylvania is ranked second at $77.7 M (8.4 %), largely owing to elevated energy prices—natural gas averaged $8.27/MMBtu in the state (see SM Section 2). Alabama ($68.7 M), Florida ($62.9 M), and Wisconsin ($58.3 M) also report substantial drying energy costs owing to a combination of production levels and fuel prices. Washington and Maine stand out as well,

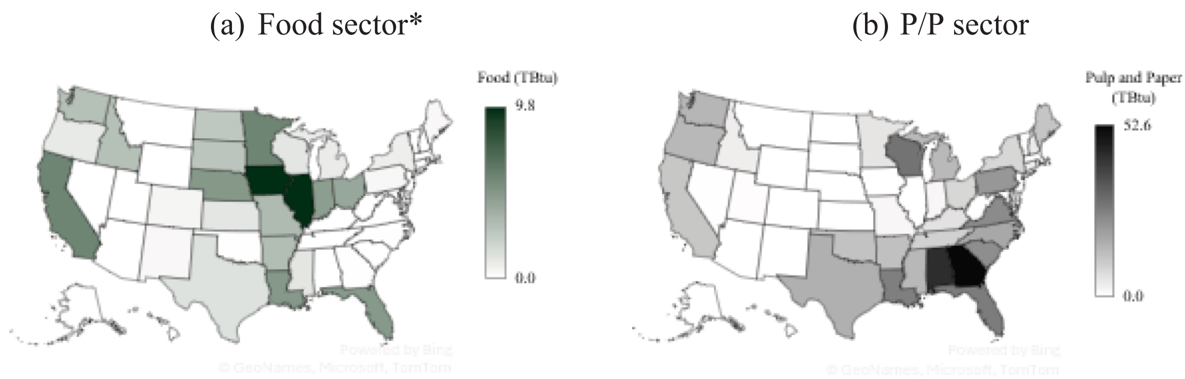


Fig. 9. US energy consumption for the drying process of (a) the food sector and (b) the P/P sector in 2020 for each subsector and each product in all 50 states. (*Three food sector products are not included in the state-level analysis because of a lack of data: dry pet food, breakfast cereal, and dry pasta.).

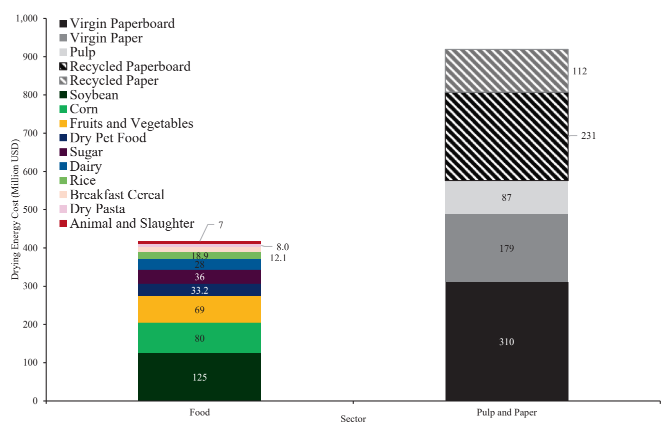


Fig. 10. Total energy cost for drying in 2020 for the food and P/P sectors and broken down into various subsectors.

accounting for 5.4 % and 4.6 % of total sector drying costs, respectively, largely because of their higher-than-average energy prices.

Environmental analysis

Fig. 13 presents the CO_2e emissions for the food and P/P sectors, highlighting their relative contributions. The P/P sector emitted about 33,995 MT CO_2e in 2020. Of this amount, 71 % is considered biogenic (from black liquor and biomass), whereas the remaining 29 % is fossil-based emissions (i.e., natural gas). In comparison, the food sector accounts for 6,868 MT CO_2e emissions, with 76 % originating from natural gas, 15 % from biomass, and 10 % from coal.

DOE [4] reports total on-site CO_2e emissions for the food and beverage sector at 45,000 MT CO_2e, with 10,700 MT CO_2e linked to process heating and 9,600 MT CO_2e linked to conventional boilers, both of which can be relevant to drying. Consequently, drying accounts for 15 % of total CO_2e emissions and 64 % of process heating emissions in the food sector. Fig. 14 breaks down the CO_2e emissions by subsectors and key products for the food sector.

Similarly, the US Environmental Protection Agency estimates total CO_2e emissions for the P/P sector at 135,200 MT CO_2e, with 55 % from black liquor, 26 % from natural gas, and 19 % from biomass [152]. Based on our calculated CO_2e emissions (33,995 MT CO_2e), the implication is that 25 % can be attributed to thermal dryers. However, the report covers only facilities emitting over 25,000 MT CO_2e annually.

Fig. 15 highlights the 10 states with the highest CO_2e emissions from drying processes in the food and P/P sectors. In the food sector, emissions are concentrated primarily in the Midwest because of substantial grain drying activities, with additional contributions from blood meals and dairy product drying. California also is a significant emitter, driven by its large-scale fruit, vegetable, rice, and dairy productions. Florida

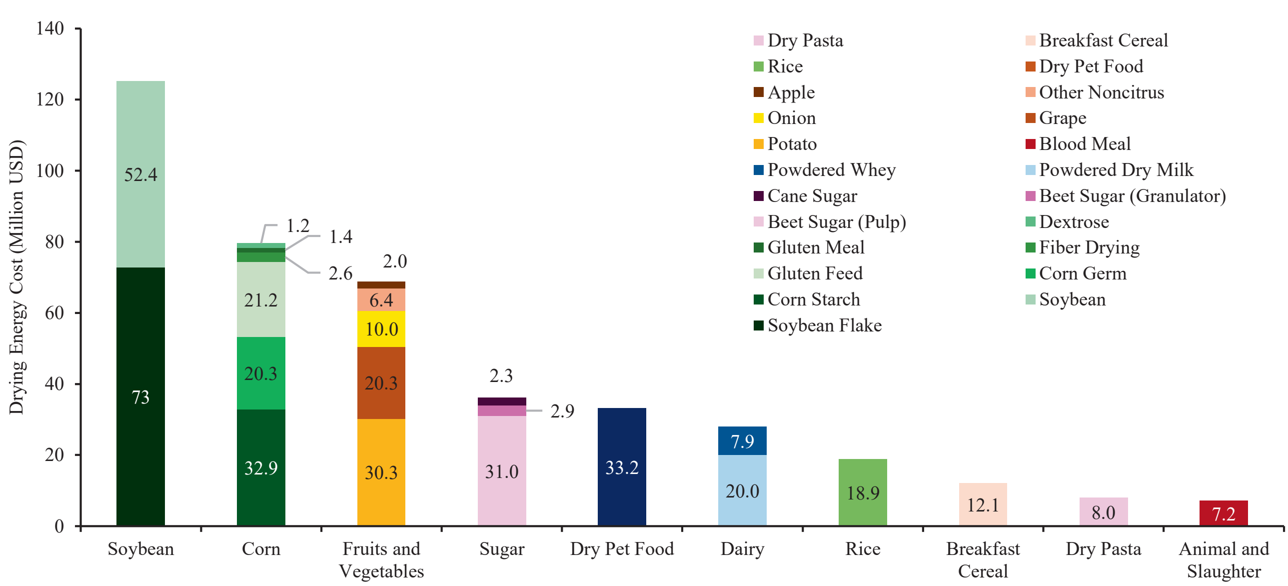


Fig. 11. Food sector total energy cost for the drying process in 2020 for each subsector and products within those subsectors.

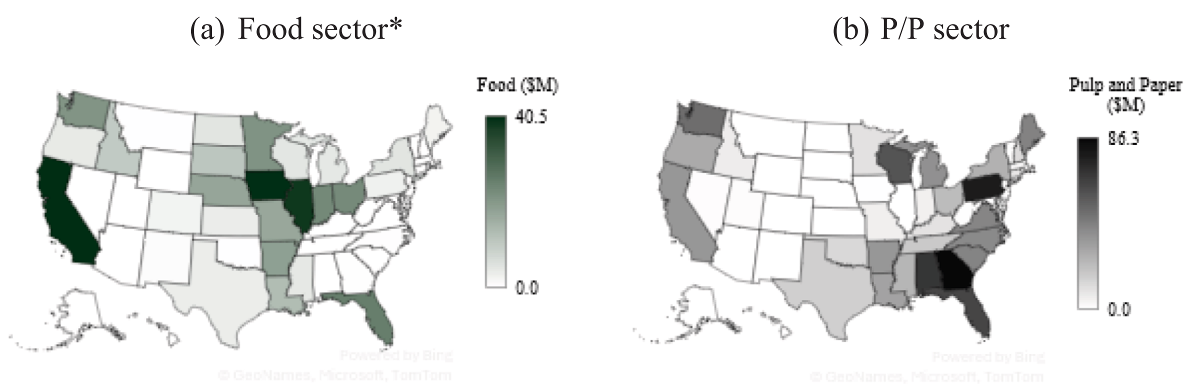


Fig. 12. US drying energy costs for the drying process of (a) the food sector and (b) the P/P sector in 2020 for each subsector and each product in all 50 states. (*Three food sector products are not included in the state-level analysis because of a lack of data: dry pet food, breakfast cereal, and dry pasta.).

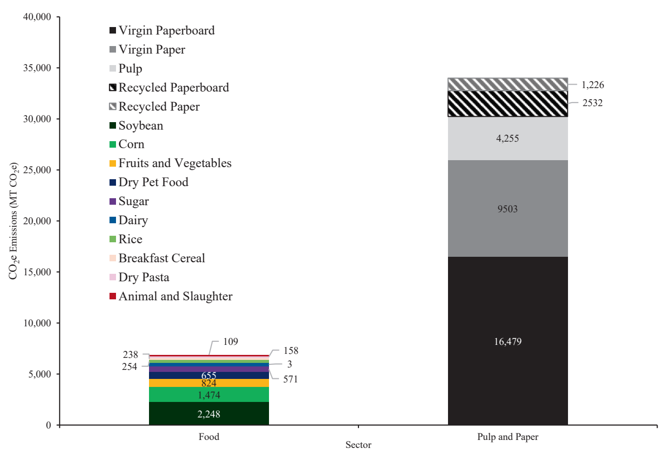


Fig. 13. Total CO_2e emissions for drying in 2020 for the food and P/P sectors and broken down into various subsectors.

ranks high in emissions because of its substantial sugar production. This analysis emphasizes regional CO_2e emissions variability that is shaped by specific drying processes and energy sources used in each state. Thus, innovative and energy-efficient technologies are necessary to minimize energy use for drying operations.

For the P/P sector, CO_2e emissions directly correlate with the energy consumption depicted in Fig. 9, reflecting the geographical concentration of mills. The figure also breaks down emissions by subsector, highlighting the significant role of pulp mills in certain states. For example, pulp mills in Florida and Washington contribute more CO_2e emissions than that of paper mills, primarily because those states have a higher concentration of pulp production facilities.

Future projections for drying processes (2020–2050)

In a business-as-usual scenario—in which current drying technologies remain in use through 2050—energy consumption, CO_2e emissions, and energy costs have been projected to assess (1) their impact on US energy demand and (2) potential implications for future innovative dryers that could minimize energy use, costs, and associated emissions. Based on the production and energy price trends detailed in Section 2 of the SM, Fig. 16 and Fig. 18 depict the energy and economic results (bar and line plots, respectively) for the food and P/P sectors from 2020 to 2050.

Food subsectors

In the food sector, the trends across most subsectors remain stable, see Fig. 16, with the notable exception of soybeans, which are projected to experience a 40 % increase in energy consumption. Drying-related

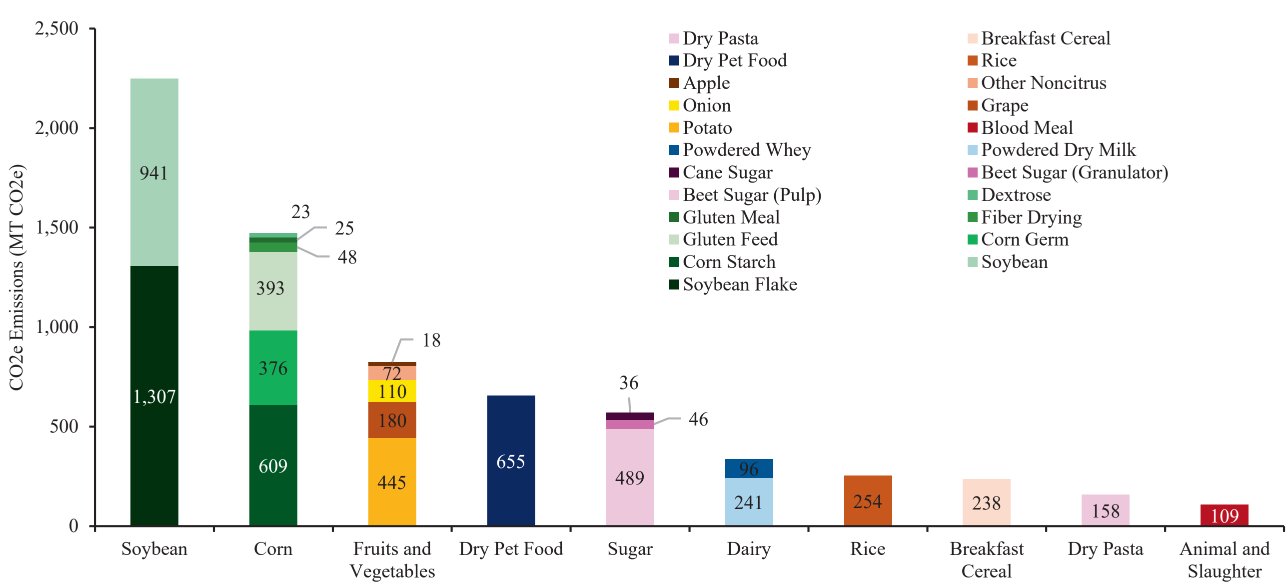


Fig. 14. Total food sector CO_2e emissions for the drying process in 2020 for each subsector and products within those subsectors.

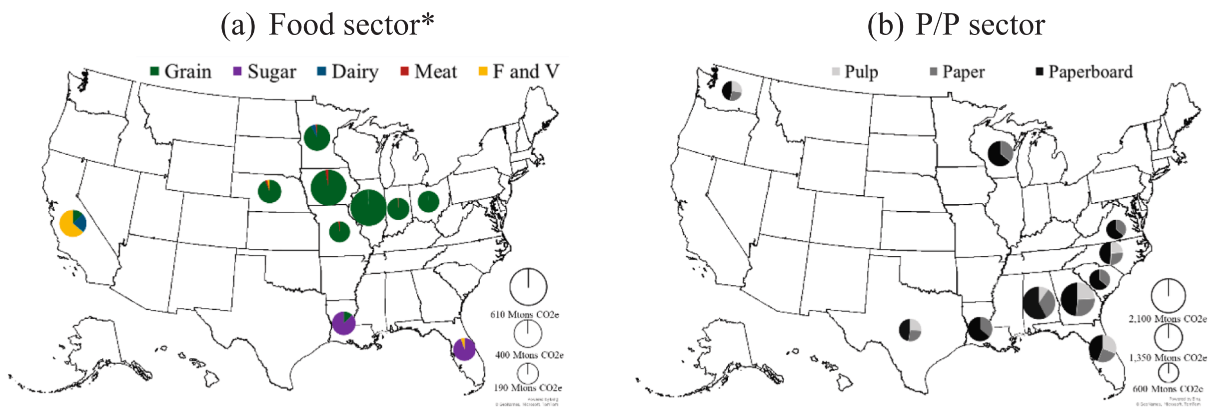


Fig. 15. US CO_2e emissions for the drying process of (a) the food sector and (b) the P/P sector in 2020 for each subsector and each product in all 50 states. (Note: F and V = fruits and vegetables). (*Three food sector products are not included in the state-level analysis because of a lack of data: dry pet food, breakfast cereal, and dry pasta.).

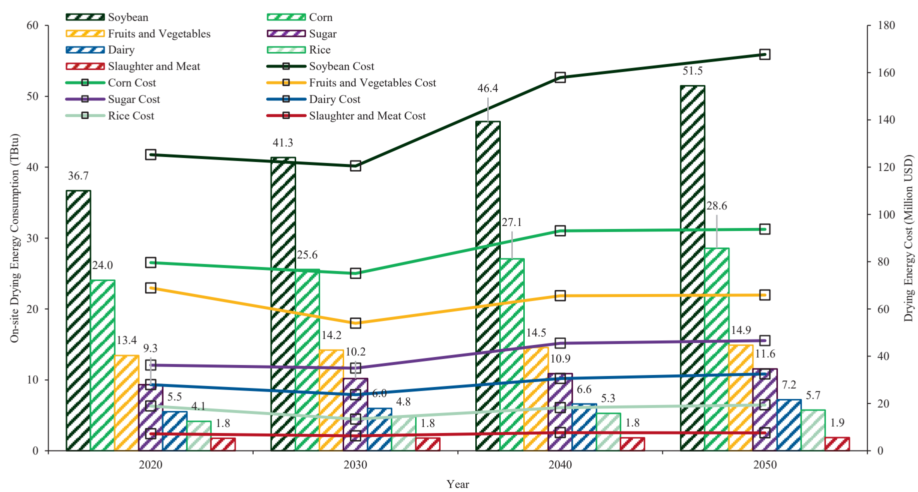


Fig. 16. Total on-site drying energy consumption and CO_2e for the decades from 2020 to 2050 for each subsector of the food sector. (*Three food sector products are not included in the state-level analysis because of a lack of data: dry pet food, breakfast cereal, and dry pasta.).

energy costs are projected to increase by 19 % overall. A projected 10 % decline takes place in the first decade, followed by a 27.7 % rise between 2030 and 2040 and then a 3.5 % increase in the final decade. These projections are mainly due to the increase in natural gas prices over the past two decades and demand for the products. Among food subsectors, soybean processing experiences the highest cost increase at 34 %, followed by the sugar subsector at 29 % and the corn subsector at 18 %. The dairy subsector also sees a notable increase of 16 %, whereas the meat and poultry slaughter subsectors experience a comparatively smaller rise of 5 %.

A detailed breakdown of the food subsectors is provided in Fig. 17. Soybean production emerges as a key driver of increased energy consumption, with an average of 40 % higher consumption. The corn-related subsector has a 16 % increase in energy consumption, with gluten feed drying being the main contributor with a 58 % increase. In the sugar industry, the growth is primarily attributed to beet sugar dryers with a 25 % increase, whereas powdered dry milk is the main contributor in the dairy sector, increasing by 31 %. Blood meal dryers show negligible changes in energy use over time. In the fruits and vegetables drying subsector, potato dryers play a significant role, with an increase of 14 % in energy consumption between 2020 and 2050.

Regarding energy costs, as previously indicated, the first decade sees a decline, followed by a rise in costs over the last two decades for key food sector products. In the soybean subsector, soybean flakes exhibit a 35 % cost increase. For the corn subsector, fiber and gluten feed drying experience a 56 % rise. In the sugar subsector, beet sugar–related products see a 29 % increase. The dairy subsector records a 16 % increase for both major products, whereas blood meal drying rises by just 5 %. Conversely, the fruits and vegetables subsector show cost reductions, with apple drying decreasing by 20 %, grape drying by 18 %, other noncitrus drying by 11 %, and onion drying by 5 %. These declines are largely driven by projected reductions in natural gas prices, particularly in California, where prices are expected to drop from $7.82/MMBtu to an average of $4.57/MMBtu between 2030 and 2050 (see Section 2 of the SM).

P/P subsectors

In the P/P sector, the drying energy consumption and cost are projected to increase by 30 % and 34 %, respectively (Fig. 18). Recycled production is expected to grow steadily over the coming decades. Recycled paperboard shows a 65 % increase in energy consumption and a 61 % rise in energy costs, whereas recycled paper is projected to grow by 52 % in energy use and 48 % in cost. In contrast, virgin paper and paperboard production is expected to decline during the first decade. By 2030, virgin paperboard energy consumption and costs are projected to decrease by 6 % and 20 %, respectively. Virgin paper shows similar trends, with a 4 % drop in energy use and a 19 % reduction in cost. Although pulp production sees a 6 % increase in energy consumption by 2030, energy costs are expected to fall by 13 %, primarily owing to lower natural gas prices. After 2030, energy consumption and costs are

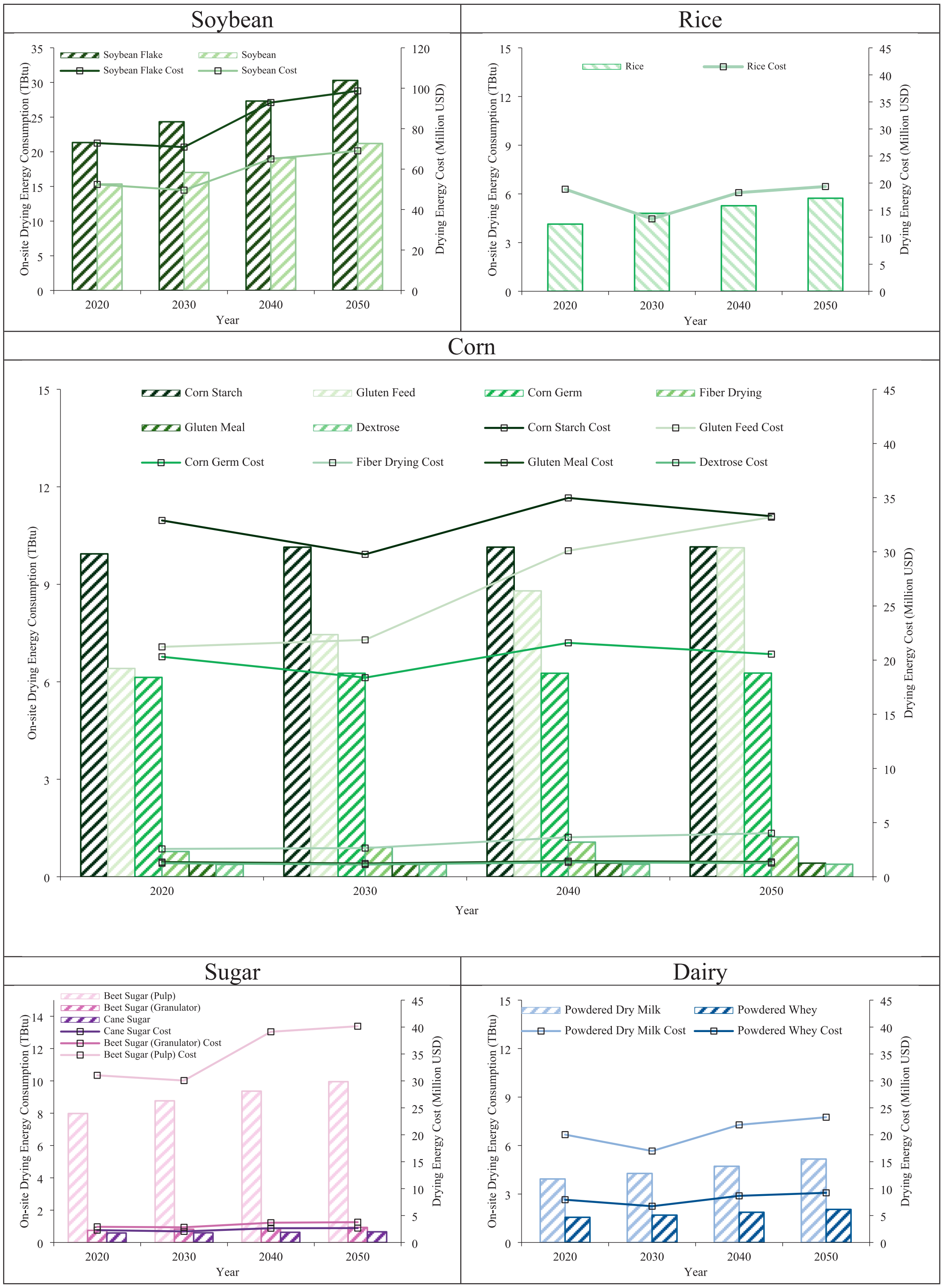


Fig. 17. Total on-site drying energy consumption and costs for the decades from 2020 to 2050 for each product of the subsectors of the food sector.

projected to rise across all subsectors.

GHG emissions across all subsectors

Fig. 19 presents the projected GHG emissions for each subsector. In the food sector, most subsectors maintain relatively stable emission trends, except for soybeans, which are expected to rise by 40 %. Conversely, in the P/P sector, all subsectors display a steady linear increase of 28 %.

Discussion of future Perspective

The literature review and this work show that we can improve the energy performance of drying systems in the following ways: (1) reducing the evaporation load, (2) increasing dryer efficiency, and (3) improving the energy supply (utility) systems. Each of these methods is discussed in detail in the following subsections.

Efforts to enhance drying energy performance may yield additional benefits for manufacturers, including reduced maintenance requirements and improved operational safety. For example, optimizing

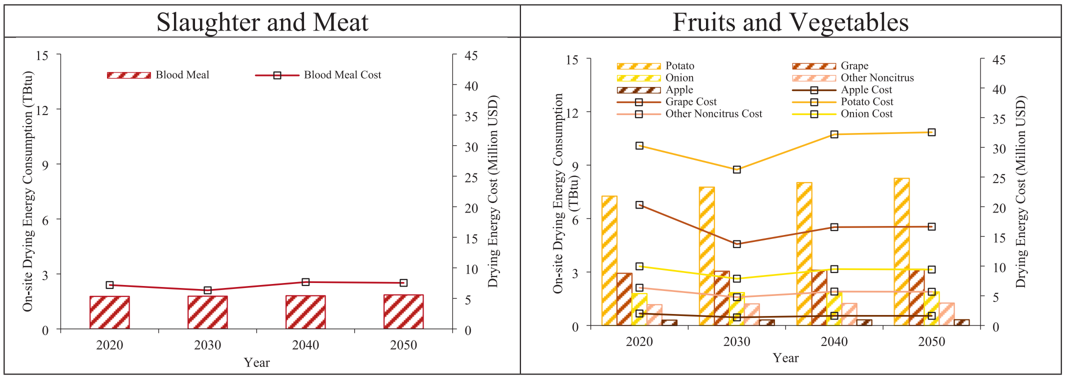


Fig. 17. (*continued*).

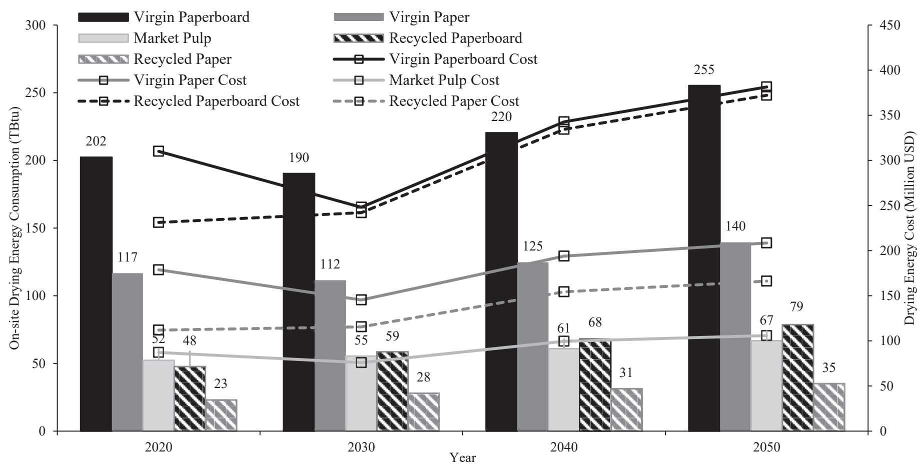


Fig. 18. Total on-site drying energy consumption and costs for the decades from 2020 to 2050 for each subsector of the P/P sector.

airflow and heat distribution in dryers not only improves energy efficiency but also ensures even drying, which reduces wear on equipment components and minimizes maintenance needs. Additionally, maintaining the correct air-to-fuel ratio avoids sub-stochiometric combustion of fuel and reduces risks of generating unburned hydrocarbons in the exhaust system, thereby improving a plant's safety standards.

Reducing the evaporation load

To remain competitive, US manufacturers need to minimize energy use per unit of product produced across the value chain. One approach to achieving this is to minimize the SEC by reducing drying temperatures, altering moisture content differentials, or improving drying efficiency. However, altering drying temperatures may have significant implications, including extended drying times [153], reduced product quality [154], or increased dryer size requirements.

Because final product moisture content is typically regulated by industry standards, the only feasible way to alter moisture content differentials is by reducing initial moisture levels. This can be achieved through chemical or mechanical pretreatment methods, such as those already employed in the P/P industry, or through the integration of evaporators before the drying process takes place.

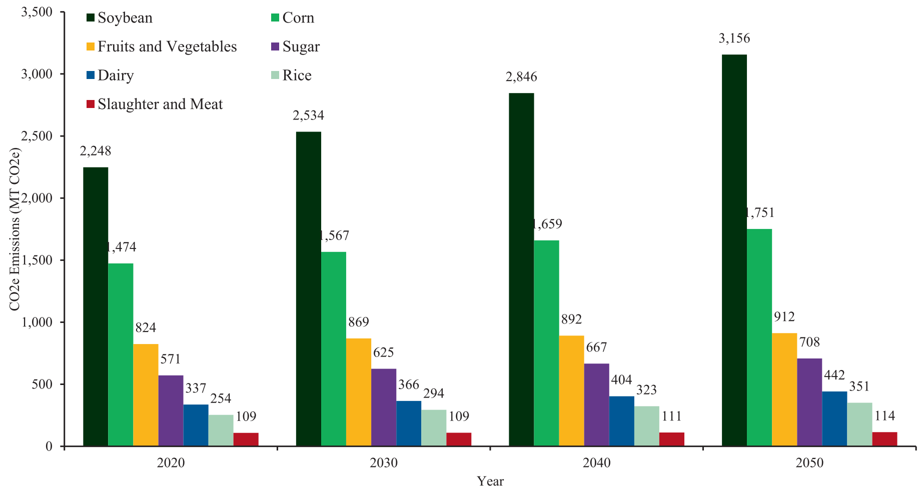
Increasing dryer efficiency

The 2024 DOE report identifies energy efficiency, electrification, and low-carbon fuels as key strategies for optimizing energy use and costs in food manufacturing [30]. Electrification is projected to play the largest role (72 %) in reducing energy consumption, followed by low-carbon fuels and feedstocks (17 %) and energy efficiency measures (9 %) [30]. Significant energy-efficiency opportunities exist in recovering waste heat from boilers—heat that can be repurposed through economizers to preheat inlet water or air, thereby improving overall system efficiency. Additionally, advancements in controls and digitalization offer potential for process optimization and enhanced monitoring, enabling smarter and more efficient drying systems.

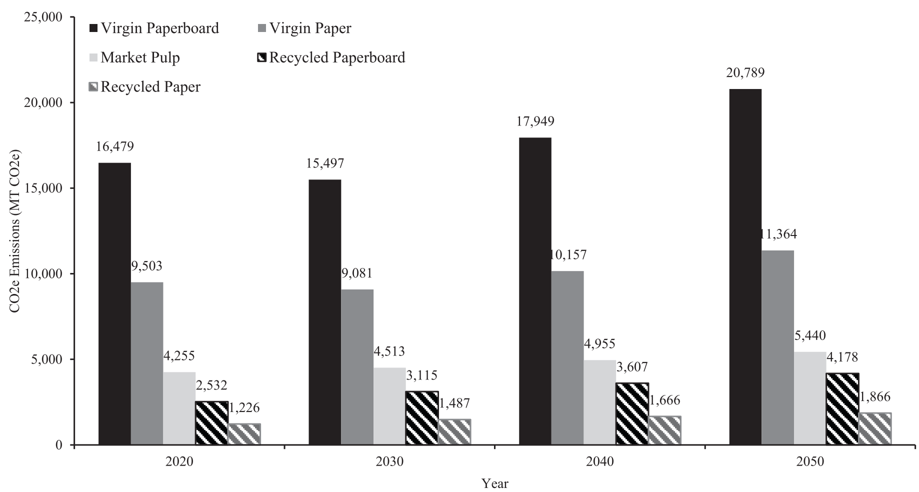
Opportunities for the food sector

As shown in Table 1 and according to some studies [155,156], most drying temperatures in the food industry are below 200 °C, a range suitable for implementing innovative drying technologies and making industrial drying competitive. Technologies such as microwave, microwave-vacuum, infrared, ohmic, and radiofrequency drying not only achieve energy savings of up to 83 % but also reduce processing times by as much as 97 % [157]. Microwave and hybrid methods have also shown improved retention of bioactive compounds and physicochemical properties in food products like garlic while still maintaining commercial feasibility [158]. Similarly, osmosonication has been found to enhance nutritional retention, reduce drying time, and improve mass transfer rates in various fruits and vegetables [159]. However, the most widely applicable technologies for this temperature range are heat pumps [157,160–162] and electric boilers [163,164].

Numerous studies have explored the potential effect of electrification on energy consumption and CO_2e emissions in the US food sector. For example, Hasanbeigi et al. [165] analyzed electrification in subsectors like beet sugar, milk powder, wet corn milling, and crude soybean oil production, with the following information among the study's findings. For milk powder, modifying conventional dryers with heat pumps or



(a)



(b)

Fig. 19. Total CO_2e emissions of drying for the decades from 2020 to 2050 for each subsector of the (a) food and (b) P/P sectors.

electric air heaters could reduce energy demand by approximately 57 %. In the wet corn milling sector, replacing existing dryers with electric drying technologies could lower energy use from 690 kWh/ US ton to 665 kWh/US ton. Specific recommendations of the Hasanbeigi et al. study include using an electrical fluidized bed dryer for germ dewatering and using electrical rotary dryers for gluten meals, starch, and gluten feed drying. Broader analyses from other studies of the food sector show its energy use could decrease significantly through electrification, decarbonization, and reduced processing intensity [6,166]. These systemic studies also highlight long-term opportunities for renewable integration, hybrid heat systems, and behavioral shifts to achieve net-zero industrial goals.

Opportunities for the P/P sector

In the P/P sector, energy efficiency improvements play a crucial role in optimizing fuel use and reducing costs. Currently, 19 % of projected energy reductions in the sector are expected to come from efficiency measures, with additional contributions from low-carbon fuels and feedstocks (45 %) and electrification (25 %) [30]. Enhancing the efficiency of drying and steam systems can help ensure that available biomass and black liquor resources are used more effectively, minimizing the need for additional natural gas. For example, membrane concentration processes can reduce steam consumption by approximately 30 % [30]. Improving heat recovery and process optimization can further support cost-effective energy management in P/P production. Complementary studies have investigated the use of waste heat in maritime transport for drying wood products using vacuum drying, supporting more flexible industrial drying options [167].

Advanced process control and energy efficiency strategies can further optimize drying processes. Machine learning algorithms have been applied to improve process efficiency, reducing steam use by 1.5 % [168]. Additional modeling-based analyses using artificial intelligence tools like ANFIS and ANN for exergy prediction in batch drying systems have shown improvements in energy performance [169]. Equipment upgrades (e.g., replacing outdated motors, boilers, and dryers or incorporating variable speed drives and waste heat recovery systems) can significantly enhance energy efficiency [170]. For instance, two studies demonstrated energy reductions of 15 % [171] and 16 % [172], with corresponding emission cuts of 12 %–13 %. Emerging technologies like supercritical CO_2 power systems also show promise by using relatively lower waste heat temperatures, achieving energy savings of 20 % and emission reductions of 45 % [7,173].

Electrification of drying processes in the P/P sector offers a transformative pathway for reducing energy consumption. Conventional boilers can be replaced with electric boilers or heat pumps [174], and infrared and microwave technologies can be integrated into conventional dryers or used in finishing operations [5]. Electrification not only reduces emissions but also enhances efficiency. For example, conventional dryers often result in uneven drying, leading to overdried regions or subregions in the charged material while both increasing energy consumption and degrading paper quality. In contrast, microwave drying targets wet spots, ensuring a more uniform moisture distribution that can yield energy savings of 7 %–21 % and boost production by 31 % [175]. Similarly, superheated steam drying can reduce energy usage by 25 % by replacing air with superheated steam as the heat carrier, enabling full heat recovery and minimizing energy losses from evaporated water in paper drying [176].

Improving energy supply systems

The renewable energy potential and infrastructure in the US provide opportunities to align drying processes with local resources. The National Renewable Energy Laboratory reported databases for national solar radiation [177], geothermal resources [178], annual average wind speed at 100 m above surface level [179], and solid biomass resources [180]. The southwest region boasts the highest solar radiation levels, enabling food sector facilities in California and Florida to leverage solar energy for processes like sugar production. Geothermal resources, prevalent in states like Washington and Louisiana, could benefit the P/P industry. The Midwest's significant wind energy potential can support facility energy needs or utility-scale integration. Biomass resources also align closely with the food and P/P industries, as highlighted in Section 2.2.3. These sectors are among the largest producers of biomass, which can be used as fuel for various technologies.

Recent studies further illustrate the technical potential of solar and biomass-based drying systems [181–183]. Solar dryers with phase change materials have shown improvements in energy efficiency, temperature stability, and drying uniformity [184,185]. Incorporating temperature control systems in indirect solar dryers enhances product quality and collector durability under varying climatic conditions [186]. Advanced collector designs, such as double-pass V-groove systems, have achieved thermal efficiencies up to 88.8 % with promising technoeconomic returns [187]. Biomass-fueled dryers, such as rice husk-fired systems, demonstrated competitive drying rates, acceptable product quality, and payback periods under 1.5 years [188]. Similarly, multipurpose dryers using biowaste heat sources and validated through computational fluid dynamics modeling showed efficiencies exceeding 89 % for paddy rice drying [189]. These technologies highlight the potential for integrating natural resource-based solutions into future decarbonization strategies for industrial drying.

Barriers and solutions

Various strategies can be adopted to address technical, knowledge, and cost-related obstacles. Table 4 presents the three main categories of challenges associated with implementing these measures and offers potential solutions for mitigation.

Conclusion

This study provides a comprehensive assessment of drying processes in the US food and P/P sectors, with evaluations of their energy consumption, energy costs, CO_2e emissions, and future projections from 2020 to 2050. This is the first study of its type to conduct such an assessment at the state and national level.

Energy and environmental models were developed and validated with the existing literature, providing a comprehensive dataset on drying parameters for the US food and P/P sectors. This dataset presents typical drying conditions for various products and can serve as a valuable resource for industry, academia, and policymakers. The following are highlights of the main conclusions in this study:

Table 4
Barriers and solutions for enhancing energy efficiency in drying processes in the food and P/P sectors.

Barrier Type	Key Barriers	Solutions
Technology/ Technical	• Low coefficient of performance of high-temperature heat pumps	• Increase R&D investment in efficiency, cost-effectiveness, and quality
	• Efficiency loss in hydrogen-natural gas blends above 20 % hydrogen	• Focus R&D on integrated systems (renewables, waste heat recovery)
	• Biomass boiler efficiency issues (impurities, heterogeneity, moisture content)	• Improve collaboration among government, universities, industries, and nonprofits
	• Compliance, product standards, and quality concerns with new technologies	• Promote partnerships and knowledge-sharing to align innovations with industry needs
	• Limited R&D in small and medium-sized enterprises; large firms focus on products rather than process innovation	• Boost DOE funding for industrial-scale technology validation
	• Grid reliability risks from widespread electrification	• Engage in international R&D and demonstration for faster commercialization
	• US electricity generation remains carbon-intensive	• Engage and communicate with industry to identify their real technology needs
Knowledge and Education	• Low awareness and understanding of advanced technologies	• Expand government and utility programs to educate stakeholders (e.g., Better Plants Program, Industrial Assessment Centers)
	• Lack of sufficient information for industrial consumers	• Strengthen academic involvement in training and workforce development
	• Dependence on costly third-party providers because of inadequate training	• Encourage cross-sector knowledge exchange for technology adoption
	• Lack of awareness of the cost of doing nothing; help needed to quantify energy and nonenergy benefits	• Highlight public health, economic, and competitiveness benefits
Cost	• High up-front investment, infrastructure upgrades, and facility modifications	• Encourage stakeholder collaboration to reduce costs
	• Higher electricity costs compared with those of natural gas	• Integrate new technologies with existing systems to minimize disruption
	• Long lifespan of existing dryers (30–60 years), making replacement slow	• Provide utility incentives (discounted electricity rates, energy storage solutions)
	• Supply chain constraints for transformers and key electrification components	• Implement flexible energy management (load shifting, storage integration)
	• Rising demand for biomass and hydrogen may increase costs and limit availability	• Expand financial support (tax breaks, grants, low-interest loans)
		• Introduce sectoral CO_2 emissions policies and carbon pricing mechanisms
		• Offer targeted state and local incentives for renewables and carbon capture
		• Expand renewable portfolio standards to mandate renewable energy integration

- The study identifies the SEC ranges for key products and compares them with existing literature.
- Total energy consumption for drying processes in the US is estimated at 442 TBtu for the P/P sector and 112.1 TBtu for the food sector.
- Drying accounts for 21.7 % and 10 % of total energy use in the P/P and food sectors, respectively.
- In the P/P industry, paperboard dominates energy consumption (57 %), followed by paper (32 %) and market pulp (12 %).
- For the food sector, the most energy-intensive subsector is soybean processing (42 %), followed by corn processing (21 %), fruits and vegetables (12 %), dry pet food (10 %), sugar production (8 %), dairy (5 %), rice (4 %), breakfast cereal (3 %), dry pasta (2 %), and animal slaughter (2 %).
- At the state level, the largest energy consumers are as follows:
  - o P/P sector—Georgia (11.9 %), Alabama (9.9 %), Wisconsin (6.6 %), Florida (6.1 %), and Louisiana (6.0 %)
  - o Food sector—Illinois (10.4 %), Iowa (10.3 %), California (6.2 %), and Minnesota (6.1
- The current drying energy cost for thermal drying is estimated to be $919 M in the P/P sector and $417 M in the food sector.
- State energy prices significantly affect the economic analysis. California and Iowa (both 11.1 %), along with Illinois (10.6 %), account for the highest share of total drying energy costs in the food sector.
- At the state level, Georgia leads in drying energy costs for the P/P sector with 9.4 % of the total, followed by Pennsylvania (8.4 %), Alabama (7.5 %), Florida (6.8 %), and Wisconsin (6.3 %).
- The CO_2e emissions from drying processes account for 25 % of the total P/P sector emissions, which are estimated at 33,995 MT CO_2e per year, with 71 % classified as biogenic emissions.
- In the food sector, drying contributes 15 % of total emissions, reaching 6,868 MT CO_2e, 75.6 % of which originates from natural gas.
- Emissions patterns align with energy use, with the Southern US being the primary emitter in the P/P sector, whereas the Midwest region dominates food sector emissions. Notably, grain processing (corn and soybeans) is concentrated in the Midwest; sugar production is heaviest in Florida and Louisiana; and dairy, fruit, and vegetable drying are most prominent in California.
- The projected energy costs for drying processes in the P/P and food sectors are expected to increase by 34 % and 19 % by 2050, respectively.
- National projections indicate a rise in both energy consumption and CO_2e emissions from 2020 to 2050 for the P/P sector, increasing by 30 % and 20 %, respectively. In the food sector, soybean processing is expected to drive a 40 % increase in drying-related energy use and emissions.

Several strategies to improve drying efficiency have been outlined, along with associated barriers and potential solutions. Implementing energy-efficiency measures is critical for reducing costs, energy consumption, and emissions, all of which are important for strengthening industrial competitiveness. Energy-efficient technologies often provide the best cost-benefit approach. Additionally, low-carbon fuels and feedstocks will play a vital role in reducing reliance on conventional fossil fuels. Electrification, particularly through heat pumps, presents a promising opportunity for the food sector, where drying temperatures are typically below 200 °C. Hybrid renewable energy systems can also be integrated with existing technologies to further lower operational costs and emissions. Addressing technical, knowledge, and cost barriers will be essential for accelerating the adoption of these solutions, ensuring a more sustainable and efficient future for drying processes in both industries.

CRediT authorship contribution statement

Ramon P.P. da Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ikenna J. Okeke:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kiran Thirumaran:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manish Mosalpuri:** Methodology, Data curation, Conceptualization. **Forooza Samadi:** Writing – review & editing, Supervision, Methodology, Investigation. **Sachin U. Nimbalkar:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Joe Cresko:** Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2025.101181.

Data availability

Data will be made available on request.

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