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Towards Sustainable Energy Management in the Pharmaceutical Industry: Optimizing Drying

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Abstract

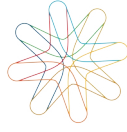
The pharmaceutical industry, with its complex processes and high energy consumption, is facing increasing economic, environmental, and regulatory pressures. Despite its crucial role in global public health, it remains one of the largest greenhouse gas emitters, surpassing even the automotive industry by 55%. This energy challenge is particularly critical in industrial pharmaceutical establishments (IPEs) in the Arab world, where almost all energy supply relies on fossil fuels, even though the pharmaceutical market is growing rapidly. In this context, optimizing energy performance is a strategic necessity, not only to reduce production costs but also to promote sustainable development and meet international climate commitments. The study reviews the current literature on energy issues in the pharmaceutical sector, emphasizing the importance of an integrated energy management approach. The article illustrates a means of rationalizing energy through a case study involving the optimization of drying in an industrial pharmaceutical environment using a two-phase fluidized bed model. The simulations show that adjusting the input parameters (temperature, speed, and moisture content) significantly reduces both drying time and energy consumption, while also reducing CO₂ emissions compared with current practices. These results demonstrate that the integration of suitable technologies, combined with a detailed analysis of process parameters, can contribute to a substantial reduction in operating costs and environmental footprint. Thus, energy optimization, coupled with robust training, financial incentives, and governance policies, appears to be a promising route to transforming the Arab pharmaceutical industry into a more sustainable and globally competitive sector.

Keywords: Energy performance; Drying; Pharmaceutical industry; Decarbonization; Arab world

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نحو إدارة مستدامة للطاقة في صناعة الأدوية: تحسين التجفيف

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ملخص

تواجه صناعة الأدوية، بعملياتها المعقدة واستهلاكها العالي للطاقة، ضغوطاً اقتصادية وبيئية وتنظيمية متزايدة. على الرغم من دورها الحاسم في الصحة العامة العالمية، إلا أنها لا تزال واحدة من أكبر مسببات انبعاثات الغازات الدفيئة، متجاوزة حتى صناعة السيارات بنسبة 55% من حيث الانبعاثات. يعد تحدي الطاقة هذا حرجاً بشكل خاص في المؤسسات الصيدلانية الصناعية في العالم العربي، حيث تعتمد جميع إمدادات الطاقة تقريباً على الوقود الأحفوري، على الرغم من أن سوق الأدوية ينمو بسرعة. في هذا السياق، يبدو أن تحسين أداء الطاقة ضرورة استراتيجية، ليس فقط لخفض تكاليف الإنتاج، ولكن أيضاً لتعزيز التنمية المستدامة والوفاء بالالتزامات الدولية المتعلقة بالمناخ. تستعرض الدراسة الأدبيات الحالية حول قضايا الطاقة في قطاع المستحضرات الصيدلانية، مع التأكيد على أهمية اتباع نهج متكامل لإدارة الطاقة. يوضح المقال وسيلة لترشيد الطاقة من خلال دراسة حالة تتضمن تحسين التجفيف في بيئة صيدلانية صناعية باستخدام نموذج قاع مميّع ثنائي الطور. تُظهر المحاكاة أن تعديل معاملات الإدخال (درجة الحرارة والسرعة ومحتوى الرطوبة) يقلل بشكل كبير من وقت التجفيف واستهلاك الطاقة على حد سواء، مع تقليل انبعاثات ثاني أكسيد الكربون بشكل كبير مقارنة بالممارسات الحالية. وتوضح هذه النتائج أن تكامل التقنيات المناسبة، إلى جانب التحليل التفصيلي لمعاملات العملية، يمكن أن يساهم في تخفيض كبير في تكاليف التشغيل والبصمة البيئية. وبالتالي، يبدو أن تحسين الطاقة، إلى جانب التدريب القوي والحوافز المالية وسياسات الحوكمة، هو طريق واعد لتحويل صناعة الأدوية العربية إلى قطاع أكثر استدامة وتنافسية على المستوى العالمي. الكلمات

الكلمات المفتاحية: أداء الطاقة، التجفيف، صناعة المستحضرات الصيدلانية، إزالة الكربون، العالم العربي

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Introduction

The energy transition lies at the core of international climate commitments, with approximately one quarter of global carbon dioxide emissions stemming from industrial energy consumption (Ghionda, 2024). This reality compels various industrial sectors to enhance their energy efficiency. Among these, the health sector, including pharmaceutical manufacturing, stands out due to its significant carbon footprint, accounting for an average of 4.9% of global emissions (Keil, 2024; Chen-Xu, 2024; Harm, 2019). The pharmaceutical sector is one of the most energy-intensive within the chemical industry, consuming up to 50% of the energy used in production facilities alone. Moreover, its greenhouse gas emissions exceed those of the automotive sector by 55% (Belkhir & Elmeligi, 2019), and its carbon footprint is increasing at a faster rate than both the healthcare services sector and the recent global average (Rosalie et al., 2025), despite receiving comparatively less attention (LEEM, 2023). Due to the complexity, costliness, and time-consuming nature of its processes, as well as its substantial energy consumption (Alzhrani, 2024), the pharmaceutical industry faces increasingly stringent economic, environmental, and regulatory challenges. Rising energy costs, dependence on fossil fuels, and mounting pressure from greenhouse gas (GHG) reduction policies make energy management a top strategic priority.

In the Middle East and North Africa (MENA) region, healthcare systems are challenged by a rising prevalence of non-communicable diseases, economic constraints, and fragmented health systems. In 2018, healthcare expenditure ranged from 2.49% to 8.35% of GDP depending on the country, with pharmaceutical expenditure averaging 24.8% of total healthcare spending—significantly higher than the OECD average of 17.4% (Kamphuis, 2021). This imbalance, combined with substantial out-of-pocket payments by patients, ranging from 6% in Oman to 62% in Egypt of current healthcare expenditure (WHO, 2018), necessitates urgent cost rationalization policies, particularly focused on controlling pharmaceutical costs given their large contribution to overall health expenditure (Kanavos, 2020).

Within this context, optimizing pharmaceutical industrial processes, especially energy-intensive ones such as drying, represents a strategic opportunity to enhance the sector's economic and environmental sustainability. This pressure is particularly acute in industrial pharmaceutical establishments (IPEs) in the Arab world, where production is primarily focused on generic drugs with lower profit margins than branded drugs (Nguyen, 2022; Frank, 2021). The generic pharmaceutical market in the region is projected to grow by 40% in volume and 12% in value (IQVIA, 2022). Simultaneously, 95% of the region's energy demand is met by fossil fuels, one of the highest shares worldwide according to the International Energy Agency (IEA), with annual per capita CO₂ emissions of 13 tons, lower than North America (17 tons) but higher than Europe (7.8 tons) (Mohtadi, 2025).

In this scenario, improving energy performance becomes critical not only for reducing production costs but also for advancing sustainable development goals. Consequently, Arab countries such as Saudi Arabia, Bahrain, and the United Arab Emirates have set ambitious net-zero emission targets (Elfarra, 2024). However, the lack of technical data and targeted initiatives addressing energy-intensive processes,

such as drying, constitutes a major obstacle to improving energy efficiency in the pharmaceutical sector within Arab countries, despite their strong stake in sustainable transition objectives.

While global progress has been made in pharmaceutical energy optimization, very few studies have addressed this issue within the Arab region. In particular, rigorous model-based approaches to optimize energy-intensive processes like drying remain scarce. Industrial practices tend to remain empirical and lack integration of simulation tools or digital frameworks that could drive performance improvements. From a theoretical perspective, the absence of region-specific frameworks limits the applicability of international solutions.

This study aims to fill both theoretical and practical gaps by evaluating the performance of drying systems in a Moroccan pharmaceutical plant. It integrates real-world data collection, simulation modeling, and energy-performance analysis to propose optimized parameters for fluidized bed drying. To our knowledge, this is the first comprehensive model-based evaluation of pharmaceutical drying energy in the MENA region, providing both a scalable methodology and practical recommendations for local adoption.

To address these challenges, the study proposes an integrated approach to energy optimization in pharmaceutical drying, combining industrial data from a Moroccan site with a robust physical simulation model. The objective is to identify key operational parameters affecting energy consumption and to recommend optimized conditions that maintain product quality while reducing energy usage and emissions.

This work contributes to the literature in three main ways: Offering a rare data-driven analysis of pharmaceutical manufacturing energy use in North Africa, a region where such studies are lacking, applying a two-phase fluidized bed drying model under real industrial constraints, providing a replicable methodology; delivering concrete recommendations to support the adoption of structured energy management systems in pharmaceutical plants across the Arab region.

The article is structured as follows: The first section reviews the literature on energy management and optimization in pharmaceutical production, focusing on the MENA region. The second part presents a case study on drying process optimization through modeling and simulation. The final section draws lessons from the results and outlines strategic recommendations for sustainable energy practices in the pharmaceutical sector.

1. Literature Review

1.1. The Pharmaceutical Industry and Energy Challenges

The pharmaceutical industry extensively relies on steam and electricity to meet its specific operational

needs, with approximately 50% of this energy associated with manufacturing processes (Chaitanya Sampat, 2022). In Austria, the pharmaceutical sector accounts for about 1.5% of the national natural gas consumption, primarily used for process steam generation via gas-fired boilers (Beck, 2024). The pharmaceutical and chemical industries rank among the most energy-intensive sectors in several countries, notably France and Germany, where they represent 32% of industrial energy consumption (Geres, et al., 2019; Chareyron, Moliranaro, & Multon, 2021). The share of renewable energy within this consumption remains largely undocumented, particularly in the Arab world.

However, it is well established that this region is highly dependent on fossil fuels, which still constitute 95% of its energy sources, the highest share worldwide according to the International Energy Agency (IEA, 2021) (Figure 1). Various programs aim to reduce this dependence. Indeed, non-oil-producing countries such as Morocco and Egypt have integrated 25 % and 17.1 % renewable energy into their energy mix, whereas oil-producing nations like Saudi Arabia and the United Arab Emirates have renewable shares below 1% (IEA, 2021; Abed, 2025; El Hafdaoui, 2025).

Although fossil fuel resources have supported the economic development of many of these countries, they face challenges such as reserve depletion, price volatility, and the impacts of climate change (ESCWA, 2023).

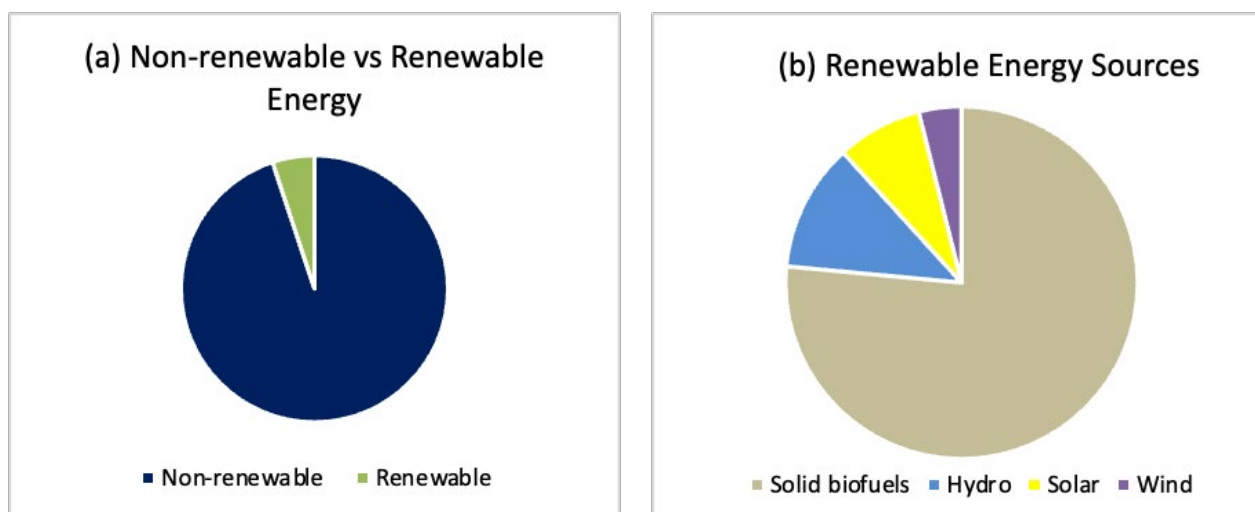


Fig. 1: Total final energy consumption breakdown by source in the Arab region, 2020 (IEA, 2021)

In the pharmaceutical industry, energy efficiency has often been relegated to a secondary priority compared to other high-energy-consuming industries. However, regulatory pressure, global climate targets, and the imperative to reduce CO₂ emissions at the process level are now driving a strategic shift towards energy sustainability (Beck, 2024). According to a recent study (Rosalie, et al., 2025), greenhouse gas emissions increased by 77% between 1995 and 2019, mainly driven by the

United States and China, and linked to the rising consumption of pharmaceuticals as well as supply chain modalities. Technological factors, however, contributed significantly to emission reductions, mitigating growth by approximately 107%.

Regarding Scope 1 and 2 emissions, often underreported in corporate disclosures, they range from 31 to 326 tonnes of CO₂ per million dollars of pharmaceuticals produced (Rosalie, et al., 2025; Belkhir & Elmeligi, 2019). For example, in Germany, the pharmaceutical and chemical industries are responsible for one-third of total greenhouse gas emissions (Geres, et al., 2019). When considering the pharmaceutical life cycle, the bulk manufacturing, research and development (R&D), and formulation/packaging phases are the most energy-intensive. Thus, the energy challenges faced by the pharmaceutical sector, particularly in the Arab world, are both economic and environmental. To address these challenges, a non-exhaustive list of potential actions is presented in (Figure 2) (Capgemini, 2023).

Various initiatives contribute to the ongoing energy transition within the pharmaceutical sector. Although their implementation remains limited in the Arab region, several emerging efforts driven by industrial stakeholders and sectoral policies demonstrate notable progress. These actions can be categorized according to three fundamental levers: reduction, reuse, and replacement (see the table above for a non-exhaustive summary of documented cases).

The specific case of fluidized bed drying, a major energy-consuming operation, is addressed in detail in the following section. Among the identified strategies, optimization of heating, ventilation, and air conditioning (HVAC) systems stands out as the most studied and widely implemented, particularly in developed countries. HVAC systems account for primary energy consumption in pharmaceutical production facilities (Figure 3) due to stringent environmental control requirements (temperature, humidity, pressure, air quality), especially in classified cleanroom areas (Capgemini, 2023).

Increasingly, energy consumption optimization relies on approaches combining numerical modeling and artificial intelligence, enabling reductions in energy use ranging from 8% to 35% (Dhage, 2016; M'baye, 2022; Gupta, 2023; Ozelame, 2024; Liu, 2024; Alassafi, 2024).

Thanks to an innovative design of the lyophilization system, a study (Keller, 2025) demonstrates a potential reduction in electric heating demand of up to 25% for large-scale installations, while improving synergy between the cooling and drying phases.

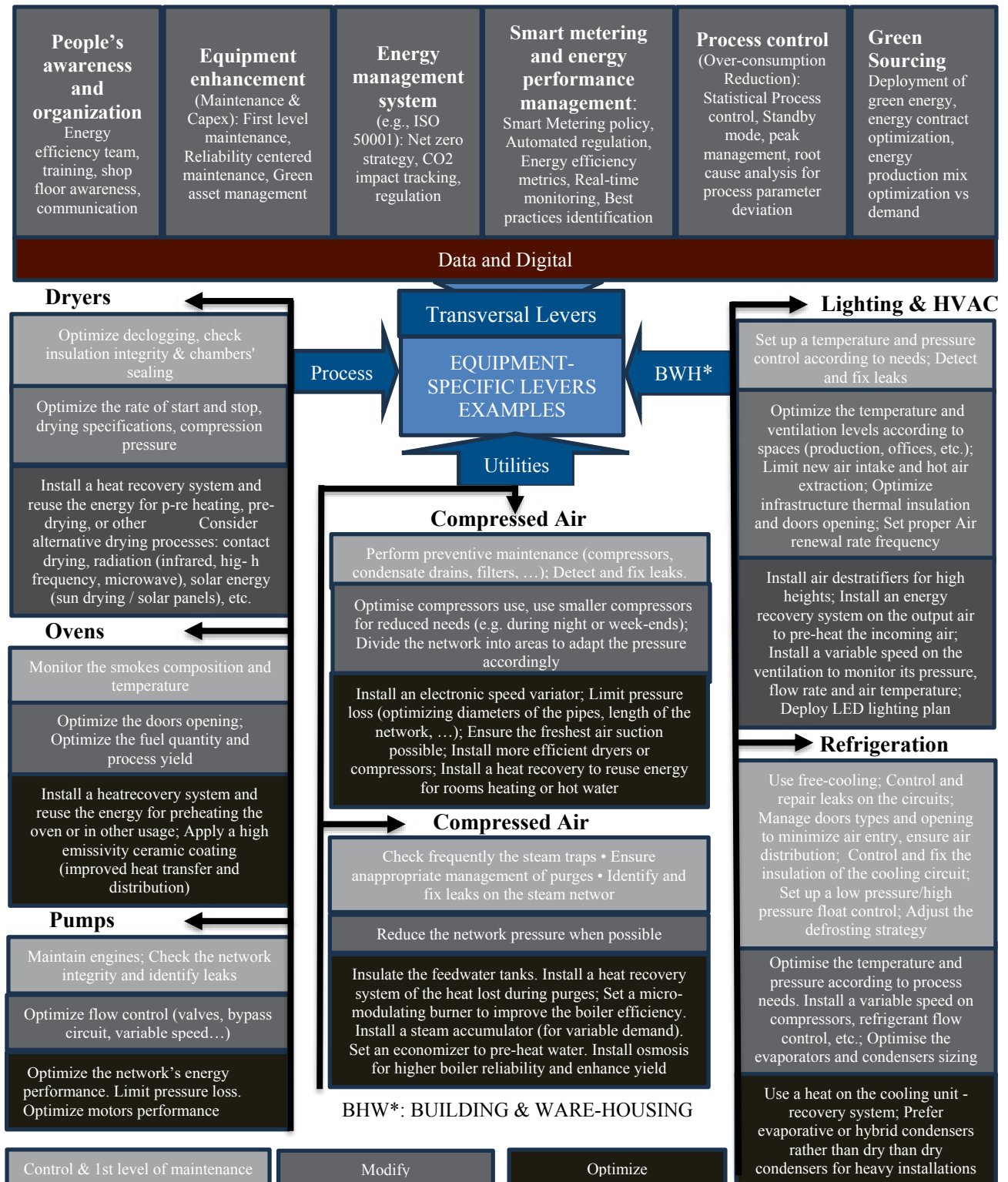


Fig. 2: Possible courses of action to improve energy performance in the pharmaceutical industry (Capgemini, 2023)

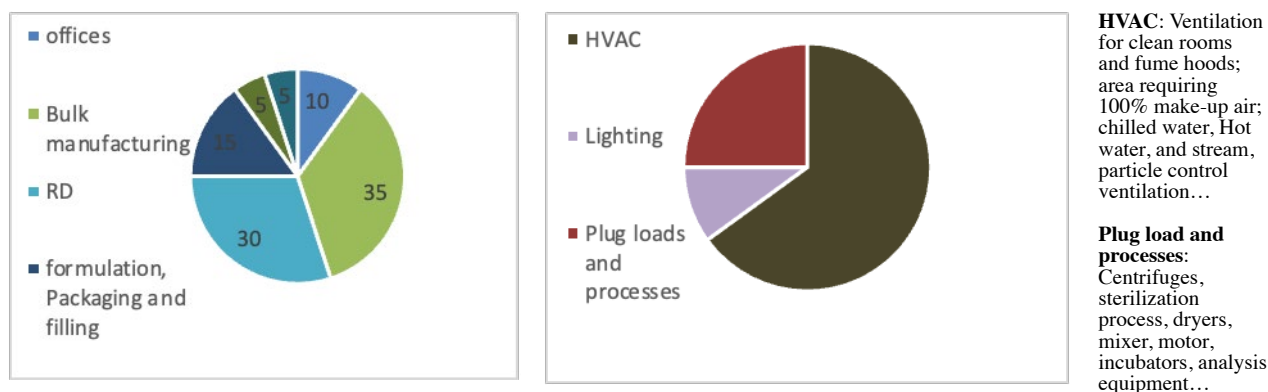


Fig. 3: Energy consumption split of a US Pharma company by process and nature (Capgemini, 2023)

Within the broader context of dry dosage form production, another study demonstrated energy savings of up to 30% by transitioning from batch production to continuous manufacturing (PAT) (Sampat, 2022). Additionally, a separate study reported energy savings of 83.3% (Chen, 2023).

Beyond thermal processes such as drying, industrial utilities like compressed air represent a significant energy consumer in pharmaceutical manufacturing. A study conducted in packaging demonstrated that optimization at two levels, production (source point) and usage (user point), enabled a 23% reduction in compressor electricity consumption and a 7 to 8% decrease in compressed air usage (Candra, 2024). These findings highlight the potential for energy savings even in peripheral equipment, which is often overlooked, aligning closely with the objectives of this study: to identify and optimize energy performance levers within processes, particularly drying, through a combined approach of field observation and technical modeling.

Furthermore, another study showed that the intelligent integration of low-carbon hybrid technologies, enabled by customized energy modeling and multi-objective optimization, including renewable energies, heat recovery, and process electrification, resulted in significant emission reductions at moderate costs (Ghiondaun, 2024). Although several initiatives have been documented (Table 1), data within Arab countries remain scarce and often lack conclusive evidence.

Beyond actions targeting energy consumption, additional improvement levers can be identified, particularly the eco-design of pharmaceuticals (Duc-Nam Luu, 2022; Van Nguyen, 2025) and their packaging. This approach is based on three complementary strategies: (i) reducing the weight and/or volume of products and packaging, (ii) adopting alternative packaging materials with a lower environmental impact, and (iii) optimizing transportation methods to minimize the carbon footprint associated with logistics (Bassani, 2022).

Table 1: Strategies for Improving Energy Performance in the Pharmaceutical Industry*

	Optimization	Reuse	Maintenance / Replacement
Advantages	- Improved efficiency without major system changes - Quick, low-cost implementation - Reduced energy losses and long-term savings	- Reduced energy use by recovering excess energy - Lower operating costs - Improved sustainability	- Durable and continuous improvements - Reduced maintenance costs and carbon footprint
Limitations	- Limited benefits on outdated systems - Requires control equipment or software - Delayed returns in some cases	- Requires investment in recovery systems - Not applicable if the infrastructure is incompatible	- High initial investment - Potential downtime during replacement - - Need for staff training
Examples outside Arab countries	- Sanofi: HVAC optimization (Sisteron) → 15% savings - SALF: Smart sensors + AI → 28% savings (Evogy, 2023) - Sanofi: ISO 50001 certification for 30 sites (2021) - J&J: Transition to 100% renewable electricity (Johnson & Johnson, 2021)	- GSK: Heat recovery from cooling water (Mayenne) → 70% of hot water needs covered (GSK, 2021) - Merck MSD: 90 GWh/year of green electricity (TotalEnergies, Spain)	- Pfizer: Annual investments of \$25–40M in sustainable tech and heat recovery - Douglas Pharmaceuticals: Solar panels (Auckland) → -40% carbon footprint (2020–2024) (Douglas Pharmaceuticals, 2024)
Examples in Arab countries	- Sothéma (Morocco): -13% via HVAC optimization + ISO 50001 strategy - Maphar (Morocco): ISO 50001 certified since 2016 - FMIIP-IFC (Morocco): Sectoral improvement via water/energy management (FMIIP-IFC, 2022)	- RAM Pharma (Jordan): Heat recovery with Fresnel solar collectors → 30,000 L of diesel saved annually (Haagen, 2015)	- GEFF (Egypt): New pharmaceutical line → -33% energy and -240 t CO₂/year (GEFF, 2024) - Rameda (Egypt): Partnership with IFC for greener production (Rameda-IFC, 2022)

Source: Authors' own work

2. Focus on Fluidized Bed Drying Processes

Dry dosage forms represent the most widely marketed pharmaceutical formulations due to their inherent stability, ease of storage, and high patient acceptability. Their manufacturing processes typically follow a sequence of critical steps, among which drying plays a central role.

Drying is a unit operation that involves the thermal removal of volatile substances, primarily moisture, to obtain a solid product. It entails a simultaneous transfer of both energy and mass (Mujumdar, 2015; 2022). Among various drying technologies, fluidized bed drying is widely employed in pharmaceutical manufacturing, particularly for drying granules produced via wet granulation. This preference stems from its high efficiency and the consistent product quality it enables (Parikh, 2017). However, this process also presents significant energy and operational challenges. A typical fluid bed dryer operates through three distinct phases: (i) Preheating of the equipment without product load, (ii) Active drying of the granules, and (iii) a Cooling phase to stabilize the final product (Barriga, 2023). Each of these phases incurs substantial costs in terms of time, labor, and particularly energy consumption, due to the need for air heating, forced circulation, and ventilation. These factors constitute major drawbacks of fluid bed drying systems (Barriga, 2023). Moreover, it is estimated that only 55–65% of the energy input is effectively used to evaporate moisture, with the remainder being lost (Majumder, 2022).

In contrast to the relatively advanced optimization of HVAC systems, efforts to optimize fluidized bed drying in pharmaceutical settings, especially in the Arab world, remain limited, despite the availability of several tools described in the literature. These tools include mathematical process modeling, data analytics, artificial intelligence, and machine learning techniques, which are now widely used across the pharmaceutical industry (Chen, 2023; Barriga, 2023; Diaz, et al., 2023; Sampat, 2022; Aziz, 2022; Kim, 2020; Gavi, 2019; Ghijs, 2019; Sciuto, et al., 2016). A study (Majumder, 2022) suggests that defining optimal process parameters can reduce energy consumption by 10–30%. Another study (Barriga, 2023), which employed a combination of exploratory data analysis (EDA) and a CatBoost machine learning model, demonstrated that this approach could predict and achieve a 50.45–59.68% reduction in preheating time, corresponding to an average 50.48–59.76% reduction in energy consumption during this phase.

2.1. Limitations and Gaps in Actions Undertaken, particularly in the MENA Region

Despite the growing number of initiatives aimed at improving energy performance, their impact remains limited by several structural and strategic constraints, particularly in the pharmaceutical sector of the Arab world.

Efforts such as the Race to Zero campaign have led to a significant increase in commitments within the MENA region, with a reported growth of over 104% between 2022 and 2023 (Al Mubarak, 2023). However, these advances are largely declarative, due to the absence of established standards and independent verification mechanisms, resulting in major disparities in the scope and credibility of transition plans reported by companies (Al Mubarak, 2023).

Moreover, these initiatives are often implemented in isolation, lacking both comprehensive energy programs and integrated Energy Management Information Systems (EMIS), thereby limiting the overall effectiveness of the actions undertaken, as shown in (Figure 4). Yet, to achieve Sustainable

Development Goal (SDG) 7.3, which aims to double global energy efficiency by 2030, an annual improvement rate of +3.8% is required from 2022 to 2030. This calls for a systemic and sector-specific approach, particularly within the pharmaceutical industry.

Such strategies have already been observed in other countries and regions, most notably in Europe, through initiatives like the Health Sector Decarbonization Plan (DGE, 2023) and efforts by the European Medicines Agency (EMA) to promote sustainable production of new pharmaceutical products.

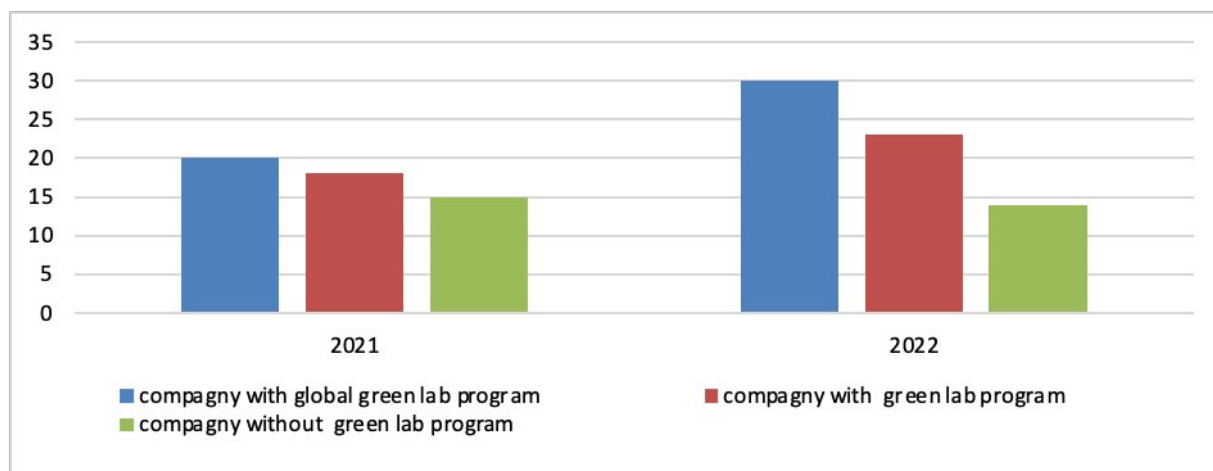


Fig. 4: Progress Race to Zero by monitoring the level of their green program (CCNUCC, 2023)

In addition to lacking standardization, regional pooling, and coordination, which hinder the dissemination of best practices, the MENA region also suffers from a funding shortage, similar to trends observed in other parts of the world. This challenge is particularly critical for pharmaceutical manufacturers in the MENA region, whose economic model is primarily based on the production of generic medicines, which generate lower profit margins than branded drugs (Research Expert Market, 2024). As a result, it becomes difficult to adapt internationally developed solutions to the specificities of the Arab pharmaceutical context. This situation is further exacerbated by limited awareness and a scarcity of published research on energy optimization in the region's pharmaceutical sector.

This study is part of a broader effort to advance the energy transition within the pharmaceutical industry in the Arab world. Its objective is to promote energy efficiency through the optimization of a process that is particularly widespread in local pharmaceutical production facilities: drying. To the best of our knowledge, this is the first study specifically dedicated to the energy optimization of drying operations in the pharmaceutical context of the MENA region.

As such, this work offers an original contribution, providing practical insights to help shape industrial-scale energy efficiency policies, while also considering the economic and technical constraints specific to countries focused on generic drug production.

3. Methodology

This project involved transferring a granulation process with tray drying, which had reached the saturation point, to a workshop equipped with a fluidized air bed (FBD) that had recently been installed but was underused. The approach adopted considers economic, quality, and environmental considerations, in line with the organization's sustainable development policy, to optimize the operating conditions of the process.

In this workshop, dedicated exclusively to non-injectable dry forms, drying and the HVAC system represent the main sources of energy consumption. In this article, we focus solely on drying, as its energy impact far exceeds that of the other stages of the transferred process. The aim is to determine the optimum drying parameters for reducing energy consumption and operational costs, while guaranteeing product quality.

The granulation line used is Boch's Granuleean 600, with its FGL 600 mixer, shown below. The initial granulation line consists of a Collette IMH 450 planetary mixer, a drying oven, a Frewit sizer, and a VMI agitator for preparing the fount solution.

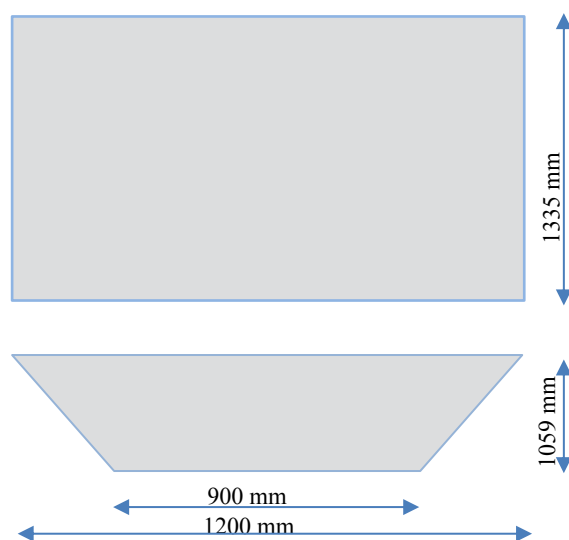


Fig. 5: Représentation schématique du FBD-FGL 600

Source: Authors' own work

The properties of the active substance of the drug are grouped in the table, and the estimated properties of the wet granules are estimated via different correlations in the following (*Table 2*).

Table 2: Characterization of active substance

AS	Terbinafine
Formula	$C_{21}H_{26}ClN$
Aspect	White or almost white powder
Molar mass (g/mol)	327,9
Solubility	Very slightly or sparingly soluble in water (solubility), freely soluble in anhydrous ethanol and methanol, sparingly soluble in acetone
Melting point (°C)	205,0
Polymorphism	No

Source: Authors' own work**Table 3:** Characterization of wet granules

AS	Terbinafine
Water content	0,4
Heat Capacity Coefficient-dry particle (J/kg.K)	1100
Density (kg/m^3)	1000
Sphericity	0,8
Diameter (mm)	9

Source: Authors' own work

Simulations and optimization are carried out on the drying stage, using the two-phase fluidized air bed model implemented in MATLAB.

3.1. Mathematical model

The two-phase fluidized bed (FBD) model was chosen because it accurately represents the industrial fluidized bed drying process, which is widely used in the pharmaceutical industry due to its combination of energy efficiency and product quality. This model precisely captures the interactions between the solid phase (particles) and the gas phase (hot air), which is essential for optimizing heat and mass transfer. The key assumptions include homogeneous flow, constant material properties, and no changes in the particles during drying.

Description of the model:

The two-phase model (Figure 6) serves as a robust framework for elucidating the drying process of pharmaceutical powders within fluidized beds. This model categorizes the volume of the fluidized bed into two distinct phases:

- The dense phase, which comprises particles and interstitial gas that engage in interactions, thereby facilitating mass and heat transfer processes.
- The bubble phase, characterized by voids filled with residual gas that manifest as ascending bubbles within the fluidized bed.

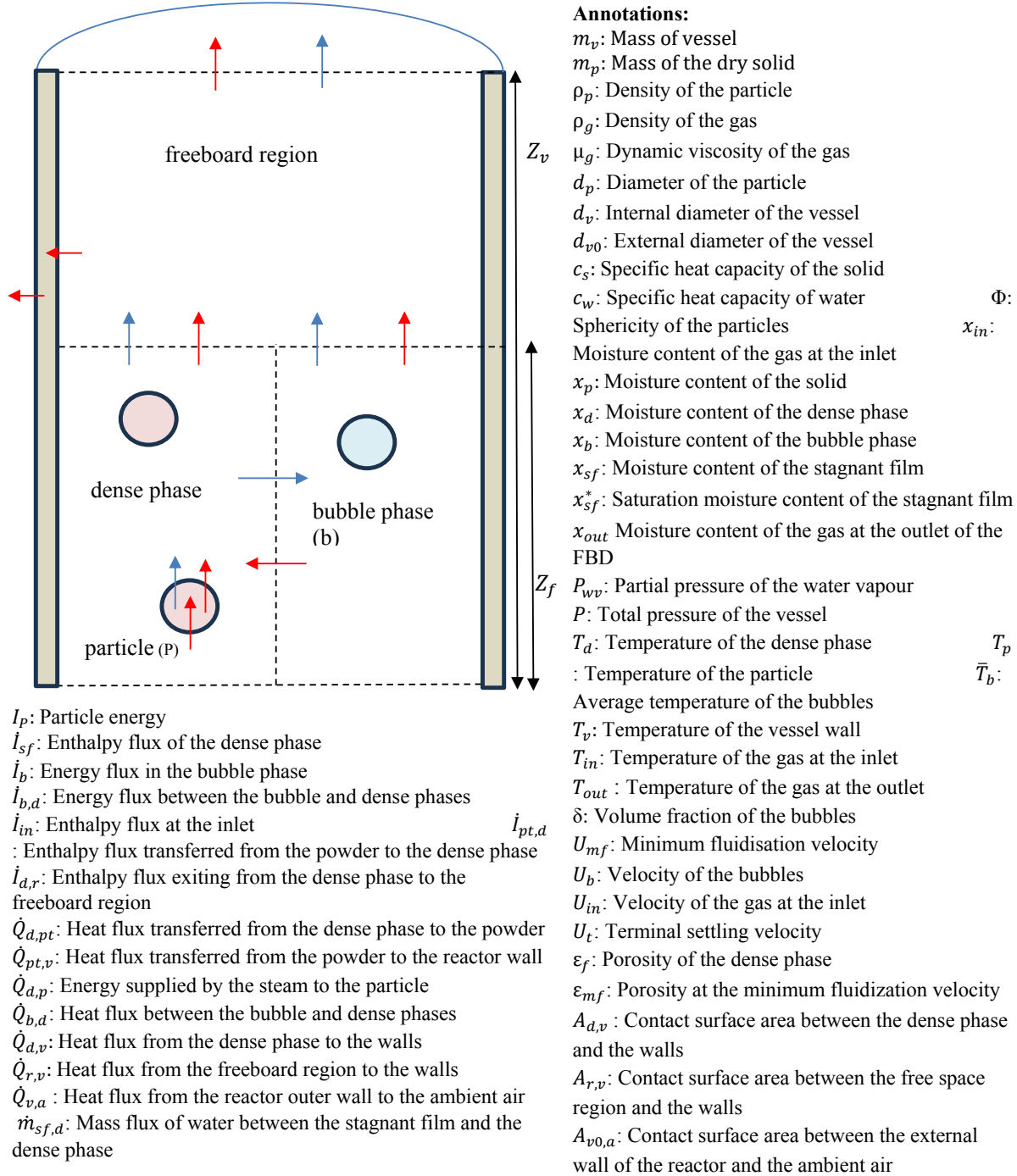


Fig. 6: Schematic representation of mass and energy transfer in the model, adapted from (Gagnon, 2021; Lau, 2023)

The following differential equations delineate the system's dynamics:

$$\bullet \quad \frac{dx_p}{dt} = -\frac{6}{\Phi d_p} K_{sf,d} \rho_g (x_{sf} - x_d) \quad (1)$$

$$\bullet \quad \rho_p d_p (c_s + x_p c_w) \frac{T_p}{dt} = \frac{6}{\Phi d_{s..}} H_{d,sf} (T_d - T_p) - \frac{6}{\Phi d_{s..}} K_{sf,d} \rho_g (x_{sf} - x_d) (\Delta H_{evap} + (c_{wv} - c_w)(T_p - T_d)) \quad (2)$$

$$\bullet \quad U_b \frac{dx_b}{dz} = K_{d,b} (x_d - x_b(z)) \quad (3)$$

$$\bullet \quad U_b (c_g + x_b(z) c_v) \frac{dT_b}{dz} = -(T_b(z) - T_d) \left(\frac{H_{b,d}}{\rho_g} + K_{b,d} (x_{in} - x_b(z)) \right) \quad (4)$$

$$\bullet \quad \frac{U_{mf}}{z_f} (x_d - x_{in}) = \frac{6(1-\varepsilon_f)}{\Phi d_p} K_{sf,d} - \delta K_{b,d} (x_{in} - \bar{x}_b) \quad (5)$$

$$\bullet \quad \frac{U_{mf}}{z_f} (c_g + x_{in} c_v) (T_d - T_{in}) = \frac{\delta K_{b,d}}{\rho_g} (\bar{T}_b - T_d) + \frac{6(1-\varepsilon_f)}{\Phi d_p} (K_{sf,d} (x_{sf} - x_d) c_v + \frac{H_{d,sf}}{\rho_g}) (T_p - T_d) - \frac{4H_{d,v}}{d_v \rho_g} (T_d - T_v) \quad (6)$$

$$\bullet \quad \frac{m_v c_v}{\pi d_v} \frac{dT_v}{dt} = z_f h_{d,v} (T_d - T_v) + (z_v - z_f) H_{r,v} (T_{out} - T_v) - \frac{d_{v0}}{d_v} z_v h_{v,a} (T_v - T_a) \quad (7)$$

$$\bullet \quad U_{in} x_{out} = U_{mf} x_d + \delta v_b x_b \quad (8)$$

$$\bullet \quad \left(U_{in} (c_g + x_{out} c_v) + \frac{4(z_v - z_f) H_{r,v}}{d_v \rho_g} \right) T_{out} = \delta U_b (c_g + x_b(z_f) c_v) T_b(z_f) + U_{mf} (c_g + x_d c_v) T_d + \frac{4(z_f - z_v) H_{r,v}}{d_v \rho_g} T_v \quad (9)$$

The parameters and transfer coefficients are given in (Table 4) and (Table 5).

Table 4: Correlation parameters

Parameters	Correlation	Operating conditions	References
ε_{mf}	$= 0,586 \Phi_p^{-0,72} \left[\frac{\mu_g}{d_p^3 (\rho_p - \rho_g) \rho_g g} \right]^{0,029} \left(\frac{\rho_g}{\rho_p} \right)^{0,021}$	-	(Kunii, 1991)
U_{mf}	$= \frac{d_p^2 (\rho_p - \rho_g) g}{150 \mu_g} \frac{\varepsilon_{mf}^3 \Phi_p^2}{1 - \varepsilon_{mf}}$	$Re_{p,mf} = \frac{\rho_g U_{in} d_p}{\mu_g} < 20$	(Kunii, 1991)
U_t	$= \frac{18}{(d_p^*)^2} + \frac{2,335 - 1,744 \Phi_p}{(d_p^*)^2}$	$0,5 < \Phi < 1$	(Kunii, 1991)
U_b	$= (U_{in} - U_{mf}) + 0,71 (g d_b)^{0,5}$		(Kunii, 1991)
Δ	$= \frac{U_{in} - U_{mf}}{U_b - U_{mf}}$	$U_b > 5 U_{mf} / \varepsilon_{mf}$	(HG Wang un, 2007)
ΔH_{evap}	$= 3168 - 2.4364 T_p$	-	(Kunii, 1991)
ε_f	$= (1 - \delta) * \varepsilon_{mf} \delta$	-	(Lau, 2023)

With: $d_p^* = d_p \left(\frac{(\rho_p - \rho_g) \rho_g g}{\mu_g^2} \right)^{1/3}$

Table 5: Correlations transfer coefficients

Coefficients	Correlations	References
$H_{d,sf}$	$\frac{\lambda_g}{d_p} N_u$	(LimLaw, 2007)
$K_{d,sf}$	$\frac{H_{d,sf}}{c_g}$	(Mujumdar, 2015)
$K_{d,b}$	$\left(\frac{1}{K_{b,c}} + \frac{1}{K_{c,d}} \right)^{-1}$	(Kunii, 1991)
$H_{d,b}$	$\left(\frac{1}{H_{b,c}} + \frac{1}{H_{c,d}} \right)^{-1}$	(Kunii, 1991)

$K_{b,c}$	$4,5 \frac{U_{mf}}{d_b} + 5,85 \frac{D_{wb}^{0,5} g^{0,25}}{d_b^{1,25}}$	(Kunii, 1997)
$K_{c,d}$	$5,71 \left(\frac{\varepsilon_{mf} D_{wb} g^{0,5}}{d_b^{2,5}} \right)^{0,5}$	(Kunii, 1997)
$H_{b,c}$	$4,5 \frac{U_{mf} \rho_g c_g}{d_b} + 5,85 \frac{(\lambda_g \rho_g c_g)^{0,5} g^{0,25}}{d_b^{1,25}}$	(Kunii, 1997)
$K_{c,d}$	$5,71 \left(\frac{\varepsilon_{mf} \lambda_g \rho_g c_g g^{0,5}}{d_b^{2,5}} \right)^{0,5}$	(Kunii, 1997)
$H_{d,v}$	$47 \left(\frac{\lambda_g}{d_v} \right) (1 - \varepsilon_f) \left(\frac{d_v U_{in} \mu_g}{\rho_p d_p^2 g} \right)^{0,325} \left(\frac{\rho_p c_p d_p^{0,5} g^{0,5}}{\lambda_g} \right)^{0,23} (c_g \mu_g)^{0,3}$	(Grewal & Saxena, 1980)
$H_{r,v}$	$3,95 \left(\frac{\lambda_g}{d_v} \right) \left(\frac{d_v U_{in} \rho_g}{\mu_g} \right)^{0,55} \left(\frac{c_g \mu_g}{\lambda_g} \right)^{\frac{1}{3}}$	(Osman, Upadhyay, & Saxena, 1982)
$H_{v,a}$	$\frac{\lambda_g}{z_f} \left(0,825 + \frac{0,387 (G_r \frac{c_g \mu_g}{\lambda_g})^{1/6}}{(1 + (\frac{0,492 \lambda_g}{c_g \mu_g})^{9/16})^{8/27}} \right)^2$	(Churchill & Chu, 1975)

With: $N_u = 0,0282 R_{ep}^{1,4} Pr^{\frac{1}{3}}$ if $0,1 < R_{epmf} < 50$

$$N_u = 1,01 R_{ep}^{0,48} Pr^{\frac{1}{3}} \quad \text{if } 50 < R_{epmf} < 1 * 10^4 \quad Pr = \frac{c_g}{\lambda_g \rho_g}, \quad G_r = \frac{g z_v^3 |T_v - T_a| \rho_g^2}{0,5 (T_v + T_a) \mu_g^2}$$

Where:

$H_{d,sf}$: Particle Heat Transfer	:	$K_{c,d}$: Cloud/Dense
$K_{d,sf}$: Particle Mass Transfer	:	$H_{d,v}$: Dense/Vessel Heat Transfer
$K_{d,b}$: Bubble/Dense Mass Transfer	:	$H_{r,v}$: Freeboard/Vessel Heat Transfer
$H_{d,b}$: Bubble/Dense Heat Transfer	:	$H_{v,a}$: Vessel/Ambient Heat Transfer
$K_{b,c}$: Bubble/Cloud Mass transfer	:	N_u : Nusselt Number
$K_{c,d}$: cloud/ Dense Mass transfer	:	Pr : Prandtl Number
$H_{b,c}$: Bubble/Cloud Heat transfer	:	G_r : Grashof Number
	:	R_{epmf} : Reynolds Number

3.2. Objective function and optimization constraints:

The objective function maximizes profit, considering drying time and energy performance, and the constraints are grouped in the (Table 6).

Table 6: Optimization constraints

Parameters	Lower bound	Upper bound	Justification
U_{in}	U_{mf}	$ U_t $	Speed range allowing fluidization
T_{in}	303,15	333,0	The temperature range is deemed to pose an acceptable risk to the destruction of the substance
χ_{in}	0,02	0,0001	The humidity range is easily achieved and controllable with the available equipment

4. Economic evaluation and environmental impact

The economic evaluation of the three studied solutions is based on a comparative analysis of the energy costs associated with the operation of the fluidized air bed drying system (FAB). The following

scenarios were considered:

- Scenario 1: Baseline process using the original FAB parameters (prior to any intervention);
- Scenario 2: Standard FAB parameters applied post-intervention, without specific optimization;
- Scenario 3: FAB system optimized using a dynamic two-phase simulation model.

Energy consumption data for Scenario 1 were measured on-site during actual drying cycles, while those for Scenarios 2 and 3 were obtained via simulation using MATLAB. These energy values were then converted into annual costs using the local electricity tariff (1.2 MAD/kWh), assuming an average annual operation time of 2,400 hours. In parallel, greenhouse gas emissions were estimated using conversion factors provided by the Mohammed VI Foundation for Environmental Protection.

The results pertain exclusively to the drying of wet granules, with a residual moisture content estimated at 0.4, based on product formulation parameters described in the manufacturing protocols.

Additional investments were annualized over an assumed equipment lifespan of five years, using the standard constant annuity formula with a discount rate of 5%.

5. Findings and Analysis

6. Simulation and Optimization:

Eight initial simulations were carried out; the simulation parameters and results are presented in (Table 7). These simulations show that low temperature conditions (30°C) and high input moisture content (0.017) result in long drying times and lower energy efficiency. The process has a lower energy efficiency than that generally obtained in practice, which is around 50% (Majumder, 2022). High temperatures and speeds, with low inlet moisture, shorten the drying time, while low speed and high temperature improve energy efficiency. Simulation 3, although better in terms of energy consumption and efficiency, is sixth out of eight in terms of drying speed. Optimizing the parameters means considering both energy performance and the costs associated with a longer drying time, posing a multi-objective optimization problem.

Table 7: Results of the initial simulation

N°	T_{in} (°C)	U_{in} (m/s)	x_{in}	t_{dr} (min)	$E_c(j)$	E_{en}	E_{ex}
1	30	0,874	0,017	>133,33	$> 170 * 10^6$	0,45	0,04
2	60	0,874	0,017	55	$138,03 * 10^6$	1,2	0,2
3	30	0,874	0,0001	77,1	$97,44 * 10^6$	1,7	0,06
4	60	0,874	0,0001	41,3	$100,4 * 10^6$	1,6	0,12
5	30	1,048	0,017	>133,33	$>203,64 * 10^6$	0,4	0,04
6	60	1,048	0,017	53	$162,1 * 10^6$	1	0,11
7	30	1,048	0,0001	75,66	$114,9 * 10^6$	1,4	0,05
8	60	1,048	0,0001	38,7	$118,22 * 10^6$	1,4	0,1

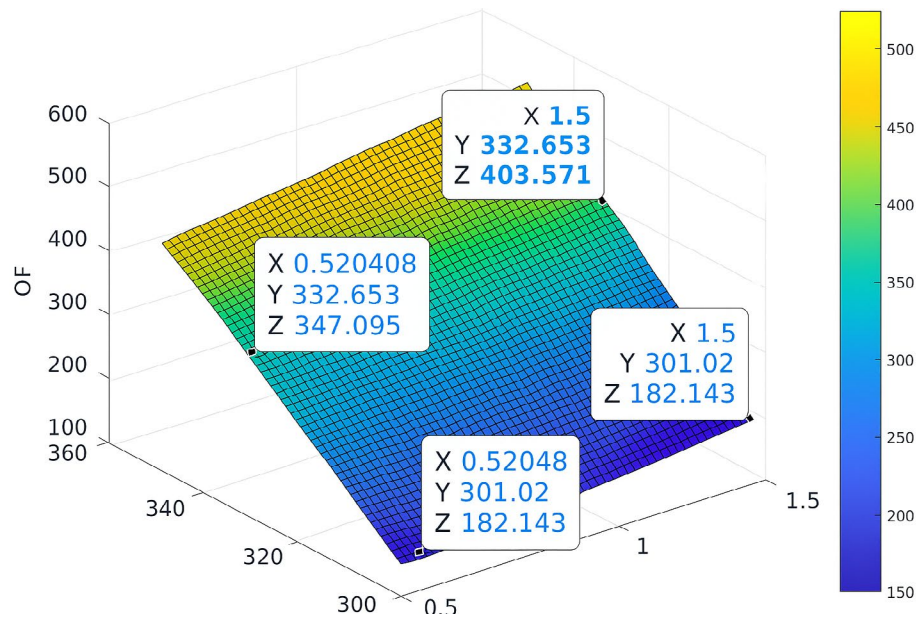


Fig. 7: Objective function response surface as a function of input parameters (temperature and velocity)

The optimum solution is the one with the following parameters: moisture content: 0.001; inlet temperature: 333 K; speed: 1.5. In the simulation with these parameters, it can be seen that the drying time required to reach the target moisture content (0.03) is 38.09 minutes, with an energy consumption of 160.55×10^6 Joules. The temperature and humidity curves show that beyond 2500 seconds, the moisture content remains almost constant, while the temperature of the particles and the container increases. This suggests that the energy supplied beyond this time is used primarily for superheating the particles and vessel, rather than for drying.

It is also observed that before reaching the target point, the temperature of the vessel decreases. This reflects the loss of energy stored by the equipment during the FBD preheating phase at 323 K. This observation suggests that the FBD preheating temperature is not optimal. By adjusting the inlet temperature to 305 K, which would make it possible to maintain a constant vessel temperature before reaching the target point, it would be possible to reduce energy losses during preheating.

7. Economic evaluation and environmental impact

In this section, three possible technical solutions have been defined, two of which serve as a basis for comparison with the optimal solution defined. These possible solutions are listed in Table 10. As solution 1 (with drying under a tray) is not a simulated solution, the energy consumption required is that of the whole equipment (product of the equipment power and the drying time). The calculation of electrical energy consumption considers that of the oven, the FBD, and the dehumidifier in cases where a humidity of 0.0001 is required. In addition, the assessment is based on the number of annual batches of Terbinafine alone (24 batches/year), which represents only a tiny fraction of the annual production capacity of the plant, so percentage comparisons are the most relevant.

In this section, three possible technical solutions have been defined, two of which serve as a basis for comparison with the optimal solution defined. These possible solutions are listed in (Table 8). As solution 1 (with drying under a tray) is not a simulated solution, the energy consumption required is that of the entire equipment (product of equipment power and drying time). The calculation of electrical energy consumption considers that of the oven, the FBD, and the dehumidifier in cases where a humidity of 0.0001 is required. In addition, the assessment is based on the number of annual batches of Terbinafine alone (24 batches/year), which represents only a tiny fraction of the annual production capacity of the plant, so percentage comparisons are the most relevant.

Table 8: Feasible technical solution

N°	Possible solutions	U_{in} (m/s)	T_{in} (°C)	x_{in}	$t_{dr}(h)$	$P_e(Kw)$	$E_c(j)$	$Q_{water}(l)$
1	Scenario 1 (Initial situation)	-	60	0,017	21	10	-	54
2	Scenario2 (FBD + classic parameters)	0,96	30	0,017	4,69	2,5	444,63 * 10^6	555
3	Scenario 3 (FBD + optimized parameters)	1.5	60	0,0001	0,633	2,5+ 20,05	160,55 * 10^6	555

It was observed that, when accounting for the energy consumption of both the equipment involved and the associated utilities, a reduction of 56% in total energy use was achieved, reaching up to 70% compared to Scenario 1.

• Economic evaluation:

The only additional investment considered was the purchase of a calibrator, costing 2,470.00 MAD. This cost was annualized over the estimated lifespan of the equipment (5 years). All financial values are referenced to the base year 2024 and expressed in constant dirhams. The comparative economic analysis demonstrates that Solution 3 (optimized FAB parameters) provides the best economic performance (Table 9), with a reduction in operational energy costs of 9.5% and 58.6% compared to Solution 1 (initial state) and Solution 2 (standard FAB configuration), respectively.

Table 9: Summarizes the cost data associated with each solution

Possible solutions	C_I	C_I^A	$OPEX_{an}$	$Costs_{an}$	% Energy cost	% Cost of labor	% Investment
1	0	0	20395,77	20395,77	30,18%	76,49,1%	0
2	2479,2	396,08	44177,51	44573,59	63,94 %	35,00%	0,89%
3	2479,2	396,08	18061,23	18457,31	12,90%	84,51%	2,14%

• Environmental Impact

Greenhouse gas (GHG) emissions are quantified by multiplying the amount of each emission source by its respective conversion factor. The emission factors utilized in this calculation are sourced from the Mohammed VI Foundation for Environmental Protection (fm6e, 2023). The findings are summarized in (Table 10) below. To facilitate impact assessment across a comprehensive range of scenarios, the worst-case FBD solution has been introduced. Notably, Solution 3, characterized by optimized FBD drying, demonstrates superior performance, yielding an emission level of $0,879 \text{ } t_{eq}CO_2/year$, compared to the initial solution at $3,696 \text{ } t_{eq}CO_2/year$ and the final solution employing standard parameters used within this workshop at $1628,57 \text{ } t_{eq}CO_2/year$. This indicates a significant reduction in GHG emissions of 80% and 50%, respectively, on drying. These results stand in contrast to existing literature, which posits that tray drying exerts a lesser environmental impact; this discrepancy can primarily be attributed to variations in the energy mix across different countries. Specifically, energy production methods, particularly for electricity, vary significantly between nations, leading to corresponding differences in conversion factors; for instance, Morocco has a conversion factor of 0.735 while France's is substantially lower at 0.08.

Table 10: Emissions by Scope and Technical Solution

Scope	1		2		3		Total (kg/ batch)	Total (kg/year)
Emission Source (Conversion Factor)	Electricity (kWh) (*0.735)		Fuel (kg) (*3.14)		Water (m^3) (*0.262)			
	Quantity	Emission	Quantity	Emission	Quantity	Emission		
Solution 1	210	154,35	0	0	54.10^{-3}	0,0142	154,01	3696,24
Solution 2	18,56	13,64	17,22	54.07,30	555.10^{-3}	0,1464	67,86	1628,57
Solution 3	23,06	16,95	6,21	19,524	555.10^{-3}	0,1464	36,62	878,89

8. Discussion

This study proposes an innovative approach to improving energy performance in pharmaceutical drying through advanced modeling of fluidized bed drying systems. By integrating a two-phase model, this method allowed the identification of optimal process parameters, leading to a reduction in energy consumption by -56.49% and -72.08% compared to Scenarios 1 and 2, respectively, and a decrease in greenhouse gas emissions by 76.24% and 46.05% compared to the same scenarios. These reductions in energy use and emissions were accompanied by operational cost savings of 9.5% and 58.6% relative to Scenario 1 (initial state) and Scenario 2 (standard FAB configuration). This performance demonstrates that transitioning to cleaner pharmaceutical production does not necessarily compromise economic outcomes; on the contrary, it can deliver substantial operational gains.

Our results are consistent with the findings of Majumder (Majumder., 2022), who showed that strict control over drying parameters can reduce energy consumption by 10% to 30%. More ambitiously, Chen (Zhengyun, 2024) reported savings of up to 71.7% in optimized batch production and 80% in continuous production using Process Analytical Technologies (PAT). However, our study goes further by integrating a multi-criteria analysis, simultaneously considering energy consumption, drying time, and labor costs, an approach rarely addressed collectively in the existing literature.

Another key strength of this study lies in the transferability of the methodology: the use of a simulation-based model makes it possible to adapt the system to other industrial configurations or product types, without being exclusively reliant on empirical trials. This ability to generalize is particularly critical for pharmaceutical manufacturers in the MENA region, who often face specific economic and technological constraints.

These actions, while already contributing to energy reduction, can be further enhanced by incorporating renewable energy sources, particularly in countries with high renewable energy potential. A recent study (Ibrahim, 2024), focused on hybrid solar dryers (HSD) applied to medicinal plants (lavender, basil, lemongrass, etc.), demonstrated that combining solar energy (via photovoltaic panels) with conventional electricity could reduce energy consumption by 37% to 54%, with a corresponding decrease in CO₂ emissions (up to 54% depending on the operating temperature), all while preserving product quality (essential oil content and microbial load optimized at 40°C). Even more promising, the exclusive integration of photovoltaic power (HSD-PVSE) led to a 100% reduction in CO₂ emissions and energy costs, with an annual financial yield estimated at over 15,000 EGP depending on the substituted energy source. These findings offer valuable perspectives for pharmaceutical drying processes, where energy requirements and operating temperature ranges can often be met through solar energy.

The convergence of such findings across different sectors highlights that a strategy combining low-carbon technologies with technical modeling is a relevant path for energy transition in the pharmaceutical industry. In Spain, for instance, up to 70% of the energy used by the pharmaceutical sector is of renewable origin, according to Farmaindustria's Director General, Juan Yermo (Farmaindustria, 2023). Despite these promising results, several limitations must be acknowledged. First, the current model relies on simplifying assumptions, such as uniform temperature and lack of product/process feedback, and on estimated granule parameters based on correlations. Moreover, implementing such approaches requires digital simulation expertise and energy metering infrastructure, which remain scarce in many pharmaceutical facilities across the MENA region. In this case study, the initial investment was modest because the process transfer was made from a tray dryer to an already installed fluidized bed dryer. However, this may not be the case in other facilities, where higher capital expenditure may pose a barrier. Additionally, this work focuses solely on drying and does not fall within a full life cycle assessment (LCA) framework.

Future analyses should include scenarios that integrate alternative energy sources, such as solar thermal collectors or electrification via renewables, and extend the scope to encompass the full life cycle of pharmaceutical products for a more comprehensive assessment of environmental impact. Energy hybridization in pharmaceutical drying, mirroring approaches in the agri-food sector, represents a promising avenue for enhancing the energy resilience of manufacturing sites.

This research highlights the value of an integrated optimization approach to pharmaceutical fluidized bed drying, combining dynamic modeling, carbon footprint reduction, and economic improvement. It underscores the benefits of a sector-specific strategy tailored to the industrial realities of the MENA region, and calls for deeper exploration of disruptive technologies such as hybrid solar dryers and renewable energy integration into critical pharmaceutical processes.

9. Policy discussion and recommendations

The results of this study highlight the importance of process-specific operational optimization in the energy transition of the pharmaceutical industry. Specifically, the optimization of fluidized bed drying (FBD), as implemented here, enabled up to a 58.6% reduction in operational costs and a 76% decrease in greenhouse gas (GHG) emissions, all while maintaining pharmaceutical product quality. These findings demonstrate that environmental and economic gains are achievable without major structural reform, provided the right technical and operational levers are targeted.

Based on these findings, we propose the following recommendations, organized by intervention level and stakeholder, following a logic of progressive scaling, from immediate procedural adjustments to systemic reforms.

9.1. Operational level: Direct improvement of existing processes

Stakeholders: Pharmaceutical manufacturers (production, engineering, and quality teams)

- Conduct targeted energy diagnostics by consumption unit, focusing particularly on thermal processes such as drying, HVAC, and compressed air systems.
- Use modeling and simulation tools (e.g., two-phase fluidized bed models) to determine optimal drying conditions (temperature, humidity, air velocity) tailored to the products being manufactured.
- Train operators and engineers in the interpretation of critical energy parameters and in preventive maintenance of drying equipment.

Our results show that simple adjustments of input parameters (velocity, temperature, humidity) can drastically reduce energy consumption and associated costs, which is in line with the findings from the literature.

9.2. Organizational level: Internal structuring of energy management

Stakeholders: Pharmaceutical industry executives

- Implement energy management systems aligned with ISO 50001, including performance indicators by equipment (e.g., kWh per kg of dried product).
- Develop dedicated investment plans for energy efficiency, including the replacement of obsolete equipment (e.g., FBD units, dehumidifiers, steam generators).
- Systematically integrate energy audits into internal quality audits and GMP or environmental certification processes.

The adoption of a structured energy management approach ensures the sustainability of operational-level gains while enhancing environmental compliance during certification audits.

9.3. Sectoral level: Incentives and support for energy transition

Stakeholders: Governments, health authorities, industrial federations

- Establish financial incentive mechanisms (e.g., subsidies, tax credits, energy savings certificates) for companies integrating low-carbon solutions (e.g., hybrid dryers, electrification of processes).
- Develop a regional industrial energy performance database, including pharmaceutical sectors, to guide policies and facilitate cross-country benchmarking.
- Incorporate energy performance criteria into pharmaceutical compliance programs, similar to the EMA's sustainability requirements.

Pharmaceutical manufacturers in the MENA region often operate in cost-constrained environments. Regulatory and economic incentives are therefore essential to offset the initial cost of adoption.

9.4. Academic and R&D level: Supporting process innovation

Stakeholders: Universities, research centers, funding agencies

- Support applied research projects aimed at modeling, optimizing, and electrifying energy-intensive processes, particularly drying, through targeted funding.
- Create academia-industry partnerships to co-develop digital energy management tools at the process level (e.g., digital twins, predictive AI, dynamic LCA).
- Integrate modules on energy sustainability into curricula for industrial pharmacy, process engineering, and pharmaceutical management programs.

The lack of technical expertise has been identified as a key barrier to the on-site adoption of energy performance innovations. Applied research and education can bridge this gap.

Therefore, rather than initiating heavy reforms or regulatory overhauls, this study advocates for a progressive, pragmatic, data-driven approach. In this context, the optimization of drying processes serves as an entry point for a broader energy transformation of the pharmaceutical industry. Coordinated efforts among industry (implementation), government (incentives), and academia (innovation) are essential for a successful transition toward more sustainable, resilient, and competitive pharmaceutical manufacturing.

10. Conclusion

The rational management of energy in the pharmaceutical industry is now a strategic lever for ensuring both economic and environmental sustainability, particularly in the context of a historical dependence on fossil fuels in the Arab world. This study has highlighted the sector's specific energy challenges, as well as local and international initiatives aimed at optimizing energy consumption without compromising drug quality and safety.

Our findings confirm that energy performance data for the pharmaceutical sector remain fragmented, especially in Arab countries, in contrast to better-documented industrial sectors such as agri-food. This underscores the urgent need to strengthen applied research, document existing practices, and implement systematic energy audits, as already mandated by the legislative frameworks of some countries, such as Morocco. The case study conducted on the optimization of pharmaceutical drying, a highly energy-intensive process, concretely illustrates that targeted technical adjustments can lead to significant reductions in energy consumption (up to 58.6%) and greenhouse gas emissions (up to 76%) without requiring major investments, while maintaining pharmaceutical quality standards. These findings demonstrate the relevance of integrating energy analysis into the development and industrial transfer phases of pharmaceutical production. However, the effectiveness of such initiatives remains limited in the absence of a structured, sector-wide strategy. The diversity of approaches, the lack of standardized indicators, and the risk of greenwashing hinder inter-site comparisons and the monitoring of performance. It is therefore imperative to define a sector-specific framework for pharmaceutical manufacturing, including: (i) harmonized indicators, (ii) clear functional units, and (iii) integrated energy management systems (such as ISO 50001).

Based on this framework, three complementary pathways for action can be proposed:

Short-term: Promote on-site operational optimization through procedural adjustments, targeted training, and energy diagnostics.

Medium-term: Structure energy management at the facility level through the implementation of standardized systems, supported by incentive policies (e.g., subsidies, tax relief).

Long-term: Drive a structural transformation of the sector through the creation of energy performance databases, integration of sustainability criteria into pharmaceutical regulations, and

development of cross-sectoral models inspired by other industries.

Finally, this study opens concrete research perspectives to support the transition:

- Assessing the energy maturity of pharmaceutical manufacturing facilities;
- Analyzing the sector's carbon footprint through a life cycle assessment (LCA) approach;
- Testing integrated energy management models tailored to the industrial realities of the Arab world.

In conclusion, this study demonstrates that it is possible to make the Arab pharmaceutical industry greener, more competitive, and more resilient, provided that local action is rigorously linked to a coordinated global strategy.

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