People’s Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Mohamed Khider University of Biskra
Faculty of Sciences and Thechnology
Department of Mechanical Engineering

Ref: ....

THESIS

In Candidacy for the Degree of
DOCTOR IN MECHANICAL ENGINEERING
Option: Energetics

TITLE

Study and Analysis of Air Conditioning in Industrial Poultry Buildings Using Renewable Energy Systems in the Biskra Region

Presented by **Yousra BOUTERA**

Defended on: 14/10/2025

In front of the jury composed of:

Dr. Belhi GUERIRA	**Professor**	**President**	**University of Biskra**
Dr. Noureddine MOUMMI	**Professor**	**Supervisor**	**University of Biskra**
Dr. Abdelhafid MOUMMI	**Professor**	**Examinator**	**University of Biskra**
Dr. Abdelhafid BRIMA	**Professor**	**Examinator**	**University of Batna**

2024/2025

République Algérienne Démocratique et Populaire
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique
Université Mohamed Khider de Biskra
Faculté des Sciences et de la Technologie
Département de Génie Mécanique

Ref: ....

THÈSE

En vue de l'obtention du diplôme de

DOCTEUR EN GÉNIE MÉCANIQUE

Option : Énergétique

TITRE

Etude et analyse du conditionnement des bâtiments industriels de volailles par des systèmes énergétiques renouvelables dans la région de Biskra

---

Présentée par : **Yousra BOUTERA**

Soutenue le : 14/10/2025

Devant le jury composé de :

Dr. Belhi GUERIRA	**Professeur**	**Président du jury**	**Université de Biskra**
Dr. Noureddine MOUMMI	**Professeur**	**Rapporteur**	**Université de Biskra**
Dr. Abdelhafid MOUMMI	**Professeur**	**Examinateur**	**Université de Biskra**
Dr. Abdelhafid BRIMA	**Professeur**	**Examinateur**	**Université de Batna**

2024/2025

Acknowledgments

All praise is due to Allah, whose grace and guidance have carried me through the challenges and triumphs of this academic journey. What began as a question became a path, and that path, with patience, effort, and support, led to this moment.

This thesis is not the product of a solitary effort, but the outcome of collective wisdom, encouragement, and generosity from many individuals to whom I owe heartfelt gratitude.

I would like to express my heartfelt gratitude to my supervisor, **Prof. Moummi Noureddine**, for his steady support, insightful feedback, and the trust he placed in me, which allowed this research to develop with both independence and depth. My sincere thanks also go to **Dr. Nora Boultif** for proposing the research topic and providing continuous guidance, valuable advice, and constant encouragement throughout the work. I am equally grateful to **Dr. Amar Rouag** for his kind mentorship, critical insights, and thoughtful guidance, which significantly enhanced the quality of this study and my growth as a researcher.

I am especially honored to thank the esteemed members of the examination committee: **Prof. Guerira Belhi**, for graciously chairing the committee. **Prof. Moummi Abdelhafid**, **Prof. Brima Abdelhafid**, whose scholarly input and detailed feedback were immensely valuable and enriched this thesis in ways I could not have achieved alone.

To **Prof. Muslum Arici** of Kocaeli University, I express my warmest thanks for the opportunity to work in his laboratory. His professionalism, collaborative spirit, and scientific generosity greatly benefited my research and broadened my perspective.

My gratitude also extends to all the professors who shaped my academic path and contributed to my formation; every class, every conversation, and every challenge left a mark I carry forward.

Finally, to the pillars of my life, my beloved parents, **Hocine** and **Mokhtari Fatima**, no words can capture the depth of my love and gratitude. Your sacrifices, prayers, and unconditional love are the silent forces behind every page of this work. This achievement belongs to you as much as it does to me.

To my dear sister **Amina**, whose kindness, faith, and encouragement have been a constant source of light and motivation, and to my beloved brothers **Aymen** and **Anis**, whose unwavering support, humor, and pride have lifted my spirit in difficult times and made this journey brighter, thank you for always believing in me.

May this humble effort contribute to the greater good of science, serve future researchers, and be a source of benefit and inspiration, God willing.

Abstract:

This thesis presents a comprehensive study of the energy performance of industrial poultry houses, which are among the highest energy consumers due to the high bird density and the constant need to maintain optimal indoor climate conditions. The aim of this study is to assess the potential of an earth-air heat exchanger (EAHE) system as a renewable energy technology to reduce energy consumption and its environmental impact.

The study begins with a detailed analysis of the thermal requirements of an industrial poultry house in Biskra, a region with a hot desert climate. A comprehensive thermal model was developed, accounting for heat gains and losses through the building envelope, solar radiation, and internal heat from birds, workers, and equipment. Results showed that the cooling load reached 448.96 kW, which is 4.5 times higher than the heating load of 99.66 kW, highlighting the significant cooling demand in such a climate.

The EAHE system was independently designed and studied to evaluate its heating and cooling potential before being integrated into the building. Results demonstrated that the system could meet 45% of the heating needs and 35% of the cooling needs, significantly reducing CO_2 emissions. Numerical simulations were also conducted to analyze system performance post-installation and identify the optimal scenario for air inlet positioning and configuration. The optimal scenario improved internal air distribution.

The study concludes that the EAHE system is an environmentally friendly, energy-efficient, and economically viable solution, especially as a supplementary system in large industrial buildings or as a primary system in smaller facilities.

Keywords: Poultry house; Cooling demand; Heating demand; Renewable energy technologies; Earth air heat exchanger; Soil temperature; Computational fluid dynamics.

Résumé :

Cette thèse présente une étude approfondie sur la performance énergétique des bâtiments industriels d'élevage de volailles, parmi les plus grands consommateurs d'énergie en raison de la forte densité d'animaux et de la nécessité constante de maintenir des conditions climatiques intérieures optimales. L'objectif de cette étude est d'évaluer le potentiel d'un système d'échangeur de chaleur air-sol (EAHE) comme source d'énergie renouvelable afin de réduire la consommation énergétique et son impact environnemental.

L'étude débute par une analyse détaillée des besoins thermiques d'un bâtiment avicole industriel à Biskra, une région au climat désertique chaud. Un modèle thermique complet a été développé, tenant compte des gains et pertes de chaleur à travers l'enveloppe du bâtiment, du rayonnement solaire, ainsi que des apports internes dus aux animaux, aux occupants et aux équipements. Les résultats ont montré que la charge de refroidissement atteignait 448,96 kW, soit 4,5 fois plus que la charge de chauffage de 99,66 kW, soulignant la forte demande en refroidissement dans un tel climat.

Le système EAHE a été conçu et étudié indépendamment pour évaluer son potentiel de chauffage et de refroidissement avant son intégration dans le bâtiment. Les résultats ont montré que le système pouvait couvrir 45 % des besoins en chauffage et 35 % des besoins en refroidissement, avec une réduction significative des émissions de CO_2. Des simulations numériques ont également été réalisées pour analyser les performances du système après son installation et déterminer le meilleur scénario pour le positionnement et la configuration des entrées d'air. Le scénario optimal a permis d'améliorer la distribution uniforme de l'air intérieur.

L'étude conclut que l'échangeur de chaleur air-sol est une solution écologique, éconergétique et économiquement viable, particulièrement en tant que système d'appoint pour les grands bâtiments industriels ou comme système principal dans des installations de plus petite taille.

Mots-clés: Poulailler industriel; Demande de refroidissement; Demande de chauffage; Technologies d'énergie renouvelable; Échangeur de chaleur air-sol; Température du sol; Simulation numérique.

الملخص:

تتناول هذه المذكرة دراسة شاملة لأداء الطاقة في حظائر الدواجن الصناعية، التي تعد من أكثر المباني استهلاكًا للطاقة نتيجة لكثافة الطيور العالية والاحتياج المستمر لضمان ظروف مناخية داخلية ملائمة. تهدف هذه الدراسة إلى تقييم إمكانية استخدام نظام مبادل حراري أرض-هواء (ECSA) كمصدر للطاقة المتجددة بهدف تقليل استهلاك الطاقة وتقليل تأثيراتها البيئية.

بدأت الدراسة بتحليل دقيق للاحتياجات الحرارية لمبنى دواجن صناعي في مدينة بسكرة ذات المناخ الصحراوي الحار، حيث تم تطوير نموذج حراري شامل يأخذ بعين الاعتبار كسب وفقد الحرارة عبر غلاف المبنى، بالإضافة إلى الإشعاع الشمسي والمكاسب الداخلية من الطيور والمعدات. أظهرت النتائج أن حمل التبريد بلغ 448.96 كيلوواط، وهو أعلى بـ 4.5 مرات من حمل التدفئة البالغ 99.66 كيلوواط، مما يدل على الحاجة الكبيرة للتبريد في مثل هذا المناخ.

تم تصميم نظام المبادل الحراري أرض-هواء ودراسته بشكل مستقل لتقييم قدرته على التدفئة والتبريد قبل تركيبه في المبنى. بينت النتائج أن النظام قادر على تغطية 45% من احتياجات التدفئة و35% من التبريد، مع تقليص كبير لانبعاثات ثاني أكسيد الكربون. كما تم إجراء محاكاة عددية لتحليل أداء النظام بعد تركيبه في المبنى، وتحديد أفضل سيناريو لتركيب المداخل الهوائية (الموضع والتكوين الأنسب). أظهر أن اختيار السيناريو المثالي يساهم في تحسين توزيع الهواء الداخلي بشكل متجانس.

خلصت الدراسة إلى أن النظام المعتمد يُعد حلاً بيئيًا وطاقويًا واقتصاديًا واعدًا، خاصة إذا ما استُخدم كنظام مساعد في المباني الصناعية الحديثة ذات الحجم الكبير، أو كنظام رئيسي في المنشآت الصغيرة.

الكلمات المفتاحية: مباني الدواجن الصناعية؛ الطلب على التبريد؛ الطلب على التدفئة؛ تقنيات الطاقة المتجددة؛ المبادل الحراري أرض-هواء؛ درجة حرارة التربة؛ ديناميكيات السوائل الحسابية.

TABLE OF CONTENTS

List of Figures

List of Tables

Nomenclature

A	Surface	m^2
D	Diameter	m
E_{CO2}	CO_2 emissions	kg
E_{elec}	Electricity consumption	kWh
EF_{elec}	Emission factor of electricity consumption	$kgCO_2/kWh$
EF_{fuel}	Emission factor of fuel	$kgCO_2/L$
E_{save}	Energy saving	kWh
f	Friction factor for smooth pipe	—
It,b	Total base radiation for the month, latitude, and orientation considered	W/m^2
It,b(40)	Total base radiation for July, latitude 40° N, and the orientation considered	W/m^2
K	Surface transmission coefficient	$W/(m^2 \cdot °C)$
kg	Linear transmission coefficient of the low floor or buried wall; kg = 1.75 [25]	$W/(m \cdot °C)$
kl	Linear transmission coefficient	$W/(m \cdot °C)$
l	Internal length of the thermal bridge	m
L	Tube length	m
$\dot{m}$	Mass flow rate	kg/s
m_{chick}	Chicken mass	kg
M_{CO2}	CO_2 mitigation	kg
M_{fuel}	Volume of fuel consumed	L
N	Hourly air renewal rate for the unheated room volume	h^{-1}
Nu	Nusselt number	—
Per	Perimeter of pipe	m
Pr	Prandtl number	—
qv	Minimum ventilation rate	m^3/h
r	Radius	m
R	Thermal resistance	$m^2 \cdot °C/W$
Re	Reynolds number	—
T	Temperature	°C
T_{amp}	Surface temperature amplitude	°C
T_{au}	Temperature reduction coefficient	—
T_{avrg}	Average surface temperature	°C
t	Time	day
t_0	Day of the year corresponding to the minimum surface temperature	—
V	Volume	m^3
Z	Depth	m

Symbol

$\Phi_{elec,m}$	Heat gain due to machines driven by an electric motor	W
Φ_G	Heat loss through the floor	$W \cdot °C^{-1}$
Φ_{GW}	Heat gains through a floor in contact with the ground	W
Φ_I	Internal heat	W
Φ_L	Heat loss through thermal bridges	$W \cdot °C^{-1}$

Φ_{lat}	Latent heat gains	W
Φ_{light}	Heat gain by lighting	W
Φ_{OW}	Heat gains through opaque walls	W
ϕ_R	Heat loss due to ventilation and infiltration	$W \cdot °C^{-1}$
Φ_{RS}	Air loss due to wind	$W \cdot °C^{-1}$
Φ_{RV}	Losses due to the normal operation of the ventilation devices	$W \cdot °C^{-1}$
Φ_S	Surface heat loss through the walls in contact with the outside	$W \cdot °C^{-1}$
Φ_{sen}	Sensible heat gains	W
Φ_T	Heat loss due to transmission through the building envelope	$W \cdot °C^{-1}$
Φ_U	Heat loss through walls in contact with unheated rooms	$W \cdot °C^{-1}$
$\Delta t_e(t)$	Equivalent temperature difference at time *t*	°C
$\Delta t_{es}(t)$	Temperature difference equivalent to hour *t* considering that the wall is in the shade	°C
$\Delta t_{em}(t)$	Equivalent temperature difference at time *t* for the orientation of the wall considered	°C
ν	Kinematic viscosity of air	m^2/s
λ	Thermal conductivity	$W/(m \cdot K)$
φ	Thermal diffusivity of the soil	m^2/h
η	Efficiency of the motor	—
α	Absorption factor of the wall	—

Subscripts

A	air	—
b	base	—
ext	external	—
int	internal	—
lat	Latent	—
m	medium	—
S	soil	—
sen	sensitive	—

GENERAL INTRODUCTION

Contents of Introduction

General Introduction

0.1 Overview

Energy is a pivotal element in the progress and prosperity of nations, as it is deeply intertwined with all aspects of human life, whether essential or supplementary. However, excessive reliance on traditional energy sources threatens national security stability due to market volatility, price fluctuations, and susceptibility to geopolitical developments and global crises, such as pandemics, economic recessions, and international conflicts, as well as the associated negative environmental impacts. This has driven many countries to adopt strategies aimed at diversifying energy sources by transitioning toward renewable and clean energy to reduce dependence on fossil fuels and mitigate their environmental and economic risks [1, 2].

The poultry sector is among the most energy-intensive agricultural industries. Energy is used to regulate the internal environment of farms, including heating, cooling, ventilation, lighting, feed processing and distribution, and waste management. Due to poultry's high sensitivity to environmental conditions, heating and cooling costs represent the largest share of total energy consumption, particularly in broiler production, which accounts for approximately 75.5% of total electrical energy and 96.3% of thermal energy required to maintain optimal growth and production conditions [3].

As with many critical sectors, the poultry industry's reliance on traditional energy sources and volatile markets directly threatens food security. Especially since poultry meat is one of the most widely consumed sources of animal protein globally, accounting for 40.6% of total meat production [4], due to its availability and low cost. Which, in turn, drives increased global demand, according to statistics from the Food and Agriculture Organization (FAO) [5], global poultry meat production reached 144 million tons in 2023, with the sector experiencing a remarkable growth of 1509% between 1961 and 2023 (**Figure 0.1**).

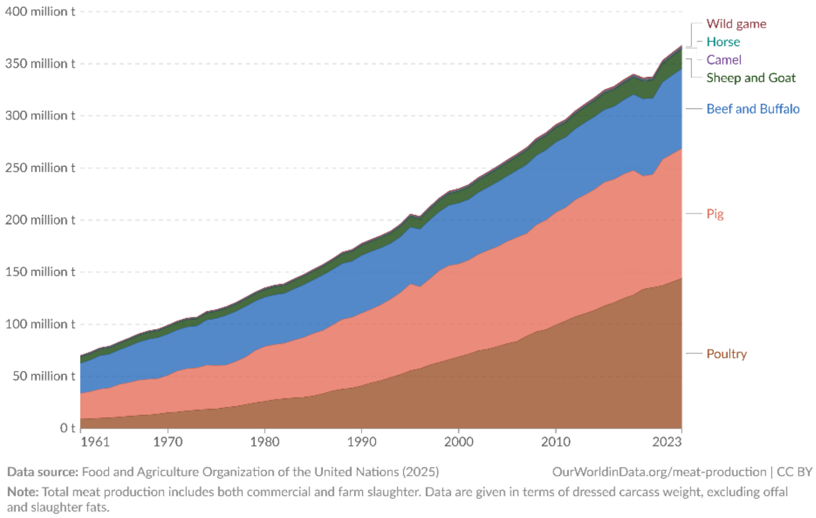


Figure 0.1. Meat production by livestock type, 1961 to 2023 [5].

At the national level, Algeria is classified among the poultry-producing countries and has witnessed significant growth in this sector in recent years (**Figure 0.2**), with production reaching approximately 458,094 tons in 2023 [6]. According to the national statistics office [7], poultry meat is the primary source of domestic animal protein. In response, the Algerian government and relevant authorities are implementing a roadmap to revitalise and modernise the poultry industry. This plan includes short, medium, and long-term measures focused on improving production efficiency, regulating the market, and increasing production to enhance national food security.

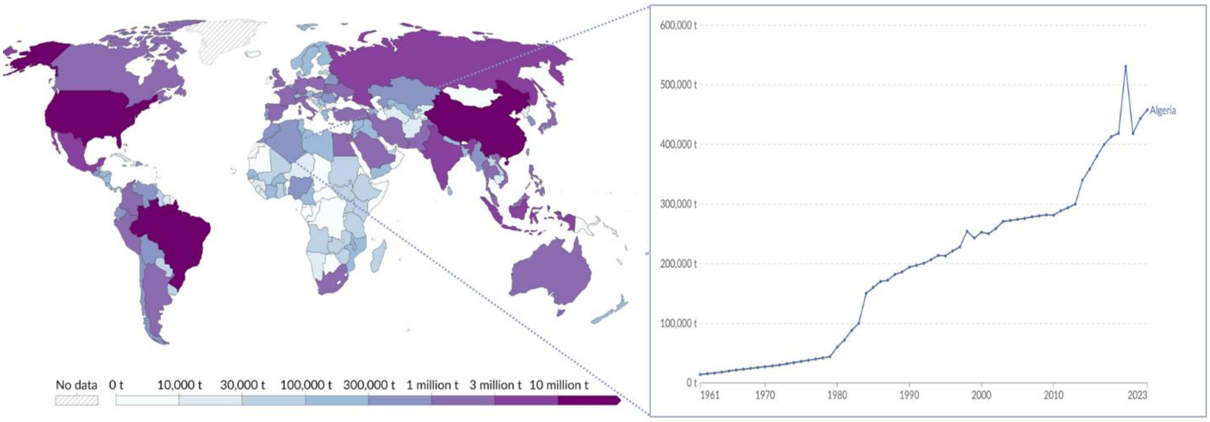


Figure 0.2. Global poultry production [6].

0.2 Research Motivation

Global and national statistics highlight the growing strategic importance of the poultry sector, which is no longer viewed simply as a primary source of animal protein but as a fundamental pillar of the global food security system. This sector provides an accessible and affordable food source, making it pivotal in meeting the population's nutritional needs.

Due to accelerating local and global demand, the poultry industry has witnessed steady growth, leading to a significant increase in energy consumption within the agri-food production sector. This expansion, while necessary, has contributed to the sector's increasing environmental impact, particularly in terms of Greenhouse Gas (GHG) emissions, which has become an undeniable environmental challenge.

In light of these transformations, two critical dimensions become urgent for decision-makers and researchers: First, the need to enhance the resilience of the poultry sector in the face of fluctuations in global energy prices and markets, which could threaten its economic sustainability. Second, mitigating the sector's growing carbon footprint by adopting sustainable and environmentally friendly practices and technologies.

From this perspective, the industry must adopt a balanced approach that combines securing food supplies and ensuring environmental sustainability. This constitutes the general framework for this doctoral thesis, entitled "***Study and Analysis of Air Conditioning in Industrial Poultry Buildings Using Renewable Energy Systems in the Biskra Region***" This study seeks to align the goals of the national transition to sustainable energy with the requirements of developing the poultry sector. It focuses specifically on exploiting shallow geothermal energy through the Earth Air Heat Exchanger (EAHE) as an alternative and sustainable solution for air conditioning poultry buildings. This low-emission technology is a promising option compared to traditional air conditioning systems that rely on electricity or fossil fuels, despite its current limited use in Algeria.

0.3 Problem statement

Industrial poultry houses have complex structures, primarily due to their function of accommodating large numbers of birds that are highly sensitive to environmental conditions.

Poultry have unique thermoregulatory mechanisms that differ from humans, and their thermal needs evolve significantly with age. Consequently, the internal conditions of these buildings, such as temperature, humidity, and ventilation, must be continuously adjusted to ensure optimal conditions and productivity throughout their growth cycles.

Any deviation from ideal environmental conditions can result in high mortality rates or reduced productivity, leading to considerable economic losses for farmers. To maintain these conditions, traditional systems for heating and cooling are often used, which are energy-intensive and contribute significantly to operating costs and environmental degradation, especially in regions dependent on fossil fuels.

At the same time, the poultry industry contributes to environmental pollution through high energy consumption, raising concerns about its sustainability.

In light of these challenges, the main problem addressed by this research is: How can the thermal and energy performance of industrial poultry buildings be improved using renewable energy sources, especially by exploiting available renewable resources to improve production conditions in industrial livestock buildings, while reducing the energy and environmental footprint of the poultry sector?

0.4 Research Scope and Limitations

This study aims to achieve the following objectives:

a) <u>Theoretical objective:</u>

- Provide a comprehensive overview of the various energy-related aspects of the poultry sector. This will serve as a solid scientific foundation and a unified reference point for researchers and stakeholders interested in the field of energy efficiency and sustainability in poultry production.

b) <u>Practical and numerical objectives:</u>

- Develop a thermal model tailored to the Algerian context for calculating industrial poultry buildings' heating and cooling requirements.
- Investigate the contribution and effectiveness of the Earth-to-Air Heat Exchanger (EAHE) system as an independent heating and cooling solution specifically designed for modern industrial poultry houses.
- Compare the performance of the proposed EAHE system with conventional Heating, Ventilation, and Air Conditioning (HVAC) systems currently used in poultry farms, with a focus on energy savings, consumption reduction, and environmental impact mitigation.
- Assess the actual performance of the EAHE system when integrated into a poultry building, evaluating its impact on improving thermal and air distribution uniformity, particularly in addressing the issue of high internal temperatures in the rear part of the building.

While this study aims to provide accurate and applicable results, several limitations should be acknowledged:

- Geographic scope: The study was conducted in the Biskra region of Algeria, and the findings are based on the local climatic characteristics.
- Climatic and temporal conditions: The investigation was carried out during specific time periods selected to reflect the most extreme climatic scenarios, particularly those representing peak heating or cooling demands.
- Economic assessment: The economic analysis is based on actual costs and market prices during the study period.

0.5 Research Methodology

This study follows a structured and sequential methodological approach to ensure a scientifically sound investigation into the energy performance and sustainability potential of poultry houses in Algeria. The methodology is composed of the following stages:

a) Comprehensive literature review

- Analysis of the current state of art in poultry building.
- Review of conventional HVAC systems used in poultry farms and their challenges and limitations.
- Study and analysis of sustainability strategies directed towards poultry farms.
- Identification of key research gaps in this field.

b) Field study and data acquisition

- On-site visits to the industrial farm of Salem Avicole to collect necessary data.
- Collection of geometric and constructional data: dimensions, materials, and existing systems.
- Monitoring of internal and external climate data across different periods.

c) Selection of case study and boundary conditions

- Assessment of extreme climatic conditions potentially faced by poultry houses.
- Cross-analysis of field data to select the building that reflects the most critical thermal demands (heating and cooling).
- Select the case study building and the operating conditions.

d) Thermal performance analysis

- Calculate the building's heating and cooling loads using analytical and numerical methods.

e) Study of the EAHE system as an independent unit before integration.

- Determination of the optimal burial depth in the soil.
- Identification of the most energy and cost-optimal dimensions.

- Comparison of the EAHE system's performance with conventional HVAC systems currently used in poultry houses.

f) EAHE integration and simulation within the poultry building

- The optimal configuration for the integration of the EAHE into the poultry house.
- Analysis of indoor thermal environment improvements: air distribution uniformity, thermal stratification reduction, and comfort enhancement.
- Quantitative evaluation of energy savings, peak load reduction, and environmental impact mitigation.

Each of these steps is built upon the findings and outputs of the previous one, ensuring a coherent and data-driven research process.

0.6 Thesis Structure

Based on the adopted research methodology, this thesis is structured into four main chapters, in addition to a general introduction and a concluding chapter that presents conclusions and recommendations.

❖ **General Introduction**

The introduction aims to highlight the significance of this work, present its main objectives, and define the research problem. It also outlines the study's structure and scope.

❖ **Chapter 1: Comprehensive Literature Review**

This chapter discusses the various advanced strategies and technologies used in designing and managing poultry houses, as reported in scientific and technical literature. It categorises these approaches and emphasises the most effective means for achieving sustainable and productive poultry farming.

❖ **Chapter 2: Thermal Behaviour of an Industrial Poultry House**

The aim of this chapter is to analyse the thermal behaviour of the studied poultry building and identify appropriate sustainable strategies. It includes the estimation of the building's heating and cooling needs under real operating conditions.

❖ **Chapter 3: Numerical Modelling of the Earth Air Heat Exchanger**

This chapter focuses on applying Net Zero Energy Poultry Building (NZEPB) strategies, utilising Renewable Energy Technologies (RETs), to meet the thermal requirements of modern poultry house. It includes modelling the EAHE system as an independent unit for potential use in the studied poultry house.

❖ **Chapter 4: Integration of the EAHE System in the Poultry House**

This chapter aims to assess the EAHE system's contribution to enhancing indoor air quality and airflow uniformity within the poultry house after integration. It also aims to determine the optimal design and layout of the system (e.g., separated or integrated inlets) to maximise efficiency. Furthermore, this chapter examines the system's effectiveness in addressing the overheating problem commonly observed in the rear part of the building.

- **Conclusions and Recommendations**

This section comprehensively summarises the main findings, highlights the scientific contributions of the study, and provides recommendations and potential directions for future work

CHAPTER 1

COMPREHENSIVE LITERATURE REVIEW

Contents of Chapter 1

Comprehensive Literature Review

1.1 Chapter Outline

This chapter will discuss various advanced strategies and techniques for designing and managing poultry houses as reported in scientific and technical literature. The discussion will focus on three axes, highlighting the most important paths toward sustainable and productive poultry farming.

- First axis analyses the key factors that must be maintained inside poultry buildings, emphasising the critical roles of ventilation, heating, and cooling. This section addresses their direct impact on productivity and energy consumption, highlighting the importance of improving these factors for healthy and efficient poultry production.
- Second axe explores typical management strategies and conventional heating, ventilation, and air conditioning (HVAC) systems, pointing out their challenges, limitations, and adverse environmental effects.
- Third axis deals with sustainable management strategies for poultry buildings and integrating renewable energy technologies. This includes discussions on energy efficiency and conservation, in addition to various innovations in using renewable energy, and an evaluation of their contribution to improving production performance and reducing the environmental footprint of poultry farming.

By the conclusion of this chapter, the reader will have a comprehensive understanding of the challenges and opportunities associated with poultry farm management and how modern technologies and best practices can contribute to achieving an ideal environment for raising poultry and reducing its environmental impact.

1.2 Key Factors in Poultry Buildings

1.2.1 Poultry Thermoregulation Mechanism

Poultry are sensitive creatures to their surroundings environment, and they have unique ways of dealing with environmental changes to maintain the thermal balance of their body between 40 to 41 °C [8], as they use a set of mechanisms to manage and dissipate heat, including conduction, convection, radiation, and evaporation through respiration, in addition to the feathers that adjust their direction to regulate the insulation process. They inflate them to increase insulation in cold weather or flatten them against their body to reduce insulation and allow for better heat dissipation.

In cases of heat stress, birds also change their feeding behaviour, as they reduce consumption when ambient temperatures exceed their comfort range, intending to reduce internal metabolic heat production, while at temperatures below the comfort range, they tend to increase food consumption, which is directed to produce more internal heat [9]. These behavioural adaptations cost breeders, as food consumption is directed toward regulating the body's temperature rather than growing muscle mass, thereby reducing production efficiency.

Just as birds are affected by their environment, their physiological responses, in turn, affect environmental factors such as rising temperatures, humidity, and gas concentrations, thus requiring more thermal management of the building, which translates into additional energy consumption. Therefore, understanding the thermoregulation mechanisms of birds and providing appropriate conditions for raising them may contribute effectively to directing this industry toward sustainability.

1.2.2 Basic Requirements for Poultry Housing Climate Control

According to specialised research in the field of poultry farming, indoor temperature, humidity, gas concentration, and velocity are among the key factors that affect the comfort and health of poultry. In their comfort zone, these animals do not need to expend energy to maintain or adjust their body temperature; instead, this energy is redirected toward promoting muscle growth. Ensuring comfort conditions during the breeding stages enhances production while reducing the impact of thermoregulation behaviours on energy consumption and the internal environment of the farm. Therefore, research in this field must prioritise understanding these aspects, especially in light of the change in the comfort range of birds according to their age, which requires continuous monitoring and improvement of the internal environment of the building throughout the birds' life cycle.

Temperature is one of the most critical factors controlling poultry building management. As birds develop adaptive strategies to regulate their body temperature, the ambient temperature requirements of the building vary, which requires providing a heating and cooling cycle throughout the growth period.

In the first week, the birds are unable to regulate their body temperature, and this process necessitates a mild environment ranging from 33 to 30°C. As the development of thermoregulation mechanisms in their bodies and the growth of feathers occur, these requirements reduce, and their comfortable temperatures gradually decrease to a range of 26-24°C during the third to fourth week, and by the fifth to sixth week, they require a comfort range between 21 and 18 °C [8, 10, 11].

According to the studies, the optimal relative humidity range, recommended by many researchers, ranges between 60% and 80% during the brooding period and between 50% and 70% in the other growth stages [12, 13]. In addition to its effect on the thermal comfort of birds, this factor also controls the risks of litter, affecting the growth and spread of microbes. The litter becomes too wet and anaerobic in high-humidity conditions, increasing bacterial and mould growth and ammonia emissions. Conversely, in dry conditions, litter can become very dry and powdery, emitting minute, irritating particles into the atmosphere, increasing the potential for disease transmission and indoor air pollution [14, 15].

On the other hand, birds and their litter produce significant emissions of polluting gases, such as ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen sulfide (H_2S). These gases negatively impact birds, humans, and the environment. Therefore, it is recommended that the concentration of these gases not exceed 20, 3000, 10, and 0.5 ppm, respectively [13, 16].

The previously mentioned parameters can be controlled by ventilation and the constant renewal of the building air, thereby improving the air quality. Studies show the optimal air velocity range between 2 and 3 $m.s^{-1}$ [17, 18].

To achieve these required internal conditions, the farmers adhere to strict management standards based on using a set of heating, ventilation, and air conditioning (HVAC) systems that operate according to the thermal needs required at each growth stage.

1.3 Conventional Poultry Building and Management Strategies

1.3.1 Conventional Building HVAC Systems

Conventional strategies for managing a poultry house include using cooling, heating, and ventilation systems that depend on non-renewable energy sources, such as electricity and fossil fuels. These systems are regarded as the primary components of the structure since they are the main controller of its internal climate.

There are three types of heating systems used in poultry farms: radiators, forced air heaters, and heat exchanger systems.

Heating radiators are characterised by their ability to spread radiant energy in the air through electromagnetic waves. The radiant energy is absorbed and converted into heat when it collides with the bird's body. Meanwhile, forced air heaters use the energy released by the combustion process to heat the air. The unit's fans then distribute the warm air throughout the house. These radiators are usually installed on one side of the house, allowing for better heat distribution throughout it [19, 20]. On the other hand, the heat exchanger system's principle lies in heating the cold air entering the house with the hot air leaving it. The warm air flows from the house to the heat exchanger, while the cold outside air flows to the heat exchanger, where heat transfer (counterflow) in the heat exchanger leads to the cold outside air being heated by the warm air coming from the house [21].

Regarding ventilation systems in poultry houses, breeders and specialists in this field rely on two ventilation methods: natural and mechanical ventilation.

Natural ventilation is achieved by opening the building as much as necessary, allowing outside breezes and internal convection currents to circulate air into and through the building. This is often achieved by lowering side curtains, shutters, or doors. This type of ventilation is only acceptable when outside conditions are similar to those required inside the poultry house [20].

In hot weather, mechanical ventilation is recommended, where fans are placed to distribute air into and across the building with a higher airflow rate. Tunnel ventilation is one of the most important categories of mechanical ventilation recommended in cases of high temperatures. This ventilation method draws significant amounts of air down the entire length of the building, allowing rapid air renewal. This causes high-velocity airflow over the birds, creating a cool air stream that helps them rest. In addition, this type of ventilation has the ability to control the amount of air and the speed of its flow into the building by controlling the number of operating fans [9, 22, 23].

In cases where ventilation is insufficient to reduce indoor temperatures, cooling systems, which are evaporative cooling, are often used. The basis of this system lies in lowering the air temperature through the process of water evaporation, which enhances the ambient conditions and improves the effectiveness of tunnel ventilation. Evaporative cooling can be classified into two main types: water spray and evaporative cooling pad.

In water spray systems, the inlet air is cooled by evaporating water droplets obtained by pumping through spray nozzles located near the air inlets. On the other hand, direct evaporative cooling pad systems include mist nozzles that humidify the pads, and when air is drawn through them toward the house, the water evaporates, causing the temperature to drop [20, 24].

1.3.2 Challenges and limitations of Conventional HVAC Systems.

Although these HVAC systems may cover most of the thermal requirements of poultry houses, they consume the most significant proportion of the total thermal and electrical energy in poultry houses. According to Cui et al. [25], this percentage may range between 96.3% and 75.5%, respectively. Even if these percentages may change from one house to another and from one climate to another, they remain the highest percentage of the total energy consumed in poultry houses, which also has side effects on the environment.

In addition, the performance of these systems may sometimes be limited compared to their energy consumption. For example, in desert climates that require cooling, these technologies may face some challenges associated with weather fluctuations, such as sandstorms or air pollution, which reduce the system's efficiency or may constitute an obstacle to its use. On the other hand, in humid climates, it will be difficult to benefit from the performance of evaporative cooling due to its reduced cooling capacity and high humidity levels inside the poultry house, which leads to production losses.

On the other hand, despite the efficiency of some heating systems in providing the appropriate temperatures, they affect the indoor air quality, such as forced air heaters that depend on combustion, which raises the humidity and carbon dioxide levels in the indoor environment. While radiant heaters and heat exchanger heating systems are known for their limited efficiency in providing the necessary heating [21].

The previous challenges have motivated many researchers to search for solutions and strategies that enhance the efficiency and sustainability of this field.

1.4 Net-Zero-Energy Poultry Buildings Strategies: A Literature Review.

With increasing awareness of the environmental impacts of the poultry sector and its high energy consumption, researchers are increasingly focusing on finding solutions to achieve sustainability in this vital field. This section aims to review a set of strategies that have been studied in the literature to achieve sustainability in the poultry sector, which can be divided into three main strategies:

- Energy saving in buildings: research in this field has focused on reducing energy consumption by improving the design of buildings and structural elements that affect energy efficiency. This includes improving the building envelope and using effective insulation materials.
- Energy efficiency in buildings: this strategy aims to improve the energy efficiency of HVAC systems in poultry buildings. This includes finding the optimal dimensions and locations to get the most benefit from them.
- Renewable energy technologies: this strategy focuses on integrating renewable energy sources into climate control systems inside poultry buildings, which contributes to reducing the dependence on non-renewable energy sources and minimising the carbon footprint of this sector.

Studying the thermal behaviour of poultry buildings is essential to achieving efficient and sustainable energy strategies. Understanding how heat is transmitted, stored, and distributed within buildings can significantly improve bird comfort and health, energy efficiency, and reduce environmental impacts. This field is closely related to energy saving in buildings, improving energy efficiency, and exploiting renewable energy sources, which makes it an indispensable step in the design and operation of modern poultry farms. Therefore, this review was organized on the following basis: analysis of the thermal behavior of the building, study of energy-saving strategies in buildings, energy efficiency in buildings, and exploitation of renewable energy technologies, as shown in **Figure 1.1**.

Scientific search platforms such as Scopus and Google Scholar were used to collect relevant literature using appropriate keywords. The review included peer-reviewed research articles, review papers, and doctoral theses related to the strategies mentioned that were published in the last 25 years, i.e., from 2000 to 2025. In addition, the study covered the fields of engineering, energy, agricultural and biological sciences, environmental sciences, and computer sciences. Literature written in English and French was included.

Finally, this section will provide a comprehensive overview of the thermal behaviour of poultry buildings, including its importance, methods for calculating it, and its impact on energy use. Furthermore, it will discuss the various Net-Zero-Energy Poultry Buildings (NZEPB) strategies proposed in the literature, analyse their advantages, and delve into the obstacles they face to achieving sustainability in this sector.

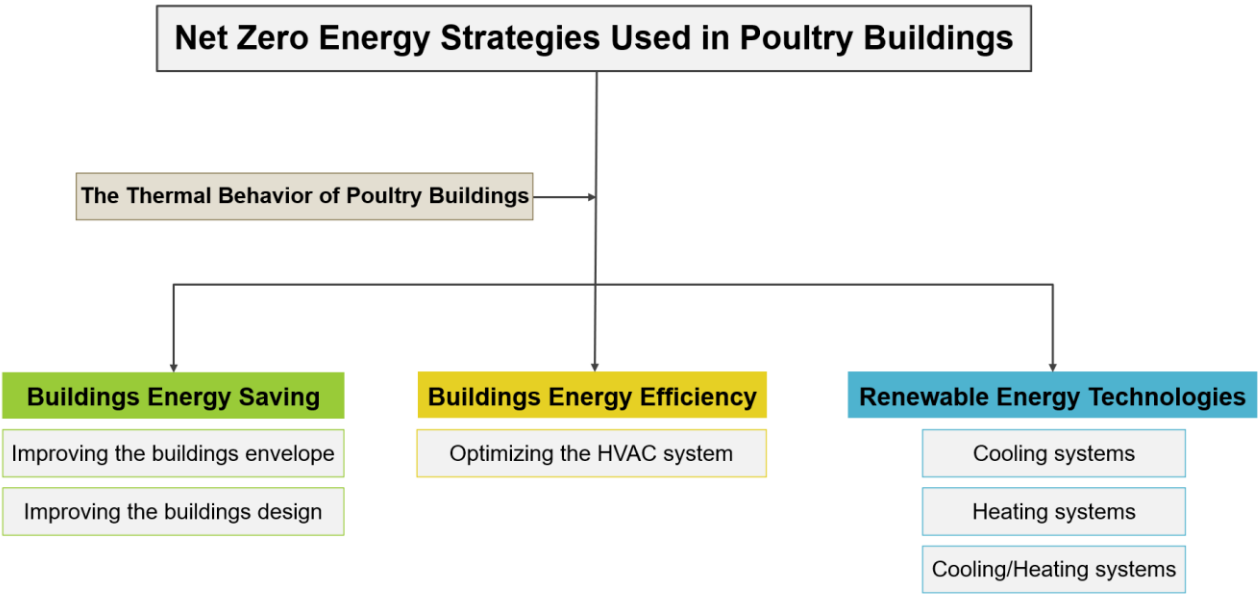


Figure 1.1. The overall structure of the literature review.

1.4.1 Thermal Behaviour of Poultry Buildings

Analysing thermal behaviour and accurately estimating building thermal loads is crucial for determining energy requirements and evaluating appropriate NZEPB strategies, such as modifying the building or its components, using additional systems, or reducing them, which contributes to better planning of the production process and improving production and energy costs. The thermal loads represent the amount of energy, whether sensible or latent, that will be removed or added to the indoor environment by equipment designed to maintain this environment [26]. Several factors control the cooling and heating loads in poultry buildings, such as the dynamic external and internal conditions [27], the building envelope's quality [28], ventilation rates [29], air infiltration [30], the density of birds, and the energy generated from them [26]. For this reason, many researchers have worked to develop models and tools to estimate energy consumption in this kind of building and analyse their thermal behaviour, considering these factors.

According to Cui et al. [31], determining insulation requirements for poultry houses based on engineering design air temperatures without considering the effects of the surrounding weather, such as convective cooling, heating, and solar radiation, is considered insufficient. Therefore, they investigated the suitability of using solar air temperature as a design parameter for this building. Outside temperatures were monitored; solar air temperature was used to simulate the effects of solar radiation on conductive heat gain during warm weather at different climate locations. The simulation results showed that the conductive heat transfer calculated using sol-air temperatures was considerably higher than that calculated using ambient temperature. Therefore, this approach gives more accurate forecasts of daylight conductive heat transfer.

Banuelos-Gonzalez et al. [29] developed a quasi-static thermal model to estimate heating and cooling loads for poultry houses using MATLAB for hourly simulation of different energy balance components, including solar heat gain, sensible heat from chickens, heat conduction through walls and floors, and convection through ventilation, in contrast, they neglected heat gains from machinery and lighting. They found, through the thermal analysis of the building, that heat loss through ventilation and air exchange with the outside represents 85% of the total heat transfer, followed by heat transfer through the roof of 8%, while heat gain from chickens is the primary source of sensible heat, followed by heat gain from solar energy.

Gao et al. [32] conducted a study to improve the climate of closed chicken brooder houses to achieve better growth performance and health of the chicks; therefore, they developed an acquisition system to collect environmental data and analyze the various factors of the brooder houses, such as the structural characteristics and growth environment of the chicks, then a microclimate simulation model was created based on the energy balance equation. The results showed that the coefficient of determination (R^2) between the simulated and measured values for both temperature and humidity was 0.7634 and 0.9740, respectively, while the root mean square error (RMSE) gave values of 1.55°C and 2.61%, respectively, which confirms the validity of the model.

Costantino et al. [33] presented a simulation model to estimate the energy consumption required for climate control of the poultry house. This model is based on the customisation of the ISO 13790 simple hourly method, taking into account the geometric and thermophysical characteristics of the building, the required indoor conditions, and the outdoor weather data. The model structure includes five steps: i) Determination of boundary conditions, establishing crucial information such as bird weight, the ventilation rate, and target temperatures. ii) Energy balance resolution: the model uses the simple hourly method to calculate the internal conditions for each period based on meteorological data and those collected in the first step. iii) Calculation of ventilation and tunnel cooling: based on the theoretical heat load calculated in the previous step. iv) Humidity balance resolution: relative humidity conditions are calculated hourly. v) System performance: this step provides the actual thermal and electrical energy consumption values. The model was validated by comparing its results to a dataset obtained while monitoring the house during a production cycle. According to the authors, the model has proven its worth from the point of view of both environmental parameters and energy consumption estimation.

In another study, Du et al. [34] used the simple hourly method described in ISO 13790 to build a model to estimate energy consumption in poultry farming. The input data included hourly external environmental data (temperature, humidity, solar radiation), the building characteristics, the bird physiology (age, weight, heat production), and boundary conditions (approved indoor air temperature), which are determined based on local management requirements. Moreover, the moisture and gaseous balance (ammonia and carbon dioxide) were resolved in each period. The indoor climate is updated at the end of each period, and the electricity consumption resulting from climate control is calculated considering efficiency. The results showed good agreement with the measured and computed data, indicating that the customised model was able to accurately predict the indoor environment and total energy consumption during poultry farming.

Wang et al. [26] developed a toolkit to simulate the load of a commercial poultry building over a year, in which the effect of the building envelope, infiltration air flow rates, air seal, and ventilation rate under three mortality levels was studied on basic room temperature (BRT), and the cooling and heating load was evaluated in each case. The BRT simulation results show that the building requires air conditioning operations 61.20% of the time per year. Enhancing the building's envelope isolation materials (doors and windows) decreased the maximum annual cooling load (ACL) and annual heating load (AHL) by 4.81% and 11.10%, respectively. By adjusting the tightness of the envelope construction from "loose" to "medium," the maximum ACL and AHL were reduced by 4.45% and 15.45%, respectively. Similarly, when the envelope construction was changed from "medium" to "tight," the maximum ACL declined by 5.72%, and the maximum AHL decreased by 19.86%. Decreasing the ventilation rate reduced the hourly cooling load (HCL) from 12.51 to 50.04 kW and the hourly heating load (HHL) from 3.75 to 15.01 kW due to different mortality rates.

Wang et al. [35] developed a model to maintain the desired internal environment in laying hen houses. The effect of the main parameters of poultry density (33%, 66%, 100%, 133%, 166% of the original density), internal temperature (13°C, 16°C, 19°C, and 22°C) and ceiling insulation level (0.83 $m^2.kW^{-1}$ (110 mm), 0.98 $m^2.kW^{-1}$ (140 mm), 1.11 $m^2.kW^{-1}$ (170 mm), 1.26 $m^2.kW^{-1}$ (200 mm)) on the ventilation rate, temperature balance and thermal resistance of the house. According to the results, increasing poultry density from 133% to 166% decreased the ventilation rate by a maximum of 7.1% at external temperatures less than -35°C. The indoor temperature set point did not significantly affect the ventilation rate at external temperatures below -12.5°C. Improving the roof insulation reduced the temperature balance.

Rojano et al. [36] created a 3D CFD model using Fluent Ansys to analyse the effect of natural ventilation on the internal climate dynamics of poultry houses. They considered the impact of external climatic factors, including air temperature, air humidity, solar radiation, and wind velocity (excluding wind direction), in addition to internal factors such as heat produced by animals, water vapour, radiant heat transfer, and ventilation. The results showed good agreement between experimental and simulation data. Additionally, this tool demonstrated its ability to estimate the air exchange rate and exchanges of sensible and latent heat. However, the system's complexity suggests the need for further investigation to find a variable time step that better manages indoor temperature and humidity dynamics.

ElZanaty [37] used TRNSYS software to study the thermal performance of the poultry house throughout the year. Construction specifications, including materials used and infiltration rate, were taken into account at the interface of building components. The study included hourly weather data representing ambient temperature, heat input gained from conduction, and heat generated by birds, as well as the heat generated by lighting and workers' movement inside the house. It was found that the highest heating requirements occurred at the beginning of the growth cycle, with a heating power demand of 581,000 kJ/h.

On the other hand, Jalali et al. [38] used TRNSYS software to simulate and analyse the energy consumption for heating a poultry house in Iran by performing hourly dynamic simulations and calculating the heat and humidity generated by the poultry and its effect on the building's thermal load. This simulation showed that the building needs 1.37×10^8 kJh^{-1} throughout the year for heating, equivalent to 17,180 m^3 of natural gas.

On the other hand, some studies have utilised artificial intelligence to assess a building's performance and energy consumption, as seen in the study presented by Akolgo et al. [39], which employed an artificial neural network (ANN) model to analyse energy consumption in poultry farms. They collected energy consumption data from a poultry production facility. This data included the number of birds, water consumption, feed consumption, and weather variables such as temperature and humidity. Next, the ANN model was designed, trained, and tested using the collected data. On the other hand, the Energy Plus software was used to simulate the facility's energy consumption, and the simulation results were compared with those of the ANN model to monitor the model's performance in predicting energy consumption. The results of the ANN model indicated that the average annual energy consumption for lighting was approximately 2044 kWh, while the consumption of equipment, including feed mills, water pumps, and refrigerators, was approximately 1452 kWh.

Based on what has been found in the literature, as summarised in **Table 1.1**, existing models and tools used for predicting the thermal performance and energy consumption of poultry buildings can be classified into two categories:

- Simulation tools make it possible to create detailed digital models of poultry buildings and simulate their thermal and energy behaviour over a given period. Popular simulation tools used are Energy Plus, TRNSYS, and ANSYS Fluent.
- Thermal calculation models utilise simplified mathematical equations to estimate poultry building heat loads and energy consumption. They are typically based on energy balance equations and standard methods, such as the ISO 13790 simple hour method and the ASHRAE standard.

Furthermore, the researcher considered the following heat sources to calculate building thermal loads: heat transfer through the building structure, solar heat gain, heat gain from chickens, and heat loss through ventilation. In contrast, few studies have considered the effects of air infiltration, animal densities, and heat production by equipment, lighting, workers, and manure.

Table 1.1. Summary of publications related to poultry houses' thermal behaviour.

Climate zone	Building characteristics	Heat gains/ losses	Method and tool	Main findings
USA [31]	(152.4 m×15.2 m). Walls (Painted metal, fibreglass insulation, and vapour barrier). Roof (galvanised metal, plastic vapour barrier, banded and blown cellulose insulation).	Heat transmission through the building's structure.	Conducted for daytime hours based on ASHRAE standards.	– Conductive heat transfer calculated using sol-air temperatures was considerably higher than that calculated using ambient temperature.
USA [29]	(167.6 m×11.2 m). 69,376 chickens.	Solar heat gain. Heat gains from chickens. Heat transmission through the building's structure. Heat loss through ventilation.	Hourly simulation using MATLAB	– Ventilation and air exchange with the outside account for 85% of heat transmission, followed by roof heat transfer at 8%. The house's main sensible heat source was chickens, followed by solar energy.
China [32]	(63 m×11.5 m×4m). Walls (bricks with cement mortar). Roof (colour steel plates, thermal insulation foam). Floor (cement). 30,000 chickens.	Solar heat gain. Heat gains from chickens. Heat transmission through the building's structure Heat loss through ventilation. Heat through the heating system.	Environmental data acquisition system. A microclimate simulation model based on energy balance.	– Model showed a close agreement with the measured data.
Italy [33]	(120m×10m×4.4m). Walls (sandwich panels), Roof (sandwich panels), Floor (reinforced concrete screed over a waterproofing sheet). Windows (polycarbonate alveolar panels). 14,500 chickens.	Solar heat gain. Heat gains from chickens. Heat transmission through the building's structure. Heat gains through climate control systems	Simulation model based on the simple hourly method described in ISO13790 Standard.	– Total energy consumption for heating was 3551 kWh, while the model estimated it to be 3184 kWh, which means that the model reduces thermal energy consumption by about 10%. – Electrical energy consumption for ventilation reached 5061 kWh, while the model estimated consumption to be 5463 kWh, which means that the model

				increases electrical energy consumption by about 7.9%.
China [34]	(40m×9.2m×2.5m). Walls (firebrick). Roof (rock-wool insulation board). Floor (concrete). Windows (polystyrene and metal frame). Door (single-decker wood). 15,000 chickens.	Solar heat gain. Heat gains from chickens. Heat transmission through the building's structure. Heat loss through ventilation. Heat through the heating system.	Simulation model based on the simple hourly method described in ISO13790 Standard.	– Largest proportion of energy consumption was for heating – Validation showed a 10.6% difference in energy consumption prediction accuracy.
China [26]	(90m×11m×4.7m). Walls (rock-wool insulation board and steel panel). Roof (rock-wool insulation board and steel panel). Floor (concrete). Windows (polystyrene and metal frame). Door (single-decker wood).	External insulation Infiltration and airtightness Total ventilation rates under different stocking densities	Simulation Toolkit (dest)	– Building requires air conditioning operations 61.20% of the time annually. – Improving insulation materials reduces the maximum ACL and AHL by 4.81% and 11.10%, respectively. – Adjusting the tightness of the building envelope from "loose" to "tight" reduces the ACL and AHL by 10.17% and 35.31%, respectively.
China [35]	House A: (90m×10.5m×3m). Walls (Polystyrene of the metal frame). Door (Single wooden). 20,000 chickens. House B: (90m×11m×3.5m). Walls (Polystyrene of the metal frame). Door (Single wooden). 30,000 chickens.	Solar heat gain. Heat gains from chickens. Heat transmission through the building's structure. Heat loss through ventilation. Heat production by the equipment and manure.	Microsoft Excel	– Increasing poultry density from 133% to 166% resulted in a maximum reduction in ventilation rate of 7.1%. – Indoor temperature setpoint did not significantly affect the ventilation rate at outdoor temperatures below -12.5°C. – Increasing the roof insulation from 110 to 400 mm decreases the equilibrium temperature by 1°C.

France [36]	(12.5m×6m×2.5m) Walls (polystyrene). Roof (polystyrene). 750 chickens.	Heat gains from chickens. Heat transmission through the building's structure. Heat loss through ventilation. Heat gains from manure.	Ansys Fluent	– Simulation results showed a good agreement with experimental data. – This tool has proven its ability to estimate air exchange rates and sensible and latent heat exchanges.
Iran [38]	(8m×5m×2.5m) Walls (black cement). Roof (plastic cartons, glass wool, and metal sheets). Floor (cement). Windows (ordinary single-walled metal). Door (metal). 15,000 chickens.	Heat gains from chickens. Heat transmission through the building's structure. Weather conditions (temperature, solar radiation, relative humidity, and wind speed). Heat loss through ventilation.	Transient simulation in TRNSYS software	– Building needs 1.37×10^{8} $kJ.h^{-1}$ throughout the year for heating.
Egypt [37]	(108m×14m×3m) Walls (layer of gypsum, plastic, cement mortar, limestone bricks and lime mortar). Roof (corrugated pre-painted galvanised sheets, air isolates, fibreglass insulation). 24,000 chickens.	Heat gains from chickens. Heat transmission through the building's structure. Internal lighting. Workers.	Transient simulation in TRNSYS software	– Maximum heating demand was on the first day of the cycle, with a value of 581,000 $kJ.h^{-1}$.
Ghana [39]	Walls (cement block, sandcrete plaster and sandcrete block). Roof (sheet Roof deck). Floor (concrete). Windows (Wooden frames, steel wire mesh). Door (single-decker wood). 1,500 chickens.	Heat gains from chickens. Weather conditions (temperature, solar radiation, relative humidity, and wind speed). Internal lighting. Equipment.	Sketchup, Energy Plus, and MATLAB.	– Annual energy consumption estimates for lighting and equipment were 2,044 kWh and 1,452 kWh, respectively. – Highest average energy consumption in 30 min intervals is 5.8539 kWh. – ANN successfully modelled and predicted energy consumption for a poultry production facility.

1.4.2 Building Energy Saving

Poultry building is the environmental envelope that protects birds from harsh external climatic conditions that may have a negative impact on the performance and productivity of this sector. The envelope consists of windows, walls, roof, and floor. These parts form the thermodynamic system boundaries of the poultry house, regulating the exchange of energy and mass between the environment inside and outside the house. According to studies related to the building's thermal behaviour, the envelope has a vital role in saving energy, maintaining the performance of climate control systems, and reducing the total consumption of thermal and electrical energy [40]. Therefore, many researchers have been interested in studying the optimal materials, thicknesses, and envelope layers to improve the building's thermal insulation (**Figure 1.2**).

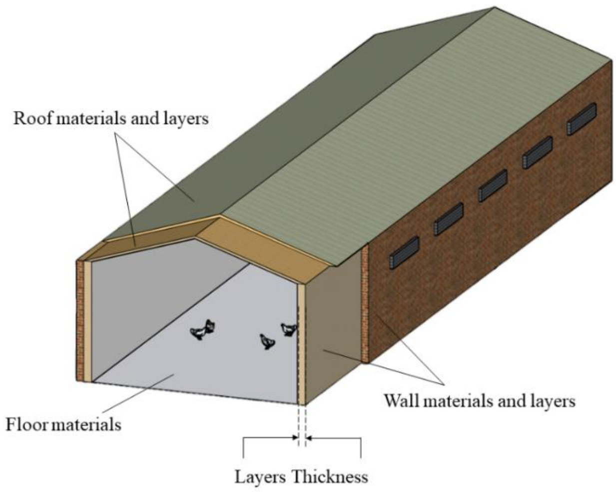


Figure 1.2. Parameters included in the literature in studying the poultry building envelope.

In this regard, Panagakis-FBC et al. [27] used detailed transient simulations to model and calculate a poultry house's annual heating and cooling loads. Heat and humidity gains and losses due to birds, heat flow through the building envelope, mechanical ventilation, and climate data were all considered. An economic analysis based on the Life Cycle Savings (LCS) method was performed for walls and roofs for different insulation thicknesses and directions. The results showed that the optimal insulation thickness for the external roof and walls ranged between 4.0 cm and 4.5 cm, depending on their orientation, while the north-side wall provided the greatest economic benefit compared to the other orientations. In addition, they found that the annual cooling load was 3.3 times higher than the heating load.

Küçüktopcu and Cemek [41] examined the effect of optimal insulation thickness on energy savings, payback periods, and CO_2 emission rates for poultry buildings in four climates in Turkey (Samsun, Antalya, Erzurum, and Ankara). Expanded polystyrene (EPS) and extruded polystyrene (XPS) were tested as insulation materials, and five fuels were studied (coal, fuel oil, natural gas, liquefied petroleum gas, and electricity). The results showed that the optimum thickness for both EPS and XPS ranged between 2.00-11.80 cm and 1.20-8.10 cm, respectively. This corresponds to energy savings ranging between 21.82%-70.61% and 15.38%-69.90%, with payback periods ranging from 0.78-2.64 years and 0.90-3.02 years for each insulator, respectively. As for CO_2 emissions, their percentage varied depending on climate and fuel type, with Erzurum recording the highest reduction of 83.98% when using EPS and liquefied petroleum gas, while Antalya had the lowest reduction of 39.82% when using XPS and natural gas. From an environmental perspective, they found that LPG is the best fuel and EPS is the best insulating material.

Wang et al. [42] The effect of six insulation materials (mineral wool, foamed glass, foamed polyurethane, expanded polystyrene, expanded polyethene, and foamed polyvinyl chloride) and thickness was tested on total life cycle cost, savings, and payback time, and this study was conducted in five different cities. From the results related to the poultry house, they discovered that the optimal insulation thickness might range from 0.02 m to 0.24 m depending on the city climate, while the total life cycle costs, life cycle savings, and payback time may range between 13.37-36.84 $\$.m^{-2}$, 0-202.13 $\$.m^{-2}$ and 1.19-20.76 years, respectively. They concluded that insulating thickness increases with heat conductivity and degree of day. Increasing insulation thickness decreases total life cycle cost, while higher insulation material costs raise it. Increasing the costs of insulating materials and their thickness leads to increased life cycle savings, and their value stabilises at the optimum thickness. Foam glass and mineral wool insulation have shorter payback periods, and this period varies depending on the city.

Costantino et al. [40] evaluated 18 scenarios characterized by three different types of envelopes (Medium insulation and low mass, high insulation and low mass, and Low insulated and high mass) and six different external climate conditions (Poland, France, United Kingdom, Germany, Spain, and Italy), as well as a global cost analysis to assess the financial implications. The study's findings revealed that although the highly insulated envelope is suitable for considering outside weather conditions, it is not financially sustainable. In contrast, the medium-insulated envelope provides appropriate energy performance at a cost similar to that of a non-insulated envelope. A comparison of the findings shows that the energy-saving approach significantly reduces the poultry house's energy consumption.

The roof is considered one of the primary components of the poultry building's envelope and the one that receives the most solar radiation. As a result, indoor temperatures, particularly near the roof, increase significantly due to convective heat transfer between the roof's surface and the indoor air. Therefore, some studies have been conducted on roofing materials and their impact on insulation and improving indoor thermal comfort. In this regard, Almeida and Passini [43] evaluated five roofing materials commonly used in poultry houses: asbestos cement tiles, bamboo tiles, white-painted bamboo tiles, vegetable fibre and bitumen tiles, and Vegetable fibre tiles and white-painted bitumen. The house's thermal comfort was measured through the Black Globe and Humidity Index (BGHI), enthalpy, and thermal heat load during April and May. The results showed that the time of day that is considered the least comfortable is the time observed at 2:00 pm with vegetable fibres and bitumen, gave the highest value of BGHI compared to other types of coverage, which characterizes a state of low thermal comfort, and no difference was found between the thermal heat load and the enthalpy on the treatments in the studied area.

By analysing the literature in this sector, it can be said that a limited number of studies have investigated the effectiveness of improving the building envelope in reducing consumption and saving energy. In contrast, the researchers' solutions in the reviewed literature were limited to studying the effect of various insulating materials and their optimal thickness. The results of these studies, as shown in 2.2, conclude that insulation plays a pivotal role in conserving energy and reducing environmental impact, and the effectiveness of this role varies according to the insulation material, its optimal thickness, and the climatic conditions surrounding the building.

Table 1.2. Summary of publications related to energy saving in poultry houses.

Climate zone	Scope of the study	Main findings
Greece [27]	Analysing the LCS method for walls and roofs for different insulation thicknesses and directions.	– Optimal insulation thickness for the external roof and walls ranged between 4.0 cm and 4.5 cm, depending on their orientation. – North-side wall provided the greatest economic benefit compared to the other orientations.
Turkey [41]	Examining the effect of optimal insulation thickness on energy savings, payback periods, and CO_2 emission rates for poultry buildings in four climates in Turkey.	– Optimal thickness for EPS and XPS ranged between 2.00-11.80 cm and 1.20-8.10 cm, respectively. – Energy saving rates for EPS and XPS ranged from 21.82%-70.61% and 15.38%-69.90%, respectively. – Payback periods for EPS and XPS ranged from 0.78-2.64 years and 0.90-3.02 years, respectively. – Highest reduction in CO_2 emissions was recorded in Adrum by 83.98% using EPS and liquefied petroleum gas.
China [42]	Studying the effect of six insulation materials and thickness on total life cycle cost, savings, and payback time in five different cities.	– Optimal insulation thickness might range from 0.02 m to 0.24 m, depending on the city's climate. – Total life cycle costs, life cycle savings, and payback time may range between 13.37-36.84 $\$.m^{-2}$, 0-202.13 $\$.m^{-2,}$ and 1.19-20.76 years, respectively.
Europe [40]	Evaluating 18 scenarios characterised by three different types of envelopes and six different external climate conditions and analysing the global cost.	– Although the highly insulated envelope is appropriate for considering outside weather conditions, it is not financially sustainable. – Medium-insulated envelope provides appropriate energy performance at a cost similar to that of a non-insulated envelope. – Energy-saving approach greatly decreases the poultry house's energy consumption.
Brazil [43]	Evaluating the performance of five roofing materials commonly used on the poultry house's thermal comfort.	– Time of day that is considered least comfortable is the time observed at 2:00 pm. – Vegetable fibres and bitumen gave the highest value of BGHI compared to other types of coverage.

1.4.3 Building Energy Efficiency

Improper design or distribution of HVAC systems in poultry houses can create areas of stagnant air or excessive airflow. These problems contribute significantly to birds' thermal stress, increasing productivity and energy consumption losses [33]. In response to these challenges, many researchers have adopted strategies to improve the energy efficiency of this type of building. These efforts focus on developing innovative designs and determining the optimal dimensions of the components of these systems to ensure balanced air and heat distribution. The performance of the systems is also adjusted to suit changing indoor and outdoor environmental conditions. These improvements aim to achieve maximum operational efficiency while minimising energy consumption.

Du et al. [44] evaluated four scenarios for designing air inlets and outlets and studied their effect on the indoor environmental performance of the house. The simulation results showed that the design of the inlet locations had a significant impact on the air and temperature distribution inside the poultry house. Only side openings in the original design caused irregular air flow due to the collision of currents in the middle, which led to air turbulence and a significant temperature difference between the house's front and back. Meanwhile, the side and front inlets in the second design improved the thermal distribution and reduced air turbulence compared to the original design. In contrast, the presence of only front inlets in the third design resulted in a more uniform distribution of air and heat, with a reduced temperature difference between the front and back of the house and was the most effective in lowering flow turbulence. The fourth design, which contains front and middle side inlets, was the most efficient, achieving an excellent balance in air distribution and reducing temperatures at the back of the house without increasing energy consumption, making it the ideal choice for large farms.

Wang and Wang [45] proposed two designs to enhance the performance of the ventilation and cooling system in poultry houses. The house's original design contained five cooling pads installed on the side walls and eleven exhaust fans on the east wall. In the first proposed design (D1), the side cooling pads of the original design were removed. In the second proposed design (D2), the pads and fans were repositioned, with two pads installed in the middle of the side walls and five exhaust fans placed on each end wall. They studied the effect of the system's position and size on the building's indoor conditions by computational fluid dynamics simulation. The simulation results showed that the velocity and temperature were inconsistent in the original ventilation scheme design. On the other hand, the velocity consistency was better in D1, and the temperature consistency was more significant in D2.

Babadi et al. [16] took the same approach, first analyzing the performance of the three previous models of Wang and Wang [45] to understand their shortcomings in the distribution of velocity and temperature in the house and then proposing three new models to overcome the shortcomings of the previous models by performing CFD simulations to obtain the distribution of velocity, temperature, humidity, and pollutant gas concentration. The results showed that the previous three models did not achieve the required distribution in terms of velocity and temperature. In contrast, the second improved design by Wang and Wang [45] performed better in terms of relative humidity and pollutant gas concentration compared to the original design, providing a more suitable environment. On the other hand, the second new design proposed by Babadi et al. [16] gave better results than the original design, with a velocity at the bird level of 2.5 $m^3.s^{-1}$, a maximum temperature of 308 K, and a relative humidity between 60% and 75%, and it kept the concentrations of CO_2 and NH_3 within the permissible range.

Chen et al. [46] simulated indoor and outdoor air flows to determine the optimal ventilation design for cage-free chicken houses. The study included the original ventilation model of the house, which relies on upper wall inlets and side exhausts, as well as three alternative designs: a mid-wall inlet with a roof exhaust, a mid-wall inlet with a ridge exhaust, and a mid-wall inlet with an attic exhaust with pre-treatment of the exhaust air. The simulation results showed that the alternative models were able to achieve comfortable temperatures and air velocities at the chicken level, thereby contributing to improved welfare conditions for the birds. A full-scale CFD model with an individual representation of the chicken was also influential in accurately assessing these conditions.

AM [47] tested how differential pressures of 20, 30, and 40 Pa and fan activation from 5 to 7 fans affected air velocity and temperature in the chicken house. Through the results, they discovered that air velocity was highest in the cross-section of the house and lowest near the side walls. As the differential pressure increased, the velocity increased to 2 $m.s^{-1}$, while temperatures increased near the exhaust fans, potentially causing significant thermal discomfort to the chickens.

According to Cheng et al. [48], in cage-free chicken houses, the space under the roof is usually large enough to allow the cool air from the ventilation to mix efficiently with the room air in winter. However, this design is unsuitable for summer tunnel ventilation as air is drawn to one end of the house and expelled from the other. To solve this problem, the effect of under-roof mounted reflectors was studied. The effect of reflector heights ranging from 0.4 m to 1 m and their spacings varying from 6 m to 18 m on the air velocity and distribution in the poultry area was analysed. The results showed that the reflectors significantly improved the downward airflow, with air velocity increasing by 0.66 $m.s^{-1}$ and 0.91 $m.s^{-1}$, respectively, when reflectors of 1 m height and 6 m spacing were used. The uniformity of air distribution in the poultry area was also significantly improved with the use of reflectors, with a positive relationship with the reflector height and a negative relationship with the reflector area.

Fezai et al. [49] studied the airflow and thermal conditions inside a poultry house using a natural ventilation system supported by wind traps. The study focused on the effect of wind trap dimensions, outdoor wind velocity, and ambient temperature on the efficiency of the ventilation system. The results showed a significant decrease in the average indoor temperature of 9.15°C with a uniform air velocity ranging from 0.04 to 0.7 $m.s^{-1}$ at the cage level. In addition, the variations in windcatcher dimensions showed that larger openings improved thermal stability but could introduce excessive air speeds.

In their study, Fidaros et al. [50] evaluated the effect of the five fans available in the studied poultry house on the indoor climate. From the results, they found that operating two or three central fans is the optimal choice in terms of temperature, ventilation, and air velocity, while operating only one fan fails to maintain the required temperature, and operating more than three fans does not improve ventilation rates but is a factor in increasing energy consumption. On the other hand, Küçüktopcu et al. [51] found that adding four 0.5m diameter circulating fans spaced 20 m apart inside the barn effectively eliminated areas of stagnant, humid air in winter.

Coulombe et al. [52] studied three alternative heat exchanger distribution configurations and compared them to a reference configuration in which the heat exchangers were placed in parallel over one-third of the track length. These configurations included a first configuration in which the distance between the exchangers was increased to one-quarter of the track length, a second configuration in which the exchangers were placed over one-sixth of the track length, and a third configuration in which the exchangers were arranged in reverse at each end of the house. The first configuration showed a significant improvement in air distribution quality, reducing the standard deviation of air lifetime from 477 to 179 s and increasing the floor area with adequate air quality from 55% in the reference configuration to 72% in the first configuration. Despite using the same heating capacity in all configurations, differences of up to 2°C in the average air temperature in the broiler area were observed between the different configurations. These results demonstrate the effect of heat exchanger locations on air distribution quality and the overall indoor environment.

Through what was found in the literature related to this section (**Table 1.3**), researchers agreed on the effectiveness and accuracy of the CFD tool to predict and evaluate different ventilation and cooling designs and study their impact on the indoor environment, as this tool was used to simulate and analyze airflow, temperature and humidity distribution, and the augment of gas concentration, as well as highlighting its importance in testing different designs of cooling and ventilation systems before their actual implementation, which contributes to reducing operational costs and increasing efficiency. Most studies focused on determining the optimal locations and dimensions for fans and air inlets to achieve uniform indoor conditions and minimise stagnant areas that could negatively impact the health and productivity of birds. In contrast, few studies have investigated the effect of the design and location of heating systems or changes in building design, such as roof shape or building size.

Table 1.3. Summary of publications related to enhancing the energy efficiency of HVAC systems in poultry houses.

Climate zone	Scope of the study	Main findings
China [44]	Optimising inlet configurations to improve indoor climate and reduce energy consumption.	– Combination of the front and middle side wall inlets in the fourth configuration effectively reduced high temperatures at the end of the building without increasing energy consumption. – Area ratio balance between the front and middle side wall inlets is critical to maintaining efficient airflow.
China [45]	Investigating the impact of ventilation and cooling systems on improving environmental uniformity and comfortable temperatures in poultry.	– Second optimised case achieved the best heat distribution, while the first optimised case achieved the best air distribution. – Ideal temperatures and speeds were not met in all the cases studied.
China [16]	Improve the velocity and temperature distribution and reduce humidity and concentration of gas pollutants by finding the appropriate ventilation and cooling system design.	– Modifying the ventilation design significantly reduces the variation in air and humidity distribution and helps ensure better air quality levels, enhancing the birds' health.
USA [46]	Evaluating airflow patterns, temperature distribution, and static pressure by studying four different ventilation configurations.	– Alternative designs were more effective in reducing thermal stratification, with temperatures ranging from 18 to 24°C in all alternative designs. – Air circulation was enhanced compared to the original design, with air velocities ranging from 0.25 to 1.0 m.s^{-1}, meeting the comfort levels of the birds.
China [48]	Improving indoor airflow distribution using roof deflectors and evaluating the effect of changing their height and spacing on airflow.	– Integration of roof reflectors significantly improved airflow. – Reflectors 1 m high and 6 m apart enhanced air velocity by 0.66 and 0.91 m.s^{-1}, respectively, compared to no reflectors. – Use of reflectors improved airflow uniformity.
Tunisia [49]	Investigating the effectiveness of natural ventilation in poultry houses using windcatcher systems.	– System reduces the average indoor temperature by 9.15°C, and the air velocity at the cage level ranges from 0.04 to 0.7 m.s^{-1}. – Size of 1 m in the windcatcher opening achieves the optimum balance of the indoor conditions of the house.
Greece [50]	Discovering the optimal number of fans and their operating settings to achieve optimal thermal comfort.	– Using a single fan does not reduce the temperature to the desired levels and gives air velocities of less than 1 m.s^{-1}.

		– Adding two fans reduces the birds' temperature level by 0.5°C, while the air velocity remains below the acceptable limit of 1 $m.s^{-1}$ while exceeding the limit when using three fans. – Using more than three fans does not significantly improve the temperature, but it increases air velocity and energy consumption.
Turkey [51]	Understanding airflow distribution and indoor temperature and humidity patterns to optimise indoor environmental conditions during the summer and winter.	– Using an evaporative cooling pad during summer can reduce temperature by around 3°C. – In the winter, installing four 0.50 m circulation fans within the house with a 20 m spacing prevents the accumulation of hot and humid air in stagnant zones.
Canada [52]	Analysing the effect of heat exchanger configuration on indoor conditions in a broiler house in a cold climate.	– Standard deviation of air lifetime decreased from 477 seconds to 179 s using the first configuration, in addition to increasing the floor area with suitable air quality from 55% to 72%. – Average air temperature varied by 2°C between the different configurations.

1.4.4 Renewable Energy Technologies

Several studies indicate the significant role of renewable energy technologies in enhancing the efficiency and sustainability of poultry houses. Accordingly, this part of the study analyses the technologies used in the areas of cooling, heating, or combined cooling and heating to identify best practices for improving thermal performance in these facilities.

1.4.4.1 Cooling Systems

Hong et al. [53] utilised the wind generated by a ventilation fan in poultry houses to produce energy. They designed new and improved blades to match the airflow generated by the house fans. They were connected to a three-phase alternating current permanent magnet synchronous generator (PMSG), a power transformer, and other elements. The system was tested with an AC load tester. As a result of the evaluation, the new blades demonstrated an output of 350 W of electricity, recovering 30% of its energy and converting it into usable energy.

Du et al. [54] used wind energy to develop a ventilation energy recovery system for poultry houses. They installed the wind turbine at the exit of the flow tunnel and calculated the energy recovery rate in addition to the life cycle assessment (LCA). The research findings indicate that wind turbines have the capacity to recover 13.5% of the energy used for ventilation and about 10.2% of the overall yearly energy needs for the house. From an environmental perspective, this system's energy and GHG recovery times were 3.36 and 1.17 years, respectively. This suggests that the system is ecologically benign and sustainable, especially given its age of 20 years.

The thermal performance of the earth air heat exchanger (EAHE) in dry and wet soils was compared by Morshed et al. [55]. Two experimental EAHEs were constructed on a poultry farm. One functioned in dry soil (DE), while the other operated in wet soil (WE). According to the study's findings, moistening the soil around EAHE enhances the overall effectiveness of heat exchange. At night, the WE system warmed the air more than the DE system, and during the warmest hours of the day, the WE outlet temperature was 1.56°C lower than the DE.

Hasan and Muter [56] studied the effect of design parameters such as pipe length, diameter, and design shapes on the performance of an EAHE system used in poultry houses. The results showed that a larger pipe length leads to better cooling but with a lower overall system performance efficiency, while larger diameter pipes provide better thermal performance. The study also showed that grid design provides optimal performance compared to coiled and spiral pipe designs. In contrast, Hasan and Muter [57] focused on the effect of air flow rate on the performance of the EAHE system in another paper, while they found that increasing the air flow leads to an increase in the required cooling load.

Harrouz et al. [58] compared a hybrid cooling system combining a direct evaporative cooler (DEC) system and an EAHE with a conventional DEC system, as shown in **Figure 1.3**. Mathematical models have been developed to determine each system's size according to the house's area and its thermal needs. The comparison results demonstrated that the hybrid system has a higher cooling capacity and is more effective in meeting the cooling needs throughout its operating period than the conventional DEC system. Additionally, the hybrid system resulted in a 40% reduction in water and air consumption rates during the summer compared to the DEC system.

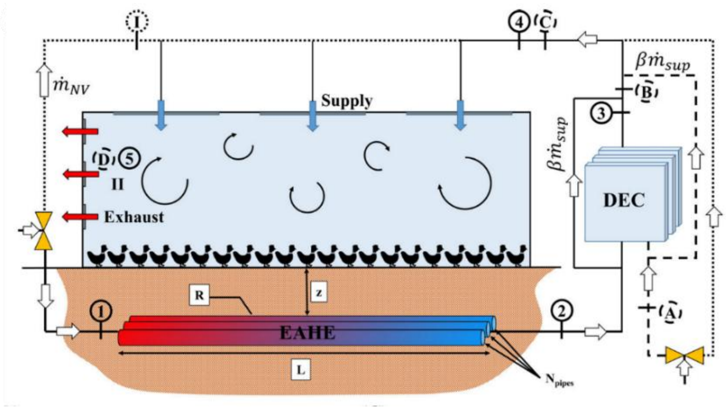


Figure 1.3. Schematic of a hybrid cooling system combining DEC and EAHE [58].

In a similar study, Petek et al. [59] conducted an experimental study to compare the cooling performance of a conventional cooling system consisting of tunnel ventilation cooling pads with a two-stage evaporative cooling system consisting of an EAHE integrated with the cooling pads. Air humidity, temperature and saturation efficiency were monitored to determine the cooling performance of the systems, while changes in body weight, mortality rate and feed conversion ratio were analysed to evaluate the effect of each system. The findings indicated that the hybrid system's cooling and saturation efficiencies were more significant than those of the traditional system, and that adding the EAHE decreased the air temperature and humidity. As a consequence of these findings, production was enhanced.

1.4.4.2 Heating Systems

A study by Choi et al. [60] evaluated the efficacy of a geothermal heat pump heating system in improving indoor air quality and productivity of broiler houses. The researchers examined the gas concentration levels, energy consumption, heating costs, and productivity of poultry houses compared to conventional heating systems that depend on diesel fuel. Investigations indicated that the GHP system effectively preserved air quality compared to the conventional heating system, leading to a notable rise in ammonia and CO_2 levels inside the premises. On the other hand, although fuel consumption decreased when using GHP, electricity consumption increased. However, the total energy cost for heating was much lower than that of the conventional system. In terms of productivity, the GHP system contributed to increasing the weight of birds and reducing their mortality compared to the conventional system.

Zhou et al. [61] studied the effects of trench spacing between 1.2 and 3.5 m and different configurations, such as dense slinky loop, horizontal straight, and slinky loop for ground source heat pumps for use in poultry house heating. The results showed that lower trench spacing resulted in a slight increase of 0.5°C in the transport fluid temperature due to thermal interference between the trenches, while the dense slinky loop configuration showed better performance with a temperature decrease of 1.5°C compared to the other configurations.

Using a Trombe wall to heat a brooding house was the subject of an experimental investigation by Okonkwo and Akubuo [62]. Based on the findings, it was found that the brooder house could maintain a brooding temperature range of 28-35°C with an ambient temperature range of 18-37°C and that the temperature of the Trombe wall heat storage device ranged between 22-60°C. Furthermore, the chickens had a 3% mortality rate, indicating a 97% efficiency.

Sleem et al. [63] led a comparative study between a green poultry farm equipped with a local heating system powered by solar energy and photovoltaic panels and a conventional poultry farm powered by traditional electricity to evaluate the energy consumption, efficiency and economic return of the two systems during two production cycles in the warm and cold seasons. The results showed that the energy inputs in the greenhouse amounted to 33,995.39 and 37,058.25 MJ during the warm and cold seasons, respectively, compared to 40,656.97 and 45,770.05 MJ in the traditional house. As for energy efficiency, it was found that the greenhouse was more efficient by an average of 0.58 and 0.46 in the warm and cold seasons, respectively, compared to 0.50 and 0.41 in the traditional house. Regarding economic returns, net returns were negative for both systems, while life cycle cost (LCC) analyses showed that the conventional system was 18.89% more profitable over 20 years. It was concluded that poultry production on small farms is unprofitable under the conditions studied. Therefore, the use of renewable energy may be more suitable for large farms to achieve the goal of reducing production costs.

Fawaz et al. [64] evaluated the performance of an innovative solar-powered local heating system for heating poultry farms (**Figure 1.4**) using a 3D simulation model of the heated space. The heated pen with a warm air stream meets recommended ventilation, temperature, humidity, and air quality requirements. The results showed that the system performance was compared to that of a conventional fuel-based, thoroughly mixed heating and ventilation system. The results show that the localised system has reduced energy demand by 74% compared to the conventional fully mixed system. Moreover, a solar system that relies on parabolic concentrators has covered 84% of the load required for a winter flock of six weeks.

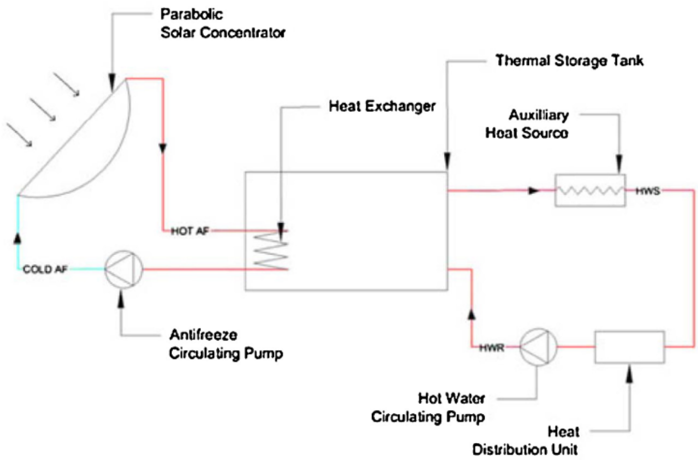


Figure 1.4. A solar heating system based on a parabolic solar concentrator [64].

Cordeau and Barrington [65] investigated the energy recovery efficiency of a solar air pre-heater consisting of unglazed black corrugated sides where the incoming fresh ventilation air captures heat from its face and back. Solar air heaters were installed, and their performance was monitored over two years. Sensors inside the hangars monitored the ambient air temperature, which was preheated by the solar collector and exhausted by one of three operating fans. The results showed that the efficiency of unglazed solar air heaters reached 65% for wind speeds less than 2 $m.s^{-1}$ but decreased to less than 25% for wind speeds exceeding 7 $m.s^{-1}$. However, unglazed solar air heaters reduced the heating load, especially in March of both years. Over a period beginning in November and ending in March, the solar air heaters returned an energy value equivalent to an annual return on investment of 4.7%.

To find an alternative source of conventional energy to meet the energy requirements of the poultry industry, Gad et al. [66] studied a solar heating system consisting of flat solar collectors and ventilation fans operating at different rates every 2 and 4 min. The results revealed that productivity increases when the ventilation rate increases and when using the solar heating system, as productivity reached 2.3 kg at a ventilation rate of every 2 min, compared to 2 kg in the conventional heating system. On the other hand, enhancing the ventilation rate helps increase production while reducing ammonia levels. In another paper, Gad et al. [67] developed this system by adding photovoltaic panels to generate electricity, reducing dependence on conventional energy sources. The system included an integrated system consisting of flat solar collectors, PV panels, ventilation fans operating at different stop periods (2, 5, and 8 min), and humidity and ammonia concentration sensors (**Figure 1.5**). The results showed that the system contributed to achieving higher productivity of poultry with a production weight of 2.29 kg, a feed conversion rate of 1.45 kg $_{feed}$.kg^{-1}$_{weight}$, and reduced the ammonia concentration in the poultry house to 13.65 ppm in the fifth week of growth. In addition, the production cost was reduced to 1.12 \$.kg^{-1} using the integrated solar system compared to the traditional system that relies only on electricity.

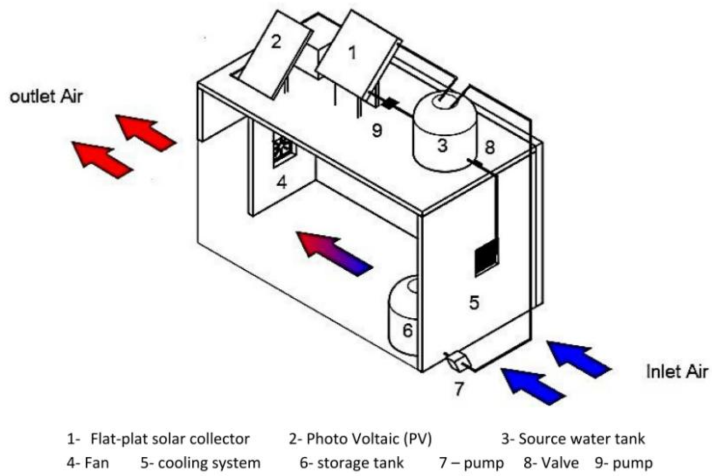


Figure 1.5. Illustration of a hybrid solar heating system for generating electricity and heat energy [68].

Kapica et al.[68] conducted a study to assess the viability of a hybrid system combining solar and wind energy to heat a poultry house housing 2,400 birds. The sizing of both the wind turbine and solar collector was evaluated based on the building's thermal requirements. The system was modelled using the MATLAB/Simulink program, and various system configurations were analysed under typical climatic conditions of Central Europe. The findings revealed that the solar collector area could reach up to 80 m^2, with turbine diameters potentially reaching 20 m. Additionally, the required number of tanks ranged from 1 to 4. However, these sizes were deemed unrealistic as turbine heights could reach 30 m. Depending on wind speeds in the region, the turbine would operate roughly half the time, often at minimal power output. Larger turbines would be necessary to meet energy demand, posing significant costs and technical challenges. However, wind energy offers the advantage of a relatively uniform annual distribution, with slightly higher values in winter. Conversely, the solar energy potential in the analysed region is relatively high but unevenly distributed throughout the year, particularly limited during the winter months. Consequently, storing more energy is necessary compared to that acquired from wind sources. The study findings also indicated that larger systems result in more significant CO_2 reduction but lower energy utilisation ratios.

Gurler et al. [69] presented a study on an innovative hybrid heating system for poultry houses, which integrates photovoltaic/thermal (PVT) panels with a polyethene heat exchanger (PHE) connected to a geothermal heat pump system (**Figure 1.6**). Experimental evaluations showed that the heat pump produced 15.02 MWh of thermal energy annually, with the solar panels meeting the pump's annual electrical needs and generating excess electricity exported to the grid. In addition, the annual coefficient of performance was 3.73. In another study, Cui et al. [70] developed a mathematical model using the finite volume method to simulate the same system. The model was verified using experimental results, which showed good agreement. The results showed that the system's electrical yearly and thermal output amounted to 11,867 kWh and 30,245 kWh, respectively. The system can meet the electricity needs of the poultry farm and save about 43.5% of the electricity demand of the heat pump. The maximum electrical efficiency was achieved in July (about 15%) and the minimum in December (about 6.3%).

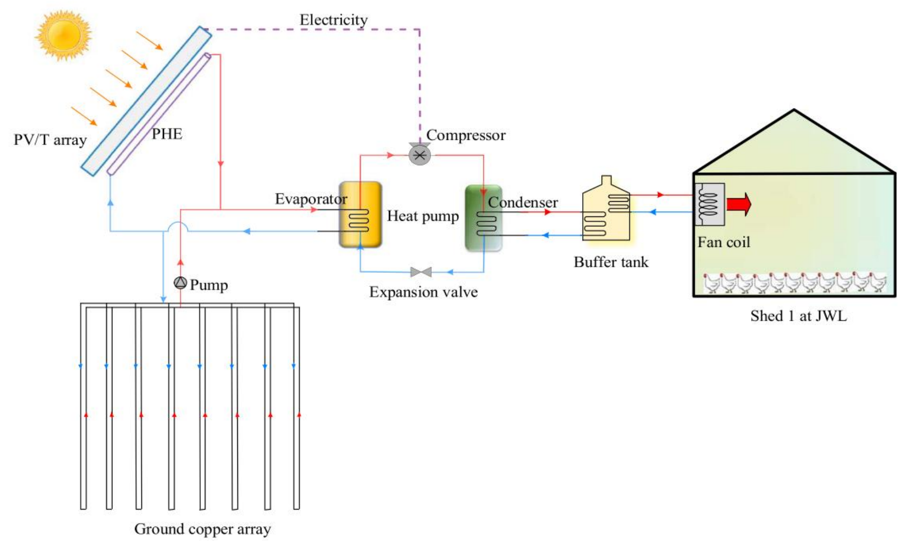


Figure 1.6. Schematic diagram of the hybrid heating system [70].

Omar et al. [71] investigated the possibility of producing energy from poultry farms' waste and using it to meet energy needs. Therefore, a mathematical model was developed using the MATLAB program to simulate energy production from poultry waste, and practical experiments were also conducted on an actual farm to measure the system's efficiency that generates electrical energy from poultry waste using a generator that runs on biogas and then uses a heat exchanger to transfer heat from the exhaust gas to the farm. From the results, the system can generate approximately 19.85 kWh.day^{-1} of electricity and recover 32.28 kWh.day^{-1} of thermal energy from the generator exhaust gas. Biological fermentation also meets about 49% of the farm's energy needs.

Arshad et al. [72] carried out another investigation on the viability of generating electricity from chicken waste in Pakistan. This research delves into the methods for recycling this trash into biogas, which may be used to generate electricity. The author discovered that it is feasible to produce 280 MWh.day^{-1} of electricity utilising the biogas that may be generated from chicken manure. Furthermore, it will lessen the ecological footprint of chicken excrement.

Zhou et al. [73] presented a study focusing on optimising geothermal, solar, and gas-fired hybrid heating systems to reduce life cycle costs and global warming gas emissions, especially for applications such as poultry houses. The approach integrates geothermal heat pumps as the primary heating system, complemented by solar PV panels for electricity generation and LPG burners to meet peak demand. The proposed hybrid system reduced life cycle costs by up to 55% compared to conventional systems. In addition, the hybrid system achieved up to 50% reduction in global warming gas emissions. This was primarily influenced by the optimised use of solar PV panels, significantly reducing dependence on fossil fuels.

1.4.4.3 Cooling and Heating Systems

For the purpose of heating and cooling a poultry house, Laknizi et al. [74] developed and studied an EAHE. The effect of dynamic, physical, and geometrical features on the system's thermal performance was examined in a parametric analysis. In addition, the EAHE was evaluated in terms of its environmental impact. Based on the results, the most efficient and effective heat exchanger specifications were a polyethene tube, 30 m long, 0.1 m in diameter, with air flowing at 2 $m.s^{-1}$. According to the system's energy performance under the climatic conditions of Marrakech, the heating mode can provide 146.38 MWh per year, while the cooling mode can provide 104.3 MWh per year. An estimated 32.2 tons of CO_2 are saved for the environment due to reduced GHG emissions. In another paper, Laknizi et al. [75] developed an air-ground heat exchanger system by integrating it with a mixing box and air-air heat recovery, which are combined to control the temperature inside the poultry house efficiently. According to the findings, the suggested method may reduce energy consumption in heating mode by 34.7% and cooling mode by 96%.

In their study, Doughan and Salam [76] compared experimental data from two types of poultry houses: one using solar collectors and PV panels and the other using a more conventional energy source. Although the implemented energy system helped reduce energy and environmental costs, the results indicated that overall broiler production costs were higher, and revenues were lower.

Elmer et al. [77] developed the innovative heating system proposed by Gurler et al. [69], adding an evaporative cooling system. The results showed that the system provides high energy efficiency, achieving the highest thermal efficiency of 28.3% and the highest electrical efficiency of 16% during the summer, with a capacity to generate 11,967 kWh per year. The system also maintained a temperature of 24°C even in hot outdoor conditions of up to 35°C and a relative humidity of 55%.

Kharseh and Nordell [78] studied an integrated sustainable heating and cooling system based on a geothermal heat pump and solar panels. The results concluded that the combination of solar and geothermal energy led to a significant reduction in energy consumption compared to conventional heating and cooling systems.

Analysing the published papers on RETs in poultry houses (**Table 1.4**) shows that the energy sources exploited in this field include solar, geothermal, wind, and biomass. On the other hand, solar energy was widely exploited in heating or dual-use cooling and heating systems. There were no studies on exploiting solar energy in cooling, while geothermal energy systems were more comprehensive in dual-use cooling and heating. Many studies addressed the study of RETs for heating, while cooling and dual-use systems were the least studied in the research. In addition, some papers discussed the use of integration between different RETs, where integration was done between solar and wind energy and solar and geothermal energy.

Table 1.4. Summary of publications related to RETs in poultry house cooling/heating systems.

Climate zone	Heating Cooling	Source	Energy technology	Aspects of design and technologies	Main findings
Korea [53]	Cooling	Wind	Wind turbine	a turbine with a diameter of 1.5 m.	– System recovered 30% of the energy consumed by the ventilation fan, with an average reduction of 1.5% on the ventilation system.
China [54]	Cooling	Wind	Wind turbine	5 HAWT-300 wind turbines with a diameter of 1.3 m.	– Wind turbine recovers 13.5% of ventilation energy and covers 10.2% of poultry farming's yearly energy needs. – Renewable energy production reduces GHG emissions by about 3.01g$_{CO2eq}$/egg year. – Related energy and GHG emission payback times were 3.36 years and 1.17 years.
Iraq [55]	Cooling	Geothermal	EAHE	2 PVC pipes have a length of 37 m, and a diameter of 0.2 m buried at 2 m depth.	– System's performance in WE was better, whether cooling during the day or heating at night, compared to its performance in DE.
Iraq [57] [56]	Cooling	Geothermal	EAHE	The length of the pipe ranges from 355-410 m. The diameter of the tube ranges from 2 to 6 in [56]. The inner diameter is 0.1016 m [57].	– Larger diameter pipes improve thermal performance. – Grid design provides optimum performance [56]. – Pressure drop rises as the mass flow rate increases, independent of pipe length. – Incoming air temperature decreases as the length of the pipe increases [57].
Lebanon [58]	Cooling	Geothermal	EAHE and DEC system	10 PVC pipes with a length of 14 m and diameter of 0.52 m buried at 4 m depth. 410 DEC channel with 2m ×2 m length and width.	– EAHE/DEC hybrid outperformed the standalone DEC in providing optimal relative humidity, saving 33% of electrical energy and 41% of water consumption. – Cost of the ventilation system is reduced by 40% when using the EAHE/DEC hybrid system.

Turkey [59]			EAHE and DEC system	A 24 m metal pipe with a 0.28 m diameter and a 0.20 m polyethene pipe within. The gap between the pipes is filled with water. The buried depth is 2.5 m. The cooling pad surface is 15 m^2.	– Compared to the conventional system, the EAHE resulted in a 2°C and 10.25% reduction in temperature and humidity at the pad inlet. – Saturation efficiency of the two-stage cooling system is 43%, while that of the conventional cooling system is 42%.
China [60]	Heating	Geothermal	Geothermal heat pump	A collector with 2 pipes reaching a depth of 450 m and a heat pump.	– Maximum difference in the mean indoor air temperature and relative humidity of the conventional heating system and GHP system is 0.5°C and 16.6% respectively, during the experimental period. – The CO2 and NH3 concentration increases were approximately 32.09% and 102.44%, respectively, compared to their concentrations in the GHP system.
China [61]			Geothermal heat pump	HDPE pipe with an inner diameter of 0.026m and a total length of 4500m.	– Smaller the trench separation, the higher the carrier fluid temperature by 0.5°C. Average fluid temperature was 1.5°C lower in the dense slinky loop than in the horizontal straight and slinky loop.
Nigeria [62]		Solar	Trombe wall	-	– Wall helped maintain an internal temperature of 28-35°C. – System improved the average chick's body weight to 0.586 kg, with a 3% mortality rate.
Lebanon [29]			Solar collector and PV panels	The solar collectors have an area of 36m^2. 16 PV panels with a capacity of 280 W. $Panel^{-1}$.	– Green farms require 6,661.58 and 8,711.80 MJ less energy input than conventional farms in warm and cold seasons. – Energy efficiency of the green farm is higher in both seasons than that of a conventional farm.

Lebanon [64]		Parabolic solar concentrator with a thermal storage tank, a shell and tube heat exchanger, and a pump	-	– Parabolic concentrator-based solar system has met 84% of the load needed for a six-week winter flock.
Canda [65]		Unglazed solar air heater	The solar air heater has an area of 73.6 m^2. $floor^{-1}$	– For wind speeds below 2 $m.s^{-1}$, the average efficiency of solar air heaters was 65%; however, for wind speeds above 7 m/s, the efficiency dropped to less than 25%. – Solar air heaters achieved an annual return on investment of 4.7%.
Eygpt [66] [67]		Flat-panel solar collector, heat storage unit, evaporative cooling system [66], PV panel [67].	Absorption surface of flat plate solar collector of 0.9025 m^2 Heat storage unit consists of two water tanks of 300 l capacity. Evaporating pad system surface of 0.3 m^2 Fan with a flow rate of 45 $m^3.min^{-1}$. 8 PV solar panels with a surface of 0.55 $m^2.panel^{-1}$ [67].	– Average weight of chickens was 2.3 kg when using solar heating with ventilation every 2 min [66]. – System contributed to achieving the highest productivity of poultry, with a production weight of 2.29 kg. – System reduced the ammonia concentration to 13.65 ppm in the fifth week. – System reduced the production cost to 1.12 $$.kg^{-1}$ compared to the traditional system [66].
Eygpt [71]	Bioenergy	Fermentation system, cogeneration system, and heat exchanger.	-	– Electrical energy generated by the system was 19.85 kWh per day^{-1}, while the thermal energy recovered from the generator engine was 32.28 kWh per day^{-1}. – Biological fermentation meets about 49% of the farm's energy needs.
Pakistan [72]		-	-	– 280 MWh of electricity can be generated per day from using 95×10^6 $m^3.kg^{-1}$ of biogas produced using 1900×10^6 kg of organic matter.

Central Europe [68]		Solar + Wind	Wind turbine and solar collector	The solar collector area could reach 80 m^2. The turbine diameters could reach 20 m.	– Larger systems result in more significant CO_2. Optimising the design of confined laying hen house insulation requirements in cold climates, without using supplementary heat, but with lower energy utilisation ratios, is also important.
UK [69] [70]		Solar + Geothermal	The hybrid system consists of PVt panels connected to a geothermal heat pump system.	52 PV panels with a capacity of 260 W. $Panel^{-1}$. 4 PHE with a diameter of 4.3mm. The geothermal system comprises 50 copper tubes 2.5m long (3.5m deep) and 15mm in diameter.	– Heat pump produces 15.02 MWh of thermal energy annually. – Annual coefficient of performance was 3.73 [69]. The system gave an annual electrical and thermal output of 11,867 kWh and 30,245 kWh, respectively. – System provided about 43.5% of the electricity demand [70].
Australia [73]			Geothermal heat pump and PV panels	HDPE pipe with an inner diameter of 0.026m and a total length of 4500m.	– GHG emissions are reduced by 50% compared to conventional systems.
Morocco [74]	Cooling and Heating	Geothermal	EAHE	EAHE with polyethene tube, length 30m, diameter 0.1m. Air velocity 2m/s.	– EAHE could decrease the poultry house's yearly energy expenditure by 250.675 MWh, with 146.377 MWh and 104.297 MWh in heating and cooling mode, respectively. – EAHE may reduce GHG emissions by 108.4668 tons $_{of\ CO2}$.$year^{-1}$.
Morocco [75]			EAHE	80 parallel tubes with a diameter and length of 0.2 and 30 m, respectively. Mixing box. An air-to-air heat recovery system consists of a heat exchanger with an efficiency 0.7.	– Proposed system can cover 96% and 34.7% of the cooling and heating demand, respectively.

Lebanon [76]	Solar	Thermal water collectors and PV panels	16 solar collectors with an area of 36 m^2. 16 PV panels of 280 W.	– Conventional system achieved a 5.55% higher total revenue and 2.25% lower total production cost than the solar system.
UK [77]	Solar + Geothermal	Heat pump, PVt, and an evaporative cooling unit.	Heat pump with 15 kW and the PVt system consists of 86 m^2 of PV panels and 48 m^2 of heat exchanger.	– System can achieve high efficiency in summer, with the highest thermal performance of 28.3% and electrical efficiency of up to 16%. – Lowest thermal efficiency in winter was 7.3%, while the electrical efficiency was 14.85%.
Syria [78]		Heat pump and Thermal water collectors	Polyethene U-pipes were installed in 10 boreholes with a diameter of 0.11 m and a depth of 120 m. Thermal solar collectors with an area of 37 m^2.	– System achieved COP of 6.2 and 10 in heating and cooling mode, respectively. – System reduced fuel consumption by 38% and 57.2% compared to the ASHP system alone and ASHP with coal heater. – System payback period was estimated to be between 3 and 5.3 years, with an installation cost of 15,000 $.

1.5 Chapter conclusions

This chapter highlights the importance of providing optimal climatic conditions within poultry houses, their impact on the thermal behaviour of birds, and their direct impact on energy and food consumption. It also discusses strategies for regulating the internal environment through HVAC systems, highlighting the potential limitations of these systems. Consequently, this has motivated researchers to explore more energy-efficient alternatives within the context of NZEB.

Through an extensive literature analysis, strategies for improving energy efficiency in poultry houses are classified into three main categories:

- Pertains to energy-saving strategies (ESSs), which focus on enhancing the building envelope and structural components.
- Involves energy efficiency strategies (EESs), which aim to optimise the performance of operational systems.
- Explores integrating renewable energy technologies (RETs) as alternative or supplementary systems.

Furthermore, the review highlights the importance of studying the thermal behaviour of poultry houses to better understand the impact of various energy sources on overall consumption, thereby facilitating the identification of the most effective strategies for implementation.

The review revealed that studies addressing the use of RETs accounted for 36.82% of the total studies reviewed in this chapter. In contrast, studies focusing on the TBB accounted for 15.49%, while research papers on EESs and ESSs comprised 12.68% and 7.04%, respectively.

With regard to the application of RETs, geothermal energy emerged as the most widely utilised, constituting 30.77% of the studies, followed by solar energy at 23.08%, and biomass and wind energy at 7.69%. The integration of geothermal and solar energy technologies was observed in 15.38% of the studies, while the combination of solar and wind energy appeared in 3.85%.

Despite the progress made in this field, significant research gaps remain, particularly in identifying optimal solutions for poultry houses that take into account changing environmental and production factors, such as bird density, ventilation requirements, and humidity levels, which vary with the growth stage of the poultry. Although the review indicates that various RETs can significantly contribute to reducing energy needs, most studies have examined traditional or typical poultry houses and do not emulate modern industrial poultry farms, which feature advanced designs that contribute to energy savings through the use of advanced HVAC systems.

Considering this point, a gap remains in studying the effectiveness of renewable or alternative systems compared to existing systems in terms of energy savings, reduced consumption, and environmental impact. There is also a lack of studies evaluating the costs of installing sustainable systems, which is critical in this sector and closely linked to economics. Furthermore, studies have examined the effectiveness of renewable systems as stand-alone systems; however, their performance after installation has not been thoroughly studied. Furthermore, there is a lack of information regarding the optimal location for installing the system within the barns.

CHAPTER 2

THERMAL BEHAVIOUR OF AN INDUSTRIAL POULTRY HOUSE

Contents of Chapter 2

Thermal Behaviour of an Industrial Poultry House

2.1 Chapter Outline

Based on the discussions in the previous chapter and the research conducted by experts, this chapter focuses on analysing the thermal behaviour of the studied industrial poultry house. This is to identify appropriate sustainable strategies and calculate the cooling and heating requirements of the building. This chapter covers the following points:

- Provide a comprehensive description of the research site and evaluate its climatic conditions.
- Analysing the selected structure's architectural features, including internal and external conditions.
- Develop a mathematical model to study the thermal behaviour of the building and its cooling and heating requirements.

This chapter presents a comprehensive mathematical model that considers various factors influencing energy consumption in poultry houses.

2.2 Case of study

2.2.1 Description of the Climatic Zone

Biskra is located in the northeastern region of the Algerian Sahara and is known for its importance as an agricultural centre. This region is characterised by its dry and semi-arid desert climate, with very high temperatures during the summer and a moderate to cold climate in the winter.

To assess the feasibility of conducting the study in the Biskra region, a bioclimatic analysis was performed using average annual climate data from 2009 to 2023 [79]. The climatic comfort conditions for each growth period of breeding were assessed in accordance with the information provided in **section 1.2.2**.

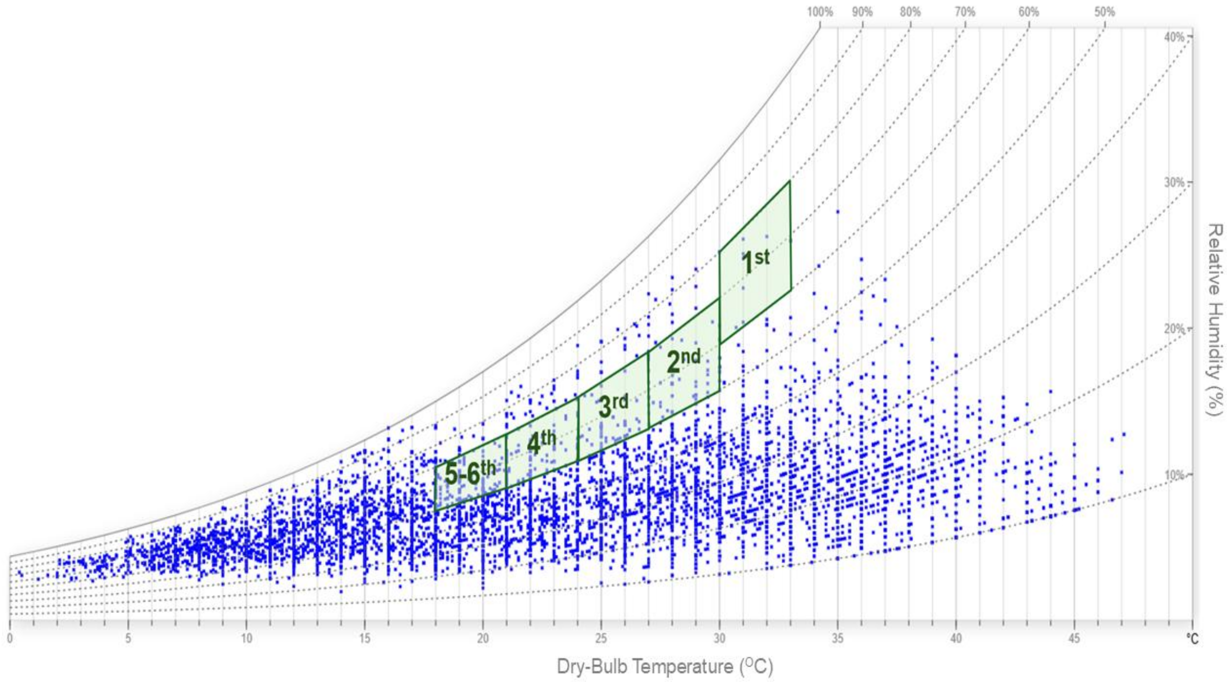


Figure 2.1. Bioclimatic chart of the comfort hours in each growth stage of birds.

As shown in the bioclimatic chart, the number of hours per year that correspond to the comfort climatic conditions was only 13 $h.year^{-1}$ in the first growth stage, 98 $h.year^{-1}$ in the second week, 85 $h.year^{-1}$ in the third week, and between 154 to 283 $h.year^{-1}$ in the last three weeks of growth with a total number of comfort hours was 633 $h.year^{-1}$. This means that 92% of the annual climate conditions in this region are unsuitable for raising poultry, necessitating the implementation of strategies to ensure thermal comfort inside buildings.

Therefore, the application of this study in this region may contribute to finding solutions to these climate challenges and evaluating the effectiveness of the proposed strategies in this context. In addition, Biskra contains a large group of modern poultry farms with insulated structures and equipped with advanced control management systems and modern HVAC systems. This provides an additional opportunity to study the modern technologies available in the global markets in this field, which makes this study compatible with current developments and provides results that may contribute to enhancing these technologies and addressing any potential shortcomings.

A modern poultry house from the farm of Groupe Salem Avicole was selected for the study, where the experimental data were required to be collected accordingly. The farm is located in Sidi Okba, Biskra, Algeria (latitude 34°45′ N, longitude 5°54′ E, height 54 m) and contains 18 modern poultry houses oriented NW-SE as shown in **Figure 2.2**, with a total area of 1496.25 m^2 and a capacity of 20,000 chickens for each building.

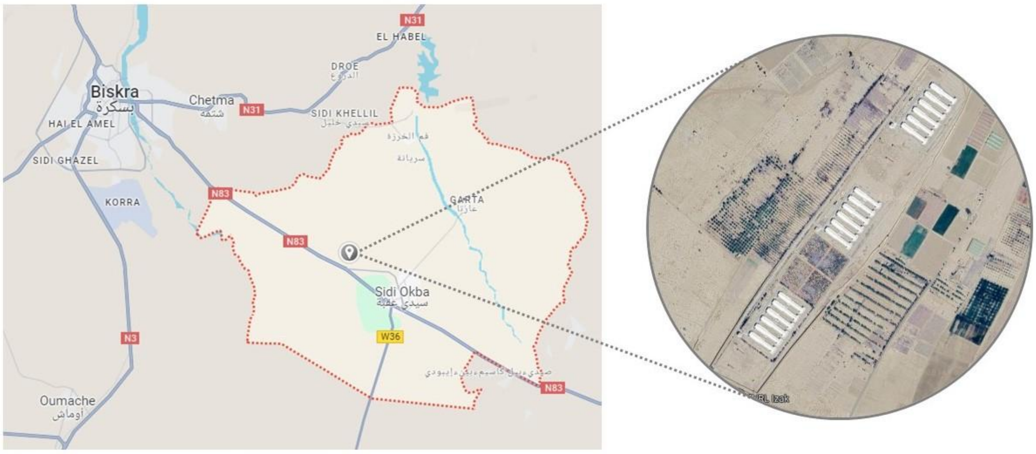


Figure 2.2. Location of Salem Sidi Okba group [80].

2.2.2 Description of the Building

2.2.2.1 Building Characteristics

The building's geometric dimensions are 105 m in length, 14.25 m in width, and 3.225 m in wall height, while the roof has a 20 ° curvature. The overall space of the building is 1496.25 m^2, whereas the useful area occupied by the birds is estimated to be 1425 m^2.

In addition, the NE and SW side walls of the building contain 55 windows with dimensions (0.588 m × 0.3 m) and 4 doors, two on the side walls (NE and SW) with dimensions (2.60 m × 2 m), one separating the useful space from the control room, and the other providing access to the control room with dimensions (1.60 m × 2 m) as shown in **Figure 2.3**.

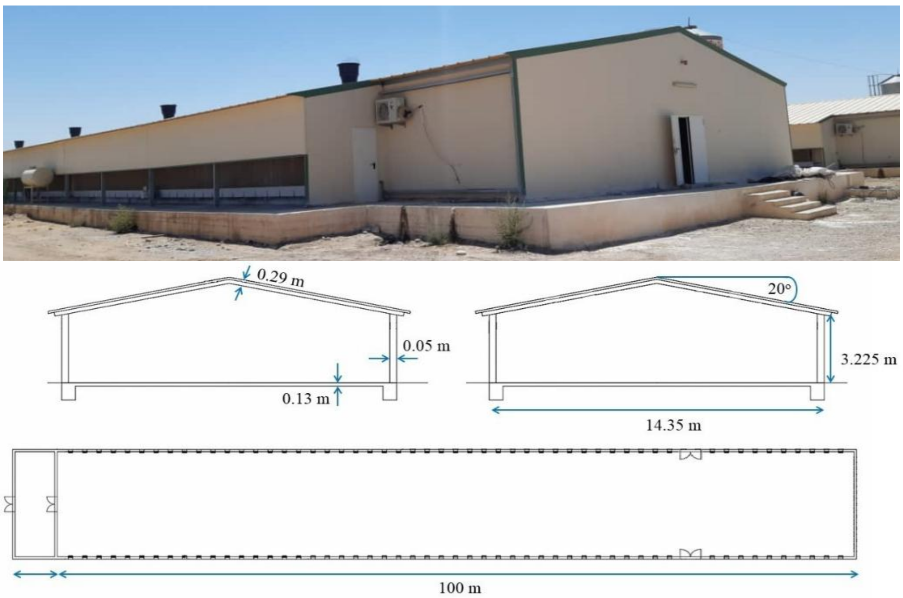


Figure 2.3. Actual photo and schematic showing dimensions of the poultry house.

The walls are made of 0.05 m thick sandwich panels, while the curved roof comprises two layers of sandwich panels, each 0.04 m and 0.05 m thick, with a 0.2 m thick interlayer of glass wool. Furthermore, the house has a 0.13 m thick reinforced concrete floor. The doors are made of two aluminium surface layers with a 0.005 m thick and a 0.06 m thick polystyrene layer in between, whereas the windows consist of two 0.002 m thick polypropylene layers with a 0.01 m thick polystyrene interlayer. The average thermo-physical properties of the analysed building are summarised in **Table 2.1**.

Table 2.1. Physio-thermal properties of different building components.

Components	Orientation	R ($m.W^{-1}$)	$1/h_e+1/h_i$ ($m^2.W^{-1}$)	K_{value} ($W.m^{-2}.K^{-1}$)
Walls	NE	1.96	0.17	0.47
	ES			
	SW			
	WN		0.22	0.46
Roof	-	8.53	0.14	0.12
Floor	-	0.09	0.22	3.26
Doors	NE	1.58	0.17	0.57
	-			
	SW			
	WN		0.22	0.56
Windows	NE	0.28	0.17	2.22
	SW			

2.2.2.2 Building Equipment

The studied building is equipped with a set of HVAC systems, feeding, and lighting systems, as shown in **Figure 2.4**. The cooling system in the farm operates on the tunnel principle, where air is drawn in through four cooling pads (6 m × 1.5 m) and expelled by 14 high-flow exhaust fans (Air-master V130) with a diameter of 1.5 m, installed on the opposite side of the building. In contrast, the heating system comprises four Jet-Master P40-P120 heaters and internal fans (6E50), enabling hot air to circulate throughout the building. **Table 2.2** provides more details of each system.

Figure 2.4. Actual photo inside the building shows part of the systems used in it.

Table 2.2. Systems used in the poultry house.

System	Number of systems	Power (W. system^{-1})
Heating	4	770
Fan	4	540
Exhaust fan	14	1500
Pump	4	750
Feeding	4	550
Lightning	34	32.5

2.2.3 Conditions of study

The selected building was chosen based on a methodology designed to capture the most extreme climatic scenarios, ensuring an accurate assessment of its thermal performance under critical operating conditions. This approach involved analysing climatic data for Biskra to identify the hottest and coldest periods of the year, then cross-referencing these with occupancy data from the farm's database.

Two critical scenarios were considered:

a) The first stages of bird growth coincide with the year's coldest days, which means high internal heating requirements during extremely cold external conditions.
b) The last stages of bird growth coincide with the year's hottest days, when internal cooling requirements are highest during extreme external heatwaves.

Accordingly, both the building and study periods were selected to reflect the worst-case thermal requirements for the breeding process, as shown in the table below.

Table 2.3. Conditions of the study.

Conditions	External		Internal	
Date	07/02/2020 [a]	14/07/2019 [b]	First weeks of growth	Last weeks of growth
Temperature (°C)	4	47	27	22
Velocity (m.s^{-1})	3.06	4.44	0.3	2.5
Chicken Age (day)	-	-	12	31
Airflow (m^3.h^{-1})	-	-	8,028	24,400

a: Third coldest day in 2020; b: The hottest day in 2019.

2.2.4 Experimental measurement

The studied building is equipped with a Big Dutchman Computer Viper Touch, which is a climate computer that monitors and records various environmental factors inside the building by using multiple sensors, including the Dol12 sensor for measuring internal and external temperature, the Dol114 humidity sensor, the Dol19 carbon dioxide sensor, and the Dol53 ammonia sensor. The Viper Touch was used to collect the average internal temperature of the building through four Dol12 temperature sensors (P_1, P_2, P_3, P_4) with an accuracy of +0.5°C distributed at a height of 0.25 m, as shown in **Figure 2.5.**

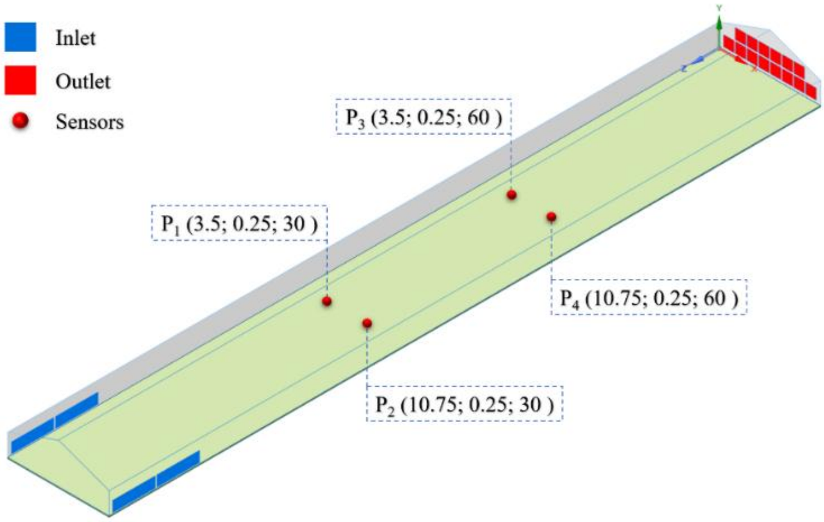


Figure 2.5. Temperature sensor position in the poultry house.

2.3 Building Energy Balance

To evaluate the poultry house's thermal behaviour and estimate the cooling and heating demand, all factors affecting the building's temperature must be taken into account. Current studies lack a comprehensive model that reflects the impact of all heat sources on the building (**section 1.4.1**). Therefore, in this chapter, a comprehensive mathematical model has been developed that addresses this gap by accurately identifying the sources of heat losses and gains including: heat gain from solar, chickens, equipment, lighting, workers, heat transmission through the building's structure, and heat loss through ventilation, which enhances the ability to estimate heat requirements more accurately (**Figure 2.6**). The model developed is specifically designed for this type of building and is based on the Algerian Technical Document for Building Regulation (DTR) as its primary reference.

The following assumptions were considered:

- Air infiltration and thermal bridges are negligible due to the building's high-quality construction and effective sealing.
- Internal temperature in the building is uniform.
- Windows are closed during the summer.

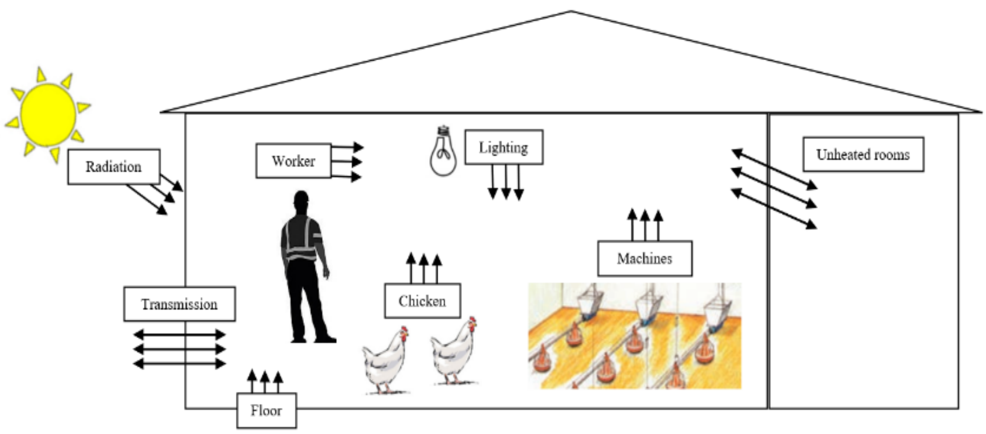


Figure 2.6. Illustration of the energy balance equation for poultry houses, showing energy gain and loss sources.

2.3.1 Heating demand

The heating load Q_{Heat} (W) represents the amount of energy required to maintain indoor temperatures at a desired level during cold periods. It is calculated as:

$$Q_{Heat} = \left[\left(1 + \mathrm{Max}\,(c_r, c_{in})\right) \phi_T + (1 + c_r)\, \phi_R\right](T_{int} - T_{ext}) \quad (2.1)$$

Where:

- ϕ_T : Heat loss due to transmission through the building envelope (W. °C^{-1}).
- ϕ_R : Heat loss due to ventilation and infiltration (W. °C^{-1}).
- c_r : Ratio of heat losses due to the possible piping network. In this study, c_r=0 [81].
- c_{in} : Overpower coefficient. In this study, c_{in}=0.15 [81].
- T_{int} : Internal base temperatures (°C).
- T_{ext} : External base temperatures (°C).

The heat losses by transmission refer to the heat loss through structural elements, such as walls, floors, roof, windows, and doors. The extent of this loss depends on the properties of the materials' insulation, the surface area of the elements, and the temperature difference between the interior and exterior. It is given as follows:

$$\phi_T = \phi_S + \phi_L + \phi_G + \phi_U \quad (2.2)$$

Where:

- ϕ_S : Surface heat loss through the walls in contact with the outside (W. °C^{-1}).
- ϕ_L : Heat loss through thermal bridges (W. °C^{-1}).
- ϕ_G : Heat loss through the floor (W. °C^{-1}).
- ϕ_U : Heat loss through walls in contact with unheated rooms (W. °C^{-1}).

The surface heat losses through the walls in contact with the outside ϕ_S (W. °C^{-1}) are given by:

$$\phi_S = \sum(A.\, K_{win}) \quad (2.3)$$

Where:

- K_{win} : Surface transmission coefficient in winter (W.m^{-2}.°C^{-1}).
- A : Wall surface (m^2).

The losses by thermal bridges ϕ_L (W. °C^{-1}) can be evaluated as 20% of the surface heat losses by transfer through the walls:

$$\phi_L = \sum(l.\, k_l) = 0.20 \sum(A.\, K_{win}) \quad (2.4)$$

Where:

- k_l : Linear transmission coefficient (W.m^{-1}.°C^{-1}).
- l: Internal length of the thermal bridge (m).

The heat losses through the floor ϕ_G (W. °C^{-1}) are determined by:

$$\phi_G = P_{er}.k_g \quad (2.5)$$

Where:

- k_g : Linear transmission coefficient of the low floor or the wall is given according to the level difference z (W.m^{-1}.°C^{-1}). In this study, $k_g = 1.75$ [81].
- P_{er} : Perimeter (m).

An unheated room refers to any space that lacks a heating system or experiences prolonged periods of interrupted heating. It also includes areas where heating is only provided intermittently and the losses through walls in contact with unheated rooms ϕ_U (W. °C^{-1}) are calculated by:

$$\phi_U = T_{au}(\sum \phi_S + \sum \phi_L) \quad (2.6)$$

Where T_{au} is the temperature reduction coefficient and given by:

$$T_{au} = \frac{\phi_{UHR}}{\phi_{UHR} + \phi_{HR}} \quad (2.7)$$

ϕ_{HR} (W) are the heat gains from the various heated rooms to the unheated room are calculated by:

$$\phi_{HR} = \sum(A.K_{win}) + \sum(L.k_l) \quad (2.8)$$

While ϕ_{UHR} (W. °C^{-1}) is the losses from the unheated room to the outside, and given by:

$$\phi_{UHR} = \sum(A.K_{win}) + \sum(L.k_l) + \phi_r \quad (2.9)$$

And ϕ_r (W. °C^{-1}) are the losses by air renewal in the unheated room are calculated by:

$$\phi_r = 0.34\, N.V \quad (2.10)$$

Where:

- N : Hourly air renewal rate for the volume of the unheated room (h^{-1}). In this study, N=0.5 [81].
- V : Volume of the unheated room (m^3).

Heat losses due to air renewal ϕ_R (W.°C^{-1}) are the energy lost when cool, fresh air replaces warm indoor air in the building. This process typically occurs through ventilation systems, whether natural or mechanical. The amount of heat lost depends on factors such as the temperature difference between the indoor and outdoor air and the ventilation rate, and is calculated as follows:

$$\phi_R = \phi_{RV} + \phi_{RS} \quad (2.11)$$

Where:

- ϕ_{RV} : Losses due to the normal operation of the ventilation devices (W.°C^{-1})

- ϕ_{RS} : Air loss due to wind (W.°C^{-1}). In this study, it is negligible because the air enters the building only through ventilation devices at high external temperatures.

The losses due to the normal operation of the ventilation devices ϕ_{RV} (W.°C^{-1}) are calculated by:

$$\phi_{RV} = 0.34\ q_v \tag{2.12}$$

Where:

- 0.34 : Volumetric heat of air (Wh.m^{-3}.°C^{-1})
- q_v : Minimum ventilation rate in the poultry house (m^3.h^{-1}).

2.3.2 Cooling Demand

Cooling requirements refer to the capacity to remove excess heat within a building, ensuring thermal comfort, including both sensible and latent heat.

Total sensitive $\phi_{T_{sen}}$(W) and latent heat gains $\phi_{T_{lat}}$ (W) are given by:

$$\phi_{T_{sen}} = \left(C_{\Delta a,sen}.\phi_{sen}\right) \tag{2.13}$$

$$\phi_{T_{lat}} = \left(C_{\Delta a,lat}.\phi_{lat}\right) \tag{2.14}$$

Where:

- $C_{\Delta a,sen}$: Sensitive major coefficient. In this study, $C_{\Delta a,sen} = 1.15$ [81].
- $C_{\Delta a,lat}$: Latent major coefficient, in this study, $C_{\Delta a,lat} = 1.1$ [81].
- ϕ_{sen} : Sensitive heat gains (W).
- Φ_{lat} : Latent heat gains (W).

Total sensible heat gain ϕ_{sen} (W) refers to increased indoor temperature, whether due to internal factors such as birds, electrical appliances, lighting, or workers or external factors such as heat transfer through the building structure. It can be calculated as follows:

$$\phi_{sen} = \phi_{OW} + \phi_{GW} + \phi_{I_{sen}} \tag{2.15}$$

Where:

- ϕ_{OW} : Heat gains through opaque walls (W).
- ϕ_{GW} : Heat gains through a floor in contact with the ground (W).
- $\phi_{I_{sen}}$: Total internal heat gains (W).

The heat gained by the opaque walls ϕ_{OW} (W) take into account the temperature difference between the faces of the walls, the sunshine, the damping, and the phase shift in the wall of the induced heat flow [81]:

$$\phi_{OW}(t) = 1.2\ K_{sum}.A.\Delta t_e(t) \tag{2.16}$$

Where:

- 1.2 : Increasing coefficient considering the linear lateral contributions (through thermal bridges).
- K_{sum} : Surface transmission coefficient in summer (W.m^{-2}.°C^{-1}).
- Δt_e (t) : Equivalent temperature difference at time t (°C).

The equivalent temperature difference Δt_e (t) is given by:

- For the sunny wall:

$$\Delta t_e(t) = \Delta t_{es}(t) + C_{\Delta te} + \frac{\alpha}{0.9}\left(\Delta t_{em}(t) - \Delta t_{es}(t)\right)\frac{I_{t,b}}{I_{t,b}(40)} \quad (2.17)$$

- For the wall in the shade 24/24 h:

$$\Delta t_e(t) = \Delta t_{es}(t) + C_{\Delta te} \quad (2.18)$$

Where:

- $\Delta t_{es}(t)$: Temperature difference equivalent to an hour, considering that the wall is in the shade (°C).
- $\Delta t_{em}(t)$: Equivalent temperature difference at time t for the orientation of the wall considered (°C).
- $C_{\Delta t_e}$: Increasing coefficient of gains (°C).
- α : Absorption factor of the wall. In this study, α = 0.5 [81].
- $I_{t,b}$: Total base radiation for the month, latitude, and orientation considered (W.m^{-2}).
- $I_{t,b}(40)$: Total base radiation for July, latitude 40° north, and the orientation considered (W.m^{-2}).

The values of each of the following constants, $\Delta t_{em}(t)$, I, $I_{t,b}$, and $I_{t,b}$ (40), are taken from DTR [81].

The gains through a floor in contact with the ground ϕ_{GW} (W) are calculated as follows:

$$\phi_{GW} = K_{sum}.A.\left(T_m - T_{int,b}\right) \quad (2.19)$$

Where:

- T_m: Outside medium temperature (°C).
- $T_{in,b}$: Inside base temperature (°C).

The sensitive internal heat gains $\phi_{I_{sen}}$(W) given by:

$$\phi_{I_{sen}} = \phi_{sen,bird} + \phi_{sen,oc} + \phi_{elec,m} + \phi_{light} \quad (2.20)$$

Where :

- $\phi_{sen,bird}$: Sensitive heat gains generated by chicken (W).
- $\phi_{sen,oc}$: Sensitive occupant gain (W).
- $\phi_{elec,m}$: Heat gain due to machines driven by an electric motor (W).

- ϕ_{light} : Heat gain by lighting (W).

The sensitive heat production of chicken can be calculated according to Silva et al.[82] as shown below:

$$\phi_{tot,bird} = 9.84\ m_{bird}^{0.75}\left(4.10^{-5}\left(20 - T_{int,b}\right)^3 + 1\right) \tag{2.21}$$

$$\phi_{sen,bird} = 0.83\ \phi_{tot,bird}\left(0.8 - 1.85.10^{-7}\left(T_{int,b} + 10\right)^4\right) \tag{2.22}$$

Where m (kg) is bird mass.

The sensitive occupant gains:

$$\phi_{sen,oc} = n.C_{sen,oc} \tag{2.23}$$

Where:

- n : Number of workers.
- $C_{sen,oc}$: Sensitive heat generated by occupants (W). In this study, $C_{sen,oc} = 100$ [81].

The gains due to machines driven by an electric motor are calculated by:

$$\phi_{elec,m} = W_a = \frac{W_{eff}}{\eta} \tag{2.24}$$

Where:

- W_{eff} : Nominal power (W).
- η : Efficiency of the motor. In this study, $\eta = 0.72$ [81].

Lighting gains are given by:

$$\phi_{light} = \sum(W_n.C_{me}.C_{cr}) \tag{2.25}$$

Where:

- W_n : Nominal wattage of a bulb or fluorescent tube (W).
- C_{me} : Coefficient of increase, in this study, $C_{me} = 1.2$ [81].
- C_{cr} : Residual heat corresponding to the share of energy remaining in the room %, in this study, $C_{cr} = 1$ [81].

Latent heat gains are a key component in calculating cooling needs within poultry buildings. They arise from the presence of moisture in the ambient air. This requires additional cooling to remove excess moisture and maintain a suitable environment. These gains include heat generated by the bird's biological activities, such as respiration, as well as human activities, such as breathing and perspiration. These gains are calculated based on the following equation:

$$\phi_{I_{lat}} = \phi_{lat,bird} + \phi_{lat,oc} \tag{2.26}$$

Where:

- $\phi_{lat,oc}$: Latent heat generated by the occupants inside the building (W).
- $\phi_{lat,bird}$: Latent heat generated by the birds inside the building (W).

The latent occupant gains are given by:

$$\phi_{lat,oc} = n.\, C_{lat,oc} \tag{2.27}$$

Where $C_{lat,oc}$ is latent heat generated by occupants (W), in this study, $C_{lat,oc} = 120$ [81].

The latent heat production of chicken can be calculated as:

$$\phi_{lat,bird} = \phi_{tot,bird} - \phi_{sen,bird} \tag{2.28}$$

The following calculation chart is provided to show the data supplied and the calculation steps made to determine the poultry house's thermal requirements:

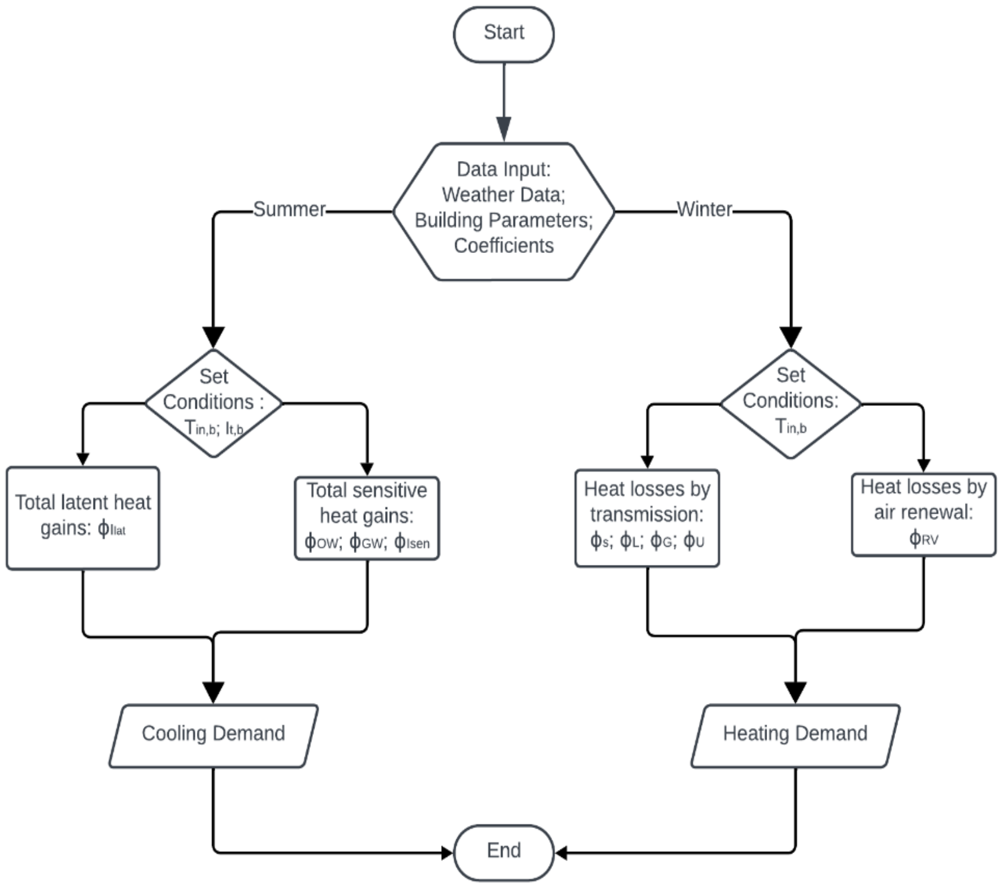


Figure 2.7. Calculating flowchart of the thermal requirements of a poultry house.

2.4 Results and Discussions

The thermal balance assesses the building's energy inputs and outputs over a specific period. It serves to:

- Determine energy consumption for heating and cooling.
- Analyse the various heat flows through the building envelope, including internal and external losses and gains.
- Assist in sizing the technical systems required for heating and cooling.

2.4.1 Heating Required

To estimate the total thermal energy demand required to maintain optimal indoor environmental conditions, the distribution of heat loss within a poultry house was analysed to assess the contribution of various building envelope components. The study comprehensively evaluates heat transfer through the building envelope and losses resulting from ventilation and adjacent unheated areas, as shown in **Table 2.4**.

Conduction through the walls, windows, doors, and roof results in a combined heat loss of 541.66 W.°C^{-1}. The NE and SW sections exhibit the highest thermal losses among the walls, each measured at 144.57 W.°C^{-1}. This is primarily attributed to their relatively large surface areas and greater exposure to external environmental conditions. Windows also contribute to conductive heat loss, with each unit accounting for 21.53 W.°C^{-1}.

The estimated heat loss through the floor is 399.88 W.°C^{-1}, a considerable value that highlights the need for improved floor insulation to enhance thermal efficiency and reduce energy consumption. Additionally, net heat loss to adjacent unheated areas is projected at 18.13 W.°C^{-1}, typically resulting from direct contact between conditioned and unconditioned spaces lacking adequate thermal separation.

However, ventilation emerges as the predominant source of heat loss, contributing 2,729.52 W.°C^{-1}. This underscores the substantial thermal load associated with air exchange required to maintain air quality and suitable environmental conditions in livestock housing.

Based on these findings, the total heating power required to sustain appropriate thermal conditions within the poultry house is estimated at approximately 99.661 kW. In percentage terms, as shown in **Figure 2.8**, ventilation accounts for about 74% of the total heat loss, while transmission through the building envelope comprises roughly 26%. These results highlight the critical role of ventilation in the building’s thermal energy demand and point to the potential for energy savings through targeted improvements in envelope insulation.

Table 2.4. Heat losses and heating requirements in the poultry house.

Transmission losses				
	A (m^2)	K_{win} ($W.m^{-2}.°C^{-1}$)		ϕ_S ($W.°C^{-1}$)
Wall NE	**307.60**	**0.47**		**144.57**
Wall ES	**45.96**	**0.47**		**21.60**
Wall SW	**307.60**	**0.47**		**144.57**
Wall WN	42.76	0.46		19.67
Window NE	**9.70**	**2.22**		**21.53**
Window SW	**9.70**	**2.22**		**21.53**
Door NE	**5.20**	**0.57**		**2.96**
Door SW	**5.20**	**0.57**		**2.96**
Door WN	3.20	0.56		1.79
Roof	**1516.00**	**0.12**		**181.92**
Transmission losses through the walls in contact with the outside ϕ_S ($W.°C^{-1}$)				**541.66**
Heat losses through the floor				
	Per (m)	k_g (W/m^2. °C)		ϕ_G ($W.°C^{-1}$)
Floor	228.5	1.75		399.88
Losses through the walls in contact with unheated rooms				
	A(m^2)	K_{win} ($W.m^{-2}$. $°C^{-1}$)	ϕ_S ($W.°C^{-1}$)	ϕ_r ($W.°C^{-1}$)
Wall NE	**16.13**	**0.47**	**7.58**	
Wall ES	42.76	0.46	19.67	
Wall SW	**16.13**	**0.47**	**7.58**	
Wall WN	**42.76**	**0.47**	**20.10**	**70.49**
Door ES	3.20	0.56	1.79	
Door WN	**3.20**	**0.57**	**1.82**	
Roof	**76.00**	**0.12**	**9.12**	
Losses from the unheated room to the outside ϕ_{UHR} ($W.°C^{-1}$)				**116.70**
Gains from the heated rooms to the unheated room ϕ_{HR} ($W.°C^{-1}$)				21.38
	T_{au}	ϕ_S ($W.°C^{-1}$)		ϕ_U ($W.°C^{-1}$)
Wall ES	0.84	19.67		16.61
Door ES	0.84	1.79		1.51
Losses through the walls in contact with unheated rooms ϕ_U (W/°C)				18.13
Heat losses due to air renewal				
q_v($m^3.h^{-1}$)	(ρ.cp)/3600	ϕ_{RV} (W/°C)		
8028	0.34	2729.52		
HEATING POWER		**99661.43 W**		

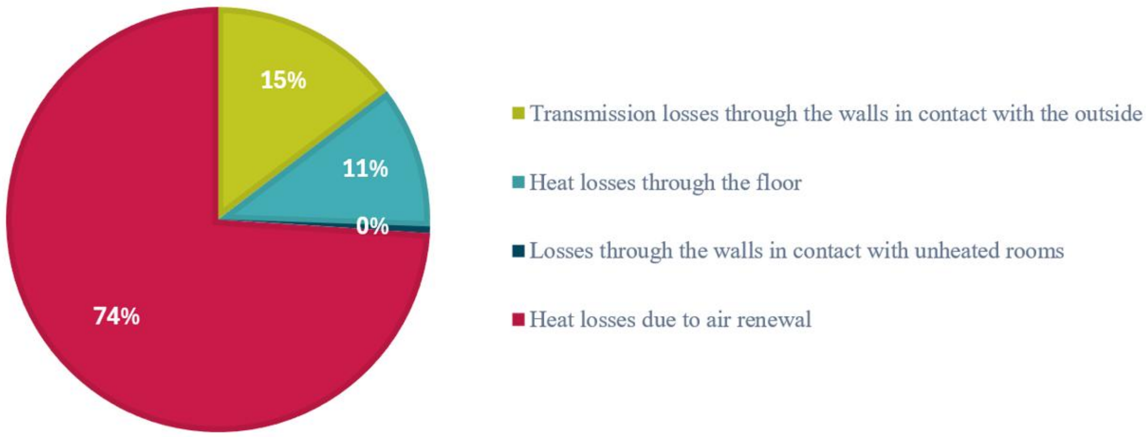


Figure 2.8. Heat losses from building components.

2.4.2 Cooling Required

Table 2.5 presents a detailed overview of the heat gains affecting the studied poultry house, which originate from external and internal sources. External gains include solar radiation and ambient heat transferred through the building envelope, while internal sources comprise metabolic heat produced by the poultry, in addition to heat generated by equipment operation and human occupancy.

The analysis indicates that the combined heat gains through the building's walls, windows, doors, and roof amount to approximately 16.012 kW. Among the walls, the NE and SW facades exhibited the highest heat transfer rates. The roof accounts for an additional 5.296 kW of heat gain, primarily due to its direct exposure to solar radiation. Furthermore, the floor was identified as a major contributor to external heat gains, with an estimated value of 75.846 kW.

In contrast, internal heat gains were found to be substantially higher. Notably, the metabolic heat generated by the poultry amounted to 301.134 kW, representing the dominant source of internal heat. Based on these values, the total cooling load required to maintain appropriate thermal conditions within the facility is estimated at approximately 448.964 kW.

According to the analysis in **Figure 2.9**, the internal sources account for approximately 77% of the total heat load entering the structure. Of this proportion, the metabolic heat emitted by the birds alone constitutes nearly 76%, highlighting its critical role in the overall thermal balance. In comparison, the contributions from equipment, lighting, and human presence are minimal and may be considered negligible relative to the heat produced by the animals. With regard to external gains, heat transfer through the walls and roof remains relatively low, largely due to the effectiveness of the installed insulation. However, the floor continues to be a significant pathway for external heat gain, underscoring the importance of improving subfloor insulation to enhance overall energy efficiency.

Table 2.5. Heat gains and cooling requirements in the poultry house.

Gains through the walls				
	Δte (t) (ºC)	A(m^2)	K_{sum} (W/m^2. ºC)	ϕ_{OW} (W)
Wall NE	19.70	307.60	0.48	3460.98
Wall ES	19.85	45.96	0.48	521.13
Wall SW	27.15	307.60	0.48	4771.05
Wall WN	19.31	42.76	0.46	456.28
Window NE	19.70	9.70	2.37	544.28
Window SW	27.15	9.70	2.37	750.31
Door NE	19.70	5.20	0.58	71.50
Door SW	27.15	5.20	0.58	98.57
Door WN	19.31	3.20	0.56	41.44
Roof	25.42	1516	0.11	5296.99
	Total gains through the walls			16012.54
Inputs through a floor in contact with the ground				
	T_m(ºC)	A(m^2)	K_{Sum} (W/m^2. ºC)	ϕ_{GS} (W)
Floor	33	1425	4.84	75846.77
Internal gains				
Chickens	--			
m_{chick} (kg)	nº	$\phi_{tot,chick}$ (W)	$\phi_{sen,chick}$ (W)	$\phi_{lat,chick}$ (W)
1,585	20000	301134.16	151467.82	149666.34
Electric motor	--			
nº	W_{eff} (W)		η	$\phi_{elec,m}$ (W)
4	550		0.72	3055.5555
Occupants	--			
nº	$C_{sen,oc}$ (W)	$C_{lat,oc}$ (W)	$Q_{sen,oc}$ (W)	$Q_{lat,oc}$ (W)
1	100	120	100	120
Lighting	--			
nº	W_n (W)	C_{me}	C_{cr}	Q_{light} (W)
34	32.5	1.2	1	1326
Sensitive and Latent internal gains				
	C_s	N_{AI}	Q_s (W)	QI_s (W)
Chickens	1	1	151467.82	151467.82
Electric motor	0.85	1	3055.56	2597.22
Occupants	0.90	1	100	90
Lighting	0.85	1	1326	1127.1
	Total sensitive internal gains			155282.14
	C_l	Q_l (W)		QI_l (W)
Chickens	1	149666.34		149666.34

Occupants	0.90	120	108
	Total latent internal gains		149774.34
Cooling Power			
$C_{\Delta as}$	$C_{\Delta al}$	QT_S (W)	QT_L (W)
1.15	1.1	284212.67	164751.78
COOLING POWER			**448964.45 W**

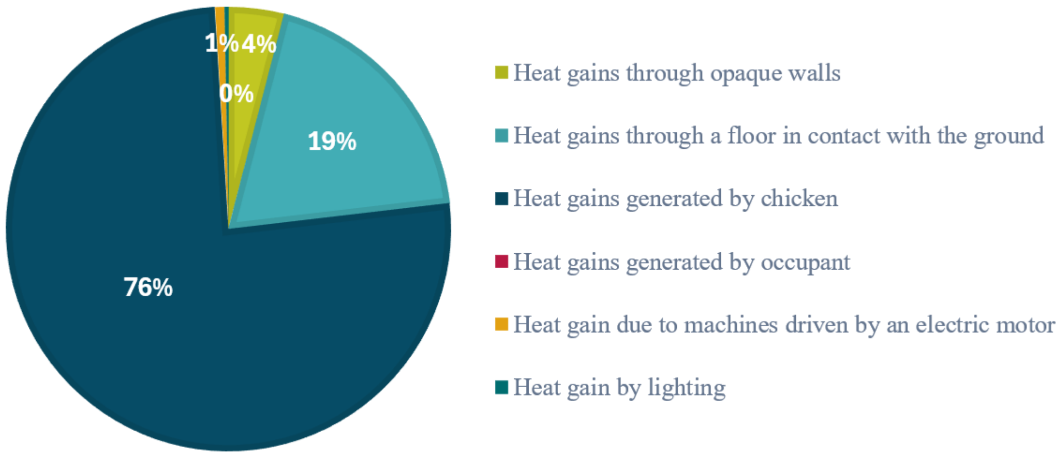


Figure 2.9. Heat gains from building components.

2.5 Chapter Conclusion

This chapter reviews the feasibility of the study and presents the reasons for selecting the Biskra region. Thermal comfort hours for poultry in this region were analysed over 14 years. The results showed that 92% of annual hours fall outside the thermal conditions suitable for poultry farming. An analysis of thermal comfort hours for poultry was conducted over 14 years. The results revealed that 92% of the annual hours fall outside the optimal temperature range for poultry production.

The building under study was selected based on its extreme indoor and outdoor conditions, which require significant cooling and heating efforts. Experimental temperature data were collected, and a comprehensive mathematical model was developed that takes into account all heat sources involved in calculating the building's thermal requirements. This model was specifically designed to suit the characteristics and operational requirements of this type of industrial building.

Results demonstrate that the developed model allows for a detailed analysis of the thermal performance of each building component, providing clearer insight into the sources of heat gain and loss. This, in turn, supports the identification of effective strategies to optimise energy saving. Moreover, the model enabled accurate estimation of the thermal loads required for both cooling and heating, which were calculated to be 448.964 kW and 99.661 kW, respectively. The significantly higher cooling demand, approximately 4.5 times greater than that of heating, is primarily attributed to the climatic conditions of Biskra, characterised by a hot, dry desert environment and prolonged periods of high ambient temperatures. This disparity is also influenced by the specific thermal requirements of poultry at different growth stages: heating needs were evaluated during the early life stages, when only minimal warm airflow is required, whereas cooling needs were assessed during the last weeks of growth, when the demand for cooler airflow increases substantially due to higher heat production.

The highest heat loss occurred through air renewal, accounting for approximately 74%, followed by the walls at 15%. In terms of heat gains, the heat produced by the poultry represented the largest at 76%, followed by heat gains through the floor at 19%.

These findings underscore the crucial need to enhance thermal insulation in both walls and floors, as well as to implement a ventilation system that delivers air at controlled temperatures according to demand. Such measures are vital for achieving optimal thermal conditions within the facility, reducing energy consumption, and minimising thermal stress in the poultry environment.

CHAPTER 3

NUMERICAL MODELLING OF THE EARTH AIR HEAT EXCHANGER

Contents of Chapter 3

Numerical Modelling of the Earth Air Heat Exchanger

3.1 Chapter outline

This chapter is a key part of the study, based on the discussions presented in the previous chapters. It aims to address the research gaps highlighted in Chapter 1 by exploring some scientific aspects that have not yet been fully covered.

In this context, the chapter focuses on applying Net-Zero Energy Poultry Building (NZEPB) strategies using renewable energy technologies (RETs) to meet the thermal requirements of a modern industrial poultry house based on the findings of the previous chapter.

To systematically achieve these objectives, the following methodology was employed:

- Selecting the appropriate RET for the case study.
- Developing a numerical model to simulate the profile of the soil temperature and determine the optimal installation depth.
- Developing a mathematical model to define the appropriate system dimensions aligned with the building's operational needs.
- Comprehensive evaluation of the proposed system’s performance in terms of energy efficiency, economic viability, and environmental impact.

This chapter studies the proposed system as an independent unit based on its outputs. Its ability to meet the building thermal requirements was analysed, and its performance was compared to the conventional HVAC systems currently in the building.

3.2 Proposed system:

The previous scientific studies indicate various RETs that can be exploited in poultry houses, such as solar, geothermal, wind, and bioenergy. However, the efficiency of these systems is closely linked to their compatibility with the characteristics of the target area, local consumption needs, economic costs, and sustainable maintenance. Therefore, selecting the region's most appropriate renewable energy sources is paramount.

3.2.1 Selecting the appropriate RET

Biskra is one of Algeria's regions rich in diverse natural resources, making it a fertile environment for developing RETs. Its high solar radiation makes it an ideal environment for solar energy generation [83]. The region is also known for its thriving palm cultivation, livestock, and poultry farming, providing abundant biomass resources that can be exploited for bioenergy production. Furthermore, Biskra has been classified as a promising area for exploiting wind energy due to its high wind speeds [84, 85]. On the other hand, geothermal energy has received significant attention from researchers at the University of Biskra, where studies have demonstrated its promising potential, making it an important focus of scientific research in the region [86-89].

Geothermal energy was chosen in this study for several reasons, most notably its technical simplicity compared to wind energy and bioenergy, which require multiple steps and conversion processes, in addition to its heavy reliance on the availability of biomass, which may be affected by seasonal changes and high demand [90, 91]. Despite the abundant availability of solar energy, some environmental factors, such as sandstorms [92, 93] and high temperatures during the summer [94-96], can negatively affect the efficiency of photovoltaic systems. Furthermore, solar thermal energy is limited to heating purposes, reducing its effectiveness in some applications. Given the sensitivity of the poultry sector to temperature fluctuations, choosing a stable energy source not affected by changing climatic conditions is ideal, making geothermal energy more reliable and sustainable within the region's local context.

3.3 Methodology

To study the EAHE system as a suitable unit for poultry houses, it is necessary to determine the optimal burial depth of the system based on the appropriate temperature range (**Figure 3.1**). Following this, the dimensions that ensure the required conditions must be determined while considering the economic aspects to achieve an optimal balance between performance and cost. Therefore, the following steps were taken:

- First, a mathematical model was developed to simulate the soil temperature distribution at various depths to determine the optimal burial depth.
- Second, a mathematical model was built to determine the appropriate dimensions for the EAHE system based on the required internal conditions, considering airflow rates and temperature variations throughout the poultry growth stages.

The assumptions adopted in the mathematical models were:

- Soil is a homogeneous environment.
- Soil moisture level is neglected.
- Pipe's outer surface temperature is constant.

– Air velocity is assumed to be constant throughout the pipes.
– Thermophysical properties of the air are calculated using correlations from the literature.

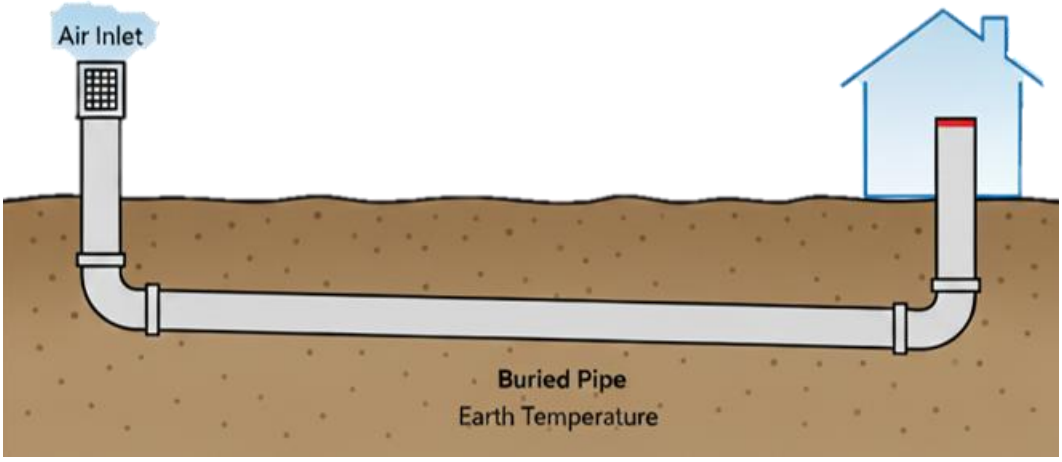


Figure 3.1. Scheme of the EAHE system.

3.4 Mathematical model

3.4.1 Soil model

The model presented by Al-Ajmi et al. [15] and Florides et al. [16] was used to estimate soil temperature at multiple depths throughout the year T_{soil}, where it shows that soil temperature is affected by two main factors: air temperature variation and the soil depth. This relationship can be represented mathematically by the following equation:

$$T_{soil}(z,t) = T_{avg} - T_{amp}.\exp\left(-z.\sqrt{\frac{\pi}{365.\varphi}}\right).\cos\left(\frac{2\pi}{365}.\left(t - t_o - \frac{z}{2}\sqrt{\frac{365}{\pi.\varphi}}\right)\right) \quad (3.1)$$

- T_{avg} : Average surface temperature (°C).
- T_{amp} : Surface temperature amplitude calculated as (T_{max} - T_{min})/2 (°C).
- z: Depth below the ground surface (m).
- φ : Thermal diffusivity of the soil ($m^2.day^{-1}$).
- t : Time of observation (day).
- t_o : Day of the year of the minimum surface temperature (day).

3.4.2 EAHE model

The numerical model used to calculate the outlet temperature of the EAHE system was developed based on the heat transfer equation [6, 15, 16]:

$$\dot{m}_{air}.cp_{air}\frac{DT}{Dt} = \frac{\Delta T}{R_{total}} \quad (3.2)$$

Where the energy balance equation between two pipe sections separated by Δx distance can be expressed as:

$$\dot{m}_{air}.\,cp_{air}\frac{DT}{Dt} = \frac{(T_{soil}-T_{air}(x))}{R_{total}} \tag{3.3}$$

The transformation to Eulerian form gives:

$$\dot{m}_{air}.\,cp_{air}\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x}\right) = \left(\frac{T_{soil}-T_{air}(x)}{R_{total}}\right) \tag{3.4}$$

In this study, the system is analysed under steady-state conditions:

$$\rho_{air}.\,A.\,\Delta x.\,cp_{air}.\,u.\frac{dT}{dx} = \left(\frac{T_{soil} - T_{air}(x)}{R'_{total}}\right).\,\Delta x \tag{3.5}$$

Rearranging the equation allows the separation of temperature and spatial variables, leading to the differential form presented as follows:

$$\frac{1}{(T_{air}(x)-T_{soil})}dT = -\frac{dx}{\rho_{air}\pi.r^2.u.cp_{air}.R'_{total}} \tag{3.6}$$

By integrating both sides of the equation, the solution takes the logarithmic form shown in equation (7), where C is the constant of integration.

$$\ln\ (T_{air}(x) - T_{soil}) = -\frac{x}{\rho_{air}.\pi.r^2.u\ .cp_{air}.R'_{total}} + C \tag{3.7}$$

To determine the value of C, the boundary condition at x=0 is used, where $T_{air}(x = 0) = T_{amb}$

which provides: $C = \ln\ (T_{amb} - T_{soil})$

Replacing the constant in the logarithmic expression gives a relation between air temperature and distance along the pipe as follows:

$$\ln\left(\frac{T_{air}(x)-T_{soil}}{T_{amb}-T_{soil}}\right) = -\frac{x}{\rho_{air}.\pi.r^2.u\ .cp_{air}.R'_{total}} \tag{3.8}$$

Solving this expression yields the final formula that describes how the air temperature evolves as it moves through the buried pipe, based on the heat exchange with the surrounding soil.

$$T_{air}(x) = T_{soil} + (T_{amb} - T_{soil}).\exp\left(-\frac{x}{\rho_{air}.\pi.r^2.u.cp_{air}.R'_{total}}\right) \tag{3.9}$$

Noting that R'_{total} is the total thermal resistance per unit length, given that the total thermal resistance can be expressed by:

$$R_{total} = R_{soil} + R_{pipe} + R_{air} \tag{3.10}$$

The thermal resistance associated with conductive heat transfer from the outer surface of the pipe to the surrounding soil in the radial direction can be expressed as follows:

$$R_{soil} = \frac{\ln\left(r_s/r_o\right)}{2\pi.\lambda_{soil}.\Delta x} \quad (3.11)$$

In this study, the thickness of the soil annulus is assumed to be equal to the pipe's diameter (r_s=3×r_i) based on the literature [97].

The thermal resistance associated with conductive heat transfer through the pipe wall in the radial direction is calculated according to the following equation:

$$R_{pipe} = \frac{\ln\left(r_o/r_i\right)}{2\pi.\lambda_{pipe}.\Delta x} \quad (3.12)$$

The thermal resistance associated with convective heat transfer between the air and the pipe's inner surface is given by:

$$R_{air} = \frac{1}{h.2\pi.r.\Delta x} \quad (3.13)$$

Where:

$$h = \frac{Nu.\lambda_{air}}{D} \quad (3.14)$$

Where the Nusselt number for the airflow inside the pipe is given as [98]:

$$Nu = \frac{Pr.\left(f/8\right).(Re-1000)}{1+\left(12.7\left(f/8\right)^{1/2}.\left(Pr^{2/3}-1\right)\right)} \quad (3.15)$$

This correlation is applicable for : $3.10^3 \le Re \le 5.10^6$ and $0.5 \le Pr \le 2000$

$$f = (0.790\ \ln(Re) - 1.64)^{-2} \quad (3.16)$$

The kinematic viscosity of air is calculated using the following expression [99]:

$$\nu_{air} = 10^{-8}.(1335 + 9.25\, T_{amb}) \quad (3.17)$$

The thermal conductivity is calculated using the following expression [99]:

$$\lambda_{air} = 10^{-5}.(2442 + 6.992\ T_{amb}) \quad (3.18)$$

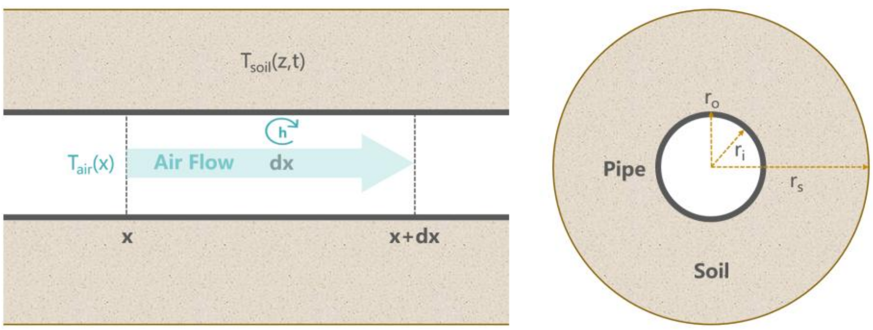


Figure 3.2. Schematic of airflow and heat transfer in a pipe buried in soil.

The following calculation chart presents the provided data and outlines the steps taken to determine the dimensions of the EAHE and the air temperature it produces.

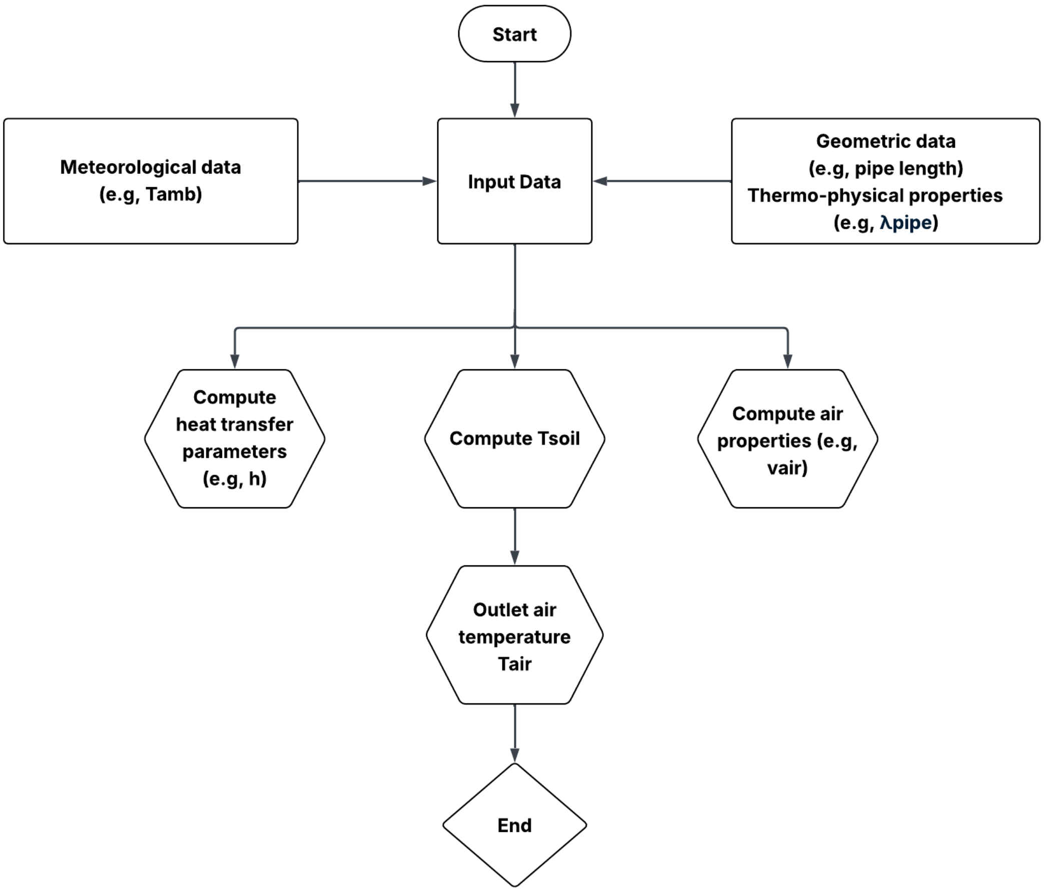


Figure 3.3. EAHE Outlet Temperature Calculation Flowchart.

3.5 Validation

To ensure the reliability of the results presented in this study, the outputs of the various models were compared with experimental data reported in the literature, as detailed below:

3.5.1 Soil temperature

The accuracy of the numerical model for soil temperature was validated using measured data from Kuwait, as reported in reference [100]. The same meteorological conditions were applied, as presented in the table below.

Table 3.1. The metrological data of Kuwait [100].

T_{avrg} (ºC)	T_{amp} (ºC)	φ ($m^2.h^{-1}$)	t_0 (h)	z(m)
27	13.3	0.0038	552	4

3.5.2 EAHE temperature

The model's predictions for the EAHE outlet temperature were validated using experimental results from Moummi et al. [86], conducted at the University of Biskra. The same geometrical and climatic parameters, as listed in **Table 3.2**, were used for comparison.

Table 3.2. EAHE characteristics used by Moummi et al[86].

Pipe material	Pipe length (m)	Piping depth (m)	Inside diameter (m)	Pipe thickness (m)	Inlet temperature (°C)	Outlet temperature (°C)	Volumetric flow ($m^3.h^{-1}$)
PVC	60	3	0.11	0.003	36.572	24	155.43

The comparison results in **Figure 3.4** show a good agreement between the measured soil temperature and calculated values with an accuracy of 3%. At the same time, **Figure 3.5** shows a good agreement between the air temperature calculated by the numerical model and those reported in the study by Moummi et al. [86]. The code reflects the actual phenomenon with a maximum error of 1%.

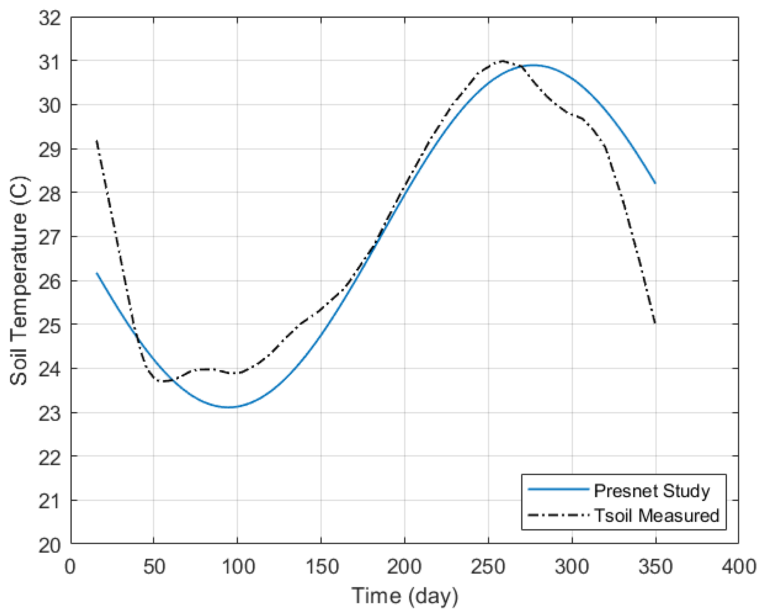


Figure 3.4. Validation of numerical soil temperature with measured data at a depth of 4 m [100].

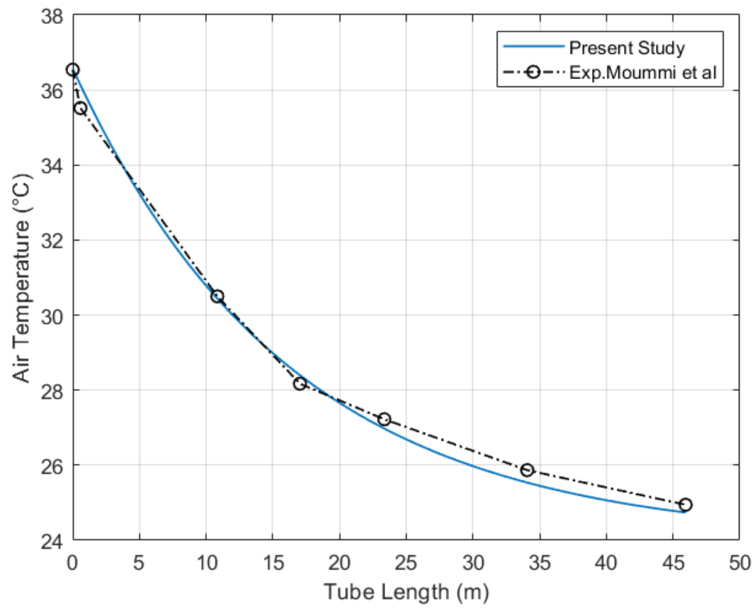


Figure 3.5. Validation of the numerical results of the EAHE outlet temperature using experimental data [86].

3.6 Results and discussion

In this chapter, the EAHE system was selected as an HVAC system for a modern poultry house in Biskra, due to its capacity to provide both heating and cooling. To support this choice, the soil temperature profile was analyzed over the two years defined in the study conditions (**section 2.2.3**) to determine the optimal installation depth where soil temperatures align with the temperature requirements in the building.

A subsequent parametric study was carried out to identify the geometric dimensions (the length and diameter) that would deliver the best energy performance. The minimum ventilation airflow needed at each stage of poultry growth was also considered, which enabled the calculation of the total air volume the system must handle, thereby determining the appropriate number and size of pipes.

A comprehensive economic analysis was also performed, factoring in the costs of pipes of different dimensions and the associated installation expenses. This evaluation aimed to guide the selection of system dimensions based on energy efficiency, overall system performance, and economic viability. Finally, the efficiency of this system was discussed from an environmental perspective. The results are presented in detail in the following subsections:

3.6.1 Soil temperature

Figure 3.6 and **Figure 3.7** present the annual soil temperature variations at different depths for the years 2019 and 2020, respectively, in Biskra, Algeria. The data show that temperature fluctuations decrease with increasing soil depth, eventually stabilizing around 24 °C at a depth of 10 m. At this depth, soil temperature remains nearly constant throughout the year, unaffected by diurnal or seasonal changes.

At a depth of 5 m, soil temperatures ranged from 21.2 °C to 27.5 °C in 2019 and from 21.2 °C to 27.4 °C in 2020. This relatively stable range (21–27 °C) indicates that a 5 m depth is suitable for EAHE applications.

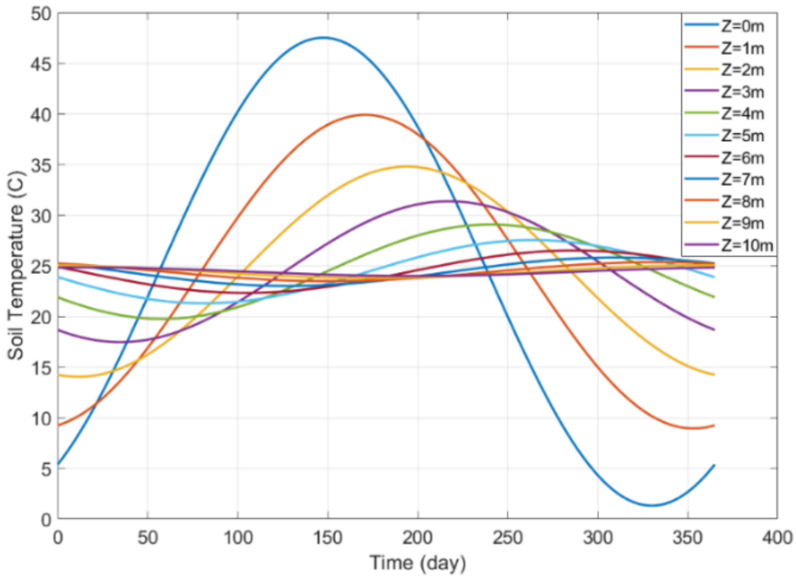


Figure 3.6. Soil Temperature Distribution at Various Depths for the Year 2019.

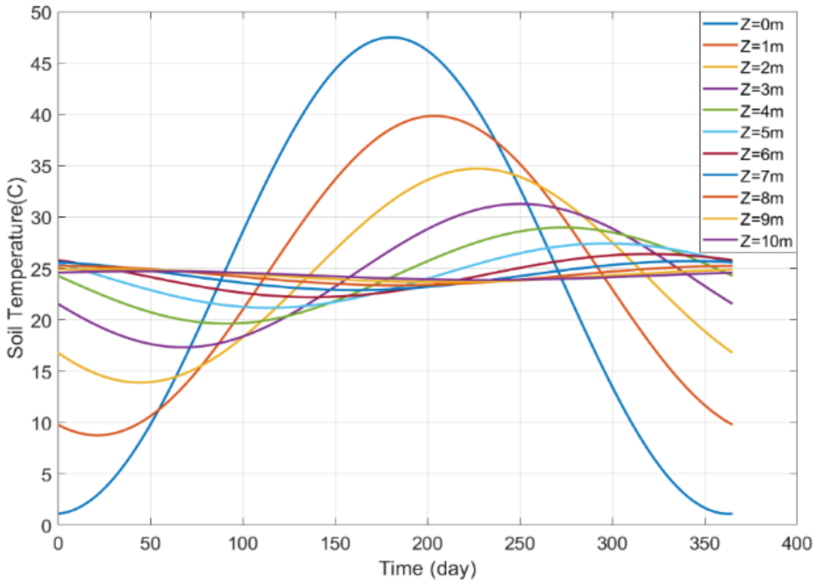


Figure 3.7. Soil Temperature Distribution at Various Depths for the Year 2020.

3.6.2 EAHE

3.6.2.1 Effect of length

Figure 3.8 illustrates the variation in local air temperature along the length of the EAHE pipe at an air flow rate of 441.7862 $m^3.h^{-1}$, for both cooling and heating modes.

In cooling mode, heat is transferred from the air to the surrounding soil, resulting in a progressive decrease in air temperature along the pipe. Conversely, in heating mode, the air absorbs heat from the soil, leading to a temperature increase along the flow direction. These variations are primarily driven by the seasonal thermal behavior of the soil, which remains relatively cool in summer and warm in winter.

The most significant temperature changes occur within the first 80 m of the pipe. This is attributed to the initially large temperature gradient between the air and the soil, which decreases as thermal equilibrium is approached further along the pipe.

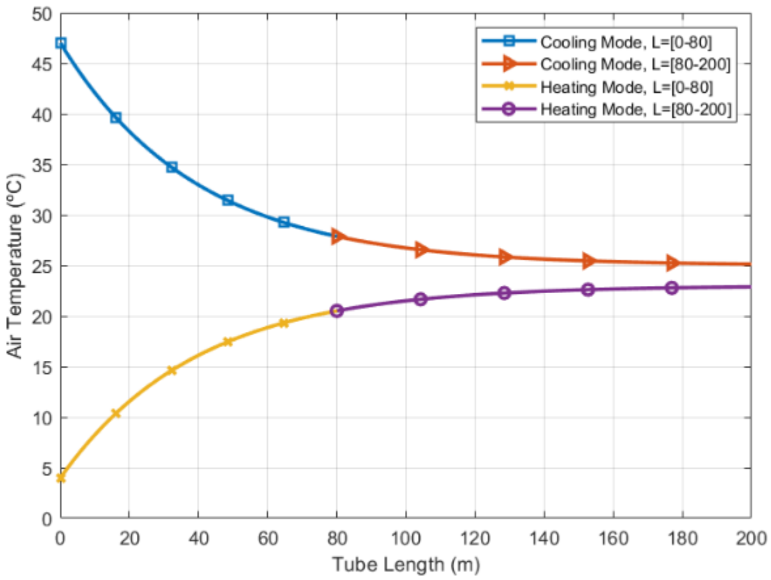


Figure 3.8. Effect of the tube length on the air temperature for an air flow of 441.7862 ($m3.h^{-1}$).

3.6.2.2 Effect of diameter

Figure 3.9 and **Figure 3.10** depict the influence of pipe diameter on air temperature under summer (cooling mode) and winter (heating mode) conditions, respectively.

In cooling mode, a smaller pipe diameter results in a greater decrease in air temperature. Conversely, air temperature increases in heating mode as the pipe diameter decreases.

Among the diameters studied, the 0.11 m tube yields the lowest air temperature in cooling mode and the highest in heating mode, followed by diameters of 0.20, 0.25, and 0.315 m in ascending order. This behavior is attributed to airflow dynamics: for a constant air velocity, smaller diameters result in lower flow rates, which enhance heat exchange due to longer residence time and increased contact between the air and the pipe wall.

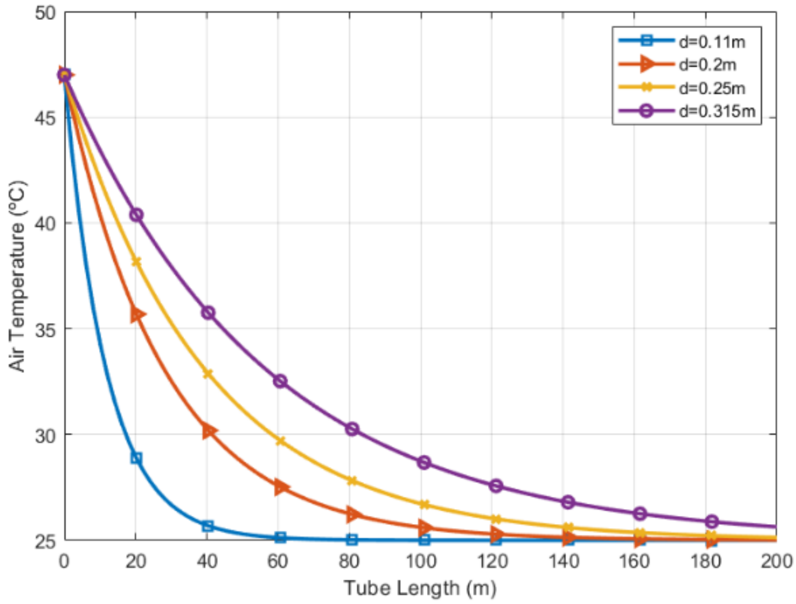


Figure 3.9. Effect of pipe diameter on air temperature at an air velocity of 2.5 $m.s^{-1}$ (cooling mode).

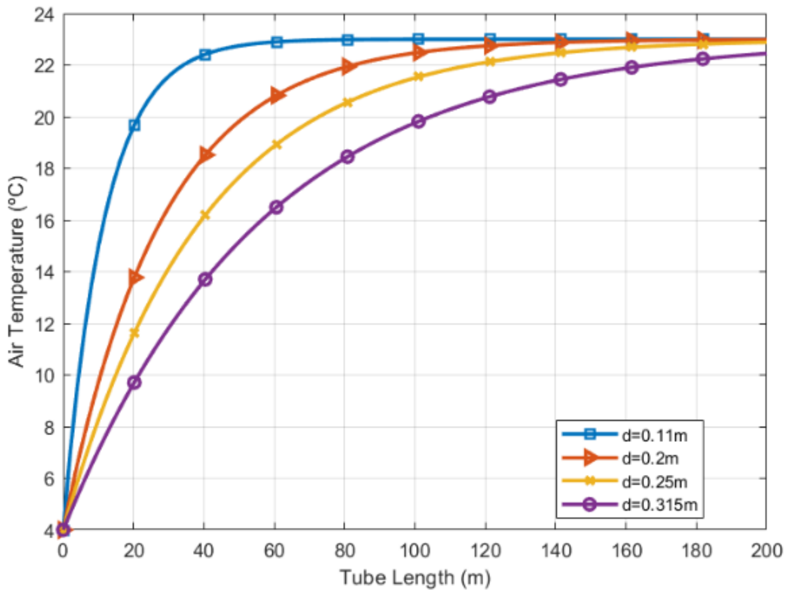


Figure 3.10. Effect of pipe diameter on air temperature at an air velocity of 2.5 $m.s^{-1}$ (Heating Mode).

3.6.3 Economic study

Selecting appropriate dimensions for the EAHE requires careful consideration of both economic feasibility and spatial constraints. The analysis focuses on the final week of the broiler growth cycle, when ventilation demand is at its highest. As indicated in **Table 3.3**, the minimum air ventilation increases progressively with each week of growth, highlighting the need to design the EAHE based on peak airflow requirements.

Table 3.3. Minimum air ventilation required each week of growth.

Weeks of growth	1	2	3	4	5	6
Airflow necessary ($m^3.h^{-1}$)	3034	6711	11363	18057	25406	32311

The data presented in the table below allow for determining the number of pipes required to meet the maximum airflow demand during the final week of the chickens' growth cycle. The table indicates that increasing the pipe diameter results in a higher airflow per pipe. However, this also necessitates a longer pipe length to ensure sufficient heat exchange between the air and the surrounding soil to achieve a target temperature reduction of 20 °C. Additionally, larger diameters lead to a greater overall EAHE surface area, as the spacing between pipes is defined as three times the pipe radius or more.

Table 3.4. Land area and cost estimation of the EAHE under peak operation conditions.

d (m)	Distance between pipes (m)	q_v ($m^3.h^{-1}$)	Nº of pipes	L (m)	l (m)	Surface occupie (m^2)	ΔT (ºC)	Pipe price *[101]* ($)	Installation cost ($)	Total cost ($)
0.11	0.22	85.53	378	28	124.52	3487	20	10142.30	31322.41	41464.71
0.2	0.40	282.74	115	65	68.60	4459		26861.43	40058.57	66920.01
0.25	0.50	441.79	74	90	55	4950		31910.31	44469.60	76379.91
0.315	0.63	701.38	47	130	43.79	5692		62209.53	51136	113345.50

Figure 3.11 illustrates the area occupied by the heat exchanger in the soil relative to the footprint of the poultry house, across different pipe diameters. The results indicate that a pipe diameter of 0.25 m is the most optimal choice, assuming the heat exchanger is installed directly beneath the poultry house. Given that the farm includes 18 poultry houses, implementing this system must also account for the 30 m spacing between the houses to ensure proper layout and functionality.

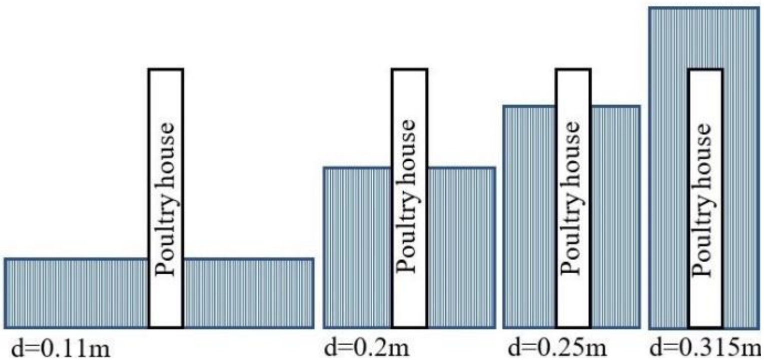


Figure 3.11. Schematic Representation of the Area Occupied by the EAHE for Different Pipe Diameters.

Based on the parametric and economic study findings, a PVC EAHE system employs 7 pipes during the first week of broiler growth, gradually increasing to 74 pipes by the final week. This configuration is designed to deliver a total airflow of approximately 32634 $m^3.h^{-1}$, as shown in **Table 3.5**. Each pipe has a length of 90 m, a diameter of 0.25 m, and provides an airflow rate of 441.78 $m^3.h^{-1}$ at a velocity of 2.5 $m.s^{-1}$.

As previously mentioned, the study period corresponds to the thermal stress conditions typically observed in the poultry house, specifically during the 2nd and 5th weeks of broiler growth. According to **Table 3.5**, the system operates with a minimum of 15 pipes for heating during the second week and 58 pipes for cooling during the 5th week. It is important to note that these numbers are subject to adjustment based on the actual ventilation requirements on any given day.

Table 3.5. Number of operational pipes according to the minimum airflow requirement.

Age of chickens (weeks)	1	2	3	4	5	6
Number of pipes	7	15	26	41	58	74

3.6.4 The ability of the EAHE to satisfy the building's thermal requirements

3.6.4.1 Energy produced by EAHE

Figure 3.12 illustrates the variation in the quantity of heat transferred along the EAHE under two different operating conditions:

- Cooling mode: With a total airflow of 24,740 $m^3.h^{-1}$ (56 tubes active) and an inlet air temperature of 47°C.
- Heating mode: With a total airflow of 8,393 $m^3.h^{-1}$ (19 tubes active) and an inlet air temperature of 4°C.

In both modes, the amount of heat transferred increases progressively along the flow direction. At a length of 90 m, the transferred heat reaches 158.632 kW in cooling mode and 45.070 kW in heating mode. This increase is attributed to the growing temperature difference (ΔT) along the tube's length.

Based on prior analyses, the thermal requirements align with seasonal extremes: during the 1st week, chickens require high temperatures corresponding to the 3rd coldest day of the year, while in the 4th week, lower temperatures are needed, coinciding with the hottest day of the year.

The EAHE's contribution to meeting thermal demands can be summarized as follows:

- Heating: The peak heating demand, calculated via heat balance, is 99.661 kW. The EAHE supplies 45.070 kW, covering approximately 45% of the need.
- Cooling: The peak cooling demand is 422.896 kW, with the EAHE providing 158.632 kW, covering about 35% of the requirement.

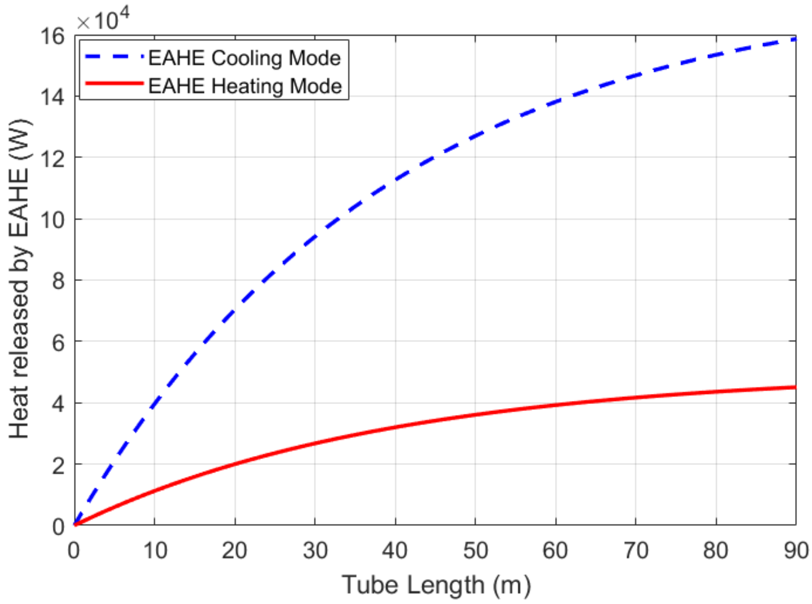


Figure 3.12. Heat produced by the EAHE.

3.6.4.2 Air temperature produced by EAHE

Figure 3.13 and **Figure 3.14** present the air temperature profiles outside and inside the poultry house, recorded every 2 min on the hottest day of the year (14 July) and the 3rd coldest day (7 February), respectively. The data indicate a clear deviation between the external and internal air temperature required for optimal poultry comfort.

In **Figure 3.13**, the EAHE significantly reduced the incoming air temperature during extreme heat conditions. Specifically, outdoor air at a peak temperature of 47°C was cooled to 27.1°C by the EAHE before entering the building. In contrast, the standard ventilation system currently employed in poultry houses achieved an internal temperature of 29.7°C under the same conditions. Nevertheless, the recommended comfort temperature for poultry at this developmental stage is 22°C, suggesting that although the EAHE enhances cooling performance, it may require supplementary cooling to meet optimal conditions.

Figure 3.14 illustrates the EAHE's performance in heating mode. On 7 February, when the outside air temperature reached a minimum of 4.8°C, the system increased the air temperature to 22.9°C. By comparison, the existing heating system raised the indoor air temperature to 27°C, corresponding to the recommended comfort level for poultry at that stage. Although the EAHE does not fully reach this target independently, it substantially contributes to preheating the air, reducing energy demand for conventional heating systems.

These findings underscore the effectiveness of the EAHE system in moderating extreme temperature conditions, offering significant potential for improving energy efficiency and maintaining animal welfare standards in poultry production facilities.

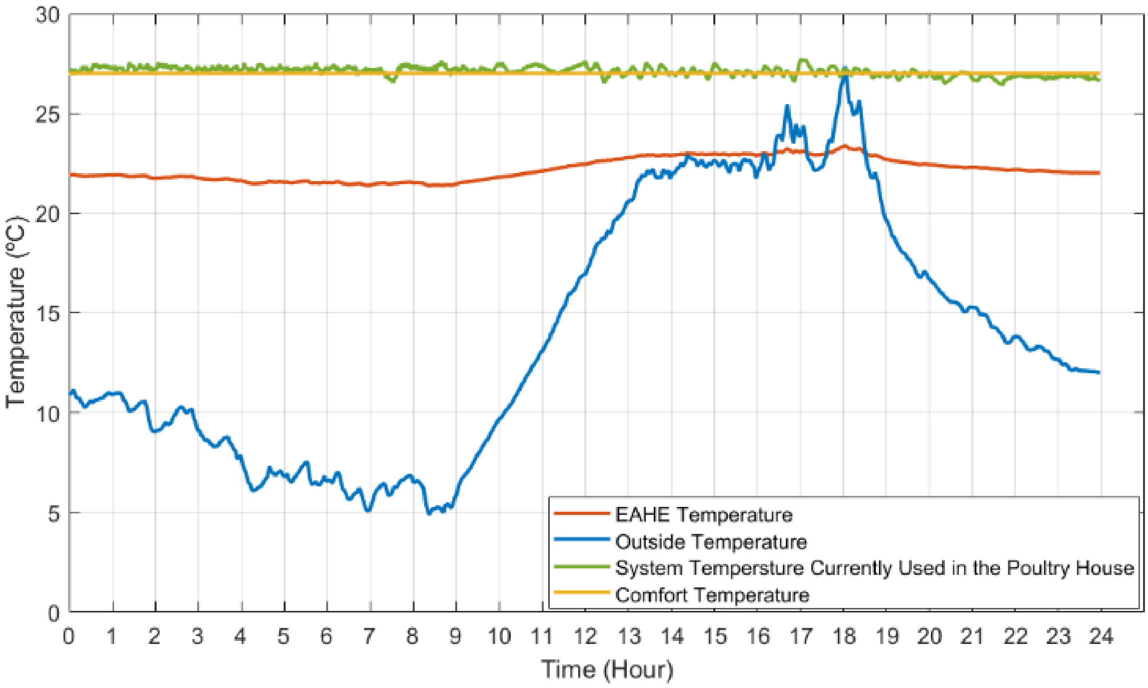


Figure 3.13. Temperature profiles during the third coldest day of the year, corresponding to the 2nd week of broiler growth (heating mode).

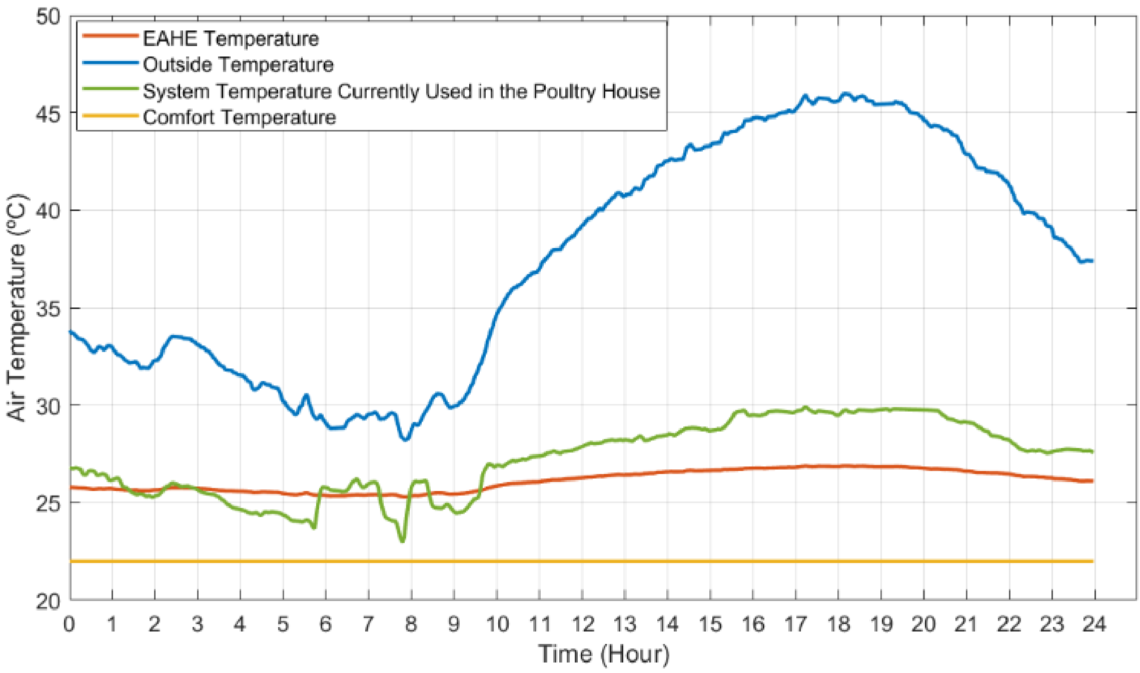


Figure 3.14. Temperature profiles during the year's hottest day correspond to the 4th week of broiler growth (cooling mode).

3.6.5 EAHE environmental effect

This section assesses the environmental impact of the EAHE system in comparison to a conventional HVAC system.

The conventional system relies on a combination of fuel and electricity as energy sources. The estimation of CO_2 emissions resulting from fuel combustion follows the methodology proposed by Sumabat et al. [102].

$$E_{CO_2} = M_{fuel}.EF_{fuel} \tag{3.19}$$

In this study, the emission factor for fuel (EF_{fuel}) is taken as 2.697 $kg_{CO_2}.l^{-1}$, as reported by the U.S. Environmental Protection Agency [103].

On the other hand, CO_2 emissions associated with electricity consumption are calculated following the approach presented by Bajpai et al.[104]:

$$E_{CO_2} = E_{elec}.EF_{elec} \tag{3.20}$$

In Algeria, the electricity emission factor (EF_{elec}) is reported to be 0.734 $kg_{CO_2}.kWh^{-1}$[105].

In contrast, the reduction in GHG emissions resulting from energy savings achieved through the application of the EAHE in poultry houses is determined using the following expression [106]:

$$M_{CO_2} = \left(C_{CO_2} + C_{CH_4} + C_{N_2O}\right).E_{save} \tag{3.21}$$

where the emission factors for Algeria are as follows [105]:

- C_{CO2} = 0.66420926 $kg_{CO2}.kWh^{-1}$.
- C_{CH4} = 0.00001224888 $kg_{CH4}.kWh^{-1}$.
- C_{N2O} = 0.00000129799 $kg_{N2O}.kWh^{-1}$.

Methane (CH_4) and nitrous oxide (N_2O) emissions were converted to CO_2 equivalents using global warming potential (GWP) multipliers of 28 for CH_4 and 265 for N_2O, as recommended by Laknizi and Mahdaoui [106].

Figure 3.15 illustrates the potential reduction in CO_2 emissions achieved through implementing the proposed EAHE system, compared to the emissions associated with the conventional heating and cooling systems currently used in poultry houses.

In heating mode, the EAHE is capable of mitigating approximately 719 $kg_{CO_2}.day^{-1}$, whereas the existing heating system emits approximately 333 $kg_{CO_2}.day^{-1}$. Although the mitigation exceeds the emissions from the current system, this reflects the total potential reduction if the heating demand were entirely met using conventional fossil-fuel-based methods.

In cooling mode, the EAHE demonstrates even greater impact, potentially reducing 2,531 $kg_{CO_2}.day^{-1}$, compared to 3,135 $kg_{CO_2}.day^{-1}$ per day emitted by the conventional cooling system.

In addition to its energy and emissions benefits, the EAHE system demonstrates strong sustainability credentials due to its long service life and minimal material waste. Notably, the lifespan of PVC pipes used in EAHE systems exceeds 50 years [107], making it a long-term, low-maintenance solution. In contrast, conventional cooling systems such as evaporative cooling pads have a significantly shorter lifespan, typically requiring replacement every three years [108, 109]. Over a 50-year period, this would necessitate approximately 68 replacements for a poultry house equipped with four pads, resulting in frequent material consumption and waste generation. This repeated replacement cycle not only increases operational costs but also contributes to a double environmental burden, first through the production and transportation of the replacement materials, and second through the disposal of used pads, which are often non-biodegradable.

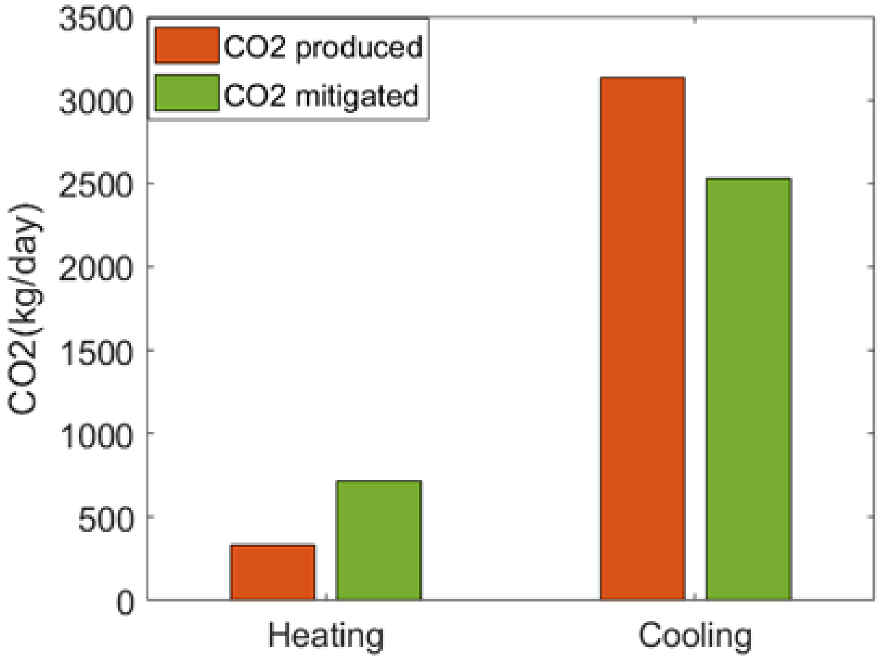


Figure 3.15. CO_2 emissions.

3.7 Chapter Conclusion

In this chapter, an EAHE system was proposed, and its performance was evaluated as an independent unit. The comparison was conducted between the proposed system's output and the poultry house's thermal requirements, as studied in the previous chapter.

To achieve this, the soil temperature distribution in the region was first analyzed to determine the optimal installation depth based on the suitable temperature range. A parametric and economic analysis was then conducted to define the system's dimensions and estimate its cost, tailored to the required airflow rates.

Finally, the temperature at the EAHE outlet was compared with the indoor conditions achieved by the existing HVAC systems in the poultry house, focusing on the most extreme temperature days of the year.

The study's key Findings are:

- At a soil depth of 5 m, temperatures ranged between 21°C and 27°C, making it a suitable zone for installing the EAHE system.
- The parametric and economic studies supported the selection of a system with at least 7 to 74 pipes (depending on airflow demand), each 0.25 m in diameter and 90 m in length.
- Comparing the EAHE outputs with the poultry house's thermal requirements showed that the system could cover approximately 45% of the heating demand and 35% of the cooling demand.
- In terms of comparing the EAHE outlet temperatures and the air temperatures inside the building resulting from the existing HVAC systems, in winter, the EAHE raised the air temperature from 4.8°C to 22.9°C, while the current heating system in the poultry house raises it to 27°C. In summer, the EAHE reduced the air intake from 47°C to 27°C, while the existing cooling system could only bring it down to 29.7°C.
- Regarding CO_2 emissions, the EAHE demonstrated significant potential: In heating mode, it reduced emissions to 719 kg $kg_{CO_2}.day^{-1}$, compared to 333 $kg_{CO_2}.day^{-1}$ from the conventional heaters. While in cooling mode, it reduced emissions to 2531 $kg_{CO_2}.day^{-1}$, compared to 3135 $kg_{CO_2}.day^{-1}$ from the existing cooling system.

These results represent the performance of the EAHE under extreme operating conditions. Under normal weather conditions, the system is expected to perform even more efficiently.

CHAPTER 4

INTEGRATION OF THE EAHE SYSTEM IN THE POULTRY HOUSE

Contents of Chapter 4

Integration of the EAHE System in the Poultry House

4.1 Chapter outline

After determining the thermal requirements of the poultry house under study, and evaluating the dimensions and capacity of the EAHE as an independent unit to meet those needs. This chapter aims to evaluate the EAHE's contribution to enhancing indoor air quality and uniformity after its installation, taking into consideration the optimal position and configuration to maximise its efficiency. Furthermore, the study investigates the system's effectiveness in addressing the common issue of overheating in the rear section of the building, which is typically farthest from the cooling pads.

To achieve these objectives, the study was divided into two main cases:

- Before the installation of the EAHE, this phase includes an analysis of the poultry house in its original design, along with the development of an alternative layout to assess the effect of cooling pad placement on internal environmental conditions.
- After the installation of the EAHE, four scenarios were proposed to evaluate how different positions and inlet configurations of the EAHE influence the building's thermal performance.

4.2 Numerical Methodology

This study employed a three-dimensional Computational Fluid Dynamics (CFD) model, developed using ANSYS Fluent, to simulate the internal environmental conditions of a mechanically ventilated poultry house. The simulation process followed the conventional CFD workflow, comprising the preprocessing, solving, and postprocessing steps (**Figure 4.1**).

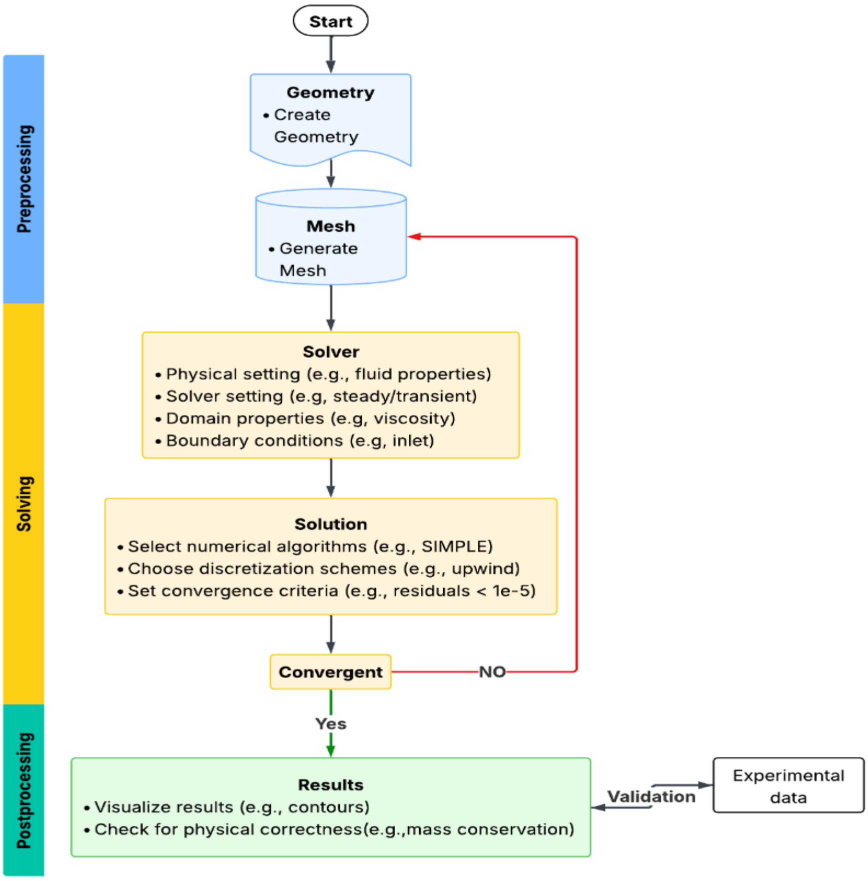


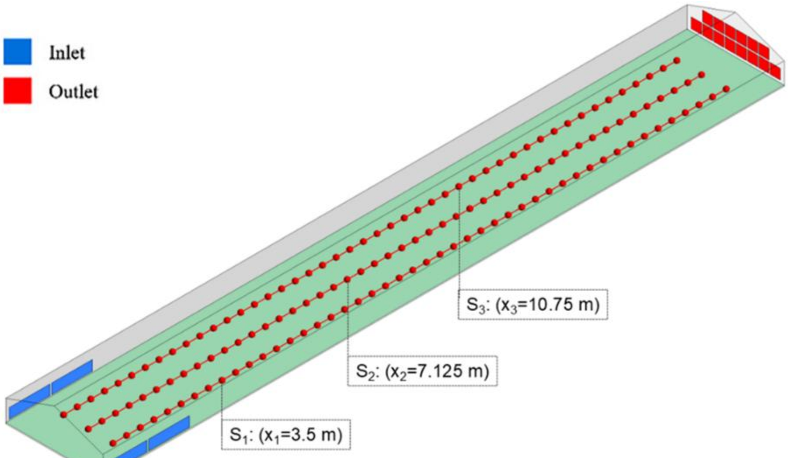
Figure 4.1. The CFD simulation Workflow.

In the preprocessing phase, the building geometry was precisely constructed using ANSYS DesignModeler, based on the actual dimensions of the poultry house as outlined in **section 2.2.2.1.** Key structural elements such as cooling pads and EAHE inlets were incorporated or modified to reflect the scenarios under investigation. All the details about the simulated scenarios are summarised in **Table 4.1**.

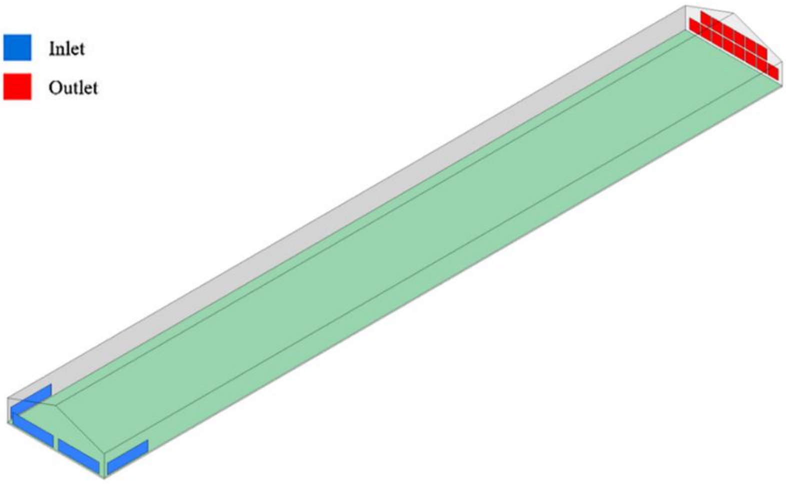
The mesh was created using ANSYS Meshing with an unstructured tetrahedral grid to capture the complex geometry of the poultry house, including inlets and outlets. Mesh quality was assessed based on skewness and orthogonal quality, key indicators of numerical performance. Skewness reflects cell shape distortion, while orthogonal quality measures alignment between flux direction and cell faces. Excessive skewness or poor orthogonality can reduce accuracy and solution stability. The mesh achieved a maximum skewness of 0.7 and a minimum orthogonal quality of 0.3, both within the good ranges per ANSYS guidelines [110]. To optimise computational efficiency without compromising accuracy, the total number of cells was carefully selected to achieve a balance between solution fidelity and processing time. Furthermore, a grid independence test was conducted to verify that the simulation results remained consistent with increased mesh resolution, confirming the adequacy of the chosen mesh configuration.

Table 4.1. Study Scenarios.

Poultry house without the EAHE

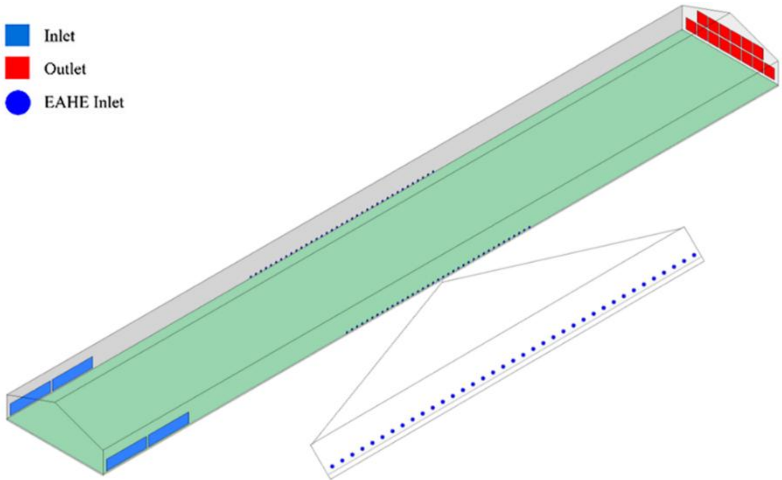


Original scenario: Four cooling pads are installed on the lateral walls.

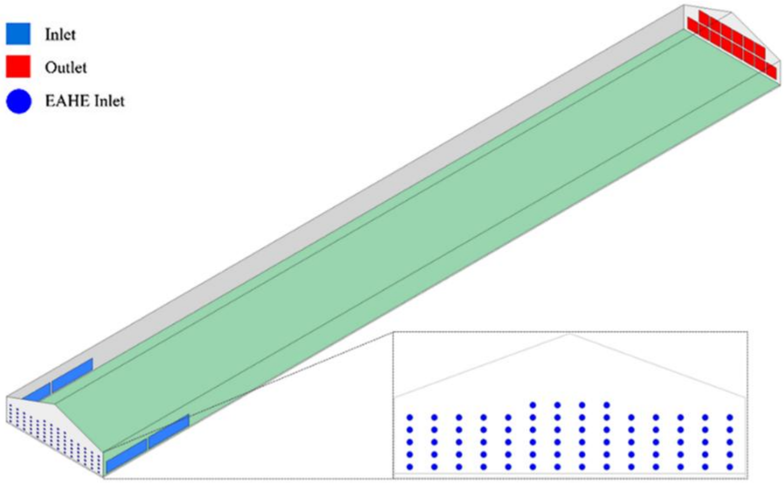


1st Scenario: Two pads are positioned on the wall opposite the exhaust fans (outlet), while the remaining two were retained on the lateral walls.

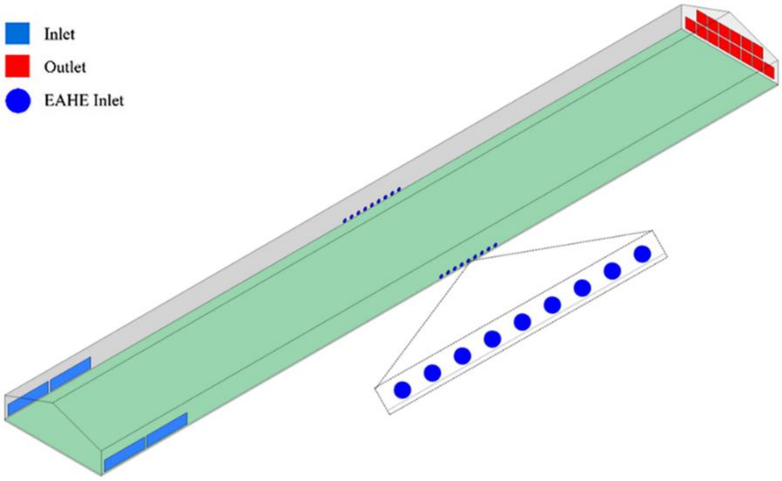
Poultry house with the EAHE



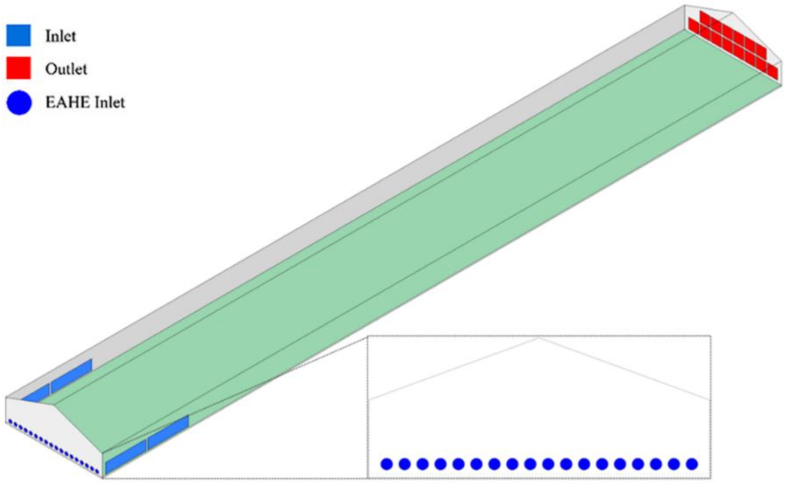
2nd Scenario: A total of 74 pipes, each equipped with an individual inlet measuring 0.25 m in diameter, are installed along the lateral walls.



3rd Scenario: 74 pipes, each featuring an individual inlet with a diameter of 0.25 m, are installed on the wall opposite the exhaust fans.



4th Scenario: 18 EAHE inlets were grouped along the lateral walls, with every 4 combined into a 0.5 m diameter collector. Total airflow and inlet velocity approximately remained consistent with previous scenarios for comparison.



5th Scenario: 18 grouped EAHE inlets were installed on the wall opposite the exhaust fans. every 4 individual inlets were combined into a single collector inlet with a diameter of 0.5m.

4.2.1 Numerical model

The airflow inside the poultry house was simulated using ANSYS Fluent 19. The flow was assumed to be steady-state, incompressible, and turbulent. The governing equations used in the simulations include the continuity equation, the momentum equation, and the energy equation, as outlined in ANSYS Fluent Users Guide ANSYS [111]:

$$\frac{\partial}{\partial x_i}(\rho . u_i) = 0 \tag{4.1}$$

$$\frac{\partial}{\partial x_j}\left(\rho . u_i . u_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + S_i \tag{4.2}$$

$$\frac{\partial}{\partial x_i}(\rho . cp . u_i . T) = \frac{\partial}{\partial x_i}\left(k_{eff} . \frac{\partial T}{\partial x_i}\right) + S_h \tag{4.3}$$

Where:

- u_i : Velocity vector (m.s^{-1}).
- ρ: Density (kg.m^{-3}).
- P: Pressure (Pa).
- τ : Stress tensor (Pa).
- g : Gravitational acceleration (ms^{-2}).
- c_p : Specific heat (J.kg^{-1}.K^{-1}).
- k_{eff} : Heat transmission coefficient (W·m^{-1}·K^{-1}).
- T : Temperature (K).
- S_h : Volumetric heat source (W.m^{-3}).
- S_i : Source term (Pa.m^{-1}).

The source term S_i was incorporated into the momentum equations to account for the effects of the porous medium, where the floor area occupied by broilers is modeled as a heat-generating porous layer. This source term includes both viscous and inertial resistance components, as described in previous studies [50, 111], and is expressed by the following equation:

$$S_i = -\left(\frac{\mu}{\alpha} u_i + C_2 \frac{1}{2} . \rho u_i^2\right) \tag{4.4}$$

Where:

- μ : Dynamic viscosity (Pa. s).
- u_i : Local velocity (m.s^{-1}).
- 1/α : Viscous resistance coefficient (1/α =166 m^{-2}).
- C_2 : Inertial resistance coefficient (C_2 =3.6 m^{-1}).
- Porous medium is assumed to be 90% [50, 51].

4.2.2 Turbulence model

Numerous studies have examined fluid flow behaviour using the k-ε and k-ω turbulence models, with findings indicating that the k-ε model, particularly in its realizable form, offers reliable and consistent results. It is widely regarded as the most suitable model for simulating indoor airflow within livestock and poultry housing facilities [112-114]. Consequently, this study adopts the realizable k-ε turbulence model for computational fluid dynamics (CFD) simulations, aligning with its extensive application in prior research focused on indoor airflow and environmental conditions in poultry houses [44, 112, 115].

4.2.3 Boundary conditions

The boundary conditions at the building inlets, where air enters through the cooling pads, were defined by a uniform velocity of 3 $m \cdot s^{-1}$ and an inlet air temperature of 300.15 K.

Based on the results of **chapter 3 ,** the number of EAHE pipes required to meet the minimum ventilation rate during the final week of the growth cycle was determined to be 74, operating at an air velocity of 2.5 $m \cdot s^{-1}$. **Table 4.2** presents the boundary conditions of the EAHE system.

Table 4.2. Boundary conditions of the EAHE

Number of pipes	74
Internal diameter (m)	0.25
Extarnal temperature (K)	317
The air temperature coming from the EAHE (K)	299.15
The air velocity coming from the EHAE ($m \cdot s^{-1}$)	2.5

In all study the scenarios, the exhaust fans were modeled using a pressure outlet boundary condition. No-slip boundary conditions were applied to all solid surfaces within the domain.

To reduce computational demand, particularly for simulating heat conduction through the walls, external convection, and internal energy and momentum exchanges, the average values obtained from field measurements were used as constant boundary conditions for the walls. These values are summarized in **Table 4.3**.

Table 4.3. Average wall temperature measurements of the house

	WN	ES	NE	SW	Roof
Temperature (K)	313.15	314.35	313.65	315.15	315.15

In this study, the birds were modeled as a porous layer that generates heat. Poultry produces both sensible and latent heat; the latent heat results from the evaporation of moisture from their bodies, which increases the humidity inside the house without directly affecting air temperature [116]. However, since this study focuses on analyzing temperature and airflow patterns rather than humidity levels, only the sensible heat component was considered. The total and sensible heat generated by the birds was calculated using the equation **(2.21)** and **(2.22)** (section **2.3.2**).

4.2.4 Grid independence

A grid independence test was conducted to ensure that the final results for temperature and velocity were not influenced by the mesh size. Simulations were performed using four different mesh densities, consisting of approximately 5.5, 8.1, 10.6, and 12.8 million elements. As shown in **Table 4.4**, noticeable differences in temperature and velocity were observed between the first two mesh sizes. However, with further refinement, these differences became negligible. Therefore, to balance computational efficiency and accuracy, the mesh with 10.6 million elements was selected for the analysis.

Table 4.4. Effect of mesh size on average indoor temperature and velocity

N° Mesh elements	Temperature (K)	Absolute relative error (%)	Velocity ($m \cdot s^{-1}$)	Absolute relative error (%)
5506550	304.07148	-	0.21566	-
8106170	304.46198	0.128	0.20648	4.25
10640142	**304.42845**	**0.011**	**0.20607**	**0.20**
12878456	304.42995	4.9310^{-4}	0.20654	0.23

4.3 Results and discussion

4.3.1 Verification

To establish the credibility of the numerical model, a comprehensive validation process was carried out. The simulation results were first compared against experimental measurements obtained from the original poultry house under actual operating conditions, using the boundary conditions defined for the original scenario (section **2.2.3**).

Additionally, the model's validity and accuracy were further assessed by comparing its results with both experimental and numerical data reported by Wang et al. [45] and Babadi et al.[16]. These comparisons were conducted across various parameters, including air velocity and temperature, under different boundary conditions and within a different poultry house configuration (i.e., cage-based systems).5.5 presents a comparison between the simulated results and field temperature measurements collected via the Viper-Touch monitoring system. This system records average indoor air temperatures using four Dol12 sensors strategically distributed throughout the house (**Figure 2.5**). Furthermore, **Table 4.6** summarises the validation results against the experimental and numerical findings of Wang et al. [45] and Babadi et al.[16].

The results show a strong agreement between the present simulations and both the in situ measurements of the original house and the previously published data. This high level of concordance underscores the robustness and accuracy of the numerical model employed in this study.

Table 4.5. Comparison of average temperature values in the present experimental and numerical investigations

	Experimental data	Present study	Error (%)
Average temperature (K)	301.85	302.86	0.33

Table 4.6. Velocity and temperature data from experimental [45] and numerical studies [16], and the present work

	Experimental study of Wang et al. [45]	Numerical study of Wang et al. [45]	Numerical study of Babadi et al. [16]	Present study
Maximum velocity ($m \cdot s^{-1}$)	2.3	2.25	3.21	2.96
Average velocity ($m \cdot s^{-1}$)	-	0.8	0.81	0.83
Maximum temperature (K)	306.05	308.15	312.23	308.62
Average temperature (K)	-	304.15	304.53	301.58
Minimum temperature (K)	300.25	300.15	300.02	300.24

4.3.2 Velocity distribution

This section presents the results of air velocity distribution inside the building under different configurations, both before and after integrating the EAHE system with the conventional cooling system using cooling pads.

Velocity contours were used across various sections of the building to observe airflow patterns and distribution. In addition, line graphs were used to evaluate the changes in air velocity between the centre (section 2) and the two lateral sides (sections 1 and 3). Measurements were taken at 90 points along the length of the building, ranging from z = 5 to 95 m, at x_1 = 3.5 m, x_2

= 7.125 m, and x_3 = 10.75 m, all at a fixed height of y = 0.4 m, as shown in **Table 4.1** (original scenario).

Figure 4.2 presents velocity magnitude contours for five proposed scenarios in addition to the original case.

In the original configuration (without EAHE), air is drawn through four cooling pads located on the side walls and directed toward the exhaust fans. This flow pattern results in a change in airflow direction, leading to the formation of stagnant zones near the front of the house. The interaction between opposing air streams at the pad level generates turbulence, which in turn causes air to rise toward the roof, leading to insufficient ventilation near the floor level.

In contrast, the first proposed configuration (1st scenario), where two cooling pads are positioned opposite the exhaust fans and airflow is drawn perpendicularly, shows a reduction in vortex formation. This configuration helps channel airflow more effectively toward the longitudinal direction, increasing air velocity in the central zone near the inlets and reducing poorly ventilated zones at bird level.

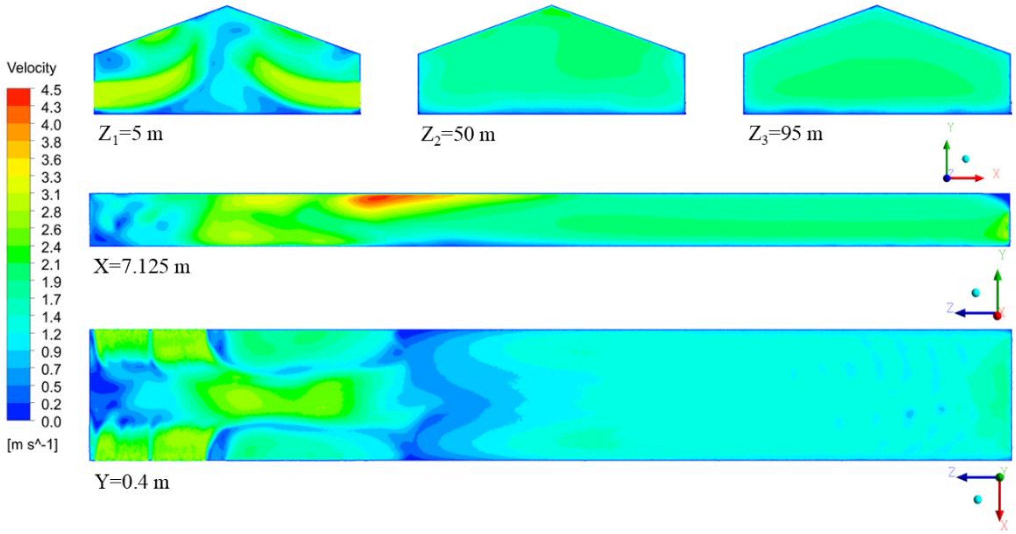
Following the installation of the EAHE, 2nd scenario (with separated EAHE inlets distributed along the side walls) shows an increase in air velocity near the sides of the building, from 1.2 to 1.6 $m \cdot s^{-1}$ compared to the original. This improvement results from the additional airflow source; however, the airflow lacks the momentum to reach the central zone effectively. Instead, the incoming streamlines are deflected toward the main outgoing stream, creating stagnant areas approximately 3.5 m from the side walls.

3rd scenario, where the separated EAHE inlets are aligned with the exhaust fans, yields a more uniform air distribution. Here, the airflow direction from the EAHE aligns with the dominant air stream, enhancing overall circulation and promoting more consistent airflow from the side cooling pads toward the exhaust fans.

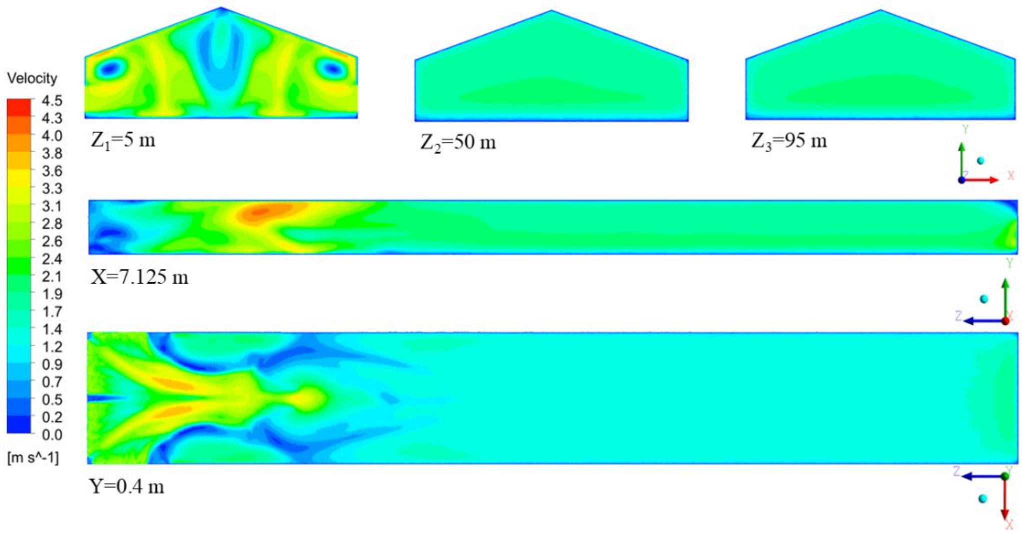
In 4th and 5th scenarios, every set of four inlet pipes (each with a diameter of 0.25 m) is integrated into a single manifold inlet with a diameter of 0.5 m. Despite maintaining approximately the same total airflow rate and inlet velocity as in the preceding configurations, scenario 4 demonstrates enhanced airflow penetration into the building interior when compared to 2nd scenario. This enhancement is primarily attributed to the unification of discrete airflow streams into a more coherent and focused jet, which improves momentum conservation and reduces the occurrence of stagnation zones in the central region of the space.

5th scenario further underscores the benefits of inlet consolidation, particularly when the inlets are strategically aligned with the prevailing airflow direction. By channelling the incoming air along a single horizontal plane, this configuration facilitates more uniform airflow distribution and minimises recirculation zones. Notably, this approach yields significant improvement in airflow delivery to the frontal zone of the building, which typically exhibits the lowest air velocity in other configurations.

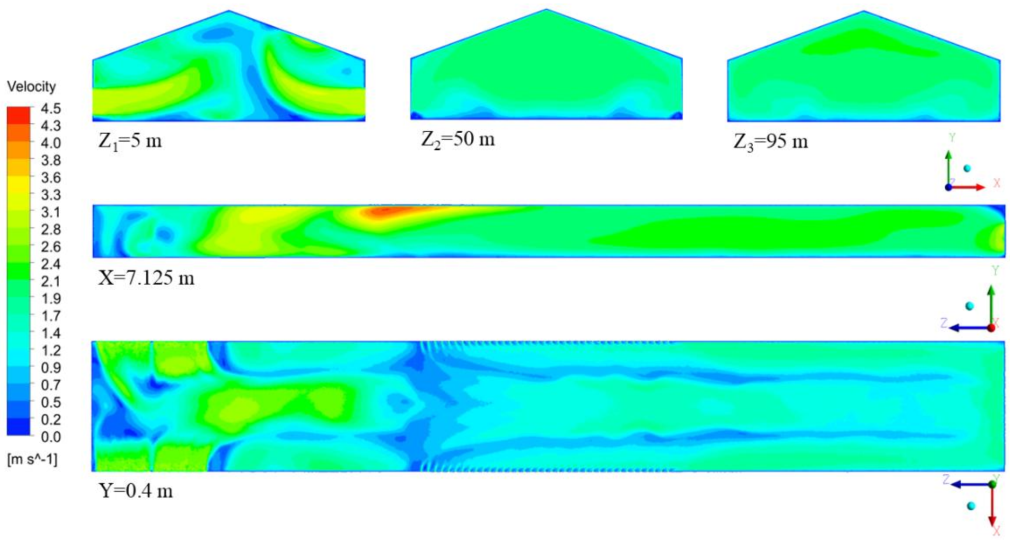
Original scenario



1st scenario



2nd scenario



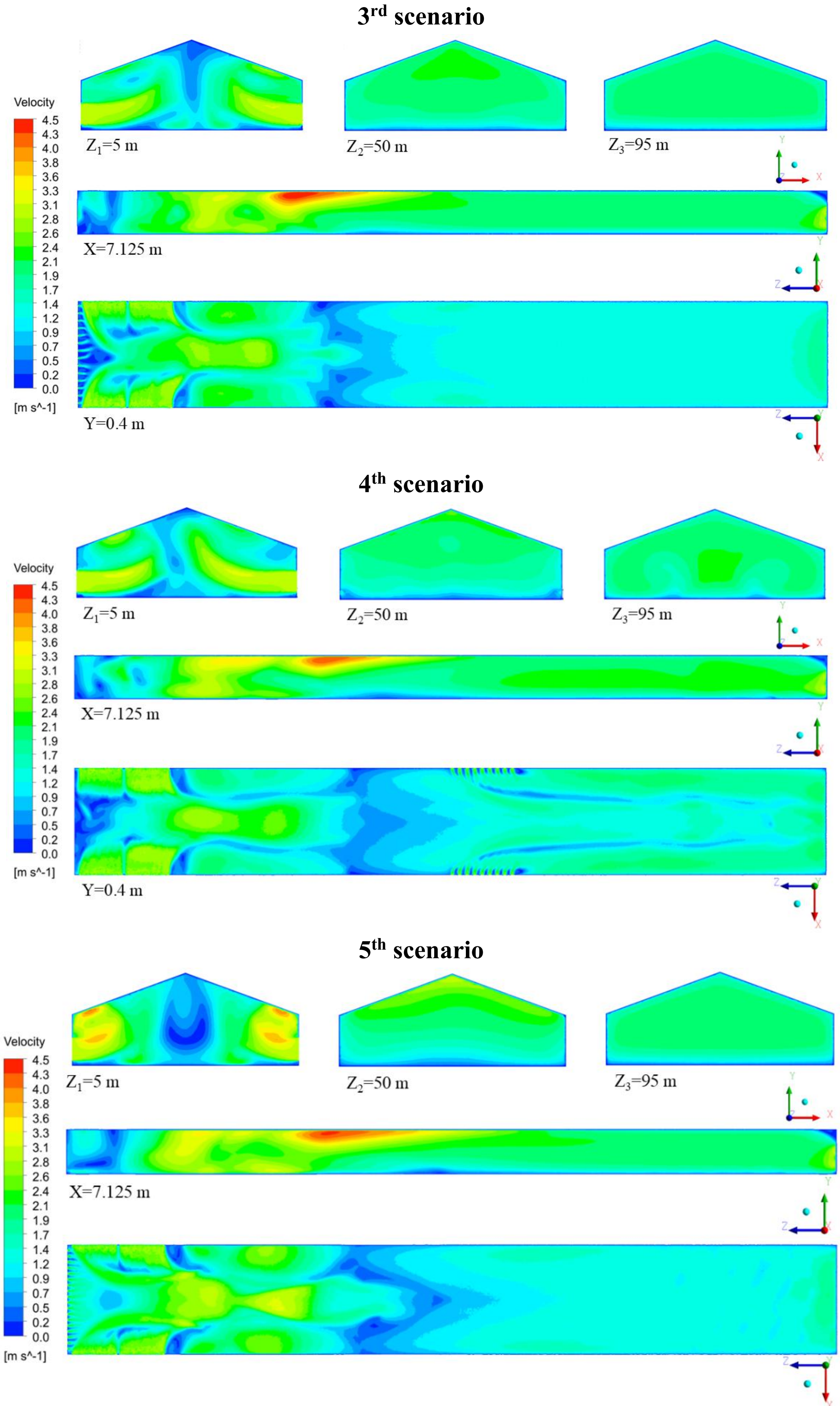


Figure 4.2. Velocity magnitude contours of the house before and after EAHE installation.

Figure. 4.3 illustrates the air velocity distribution along the length of the building in three different sections: the centerline and both lateral sides, across all study scenarios.

The results reveal significant variations in air velocity within the first 50 m of the building across all scenarios. This variation is primarily due to the presence of air inlets, especially the cooling pads located in this region. The interaction and collision of incoming air streams generate non-uniform turbulence, leading to irregular airflow patterns and a lack of velocity uniformity in the initial section of the indoor environment.

In the original scenario, the central section exhibited higher airflow velocities compared to the lateral sections, with a peak value of 2.75 $m \cdot s^{-1}$. In the first proposed scenario, repositioning two evaporative cooling pads directly opposite the exhaust fans resulted in improved airflow dynamics, leading to increased velocity not only along the central section but also across both lateral sections, with values ranging from 3.0 to 3.48 $m \cdot s^{-1}$. In the rear part of the building (beyond the 50 m), airflow velocity in both scenarios became more uniform, stabilising within a range of approximately 1.25 to 1.4 $m \cdot s^{-1}$.

In 2nd scenario, which incorporated 74 separate EAHE inlets along the side walls, new airflow patterns emerged in the second half of the building (after 50 m), resulting in velocity fluctuations. While some regions, such as the central section, experienced enhanced velocities (up to 1.52 $m \cdot s^{-1}$), other areas, particularly those 3.5 m from the walls, showed poor ventilation, with velocities dropping to 0.75 $m \cdot s^{-1}$, and this can be attributed to the behavior of the incoming air, which, upon entering through the lateral EAHE inlets, is quickly redirected toward the main airflow path leading to the exhaust fans. As a result, the airstream changes direction immediately after entering the central section, accelerating toward the outlet before it has a chance to disperse throughout the occupied area.

In contrast, 3rd scenario, where separate EAHE inlets were positioned on the wall opposite the exhaust fans, achieved a more balanced air velocity profile. Starting from 45 m along the building length, velocity values in all three sections converged around 1.25 $m \cdot s^{-1}$, indicating improved airflow uniformity.

The 4th scenario, which featured 18 collected EAHE inlets on the side walls, produced significant disturbances in the velocity distribution. Before the 50 m mark, velocities varied widely, ranging from 0.5 to 2.76 $m \cdot s^{-1}$ across the different sections. Although this variation was somewhat reduced after air entered through the EAHE inlets, values still ranged from 0.5 to 1.72 $m \cdot s^{-1}$, suggesting persistent non-uniformity.

In 5th scenario, where collected EAHE inlets were installed opposite the exhaust fans, velocity uniformity significantly improved in the rear part of the building. While the first 50 m showed variation (0.25 to 3.15 $m \cdot s^{-1}$), velocities across all three sections stabilised at approximately 1.25 $m \cdot s^{-1}$ beyond that point.

Across all studied scenarios, the maximum velocity difference between the three sections was observed to be: 2.5 $m \cdot s^{-1}$ in 1st scenario, 2.04 $m \cdot s^{-1}$ in 5th scenario, 1.99 $m \cdot s^{-1}$ in 2nd scenario, 1.94 $m \cdot s^{-1}$ in 4th scenario, 1.45 $m \cdot s^{-1}$ in the original scenario, and 1.2 $m \cdot s^{-1}$ in 3rd scenario. These results suggest that 3rd scenario provides the most consistent air velocity distribution throughout the building.

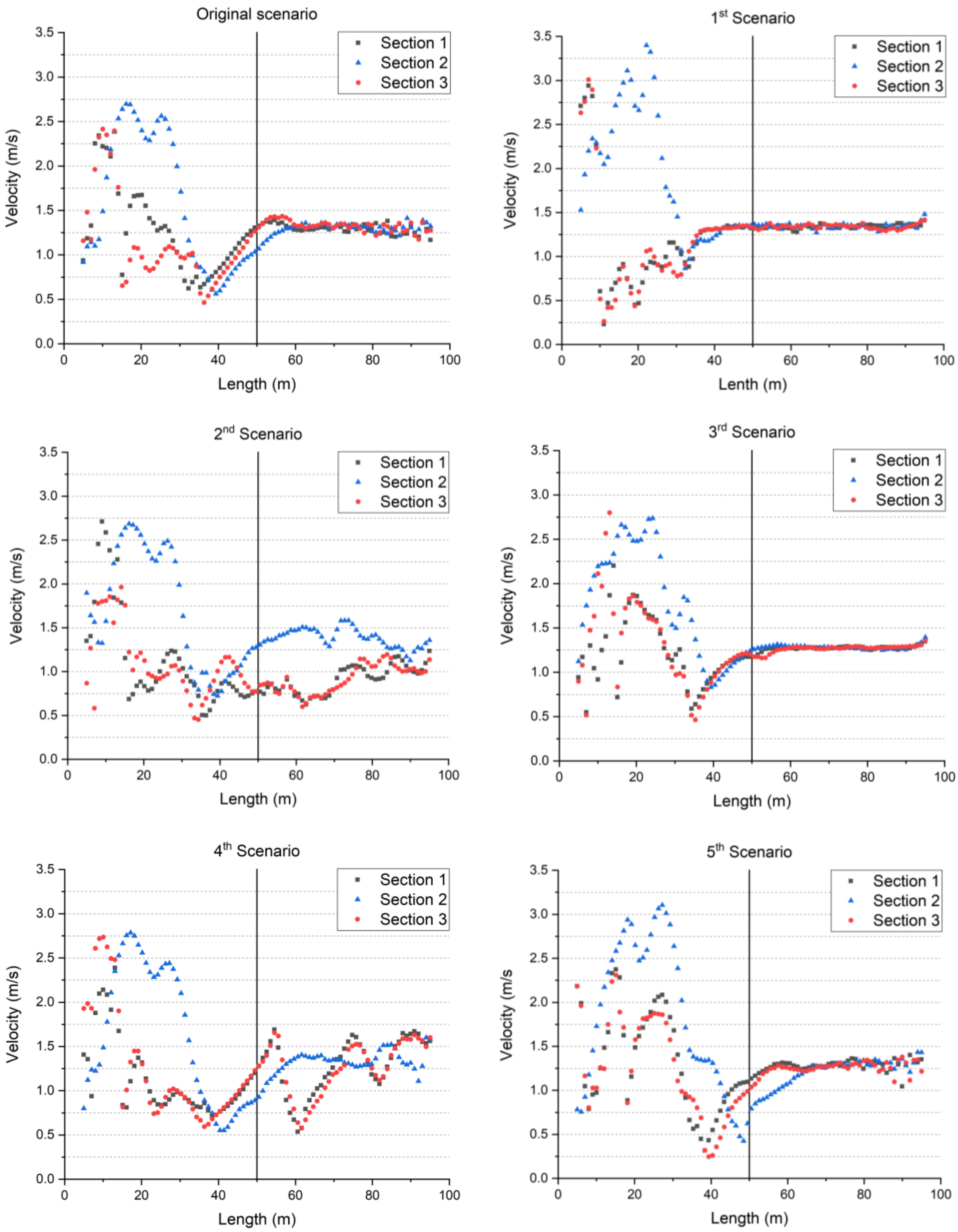


Figure. 4.3. Velocity distribution across three building sections under different study scenarios.

4.3.3 Temperature distribution

Similar to the velocity analysis, temperature contours were generated at various levels within the building. Additionally, line graphs were produced to represent air temperature values along three longitudinal sections of the building: central (section 2) and the two lateral sides (sections 1 and 3). These cross-sections aim to evaluate the thermal distribution along the airflow direction and across different zones of the internal environment.

Figure 4.4 displays the temperature contour for all studied scenarios, comparing the conditions before and after the implementation of the EAHE.

In the original scenario, a clear longitudinal thermal gradient was observed, where air temperatures in the rear half of the building were significantly higher than those in the front. This uneven distribution can negatively affect the thermal comfort and health of poultry, potentially increasing mortality rates and reducing productivity. Furthermore, the localised heat accumulation indicates suboptimal energy performance, as additional cooling may be required to counteract thermal imbalances. Therefore, reducing the temperature gradient along the building is essential for maintaining uniform thermal comfort, improving animal welfare, and lowering operational energy costs in poultry production.

To address this issue, two primary strategies were investigated: repositioning of the evaporative cooling pads (1st scenario), and integrating EAHE in various configurations (scenarios 2 to 5).

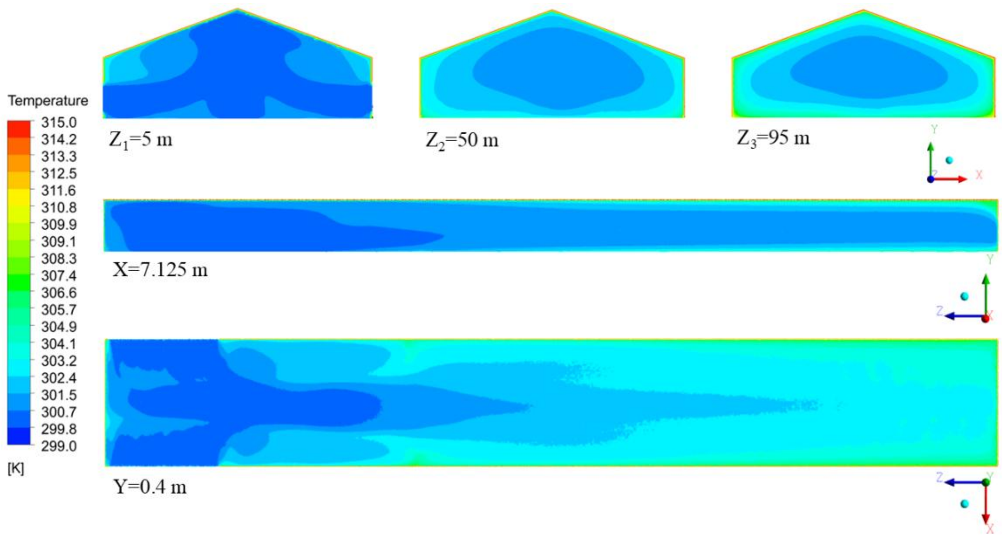
In 1st scenario, relocating two cooling pads to the wall opposite the exhaust fans improved the temperature distribution in the front half of the building (i.e., <50 m). This improvement is attributed to the direct flow of cold air along the airflow direction, which limited vertical mixing between cooler air at the bottom and warmer air at the top layers. However, this scenario did not significantly reduce temperatures in the rear half of the building at bird levels, where heat accumulation due to animal metabolism remained dominant.

2nd scenario, which included the EAHE inlets along the side walls, demonstrated promising results. Air temperatures near the EAHE inlets at the front of the building started at around 300 K and gradually increased to approximately 302 K near the side walls. The position of the EAHE inlets along the lateral walls contributed to a further reduction in temperature in the rear part of the building, particularly in the side zones, where temperatures dropped to approximately 301 K.

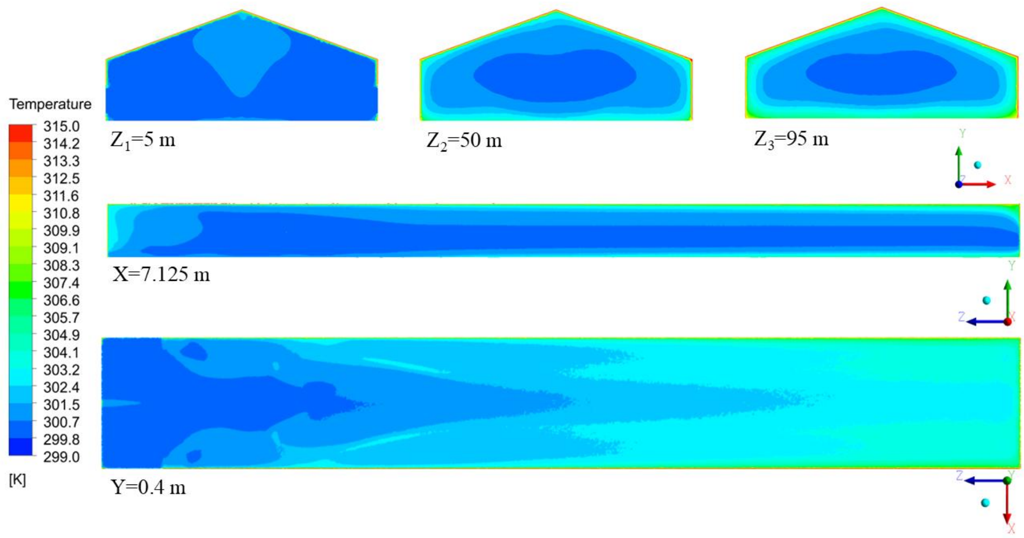
In 3rd scenario, where EAHE inlets are positioned on the wall opposite the exhaust fans, a more balanced thermal distribution was achieved. Temperatures in the front half remained between 299 K and 302 K, while those in the rear half ranged between 302 K and 303 K. The highest temperatures were recorded near the lateral walls; nevertheless, this configuration offered the most uniform air temperature distribution along both the length and width of the building.

In the 4th scenario, collected EAHE inlets installed on the lateral walls effectively reduced temperatures along the building's side zones to around 300 K. However, this scenario was less effective in the central zones, suggesting limited penetration of cooled air toward the central axis. In the 5th scenario, which involved collecting EAHE inlets installed on the wall opposite the exhaust fans, improved cooling performance was observed in the central zones of the building. Nevertheless, a slight increase in air temperature was observed in the side zones of the rear half, indicating a localised deficiency in lateral air distribution.

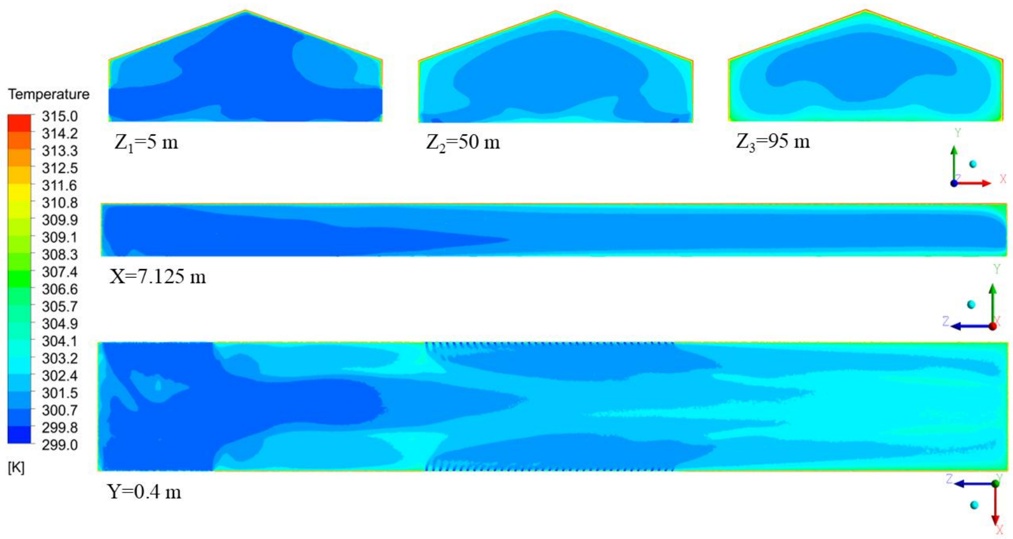
Original scenario



1st scenario



2nd scenario



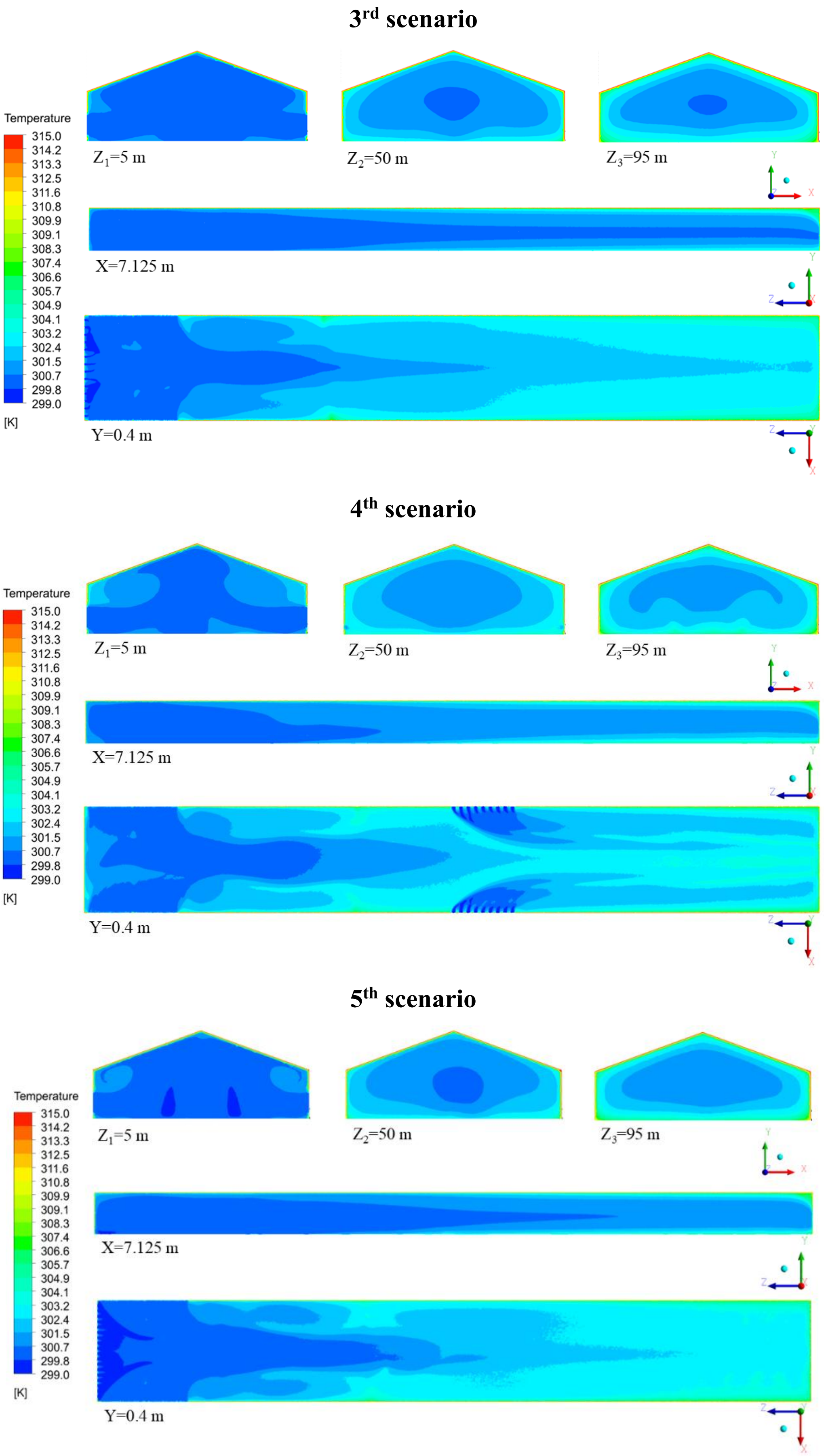


Figure 4.4. Temperature contours of the house before and after EAHE installation.

Figure. 4.5 illustrates the temperature distribution along the building at three different cross-sections (section 1 at x_1, section 2 at x_2, and section 3 at x_3) for all studied scenarios. The results confirm a general increase in air temperature along the length of the building, from the air inlets toward the exhaust fans, across all configurations. This trend is primarily due to convective heat transfer from the birds to the incoming cooler air.

In the original scenario, air temperature in the central section (section 2) was noticeably lower than in the two lateral sections (sections 1 and 3), especially in the front part of the building, with a maximum difference of 1.6 K. In the rear half of the building, air temperature increased by approximately 1 K across all sections compared to the temperature at 50 m, indicating heat accumulation likely due to bird metabolism and reduced cooling efficiency.

In the 1st scenario, a significant improvement in air temperature was observed, particularly within the first 30 m of the building, where temperatures dropped by 1 K compared to the original design. However, this scenario did not significantly enhance temperature distribution in the rear half of the building, where, after 50 m, temperatures rose by 1 K in the lateral section and 1.4 K in the central section, suggesting a limited cooling retention capacity.

Overall, the integration of the EAHE system in Scenarios 2 to 5 yielded better thermal performance than both the original and first scenarios.

In the 2nd scenario, the lateral EAHE inlets significantly reduced air temperatures in the side zones, from 303.2 K to 301.3 K, particularly where cold air entered from the EAHE's inlets located 37 m away. However, this improvement did not effectively extend to the central section. In contrast, the 3rd scenario provided better thermal uniformity across all sections. This configuration reduced peak air temperatures in the central and lateral zones by 0.5 K and 0.75 K, respectively, compared to the original design.

In 4th scenario, the collected side wall EAHE inlets effectively reduced air temperatures in the lateral zones, reaching a minimum of 300.5 K. However, the central region exhibited comparatively higher temperatures, indicating limited cooling penetration toward the building's core. Conversely, 5th scenario demonstrated enhanced thermal performance in the central zone, achieving temperatures between 300 K and 300.7 K over the initial 40 m. Despite this improvement, the cooling effect diminished beyond the 50 m, where air temperatures increased by up to 2 K. Moreover, elevated temperatures were recorded in the lateral zones, highlighting insufficient lateral air distribution and an overall decline in cooling uniformity.

When analysing all scenarios at a height of $y = 0.4$ m, the highest outlet air temperatures were recorded in the original, 1st, and 4th scenarios, reaching 303.5 K. These were followed by the 5th scenario at 303.2 K. The lowest outlet temperatures were observed in the 2nd (303.1 K) and 3rd scenarios, which achieved the best result at 303 K.

Regarding temperature uniformity between lateral and central sections, the largest differences were found in the 5th (1.8 K) and 4th scenarios (1.7 K), followed by the original and 2nd scenarios (1.6 K each), while the 1st and 3rd scenarios showed the most balanced temperature distributions, with maximum differences of 1.5 K and 1.3 K, respectively.

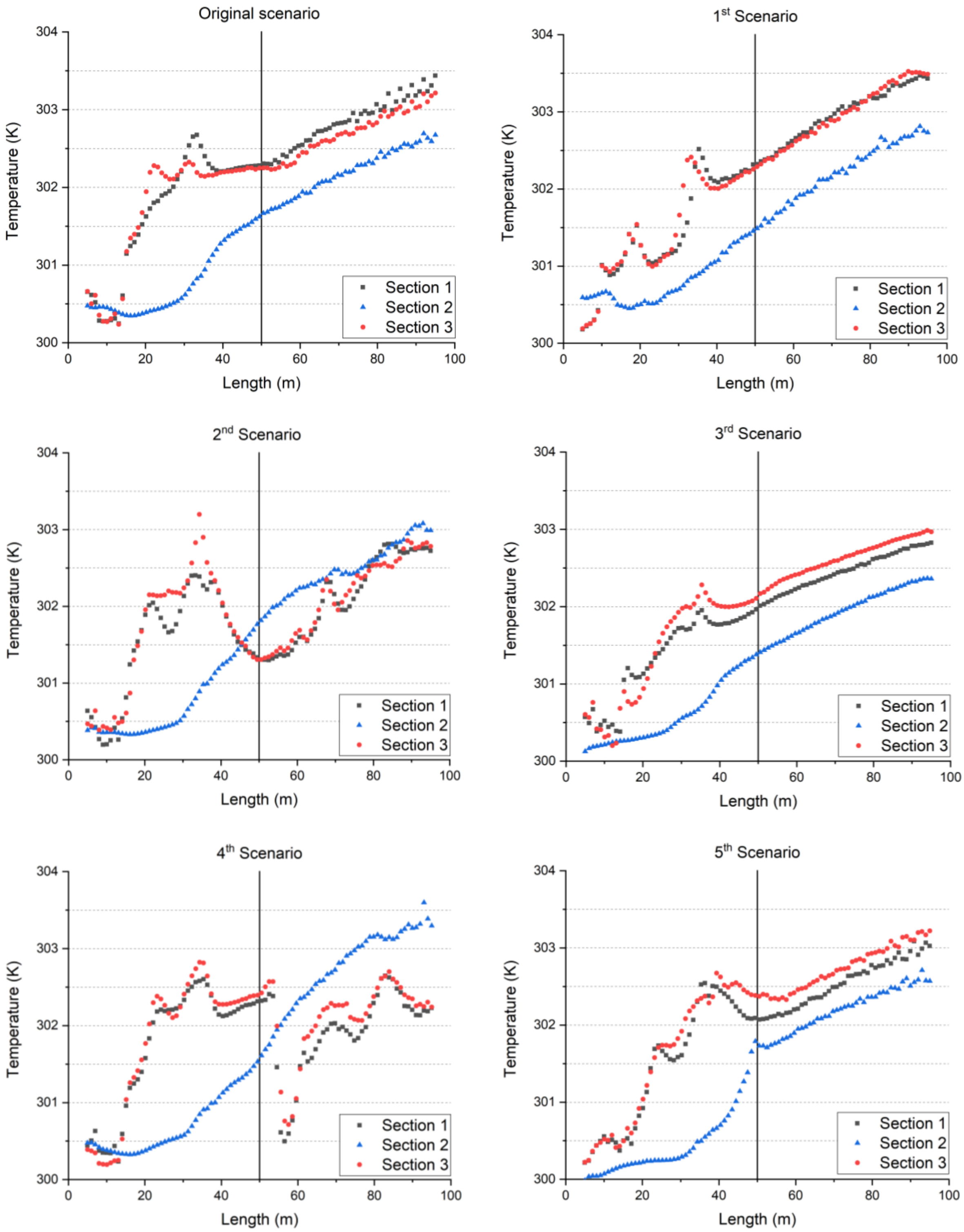


Figure. 4.5. Temperature distribution across three building sections under different study scenarios.

4.4 Chapter Conclusion

This study provides a detailed evaluation of the effectiveness of an Earth-to-Air Heat Exchanger (EAHE) as a passive cooling system for an industrial poultry house. The analysis focuses on its impact in enhancing indoor air distribution and reducing overheating, especially in the rear section of the building. To achieve this objective, six simulation scenarios were developed for a poultry house located in Biskra, Algeria, with a capacity of 20,000 chickens and equipped with four evaporative cooling pads. The scenarios examined the presence or absence of the EAHE, as well as variations in its positioning and inlet configuration (separate vs. combined inlets). The numerical model used in the simulations was rigorously validated through field measurements and comparison with existing literature. Key findings include:

- In the original scenario, an uneven temperature distribution was observed, with the rear area hotter than the front, reaching temperatures of 303.5 K. In terms of velocity, the distribution was non-uniform, with the highest value near the air inlets, especially in the central section (2.75 $m.s^{-1}$). In the second half of the building, airflow became more uniform, ranging between 1.25 and 1.4 $m.s^{-1}$.
- In the 1st scenario, cooling improved in the first 30 to 50 m, while the rear section remained hot, with temperatures reaching up to 303.5 K. While velocity increased in all front sections, particularly near the inlets.
- In the 2nd scenario, the presence of EAHE on the side walls improved cooling in the lateral zones, where the air temperature dropped to 301.3 K. However, the central section remained relatively warmer, with temperatures reaching 303.1 K. Additionally, this configuration led to dead zones near the side walls, where the velocity dropped to 0.75 $m.s^{-1}$ due to the flow being redirected toward the main stream.
- In the 3rd scenario, positioning EAHE inlets opposite the exhaust fans led to a uniform distribution of both velocity and temperature throughout the building. The highest recorded temperature in the rear section was 303 K.
- In the 4th scenario, the collected EAHE inlets on the side walls were effective in cooling the lateral zones (300.5 K), but less effective in the centre. The outlet temperature reached 303.5 K. In contrast, the velocity varied significantly, ranging from 0.5 to 2.76 $m.s^{-1}$ in the front and from 0.5 to 1.72 $m.s^{-1}$ in the rear.
- In the 5th scenario, positioning the collected EAHE inlets opposite the exhaust fans resulted in concentrated cooling in the central zones (300–300.7 K in the first 40 m), while the rear lateral areas remained hot. Velocity showed significant variation in the front (0.25–3.15 $m.s^{-1}$), with improved uniformity beyond 50 m.

In conclusion, this section of the study demonstrates that the position and configuration of air inlets have a significant influence on both airflow distribution and internal temperature. While the EAHE exhibited localised performance improvements, its overall impact was minimal in comparison to the studied domain. This limited effectiveness is primarily attributed to its relatively low contribution to the total airflow, which was only 8.43% compared to the cooling pads. Enhancing this contribution would necessitate an increase in system dimensions, potentially resulting in higher implementation costs. Consequently, the EAHE system is more suitable as a supplementary cooling strategy in large-scale buildings or as a primary system in buildings with low cooling demands. It is important to highlight that these findings were obtained under critical operational conditions, including peak summer temperatures and the final weeks of poultry growth, during which ventilation demands are at their highest. As such, the performance of the EAHE system may vary in response to external climatic conditions and the developmental stage of the birds.

CONCLUSIONS AND RECOMMENDATIONS

Contents of Conclusions and Recommendations

Conclusions and Recommendations

5.1 Outline

This section concludes the research by summarising the main aspects and contributions of the study. The work focused on the energy performance of industrial poultry houses, which are known for their high density and significant energy consumption required to maintain optimal indoor conditions, making them a major contributor to energy demand and environmental emissions.

To address this challenge, the study explored the use of renewable energy sources, specifically EAHE, as a potential solution to meet part of the thermal requirements of such buildings. A comprehensive analysis was conducted, beginning with an in-depth understanding of indoor environmental needs, the identification of key challenges, and a critical review of existing solutions in the literature. This was followed by a case study that analysed the thermal behaviour of a real poultry house.

An EAHE system was then designed and studied independently to evaluate its thermal and environmental performance. Subsequently, a detailed CFD simulation was carried out to model the building and its ventilation systems, assess the effectiveness of the EAHE as a supplementary system, and determine the optimal installation position and configuration.

The following sections present the key findings, providing recommendations and potential directions for future research. Furthermore, this part discusses the scientific contribution of these findings to the existing knowledge in the field, as well as their potential applications.

5.2 key Findings

➢ Based on the Literature Review:

Optimal climatic conditions are crucial for poultry welfare, as they directly impact energy use and feed consumption. Strategies for improving energy performance in poultry houses, as identified in the reviewed literature, are generally categorised into three main types:

- Energy Saving Strategies (ESS): Focused on improving the building envelope.
- Energy Efficiency Strategies (EES): Aimed at enhancing the performance of operational systems.
- Renewable Energy Technologies (RETs): Used as alternative or supplementary energy sources.

Among the reviewed studies, RETs accounted for 36.82% of the strategies, with geothermal energy (30.77%) and solar energy (23.08%) being the most commonly utilised.

Upon a deeper exploration of the field and analysis of existing literature, several research gaps were identified. This thesis addresses some of these gaps, including:

- The integration of renewable energy technologies into modern industrial poultry farms is not widely explored or implemented.
- Performance evaluation of EAHE systems after installation.
- Studying the optimal position and configuration for installing the EAHE system in poultry houses.
- Comparing the performance of the EAHE system with HAVC conventional systems is already exciting.
- Analysis of the economic, energy, and environmental performance of the EAHE system.

➢ Case Study:

Biskra was selected due to its harsh desert climate, where 92% of the annual operating hours fall outside the thermal comfort range for poultry.

A comprehensive thermal model was developed, considering heat gains through walls, roof, and floor, including solar radiation, as well as internal heat gains from birds, workers, lighting, and feeding systems. Heat losses through the building envelope and air renewal loads were also modelled to calculate heating and cooling requirements for a modern poultry house.

It was found that cooling loads (448.96 kW) were 4.5 times higher than heating loads (99.66 kW), indicating a dominant demand for cooling in the region. Significant heat losses occurred through air renewal loads (74%), while internal heat gains were mainly from the poultry themselves (76%).

➢ EAHE Heating/Cooling System:

The EAHE was investigated as a potential heating and cooling system for the poultry house. It was first evaluated independently, with results and comparisons based on temperature and velocity values at the system's outlet, prior to installation within the control volume (the building).

Soil temperature analysis indicated that a depth of 5 m was optimal for installing the EAHE system, with temperatures ranging from 21°C to 27°C.

The EAHE system covered 45% of heating needs and 35% of cooling requirements.

Compared to conventional systems currently installed in the building (field measurements), under extreme weather conditions:

- In winter, the EAHE raised the air temperature from 4.8°C to 22.9°C (compared to 27°C achieved with current heaters).
- In summer, it reduced air temperature from 47°C to 27°C (compared to 29.7°C with the current cooling pads).

CO_2 emissions were significantly reduced, achieving 719 kg/day savings in heating mode and 2,531 kg/day savings in cooling mode.

➢ EAHE Evaluation within the building:

a) Before Installing the EAHE System:

The analysis of the original design revealed significant thermal stratification, particularly in the second half of the poultry house. This was evidenced by elevated temperatures and poor airflow distribution, highlighting the inability of conventional cooling systems to maintain thermally comfortable indoor conditions despite high energy consumption levels. These simulation-based findings were consistent with in situ measurements recorded during field studies.

A modification involving the repositioning of the evaporative cooling pads (1st Scenario) resulted in observable improvements in airflow velocity and a corresponding decrease in indoor air temperature. This outcome underscores the importance of optimising the position of air inlets to enhance the system's efficiency.

b) After Installing the EAHE System:

Given the limitations of conventional systems in meeting cooling demands under extreme climatic and internal load conditions, an EAHE was integrated as a supplementary cooling system. Multiple design scenarios were developed and evaluated through computational simulations to determine the most effective configuration for integration.

In general, the EAHE system exhibited a localised cooling effect, contributing to moderate improvements in indoor air temperatures. However, the system was unable to deliver a sufficiently cooled airflow rate to impact the overall thermal conditions within the building.

Nevertheless, the results demonstrated that the position and configuration of the air inlets play a critical role in optimising the efficiency of the EAHE within the building. **Table 5.1** presents the average air temperature and velocity values (at y = 0.4 m), along with the improvements in temperature and velocity in each scenario compared to the original one.

According to the results, Scenario 3 yielded the most favourable outcomes, as well as achieved the best distribution uniformity across the building’s different sections, with maximum temperature and velocity variations of 1.3°C and 1.2 m/s, respectively.

While the observed improvements may appear moderate, it is essential to highlight that these results were obtained under peak stress conditions, including the highest internal heat loads generated by poultry, maximum cooling demands, and the highest ambient temperatures recorded during the year. Based on these results, under typical operational conditions, the EAHE system is expected to demonstrate improved performance and greater energy efficiency.

This segment of the study further emphasises the importance of evaluating proposed RETs solutions within the operational domain. Relying solely on isolated system performance, detached from the building and internal load dynamics, may lead to incomplete or inaccurate conclusions regarding their overall effectiveness.

Table 5.1. Average air temperature and velocity comparison across the studied scenarios

Scenario	T_{avg} (K)	V_{avg} ($m.s^{-1}$)	Temperature improvement (%)	Velocity improvement (%)
Original	302.28	1.34	-	-
1st	302.15	1.46	0.04	8.96
2nd	301.78	1.39	0.17	4.50
3rd	**301.70**	**1.44**	**0.20**	**7.50**
4th	301.89	1.46	0.13	8.96
5th	301.98	1.45	0.1	8.21

5.3 Recommendations for Future Work

This evaluation highlights the positive performance of the EAHE system, both as a standalone unit before installation and after integration into the building. The system demonstrated a significant ability to reduce the average indoor air temperature to around 301 K, even when the outdoor temperature reached 317 K.

From an environmental standpoint, the system is considered a clean and sustainable solution, as it generates no industrial waste throughout its operational life and offers a substantial reduction in embedded carbon emissions over time.

However, a notable limitation lies in the airflow contribution of the system. Despite the number and dimensions of the pipes, the EAHE system contributes to only 8.43% of the total airflow entering the building. Increasing this share would require expanding the system's size, either by increasing the number, length, or diameter of pipes, which could, in turn, lead to higher installation costs.

Therefore, based on these findings, it is recommended to :

- Utilise the EAHE system as a supplementary cooling solution in buildings with large internal spaces and high thermal loads or as a primary system in smaller buildings with lower thermal requirements.
- Given that EAHE functions as a dual-mode system for both heating and cooling, future studies should investigate its heating performance within the operational domain during colder periods, especially when heating loads are significant.
- A comprehensive evaluation of the system across the entire poultry growth cycle is recommended. Since thermal requirements vary with bird age and physiological changes, a dynamic analysis is needed to determine the system’s efficiency in maintaining optimal indoor conditions throughout different growth stages.

5.4 Thesis Contributions

- This study contributes to the scientific literature in the field of energy performance optimisation in agricultural buildings, particularly poultry houses. It presents accurate and reliable numerical models that have been validated through comparison with field measurements and previous studies, establishing a robust reference for future research.
- The study effectively addresses several existing scientific gaps by emphasising the importance of analysing RETs within an integrated context that includes both the building and the system (Building + System), rather than treating them as independent components.
- The performance assessment of the EAHE system was conducted based on actual operating conditions and field measurements, contrasting with the common reliance on simplified assumptions.
- The research presented various design scenarios for the positions and configurations of air inlets, which has supported the identification of an optimal scenario for achieving uniform ventilation and temperature control.
- From a practical standpoint, the study included a comprehensive economic and environmental feasibility analysis of the EAHE system, reinforcing its viability for real-world implementation and its potential as a sustainable, low-emission, long-term solution.

The outcomes of this research have led to the publication of a first scientific paper, which covered the content of **Chapters 2** and **3**, and was published in Journal of Energy Sources, Part A: Recovery, Utilization, and Environmental Effects under the title: " Performance of earth-air heat exchanger in cooling, heating, and reducing carbon emissions of an industrial poultry farm: A case study"

A second scientific paper, based on the study presented in **Chapter 4**, was also published in the Journal of Cleaner Production under the title: " Evaluation of the earth-air heat exchanger's performance in improving the indoor conditions of an industrial poultry house using computational fluid dynamics verified with field tests"

In addition to a review paper based on **Chapter 1,** titled "Net Zero Energy Strategies in Poultry Buildings and Future Trends towards Sustainable Production".

REFERENCES

References

[1] S. Bößner, P. Läderach, F. X. Johnson, D. Kangogo, and G. Pacillo, "Fossil fuels feed climate change and war: Time to quit them," 2022.

[2] M. Farhan Bashir, M. Sadiq, B. Talbi, L. Shahzad, and M. Adnan Bashir, "An outlook on the development of renewable energy, policy measures to reshape the current energy mix, and how to achieve sustainable economic growth in the post COVID-19 era," *Environmental Science and Pollution Research,* pp. 1-12, 2022.

[3] Y. Cui, S. Riffat, E. Theo, T. Gurler, X. Xue, and Z. Soleimani, "Energy, Economic and Environmental (3E) Assessments on Hybrid Renewable Energy Technology Applied in Poultry Farming," in *Energy Efficiency*: IntechOpen, 2022.

[4] F. a. A. O. o. t. U. Nations, "Meat Market Review: Emerging Trends and Outlook," Food and Agriculture Organization of the United Nations, December 2020 2020. [Online]. Available: http://www.fao.org/economic/est/est-commodities/meat/meat-and-meat-products-update/en/

[5] F. a. A. O. o. t. U. Nations. *Game meat production – FAO*, Food and Agriculture Organization of the United Nations. [Online]. Available: https://ourworldindata.org/meat-production

[6] F. a. A. O. o. t. U. Nations. *Poultry meat production FAO*. [Online]. Available: https://ourworldindata.org/grapher/poultry-production-tonnes

[7] D. d. S. A. e. d. S. d'Information, " Statistique Agricole: Superficies et Productions. Série "B"," Juillet 2021 2019.

[8] M. Czarick III, B. Fairchild, and N. Daghir, "Poultry housing for hot climates," *Poultry production in hot climates,* vol. 80, 2008.

[9] J. Donald, "Environmental management in the broiler house," ed: Aviagen, 2010.

[10] F. Reece and B. Lott, "Heat and moisture production of broiler chickens during brooding," *Poultry Science,* vol. 61, no. 4, pp. 661-666, 1982.

[11] D. C. Cassuce, I. d. F. Tinôco, F. C. Baêta, S. Zolnier, P. R. Cecon, and M. d. F. Vieira, "Thermal comfort temperature update for broiler chickens up to 21 days of age," *Engenharia Agrícola,* vol. 33, pp. 28-36, 2013.

[12] P. Winn and E. Godfrey, "The effect of humidity on growth and feed conversion of broiler chickens," *international Journal of Biometeorology,* vol. 11, pp. 39-50, 1967.

[13] A. Oloyo, "The use of housing system in the management of heat stress in poultry production in hot and humid climate: a review," 2018.

[14] N. S. Bolan, A. Szogi, T. Chuasavathi, B. Seshadri, M. Rothrock, and P. Panneerselvam, "Uses and management of poultry litter," *World's Poultry Science Journal,* vol. 66, no. 4, pp. 673-698, 2010.

[15] C. W. Ritz, B. D. Fairchild, and M. P. Lacy, "Litter quality and broiler performance," 2009.

[16] K. A. Babadi, H. Khorasanizadeh, and A. Aghaei, "CFD modeling of air flow, humidity, CO2 and NH3 distributions in a caged laying hen house with tunnel ventilation system," *Computers and Electronics in Agriculture,* vol. 193, p. 106677, 2022.

[17] J. Simmons, B. Lott, and D. Miles, "The effects of high-air velocity on broiler performance," *Poultry science,* vol. 82, no. 2, pp. 232-234, 2003.

[18] M. Lacy and M. Czarick, "Tunnel-ventilated broiler houses: broiler performance and operating costs," *Journal of Applied Poultry Research,* vol. 1, no. 1, pp. 104-109, 1992.

[19] J. P. Linhoss, Joseph; Chesser, Daniel, "Modern Broiler House Heating Systems," Mississippi State University Extension Service, 2020.

[20] S. J. Hoff, "HVAC Techniques for Modern Livestock and Poultry Production Systems," in *HVAC System*: IntechOpen London, UK, 2018, pp. 1-13.
[21] Aviagen, *Ross Parent Stock Management Handbook*. Huntsville, Alabama: Aviagen Group, 2023.
[22] W. R. Aviagen, "308: Broiler's Management and Nutrition Specification," *AOAC International Aviagen Inc,* 2018.
[23] S. Calvet, M. Cambra-López, V. Blanes-Vidal, F. Estellés, and A. Torres, "Ventilation rates in mechanically-ventilated commercial poultry buildings in Southern Europe: Measurement system development and uncertainty analysis," *Biosystems Engineering,* vol. 106, no. 4, pp. 423-432, 2010.
[24] Aviagen, "Arbor Acres: Broiler Management Handbook," 2018. [Online]. Available: https://en.aviagen.com/brands/arbor-acres
[25] Y. Cui, S. Riffat, E. Theo, T. Gurler, X. Xue, and Z. Soleimani, "Energy, Economic and Environmental (3E) Assessments on Hybrid Renewable Energy Technology Applied in Poultry Farming," 2022.
[26] Y. Wang, B. Li, C. Liang, and W. Zheng, "Dynamic simulation of thermal load and energy efficiency in poultry buildings in the cold zone of China," *Computers and electronics in agriculture,* vol. 168, p. 105127, 2020.
[27] P. Panagakis-FBC, D. Manolakos, and P. Axaopoulos, "Optimal financial insulation thickness of a broiler house," *Agricultural Engineering International: CIGR Journal,* vol. 23, no. 2, 2021.
[28] C. Peng, L. Wang, and X. Zhang, "DeST-based dynamic simulation and energy efficiency retrofit analysis of commercial buildings in the hot summer/cold winter zone of China: A case in Nanjing," *Energy and Buildings,* vol. 78, pp. 123-131, 2014.
[29] F. Banuelos-Gonzalez, N. Shang, R. Wilcox, and M. S. Ahamed, "Conceptual Study for a Net-Zero-Energy Poultry House in Mediterranean Climate in the USA," in *2021 ASABE Annual International Virtual Meeting*, 2021: American Society of Agricultural and Biological Engineers, p. 1.
[30] C. Younes, C. A. Shdid, and G. Bitsuamlak, "Air infiltration through building envelopes: A review," *Journal of Building physics,* vol. 35, no. 3, pp. 267-302, 2012.
[31] G. D. Chesser, J. L. Purswell, J. D. Davis, J. K. Ward, and T. Tabler, "Comparison of Outside Air and Sol-air Design Temperatures for Estimating Insulation Needs," in *10th International Livestock Environment Symposium (ILES X)*, 2018: American Society of Agricultural and Biological Engineers, p. 1.
[32] L. Gao, M. Er, L. Li, P. Wen, Y. Jia, and L. Huo, "Microclimate environment model construction and control strategy of enclosed laying brooder house," *Poultry Science,* vol. 101, no. 6, p. 101843, 2022.
[33] A. Costantino, E. Fabrizio, A. Ghiggini, and M. Bariani, "Climate control in broiler houses: A thermal model for the calculation of the energy use and indoor environmental conditions," *Energy and Buildings,* vol. 169, pp. 110-126, 2018.
[34] L. Du *et al.*, "Development and Validation of an Energy Consumption Model for Animal Houses Achieving Precision Livestock Farming," *Animals,* vol. 12, no. 19, p. 2580, 2022.
[35] Y. Wang, W. Zheng, H. Shi, and B. Li, "Optimising the design of confined laying hen house insulation requirements in cold climates without using supplementary heat," *Biosystems engineering,* vol. 174, pp. 282-294, 2018.
[36] F. Rojano, P.-E. Bournet, M. Hassouna, P. Robin, M. Kacira, and C. Y. Choi, "Computational modelling of thermal and humidity gradients for a naturally ventilated poultry house," *Biosystems Engineering,* vol. 151, pp. 273-285, 2016.

[37] H. ElZanaty, "A techno-economic study for heating poultry houses using renewable energy," 2014.
[38] M. Jalali, A. Banakar, B. Farzaneh, and M. Montazeri, "Reducing Energy Consumption in a Poultry Farm by Designing and Optimizing the Solar Heating/Photovoltaic System," *Sustainability,* vol. 15, no. 7, p. 6059, 2023.
[39] G. A. Akolgo *et al.*, "Energy analysis of poultry housing in Ghana using artificial neural networks," *Scientific African,* vol. 17, p. e01313, 2022.
[40] A. Costantino, S. Calvet, and E. Fabrizio, "Identification of energy-efficient solutions for broiler house envelopes through a primary energy approach," *Journal of Cleaner Production,* vol. 312, p. 127639, 2021.
[41] E. Küçüktopcu and B. Cemek, "A study on environmental impact of insulation thickness of poultry building walls," *Energy,* vol. 150, pp. 583-590, 2018.
[42] Y. Wang, B. Li, and W. Zheng, "Optimum insulation thickness for the sandwich structure livestock buildings external envelopes in different climate regions of China," *International Journal of Agricultural and Biological Engineering,* vol. 13, no. 1, pp. 29-41, 2020.
[43] E. A. d. Almeida and R. Passini, "Thermal comfort in reduced models of broilers' houses, under different types of roofing materials," *Engenharia Agrícola,* vol. 33, pp. 19-27, 2013.
[44] L. Du *et al.*, "Computational Fluid Dynamics aided investigation and optimization of a tunnel-ventilated poultry house in China," *Computers and Electronics in Agriculture,* vol. 159, pp. 1-15, 2019.
[45] X. Wang and K. Wang, "Optimizing the Pad Cooling Ventilation System of Laying Hen Barn Using CFD in Southeast China," in *2013 Kansas City, Missouri, July 21-July 24, 2013*, 2013: American Society of Agricultural and Biological Engineers, p. 1.
[46] L. Chen, E. E. Fabian-Wheeler, J. M. Cimbala, D. Hofstetter, and P. Patterson, "Computational fluid dynamics analysis of alternative ventilation schemes in cage-free poultry housing," *Animals,* vol. 11, no. 8, p. 2352, 2021.
[47] N. AM, "Numerical analyses of air velocity and temperature distribution in poultry house using computational fluid dynamics," *INMATEH-Agricultural Engineering,* vol. 56, no. 3, 2018.
[48] Q. Cheng, H. Li, L. Rong, X. Feng, G. Zhang, and B. Li, "Using CFD to assess the influence of ceiling deflector design on airflow distribution in hen house with tunnel ventilation," *Computers and Electronics in Agriculture,* vol. 151, pp. 165-174, 2018.
[49] M. Fezai, B. Tashtoush, M. Ghoulem, K. Elmoueddeb, and M. Elakhdar, "Investigation of the effectiveness of top-down natural ventilation of a poultry building in a hot-summer mediterranean climate," *Building Services Engineering Research & Technology,* vol. 45, no. 1, pp. 53-73, 2024.
[50] D. Fidaros, C. Baxevanou, T. Bartzanas, and C. Kittas, "Numerical study of mechanically ventilated broiler house equipped with evaporative pads," *Computers and Electronics in Agriculture,* vol. 149, pp. 101-109, 2018.
[51] E. Küçüktopcu, B. Cemek, H. Simsek, and J.-Q. Ni, "Computational Fluid Dynamics Modeling of a Broiler House Microclimate in Summer and Winter," *Animals,* vol. 12, no. 7, p. 867, 2022.
[52] F. Coulombe, D. R. Rousse, and P.-L. Paradis, "CFD simulations to improve air distribution inside cold climate broiler houses involving heat exchangers," *Biosystems Engineering,* vol. 198, pp. 105-118, 2020.
[53] S.-W. Hong, I.-B. Lee, I.-H. Seo, and K.-S. Kwon, "The design and testing of a small-scale wind turbine fitted to the ventilation fan for a livestock building," *Computers and electronics in agriculture,* vol. 99, pp. 65-76, 2013.

[54] L. Du *et al.*, "Investigation of a preliminary ventilation energy-recovery system for poultry houses," *Computers and Electronics in Agriculture,* vol. 175, p. 105521, 2020.

[55] W. Morshed, L. Leso, L. Conti, G. Rossi, S. Simonini, and M. Barbari, "Cooling performance of earth-to-air heat exchangers applied to a poultry barn in semi-desert areas of south Iraq," *International Journal of Agricultural and Biological Engineering,* vol. 11, no. 3, pp. 47-53, 2018.

[56] M. I. Hasan and D. M. Muter, "Study the effects configuration and design parameters on the performance of earth to air heat exchanger used in poultry houses," *Journal of Mechanical Engineering Research and Developments,* vol. 44, no.7 , 1024-1752, pp. 159-179, 2021.

[57] M. I. Hasan and D. M. Muter, "Numerical Investigation of The Air Flow Rate Effect Performance of Earth to Air Heat Exchanger Used for Cooling of Poultry Houses," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences,* vol. 84, no. 2, pp. 167-184, 2021.

[58] J. P. Harrouz, D. Al Assaad, M. Orabi, K. Ghali, D. Ouahrani, and N. Ghaddar, "Modeling and optimization of poultry house passive cooling strategies in semiarid climates," *International Journal of Energy Research,* vol. 45, no. 15, pp. 20795-20811, 2021.

[59] M. Petek, S. Dikmen, and M. M. OĞan, "Performance analysis of a two stage pad cooling system in broiler houses," *Turkish Journal of Veterinary and Animal Sciences,* vol. 36, no. 1, pp. 21-26, 2012.

[60] H. Choi *et al.*, "Effect of heating system using a geothermal heat pump on the production performance and housing environment of broiler chickens," *Poultry science,* vol. 91, no. 2, pp. 275-281, 2012.

[61] Y. Zhou, A. Bidarmaghz, N. Makasis, and G. Narsilio, "Ground-source heat pump systems: The effects of variable trench separations and pipe configurations in horizontal ground heat exchangers," *Energies,* vol. 14, no. 13, p. 3919, 2021.

[62] W. Okonkwo and C. Akubuo, "Trombe wall system for poultry brooding," *International journal of poultry science,* vol. 6, no. 2, pp. 125-130, 2007.

[63] S. T. Sleem *et al.*, "Solar-assisted poultry production in small-scale farms: a case study in the Bekaa semi-arid region, Lebanon," *Energy, Sustainability and Society,* vol. 14, no. 1, p. 8, 2024.

[64] H. Fawaz, M. G. Abiad, N. Ghaddar, and K. Ghali, "Solar-assisted localized ventilation system for poultry brooding," *Energy and Buildings,* vol. 71, pp. 142-154, 2014.

[65] S. Cordeau and S. Barrington, "Performance of unglazed solar ventilation air pre-heaters for broiler barns," *Solar energy,* vol. 85, no. 7, pp. 1418-1429, 2011.

[66] S. Gad, M. A. R. El-Shazly, K. I. Wasfy, and A. Awny, "Effect of using solar energy and different ventilation rate on production in poultry houses," *Journal of World's Poultry Research,* no. 4, pp. 204-210, 2019.

[67] S. Gad, M. El-Shazly, K. I. Wasfy, and A. Awny, "Utilization of solar energy and climate control systems for enhancing poultry houses productivity," *Renewable Energy,* vol. 154, pp. 278-289, 2020.

[68] J. Kapica, H. Pawlak, and M. Ścibisz, "Carbon dioxide emission reduction by heating poultry houses from renewable energy sources in Central Europe," *Agricultural Systems,* vol. 139, pp. 238-249, 2015.

[69] T. Gurler, T. Elmer, Y. Cui, S. Omer, and S. Riffat, "Performance evaluation of a novel PVT-GSHP heating system on energy-efficient poultry houses: long-term monitoring," *International Journal of Low-Carbon Technologies,* vol. 16, no. 2, pp. 393-406, 2021.

[70] Y. Cui, E. Theo, T. Gurler, Y. Su, and R. Saffa, "Feasibility of hybrid renewable heating system application in poultry house: a case study of East Midlands, UK," *International Journal of Low-Carbon Technologies,* vol. 16, no. 1, pp. 73-88, 2021.

[71] M. Omar, A. Samak, M. Keshek, and S. Elsisi, "Simulation and validation model for using the energy produced from broiler litter waste in their house and its requirement of energy," *Renewable Energy,* vol. 159, pp. 920-928, 2020.

[72] M. Arshad *et al.*, "Electricity generation from biogas of poultry waste: An assessment of potential and feasibility in Pakistan," *Renewable and Sustainable Energy Reviews,* vol. 81, pp. 1241-1246, 2018.

[73] Y. Zhou, G. A. Narsilio, K. Soga, and L. Aye, "Achieving Pareto Optimum for Hybrid Geothermal–Solar (PV)–Gas Heating Systems: Minimising Lifecycle Cost and Greenhouse Gas Emissions," *Sustainability,* vol. 16, no. 15, p. 6595, 2024.

[74] A. Laknizi, M. Mahdaoui, K. Anoune, M. Bakhouya, A. B. Abdellah, and H. Oussous, "Parametric Study and Energy Performance of an Earth-Air Heat Exchanger for a Poultry House in Morocco," *International Journal of Renewable Energy Research (IJRER),* vol. 8, no. 4, pp. 2047-2056, 2018.

[75] A. Laknizi, M. Mahdaoui, A. B. Abdellah, K. Anoune, and M. Bouya, "Energy Performance and Environmental Impact of an Earth-Air Heat Exchanger for Heating and Cooling a Poultry House," in *International Conference on Advanced Intelligent Systems for Sustainable Development*, 2018: Springer, pp. 149-157.

[76] Y. Doughan and D. A. Salam, "Techno-economic feasibility of using solar energy in small-scale broiler production," *Energy for Sustainable Development,* vol. 77, p. 101337, 2023.

[77] T. Elmer, Y. Cui, T. Gurler, and S. RIFFAT, "Development of an innovative PVt/heat pump and evaporative cooling HVAC system for poultry house applications," in *15th International Conference on Sustainable Energy Technologies—SET*, 2016.

[78] M. Kharseh and B. Nordell, "Sustainable heating and cooling systems for agriculture," *International journal of energy research,* vol. 35, no. 5, pp. 415-422, 2011.

[79] L. K. Lawrie, Crawley, Drury B. "Development of Global Typical Meteorological Years (TMYx)." Climate.OneBuilding.Org. https://climate.onebuilding.org (accessed March 13, 2025.

[80] G. Maps. "Sidi Okba, Biskra, Algeria." https://maps.app.goo.gl/Z1y2tmuoiGjSCGS39 (accessed March 13, 2025.

[81] D. C3-T, "Règlementation thermique des bâtiments," *CNERIB,* 2011.

[82] M. P. Silva, F. C. Baêta, I. F. Tinôco, S. Zolnier, and A. Ribeiro, "Evaluation of a simplified model for estimating energy balance in broilers production housing," *Revista Brasileira de Engenharia Agrícola e Ambiental,* vol. 11, pp. 532-536, 2007.

[83] A. Saadi, M. Becherif, and H. Ramadan, "Hydrogen production horizon using solar energy in Biskra, Algeria," *International Journal of Hydrogen Energy,* vol. 41, no. 47, pp. 21899-21912, 2016.

[84] A. Chabani, S. Makhloufi, and S. Lachtar, "Overview and impact of the renewable energy plants connected to the electrical network in southwest Algeria," *EAI Endorsed Transactions on the Energy Web,* vol. 8, no. 36, 2021.

[85] L. Hamane and A. Khellaf, "Wind energy resource in Algeria," in *World Renewable Energy Congress VI*, 2000: Elsevier, pp. 2352-2355.

[86] N. Moummi, H. Benfatah, N. Hatraf, A. Moummi, and S. Y. Ali, "Le rafraîchissement par la géothermie: étude théorique et expérimentale dans le site de Biskra," *Journal of Renewable Energies,* vol. 13, no. 3, pp. 399–406-399–406, 2010.

[87] A. Rouag *et al.*, "Technical solution for malfunction of air coolers and condensers in hot climates: thermal design of a Geothermal Air-Cooler," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* pp. 1-14, 2020.
[88] H. Nebbar, N. Moummi, N. Hatraf, A. Brima, and A. Moummi, "Simulation du comportement d'un échangeur Air/sol destiné au rafraîchissement des locaux," *Premier Séminaire National de Génie Mécanique (SNGM01) Biskra,* pp. 06-07, 2011.
[89] Y. Belloufi *et al.*, "Transient assessment of an earth air heat exchanger in warm climatic conditions," *Geothermics,* vol. 104, p. 102442, 2022.
[90] A. Boulal, E. Benmehdi, R. Mebarki, K. Hadri, and A. Aroussi, "Conversion of fruit kernels of Algerian date palm (phoenix dactylifera l.) into biodiesel," *Journal of Renewable Energies,* pp. 59–64-59–64, 2022.
[91] M. Djaafri *et al.*, "A route for bioenergy in the sahara region: date palm waste valorization through updraft gasification," *Energies,* vol. 17, no. 11, p. 2520, 2024.
[92] F. Wiesinger *et al.*, "Assessment of the erosion risk of sandstorms on solar energy technology at two sites in Morocco," *Solar Energy,* vol. 162, pp. 217-228, 2018.
[93] S. S. Alanzi, B. Aldalali, and R. M. Kamel, "Effects of sandstorms on hybrid renewable energy sources and load demand in arid desert climates: A case study," *Energy for Sustainable Development,* vol. 81, p. 101473, 2024.
[94] A. I. A. AL-Musawi, A. Taheri, A. Farzanehnia, M. Sardarabadi, and M. Passandideh-Fard, "Numerical study of the effects of nanofluids and phase-change materials in photovoltaic thermal (PVT) systems," *Journal of Thermal Analysis and Calorimetry,* vol. 137, no. 2, pp. 623-636, 2019.
[95] D. S. Borkar, S. V. Prayagi, and J. Gotmare, "Performance evaluation of photovoltaic solar panel using thermoelectric cooling," *International Journal of Engineering Research,* vol. 3, no. 9, pp. 536-539, 2014.
[96] V. J. Fesharaki, M. Dehghani, J. J. Fesharaki, and H. Tavasoli, "The effect of temperature on photovoltaic cell efficiency," in *Proceedings of the 1stInternational Conference on Emerging Trends in Energy Conservation–ETEC, Tehran, Iran*, 2011, pp. 20-21.
[97] V. Bansal, R. Misra, G. D. Agarwal, and J. Mathur, "Transient effect of soil thermal conductivity and duration of operation on performance of Earth Air Tunnel Heat Exchanger," *Applied Energy,* vol. 103, pp. 1-11, 2013.
[98] Y. Cengel and T. M. Heat, *A practical approach*. New York, NY, USA: McGraw-Hill, 2003.
[99] V. I. Hanby, *Combustion and pollution control in heating systems*. Springer Science & Business Media, 2012.
[100] F. Al-Ajmi, D. Loveday, and V. I. Hanby, "The cooling potential of earth–air heat exchangers for domestic buildings in a desert climate," *Building and Environment,* vol. 41, no. 3, pp. 235-244, 2006.
[101] MansouriPlast, "http://mansouriplast.com/produits/tubes/pression," Last visit: 20/07/2021.
[102] A. K. Sumabat *et al.*, "Decomposition analysis of Philippine CO2 emissions from fuel combustion and electricity generation," *Applied Energy,* vol. 164, pp. 795-804, 2016.
[103] E. p. a. (EPA), "Emission Factors for Greenhouse Gas Inventories," *U.S. Environmental Protection Agency,* 26 March 2020 2020.
[104] V. Bajpai, G. Kulkarni, S. S. Han, and T. Ramachandra, "Carbon emissions due to electricity consumption in the residential sector," *Energy & Wetlands Research Group, Centre for Ecological Sciences, Indian Institute of Science Bangalore—560 012,* 2012.

[105] M. Brander, A. Sood, C. Wylie, A. Haughton, and J. Lovell, "Technical paper| Electricity-specific emission factors for grid electricity," *Ecometrica, Emissionfactors. com,* 2011.

[106] A. Laknizi and M. Mahdaoui, "Energy Performance and Environmental Impact of an Active Domestic Solar Water Heater in Maghreb Arab Union Countries," *International Journal of Renewable Energy Research (IJRER),* vol. 8, no. 3, pp. 1572-1579, 2018.

[107] T. S. Bisoniya, A. Kumar, and P. Baredar, "Energy metrics of earth–air heat exchanger system for hot and dry climatic conditions of India," *Energy and Buildings,* vol. 86, pp. 214-221, 2015.

[108] K. Harby and F. Al-Amri, "An investigation on energy savings of a split air-conditioning using different commercial cooling pad thicknesses and climatic conditions," *Energy,* vol. 182, pp. 321-336, 2019.

[109] A. Franco-Salas, A. Peña-Fernández, and D. L. Valera-Martínez, "Refrigeration capacity and effect of ageing on the operation of cellulose evaporative cooling pads, by wind tunnel analysis," *International journal of environmental research and public health,* vol. 16, no. 23, p. 4690, 2019.

[110] I. ANSYS, "Lecture 7: Mesh Quality & Advanced Topics," *Introduction to ANSYS meshing,* 2015.

[111] ANSYS, "ANSYS Fluent Users Guide," 2013.

[112] B. Bjerg *et al.*, "Modelling of ammonia emissions from naturally ventilated livestock buildings. Part 3: CFD modelling," *Biosystems engineering,* vol. 116, no. 3, pp. 259-275, 2013.

[113] Z. Zhang, W. Zhang, Z. J. Zhai, and Q. Y. Chen, "Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part 2—Comparison with experimental data from literature," *Hvac&R Research,* vol. 13, no. 6, pp. 871-886, 2007.

[114] A. O. Jongbo, S. S. Olajide, and A. T. Atta, "The Application of Computational Fluid Dynamics (CFD) in the Ventilation of Agricultural Buildings: A Review," *JOURNAL OF AGRICULTURAL ENGINEERING AND TECHNOLOGY,* vol. 26, no. 1, pp. 104-124, 2021.

[115] F. Rojano, P.-E. Bournet, M. Hassouna, P. Robin, M. Kacira, and C. Y. Choi, "Modelling heat and mass transfer of a broiler house using computational fluid dynamics," *Biosystems engineering,* vol. 136, pp. 25-38, 2015.

[116] N. J. Daghir, *Poultry production in hot climates*. Cabi, 2008.