Energy use and indoor climate in livestock buildings for pigs

An introductory paper

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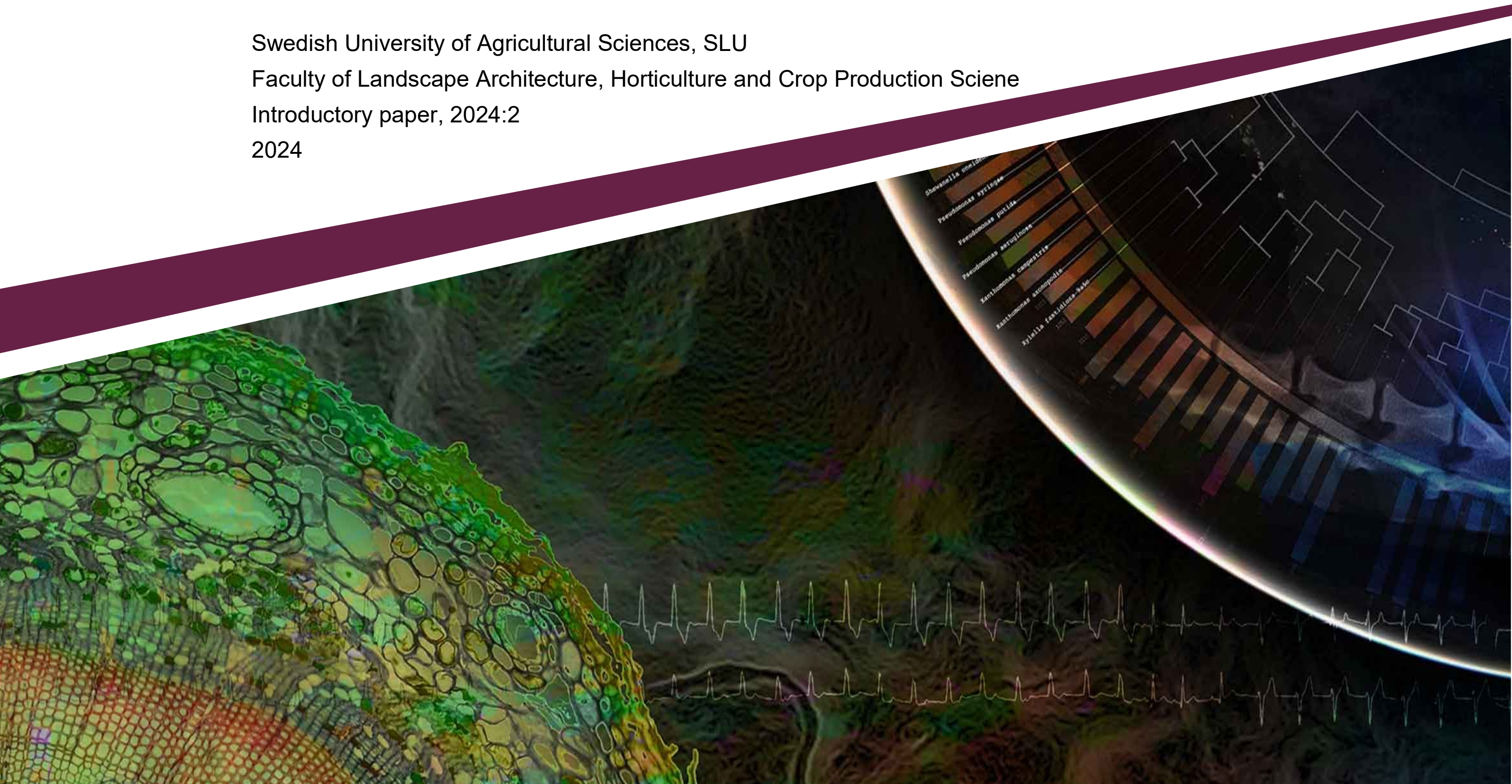

Energy use and indoor climate in livestock buildings for pigs. An introductory paper

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Abstract

Swedish pig farming is facing two climatic challenges: minimizing greenhouse gases and adapting to warmer climates in confined livestock buildings. Climate change leads to more heat waves, causing pigs in confined buildings to endure heat stress more often and for longer periods. Heat stress not only affects the animals' welfare and health negatively, but it also implies a risk of economic losses for farmers, as heat stress can result in slower growth, impacts on reproduction and increased mortality. Pigs are particularly sensitive to heat because they do have few sweat glands.

This introductory paper on the subject “Improving energy-efficiency and indoor climate of livestock buildings for pigs through passive and active adaptation measures” highlights the need for adaptation measures due to climate change. The main aim of this introductory paper is to provide a summary of current research and knowledge on the energy efficiency and indoor climate of livestock buildings for pigs, as well as the need for further research on pig buildings in Sweden. Many studies have evaluated potential adaptation measures to lower indoor temperatures and reduce heat stress in warmer climates. The most commonly implemented measures for cooling are increased airflow and air velocity, as well as evaporative cooling. The reviewed articles also indicated that insulation and mechanical ventilation are required in warmer climates to maintain an acceptable indoor climate.

The main conclusions are that:

(1) Heat stress for pigs will increase due to global warming, necessitating adaptation measures to reduce indoor temperatures in warmer climates.

(2) Technical solutions are available to reduce indoor temperatures in warmer climates. However, studies on the investment costs and energy use of these solutions are lacking.

(3) To reduce the environmental impact of livestock buildings intended for pigs, it is necessary to develop energy-saving solutions, improve management practices, and use non-fossil energy sources.

(4) Computer simulations can be used as a tool to predict thermal climate and energy use in livestock buildings.

(5) It is recommended to develop a common framework and use standardised functional units to enable comparison and simplify evaluation of results from different studies.

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Abbreviations

ADG	Average daily gain
ACH	Air changes per hour
AHU	Air-handling unit
BC	Baseline case also referred to as reference case
BW	Body weight
CFD	Computational fluid dynamics
CO_2e	CO_2-equivalents
COP	Coefficient of performance
CP	Cooling pads
CPHE	Cooling pads in combination with heat exchanger
EAHE	Earth-to-air heat exchanger
ET	Effective temperature
EWHE	Earth-to-water heat exchange
FCR/FCI	Feed conversion ratio/index
GFA	Gross floor area
GFP	Growing-fattening pigs
GHG	Greenhouse gases
HE	Heat exchange
HPE	High pressure evaporation
HPU	Heat production unit
IAQ	Indoor air quality
ICC	Indoor climate control (also referred to as thermal climate control)
LCA	Life-cycle analysis
LCT	Lower critical temperature
MV	Mechanical ventilation
NV	Natural ventilation
OT	Operative temperature
PPV	Partial pit ventilation
RH	Relative humidity

TC	Temperature control
THC	Temperature humidity control
THI	Temperature-humidity index
TNZ	Thermal neutral zone
UCT	Upper critical temperature

Terminology

All in - All out	A system where all pigs in a production cycle are taken in and out at the same time. The section is cleaned and disinfected when it is empty.
Cooling pads	A porous water filter that allows air to pass through and reduce the temperature by evaporation.
Effective temperature (ET)	Index based on temperature, humidity, and air velocity for evaluation of indoor thermal climate. Various equations are available.
Farrowing	Production cycle from pregnant sow to piglet birth.
Feed conversion (FCR/FCI)	Measure describing how well feed is converted to weight gain. Usually expressed as a ratio or index.
Gestation	Pregnancy of sow or gilt.
Gravity intakes	An air supply unit with an adjustable opening diameter that varies based on the pressure differential between the interior and exterior
Growing pigs	Weaned pigs until they reach a weight of 25-30 kg.
Growing-fattening (GFP), fattening or finishing pigs	Pigs from 25-30 kg to slaughter weight (approximately 90-130 kg).
Heat stress index	Time above the upper critical temperature. Expressed in [°Ch].
Lactating	Piglets with sow; the piglets nurse until weaning.
Live weight	Pigs’ weight before slaughter.
Operative temperature (OT)	Includes radiative effects due to temperature differences in the air and of surrounding surfaces.
Partial pit ventilation (PPV)	Manure pit equipped with an exhaust fan that takes a portion of the total ventilation requirement.

Production cycle	A cycle of production in which pigs grow from one stage to the next. Typical cycles are farrowing until weaning, fattening or growing-fattening pigs.
Slaughter weight	Includes all parts of the pigs except intestines.
Slurry	Manure including feed, water and straw remains.
Temperature-humidity index (THI)	Dimensionless index considering both temperature and humidity. Various equations are available and it includes coefficients on physiological reactions.
Thermal neutral zone (TNZ)	Temperature range when the heat dissipation from the pigs is not affected by temperature changes in the air (CIGR, 2002).
Weaned pigs, weaning	In Sweden, the piglets can be separated from the sow at 28 days if they have adapted to supplementary food. Weaning at 21 days is possible if eleven additional conditions are met (SJVFS 2019:20).

1. Introduction

Pigs spend their lives in confined buildings. Increased outdoor temperatures, due to global warming result in higher temperatures in these confined spaces; increasing the risk of heat stress for the pigs (Mikovits et al. 2019; Renaudeau & Dourmad 2022). Adaptations to warmer climates in pig buildings are essential to reduce heat stress. A review of how global climate change affects pig farming in the EU showed that, without adaptation, pig farming would most likely be vulnerable to the impacts of global warming, as livestock performance would decline while production costs would increase (Renaudeau & Dourmad 2022).

Pigs are sensitive to heat stress because they have very few sweat glands, meaning they cannot sweat to reduce their temperature. Their natural way to cool down is to wallow in mud (Jensen, 2006) and in confined buildings, they tend to wallow in manure when it is too warm. Pig behaviour changes with temperature variations. When it is colder, they huddle, meaning they lie together, sometimes in a heap. When it is warmer, respiration rate and water consumption increase, laying behaviour changes and fouling on the solid floor increases (Huynh et al. 2005, Banhazi et al. 2008), as illustrated in Figure 1.

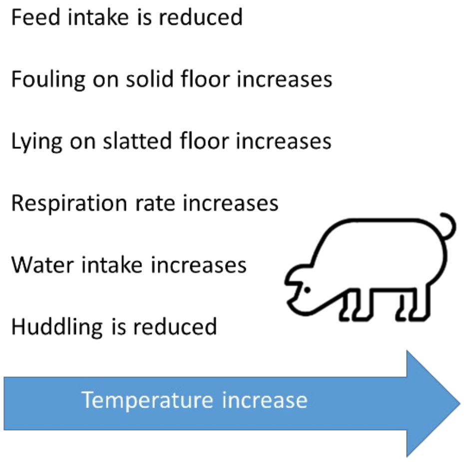

Figure 1. Behaviour changes due to temperature changes (adopted from Banhazi et al. 2008)

Pigs, especially small ones, are sensitive to cold stress and they conserve heat by huddling if the heat source is insufficient or non-existent. Therefore, piglets need to be kept in a warm and draught-free place (Sällvik, 2005). Temperatures within the thermal neutral zone (TNZ) in pig buildings are necessary to ensure animal welfare. Lower and upper critical temperatures (LCT and UCT) represent the temperature at which pigs cannot maintain an internal temperature of 39°C without supplemental heating or cooling, which can lead to hypothermia (when too cold) and hyperthermia (when too warm) (CIGR, Pedersen, S & Sällvik, K. editors (2002)).

The term "animal welfare" encompasses the conditions of health and physiology, as well as reproduction and behaviour. Behaviour is often utilised as a measure of welfare because changes in health or physiology are not always readily noticeable, and good production does not necessarily imply good welfare (Jensen, 2006). With an acceptable indoor climate, the fouling in the pens is reduced. Cooling strategies such as showers and directed air velocity have been shown to reduce fouling in the pens (Jeppsson et al. 2021a and 2021b).

Adaptation measures to warmer climates must prioritize energy efficiency to minimise the environmental impact of pig farming. In Sweden, the agricultural sector's contribution to greenhouse gases (GHG) accounted for 15 % of the territorial emissions of the 45.2 million tons CO_2- equivalents (CO_2e) in 2022 (Naturvårdsverket, 2023). From a life-cycle analysis (LCA) perspective, where all emissions throughout the product's life cycle, such as from cradle to farm gate, are considered, pig breeding contributed to 2.5-2.6 kg CO_2e per kg slaughter weight (Landquist et al. 2020, Zira et al. 2021). On a global scale, pig production has shown a contribution of up to 11.2 kg CO_2e per kg live weight from cradle to farm gate (Gislason et al. 2023). Factors such as feed production, transport, water use, manure management, and housing, including heating, mechanical ventilation (MV), cooling, lighting, as well as feed distribution, contribute to the total environmental impact from pig breeding (Costantino et al. 2016, Sharpe et al. 2018, Hörtenhuber et al. 2020, Landquist et al. 2020). Several studies indicate that manure management and feed production are responsible for a major share of total environmental impacts of pig farms, while housing factors contribute less (Landquist et al. 2020; Lammers et al. 2012; Hörtenhuber et al. 2020; Pexas et al. 2020).

1.1 Global pig production

In 2022, China produced 55 million tons of pork, while the EU and the United States produced 22 and 12 million tons respectively (Statlista 2023). The EU has traditionally been the largest exporter of pork (Rudek & Aneja 2013). However, European statistics from 2022 show that pork exports from the EU are decreasing, while exports from the United States are on the rise. Between March 2022 and March 2023, the United States surpassed the EU as the largest exporter (European Commission 2023). In the EU, pig production is expected to decline by 1% until 2032 due to the African swine fever and increased pig production in China. Overall, the production of pork is expected to increase due to population growth and higher income levels, although meat consumption per person is anticipated to decline from 2022 to 2032 (European Commission 2022).

1.2 Aims

This introductory paper is a part of a PhD project on energy use and indoor climate in livestock buildings for pigs aiming to:

- obtain an overview and summarise findings in research and knowledge on energy efficiency and indoor climate of livestock buildings for pigs since 2000.
- identify the need for further research on energy use and indoor climate in livestock buildings for pigs in Sweden.

2. Pig buildings in Sweden

2.1 History

For centuries, people have maintained certain buildings or shelters for their animals to protect them from the external, especially cold, weather conditions. Several animal species were kept in the same building for domestic needs (Svala, 1993).

At the time of the land consolidation in the 19th century, farmers received double the relocation allowance if they built with stone instead of wood, reflecting concerns about the shortage of forests in Sweden at that time (Svala, 1993). Land consolidation resulted in reallocation of land areas, often dividing villages to create adjoining properties with an associated farm. Prior to this, buildings were typically grouped together in villages, with land divided into smaller plots scattered in different areas around the village (Molén and Bergsjö, 1987).

Historically, barns were constructed using both stone and timber. In the 19th century, farmers began moving fodder such as hay, from separate barns to the attic above the animal stables. This was considered advantageous for two reasons: the hay insulated the ceiling, and the fodder was located closer to the animals. Production increased during the time of land consolidation, and buildings were constructed to be more airtight. Storing fodder in the attic, airtight buildings, and increased livestock led to a greater need for ventilation due to higher air humidity (Svala, 1993).

Agricultural buildings have always been rebuilt and adapted to new needs and technologies, transitioning from a smaller scale based on human and animal needs to a larger scale based on the space requirements of machines. Practical functions guided the location and design of the buildings, with a common practice being the reuse of building materials whenever possible (Svala, 1993, Molén & Bergsjö, 1987).

2.2 Housing systems

The design of housing systems for pigs is regulated by the Swedish Board of Agriculture (Jordbruksverket, 2019), while the heating and ventilation requirements are regulated by the Swedish Standard SS 951050:2014 (Swedish standard, 2014).

In confined buildings with insulated envelope and MV, the most common housing system is pens with sizes appropriate for the number, age, and weight of the pigs. These pens typically accommodate 10 to 15 growing pigs, often from the same litter, or one sow with piglets in each pen (Farm visits 2022-2023). The lying area must constitute 70-75% of the total area for growing pigs and growing-fattening pigs (GFP), depending on pig size, with the remaining area possibly slatted for manure drainage. The solid area for laying may be slatted with urinary drainage and smaller gaps in the floor. Urinary drainage floors, as part of the solid floor, are more common in newer buildings compared to old ones (Farm visits 2022-2023). For lactating sows, the urinary drainage area must not exceed 25% of the lying area (Jordbruksverket, 2019). The material of the slatted floor may be concrete, plastic, or cast iron (Farm visits 2022-2023). Below the slatted floor, there is a manure pit, and the manure/slurry is regularly removed with vacuum pumps or scrapers. Air from the manure pit may not be transferred to another room with pigs for biosafety. In livestock buildings with bedded floors, the manure is removed when the bedding is replaced (Jordbruksverket 2019, Farm visits 2022-2023).

Figure 2 shows a typical pen for growing pigs in an intensive system (a) and an example of organic farming at Källunda Gård in Sweden (b). The farm is a member of the Swedish association "Jord på trynet", freely translated to "Soil on the nose" (Jord på trynet, 2023). Organic farming requires outdoor access with the possibility of rooting, wallowing, or access to water for cooling (Jordbruksverket, 2023a).

Figure 2: (a) Example of pen with growing pigs in intensive pig farming (Farm visits 2022-2023). (b) Example of organic farming with pigs reared outdoors and access to shelter all year round. The owner of the farm has designed and developed the shelters (Magnus Nyman, Källunda gård, Sweden).

In Table 1, some important Swedish requirements related to animal density and indoor climate for pigs of different sizes and genders are shown. Airflow requirements are related to climate zones in Sweden, and the lower winter flows for GFP in the table refer to areas with lower outdoor temperatures. The upper limits for level of ammonia ($\leq$ 10 ppm), carbon dioxide ($\leq$ 3000 ppm), H_2S ($\leq$ 0.5 ppm), and organic dust ($\leq$ 10 mg/m^3) are the same for all pigs (Jordbruksverket, 2019).

Table 1. Selection of requirements regarding housing and indoor climate in confined buildings with mechanical ventilation (Jordbruksverket 2019, ** Swedish Standard 2014)*

Pen size per pig (whereof laying area), slatted floor*	**Pen size per pig, bedded floor***	**Temperature, sizing of heat and ventilation ****	**Ventilation, sizing per pig****
Boar			
7 m^2 (6 m^2)	7 m^2		
Gilt and small sow, pregnant			
≤ 5 pigs per group: 1.81 m^2 (0.9 m^2) *≥ 6 pigs per group:* 1.64 m^2 (0.9 m^2)	0.20 m^2 + weight [kg]/84	*Winter:* 16°C *Summer:* 25°C	*Winter:* 19 m^3/h *Summer:* 120 m^3/h
Sow, pregnant			
≤ 5 pigs per group: 2.25 m^2 (1.1 m^2) *6-39 pigs per group:* 2.48 m^2 (1.1 m^2) *≥ 40 pigs per group:* 2.05 m^2 (1.1 m^2)	2.5 m^2	*Winter:* 16°C *Summer:* 25°C	*Winter:* 21 m^3/h *Summer:* 135 m^3/h
Sow, lactating			
6 m^2 (4 m^2)	7 m^2	*Winter:* 18°C *Summer:* 25°C	*Winter:* 25 m^3/h *Summer:* 610 m^3/h
Piglets			
			For ventilation sizing: Heat lamp: 150 W
Growing pigs (≥ 10 kg)			
0.17 m^2 + weight [kg]/130 (0,10 m^2 + weight [kg]/167)	0.20 m^2 + weight [kg]/84	*Winter:* 18°C *Summer:* 25°C	*Winter:* 3.5 m^3/h *Summer:* ≤ 25 kg: 50 m^3/h ≤ 35 kg: 60 m^3/h
Growing-fattening pigs (≤ 130 kg)			
0.17 m^2 + weight [kg]/130 (0,10 m^2 + weight [kg]/167)	0.20 m^2 + weight [kg]/84	*Winter:* 18°C *Summer:* 25°C	*Winter:* 25-95 kg: 7.5-8.5 m^3/h 35-95 kg: 11-12 m^3/h *Summer:* 25-95 kg: 95 m^3/h 35-95 kg: 95 m^3/h

2.2.1 Gestating sows

A common housing system for gestating sows and gilts is a naturally ventilated (NV) or mechanically ventilated (MV) building with a thick layer of litter on the floor called deep bedding. NV buildings are usually not insulated and are ventilated through roof openings for exhaust and eaves or wall openings for air supply. Another system for sows involves larger pens for several sows with transponders and partly slatted floors (Farm visits, 2022-2023). Gilts and gestating sows are often housed together in larger groups, as shown in Figure 3 (Farm visits, 2022-2023).

Figure 3: Housing systems for gestating sows and gilts with insulated walls and mechanical ventilation. (a) Pen with deep bedding with cages temporary used during feeding and medical treatment. (b) System with food transponder and slatted floor.

2.2.2 Farrowing and piglets

Before farrowing, pregnant sows are usually moved to an insulated building with MV. Each sow is placed in a separate pen, which may allow for temporary restraint of the sow. In general, the sows are free to move, and the piglets have a separate area with extra heat and protection from the sow. There may be rails on the interior walls of the pen to protect the piglets when the sow is lying down, as shown in Figure 4 (a). (Farm visits, 2022-2023)

2.2.3 Growing and growing-fattening pigs

At weaning, the piglets are moved to a new pen in an empty section, or the sow is removed from the piglets, as shown in Figure 4. The pen is similar for growing pigs and growing-fattening pigs. The floor is usually partly slatted with a manure pit below. The placement of feeders, slatted floors, and service areas varies (Farm visits 2022-2023).

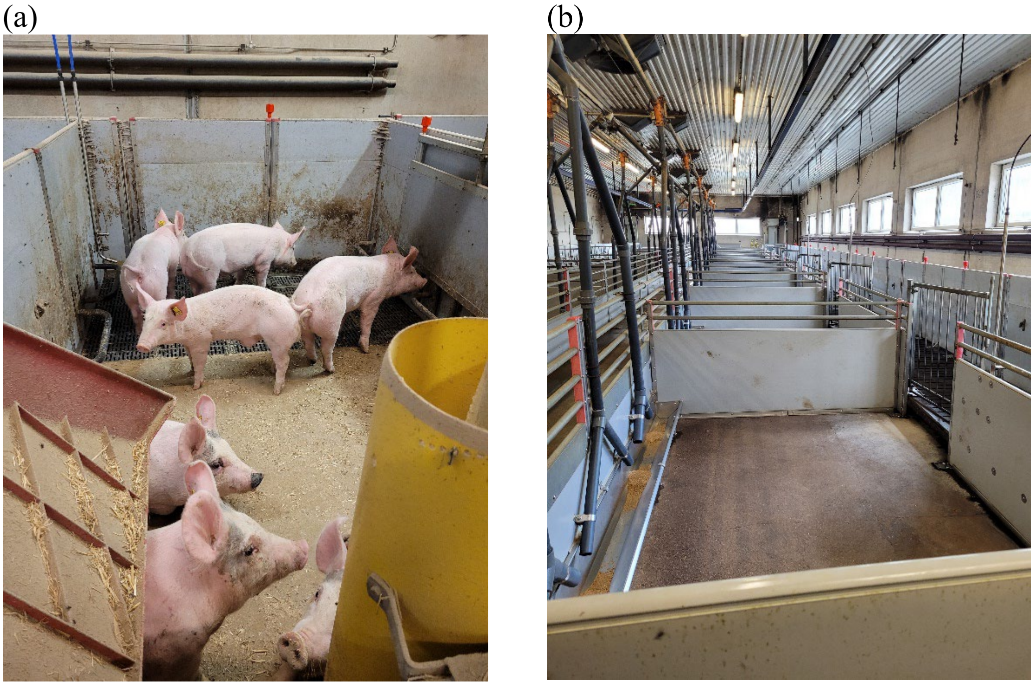

Figure 4. (a) Pen for farrowing and growing pigs with slatted floor in the back of the pen. A hatch in the slatted floor is openable for cleaning of the pen. (b) Pen for growing-fattening pigs with raised slatted floor in the back of the pen. There is an opening between slatted and solid floor for cleaning of the pen (Farm visits 2022-2023).

2.3 Building envelope

Concrete is a common material for walls and floors in pig production buildings. The roof slope is traditionally 20-27% (Molén, Bergsjö, 1987; farm visits 2022-2023), and ceilings are often constructed with corrugated metal sheets insulated with loose mineral wool. New buildings are typically insulated at the walls and ceilings (farm visits, 2022-2023). However, the regulations do not specify a preferred insulation level; instead the heat transmission coefficient is included in the calculation of the heating requirements (Swedish Standard, 2014). The concrete floor may be insulated from the ground.

2.4 Ventilation and heating

In Sweden, regulations require a minimum level of ventilation during winter to maintain acceptable indoor air quality (IAQ) concerning carbon dioxide, ammonia, and humidity levels. During summer, ventilation is used for cooling, and the maximum ventilation is determined based on the outdoor temperature. The maximum ventilation is determined to ensure that the indoor temperature does not exceed 25°C when it is 21°C outdoors (Swedish standard, 2014). The most prevalent cooling method in Sweden is showers in addition to high ventilation rates. The supply air is usually distributed through air jets in the insulated ceiling. The air enters the attic through openings in the eaves. An example of a section for GFP in a typical Swedish livestock building for pigs is shown in Figure 5.

Figure 5: Typical layout in a Swedish livestock building for pigs, including one exhaust fan, one ceiling air jet per pen, pipes for feed, heat pipes below windows, and showers for cooling and dust binding (Farm visits 2022-2023).

A farm's heating source can be centrally located within the property. Biofuel burners are common, and it is possible to obtain permission to burn carcasses for heating purposes. Depending on the type of incinerator, notice or permission may be required (Jordbruksverket, 2023b). Heat sources are usually connected to water tanks. The heated water is distributed through pipes beneath windows, pipes as part of the pen walls, underfloor pipes, or pipes for hot tap water. During the cleaning period, fans driven by diesel generators or underfloor heating may be used for faster drying after cleaning between batches. In cribs, heat lamps are usually used, often in combination with underfloor heating. Some farms have collector pipes in the manure pit connected to heat pumps for heating (Farm visits, 2022-2023). However, differences exist between farms regarding heat sources, and other heating systems and combinations are also used.

3. Method

This chapter presents the method used to find articles on the topic of energy efficiency and indoor climate in livestock buildings for pigs. The information presented in this report was retrieved using a keyword search, which included all types of references such as scientific articles and articles prepared for meetings and conferences published between January 1, 2000 and January 13, 2023. The following regions were of interest: North America (USA and Canada), Northern Europe (Denmark, Estonia, Finland, Iceland, Ireland, Lithuania, Latvia, Norway, Sweden, UK), and Western Europe (Belgium, France, Liechtenstein, Luxembourg, Monaco, Netherlands, Switzerland, Germany, Austria), as well as unspecified countries. These countries were selected because they have climates similar to Sweden and many face similar challenges in pig production related to climate change. In Europe, Spain and Italy were included as both countries had 20 or more references, indicating high research activity. The selected languages were English, German, and Swedish.

The following keywords were used in the search:

- Energy efficiency: energ* OR resource* OR {environmental impact} OR efficien*

  AND

- Indoor climate: thermal OR {internal climate} OR {indoor climate} OR air OR microclimate OR {micro climate} OR overheat* OR temperature OR humid* OR heat OR cold OR airflow OR {stay zone} OR {animal zone} OR {production zone}

  AND

- Pig: pig OR pigs OR swine* OR hog OR sow OR sows OR hogs OR piglet* OR gilt* OR pork

  AND

- Building: building* OR hous* OR pigsty OR pigsties OR {pig stable} OR farm* OR barn OR premis*

  AND

- Adaption measures: passive OR active OR cool* OR adapt* OR measur* OR ventil* OR heat* OR design OR concept* OR model*

Initially, 631 references were found. In this introductory report, all articles of interest regarding energy use and indoor climate in pig buildings, as well as LCA, were included. Articles related to medical issues, energy production, and other non-building-related matters were excluded. The reference management program Zotero was used to keep track of references.

In the second step, several articles were excluded by screening the titles for relevance, leaving only 131 articles for further examination. The third step involved reading all abstracts and classifying them according to relevance, resulting in 84 articles being selected for further review. While reading the articles, some were excluded as they were judged irrelevant. Six articles were not found in full text and were thus excluded.

Finally, 51 references were read and analysed. These are discussed in the review results section, with two additional articles added. The first one was by Anthony et al. (2015), as it was clearly related to and complemented the article by Peters et al. (2015) on relevant IAQ issues. The second was a review of used energy and thermal climate models in Europe (Costantino & Fabrizio 2019) as part of the EPAnHaus project (Bilardo et al. 2019). All references were summarised using one mind map per reference, which included the research aim, method, important results, and main conclusions. Figure 6 presents a conceptual diagram showing the addressed areas related to energy efficiency and indoor climate research. Information on energy use, indoor climate, and energy and indoor climate simulation is presented under separate headings.

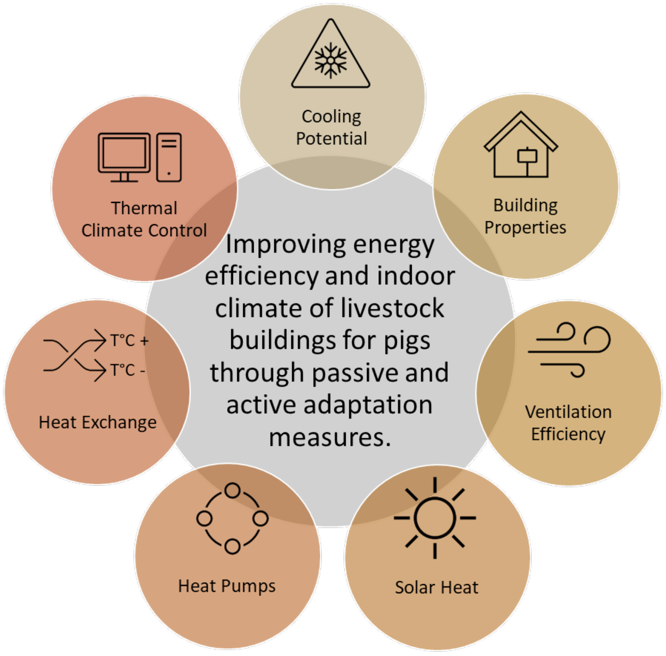

Figure 6. Diagram of included adaptation categories in the literature review.

4. Results

4.1 Energy use

Seven of the reviewed articles presented results on energy use in pig farming. Four articles measured energy use on commercial farms, with two of these reporting results from the same study. Two papers involved the development of energy and thermal climate models with calculated predicted energy use. One study experimentally compared two heat sources in piglet cribs. The presented results cannot be directly compared due to varying or unknown outdoor air conditions, different types of buildings, production stages, and functional units. The studies indicate that management, maintenance, and control settings contribute to energy use on pig farms and highlight a lack of energy use data for livestock buildings for pigs.

Hanna et al. (2014) emphasised the need for benchmarking energy use to enable the evaluation of management options for pig farmers in the US. The results of a study on energy use on farms for finishing pigs were first presented at an international meeting and then published in a journal two years later with some changes in the results and discussion (Hanna et al. 2016). The studies analysed energy use activities for farmers, including field operations, crop drying, and the performance of livestock buildings for pigs. For the buildings, the main conclusions were that management, maintenance and control settings all influence energy use and that measurements on farms are needed to enable benchmarking.

At one site, electricity use for the exhaust fan was measured for two years in two rooms for finishing pigs, returning 11 kWh per pig space. Each room was 223 m^3 for 300 pigs, and the ventilation system operated in three fan stages with a maximum ventilation rate of 1.43 m^3/min per pig. The study showed the importance of energy-efficiency for the most frequently used fan when using multiple fans. Evaluation of the remaining sites was based on reported information on energy use, and the electricity use was found to be 21-29 kWh per pig space, depending on the building type. Tunnel ventilation buildings had a higher electricity use than curtain-sided buildings. Fuel use for heating could only be accurately measured at one site, resulting in 2.5 litres of propane per growing fattening pig space and 10.6 litres of propane per weaned pig space. This article contained no information on outdoor or indoor air conditions at the time of the study.

Costantino et al. (2016) reported statistics on energy use in livestock buildings for pigs in Europe. Data on energy use for ventilation, heating, and lighting was collected from Italy and the UK. The data was recalculated to key figures in kWh/m^2 per year and Wh/kg of meat. The reported range for energy use in pig buildings was 34-37 kWh/m^2 per year, and 119-174 Wh/kg of meat. Energy use for lighting was 1-5 kWh/m^2 per year and 4-25 Wh/kg of meat. The variation in energy use was attributed to differences in climate, type of pig breeding, and heating and ventilation systems. The authors recommended gathering more data via questionnaires, measurements, and energy simulations on case studies to obtain a clearer picture of energy use in pig farming.

Another American study on total energy use for three stages in pig rearing was conducted in the Midwest (Sharpe et al. 2018). This study included six barns at different locations, housing farrowing and lactating sows, growing pigs, and finishing pigs, with two barns for each pig type. The barns varied in size and had different ventilation and heating systems. Fuel consumption, such as propane, and total electricity use were measured and recorded monthly over two years, from 2015 to 2016. Energy use included heating lamps, lighting, ventilation, feeders, and other miscellaneous items in each barn. The buildings for weaned pigs were equipped with mechanical ventilation (MV), while barns for sows and growing-fattening pigs (GFP) had either MV or natural ventilation (NV). The MV buildings had exhaust fans or tunnel ventilation, while the NV building had mixing fans. All barns were equipped with pit fans. For piglets until weaning, including energy use for gestating and farrowing, fuel consumption ranged from 1.17 to 1.29 liters per weaned pig, and electricity use ranged from 11.36 to 11.91 kWh per weaned pig. For growing pigs, fuel consumption ranged from 1.55 to 1.63 liters per pig, and electricity use ranged from 2.1 to 2.38 kWh per pig. The outcome for GFP was that the barn with NV had higher fuel consumption than barns with MV (1.85 liters and 1.29 liters per pig, respectively), whereas electricity use was 4.12 kWh per pig in the NV barn and 14.4 kWh per pig in the MV barn. Electricity use in the GFP barn was mainly for ventilation. Differences in site management, animal welfare, and indoor or outdoor climate were not considered in the study.

As part of the EPAnHaus (Energy Performance of Animal House) project (2014-2017), a study was conducted to assess the relationship between animal welfare, indoor climate conditions, and energy use for two buildings housing GFP in North West Italy (Bilardo et al. 2019). The structures of the buildings were comparable, with fully slatted concrete floors, sandwich roofs (likely metal sheets and insulation), and hollow concrete wall blocks. Additionally, the buildings were equipped with polycarbonate inlets, four exhaust pit fans (0.55 kW per fan), and two movable heaters (62 kW per heater). Building A had a 285 m^2 gross floor area

(GFA) with 155 pigs, and building B 400 m² GFA with 250 pigs. Air temperature, humidity, and electricity use were measured during three production cycles from March 2017 to April 2018, consisting of one production cycle in warm weather and two cycles in cold weather. The findings were consistent for both buildings, with results from only building A being presented in the article. The total energy use was 2514 kWh during the warm season and 1626 kWh during the cold season. The distribution of electricity use was similar for both seasons, with 89% used for ventilation, 7-8% for feeders, and 3-4% for other purposes. The specific energy use for building A was 14.52 kWh/m² of GFA or 62.93 Wh/kg of meat. The mortality rate in the warm period was comparable in both buildings, at 3.9% and 3.6% respectively. The growth rate of pigs and the heat stress index were calculated based on Gompertz function (Gompertz 1825) and Panagakis (2008). The heat stress index results were 2251 and 2324 °Ch for building A and B respectively. The authors recommended using cooling pads (CP) to alleviate heat stress.

Lane et al. (2020) conducted a study on the use of electric heat mats (85W), made of polyethylene, compared to heat lamps (125W) in cribs for piglets. The heated zone measured 34 cm by 122 cm for the mats and 40 cm by 121 cm for the lamps. The aim of the study was to monitor sow and piglet behaviour, piglet growth, piglet mortality, energy use, as well as investment and operation costs. The temperature set point was 32.2°C in the creep area. The installation height of the lamps was adjusted to provide equal temperatures for both systems, and the temperature was measured on a surface, although it is not clear where and in how many measuring points. No information was provided regarding whether these point temperature were lowered during the production cycle, according to the heat requirements for growing pigs. The results showed that contact between sows and piglets was more constant on the third and fourth day with heating mats, while contact between sows and piglets varied more in cribs with heat lamps. No significant difference in mortality rate was found. Energy use was 19.4 kWh per production cycle with heat mats and 68.5 kWh per cycle with heat lamps. However, the lamp had a single-step thermostat, and the mat a programmable thermostat. Operating and investment costs were estimated to be lower for the heat mat system compared to the heat lamp system. The lactation period was 21 days, and pre-farrowing period was two days. We should note here that the mat manufacturer partially funded the research.

Preliminary results for an EU project (2020-2024) called Res4Live (Res4Live.eu), included in Horizon 2020, have been reported (Faes et al. 2021). The aim of Res4Live is to develop an energy model for livestock buildings for pigs as a tool to reduce the GHG contribution of European agriculture. A preliminary quasi steady-state energy model was developed, which included simulations of energy use, humidity, and indoor temperature. Energy balance calculations were performed for a livestock building for pigs with an area of 2380 m², including rooms for pigs from all stages in pig farming under typical outdoor climate conditions. The calculations included heat loads from the animals (750 pigs, 600 piglets, and 105 sows), underfloor heating (assumed 1800 W for GFP and 2880 W for weaned piglets), and heat lamps (2800 W, reduced to 1400 W for growing piglets). Heat losses included transmission and unwanted infiltrations through the building envelope, as well as calculated airflow rates. This resulted in a heat demand of 157-164.6 MWh, of which 83.1 MWh was for gas heating, 7.7 MWh for lamps, and 73.8 MWh for underfloor heating. The calculated cooling requirement was 85 MWh. The heating and cooling peak loads were found to be 112 kW and 139 kW, respectively. The conclusion was that the simulated values correspond fairly well to measured values, but the model needs adjustment. The cooling load could not be verified as there was no cooling installed in the case study. Development of the model was ongoing, and the project objectives were to include the use of solar panels, air-to-air heat recovery, heat storage, and heat pumps in the simulations. A limitation of this study was that the article did not provide information on the expected indoor thermal conditions.

4.2 Indoor climate

Four review articles presented the risks related to heat stress in future warmer climates, two of which were predictive indoor temperature models, and two reviewed the effects of heat stress. The modelling results showed that heat stress will increase due to global warming, but one of the studies showed no economic impact on gross margins. Both modelling studies concluded that technical adaptations of the buildings would be necessary to maintain an acceptable indoor climate. The two reviews focused on pig behaviour and applied methods to reduce heat stress.

Turnpenny et al. (2001) developed a steady-state model to simulate production factors and stress risks due to climate change. The model, named ECCLIPS (Effect of Climate Change on Livestock Production Systems), included parameters related to weather, building characteristics, heat balance of growing pigs, and feed intake. Outcomes were related to production in terms of yield, feed intake, and final weight. Stress risk was calculated as number of hours in which the maximal ventilation rate was insufficient to keep the required indoor air temperature below the heat stress level. In this study, the heat stress level was defined as 3°C above the lower critical temperature (LCT), resulting in required indoor air temperatures of a maximum of 22°C for pigs and 33°C for piglets. Humidity was also considered in the study. The conclusion was that heat stress would be a major risk factor in the future, but at the time of the study, changes in gross margins were estimated to be negligible.

However, the authors also concluded that capital investments for ventilation and cooling are likely to be required.

Banhazi et al. (2008) performed a review of factors related to heat stress. The review summarises when behaviour changes and health effects occur. In Table 2, the information from the reviewed article has been summarised. Exceeding the upper critical temperature (UCT), which varies depending on pig size and age, results in several effects including reduced growth, reduced immunity, and reduced reproductive trait. This study indicates that traditional methods of reducing heat stress include spray cooling (showers), underfloor cooling, and building design. An application of the Auspig model, where the temperature set point automatically varied based on the measured room temperature, was reviewed and evaluated as a potential tool for dynamic climate control in pig buildings. The Auspig model was considered a holistic model including materials, airflow, pig data, and feed data.

Table 2. Reported temperature and humidity levels where behaviour change or health effect occurs (adopted from Banhazi et al. 2008).

Pig size or age	**T (°C)**	**RH (%)**	**Behaviour effect**	***Source according to Banhazi et al. 2008***
	>16°C		Wallowing, increase	*Huynh, 2005a*
	>16°C		Huddling, reduced	*Huynh, 2005a*
	~18°C		Lying on slatted floor, increase	*Huynh, 2005a*
Sows	Increase: 18 to 30°C		Feed intake, reduced	*Black et al. 1993, Quiniou et al., 2000*
	~20°C		Fouling on solid floor, increase	*Huynh, 2005a*
100 kg	20°C		Lying and excretion behaviour, change	*Aarnink et al., 2006*
45 and 85 kg	Increase: 20 to 30°C		Feed intake, reduced	*Nienaber et al., 1997, Huynh et al., 2005*
60 kg	21.3°C	80%	Respiration, increase	*Huynh et al., 2005 and 2006*
	~22°C		Water intake, increase	*Huynh, 2005a*
~ 60 kg	22.4°C	50%	Respiration, increase	*Brown-Brandl et al., 2004, Huynh et al., 2005*
	22.6°C (average)		Lying on slatted floor, increase	*Aarnink et al., 2006*
60 kg	23.4	50%	Respiration rate, increase	*Huynh et al., 2005 and 2006*
	> 23°C		Respiration rate, increase	*Huynh, 2005a*

Pig size or age	**T (°C)**	**RH (%)**	**Behaviour effect**	***Source according to Banhazi et al. 2008***
25 kg	25°C		Lying and excretion behaviour, change	*Aarnink et al., 2006*
	26.3°C (average)		Lying on slatted floor, increase	*Aarnink et al. 2006*
	28, 32 °C vs 18, 24°C (22h)		Feed intake, reduction	*Brown-Brandl et al., 1997*

Bjerg et al. (2019) conducted a review on heat stress in sows. The methods were identified in three categories related to air, materials, and water. The air measures included airflow rate, with increased cooling rate in summer, air velocity such as tunnel ventilation, air jets, and air mixing, nose cooling, and finally cooling of supply air through air conditioning by humidification namely CP and high pressure evaporation (HPE). The material-related measures included cold surfaces for conduction and radiation cooling, and improved insulation of the building envelope. The reviewed methods were evaluated with physical calculations when possible. The calculations showed that an airflow rate of 300 m^3/h per heat production unit (HPU), where one HPU corresponding to a heat production of 1 kW, could keep an indoor air temperature below 22°C if the outdoor temperature was below 16°C. By doubling this ventilation rate, the indoor air temperature could be maintained at 22°C when the outdoor temperature was below 19°C. It was estimated that an air conditioner would require 1.5 kW per HPU and cause increased humidity. In conclusion, the authors found that evaporative systems are effective in hot, dry climates, but they will also increase indoor air humidity. The main conclusion was that although there are many studies on floor cooling, nose cooling, through either air or water, and drip cooling, none of these methods were very common in reality. On the other hand, only a few studies on the effects of increased air velocity were found, despite it being a widely used cooling solution in many livestock buildings for pigs.

In Austria, a LCA was achieved that showed no future increase of the farm's overall environmental impact due to climate change (Hörtenhuber et al. 2020). The evaluation was based on Austrian temperatures from 1981 to 2017. Additionally, no significant reduction in production performance, including mortality, was observed. They found that housing factors contribute to a limited extent to the overall environmental impact of pig farming. However, under the worst case scenario, it was calculated that indoor temperatures would exceed the thermal neutral zone (TNZ) for pigs, 45.8% to 64.4% of the time in a year. Indoor temperatures were projected to be 4.5°C higher than the coldest year, which is 1984 according to measured temperatures. Therefore, the authors concluded that adapting to global warming and reducing heat stress requires insulated buildings with MV for improved animal welfare.

4.3 Adaptation measures

4.3.1 Cooling potential

This section summarises nine reviewed articles that primarily focused on cooling capacity and heat stress reduction. Five studies were model-based, four of which were conducted by the same research group in Austria. The remaining four articles presented the results of case studies. The first article concluded, by dynamic modelling, that cooling pads (CP) are sufficient to maintain temperatures below 28°C in warmer climates. The remaining four model-based articles focused on the impact of different cooling adaptations. They concluded that earth-to-air heat exchange (EAHE), CP, and cooling pads in combination with heat exchange (CPHE) reduced heat stress by 60-100% compared with conventional systems. Three case studies concluded that CP has high cooling capacity, although its potential is lower in humid climates. Figure 7 shows a simplified principle of heat exchange (HE) and cooling pads.

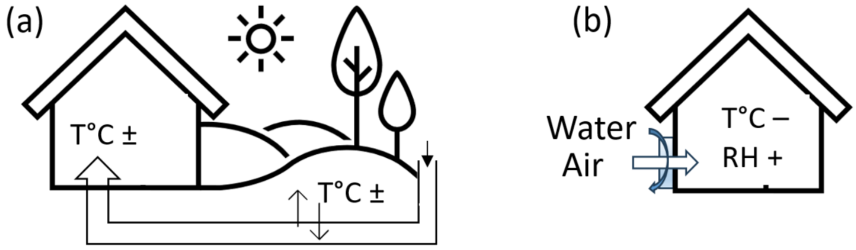

Figure 7. Principle sketches on (a) heat exchange from the ground to indoor and (b) cooling pads.

Potential adaptation measures to mitigate heat stress in GFP due to climate change were calculated with a steady-state model including various changes in cooling strategy, location, and projected climate data for 2080 (Valiño et al. 2010). The cooling strategies included MV with different air change rates per hour (20, 30, and 40 ACH) with and without CP, and NV with different air change rates (5, 10 and 15 ACH) without CP. Simulations were performed for different locations across Europe, from south to north, and the climate projections for year 2080 were based on data from the PECETA project (Ciscar et al. 2009). For the simulations, average monthly weather data were converted into hourly data with daily variations. Similarly, relative humidity (RH) and solar radiation were converted to hourly values based on monthly averages. The main conclusion was that CP would be sufficient to keep indoor air temperatures below 28°C in a future climate, but their effectiveness depend on RH, as CP are less effective in humid climates.

Threm et al. (2012) evaluated different cooling systems at a research farm in southern Germany. The results indicated that underfloor air inlets, precooled through HE in the ground, yielded the lowest energy use with some cooling effect (6.4°C on a particular summer day). However, construction costs were expected to be high. The best cooling effect was achieved with CP -9.4°C on the same summer day), but with higher energy use for ventilation and water pumps, and increased humidity.

In 2013, the same and additional data were evaluated in a published paper (Pertagnol et al. 2013). Energy and water use measurements for 2011 and 2012 were collected from four systems at a research farm, and three commercial farms. At the research farm, there was one exhaust fan per room and the systems evaluated in each room were: (1) reference room with porous ceilings, (2) underfloor channel air inlets, (3) porous ceiling and high pressure evaporation (HPE), and (4) CP and porous ceiling. Rooms (1) and (3) were heated via warm water pipes (delta tubes) below the ceiling. The systems at the commercial farms were (5) underfloor channel air inlets, (6) HPE, and (7) underfloor air inlets via an EAHE. The results showed that the underfloor channel air inlet system (2) resulted in a low energy use. At the research farm, CP were found to have the highest average cooling efficiency (5°C lower), followed by underfloor air inlets (3.5°C lower). The authors also concluded that pressure drops in the air supply system affect the fan energy use due to required operating time of the fans.

A research team in Austria published a series of articles on heat stress mitigation in pigs, four of which are reviewed in this report (Vitt et al. 2017, Mikovits et al. 2019, Schauberger et al. 2019 and Schauberger et al. 2020). In the first reviewed paper, Vitt et al. (2017) calculated the cooling efficiency of three adaptation measures: EAHE, CP, and CPHE. The study compared supply air temperature and RH to outdoor conditions using weather data from Austria from 1981 to 2010. Heat stress thresholds were defined as an indoor temperature of 25°C, a temperature-humidity index (THI) of 75, and an enthalpy of 55 kJ/kg. The results showed that the EAHE was the most efficient adaptation, followed by CP and CPHE. CP was better at lowering the temperature but led to higher RH compared to CPHE. Only supply air temperatures were assessed in this study, and the EAHE-system had low supply air temperature, which posed a risk for draughts.

The study (Vitt et al. 2017) was followed by another study by Mikovits et al. (2019), which used a steady-state model developed by Schauberger et al. (2000) for MV buildings to simulate indoor air temperature, humidity, and airflow rate. The steady-state model included sensible and latent heat loads, and mass flow of CO_2 and odour, as well as transmission losses through building envelope and ventilation. There was no definition of odour in the paper. The aim of this study was to assess the impact of global warming on the indoor climate of confined pig buildings. The model was applied to a typical livestock building housing 1800 GFP. It was validated using historical weather data from Austria between 1981 and 2017. The heat stress levels assessed were the same as in the previous study. The conclusion was that pigs in confined buildings are more susceptible to climate change than pigs in extensive outdoor systems. Without any adaption measures, the average heat stress levels were estimated to have risen annually by 0.9-6.4%, from 1981 to 2017 compared to 1981.

Schauberger et al. (2019) assessed the effectiveness of adaptations measures in livestock buildings for GFP. In this study, the same steady-state model developed by Schauberger et al. (2000) was used to evaluate seven adaptation measures. This study had identical heat stress thresholds, i.e., an indoor temperature of 25°C, a THI of 75, and an enthalpy of 55 kJ/kg. Furthermore, the UCT, at which physical reactions are anticipated to occur, was determined to be 4°C higher than the set point temperature. The assessed adaptation measures were CP, CPHE, EAHE, doubled ventilation (up to 214 m^3/h per pig), stocking density (60%, 80% compared to 100%) and a time shift of 10 hours per day. The results suggested that EAHE had the greatest potential to reduce heat stress followed by CP and CPHE calculated as exceedance area and frequency when heat stress levels were exceeded.

The study on adaptation measures (Schauberger et al. 2019) lead to a review of various cooling strategies (Schauberger et al. 2020). This article included the findings for the seven adaptation measures modelled as described in Schauberger et al. (2019), as well as several other measures evaluated by experts on the potential for reducing heat stress. The adaptation measures were divided into four categories related to:

(1) Air treatment, namely the cooling of inlet air through evaporative cooling pads (CP) and heat exchangers (HE).

(2) Building factors, including building orientation, green roofs, insulation levels, and shading.

(3) Measures at the animal level, including air velocity, cool surfaces, cold drinking water, various types of showers, and wallowing.

(4) Management factors, such as stocking density, increased ventilation, time management, breed selection, and feed composition.

The most effective measure was air treatment (1), which resulted in a heat stress reduction of 60-100% compared to conventional systems. Building factors (2) were assessed to have an efficiency of only 3-8%, according to expert evaluations. Assessments conducted by experts indicated that measures implemented at the animal level (3) and management factors (4) had an effectiveness ranging from 5% to 60% and 5% to 50%, respectively.

Limitations of all the studies conducted by the Austrian research team were that energy use was not taken into account in the calculations, and the efficiency of several adaptation measures was only estimated by experts.

A study on the effect of cooling at animal level on environmental impacts from manure handling showed a decline in heat stress due to the use of evaporative cooling and increased air velocity (Pexas et al. 2021). The cooling strategies included shower above slatted floor and increased air velocity on the solid lying floor area. The chosen critical limit for heat stress increased from 26.8°C to 31.5°C with showers and 32.2°C with increased air velocity, yielding zero hour above the UCT when using cooling strategies. Details and results from the Pexas et al. (2021) case studies in Sweden on showers and increased air velocity can be found in Jeppsson et al. (2021a, 2021b)

In a 2022 case study, the thermal climate threshold of THI ≥75, pig performance, and CP efficiency were evaluated with three different ventilation and cooling strategies (Wiegert et al. 2022). The case study was conducted on a farm for fattening pigs in North Carolina, US, with nine identically sized buildings, each containing 36 pens with fully slatted floor. Four of the nine buildings had NV with thermostatically controlled sidewall curtains and ridge openings. Air mixing fans were installed in the ceiling to cool these NV buildings. The other five buildings had tunnel ventilation, each equipped with four exhaust air fans, 32 gravity intakes on each sidewall, and a curtain on the wall opposite to the fans. Additionally, two air intakes in the attic were used during the colder months, when necessary. For cooling purposes, three of the tunnel-ventilated buildings were equipped with sprinklers while the other two were equipped with two CP each. The study concluded that CP reduce THI compared to tunnel ventilation with sprinklers, as well as compared to NV with sprinklers and air-mixing fans. The efficiency of the CP was 52% in 2016 when all inlets were closed except for those connected to the CP inlets. Sprinklers in the tunnel-ventilated building were found to lower the temperature and increase the RH. According to the conclusions, pig performance was observed to improve in tunnel-ventilated buildings with either sprinklers or CP compared to NV buildings. However, this conclusion is unclear as only the average daily gains (ADGs) were significantly higher for tunnel-ventilated buildings in 2014 and 2015. The remaining data on ADG from 2016, feed conversion ratio (FCR), survival, culls, and medication costs did not differ significantly among the three evaluated systems. Limitations of this study include unknown ventilation rates and uncertainty regarding whether the area of the cooling pad intakes was sufficient from the viewpoint of the exhaust flow rate, since supply air inlets were partly closed.

4.3.2 Building properties

Five articles related to building properties were reviewed, with one article previously discussed in section 4.3.1 on cooling potential. All four articles summarised in this section are model-based, involving calculations or simulations. In the first article, the effects of insulation and the placement of heat distributors on heat panels were evaluated. The primary conclusion was the importance of insulation below the heating panels, while side insulation led to more uniform surface temperatures and reduced heat loss. Three studies used the commercial energy simulation software program Designbuilder based on EnergyPlus to evaluate adaptation variations in the building. All three articles considered the expected indoor climate, while only two of them addressed energy use. In the fifth paper, as evaluated in section 4.3.1, experts estimated that building factors such as shading and insulation were only 3-8% efficient for cooling potential. Figure 8 shows examples of building property aspects.

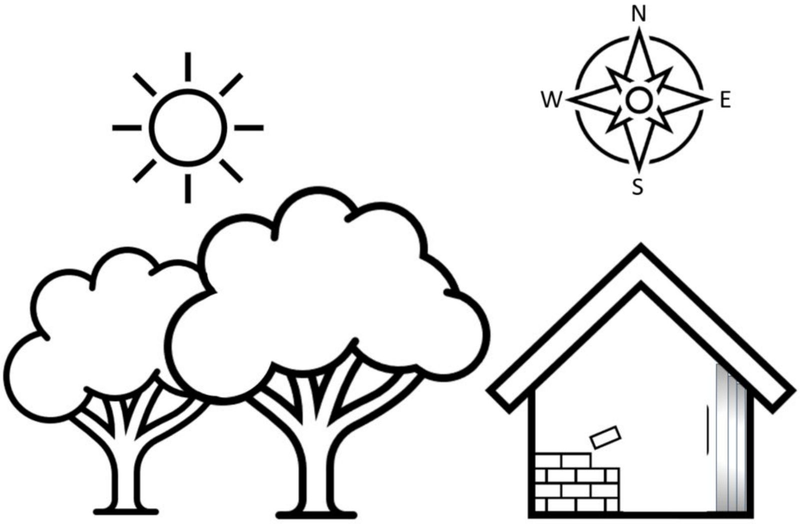

Figure 8. Building properties encompass various factors, including material choices like stone or wood, insulation levels, the presence of reflective or green roofs, orientation towards solar radiation, and the impact of shadows, such as those cast by trees.

An illustration of the importance of insulation is provided by a study on solid heat panels for piglets (Zagorska & Iljins 2011). Heat panels are occasionally employed to regulate the air temperature within the TNZ and to separate piglets from the sow, thereby reducing the risk of the sow lying on its piglets. In this study, the degree and placement of heat distributers, such as water pipes and electrical cables in the heat panel were assessed through steady-state calculations. The heat transfer coefficient in the concrete was assumed to be 1 W/mK and the panel size was 100 cm by 10 cm high. Assuming a heat transfer coefficient of 1 W/mK in the concrete and the given panel size, the study concluded that insulation at the bottom of the heating panels was crucial. Optimal performance was achieved with 12 cm of insulation featuring a heat transfer coefficient of 0.04 W/mK. Side insulation was found to reduce heat loss and result in more uniform surface temperatures. Conversely, the placement of the heat distributors within the concrete was determined to be less critical.

Fabrizio et al. (2014) developed a dynamic model for a baseline building in Torino, Italy, using the dynamic energy simulation software EnergyPlus for whole-building energy prediction and DesignBuilder for the drawing and design. The model incorporated modifications with different insulation levels and types of ventilation controls. The building, with outer walls made of 30 cm lightweight concrete, insulating roof panels (10 cm), and polycarbonate windows, had an area of 84 m^2 and housed ten sows weighing 200 kg each with 11 piglets. Temperature set points were 18°C for the sows and 26°C for the piglets, with heaters and radiant lamps serving as heat sources. Optimal energy simulation results were achieved with 5 cm insulation on concrete walls, 10 cm of roof insulation and variable ventilation rates ranging from 0.14 to 1.43 m^3/s. With this solution, the overheating index was 255°Ch, and primary energy use was 17.6 MWh. In contrast, the baseline building with a two-step ventilation fan, featuring airflow rates of 0.175 m^3/s and 1.430 m^3/s, generated 1053°Ch overheating and primary energy use of 24.2 MWh. This study demonstrated the potential to use dynamic modelling to optimize insulation use and ventilation rates, thereby reducing energy consumption and improving indoor temperatures in livestock buildings. Furthermore, the study revealed that the latent heat load from manure and animals depends on indoor air temperature and humidity and remains unknown at each step, posing challenges in obtaining accurate simulation results.

In the UK, Jackson et al. (2017) conducted thermal climate simulations for a case study building for GFP in Staffordshire, using DesignBuilder V4.2.0.054 and EnergyPlus 8.1. The baseline case (BC) building was 252 m^2 and housed 292 pigs. They simulated changes in insulation performance for the roof (0.21 vs. 0.52 W/m^2K) and walls (0.35 vs. 0.49 W/m^2K), reduced airtightness (0.3 vs. 0.7 ACH), and increased building mass (134.8 kJ/m^2K vs. 5.6 kJ/m^2K). The maximum ventilation rate was set at 50 l/s per pig at 50 Pa. Accepted operative temperatures (OTs) was set to 19-21°C, and the hours outside this range were evaluated. The results showed that in the BC, the hours below 19°C increased as pig weight increased due to higher minimum ventilation rates. However, research shows that most pig breeders and control systems adhere to recommended temperatures, which can be expected to result in poor indoor air quality (IAQ). No heat sources were installed in the case study building, and reducing the airflow rate was the only way to keep the heat inside the building in cold weather. The findings showed that the alterations improved the ability to maintain temperatures between 19-21°C during the winter. However, the summer scenario performed worse for 60 kg pigs, with more hours above 21°C compared to the base case scenario. In future climate scenarios predicted for 2030, 2050, and 2080, potential improvements of OT during winter for the base line building were achieved with only a few hours below 19°C.

In 2018, additional adjustments were made to the same case study described in Jackson et al. (2017) to enhance indoor climate conditions and animal welfare (Jackson et al. 2018). A building concept known as SPaTHE (Solar, Passive, Thermal, and Heat Exchange) was developed on the baseline building using the software programmes EnergyPlus 8.1 and Designbuilder V5.0.3.007. Thermal mass (5.6 KJ/m²K), airtightness (0.7 ACH) and insulation levels (walls 0.49, roof 0.82, and windows 1.96 W/m²K) were kept unchanged. Instead, SPaTHE involved optimising the building's orientation and geometry, as well as the characteristics of its windows, including orientation, shading, size, and daylight admission. The simulation also included the use of an earth tube for potential HE. The main findings indicated that the SPaTHE optimization reduced resource consumption and enhanced animal welfare while potentially lowering energy costs but the relative improvement was not given in the article.

4.3.3 Ventilation efficiency

While there are many studies on ventilation effectiveness, airflow patterns, and IAQ, only a few address energy use and thermal climate simultaneously. Six papers related to energy use were reviewed. Three papers focused on cleaning exhaust air for reuse as air supply, aiming to save energy during winter by reducing the intake of cold outdoor air. The results showed that while cleaning dust and particles is feasible, reducing gas emissions is more challenging, resulting in high concentrations in the air. One of the articles addressed the possibility of using mixing fans to circulate and increase air velocity in human buildings. The conclusion was that a mixing fan could reduce transmission losses through the roof due to air stratification. Another article studied the effect of the angle of air jets for air supply by using the novel effective temperature (ET) with the help of computational fluid dynamics (CFD). The conclusion was that angles of 5° or 15° were optimal while minimising risks of draughts. Finally, one experimental study examined the effectiveness of partial pit ventilation (PPV) in combination with ceiling jets or wall jets, concluding that PPV was effective.

The use of a mixing fan to increase air velocity was evaluated by Aynsley (2005). In human buildings, an air velocity of 0.8 m/s allows for an increase in the temperature set point by 2.6°C in the summer, while a 1°C increase can reduce energy use by 5.4-7.2%. In winter, heating demand could be reduced when the air is stratified due to fact that the fan leads to less transmission losses through the roof.

A Danish study from 2018 used CFD modelling to examine temperature and humidity in the preferred lying area (PLA) for pigs by varying air inlets (Bjerg et al., 2018). In a pen of 10.4 m² with 54% solid and 46% slatted floor, 15 pigs of 90 kg were modelled, considering 0.7 m^2 per pig. The research analysed four angles of air jets installed in the ceiling in the test rooms, while the reference room had diffusive ceilings. The study concluded that an air jet angle of either 5° or 15° was the most effective, providing an ET of 17.6°C and 72% RH, and 19°C and 76% RH, respectively, without making the PLA too cold. The authors also found that using air jets instead of diffusive ceilings led to less anticipated fouling of solid floors. The study introduced a novel formula for estimating ET, incorporating temperature, humidity, and air velocity. It was found that the indoor climate was expected to improve with air jets, as the ET in the pens was the same at an outdoor temperature of 19°C with air jets compared to 10°C with diffusive ceilings.

A study conducted in Iowa raised concerns about the working environment, as workers experienced issues such as dust and high levels of carbon dioxide during winter when ventilation was reduced to maintain an acceptable indoor air temperature (Anthony et al. 2014). Although respiratory protection equipment is generally recommended, most workers did not use it. Using Matlab modelling, the study demonstrated that it is feasible to clean and recycle air at a reasonable cost by analysing data from a case study to improve IAQ for workers. To maintain the indoor air temperature during the cold season, it was recommended to have a circulation rate of 75-100% and use an electrostatic precipitation filter for air cleaning. While trickle filters were found to be more effective, they posed a risk of spreading bacteria to the barn since they rely on biofilters for cleaning. However, the study revealed that using gas heaters in the stables made it challenging to reduce carbon dioxide levels with any of the studied filters.

An experimental study was conducted in Denmark on the effectiveness of PPV with different types of inlets in two identical rooms, each containing two pens (Zong et al. 2015b). The first system, referred to as C, distributed fresh outdoor air into the room through diffused ceilings and two ceiling air-jets that opened when the room temperature reached or exceeded 28.8°C. In the second system, called W, fresh air entered the building via two wall air-jets. The air jets in ceiling (system C) and wall jets (system W) had the same area. The maximum ventilation rate was 100 m^3/h per pig in both rooms, and the PPV flow remained constant at 10 m^3/h per pig.

The set point temperature was the same in both systems. A 22.3% higher airflow was measured in the summer, and a 16.0 % higher airflow in the winter for system C compared to system W. One possible reason for the higher airflows for system C was that air was preheated in the attic before entering the room, resulting in higher indoor air temperatures. Consequently, in the summer, levels of gaseous substances such as NH_3, CH_4 and CO_2 were higher in system W than in system C due to less dilution of the air. Different airflow patterns may also have resulted in different emission rates and emission levels in the room. While high air velocity in high temperatures may reduce heat stress, it can also lead to higher emission rates of ammonia (Zong et al. 2015a). A reviewed study (Zong et al. 2015b), did not show significant differences in animal growth between the systems. The main conclusion was that PPV at 10% of maximum ventilation improved IAQ and facilitated exhaust gas and odour purification. However, the study did not have any control room without PPV.

When recirculating air, it is necessary to clean the air. In 2015, a shaker dust collector filtration system underwent laboratory and field tests at a barn for farrowing sows in the USA (Peters et al., 2015). The results of the study demonstrated the high efficiency of filters with shaker dust collectors in purifying air from dust on farms. Shaker dust collectors enable filters to be cleaned on-site. When a dust cake accumulates, the filter efficiency reaches almost 100% due to pressure drops. The dust cake is especially important for small particles, measuring 1-5µm, as a new filter only captures about 28% of particles with a size of 1 µm. When the filter is shaken to remove the dust cake, the filter efficiency falls to approximately 70%. However, as pressure drops further, efficiency rises to over 90%. The study involved an airflow of 0.47 m^3/s, creating a pressure drop of around 250 Pa over the filter before shaking. The filter's maximum potential pressure drop was 1000 Pa according to the manufacturer, which indicated that a higher airflow or more dust in the air could produce similar efficiency results with the same type of filter. A parallel study (Anthony et al. 2015) analysed dust, NH_3, H_2S, CO and CO_2, concluding that the shaker dust collector filter system reduced inhalable dust (<100 µm) by 33% and respirable dust (<10 µm) by 41%. However, the analysed gaseous substances, including carbon dioxide, were not reduced with the tested filter system.

4.3.4 Solar heat collection

Two reviewed articles showed the possibility to preheat inlet air during winter to reduce heat demand. The evaluated solar wall and solar duct had capacities of 27-143 MJ/m^2 per month and 433MJ/m^2 per year, respectively. Both studies demonstrated the importance of a controlled solar heat collection system to prevent excessively cold or too warm air from entering the building.

In 2004, a south-southeast-facing 60 m^2 solar wall was installed on a building for weaned pigs in Quebec, Canada (Godbout et al. 2004). The incoming air was preheated in the solar wall and in a distribution corridor in the attic. The article did not provide information on how air was supplied to the room from the ceiling. Minimal exhaust ventilation was achieved through pit ventilation. The study concluded that during the heating season, energy demand was reduced by approximately 1623-8602 MJ per month (12.2-47.4%), with potential operating cost reductions of 23-31% with the solar wall compared to the reference method of heating with propane heaters.

Love et al. (2014) studied a transpired solar collector duct for weaned pigs in North Carolina, USA. Figure 9 shows a simplified sketch of the layout. Research conducted between 2010 and 2012 demonstrated the feasibility of preheating the air during the cold season. The building was equipped with a timer-operated exhaust air fan with a minimum airflow rate of 1.9 m^3/s at 25 Pa, and ventilation for cooling was thermostatically controlled. The supply air was preheated in an external black transpired aluminium solar collector duct, which had a collector surface of 22.3 m^2, including 0.8% openings for air circulation. The study showcased the potential for energy savings and underscored the importance of assessing expected heating needs, anticipated solar radiation, and the impact of preheated air in the attic. Key findings from the case study revealed a reduction in propane usage for heating by nearly 23%, with the solar duct boasting an average collector capacity of 433 MJ per year per m^2 of surface area. Additionally, indoor air temperature increased by up to 6°C. Measured levels of indoor air quality indicators, including carbon dioxide, humidity, and temperature, were similar in both the control and test rooms.

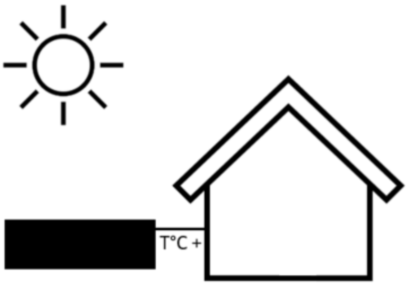

Figure 9. Simplified sketch on a solar duct collection of solar heat to a building (adopted from Love et al. 2014).

4.3.5 Heat pumps

Research shows that utilizing the ground, manure, or air as sources of heat or cooling through heat pumps (HP) offers the opportunity to save energy and potentially improve indoor climate conditions for pigs. Six papers were reviewed, three of which evaluated geothermal water-to-water HP, one air-to-air HP, and the last one focused on preventing ice formation on the external evaporator of a heat pump. The conclusion was that water-to-water HPs reduce energy demand in winter and warrant further investigation into their year-round performance. Air-to-air HPs also demonstrated potential for reducing energy consumption in both warm and cold outdoor conditions. The article on ice prevention revealed the potential to increase the coefficient of performance (COP) by heating the air at the evaporator with exhaust air. Another article assessed the use of heat pumps among other parameters, which is summarised in the next section on heat exchange (HE). Figure 10 illustrates a principle block diagram of HP operation.

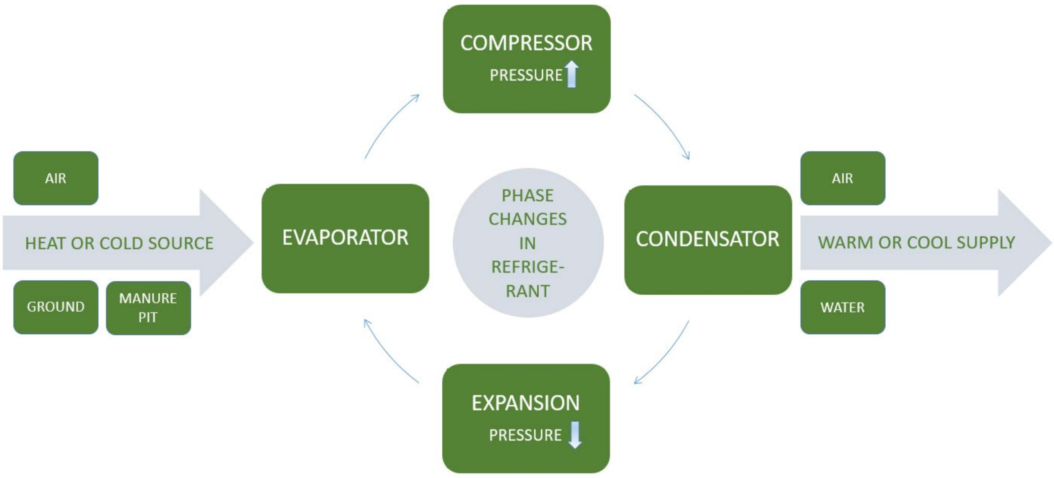

Figure 10: Principle sketch of a heat pump function (adapted from Thermia, 2023).

Riva et al. (2000) assessed three ventilation and air conditioning solutions for a pig production building in northern Italy. The case study building featured 25 cm plastered brick walls, an insulated brick roof (with 4 cm insulation), and slatted floors. Sows were accommodated in cages, with 12 cages per 52.5 m² room, maintaining a set point temperature of 26°C. Outdoor air conditions during the evaluation period ranged from temperatures of 7.5-23°C and RH of 70-87%. The evaluated systems were as follows: (1) air-to-air HP with a compressor of 1.9 kW and a fan of 1.3 kW (with a total nominal COP of 4.2) delivering conditioned air to the room; (2) An exhaust fan of 0.5 kW for MV and summer cooling, along with a 23.2 kW gas-fired boiler connected to a waterborne underfloor heating system; and (3) NV with emergency convective heating, although the heating function was not described in the paper. All three systems included power coils (24 V) in a small section of the farrowing room. Measurements of temperature, humidity, feed conversion index (FCI), ammonia levels (in system 1 only), and electrical energy were conducted. The HP solution (1) exhibited the lowest indoor air temperature variations among the three solutions and used 11 % less primary energy, compared to the system employing exhaust fans and a gas boiler (2). However, the result are challenging to interpret as only three out of five production cycles were included in the energy saving evaluation. If all cycles had been considered, primary energy use would have been higher for solution (1) compared to solution (2). Additionally, energy use was not reported for solution (3) with NV. Air changes per hour (ACH) were highest for solution (1) and lowest for solution (3), which was also reflected in the FCI. Measured ammonia levels were below 20 ppm (the recommendation in

Sweden is 10 ppm) in solution (1) and 50% lower than in solution (3) according to the conclusions. Finally, measurements of the indoor air parameters, temperature and humidity indicated similar average results for all systems. It is noteworthy that the study was funded by technology companies manufacturing HP.

Ilsters & Ziemelis (2012) proposed a method to prevent the formation of ice on external evaporators for an outdoor air-to-water HP. In their study, an unspecified fabric was utilized to construct a tunnel connecting the exhaust air to the evaporators, generating warm air to elevate the temperature around them. A fan, with a capacity of 1.2-1.4 m^3/s, was installed at the entrance of the tunnel to ensure adequate airflow. The findings indicate that the COP remained above two, even at outdoor temperatures as low as -20°C, with no occurrence of frost or ice.

Heat pumps can be linked to collector tubes in the slurry pit for heat recovery, as demonstrated in an experimental Latvian study on rooms for sows with piglets and weaned pigs (Ilsters et al. 2015). The COP of the collector tube HP (water-to-water) when connected to a floor panel reached up to 4.5, covering approximately 10-20% of the heat demand of the piglets. The power requirement per pen was 30-40 W. The primary conclusion drawn was that heat exchange occurred not only from the slurry but also from the ground, air, and concrete in connection with the slurry pit.

In northern Italy, the performance of two geothermal HP was evaluated (Alberti et al. 2018). One system involved a closed water cycle using boreholes connected to a HP in a facility for weaned pigs. This system was monitored for one month, starting in late October 2016. In addition to the HP, an air-handling unit (AHU) with 78% heat recovery was integrated into the system. A 46% reduction in primary energy (including electricity and fuel) was achieved compared to the reference system with exhaust fans, which had a ventilation capacity of 1000 m^3/h, and a 16 kW burner. The other system examined was an open system for groundwater extraction. Although this system was only modelled, data on soil and groundwater characteristics were derived from the previously described case study. During the summer, the extracted water was expected to be utilized for irrigation. One objective of the open system was to minimise nitrate leakage by collecting groundwater through extraction wells to prevent downstream contamination. The findings of the open system demonstrated potential energy savings and the capability to capture nitrate as well as particles to safeguard the HP. The authors recommended further field studies to validate the modelled outcomes.

In Germany, Licharz et al. (2020) conducted an in situ examination of HP during one winter period between December 8, 2011 and February 15, 2012. Three identical 40 kW groundwater HP were installed, one in a building for farrowing and the other two in a building for piglet rearing. The farrowing building was 3256 m^2 and housed 172 sows, while the piglet-rearing building was 2135 m^2 and housed 4000 pigs. In the farrowing building, there were two heat storage tanks, one for hot water at 50°C and one for heating at 45°C. The required water temperature in the heating loop for the lactating piglets was initially 38-39°C, decreasing to 25-27°C as the piglets grew. In the piglet rearing building, the HP were configured as master and slave HP, with the master HP controlling the slave HP, which operated only when needed. Both systems were connected to a single heat storage tank with a water temperature of 50°C. The set point air temperature was gradually lowered from 32°C to 24°C for the growing weaned pigs. The results revealed that the total COP, including electricity use for the groundwater pump, HP, and distribution, was 2.5 for the farrowing building and 2.6 for the piglet-rearing building. The conclusions were that a lower temperature in the storage tank enhances the COP and that 50°C was considered too high. The study recommended further research on the annual performance and an investigation of a HP system linked to the exhaust air.

Blázquez et al. (2022) calculated the energy saving potential of a geothermal water-to-water HP in which heat from the slurry was recovered for using in heat plates. The primary purpose of the HP was to reduce the temperature of the slurry from 20° to 5°C to reduce emissions of carbon dioxide, ammonia, methane, and nitrous oxide from the manure. The results indicated the potential to reduce energy use by up to 60%, as well as a reduction of the amount of gases generated by the manure. A reduction of GHG by approximately 40% was anticipated due to reduced electrical use and reduced manure emissions. However, the energy source for the electricity was not specified, and no information was available regarding indoor temperature or required temperature on the heat plates.

4.3.6 Heat exchange

Three reviewed papers are summarised in this section: one model-based study and two case studies. The model, conducted using the Danish software Staldvent, demonstrated that adaption measures for heating and cooling reduced energy use and improved the indoor climate. The case study evaluating a building integrated heat exchange (HE) system resulted in excessively high indoor air temperatures for growing fattening pigs (GFP). The air was preheated not only in the ground, but also in the vertical shaft and the attic. In the other case study, an earth-to-water exchange (EWHE) was evaluated. The conclusion was that the system reduced energy use by up to 50% compared to the base case.

Jacobson et al. (2011) used Staldvent to assess the energy and production performance of four adaptation measures compared to a reference building for fattening pigs located in the USA. The aim was to develop a so-called “Greener Pig Farm”. Staldvent included assessment of indoor air temperature, weather data, indoor air emissions (ammonia, hydrogen sulphide, odour, and particles), GHG emissions (carbon dioxide, methane, and nitrous oxide), and energy use. Microsoft Excel was used and adapted for cost evaluation. All evaluated systems had similar construction materials and room sizes. For the adaptation measures, the ventilation system had ceiling supply and climate-controlled exhaust fans, with an extraction capacity of 1133 l/minute (40 cfm). Adaptation measures included different floors (fully or partly slatted), heating systems (underfloor heating via a geothermal HP, furnace or geothermal HE), cooling systems (geothermal HE or evaporative pads), and improved insulation of the building envelope compared to the reference building. In the adaptation versions without geothermal cooling, the ventilation was increased to 2264 l/min or 2832 l/min (80 or 100 cfm). The manure pits were modelled as shallow and scraped twice a day, with the scraped manure assumed to be stored outside in a covered compartment. The reference building had a fully slatted floor, manually controlled tunnel ventilation, propane heaters, and a deep manure pit. The project's goal was to identify a building design that reduced energy use and emissions by 50% compared to the reference building. The main conclusion was that all adaptation measures reduced energy use in the winter and contributed to reduced emission, although the relative improvement was not specified.

An investigation was conducted in Germany to evaluate the performance of a geothermal air-to-air HE integrated into a modular housing system (Krommweh et al. 2014). The system involved preheating or precooling outdoor air in a concrete channel beneath the building and supplying it to the indoor air from the attic via an insulated vertical shaft. Temperature readings were taken at various locations, including outside the building, at the inlet and outlet of the ground channel and vertical shaft, at the supply air to the room, and above pens for fattening pigs.

Over a one-year period from the end of July 2010 to the end of July 2011, airflow volume, electricity use, and gas use were measured. The findings indicated that the air was preheated not only in the channel below the building but also in the shaft and attic, resulting in excessively high inlet air temperatures for fattening pigs most of the time. During the coldest week, the air was preheated by 11.5°C when the average outdoor air temperature was -1.9°C. In contrast, during the warmest week, when the average day temperature was 31.7°C, the air was unintentional preheated due to higher temperatures by 1.5°C in the vertical shaft and attic. The geothermal channel system cooled the supply air during 6.3% of the operating hours. Nevertheless, the indoor temperatures exhibited less variation than conventional systems. Moreover, the system allowed for more ventilation during winter, which could potentially enhance IAQ and require less ventilation during summer, leading to reduced energy use and potentially improved IAQ due to lower emissions. Based on the results, the authors concluded that the system was not suitable for fattening pigs, due to the supply air temperature being too high, but could be suitable for piglets or reared pigs with higher temperature needs.

A case study on an earth-to-water HE was conducted in the project USE by Shah et al. (2017). Water pipes were laid horizontally in the ground next to the building, and the water tubes exchanged energy with the incoming air. The case study was conducted in a naturally ventilated livestock building for fattening pigs (approximately 50-110 kg). The building consisted of one big room with 71 pens. Twelve pens, selected for test and control measurements of temperature and energy use, were located in two areas of the room. The control pens were equipped with a mixing fan and sprinklers for cooling. Some mixing fans between the test and control pens were removed during the evaluation period to minimise disturbance in the test pens. Both short-term and long-term evaluations of the systems were performed. It was found that running the cooling system for eight hours a day reduced the temperature by 3°C. During winter, running the system for 12 hours a day resulted in a temperature increase of 2.2°C. Over the long term, the temperature differences were expected to become smaller. The average temperature measured in both the test and control pens was 27.1°C. The main conclusion was that the earth-to-water HE system used 50% less energy compared to the BC. It was also found that the system could be improved through selection of pipe material and sizes. This system was recommended for existing buildings, as it required a relatively small outdoor area. Using water as a heat transfer medium minimises the risk of mould contaminating the inlet air, which is a risk when air is used as a heat transfer medium in HE systems located below ground.

4.3.7 Indoor climate control

In the area of indoor climate control (ICC), four papers were reviewed: two model-based studies, one experimental study, and one systematic literature review. The first model-based study simulated variations in set points, including temperature and humidity. The other model-based study developed a model to predict the heat requirement for piglet cribs, concluding that energy savings could be achieved by using the model. The experimental study demonstrated that reducing night-time temperatures was an effective adaptation measure to reduce energy use. The systematic literature review concluded that ICC is a potential tool to improve energy efficiency.

In Canada, a steady-state heat balance model was developed to compare two ICC strategies: temperature humidity control (THC) and temperature control (TC) (Lambert et al. 2001). The aim was to assess the effectiveness of THC in terms of carbon dioxide levels, energy use, and RH compared to TC. Humidity control simulations were performed in two ways: proportional (P-band) and proportional-integral-derivative (PID). TC was simulated at 0%, ±10%, and ±20% of minimal ventilation rate according to ASHRAE (1997). The model included set point temperatures, ventilation rates, building characteristics, heat demand, ADG of pigs (0.85 kg/day), and hourly weather data. Temperature set points for both strategies ranged from 15°C to 21°C, depending on the animals' body mass, and RH set points were simulated at intervals of 65% to 80%. After simulating different set point variations, the main conclusion was that THC with proportional humidity control at 75% and 5% P-band value was the best choice for farms with GFP in cold weather. However, the conclusion was somewhat unclear, as other set point variations indicated similar results.

Johnston et al. (2013) adjusted temperature set points at night in rooms for weaned pigs to reduce heating demand during cold weather. Two experimental setups were analysed at three and four locations respectively, all equipped with control rooms of the same size and number as the experimental rooms. In both setups, daytime temperature was gradually lowered to meet the heat demand of growing pigs over time. In the first setup, the set point temperature for acclimating weaned pigs was maintained at 30°C for seven days in all rooms. In the second setup, the acclimation time was shortened to four days in all rooms. Following the acclimation period, daytime temperature were reduced by 2°C per week in both setups. In the first set-up, the night-time set point temperature was lowered by 6°C per week (19:00-07:00 hours), after seven nights of acclimation at 30°C. In the second experiment, the night-time set point temperature was lowered by 8.3°C per week (19:00-07:00 hours), after four nights of acclimation at 30°C. The results indicated no differences in mortality, feed intake, body weight (BW), or ADG between control and test groups for both experiments. However, energy use, measured in terms of fuel use and electricity use, was significantly reduced in the second experiment, with 30% reduction in fuel usage and a 20% reduction in electricity use. This study demonstrates that lowering night-time temperatures, coupled with short acclimation periods, during winter is a feasible adaptation measure to reduce energy use without comprising production traits considered in this study.

Milan et al. (2019) developed an extensive model to predict the optimal heat demand for piglet cribs. The research included a validation case study incorporating measurements of skin temperature, hair length, and BW. The mathematical model, elaborated further in the article, utilised machine learning to forecast input temperatures, a mechanistic model for bio-heat transfer computations, Monte Carlo simulations to optimise system parameters, ensemble learning to improve prediction accuracy, and energy balance computations related to feed, growth, and heat transfer. The results indicated a saving potential of approximately 200 W for heat lamps in cribs when the indoor temperature ranged between 15-19°C. The study concluded that a novel bioenergetics model was established, with enhanced accuracy through Monte Carlo simulations and ensemble learning. Nevertheless, the authors acknowledged limitations of the model, such as restricted access to input data, and highlighted the need for further refinement and scrutiny of assumptions. Nonetheless, the study demonstrated the feasibility of anticipating the optimal heat requirement for cribs based on BW and air temperature.

Costantino et al. (2021) undertook a systematic literature review focusing on climate control and the relationship among animal welfare, indoor air emissions, health, productivity and energy use. The study found that animal welfare is intricately linked to indoor air emissions and thermal climate. Deterioration in animal welfare can impact their health, growth, and feed intake, consequently affecting productivity and, potentially, the quality of meat. Furthermore, animal health can influence human health, increasing the risk of infection and the need for antibiotic usage. Emission rates from manure were discovered to be influenced by thermal factors, including fouling behaviour, airflow patterns, air dilution, air velocity, and turbulence. However, information on energy use was found to be limited, with energy sources often being non-renewable. In conclusion, the study suggests that climate control holds promise as a tool for enhancing energy efficiency but requires further development, preferably through the integration of numerical models.

4.4 Energy and indoor climate simulation

In this section, models with the potential to incorporate energy use and indoor climate are evaluated. Six of the reviewed articles concentrate solely on energy and thermal modelling, and thus, they are summarised here (Jackson et al. 2015, Besteiro et al. 2017, Ortega et al. 2018, Xie et al. 2019, and Costantino et al. 2022). The four papers that utilise thermal and energy climate models in their research are discussed in more detail in preceding sections. However, they are included in this section to evaluate the potential for indoor climate and energy simulation in livestock buildings. Two commercial programs have been utilised: EnergyPlus (through the Designbuilder interface) and Staldvent. While EnergyPlus was developed for human-use buildings, adaptations were required for its application in livestock buildings. On the other hand, Staldvent was specifically designed for livestock buildings. Additionally, four adapted models are non-commercial, where included in the review. In one paper, three models were assessed within the EPAnHaus project, with the simple hourly-based model being recommended. These models were generally deemed potential tools for evaluating energy savings, thermal climate control (TCC) settings, and predicting indoor climate. Furthermore, it was concluded that climate energy and heat modelling could be integrated with ammonia emission models or measurements to optimise ventilation rates during cold weather.

One of the studies utilised the Danish software Staldvent to evaluate energy use and production in pig buildings (Jacobson et al. 2011). Staldvent is a commercial design tool intended for heating and ventilation in livestock buildings. Originally developed by the former Danish Building Research Institute, it is now owned and further developed by the company "Danish Exergy Technology A/S" (DXT). The program assesses indoor air temperature, weather data, indoor air emissions, GHG emissions, and energy use. It allows for the incorporation of adaptation measures such as humidification for cooling and geothermal heat exchange for cooling and energy conservation purposes.

Fabrizio et al. (2014) employed the dynamic and commercial EnergyPlus software, which encompassed overheating hours and primary energy use for heating and ventilation. The model incorporates heat loads from manure and animals. The study concluded that the latent heat loads are dependent on indoor air temperature and humidity, thereby complicating the attainment of precise simulation results and motivating the need for further developments.

In the UK, Jackson et al. (2015) evaluated the potential use of EnergyPlus with DesignBuilder as drawing software, for livestock buildings, focusing on indoor climate. Implemented on a pig farm for GFP in Staffordshire, UK, the dynamic model integrated data on building properties such as envelope and floor materials, geometry, location, and orientation. The heat balance calculations incorporated heat load from growing animals, heating requirements, solar radiation, and equipment. Heat losses included transmission through the envelope and ventilation losses. Site-specific weather data were utilized, with expected temperatures for the years 2030, 2050, and 2080 included in the simulation. Minimum ventilation rates were computed, ranging from 1.5 l/s to 5.97 l/s per pig, corresponding to body masses of 20-100 kg. Calculated hours with OTs above and below 20°C were evaluated. The primary conclusion of this study was that the model could enhance understanding of existing buildings and function as a design tool for new constructions. Additionally, it was suggested that combining ammonia measurements combined with a climate control system could enhance IAQ.

A model known as ARIMA (Autoregressive Integrated Moving Average) was adapted in Spain to predict the temperature for weaned piglets in the animal zone (Besteiro et al. 2017). The aim was to develop a model for prediction of indoor air temperature by analysing different variables. The variables that had a significant impact were the temperature in the animal zone, outdoor temperature, airflow volume, section area of the exhaust fan, and animal weight. The temperature of the heat plate for underfloor heating, ventilation power, and animal activity were assessed as negligible variables. In 2018, the model was implemented in a weaned piglet facility in Spain, using only significant variables (Ortega et al. 2018). Temperature, ventilation rate, section area of exhaust air, and BW were measured during seven production cycles over 292 days. The results indicated that the model was both accurate and robust, and the main conclusion was that it could be used to optimise climate control systems, with the potential to reduce energy use and improve animal welfare.

A review of energy modelling methods for livestock buildings, as part of the EPAnHaus-project, included a comparison of three different approaches: a quasi-steady-state method, the simple hourly method according to ISO 13790, and dynamic simulation in EnergyPlus (Costantino & Fabrizio 2019). The simulations were validated by comparing the results from a case-study presented in Costantino et al. (2017). The conclusion was that the simple hourly method, based on ISO13790, was reliable and easier to adapt and set boundaries for compared to the dynamic EnergyPlus model and the quasi steady-state method. The authors also concluded that energy use modelling was rarely performed and that there was a lack of shared methodology in evaluating energy use, whereas indoor climate modelling and evaluation were more common.

Xie et al. (2019) applied the Energy Balance Equation (EBE) to a case study in Indiana, USA, following the methodology outlined by van 't Klooster et al. (1995). The EBE accounted for heat gains from solar radiation, pigs, and heating systems, as well as heat through ventilation and transmission losses through the building envelope and floor. The EBE results were compared to case study data on calculated energy use and measured temperatures. Additionally, the EBE results were compared with those from an ANFIS model (Adaptive Neuro Fuzzy Interference System) developed as part of this study. The conclusion was that the EBE method was accurate and could be used to develop indoor TCC strategies affecting energy use. The authors also noted the potential for energy savings compared to the operation instructions. However, the definition of these operation instructions was not provided in the article.

The project Res4live has developed a preliminary quasi steady-state energy model for livestock buildings intended for pigs, encompassing energy use, humidity, and indoor temperatures (Faes et al. 2021). The energy balance accounted for heat loads from the animals and heating, as well as heat losses due to building airtightness, transmission through the building envelope, and ventilation losses. The conclusion was that the model was suitable, although it required adjustments.

Costantino et al. (2022) developed a dynamic thermal energy simulation model that integrated meteorological data, building properties, heat balance (including heating and cooling), pig growth, indoor temperatures, and humidity. The authors emphasised the necessity of combining agricultural and energy engineering knowledge to enhance livestock building design of livestock building design and to establish a common framework within agricultural engineering. The main conclusion was that the developed model has the potential to be a valuable tool for building design, capable of predicting energy use and the indoor climate of livestock buildings under future climate scenarios. The model was considered adaptable in terms of building properties, location, weather conditions, and pig rearing stage, among other factors. It was also recommended for use in trade-off studies to optimise the included parameters.

5. Discussion

Reviewed articles encompass a range of perspectives, from comprehensive reviews to detailed experiments, and they pursued diverse objectives, with effects on indoor climate, animal production, and energy use being the most common themes. Studies have indicated that heat stress increases and cold stress diminishes in warmer climates due to rising temperatures. Consequently, climate adaptation of farm buildings is essential to prevent adverse effects on pig welfare and health. Investments in ventilation and cooling systems may be necessary, as pigs raised in confined buildings are more susceptible to the effects of warmer climates compared to pigs raised outdoors. Animal health also influences the risk of human infections, increased antibiotic use, production losses, and reduced meat quality. However, some studies on effects of climate change are outdated, and the predicted outdoor air temperatures may no longer be relevant due to the acceleration of global warming (SMHI, 2023).

The energy use of a pig farming building is determined by numerous factors, including outdoor climate, indoor climate requirements, building characteristics, ventilation type, management practices, pig breed, growth rate, and stocking density. Most of the reviewed studies incorporated internal heat loads of animals and heat sources, transmission losses through building envelope, and ventilation losses in their heat balance calculations. Other factors influencing the heat balance, such as solar radiation, heat loads from manure and electric lighting, and heat losses due to the airtightness of the building envelope, were less frequently considered. Furthermore, some studies included heat load data for growing pigs, while others used average values of pig weights. Energy use was calculated, measured, or predicted as low or high, and expressed in various ways. Examples of documented units include kWh/m^2, kWh/pig, kWh/sow, kWh/piglet, kWh/pig space, kWh/kg of meat, and kWh/day per farm. It is not always clear whether these figures refer to primary, purchased, or supplied energy. All factors make it challenging to compare published results on energy use, highlighting the need for further developments in this field of research. Only a few results on actual energy use have been published, as noted in the reviewed articles.

The most common cooling method is to increase the ventilation rate. Therefore, the energy efficiency of fans and a climate control system for their operation are considered important. Ventilation capacity, the type and size of supply air diffusers, and the angles of air jets have been shown to be significant for thermal comfort, as air velocity is also considered a good measure to cool the animals. However, air velocity has been found difficult to measure, and high air velocities can cause draughts in cold weather. Air recirculation is not considered a viable adaptation measure until the air can be cleaned of carbon dioxide and other emissions.

Several studies recommended cooling pads (CP) as effective in reducing indoor temperatures in hot, preferably dry, climates. Showers and high-pressure evaporators were also found to be effective in lowering indoor air temperatures and reducing heat stress. However, water scarcity, exacerbated by climate change, was also discussed. Additionally, water used for cooling will increase indoor humidity, which can affect thermal comfort, as high humidity combined with high temperatures can negatively impact animal welfare.

Heat pumps were considered effective in reducing heat demand in the winter and lowering indoor temperatures in the summer. Heat pumps can use air or water as both the source and distributor of heating and cooling. In some studies, all supply air passes through a heat pump (HP) or heat exchange (HE) system, leading to the use of these systems even when they are not needed for cooling or heating purposes. Therefore, it is important to ensure the ability to turn off the HP or HE system when they are not required, as unnecessary use can degrade the indoor climate and increase energy consumption.

HE is also a potential technique to enhance indoor climate and reduce energy use. Unlike HP, no additional energy is required for HE. However, a drawback of air-sourced HE is the risk of moisture in the air supply ducts located underground, as warm air can condense on the cold duct surfaces. When ducts become dirty, mould can start to grow, posing a risk to IAQ. Therefore, ducts that are cleanable or equipped with drainage are preferable where possible. Water-sourced HE have the advantage of posing low risk of mould.

The common aspect between HP and HE is that the size and length of the air duct or water pipe affect the pressure drop in the system. A high pressure drop results in energy loss, meaning that pumps and fans must operate more than necessary. Additionally, studies have shown that both HP and HE can contribute to excessive heat to buildings, potentially leading to a cooling demand. Therefore, it is crucial to design the entire technical system carefully when employing HP and HE. There are more studies on the winter case than the summer case and both HP and HE were found to reduce internal temperature variations.

Solar heat has been utilised to reduce energy use during winter at a relatively modest expense. It can be deemed viable in geographical areas with sufficient solar radiation during the winter months. However, it has been deemed crucial to compute the corresponding heat capture capacity and heat demand prior to installing such systems to ensure correct sizing. Furthermore, when employing solar heat, it has been concluded that having a climate control strategy is imperative to utilise preheated air only as required to elevate the indoor air temperature.

Although building properties were assessed to have only a minor impact on cooling, according to experts, few and limited calculations or simulations have actually been conducted. However, results from studies on the insulation level of building envelopes have been reported, and the findings regarding the required insulation level vary depending on outdoor climates. This indicates the potential for utilising indoor climate and energy use simulations to optimise the insulation level of a building in a specific climate. Studies indicate that heat exchange (HE) systems reduce the incoming outdoor air temperature, but if there is insufficient insulation, such as in shafts and attics, it can preheat before entering the animal stay zone, thus losing its cooling effect. Preheating may have a beneficial effect on indoor climate in winter but a detrimental effect in summer. Measurements also indicate that nights in the attic can be warmer than inside the building. No reviewed study directly addresses the effects of sun protection, such as green or reflective roofs, trees, or solar shading above windows.

Indoor climate control (ICC) serves as an adaptation measure to enhance indoor climate conditions. The simplest method to regulate the thermostat is to align it with the outside temperature. If it is colder, ventilation decreases while heating increases, contingent on the minimum ventilation rate and the capacity of the heat source. Conversely, as temperatures rise, ventilation rates increase and the heat source switches off once it reaches certain temperature. Some studies suggest that ICC is an energy-saving measure, yet its efficacy relies on indoor climate requirements and management factors. In instances where airflow remains inadequate without thermostat intervention, the control system increases ventilation and potentially activates heating, thus increasing energy use while enhancing indoor climate. Conversely, if the ventilation or heating system operates excessively, there is a potential to curtail energy use through ICC. Ongoing research explores the viability of utilising an ICC system as a predictive tool for indoor climate management. One potential application involves adjusting ventilation during spring and autumn, when warm days are often succeeded by chilly nights. Ventilation could be tapered off earlier in the evening to mitigate draughts in case of a delay in the ICC system. Moreover, a study revealed that lower night-time temperatures during winter could diminish energy use without negative effects on animal welfare. Additionally, incorporating ammonia emission levels into climate control settings within a building could potentially enhance indoor climate. Emission rates are contingent on various parameters such as temperature, airflow patterns, and floor type. Furthermore, management practices and production type are crucial factors influencing ammonia emission rates.

The reviewed studies demonstrate the potential use of modelling and simulation to predict indoor climate and energy usage. Primarily, models for assessing temperatures and thermal climate have been employed. These models can either be custom-developed for a specific study, using mathematical modelling or tools, or adapted from commercial software programs. The advantage of commercial programs lies in their ability to facilitate study replication, with ongoing software development enhancing usability. Modelling can also aid in optimising energy use and indoor climate through trade-offs. Furthermore, it is feasible to evaluate adaptation measures on buildings across different locations without case studies, provided the software used is validated and reliable. Typically, modelled indoor climate results are expressed as average temperature and humidity at a given time. However, thermal climate variation within premises is influenced by airflow patterns, dictated by the positioning of air supply and exhaust devices, as well as animal movement. Hence, alongside energy and indoor climate modelling, Computational Fluid Dynamics (CFD) simulations can be conducted to assess airflow patterns in the animal zone. Currently, two ongoing European projects (in 2023), EPAnHaus and Res4Life, include studies on energy and climate modelling.

6. Conclusions

This introductory paper was developed through a keyword search in Scopus. Totally, 51 articles of various origin were read, analysed and reviewed on the theme "Improving energy-efficiency and indoor climate of livestock buildings for pigs through passive and active adaptation measures". Based on this review, the following conclusions can be drawn:

1. Heat stress for pigs is likely to increase due to global warming, and adaptation measures are needed to reduce indoor temperatures.
2. Technical solutions are available to reduce indoor temperatures in warmer climates and increase temperatures under cold conditions. However, studies on the investment costs and relative energy of these solutions are lacking.
3. To reduce the environmental impact of livestock buildings intended for pigs, it is necessary to develop energy-saving solutions, improve management practices, and utilise non-fossil energy sources.
4. Computer simulations are potential tools for prediction of indoor climate and energy use in livestock buildings.
5. It is recommended to establish a common framework and employ standardised units to enable comparison between studies, climates and results, and and thereby create a knowledge database.

7. Further work

Swedish pig buildings generally adhere to similar designs governed by current and past legislations. Warmer and more humid climates are anticipated in Sweden (SMHI 2023), highlighting the need for further research on the impact of global warming on pig buildings. This introductory paper has demonstrated that simulating energy use and indoor climate is achievable with commercial software programmes. Indoor climate simulations can show how outdoor climate, pig size and density, and building physics influence the indoor climate over extended periods, as well as shorter durations such as a month or a day. Furthermore, these simulations can predict the energy demand of pig buildings not only in current climates but also in future climate scenarios, which is useful to estimate current and future production and investment costs.

In the forthcoming doctoral dissertation, additional tasks will involve modelling at least one section of a typical Swedish pig building (as a case study) for growing or growing-finishing pigs using commercial software programmes. The work planned after this introductory paper is illustrated in Figure 11.

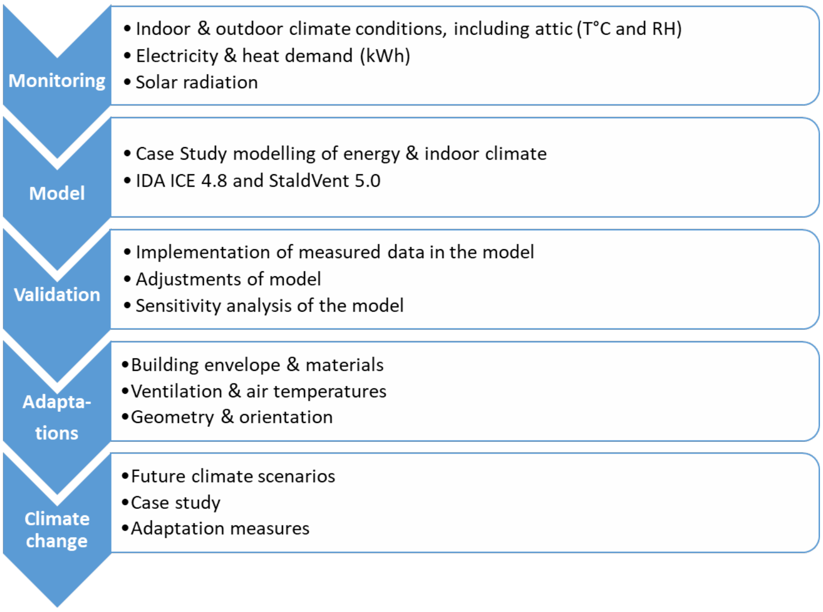

Figure 11: Work process for modelling energy use and indoor climate of typical Swedish pig building.

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