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# Design considerations for net zero energy buildings for intensive, confined poultry production: A review of current insights, knowledge gaps, and future directions

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ABSTRACT

The livestock sector is a key source of greenhouse gas emissions and other impacts. Poultry (meat and eggs) is the fastest growing livestock sector globally. Poultry housing, including both infrastructure and operating energy, may account for as much as 50% of the total non-renewable energy (non-RE) use and up to 20%–35% of some of the life cycle impacts of poultry production. The application of net zero energy (NZE) building technologies (i.e. that enable net zero non-RE consumption on site) for poultry housing represents a promising but under-considered mitigation strategy, which could help lessen reliance on fossil fuels and reduce greenhouse gas (GHG) emissions. Insights from commercial and residential net zero energy building (NZEB) research can, to a limited extent, inform design considerations for NZE poultry housing, but a variety of unique design considerations and challenges inherent to confined, intensive animal husbandry must be considered. Towards this end, this review seeks to: 1) identify insights from research of residential and commercial NZEBs that might be applied in designing NZE poultry housing; 2) quantify the magnitude and distribution of energy use in poultry housing in order to determine key energy consuming components; and 3) identify priority design considerations for NZEBs for intensive confined poultry production, taking into account the physiological requirements of poultry as well as specific requirements for intensive, confined production. To accomplish these goals, 249 relevant papers were identified and reviewed. It was found that, similar to commercial/residential applications, design strategies should focus on a combination of aspects respectively aimed at (1) reducing direct energy (DE) use via structural design, (2) improving the energy efficiency of active technology systems and (3) installing context-appropriate renewable energy (RE) generation systems. Some common passive design strategies like maximizing glazed area may be less applicable for poultry housing where photoperiod control is required. Heating (during heating seasons) and ventilation (during cooling seasons) are the two main contributors to DE use in poultry housing but vary considerably based on geography and climate. HVAC systems should hence be a priority focus, considering the high ventilation rates required in confined poultry housing in order to maintain air quality. However, any modifications to current technologies should be based on careful consideration of the physiological requirements of poultry (for example, ambient temperature, air quality, feed and water provision, etc.), along with local climatic factors, technical feasibility and availability of alternative technologies, as well as both environmental and economic payback times.

## 1. Introduction

Global population is predicted to surpass nine billion by 2050 [1], along with a commensurate increase in demand for food – in particular livestock products due to increasing affluence and associated dietary change. The livestock sector is a key source of greenhouse gas (GHG) emissions and other resource/environmental impacts. Poultry production for both meat and eggs will continue to be among the most rapidly growing food production sectors [2]. To sustainably meet the expanding

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**List of abbreviations**

| | |
|---|---|
| BIPV/T | building-integrated photovoltaic thermal systems |
| C | celcius |
| CFD | computational fluid dynamics |
| CFLs | compact fluorescent lamps |
| ERV | energy recovery ventilation |
| EEMs | energy efficiency measures |
| EPS | expanded polystyrene |
| DE | direct energy |
| DHW | domestic hot water |
| GHG | greenhouse gas |
| HEMS | home energy management system |
| HP | heat production |
| HRV | heat recovery ventilator |
| HVAC | heating, ventilation, and air conditioning |
| IAQ | indoor air quality |
| kWh | kilowatt hour |
| LCA | life cycle assessment |
| LCT | lower critical temperature |
| LEDs | Light Emitting Diodes |
| LHV | low heating value |
| LPG | liquified petroleum gas |
| LW | live weight |
| m | meter |
| MJ | megajoule |
| MP | moisture production |
| NA | not applicable |
| NZE | net zero energy |
| NZEB | net zero energy building |
| PCM | phase change materials |
| PV | photovoltaic |
| RE | renewable energy |
| RSI | thermal resistance value |
| TES | thermal energy storage |
| UCT | upper critical temperature |
| UK | United Kingdom |
| UV | ultra violet |

demand for poultry products, improving resource use efficiency and reducing the emissions associated with their production is essential. This includes attention to the development of optimal housing systems for intensive, confined poultry production that meet physiological requirements and support efficient production while reducing associated non-renewable energy use and environmental impacts [3,4].

Maintaining appropriate conditions in intensive, industrial poultry housing requires non-trivial inputs of both embodied energy and primary energy resources [5]. Embodied energy refers to energy inputs associated with provision of the actual housing system (i.e. including raw material extraction, manufacture, construction and end of life processes [6]). Primary energy (i.e. electricity and fossil fuels) resources are used as direct inputs for housing system operations including feed, water and manure delivery/removal, heating, cooling, ventilation, lighting, and sanitation [7].

To understand the magnitude and distribution of energy resource use and associated emissions in poultry production systems, life cycle thinking and life cycle assessment (LCA) have become increasingly important [8]. LCA is a standardized methodological framework for evaluating the environmental impacts associated with activities along industrial product supply chains. It enables comparing the net environmental impacts and/or benefits as well as potential trade-offs associated with management or technology interventions. Based on LCA studies, it has been reported that direct, farm-level energy use for egg production may account for as much as 25%–35% of cradle-to-farm gate life cycle energy use and GHG emissions in the Canadian and US egg sectors [9–11]. To identify the distribution of direct energy (DE) use in poultry housing, explore energy conservation strategies, and reduce the carbon footprint, well-established approaches such as energy audits or building computer-based simulations are commonly employed [12]. The results of energy audits in poultry housing vary depending on differences in locations and associated local climate factors, thermal envelope, and applied technological components.

Poultry housing design, including housing thermal envelope, layout, interior climate factors, heating, ventilation, and air conditioning (HVAC) systems, and automation all influence poultry production efficiency. Well-designed housing can benefit animal productivity while reducing waste of feedstuffs, animal injury, and incidence of diseases and parasites [13–15]. An appropriate thermal environment can, in particular, optimize feed efficiency. By contrast, housing that does not provide the appropriate thermal conditions, causing animals to dissipate or generate additional heat in order to maintain normal body temperature, will compromise productivity [15], with negative implications for life cycle environmental performance.

Given the significance of energy use to the environmental impacts of poultry production, design strategies and technologies that have the potential to reduce energy use whilst mitigating associated GHG emissions and other environmental and resource use impacts are important. This is particularly the case both in egg producing regions such as North America that are transitioning towards alternative (i.e. cage-free) layer housing systems (i.e. in light of the substantial infrastructure renewal this requires) [16], as well as in regions where egg production is rapidly expanding.

Net zero energy buildings (NZEBs) are buildings with annual net zero non-renewable energy consumption [17]. Such buildings have the potential to significantly reduce environmental impacts via changes to building design, energy efficiency improvements, renewable energy generation, etc. A variety of specific strategies and technologies for mitigating energy use impacts in poultry production have already been addressed in the literature. However, in contrast to the large body of research on net zero energy (NZE) commercial and residential buildings, the concept and application of NZEBs (which combine a variety of relevant design features) represents a promising but under-considered research area in the context of livestock production. Thus, although already a focus of policy makers worldwide for improving energy performance of residential and commercial buildings [18,19], design considerations for NZEBS for the poultry sector, specifically, as well as for the confined livestock production sector more broadly, clearly merit attention.

Moreover, while some general insights from commercial and residential NZEB research may be directly relevant for designing NZE poultry housing, it is also likely that specific design considerations will be necessary to support the unique characteristics and requirements of intensive, confined poultry production. These might include, for example: 1) the physiological requirements of poultry (such as specific lighting, thermo-neutral range, relative humidity, and air quality requirements); 2) the need for feed and water delivery and cleaning systems; 3) and the removal of manure and associated emissions. Thus, it is unclear which among the technologies and strategies currently used in residential/commercial NZEBs should be prioritized to best enable achieving NZE poultry housing.

Addressing this gap in current literature, the purpose of this review is to identify and synthesize insights from NZEB literature that may be relevant to the design of NZE housing for intensive, confined poultry production. Specifically, this review seeks to answer the following questions:

1. What are the insights/strategies from NZEB literature for commercial and residential applications that can be applied to NZEB poultry housing with respect to design features, building components, and technologies used?
2. What are the key energy-consuming activities (and their relative importance) in confined intensive poultry housing systems?
3. What recommendations can be advanced regarding priority considerations and strategies for designing NZEB poultry housing considering the unique characteristics and requirements for intensive, confined poultry production?

By answering these questions, this paper will provide a synthesis of research regarding technologies and strategies that are widely used in developing NZEBs. Analyzing these technologies and strategies alongside the unique requirements of poultry housing will then provide valuable information to researchers, producers, and other stakeholders in the poultry sector to support the development of NZE poultry housing, and contribute to improving sustainability outcomes in this globally relevant and rapidly expanding segment of the food system.

## 2. Methods

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) systematic review method (Moher et al., 2009) was used. PRISMA includes a search strategy, screening criteria, and extraction and synthesis of data stages (review framework), as detailed below.

### 2.1. Search strategy and screening criteria

The Web of Science search engine and keyword queries were employed to identify relevant literature resources, including peer-reviewed research articles and review papers topical to each of the three review questions. Relevant articles in the reference lists of selected papers were also considered. The temporal scope included papers published from 2000 to 2021, while other papers outside the temporal scope included in the aforementioned reference lists were also considered. The search queries resulted in the identification of 1311 articles. Based on screening of title and abstract for relevance, a total of 243 papers were shortlisted for detailed review. Table 1 describes the key word combinations that were used, along with the number of articles accessed/reviewed for each review question and the specific review objectives.

**Table 1**
Summary of methods used in this paper.

| Review questions | Keywords used for search | Number of articles reviewed/ accessed | Summary of review objectives |
|---|---|---|---|
| Question 1 | "design/construction, optimization/passive design/renewable technolog*/energy efficiency" OR "embodied energy" OR "case studies" AND "net zero energy buildings" | 126/308 | Case study synthesis and summary of commercial/residential NZEB design strategies |
| Question 2 | "energy use/audit/ simulation/analysis' AND poultry house/ housing/farm/facilit*" | 21/470 | Identify magnitude and distribution of energy use in poultry housing |
| Question 3 | "housing/houses/ construction" AND "poultry", "house characteristics" AND "poultry", "energy efficiency/lighting/ ventilation/cleaning/ heating/cooling/case studies" AND "poultry housing/house/facilit*" | 96/533 | Synthesis and discussion of the unique characteristics of poultry housing vis-à-vis strategies to reduce energy use, improve energy efficiency, and apply RE generation systems |

### 2.2. Framework of literature review

The first review question is aimed at identifying insights/strategies from research of NZEBs for commercial and residential applications regarding specific design features, building components and technologies for enabling the achievement of NZE status. Towards this end, the three criteria suggested by Ref. [20] (i.e. energy use reduction strategies, energy-efficient appliances, and RE generation systems) were used as a basis for cataloguing and synthesizing results from the considered papers for subsequent consideration with respect to the third research question. In addition, the following building characteristics were documented where available: building locations and climate factors, economic feasibility, energy payback time, operational requirements, energy efficiency and conservation strategies, and RE generation systems.

The second review question aims to identify the key energy-consuming activities and their relative importance in confined, intensive poultry housing systems. Literature reporting energy audits and LCA of poultry housing systems were identified and reviewed for this objective. Energy inputs, types, and uses were documented by housing system and technology system component. Energy input types included both non-renewable (e.g., liquefied petroleum gas and electricity) and RE (e.g., sunlight, wind, and geothermal heat) sources.

Considering the unique characteristics and requirements of intensive, confined poultry production, the third review question aimed to advance recommendations regarding key considerations, strategies, and technologies for designing NZEB poultry housing. Towards this end, the types and features of poultry housing, poultry heat and moisture production, and poultry physiological requirements were documented. These results were used alongside the results of review questions (1) and (2) to determine a priority subset of recommendations for designing NZE poultry housing.

For review questions 2 and 3, literature pertinent to facilities for poultry production (broilers and laying hens, exclusively) was considered. This encompasses all primary energy and material inputs for producing, constructing, and operating poultry housing systems, including technological components such as HVAC and lighting, feed delivery, and manure collection systems (Fig. 1). Feed production and manure storage activities and related infrastructure were not included.

## 3. Results and discussion

### 3.1. Insights from research of residential and commercial NZEBs

A total of 126 papers were selected for review to identify key design

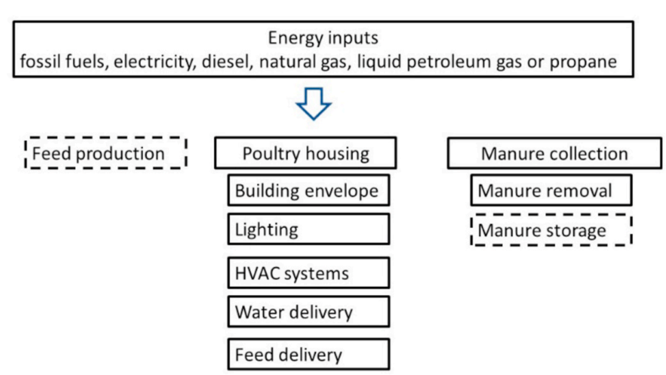


**Fig. 1.** Analyzed boundary of poultry housing (activities in the dotted boxes were excluded).

**Table 2**
Available building design energy use reduction strategies in support of achieving NZE status in residential and commercial buildings.

| Building design energy use reduction strategies | | |
|---|---|---|
| Strategies | Design considerations/technologies | Location and reference |
| Efficient thermal building envelope | - Building thermal envelope can be improved by using double/triple glazing windows; improving thermal insulation (e.g., soft foam insulation or mineral wool, synthetic mortar, expanded polystyrene (EPS), extruded polystyrene, polyurethane, silica aerogel-based insulation, thermal diodes, ventilated active thermoelectric envelope, and water-based paint); and increasing layers using plywood, external cladding (e.g., clay bricks) and vapor barriers<br>- Increasing insulation (low U-value) can decrease energy demands by 64% and 37% respectively in the summer and winter time [23], but is less effective in cooling-dominated buildings [24]. | India [25], Canada [26,27], UK [28], Kuwait [29], Portugal [30], Greece [31], Global [32,33], Europe [34], Spain [35] |
| Building geometry (factors and ratios) | - Selecting suitable building types (e.g., mixed-use, office or apartment), shapes (e.g., rectangle, L, T, cross, U, H, trapezoid and cross shape) and optimizing solar orientation, solar heat gain and natural lighting when situating glazed areas<br>- Optimal building geometry depends on local climatic factors. Different shapes and orientations have been identified as optimal in different regions, including the US [36], Europe [37], Turkey [38], Texas [39,40], and Washington D.C [41]. | USA [36,40,42], Korea [43], USA [39], Lithuania [44], Iran [45], UK [46], Portugal [47], USA, China [48], Ecuador [49], Global [50] |
| Thermal energy storage (TES) | - Includes the sensible TES (e.g., thermal mass, Trombe wall) and the latent TES (e.g., Phase Change Materials (PCM)) in walls, floor, ceilings and furniture, and PCM storage unit/deposit).<br>- Integration of thermal energy storage can reduce peak transmission load and also help to shift time of occurrence of peak load to later in the day [51]<br>- Thermal mass construction is usually only applied in climates with high diurnal temperature ranges and low relative humidity<br>- Buildings in hot and humid climates traditionally use a lightweight construction with low thermal mass to reduce heat storage, which can have negative effects on indoor temperature at night [52]<br>- Thermal mass should be integrated with nighttime ventilation (natural/mechanical) to utilize the full energy-saving potential. Such design strategies have proven to be effective in avoiding summer overheating and reducing cooling requirements [53].<br>- Multispectral design based on nanophotonic materials | Saudi Arabia [51], Australia [54], Greece [55] China [56], Slovenia [57], Algeria [58], Global [59,60], Europe [34] |
| Cooling | - Passive cooling can be achieved by using evaporative cooling walls, roofs and downdraft places, and using natural ventilation (e.g., wind driven ventilation, buoyancy-driven ventilation).<br>- In medium to low humidity regions, evaporative cooling is broadly used, making use of natural air movement to reduce heat during the day time [61]. It can reduce indoor temperature considerably, and has the potential to reduce DE use by 75% compared to a conventional air-conditioner [62,63].<br>- In hot and humid climates, high velocity natural ventilation can reduce energy use compared to air conditioning [52]. A mix-mode ventilation system that controls the opening of windows based on indoor temperature can reduce cooling energy demands by 20% [64]. | China [65], Australia [61], Iran [66], China [67], UK [28], India [52], Italy [64], Global [68–71] |
| Solar chimneys | - Convert thermal energy into kinetic energy by generating air movement due to density differences between the inflow and outflow air [65], and provide ventilation for both heating and cooling applications.<br>- In cold and moderate climates, Trombe walls can be used to preheat the air via solar collectors.<br>- In hot climates, solar chimneys can create cooling effects even during cloudy days [71].<br>- May be integrated with other active and passive heating/cooling systems. For instance, a solar chimney coupled with cooling cavities can help improve the efficiency of both ventilation and cooling [67]. | China [65], China [67], India [52] |
| Roofs with reflective materials (cool materials) | - Cooling loads are intensive at roof surfaces, where exposure to solar radiation is high.<br>- Reflective materials reflect most solar heat, reduce solar heat gain, and improve thermal comfort due to their high solar reflectance and thermal emittance [72].<br>- In warm and temperate climates, the summer cooling benefits provided by reflective roofs can offset the winter heating drawbacks year round, resulting in net energy savings [73].<br>- Benefits provided by reflective materials include reducing solar heat gain by reflecting UV rays back into the atmosphere to maintain cooling in the warm months, especially in hot climates. However, in cold climates, electricity used for heating may increase due to solar heat inhibition.<br>- Laser-sealed vacuum plate glass | India [52], Algeria [74], Mexico [72], Brazil [75], Europe [34], Ecuador [49], Global [76] |

considerations and technologies from research of residential and commercial NZEBs that might be applicable to the design of NZE poultry housing (Review Question 1). On the basis of this literature, despite varying degrees of specificity evident in the different papers, the prevalent strategies towards achieving NZE status can generally be grouped into three broad categories [20]:

(1) building design energy use reduction strategies (such as passive design);
(2) building DE use efficiency improvements (through use of energy-efficient appliances and energy monitoring systems); and
(3) RE generation systems (such as solar photovoltaics (PV), wind turbines, solar thermal water heaters, and heat pumps).

The strategies corresponding to each of these categories that were applied in the design of newly constructed NZEBs or for retrofitting existing buildings for NZE objectives are summarized and synthesized in Tables 2–4.

*3.1.1. Building design energy use reduction strategies (passive design)*

Passive design strategies capitalize on building location and available natural resources (e.g., solar radiation, wind, thermal availability,

**Table 3**
Available direct energy use efficiency improvement strategies in support of achieving NZE status in residential and commercial buildings.

| Direct energy use efficiency improvements | | |
|---|---|---|
| Strategies | Design considerations/technologies | Location and reference |
| Energy efficient lighting | - Use light emitting diodes (LEDs)<br>- Use compact fluorescent lamps (CFLs)<br>- The lifespan of LEDs ranges from five to seven years, saving 20–50% of electricity consumption compared to using CFLs | India [52], USA [79], Greece [31], China [80], Poland, Thailand, Mexico, Jamaica, Peru, Brazil, Denmark and UK [81], Brazil [75] |
| Advanced lighting controls | - Turn electrical lighting on and off automatically based on daylighting schemes (switching control)<br>- Dimming daylighting control | India [52], USA [82], China [80], Netherlands [83], Canada [27], Russia [84] |
| Load management, occupancy monitoring, unoccupied temperature setup | - Management systems enable detecting heterogeneous dynamics, such as dynamic pricing, energy peak loads etc. in multiple timescales to optimize the integration of diverse components | India [52], USA [82], Greece [31], USA [85], Europe [86], USA [87] |
| Heat recovery systems | - Recover heat from exhaust air, waste heat, and wastewater<br>- Economic payback time of heat recovery systems may be as low as 3 months, while the lifespan ranges from 15 to 25 years | China [65], USA [79], Canada [88], Maryland [89], Sweden [90] |
| Air source heat pumps, ground-coupled heat pumps | - Air source heat pumps are more cost-effective in small and moderate sized buildings, especially in temperate climates;<br>- Ground source heat pumps are better for large buildings, especially in cold climates.<br>- In cold and dry climates, the joint application of an energy recovery ventilation (ERV) system, ground coupled heat pumps, and point-source natural gas furnace reduced DE requirements by 43% compared to a conventional home in Colorado, USA [79]. | China [65], USA [79,82], UK [28], Denmark [91], Algeria [58], Europe [92] |
| Efficient chillers | - includes water-cooled centrifugal chillers and solar absorption chillers<br>- In hot climates, use of energy efficient chillers reportedly reduced total energy consumed by 33.6%.<br>- In tropical/hot climates, the application of energy efficient LED lighting and solar absorption chillers reportedly reduce energy costs by 34–44% [25,29]. | Kuwait [77] |
| Natural gas heater with storage tank | - The operational costs of a high efficiency natural gas heater with storage tank is 40% lower than that of an electric heater | Portugal [30] |
| Radiant floor, underfloor heating | - The mean water temperature, piping size and space, plus floor finish and construction affect the heat output | China [65], USA [93], UK [28] |
| Meters: Home energy management systems (HEMS), Smart meters, Energy meters | - Energy meters can record historical data as well as provide real-time data but lack the ability to predict future energy use and energy generation, owing to their unidirectional functions [94].<br>- Smart meters are used to collect, analyze, and predict data related to energy use and generation via bidirectional functions [95].<br>- Net Zero Energy Clusters (NZECs) can be developed based on energy data interchange in a network of multiple connected NZEBs<br>- HEMS similarly detect primary energy demands in buildings [94], and integrate the interactions among energy generation systems, energy consumption, and the smart grid. | Global [94,96–98], India [99], Spain [100], Denmark [91], Canada [101] |
| Efficient air-conditioning and ventilation | - For hot-dry and hot-dry with humid climatic conditions, radiant vapor compression (VC) air conditioning with VC-DOAS (dedicated outdoor air system) can help achieve about 75% of net zero energy targets.<br>- Use of desiccant humidifiers with vapor compression systems (hybrid air-conditioners) have the potential to solve problems associated with fluctuations in cooling loads in NZEBs<br>- Use of multi-zone demand-controlled ventilation (DCV) systems to reduce over-ventilation | Global [102–104], Ecuador [49], Japan [105], USA [106] |

natural light, and ground heat) to reduce non-RE consumption for building operation [21] (Table 2). In particular, they influence mechanical and electrical systems for heating and cooling, building thermal loss or gain, and the amount of energy that needs to be generated by RE generation systems [22]. The principle passive design strategies and technologies focus on the building thermal envelope, geometry and solar orientation, thermal energy storage systems (TES), passive cooling systems, and use of specific structural features such as solar chimneys and reflective roofs.

#### *3.1.2. Energy Efficiency Measures ( EEMs ) Integrated with energy control and monitoring systems*

To reduce DE consumption in buildings, energy-efficiency measures (EEMs) related to lighting, heating, cooling, ventilation and air conditioning systems, and associated energy control monitoring systems, are typically applied in NZEBs (Table 3) [77]. The basic requirement for EEMs installed in NZEBs is that they are compatible with the local energy grid and do not add any additional loads on the existing energy supply infrastructure [78].

#### *3.1.3. RE generation systems*

RE generation system installation is essential to offset non-RE use in NZEBs [107–109]. Solar PV/thermal systems are the most common (especially to support energy needs for DHW) compared to other RE systems like wind turbines or ground source heat pumps [110]. In many NZEBs, geothermal systems are connected to radiant heating equipment like radiant floors for space heating [111]. Integrating systems such as photovoltaic thermal systems (BIPV/T) can also be considered in some situations [112]. For example, in a closed loop system, a BIPV/T can be connected to solar collector absorber plates through water piping systems to recover some of the heat that can be lost in the array (solar arrays can become less efficient when hot). The solar collectors can be placed behind the solar PV array and will transfer the energy captured to a medium (such as a fluid) which is then stored or used for some productive purpose through heat recovery pumps. On the other hand, the water piping systems can also be used to cool the PV array (Table 4).

### *3.2. Magnitude and distribution of energy use in poultry housing*

Poultry housing operations may account for as much as 35% of some

**Table 4**
Available renewable energy generation technologies in support of achieving NZE status in residential and commercial buildings.

| Renewable energy generation systems | | | |
|---|---|---|---|
| Strategies | | Design considerations/technologies | Location and reference |
| Wind turbines | | - Energy payback time: 3–8 months<br>- Lifespan: 20–25 years | Greece [113], USA [114], Global [68] |
| Geothermal energy | | - Energy payback time: 5–7 years | Morocco [115], USA [116] |
| Biomass energy | | - Energy payback time: 3.5 years | Global [117,118] |
| PV systems | Rooftop PV systems<br>Building-integrated photovoltaic thermal systems (BIPV/T) | - The efficiencies of a-Si, polycrystalline, and monocrystalline PV panels were 4.79%, 11.36%, and 13.26%, respectively.<br>- Energy payback time of single-crystalline silicon, multi-crystalline silicon and amorphous silicon is 3.0–7.4 years, which is far less than the PV system's life cycle (25 years)<br>- Integrating systems such as photovoltaic thermal systems (BIPV/T) can also be considered in some situations [112]. For example, in a closed loop system, a BIPV/T can be connected to solar collector absorber plates through water piping systems to recover heat. | India [52], Canada [26,27,101], UK [28], Kuwait [29], Portugal [30], Greece [113], USA [41,106], China [119], Brazil [75], Ecuador [49], Sweden [120], Global [96] |
| Solar collector | | - Convert solar radiation into heat and then transfer the heat to water, air, etc.<br>- Economic payback time: 8 years | Canada [26], China [65], UK [28], Denmark [91], Algeria [58] |

of the life cycle impacts of poultry production [11]. However, many LCA studies do not consider the infrastructure burdens of poultry housing, as they typically contribute a very small fraction of the overall life cycle burdens of poultry production [10]. In contrast, DE inputs to housing operations are typically included in such studies since they may account for more than 50% of total life cycle non-RE use, and contribute to GHG emissions [11]. To identify priority strategies for designing NZE poultry housing, it is crucial to both understand energy use distribution in poultry housing and to consider local climate factors. Towards this end, 21 articles were reviewed, including life cycle assessment, energy audit, and energy simulation studies (Table 5) (Review Question 2).

Based on the studies reviewed (Table 5), DE inputs are required in poultry housing for feed and water supply systems, lighting, indoor climate control (i.e., heating, cooling, ventilation), egg collection, sanitization and manure removal [140,141]. However, the primary contributor to DE use is equipment operations for climate control, in particular heating and ventilation.

Electricity and fossil fuels are the most used types of energy in poultry housing. Generally, electricity is used for ventilation (30%–43.7%), heating (27%–98%) and lighting (7%–43%). Fossil fuel is often used for heating (47%–98%) and powering other machinery (5%–33%). The energy costs associated with maintaining an acceptable environment in poultry buildings varies widely, from as low as 2% of total costs to as much as 10% of total costs in inefficient buildings [142]. Energy costs can also depend on many factors. For example, when poor construction allows air infiltration to exceed the minimum ventilation rate, utility costs increase quickly. For warm regions, cooling poultry buildings may become even more expensive in both capital and operating costs [131,132]. In addition to the influence of local climate factors, the total amount of energy inputs is also strongly influenced by the building thermal envelope, the amount and size of lighting and HVAC systems, and housing capacity (i.e. bird density) [143].

Depending on factors such as age, floor types, and manure management systems, birds in poultry housing can produce varying amounts of heat, moisture and contaminants (dust, gases, etc.). A barn housing young birds will require a lower ventilation rate but higher ambient temperature, whereas a barn housing mature birds requires a high ventilation rate and lower temperature [144]. In this case, improving ventilation efficiency is more energy and economically efficient in layer barns. Minimum ventilation rate for a poultry barn can range from 2 L/s per animal for cold regions to 8 L/s per animal for warmer regions [142].

Priority energy efficiency considerations for poultry housing include thermal insulation and HVAC systems, while efficient lighting, feeding and waste handling systems are also important. Energy efficient ways to remove manure and clean housing have not been widely considered in the literature.

### 3.3. Key considerations for design of NZEBS for intensive confined poultry housing

This section summarizes and synthesizes findings from 96 papers regarding specific requirements/considerations for design of intensive, confined poultry housing, the major types and features of poultry housing, and available strategies/technologies that can be applied within and/or proximate to poultry housing to enable achieving NZE status. In addition, the insights from research of residential and commercial NZEBs will be discussed in this section with respect to NZE poultry housing design strategies (Review Question 3).

#### 3.3.1. Physiological requirements in poultry housing

Poultry houses should be designed to maximize productivity with the least cost, emissions and energy consumption [145]. Indoor climate control strongly influences the health, growth and performance of poultry and, consequently, farm profits [146]. To maintain an appropriate indoor climate, ambient temperature, relative humidity, ventilation rate, air quality, and light intensity must be considered, taking into account local climates, stocking density and housing characteristics (e.g., housing insulation and air infiltration) [142]. Table 6 summarizes the key reported physiological requirements for poultry housing.

Health and productivity of the animals is most easily achieved when the ambient temperature in poultry housing falls within the effective temperature zone – also called the zone of nominal losses or thermal neutral zone [149,150]. Environmental requirements also vary with the age of the bird. Chicks are very sensitive to temperature variations. Broilers and young turkeys reared at ambient temperatures below 18 °C are heavier than similar stock reared within the 18–35 °C range, but their feed conversion efficiency will be lower [151].

Laying birds produce the greatest number and largest eggs within the range of 13–24 °C. The best feed conversion efficiency is achieved between 21 °C and 24 °C [142]. Prolonged ambient temperatures higher than required may result in hyperthermia and reduce feed consumption. Above 24 °C, there is a reduction in egg production and size. A continued increase in temperature to 38 °C or more may prove lethal. High humidity at high temperatures creates conditions that are more likely to be lethal because of a breakdown in body cooling through respiration [142].

Conversely, temperatures below the LCT may result in hypothermia. In this case, the animal must use energy from feed to boost metabolism

**Table 5**
Energy use magnitude and distribution in conventional poultry housing.

| Barn type | Climate factor and country | Energy use accounting method | Housing type | Main energy-consuming activities | Analyzed energy type | DE use distribution and magnitude | Reference |
|---|---|---|---|---|---|---|---|
| Broiler barn | Saskatchewan, Canada (Continental) | Energy audit | Enclosed barns | Heating, ventilation, lighting, feed and water delivery | Liquefied petroleum gas (LPG), electricity | 90% of the total energy requirement was for heating the barn (18.8 kWh/bird for a well-insulated barn and 21.4 kWh/bird for a poorly insulated barn). Heating energy costs represent 68% of the total energy cost | [121] |
| | Emilia Romagna, Italy (Mediterranean) | Energy audit | Enclosed barns | Heating, ventilation | Electrical and thermal energy | 67% of electricity (40% for ventilation, 27% for heating) and 96% of thermal energy (e.g., natural gas) are used for climate control. 9% and 19.8% of electricity are used for lighting and feed delivery, respectively. | [122] |
| | Turkey (Mediterranean) | Energy input–output analysis | Enclosed barns | Lighting | Diesel fuel, electricity, machinery energy | Total diesel, electricity, and machinery energy used in broiler barn is 1.21, 3.50, 0.28 equivalent MJ/bird respectively annually. | [123] |
| | Yazd province, Iran (Hot Desert) | Energy input–output analysis | Enclosed barns | Heating, automatic feeding and lighting | Diesel fuel, electricity, machinery energy | Total average diesel, electricity, and machinery energy used in broiler barn is 11.06, 16.09, 0.20 equivalent MJ/bird respectively. 59.2% of diesel fuel is used for heating the space. | [124, 125] |
| | Michigan, USA (Humid Continental) | Not Available (NA) | NA | Heating, feed and water delivery | Gasoline, diesel fuel, heating oil, and LPG | Energy for heating accounts for 71% of annual energy use, followed by feed and water delivery and manure removal (18%), lighting (7%), and ventilation (4%). | [126] |
| | Adana province, Turkey (Mediterranean) | Cultural energy analysis | Enclosed barns | Lighting, cooling, water pump and spiral feed conveyor | Electricity, diesel, propane, coal | Most electricity is used for lighting | [127] |
| | Georgia, Arkansas, Kentucky, USA (Humid Subtropical) | Energy audit | NA | Heating, cooling | Electricity, diesel, propane, LPG | Electricity is used for heating and cooling in primary breeding facilities. Supplemental heat is generated by propane gas heaters in pullet rearing facilities. Average electricity, diesel and propane are 86.93 kWh, 0.56 gal, and 12.30 gal per live weight (LW) broiler, respectively | [128] |
| | Southern Finland (Humid Continental) | Energy monitoring | Enclosed barn | Heating, ventilation, lighting | Fuels and electricity | Major energy inputs in broiler house were feed and fuel for heating. Electricity consumption was quite minor compared to the energy inputs for feed and heating. Electricity for ventilation comprised the major part of total electricity usage. | [129] |
| | Pakistan (Temperate) | Electricity expenditure | Double story farms | Automatic feeding, drinking and ventilation | Electricity and diesel | Details not provided | [130] |
| | Arta, Greek (Warm and Temperate) | Energy audits | Insulated and enclosed barn | Ventilation, cooling, and lighting, feeding | Electricity and fuels | The average final energy consumption varies from 46.38°kWh/m2, in lowland farms with new technology, to 89.37°kWh/m2 | [131] |
| | Northwest Arkansas (Humid Subtropical) | Energy bill and monitoring | Open-curtain system | Heating, ventilation, cooling, lighting | Electricity and propane fuel | Ventilation and lighting account for 65% and 20% of the total electricity usage respectively; propane fuel mainly used for maintaining ambient temperature. Average electricity use and propane were 0.082 kWh and 0.076 L per kg of LW respectively. | [132] |
| | Northwest Arkansas (Humid Subtropical) | Energy bill and monitoring | Enclosed barn | Heating, ventilation, cooling, lighting | Electricity and propane fuel | Lighting accounted for 43% of the electrical consumption. Average electricity use and propane were 0.10 kWh and 0.07 L per kg of LW respectively | [132] |
| | Michoacán, Mexico | Energy input–output analysis | Enclosed barn | Heating, hot air extraction, | LPG, electricity | Heating, hot air extraction, ventilation, and water inputs | [133] |

(continued on next page)

**Table 5** (*continued*)

| Barn type | Climate factor and country | Energy use accounting method | Housing type | Main energy-consuming activities | Analyzed energy type | DE use distribution and magnitude | Reference |
|---|---|---|---|---|---|---|---|
| | | | | ventilation, water supply, lighting, | | account for 97.73%, 1.6%, 0.3%, 0.1% of total DE inputs respectively for a full cycle (49 days) | |
| | Turkey (Mediterranean) | Estimation based on Heating and Cooling Degree Day Numbers (HDDN and CDDN) | NA | Temperature, Ventilation, Lighting | LPG, Natural Gas, Electricity | NA | [134] |
| Laying barn | Bursa region, Turkey (Mediterranean) | Energy input–output analysis | Conventional cage | Lighting | Diesel fuel, electricity, machinery energy | Total diesel, electricity, and machinery energy used in layer hen housing is 3.49, 3.69, 0.34 equivalent MJ/bird respectively | [123] |
| | Iowa, USA (Four-season) | Electricity and propane fuel monitoring | Aviary-Laying Hen Houses | Ventilation, manure handling and cleaning | Electricity and propane fuel | Nearly 30% of electricity is used to power ventilation in the summer but only 5% in the winter. Approximately 51% of the annual electricity is used for manure handling and housing cleaning (e. g., manure-belt blowers). | [135] |
| | Michigan, USA (Humid Continental) | NA | NA | Ventilation, lighting, egg cooling | Gasoline, diesel fuel, heating oil, and LPG | Energy use for ventilation accounts for 64% of annual energy use; followed by lighting (17%), egg cooling (9%), feed delivery (5%), and the other usages (5%). 3.51 kWh/bird of electricity is used for ventilation | [136] |
| | Italy, France and Sweden (Mediterranean, Oceanic, Continental, and Mild) | Energy audit | Enriched cage farms and free range farms | Ventilation, lighting | Electrical energy | 58.9% of electrical energy (43.7% for ventilation and 15.2% for lighting) is used for indoor environmental control, while no thermal energy is needed. Electricity use ranges from 50.40 $kWh/m^2.a^1$ in a cage rearing system to 14.70 $kWh/m^2.a^1$ in a free-range system in France | [122] |
| | Karaj city, Iran (Cold Semi-Arid) | Energy Input/output analysis | NA | Machinery | Fossil fuels (diesel and kerosene), electricity | Fossil fuels are the main contributors to total indirect and DE use (21.3%). Average 151.04 MJ/bird of fossil fuels are needed to power machinery. | [137] |
| | Alberta, Canada (humid continental climate) | NA | NA | Heating | Natural gas | 98% of natural gas is used to heat space | [138] |
| | Alberta, Canada (humid continental climate) | NA | NA | Heating and lighting | Gasoline, diesel, natural gas, electricity, LPG | Natural gas is used for heating, accounting for 47% of total DE inputs. Gasoline and diesel are used to power machinery and trucks, which account for 33% of the total DE use. | [139] |

to maintain their body temperature [145]. Within the temperature range 5–30 °C, there is a reduction of about 1.6% in feed intake for every 10 °C increase in ambient temperature [142]. Maintaining appropriate temperatures is hence important to both productivity and profitability.

The sources of heat in poultry housing include heating systems, lighting, motors and animal body heat [138]. Heat production (HP) and moisture production (MP) rates of animals provide fundamental information for design and operation of housing ventilation systems [152–154]. In cold climates, heat produced by broilers was 8.12 ± 1.24 W/kg and moisture produced was 5.53 ± 1.68 g/h per kg at 20 °C [152]. In broiler houses during the last days of the production cycle, for example, the high animal stocking density produced a sensible heat emission estimated to be approximately 180 $W/m^2$, with a vapor emission of 5.2 kg $vapor/m^2/day^1$ [145]. It is important to keep an appropriate indoor moisture level because high values of relative humidity (RH) may increase the risk of heat stress of animals and is deleterious to animal health and productivity (e.g., egg and meat production). To solve this problem, well-designed heating systems that account for all heat sources (such as recovering exhaust heat to preheat inflow air) can be applied to achieve energy efficient outcomes in poultry housing [13].

Indoor air quality (IAQ) control is also crucial to maintaining an environment that is conducive to poultry health and welfare [155]. Continuous fresh air intake and exhaust air output is necessary to remove manure gases (in particular, ammonia emitted from excreta) as well as manure odor and dust. Many contaminants that are odor carriers

**Table 6**
*Poultry housing environmental requirements (Sources:* [142,145,147,148]*).*

| Poultry type | Thermoneutral zone (°C) | Heat production at 20 °C/animal (W/kg) | Moisture production at 20 °C/animal (g/h per kg) | Relative humidity (%) | Air movement (m/s) | Ventilation rate (l/s) |
|---|---|---|---|---|---|---|
| Broiler | 20–32 | 8.12 ± 1.24 | 5.53 ± 1.68 | 30–80 | 0.2–1.0 | 2.0–8.0 |
| Layer | 10–29 | 10.9 ± 0.8 | 5.6 ± 0.4 | 50–75 | 0.2–1.0 | 2.0–8.0 |

are biologically active (due to airborne microorganisms), and their concentration is extremely high [156]. Ventilation is one of the most effective ways to remove indoor air pollutants [144], but may also necessitate additional heating in cold climates.

Light intensity [157], lighting schedules [158,159], feeding regimen, circadian cycles [160], and physical activity levels of the birds [161] also need to be considered when designing either conventional or NZE poultry housing. Generally, artificial lighting is used in order to ensure optimal intensity and duration because natural light (which varies seasonally) often does not provide conditions conduvice to optimal productivity [162].

### 3.3.2. Buildings for intensive confined poultry production

Housing for poultry production typically involves single story buildings, but multi-story buildings can reduce costs and improve material and energy efficiency [151]. Birds are sensitive to ambient temperature; hence housing should be well-insulated. Table 7 demonstrates the recommended insulation levels for conventional poultry housing including walls, roof, windows, and foundation in different regions.

The recommended thermal value of insulation for conventional poultry housing ranges from a minimum of RSI 0.64, 0.84, 1.06 for walls, roofs, and foundations respectively in warm climates to at least RSI 3.52, 5.30, 1.40 for cold climates. It is obvious that a well-insulated envelope plays an important role in maintaining interior temperature and reducing heat loss [168]. However, ambient heat production needs to be taken into account when determining insulation requirements due to the variations in density of birds housed (9.25–20.54 birds/$m^2$) [164].

Wood, concrete, or steel trusses and supports are often used for constructing the frame for poultry housing [142]. Steel trusses or concrete poles are used to support the weight of the roof [169]. Dropped ceilings, which act as a vapor barrier, are often used for protecting the trusses and ceiling insulation. This also improves ventilation, and reduces heating costs [164]. The floors in poultry housing should be clean, economical, and durable to inhibit bacterial growth, enable quick manure removal, and effectively resist corrosion [170]. Litter materials may be placed upon the floors as bedding materials to reduce moisture from the manure [171]. Wood shavings are the best litter materials; others are straw, rice hulls, sand, groundnut husk, and peanut hulls [172]. It is better to maintain litter moisture below 35% (ideally between 20 and 25%) of the total weight of the material by controlling ventilation and heat [156]. In the context of NZE poultry housing, poultry litter with high moisture and ash content can be reused as a biomass fuel for electricity and heating generation. The by-products from the treatment of poultry litter are valuable, such as activated carbons and fertilizers [173].

Heating and ventilation equipment requirements vary due to different heating and cooling loads. The size of equipment (such as fans and heaters), the control strategy, and balancing among subzones (such as rooms within a building) are critical to the efficient functioning of the HVAC system [174]. Different ventilation rates create air pressure differences between rooms. These pressure differences can cause interflows among rooms, reduce the ventilation effectiveness, and even cause the ventilation system to fail [175]. Ventilation failure can as also lead to structural damage to the barn [176]. For instance, airflow backdrafts can result from inadequate pressure differences between the inside room and the attic. Warm and moist air can move backwards through dry and cold airflow inlets, causing condensation and frost at the ceiling/on the trusses [177]. The thawed frost may cause severe water damage to the building structure when the weather warms [178]. Hence, it is crucial to maintain a negative pressure difference between the inside air and outside air. To maintain negative pressure inside, fan speed, wind protection and inlet air pressure controls should be considered [178]. These methods can control indoor temperature and ventilation rate automatically, but it is also important for farmers and managers to schedule ventilation systems based on their experiences [144].

**Table 7**
Recommended insulation values for poultry housing envelopes.

| Country | Insulation (RSI value, unit: $m^2K/W$) | | | | Housing types and reference |
|---|---|---|---|---|---|
| | Wall | Roof/ ceiling | Foundation | Window | |
| Canada | 3.5 | 5.3 | 1.4 | Not Available (NA) | Enclosed breeder barn [151] |
| Greece | 0.97–1.74 | 0.97–1.74 | NA | NA | Enclosed broiler houses [131] |
| China | 0.64–1.78 | 0.84–2.56 | NA | NA | Enclosed layer housing [163] |
| USA | 1.6 | 1.25–2.25 | NA | NA | Insulated poultry housing [164] |
| Northwest Arkansas | 1.32–1.94 | 1.76–3.35 | NA | NA | Enclosed broiler barns [165] |
| Italy | 1.23 | 0.85 | 1.06 | 0.27 | Enclosed broiler barns [166] |
| Northwest Arkansas | 1.32 | 1.76 | NA | NA | Insulated sidewall broiler barns [167] |

### 3.4. Priority strategies to support achieving zero energy status for intensive, confined poultry housing

No peer reviewed literature specific to strategies for design of NZE buildings for intensive, confined poultry (or other livestock) housing is available to date. However, some of the insights from available research of residential and commercial NZE buildings (review question 1) are applicable, subject to considerations of the poultry-specific housing system requirements discussed above. These insights from residential and commercial NZE buildings are grouped under three categories: (1) housing design strategies that enable reducing energy demand; (2) Energy Efficiency Measures (EEMs); and (3) integration of RE generation systems.

#### 3.4.1. Housing design for reducing energy use

Many commercial and residential NZEBs have optimized building geometry and orientation to gain sufficient passive daylight and solar heat gain. However, in large-scale industrial poultry production, facilities are often fully opaque in order to enable control of lighting conditions (duration and intensity) to support optimal productivity, and heat removal may be more important than heat gain. The literature generally agrees that increasing the insulation of the building envelope supports maintaining desirable indoor temperatures without supplemental heating [152,168]. Metabolic heat produced by the birds can obviate the need for supplemental heating in poultry housing in many climates – in particular, when the housing is well insulated. Several promising materials have been identified from the NZEB literature (Table 2) for potential use in the thermal envelopes of poultry barns. However, optimal materials and thickness must be informed by local climatic factors. Also, excess insulation cannot compensate for large amount of heat lost through ventilation [131].

Ventilation, as another significant contributor to energy use in poultry housing, should be carefully controlled due to its significant influence on both electrical and thermal energy consumption, as well as bird health. Normally, positive pressure ventilation systems are necessary for intensive confined poultry housing to avoid cold drafts. Natural ventilation may enable reducing mechanical ventilation energy requirements, as well as the risks associated with power or mechanical failures [179]. However, it may be difficult to predict and control airflow velocity and direction, resulting in detrimental temperature and/or air quality conditions [180]. Natural ventilation may also enable ingress of snow and rain, which can damage the housing structure. Hence, natural ventilation might be best used to supplement powered operations rather than considered as a stand-alone strategy.

Maintaining stable temperatures in poultry houses could also be supported by use of latent and sensible thermal energy storage (TES) systems. TES with phase change materials (PCM) can maintain appropriate indoor temperature even during nighttime and cloudy days [181]. Such systems reduce temperature fluctuations since it takes time to change the phase at a steady-state temperature. Another sensible TES that could be utilized in NZE poultry housing is the Trombe wall. Such systems are typically coloured black and situated facing south to obtain solar heat [182]. Trombe walls are generally easy to design and maintain [183]. TES systems can not only reduce costs and improve reliability, they also have the potential to significantly reduce GHG emissions associated with direct energy use in buildings [184].

### 3.4.2. *Energy Efficiency Measures ( EEMs )*

In recent decades, advancements in energy-efficient technologies for heating, cooling, and ventilation systems, artificial lighting, energy monitoring, and feeding/egg collecting/manure removal automation, have enabled reducing labor and energy inputs per unit of egg produced in intensive egg production systems [16]. Table 8 summarizes EEMs utilized in commercial/residential NZEBS or reported to be used in some poultry facilities that should be considered for the most significant energy consuming activities in poultry housing when designing NZEBs.

**Table 8**
Energy-efficiency measures for heating, cooling, ventilation, and lighting in poultry housing.

| Energy-efficient measures | | Reference |
|---|---|---|
| Heating | | |
| Air pre-warm systems | Earth tube system | [185–187] |
| | Transpired solar walls | |
| | Trombe walls | |
| Gas-fired radiant heating (such as natural gas heater with storage tank) | | [188,189] |
| Convective heating/hot water heating/hydronic heating (such as in-floor heating) | | [190] |
| Zone heating/unit heaters | | [190] |
| Heat pumps (air source, ground source or water source) | | [191] |
| Thermal energy storage (TES) systems | | [181] |
| Ventilation | | |
| Dual ventilation | | [192] |
| Exhaust ventilation system | | [174] |
| Tunnel ventilation | | [193] |
| Pit ventilation | | [174] |
| Air-to-air heat recovery ventilator | | [194] |
| Lighting | | |
| Energy efficient lighting | | [195] |
| Advanced lighting controls such as dimming daylighting controls | | [195] |

#### 3.4.2.1. *Heating.*

The three common types of heating systems in poultry housing are convective, radiant, and conductive heaters [138]. In addition to the traditional heating methods, heat pumps (air source, ground source or water source) provide a potential alternative, more energy efficient method for heating barns [191] as well as for cooling. Such heating/cooling systems are relatively common in commercial/residential NZEBs. By replacing traditional heating energy inputs such as fossil fuels, heat pumps can save 30–70% of heating costs. In addition, use of heat pumps can contribute to regulating indoor relative humidity and hence improve bird living conditions [191]. Use of heat pumps with TES systems has also been identified to have significant potential in NZEBs [184].

Among the three types of heat pumps, ground source heat pumps, which use geothermal energy, are most amenable to use both for winter heating and summer cooling. The reason is that soil provides higher temperature environments in winter and lower in summer [196–200]. Water source heat pumps may be easier to install compared to the ground source heat pumps [201]. Air source heat pumps are most common and are easiest to install, but can be noisy and less efficient than the other types [202].

Another heating measure that may also be applicable for NZE poultry housing are air pre-warming systems. In these systems, air is heated by geothermal energy or solar heat before ingress. In earth tube systems, for example, fresh air is heated or cooled (depending on exterior temperature) by the earth to moderate the inlet airflow temperature [115]. In transpired solar wall systems, heated air enters the housing through small holes in the perforated transpired walls that are heated by the sun [186]. These systems have low operating costs as the walls do not move and there are no liquid components. However, location and climate factors determine the potential efficacy of such systems. For instance, earth tubes without humidity control do not work well in hot humid climates as condensation occurs in the earth tubes and may affect their function. Transpired solar walls function best in regions with ample winter sun, but may be sub-optimal where cloudy conditions prevail [192].

#### 3.4.2.2. *Ventilation.*

Ventilation systems are crucial to inlet fresh air and remove excess heat and moisture containing pollutant emissions and dust [203]. Four common ventilation methods in confined poultry housing are dual ventilation, exhaust ventilation, tunnel ventilation and pit ventilation. These may be used singly or in combination [144].

In dual ventilation systems, it is important to optimize the combination of natural ventilation and mechanical ventilation. This can be achieved by controlling inlet and outlet air using wall openings. In exhaust ventilation systems (also referred to as negative pressure systems), waste heat in exhaust air can mix with the incoming fresh air to moderate temperature in the barn [192]. Tunnel ventilation (forced air) is a variant of negative pressure systems. In these systems, axial fans are located on one side of the barn to exhaust air while air inlets with evaporative cooling pads are used to inlet fresh air on the other side of the barn [193]. Another variant of exhaust ventilation is pit ventilation, which is commonly used in deep-pit buildings with manure storage. In these systems, concrete annexes are installed in the deep pit to pump manure from the barns [174]. [204] provides several recommendations for improving the efficiency of ventilation systems, including:

- Selecting the appropriate types and size of ventilation systems
- Cleaning and maintaining fans, ducts and louvers to improve airflow
- Replacing old fans with energy-efficient systems
- Using recirculation fans to improve heat distribution
- Reducing air leakage to increase static pressure, improve ventilation efficiency, and maintain normal airflow
- Fitting “bell-mouths” to fans or “cones” to outlet fans to increase aerodynamic efficiency by $\sim$ 10%

A common problem with all such systems in cold climates is that ventilation also continuously removes heat, hence necessitating exogenous (often fossil fuel-based heating). Indeed, this presents a distinct challenge for achieving NZE status in confined poultry housing compared to commercial/residential applications. To recover exhaust heat from excurrent ventilation air, air-to-air heat recovery ventilators (HRVs) may be applied [138]. Heat recovery efficiencies of around 40% have been reported. This may reduce energy use by as much as 54%, especially when combined with a forced air convection heater [194]. However, it is difficult to maintain optimal function of the heat exchangers because they may become quickly fouled from moisture, dust, and corrosive matter in the excurrent air [194].

*3.4.2.3. Lighting.* Lighting systems are important electricity consumers in confined poultry housing. Fluorescent/incandescent tubes with energy-efficient ballasts can save 15–70% of energy compared to those with less efficient ballasts. However, LED lighting systems with appropriate modules (spectral and power characteristics) can reduce energy use for lighting by 80–85% compared to incandescent/fluorescent bulbs [195]. Although not often used in confined poultry housing, natural lighting combined with films or shades to control photo period and optimize production efficiency offers additional potential energy savings [195].

*3.4.2.4. Sensors.* Use of sensor networks that capture real-time data regarding relative humidity, temperature, light intensity and bird density to support real-time decision-making in poultry housing has been reported [205,206]. In addition to real-time data collection using sensors, computational fluid dynamics (CFD) models are used to estimate indoor climatic variables based on housing geometry [207], ventilation types [208], and external thermal and humidity conditions [209]. In commercial/residential NZEBs, both sensor networks and models are commonly used to optimize energy efficiency, hence it is likely that these strategies are similarly applicable and important for the design and operation of confined poultry housing for energy efficiency objectives.

### 3.4.3. RE generation systems

RE generation systems will play a crucial role in offsetting non-RE use in NZE poultry housing. Several examples of integration of RE systems into intensive livestock housing have been reported, including use of solar PV panels, wind turbines, biomass energy systems, and anaerobic digestion [210,211]. Best fit systems must be selected based on specific environmental requirements, local technical availability and climate parameters [174,212]. A subset of farms already operating RE technologies are described in Table 9.

*3.4.3.1. Solar PV and thermal technologies.* The RE systems most commonly integrated with poultry production are solar (PV and thermal) - especially in areas with more winter sun. Solar technologies like PV panels generate electricity directly with low energy payback times (3–7.4 years) [129]. Solar thermal energy can also be used in grain drying, manure drying, space heating, and water heating. An appropriate combination of renewable technologies can improve overall outcomes. For instance, a hybrid solar-wind system including solar collector, wind turbine and heat storage tank can effectively help reduce energy use and greenhouse gas emissions [220].

In recent decades, as global PV module production has increased, costs steadily decreased from $25/W in the 1970s to $3.50/W by 2009 [221]. In the US, economic payback time of solar PV was estimated at 2.5–8 years, depending on state rebates, electricity price etc. [221]. In a typical Delaware poultry house, a 1.5 kW PV system is reportedly sufficient to satisfy electricity needs, and will also reduce emissions by 112 tons of $CO_2$, 1.8 tons of $SO_x$, and 0.4 tons of nitrogen oxides in its lifetime [222].

*3.4.3.2. Biomass.* Poultry litter is generally recognized as a low heating (calorific) value (LHV) biomass fuel, due to its high moisture and ash content [223]. Poultry farming operations - especially intensive confined broiler barns - generate a large amount of poultry litter containing a mix of bedding materials (e.g., wood shavings, sawdust and straw), spilled feed and accumulated droppings [224]. Poultry litter after gasification and pyrolysis can be used as biochar to maintain soil fertility and generate energy for heat and power [225]. This RE resource has been utilized as an alternative fuel in the UK, where Fibropower runs a poultry litter-fired power plant in Suffolk [171].

*3.4.3.3. Anaerobic digestion.* Anaerobic digestion is widely used as a treatment method for organic waste such as poultry manure in industrial agriculture systems [226]. The gas produced from anaerobic digestion can be used to generate heat and/or electricity. As such, anaerobic digesters could potentially be integrated into NZE poultry housing systems

**Table 9**
RE technologies applied in poultry housing (N/A: not available).

| Farm name | Climate and location | RE generation technology | Mechanical features and considerations | Advantages or disadvantages | Reference |
|---|---|---|---|---|---|
| Yorkshire Valley Farm | Humid continental climate, Peterborough Ontario, Canada | Photovoltaic | The roof pitch is increased for improving PV performance, and the roof structure is designed to accommodate vertical PV mounting rails and a landscape module orientation | Not Available (NA) | [213] |
| Ledge Farms | Humid continental climate, New York, USA | Wind power | An Endurance E−3120 50 kW wind turbine has been installed. The lattice tower of the turbine is at a height of 140 feet, and the average annual wind speed of this site is 13.85 mph (6.19 m/s). | Potential power generation: over 138,050 kWh/year, covers 100% of electricity needs for 25,000 egg-laying hens and the production of grain for feed and sale | [214] |
| Bayview Poultry Farms Ltd. | Moderate continental climate, Nova Scotia, Canada | Wind turbines | Three on-farm wind turbines | They generate 2.4 kW per hour and supply 75% of the farm's electricity demands. Annual electricity consumption is 110,000 kW to support their 12,000-layer hens | [215] |
| Rondeel Farm | Temperate maritime climate, Netherlands | Future goal: solar PV panels | This system utilizes as much natural light as possible and has no mechanical ventilation system. An insulated sidewall is rolled up and down to control light hours and supply natural airflow. | The day and night quarters allow the birds to perform all their behaviors naturally and safely. Manure dries rapidly on site. | [216] |
| Lakes Free Range Eggs Barn | Temperate maritime climate, UK | Solar power generation with water collection and storage | The photovoltaic cells are used to generate solar power, as well as harvest rainwater for non-food use on the site. All electrical and mechanical systems are automated, and the barn has 300 mm thick insulation on all walls and roofs | The UK's first carbon neutral egg producer | [217] |
| PROAN | Semi-moist, temperate climate, Jalisco, Mexico | N/A | Transforms the organic farm waste into compost and electrical power | Lessen the reliance on natural resources | [218] |
| Brant Colony Net Zero Layer Barn | Continental climate, Brant Hutterite Colony, Alberta, Canada | 1) 100 solar panels on the roof, and 2) heat recovery ventilator (HRV) | Solar PV panels to offset the facility's energy needs and HRV used to preheat the air coming into the barn using energy extracted from outgoing ventilation air | Produce nearly 13,000 eggs a day with no net GHG emissions from the barn system | [219] |

to provide both heat and electricity. However, maintaining appropriate operational conditions is important as high/excessive levels of ammonia or pH may inhibit the reaction processes [227].

*3.4.3.4. Wind turbines.* Wind turbines are potentially attractive for use in NZE poultry housing systems where sufficient wind resources exist because they have low Energy Payback Time (3–8 years) and maintenance costs [228]. Due to the intermittent nature of wind, however, such systems require either independent storage or grid integration in order to ensure consistent electricity supply to poultry barns. Hybrid systems that integrate wind turbines and tunnel fans can enhance the efficiency of both electricity generation and ventilation. For instance, the average air speed of a 46″ fan moving 20,000 cfm is 15 mph. When integrated with a 46″ diameter wind turbine at an air speed of 15 mph, the wind turbine can generate 0.06 kWh electricity to power machinery in poultry housing [229]. However, similar to implementation of HRVs, designers of integrated wind energy/ventilation systems should consider the treatments of exhaust airflow with high dust and moisture content [229].

## 4. Conclusions

The purpose of this review was to identify and synthesize insights from the literature that will be relevant to the design of NZE housing for intensive, confined poultry production, considering the unique features and requirements of poultry production facilities. Based on studies of residential and commercial NZEBs (review question 1), the key strategies for achieving NZE status can generally be grouped into three broad categories: energy use reduction via passive design strategies, operational energy use reduction through use of energy-efficient technology systems; and the implementation of RE generation systems to offset non-RE use.

Review question 2 showed that in conventional poultry housing, electricity and fossil fuels are the most used types of energy. Generally, electricity is used for ventilation, lighting, and sometimes for heating. Fossil fuels such as propane and natural gas are typically used for heating in cold climates. HVAC systems often dominate DE use in poultry housing systems, followed by lighting. These should hence constitute priority considerations in the design of NZE housing for intensive, confined poultry production.

Based on the strategies/technologies used in commercial and residential NZEBs, the energy use profile of poultry housing, and the physical and physiological requirements of intensive poultry production, the following recommendations are being made as priority considerations in the development of Net Zero Energy poultry barns (review question 3).

- Although increasing solar heat gain through optimizing building geometry and glazing is common in commercial/residential applications, priority for NZE poultry barns should be given to improving housing insulation, which can provide significant benefits with respect to reducing heat losses and energy use for heating.
- Despite ventilation's high contribution to energy requirements, natural ventilation should only be used to supplement powered operations in poultry housing due to the issues of air flow control, air quality maintenance, and potential snow/rain ingress associated with natural ventilation.
- Integration of innovative solar thermal technologies like Trombe walls in cool climates and other passive heating/cooling systems such as earth tubes should be considered for poultry barns. Particular focus should be given to sensible Thermal Energy Storage (TES) systems such as those involving phase change materials due to their potential to help maintain stable indoor temperatures in poultry barns.
- Heat pump technology – in particular, ground source heat pumps –offer an energy efficient and cost-effective alternative to conductive, radiant, and convective heaters commonly used in poultry housing.
- Powered operations (mechanical ventilation) are required in intensive, confined poultry production facilities. Hence, irrespective of type of ventilation system used, selection of appropriate equipment (such as fans), proper maintenance, and removal of air leakages should be prioritized to improve energy efficiency.
- In cold climates, the use of heat recovery ventilators (HRVs) can significantly reduce exogenous heating demands by recapturing some of the heat removed through ventilation and hence contribute to achieving NZE status.
- With respect to lighting, LED technology currently provides the most energy-efficient, durable, and environmentally friendly option. Use of natural lighting may also be feasible when integrated with blinds/screens that enable controlling photoperiod - which is important for bird productivity.
- Use of sensor networks that help support real-time monitoring and decision-making for climatic variables is a promising energy efficiency solution to achieve NZE poultry barns. These systems also have the potential to be expanded to enable information flow between multiple buildings to create NZE poultry housing clusters.

Several RE technologies for offsetting electricity and natural gas in NZE poultry housing are available, including solar PV, solar thermal, wind turbines, and other systems. These often require a high capital investment; hence considering both the energy and economic payback time of RE generation systems is important. The suitability of a technology will be conditioned by local climatic factors – in particular, RE resource availability. A variety of energy efficiency and RE innovations have already been implemented on a small subset of poultry farms globally, each of which may potentially contribute to developing NZE barns in different contexts. However, further research is required to determine the scalability and relative efficacy of these innovations. Additional insights from commercial/residential NZEBS – in particular with respect to technology system control, integration and monitoring for energy efficiency objectives – suggest that important research is still required in support of designing functional and efficient NZE poultry housing. We highlight the following challenges that may be particularly salient for future research towards achieving NZE poultry housing.

- Most NZE technology options for poultry housing have been considered in isolation to date. Thus, more research into hybrid technologies may enable achieving better energy-saving outcomes.
- Challenges in technology system integration for poultry housing are non-trivial. For example, the bidirectional connections and two-way information flow between the buildings and smart grids bring new challenges for system optimization, operations, and scheduling. Future research should focus on both the application and system integration of smart control technologies, considering the dynamic variance of ambient temperatures, RH, ventilation rates, etc. that are required to meet the physiological requirements of poultry
- Further research to investigate the appropriate size/scale of efficient systems for heating, ventilation and RE generation in NZE poultry housing is required. Simulation models should be developed for poultry housing designers and engineers to simulate energy use in new design or retrofitting of poultry housing, considering local climatic factors, RE resource availability, and farm-specific production characteristics/requirements.
- Design of NZE poultry housing must consider the heat and moisture produced by poultry as well as air quality requirements, which can vary considerably depending on bird housing density and type of housing system used. Considering different ages and weight of birds, feed inputs, lighting and indoor temperature, moisture and air

velocity, etc. are also critical. This presents challenges not commonly encountered in design of commercial/residential NZEBs.

- Finally, the current study focuses primarily on the design of NZE poultry housing systems. Even though there are considerable differences in physiological requirements among different livestock species, some of the insights presented herein will be transferable to design of NZE housing for pigs, cattle, sheep, etc. However, ensuring species-specific physiological and production requirements are met will likely require additional considerations not addressed in the current review in order to design NZE housing for other livestock species.
- While the technological rationale for the recommendations is clear, it is important for future research to thoroughly analyze the environmental and other sustainability implications associated with these technologies and strategies using systems-based, multi criteria frameworks such as Life Cycle Assessment and Life Cycle Costing.

## Credit author statement

**Yang Li:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft; **Vivek Arulnathan:** Formal analysis, Writing – review & editing; **Mohammad Davoud Heidari:** Conceptualization, Writing – review & editing, Supervision; **Nathan Pelletier:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of competing interest

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

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