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Net zero energy barns for industrial egg production: An effective sustainable intensification strategy?

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ABSTRACT

Net zero energy buildings (NZEBs) are energy efficient buildings that incorporate renewable energy generation systems so as to produce sufficient renewable energy to at least offset the total amount of non-renewable energy used by the building on an annual basis. NZEB technologies have widespread commercial and residential application, but their feasibility and efficacy in the livestock sector in support of sustainable intensification have received little attention. This study quantifies the potential for such technologies to improve sustainability outcomes in the livestock sector based on an ISO 14044-compliant life cycle assessment of a pilot net zero energy laying hen facility in Alberta, Canada compared to a conventional facility. It was found that direct energy inputs account for 6.47% and 31.64% of the life cycle cumulative energy use of egg production in NZE and non-NZE hen housing, respectively. Average infrastructure-related contributions to the life cycle impacts of egg production are only 4.34% and 1.94% for the NZE and non-NZE barns, but NZE technologies reduce the net impacts of egg production by 0.89–64.82%. The environmental impact payback time for the NZE barn (30-year lifespan) ranges from 1.38 to 20.66 years, considering the largely fossil fuel-based electricity grid in Alberta, which indicates that non-trivial environmental benefits would accrue across impact categories considered. However, this could vary considerably elsewhere depending on the types and amounts of green energy utilized in regional grid mixes. The type and availability of renewable energy resources that are integrated into NZE barns will similarly be important in determining the potential of such technologies to support sustainable intensification in this sector.

1. Introduction

Eggs make a significant and growing contribution to global diets (Windhorst, 2014). As in other food sectors, which together account for a non-trivial share of anthropogenic resource use and environmental impacts, the industrial egg industry is facing increasing expectations from stakeholders with respect to sustainably intensifying production (i.e. using fewer resources and creating lower impacts per unit of food produced) (Pelletier, 2018). In light of the complex and interconnected nature of the industrial supply chains that enable agricultural production, life cycle thinking and derivative analytical frameworks like life cycle assessment (LCA) (ISO, 2006) are increasingly applied to understand sustainability impacts and opportunities, and to support sustainability initiatives in the agri-food sector, including in egg production. This approach is desirable both to enable identifying key opportunities to improve outcomes at a systems level as well as to ensure identification of potential trade-offs – whether between supply chain activities or different aspects of resource efficiency and environmental performance.

LCA studies of egg production systems, which provide distinct benefits over single criterion studies such as carbon footprint studies, have helped to map the magnitude and distribution of diverse impacts associated with egg supply chain activities, including those associated with feed production, pullet and layer facilities, manure management, transportation and retailing (Pelletier et al., 2013; Xin et al., 2011a,b; Ghasempour and Ahmadi, 2016). Such studies generally agree that the production of feed inputs accounts for the largest share of life cycle impacts attributable to egg products. Some studies have, however, also suggested that direct energy inputs to housing operations may account for up to 50% of total non-renewable energy use along egg supply chains (Bengtsson and Seddon, 2013). In addition, none of the LCA studies reported to date considers the life cycle burdens associated with

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Abbreviations

NZE	Net zero energy
LCA	life cycle assessment
NZEBs	Net zero energy buildings
GHG	Greenhouse gas
HRV	Heat recovery ventilator
eIPBT	Environmental impact payback time
LCI	Life cycle inventory
PV	Photovoltaic
LCIA	Life Cycle Impact Assessment
IPCC	Intergovernmental Panel on Climate Change
ADP	Abiotic depletion potential
GWP100	Global warming potential
TETP100	Terrestrial ecotoxicity potential
FAETP100	Freshwater aquatic ecotoxicity potential
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical ozone creation potential

construction, maintenance, and eventual decommissioning of the buildings in which intensively reared poultry are housed.

Net zero energy buildings (NZEBs) are energy efficient buildings that incorporate renewable energy generation systems so as to produce sufficient renewable energy to at least offset the total amount of non-renewable energy used by the building on an annual basis (Marszal et al., 2011; Wells et al., 2018; Attia, 2018). Similarly, net zero carbon buildings refer to buildings with net zero carbon emissions annually. These buildings are carbon-neutral, as the CO_2 produced by non-renewable energy use is offset by the same amount of CO_2 that is saved by generating renewable energy (Liu et al., 2019a,b). (Liu et al., 2019a,b) review definitions of NZEBs and technologies to achieve net zero energy status.

The primary design strategies for NZEBs can be generally grouped into three categories: structural and siting considerations that reduce energy use (e.g., passive design); energy efficient technology systems within the building (e.g., energy-efficient lighting, heating and ventilation, and appliances, including energy management systems); and on-site renewable energy installations (e.g., solar electric/thermal, wind, or geothermal systems) (Silva et al., 2016). Solar photovoltaic (PV)/thermal systems are most commonly utilized in NZEBs compared to other renewable energy systems like wind turbines or ground source heat pumps (Gorgolis and Karamanis, 2016).

LCA has been widely used to assess the environmental benefits and trade-offs associated with residential and commercial NZEBs, considering material production, construction, operation and end of life stages. In a conventional building, most direct energy is used in the operational phase, such as electricity and natural gas used for heating/cooling and lighting (Sharma et al., 2011). Embodied energy, the energy utilized during all of the processes associated with the manufacturing, transportation, construction, and end-of life of materials, typically accounts for a small fraction (10%–38%) of a building's total life cycle energy consumption (Cellura et al., 2014; Scheuer, Keoleian, and Reppe, 2003). In contrast, direct energy use in NZEBs is typically much lower, and also offset by renewable energy generation (Ramesh et al., 2010). Compared to traditional buildings, the embodied energy use of NZEBs may be higher due to the highly insulated building envelope and renewable energy generation systems incorporated in the building (Deng et al., 2014).

Despite their widespread application in the commercial and residential sectors, little attention has been paid to date to the feasibility and mitigation potential of NZEB technologies in the intensive animal agriculture sector which is, itself, a significant source of anthropogenic resource and environmental pressures. It is also unclear whether insights from research of commercial/residential NZEBs are transferable for design of NZE livestock housing, which must accommodate unique features of confined animal production such as high ventilation requirements to remove ammonia and maintain air quality, as well as systems for feed delivery, manure removal, etc. However, a net zero energy (NZE) egg barn pilot project is currently underway in Alberta, Canada, with the aim of trialing technologies for reducing energy consumption and greenhouse gas (GHG) emissions in this sector. The facility comprises a single-story free-run barn with a well-insulated building envelop. A 25-kW solar PV array has been installed to offset electricity use in the layer barn, and a heat recovery ventilator (HRV) is used to recover heat from exhaust air during winter months. The barn houses roughly 13,540 hens and produces approximately 370,685 dozen eggs per year.

The aim of the current study was to characterize and evaluate the environmental profile (life cycle resource use and emissions) of this NZE poultry housing system compared to a reference (non NZE facility) scenario using ISO 14044 compliant life cycle inventory modelling and assessment. Specifically, the study aims to: (1) understand the comparative life cycle impacts of the NZE compared to non-NZE building infrastructure; (2) compare the direct energy requirements for housing laying hens in NZE compared to non-NZE buildings; and (3) assess the extent to which utilizing NZE housing may influence the overall life cycle environmental impacts of egg production. The study also (4) calculates environmental impact payback time (eIPBT) for the NZE facility in Alberta compared to a hypothetical situation where the facility is located in other Canadian provinces so as to assess the relevance of regional electricity grid mix in determining the mitigation potential of such facilities, and (5) evaluates the relevance of renewable energy source. This study is intended to support farmer decision making with respect to infrastructure investments for sustainability objectives, as well as the development of policy recommendations regarding using net zero energy (NZE) building technologies to support sustainable intensification in livestock production.

2. Methodology: environmental life cycle assessment

The conceptual framework for the analysis is presented in Fig. 1, which provides a visual representation of the key methodological steps for those unfamiliar with life cycle assessment. The methodology used in this study, along with the report format, follows the ISO 14044:2006 standard (the international reference method for life cycle assessment) and is structured according to the four phases of the LCA framework, i.e. goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment and interpretation (ISO, 2006), as required to comply with ISO 14044.

2.1. Goal and scope

The primary objective of this study was to quantify and compare the resource and environmental life cycle impacts of a pilot NZE egg production facility located in Alberta, Canada to that of a hypothetical, parallel conventional (i.e. in line with current industry standards) non-NZE egg production facility using ISO 14044-compliant attributional LCA. The study aims to understand the potential opportunities and constraints associated with NZE technologies to support sustainable intensification of the egg industry. The results will be used to educate farmers regarding the potential for NZE technologies to improve resource efficiencies and reduce environmental impacts in livestock production, as well as inform potential policies regarding implementation of NZE egg barns.

2.1.1. System boundary

The baseline life cycle inventory (LCI) model for Canadian egg production is reported in (Pelletier, 2017). This LCI model includes all

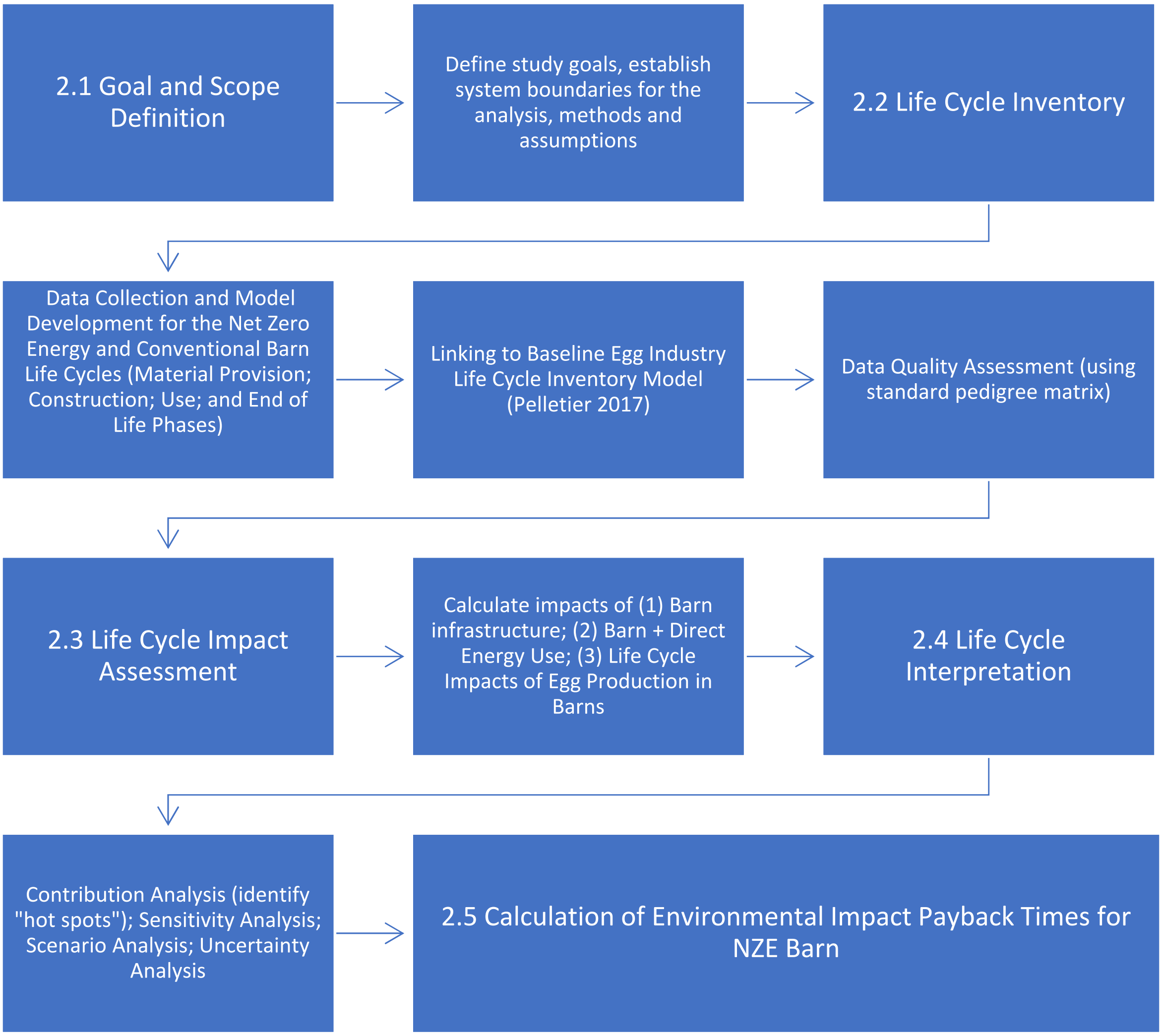

Fig. 1. Study methodology conceptual framework.

major stages of the Canadian egg supply chain (i.e. breeder flock, hatchery, pullet, and layer facilities) and associated material (e.g., feed and water) and energy inputs and emissions but does not include the barn infrastructure. The current study expands the system boundary of (Pelletier, 2017) to include the cradle-to-grave life cycle stages of the NZE free run egg barn and the hypothetical conventional free run egg barn constructed according to current industry standards. Energy use for operation of the NZE barn, including renewable energy generation and consumption, is based on 12 months of facility data from Brant Colony for the year 2017. The direct energy inputs, including natural gas and electricity, for the non-NZE barn are based on the average of two conventional free run facilities in Alberta (3D Energy and Engineering, 2018).

According to EN 15804:2012 + A1:2013, a standard LCA of a building includes the following stages: A1-3, material production stage; A4-5, construction process stage; B1-7, use stage (building operation and maintenance); and C1-4, end-of-life stage (EU Standard 2013). On this basis, the system boundary for the barn models in the current study includes the input and output flows related to each of these life cycle stages (for a detailed description of inclusions and exclusions for each element of A1-3, A4-5, B1-7 and C1-4, see Table S1 in the SI file):

2.1.2. *Functional unit and reference flow*

The functional unit is defined as one tonne of eggs produced at the farm gate.

2.1.3. *Allocation procedures*

Allocation was not required in the foreground system models for this study. Gross energy was utilized for allocation in the baseline Canadian egg supply chain model (Pelletier, 2017).

2.1.4. *Cut-offs and exclusions*

Solar PV panels are assumed to be replaced after their projected 25 years of serviceable use. Other materials and energy potentially used for modernization, expansion, reconstruction, or other similarly fundamental improvements, which change the current characteristics of the building, are excluded because they are not anticipated (Junnila et al., 2006). The embodied energy of equipment used for constructing the housing (such as hammers, for example) and direct energy use during the construction phase are excluded as well.

2.2. *Life cycle inventory of the NZE and conventional non-NZE layer barns*

2.2.1. *Flow diagram*

All upstream, core and downstream processes of the building's life cycle are considered. The flow diagram for the modelled housing systems is shown in Fig. 2.

2.2.2. *Data sources, collection, and life cycle inventory modelling*

The egg barn is located near Brant in south-west Alberta, Canada.

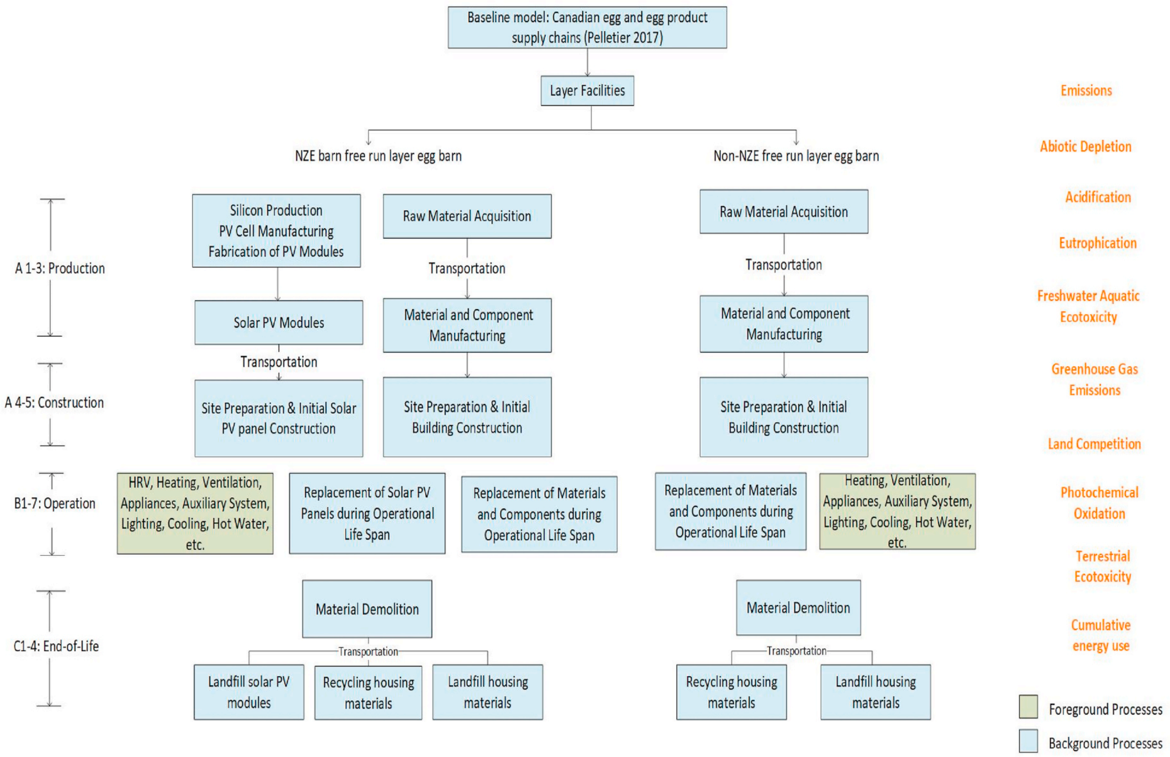

Fig. 2. Flow diagram of the cradle-to-farm gate life cycle assessment of the layer barns.

The Heating Degree Days (HDD) is 4993 based on historical climate data in this region from 1983 to 2020. Figs. 3–4 shows the photo and floor plan of the egg barn. The Brant Colony facility has a total of 3459 m^2 of area, which includes a single-story free run 1253 m^2 layer barn and 1594 m^2 pullet barn. The layer barn houses roughly 13,540 hens and produces approximately 370,685 dozen eggs (equal to 217.96 tonnes of eggs) per year. Common areas including an egg sorting room, mechanical and storage rooms, and an egg cooler are also situated in the building. A south facing 25 kW grid-connected solar PV array is mounted on the roof, producing around 24,815 kWh per year, which offsets electricity consumed in the layer barn. In addition, the barn has an HRV.

The non-NZE barn is a hypothetical conventional barn with the same dimensions and types of construction materials as the NZE barn, but with reduced insulation levels corresponding to the National Energy Code of Canada for Buildings 2011 and Canadian Farm Buildings Handbook, 1988 (Canadian Commission on Building and Fire Codes; National Research Council of Canada, 2017). In addition, the HRV and solar PV systems are not included in the non-NZE barn model. The basic characteristics of the NZE and non-NZE barns are summarized in Table 1.

The openLCA 1.7 software package (one of the three leading LCA software platforms, all of which have broadly similar functionality) was used to model the life cycle inventory and assess the life cycle environmental impacts. Background system models were sourced from the Ecoinvent v3.4 database, which is the largest and most comprehensive available database. The quantities of raw materials used in the production and construction phases of the housing systems were calculated with the MMG+_KULeuven tool. This tool, which is comparable in functionality to similar tools, was developed by the Architectural Engineering research division at KU Leuven, Belgium for LCA studies of

Fig. 3. 2 Photo of the studied net zero energy poultry housing.

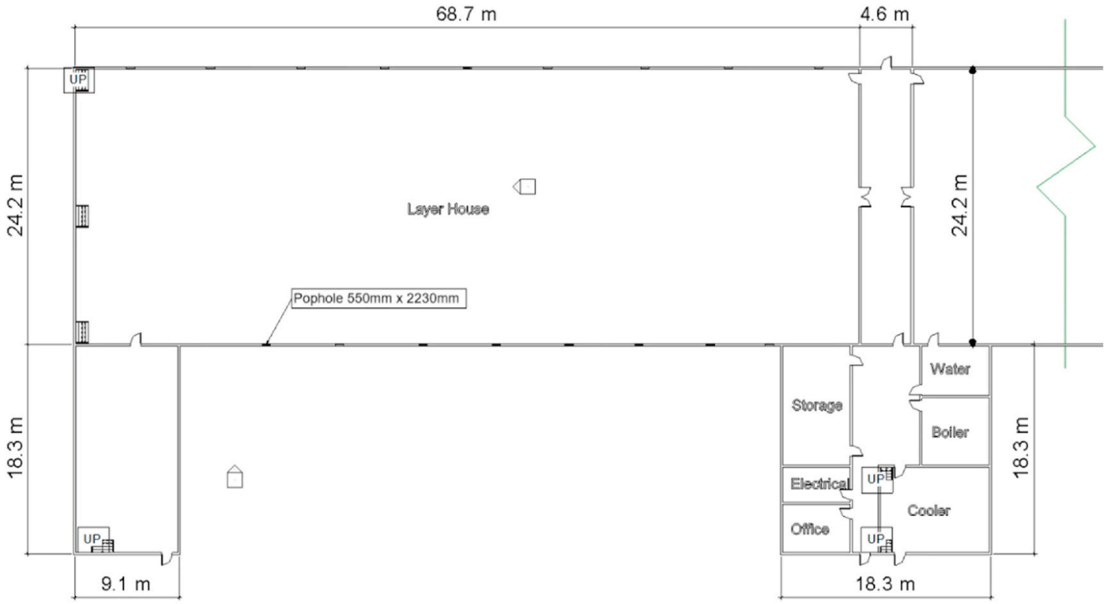

Fig. 4. Floor plan of the net zero energy barn.

Table 1
Characteristics of the NZE and conventional free run layer barns.

Housing types	Basic characteristics	R value of housing components
		Unit (m^{2}k/w)
NZE Barn	1487.26 m^2 rectangular barn with a gabled roof pitched east and west, high insulation level, heat recovery ventilator and a 25 kW solar PV array	Walls: 155.1 Cooler walls: 345.8 Roof: 285.1 Floor: 13.6 Doors: 85.2
Non-NZE Barn	1487.26 m^2 rectangular egg barn with a gabled roof pitched east and west, insulation level in line with National Energy Code of Canada for Buildings 2011	Walls: 153.3 Cooler walls: 141.9 Roof: 187.4 Floor: 13.6 Doors: 85.2

Table 2
Life cycle total material mass for NZE/conventional free run egg barns per tonne of eggs produced.

Material types	Material	Quantity		Unit
		NZE free run egg barn	Convectional free run egg barn	
Building material	Tin metal siding	0.38	0.38	kg
	Softwood plywood	0.58	0.58	m^3
	Stone wool insulation	3.07	2.16	kg
	Wood hardwood framing	0.001	0.001	m^3
	Wood softwood framing	0.008	0.008	m^3
	Screw	0.005	0.005	kg
	Vapor barrier-Polyethylene	0.11	0.11	kg
	HDPE sheathing	0.70	0.70	kg
	Polyurethane panels insulation	0.28	0.11	kg
	Reinforcement bar	2.39	2.39	kg
	Concrete foundation	0.03	0.03	m^3
	Rigid polystyrene insulation	0.32	0.32	kg
	Polypropylene vapor barrier	0.03	0.03	kg
	Polystyrene core insulated metal double door	0.0001	0.0001	item
Renewable energy generation systems	25 kW Solar PV modules	0.001	0	item
Recycling waste materials	Metal	2.78	2.78	kg
	Concrete	0.03	0.03	m^3
	Wood	0.29	0.29	m^3
Landfill waste materials	Waste concrete	0.001	0.001	m^3
	Wood waste	0.29	0.29	m^3
	Polyethylene waste	0.78	0.78	kg
	Waste polypropylene	0.073	0.073	kg
	Waste polystyrene	0.37	0.37	kg
	Waste polyurethane foam	0.29	0.11	kg
	Limestone waste	3.07	2.16	kg

buildings, in line with the Belgian LCA method for buildings (Allacker et al., 2013). The tool includes an extensive database.

Information about the construction of the NZE barn was collected from as-built drawings and relevant engineering design documents provided by the architectural designers, Brant Colony egg farmers, and other project experts (Feng et al., 2019). Additional, detailed information was collected during an on-site visit. Building material types and amounts are described in Table 2.

The Fortica system installed at the Brant Colony NZE pilot project enabled continuous real-time data collection for indoor climate, ventilation conditions, feed delivery conditions, water supply, egg flows and animal weights. Data collected from the Fortica system over a twelve-month interval (2017) were used. Data for farm-level exogenous energy inputs (electricity and natural gas use) were derived from farm utility bills. Data regarding electricity generation from the solar PV system and the efficiency of mechanical systems (such as the HRV) were also collected from the facility operators.

All electricity used in the non NZE barn model is sourced directly from the provincial electricity grid. Operational phase direct energy inputs (electricity use and natural gas) were based on an average of direct energy use for two conventional, free run barns in Alberta per tonne of eggs produced (3D Energy and Engineering, 2018). The heat recovery efficiency of the layer barn unit is estimated to be 50%, based on monitoring equipment on-site. The efficiencies of the natural gas boilers range from 92% to 97%. Brant Colony conducted an energy assessment in 2017, and this report is the main data resource utilized in the current study. Based on this report, space heating is the largest consumer of energy within the building, accounting for 84% of total energy consumed on-site due to the high amounts of fresh air being ventilated through the building to maintain air quality. The second largest energy is the ventilation fans, at 12%, followed by the lighting, motors & pumps at 2%. The end-of-life strategies for the conventional barn are assumed to be like those of the NZE barn but adjusted to reflect differences in materials used.

The detailed life cycle inventory table, including any third party LCI database processes utilized, for the NZE and non-NZE barns are shown in Table S2. Table 2 summarizes and expresses the material quantities required for the NZE and conventional non-NZE barns per tonne of eggs produced.

2.2.3. Data quality assessment

Data quality criteria and scoring levels based on the standard pedigree matrix available in Open LCA 1.7 were used to assign data quality scores for both foreground and background system data. This is currently the only widely utilized method for data quality scoring in LCA. This assessment provides a basis for data improvements and allows to prioritize variables for sensitivity analysis, as well as to support quantitative uncertainty analysis. The full LCI model (with proprietary background LCI model providers disconnected), including all data quality scores, are available as a .zolca file on the Open Science Framework at https://osf.io/6dbj7/.

2.3. Life cycle impact assessment (LCIA)

The openLCA 1.7 software platform was used to complete the LCIA phase. The impact categories considered were abiotic resources, land use, climate change, ecotoxicity, acidification, eutrophication, photochemical oxidant formation, and cumulative energy use based on their materiality for LCAs of NZEBs and livestock production (Roy et al., 2009; Wells et al., 2018; Cellura et al., 2014; Guinee, 2002). All categories were assessed at mid-point level. The assumptions and methodologies for the characterization models, including category indicators and characterization factors are shown in Table 3.

2.4. Interpretation

Interpretation is the final phase of an LCA study in which the results, as well as all the assumptions and methodological choices made are further evaluated with respect to the study goal and scope. The important steps of this phase are the identification of significant elements, the evaluation of the results of preceding phases in terms of completeness, sensitivity and consistency, and the explanation of final conclusions, potential limitations and recommendations (ISO, 2006).

2.4.1. Sensitivity analysis

Sensitivity analyses are used to test the influence of key assumptions on model results. In this study, sensitivity of results to the thickness of materials (HDPE sheathing, plywood, and stone wool insulation), the thickness of the tin used for the roofs and walls, natural gas use, and the assumed service life of the barn buildings are analyzed. These were chosen because they represent either the major housing material elements and reasonably anticipated ranges in material intensity, or other key variables where non-trivial uncertainty may unduly influence the estimated results. Scenario analyses were also used in complement to sensitivity analyses.

2.4.2. Scenario analysis

To compare the feasibility and potential efficacy of an alternative renewable energy generation system, a hypothetical grid-connected wind turbine plant tailored to conditions at Brant, Alberta was modelled instead of the PV system. The model is based on a wind turbine installation at Ledge Farm in Basom, New York, which uses an Endurance E−3120 50 kW wind turbine to provide power to support their 25,000-hen barn. It was hence chosen because it represents a proven technology configuration for an egg barn of comparable size. The lattice

Table 3
Summary of characterization models applied in the LCIA.

Impact Categories		Characterization Model	Category Indicators	Characterization Factor	Unit of Indicator Result	References
Abiotic depletion		Ultimate reserves and extraction rates	Depletion of the ultimate reserve in relation to the annual use	Abiotic depletion potential (ADP) for each extraction of minerals and fossil fuels	kg Sb eq.	Guinee (2002)
Land use		Unweighted aggregation	Land occupation	1 for all types of land use	m^2a	Guinee (2002)
Climate change		Baseline model of 100 years of the Intergovernmental Panel on Climate Change (IPCC)	Infrared radiative forcing (W/m^2)	Global warming potential (GWP_{100}) for each greenhouse gas emission to the air	kg CO_2 eq.	IPCC 2001 (Nakicenovic and Swart, 2000; ISO, 2006)
Ecotoxicity	Freshwater aquatic ecotoxicity	USES 2.0 model of 100 years developed at RIVM, describing fate, exposure and effects of toxic substances, adapted to LCA	Predicted environmental concentration/predicted no-effect concentration	Freshwater aquatic ecotoxicity potential ($FAETP_{100}$) for each emission of a toxic substance to air, water and/or soil	kg 1,4-DB eq.	Guinee (2002)
	Terrestrial ecotoxicity			Terrestrial ecotoxicity potential ($TETP_{100}$) for each emission of a toxic substance to air, water and/or soil		
Acidification		RAINS10 model, developed at IIASA, describing the deposition of acidifying substances, adapted to LCA	Deposition/acidification critical load	Acidification potential (AP) for each acidifying emission to the air	kg SO_2 eq.	(Hauschild et al., 1997; Guinee, 2002; Heijungs et al., 1992)
Eutrophication		The stoichiometric procedure, which identifies the equivalence between N and P for both terrestrial and aquatic systems	Deposition/N/P equivalents in biomass	Eutrophication potential (EP) for each eutrophic emission to air, water and soil	kg PO_4 eq.	(Heijungs et al., 1992; Guinee, 2002)
Photochemical oxidant formation		UNECE trajectory model	Tropospheric ozone formation	Photochemical ozone creation potential (POCP) for each emission of VOC or CO to the air	kg C2H4 eq.	(Derwent et al., 1998; Andersson-Skold et al., 1992)
Cumulative energy use		Life cycle total primary energy use	Cumulative energy demand	1	MJ	(Frischknecht and Jungbluth, 2007; Hellweg et al., 2010)

tower of the turbine is at a height of 42.67 m and the average wind speed of this site is 13.85 mph (6.19 m/s). It is estimated that this wind turbine can produce over 138,050 kWh annually, which meets 100% of the farm electricity needs (Endurance Wind Power) (NYSERDA, 2012).

Detailed parameters for the wind turbine system (LCI model derived from the Ecoinvent v3.4 database) are as follows:

- Average annual wind speed in Alberta is 8.8 mph (3.93 m/s)
- A service life of 20 years is assumed
- Two Aeolos grid-connected 20 kW wind turbines are assumed, producing 36,422 kWh of electricity annually (Aeolos, 2012)
- The annual electricity used in the NZE barn is 24,815 kWh to support 13,540 hens
- The steel tower height is 6.5 m, and the rotor diameter is about 10 m
- The foundation (concrete and reinforcing steel) is assumed to remain in the ground after the demolition of the power plant
- Materials used for fixed parts such as tower and base and their disposal are included, as are processing and transportation of the materials
- The area and energy required for the installation are included
- To model the LCI of the end-of life phases, most quantitative and qualitative data for materials are derived from the Ecoinvent v3.4 database. Main components, i.e. 100% metals and the 20% blades materials, would be recycled. The others would be delivered to waste treatment sites; the estimated transportation distance was 280 km from Brant to a waste sorting site using a freight lorry. Infrastructure, such as building and foundations, would be demolished or decommissioned. Missing materials are assumed and calculated based on alternative wind turbine manufacturing documents (Aeolos, 2012) or other literature sources (Ardente et al., 2008).

$$eIPBT(i) = \frac{TotalEI_{i}ofaNZEsystem[Unitofindicatorresults]}{Annual\ environmental\ benefits\ relative\ to\ a\ non-NZE\ scenario\ \left[Unitofindicator\frac{results}{year}\right]} \tag{2}$$

2.4.3. Uncertainty analysis

Uncertainty comes from data uncertainty (parameter uncertainty), the mathematical models (model uncertainty) and normative choices (scenario uncertainty) (Huijbregts et al., 2003). Scenario uncertainty is accommodated using sensitivity and scenario analyses. Model uncertainty largely relates to the LCIA methods. It hence applies equally to both the NZE and non-NZE models. Data uncertainty (including both data quality-related uncertainty and stochastic uncertainty) and model uncertainty are directly quantified in the current study. A standard LCA pedigree matrix is used to generate data quality-related uncertainty estimates for all data points in the LCI model. These are combined with stochastic uncertainty data in order to produce a characteristic probability distribution for each data point. If the stochastic uncertainty for data points is unavailable, the generic basic sectoral empirical uncertainty parameters are applied for different types of inputs and outputs following (Frischknecht et al., 2005). The latter represents the most utilized source of generic, sector-specific uncertainty parameters for LCA. Monte Carlo simulations (1000 runs) are used to quantify uncertainty for the LCIA results (reported as standard error). This is the most common approach for propagating uncertainty in LCA models, and is supported by the major LCA software platforms, including openLCA. Differences in LCIA results are tested for statistical significance using t-tests in R studio for instances where the data are normally distributed. Otherwise, a Wilcoxon test is used instead. If the P-value is < 0.05, the two compared groups are statistically, significantly different.

2.5. Additional analyses

The concept of 'payback time' is often used in comparative LCA studies of NZEBs. Energy Payback Time (EPBT) is the time required for a renewable energy system to generate as much energy as is consumed during its production and lifetime operation (Berggren et al., 2013; Knapp and Jester, 2001; De Wild-Scholten, 2013). Environmental impact payback time (eIPBT) is another commonly utilized comparative parameter. The eIPBT is the time required for a NZEB to offset the resource/environmental impacts (EI) associated with its life cycle relative to a non-NZE scenario. From the literature, two widely used formulas for calculating eIPBT derived from (Xie et al., 2018a) for formula (1) and (de Simón-Martín et al., 2017) for formula (2) were employed to calculated eIPBT and to demonstrate potential differences resulting from calculation methods.

$$eIPBT(i) = \frac{TotalEI_{i}ofaNZEsystem[Unitofindicatorresults]}{AnnualEI_{i}ofanon-NZEsystem\left[Unitofindicator\frac{results}{year}\right]} \tag{1}$$

In addition, a sensitivity analysis of these two different ways of calculating eIPBT was undertaken using the following formula.

By generating renewable electricity, an NZEB relies less on electricity provided by the local electricity grid and may (depending on the specific grid mix) reduce associated resource use and emissions. An NZEB also relies less on fossil fuels for heating. After the eIPBT has passed, the NZEB housing system has net environmental benefits compared to the non-NZEB building.

In this study, eIPBT was used to estimate the time needed for the NZE free run egg barn to offset its environmental impacts compared to a reference conventional non-NZEB barn. This was first calculated for the Brant Colony NZE barn, then subsequently for a scenario in which the NZE barn was assumed to be located in the different provinces and territories in Canada (each of which has its own independent electricity grid) in which egg farms are currently located. This includes Ontario (ON), Quebec (QC), Nova Scotia (NS), New Brunswick (NB), Manitoba (MB), British Columbia (BC), Prince Edward Island (PE), Saskatchewan (SK), Alberta (AB), Newfoundland and Labrador (NL), and the Northwest Territories (NT). This scenario assumes similar barn energy requirements in all provinces.

3. Results and discussion

3.1. Life cycle impact assessment

The comparative LCIA results for the NZE and non-NZE free run egg barns are presented in three sections respectively considering: 1) infrastructure inputs per tonne of eggs (direct energy inputs for operations excluded); 2) infrastructure plus direct energy use for operations per tonne of eggs; and 3) including all inputs and emissions associated with the cradle-to-farm gate production of one tonne of eggs (i.e. section 2 + all activities related to egg production).

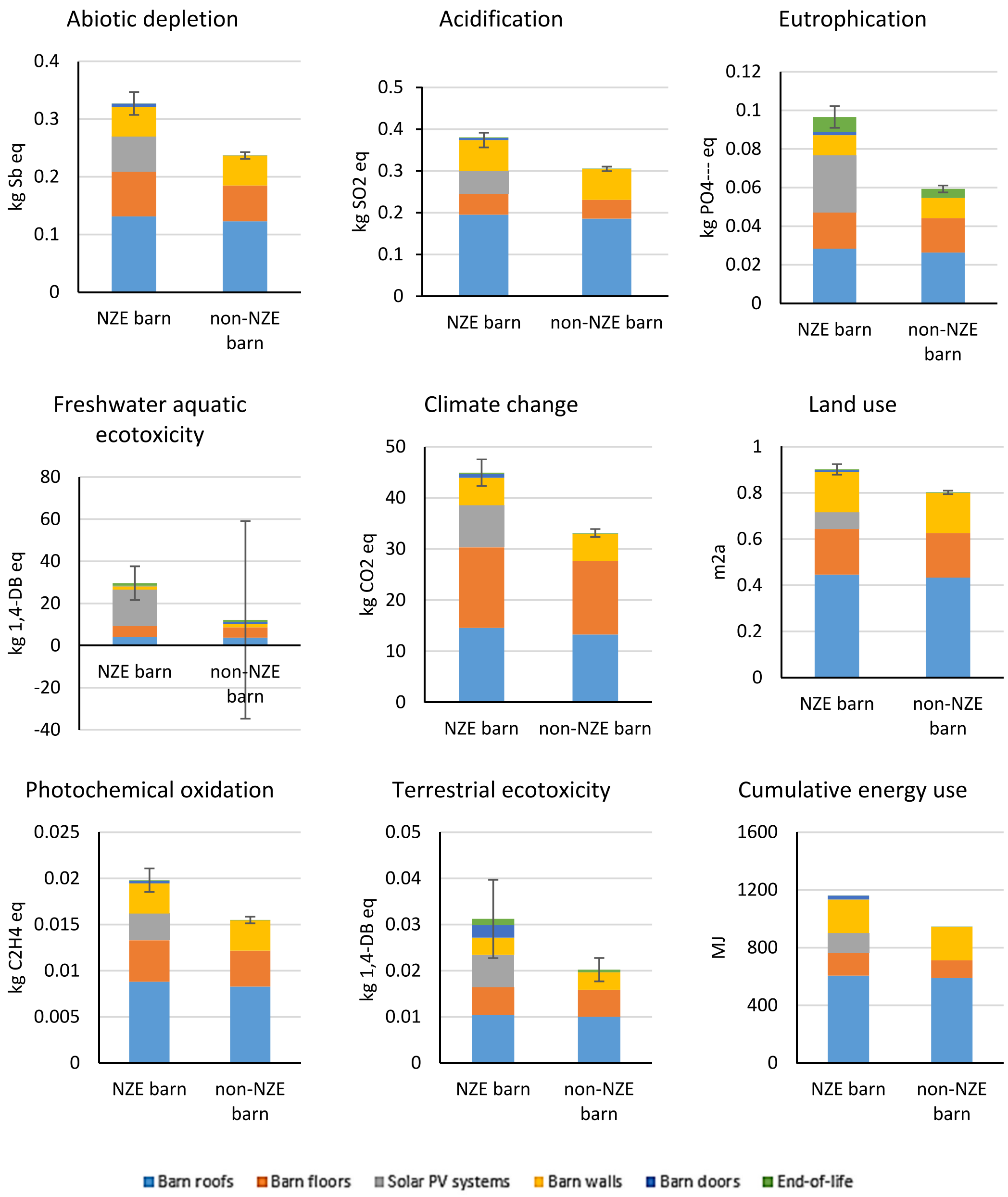

Fig. 5. Comparison of the life cycle environmental impacts attributable to housing infrastructure only per tonne of eggs produced in the NZE compared to non-NZE free run egg barns. Error bars represent standard error. The uncertainty results for cumulative energy use are reported in Table S8.

3.1.1. *Comparative LCIA results for the NZE and conventional free run layer barn infrastructure*

Table S3 and Fig. 5 present the comparative LCIA results for the infrastructure-related burdens of the NZE and non-NZE eggs barns.

Infrastructure-related life cycle impacts of the NZE layer barn are higher than those of the non-NZE barn across all impact categories considered (abiotic depletion (38%), acidification (23%), eutrophication (49%), freshwater aquatic ecotoxicity (157%), climate change (34%), land use (12%), photochemical oxidation (27%), terrestrial ecotoxicity (44%) and cumulative energy use (22%)) (Fig. 5). This is primarily due to the life cycle environmental impacts of the solar PV panel array (in particular, its production) and, to a small degree, the higher amount of materials (e.g. insulation) used in the walls and roof. Producing PV panels is widely recognized as an energy-intensive process, and a large share of them are produced in China, which has a fossil fuel-based electricity grid (Xie et al., 2018b). The embodied energy share of the total cumulative energy use hence increased from 29.07% to 66.79% between the non-NZE and NZE barn infrastructure. These results are consistent with an Italian study that compared embodied energy in a standard residential house to a low energy house, where the comparative share of embodied energy increased from 17% to 50% (Blengini and Di Carlo, 2010). The emissions and associated impacts of NZE poultry housing are higher for the production and construction phases compared to conventional buildings but are lower in the operational phases and at end-of-life. This is in line with the findings of LCA studies of residential and commercial NZEBs (Thiel et al., 2013).

In the NZE system, the floor, roof and solar PV system are the three main drivers of the impacts. As depicted in Fig. 5, freshwater aquatic ecotoxicity impacts per tonne of eggs are 157% higher in the NZE barn, again largely due to the solar PV panels (58.98%), followed by the floors (17.30%), roof (13.93%), walls (5.31%), end-of life activities (3.34%), and doors (1.13%). The solar PV panels are also the major contributor to

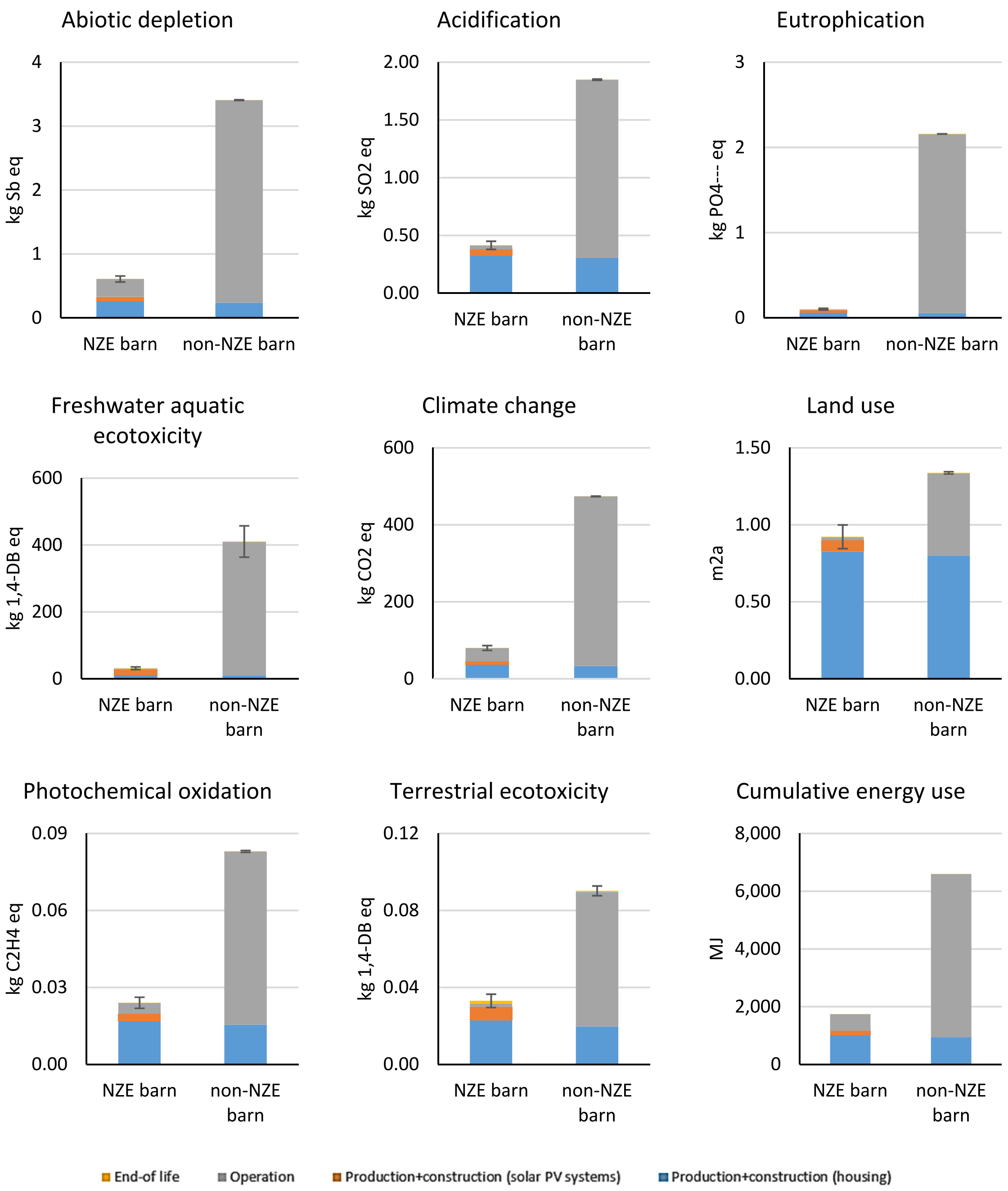

Fig. 6. Comparative LCIA results for the combined infrastructure and operational energy inputs per tonne of eggs produced in the NZE and conventional non-NZE egg barns. Error bars represent standard error. The uncertainty results for cumulative energy use are reported in Table S9.

eutrophication emissions (31.57%). In contrast, roof components (tin, plywood, stone wool insulation, and HPDE sheathing) make the largest contributions to abiotic depletion, acidification, land use, photochemical oxidation, terrestrial ecotoxicity and cumulative energy use. The primary contributors to environmental impacts in the non-NZE barn are the roof and floors, which together account for nearly 75% of impacts. Important materials here are the tin, roofing plywood (accounts for 27.75% of terrestrial ecotoxicity) and concrete floor (accounts for 25.45% of climate change).

3.1.2. *Comparative LCIA results for the infrastructure and direct energy inputs for the NZE and conventional non-NZE free run egg barns*

Table S4 and Fig. 6 present the comparative LCIA results for the infrastructure and direct energy inputs for the NZE and non-NZE egg barns, including production/construction, operation, and end of life stages.

The solar PV system enables offsetting non-renewable, grid electricity use in the NZE barn. In addition, the HRV recovers heat from the exhaust airflow in the winter, and hence reduces natural gas use for heating (the NZE barn uses 40% of the amount of natural gas used in the non-NZE barn). Heating demands are also reduced due to the higher insulation levels in the NZE barn. For these reasons, despite the higher life cycle impacts of the infrastructure, when direct energy use in the barns is also considered, impacts are lower for the NZE barn across all impact categories (Fig. 6). This ranges from a 31.12% difference for land use to a 95.40% for eutrophying emissions.

The production and construction-related impacts for the NZE free run egg barn account for the majority (53.70–97.54%) of the burdens in all impact categories (Fig. 6). Impacts due to operational energy use in the NZE barn range from 2.21% for land use to 46.30% for abiotic depletion. End-of-life activities cause the lowest impact, ranging from 0.00% for cumulative energy use to 4.71% for eutrophication.

For the conventional non-NZE barn, operational energy use accounts for the larger part (ranging from 40.00% for land use to 97.22% for freshwater aquatic ecotoxicity) of the impacts. Only for the land use impact category is the infrastructure component more important. This is due to the higher natural gas and grid electricity demands in the operational phase of the conventional barn. Production and construction of the non-NZE barn account for a small fraction of the impacts. As with the NZE barn, the end-of-life impacts (ranging from 0.01% of abiotic depletion and cumulative energy use to 1.49% of terrestrial ecotoxicity) are of minor importance.

3.1.3. Comparative cradle-to farm gate LCIA results for egg production in the NZE and conventional non-NZE free run egg barns

Table S5 and Fig. 7 report the comparative cradle to farm gate (i.e. including all inputs to egg production) LCIA results for 1 tonne egg production in the NZE and non-NZE barns.

According to the LCA study of Canadian egg production (Pelletier, 2017), the majority of cradle-to-farm gate resource use and associated

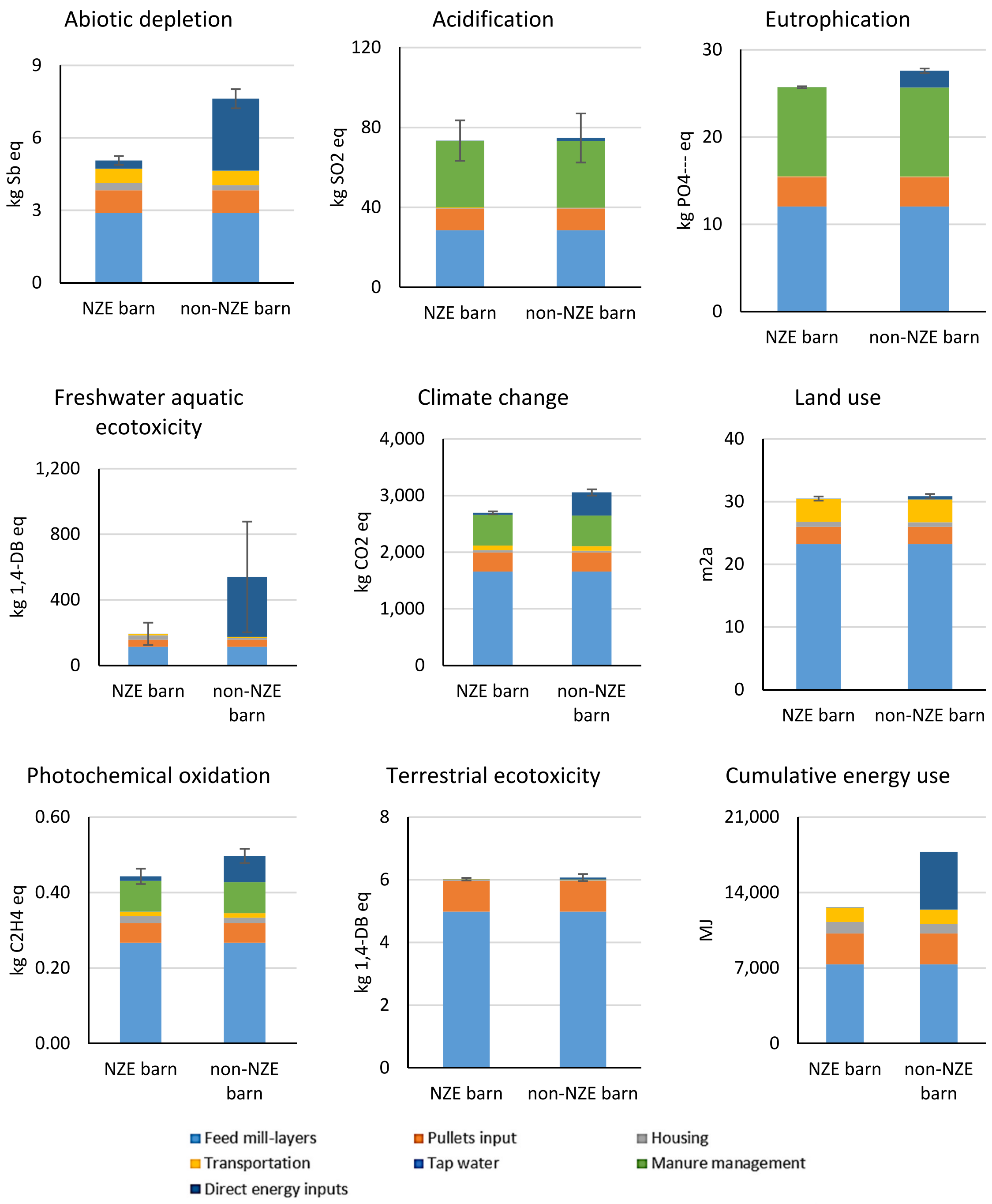

Fig. 7. Comparative cradle-to-farm gate LCIA results for egg production in the NZE and conventional non-NZE free run egg barns (per tonne of eggs). Error bars represent standard error. The uncertainty results for cumulative energy use are reported in Table S10.

emissions in the Canadian egg industry are attributable to feed production (35–81%), manure management (17–46%), and pullets (19–23%). This is consistent with a variety of other studies reporting LCAs of egg production (Ghasempour and Ahmadi, 2016; Xin et al., 2011a,b; Abín et al., 2018). Based on the LCI models of the layer barns developed in the current study, housing infrastructure adds a small amount to total life cycle impacts. Average infrastructure-related impacts across all considered impact categories are around 4.34% and 1.94% for the NZE and non-NZE barns, respectively.

Overall, however, the life cycle environmental impacts of egg production are 0.89–64.82% lower in the NZE compared to the non-NZE barn. Differences are largest for abiotic depletion (35.40%) and freshwater aquatic ecotoxicity (64.82%) because the electricity generated from the renewable generation system in the NZE barn offsets electricity use from the fossil fuel-dominated Alberta electricity grid and also because natural gas use is lower.

Direct heating energy inputs are lower in the NZE barn due to the higher insulation level and use of the HRV. As a result, cumulative energy use in the NZE and non-NZE barns are 12,443 MJ and 16,881 MJ per tonne of eggs, respectively – a difference of 36% - even taking into account the higher embodied energy of the NZE barn infrastructure. The most significant reduction is in cumulative, non-renewable fossil fuel energy use (11,030 MJ), which is 26.29% lower for eggs produced in the NZE barn. It can be concluded that replacing non-renewable energy use in the NZE barn produces substantial net environmental benefits. Technology or management interventions to further reduce natural gas use for heating in the NZE barn may yield additional benefits but should be supported by an LCA.

3.2. *Environmental impact payback time of the NZE barn compared to the non-NZE barn*

The NZE barn offsets 24,815 kWh of grid electricity use per year and uses less natural gas. The estimated service life of the NZE barn is 30 years. Assuming that inputs and available solar resources are otherwise equal, Table S6 reports the environmental impacts (per tonne of eggs) for the NZE and non-NZE barns based on the provincial electricity grid mix in each Canadian province.

Applying formulas (1) and (2), the environmental impact payback time (eIPBT) of the NZE barn in Alberta ranges from 1.38 to 20.66 years for formula (1) and 1.45-66.41 for formula (2), respectively, depending on the impact category considered (Table 4 and Table 5). This means that, if eIPBT is calculated using equation (1), despite its higher life cycle infrastructure burdens, the NZE barn will produce net environmental benefits across all impact categories within its lifetime compared to use of a conventional non-NZE barn. If equation (2) is used, however, the NZE barn will not achieve payback for the Land Use impact category.

Table 4 shows the calculated eIPBTs of the NZE barn in each province following formula (1). Bold font indicates instances where the eIPBT would not be achieved within the anticipated lifespan of the barn. Table 5 reports the calculated eIPBTs of the NZE barn in each province following formula (2). According to formula (1) and (2), except for land use, the shorter eIPBTs generally can be found in provinces with fossil fuel-based electricity generation. They average 8.8–19.89 yr across all impact categories for Saskatchewan and Nova Scotia (largely coal-based electricity), 7.51–7.63 yr for Alberta (largely natural gas-based electricity) and 12.33–17.06 yr for the Northwest Territories (petroleum-based electricity). eIPBTs are consistently less than the life span of the barn with respect to GHG emissions and cumulative energy demand, regardless of province. However, eIPBTs are not favorable in all impact categories in the province of Quebec, which has an almost entirely hydro-based grid. In these cases, use of an NZE barn would generate little or no net environmental benefits. Using formula 2, eIPBT would not be achieved for a greater number of impact categories in provinces with greener electricity grids.

3.3. *Sensitivity analysis*

Data and parameter assumptions are assessed via sensitivity analyses. Specifically, results are recalculated for a 10% increase/decrease of raw material use and natural gas use, and when a 0% recycling rate is assumed for both the building materials and the solar PV system (assumed to be landfilled instead). In addition, the service life of the barn is increased/decreased by 5 years. The sensitivity analysis results are reported in Table 6.

The sensitivity analyses indicate that estimated impacts are most sensitive to the assumed service life of the barn, followed by natural gas use, end-of-life recycling rates and, finally, amounts of tin and stone wool insulation. Results for abiotic depletion, climate change and cumulative energy use are particularly sensitive to natural gas use, especially in the NZE barn as electricity use has already been offset by the solar PV system. By decreasing natural gas use by 10%, abiotic depletion, climate change, and cumulative energy use are reduced by 4.63%, 4.39%, and 3.32% respectively in the NZE barn.

Estimated acidification, land use and photochemical oxidation impacts are sensitive to the amount of tin used, especially in the NZE barn. By decreasing the use of tin by 10%, acidification, land use and photochemical oxidation impacts are reduced by 3.42%, 4.01%, and 2.10%

Table 4
Environmental impact payback time for the NZE barn with solar PV system in different provinces in Canada (**bold** indicates that eIPBT is longer than the 30 y service life of the barn) following formula (1).

Provinces and territories	Primary electricity sources	Abiotic depletion	Acidification	Eutrophication	Freshwater aquatic ecotoxicity	Climate change	Land use	Photochemical oxidation	Terrestrial ecotoxicity	Cumulative energy use
AB	Natural gas and coal	5.36	6.70	1.38	2.29	5.06	20.66	8.67	10.63	7.91
BC	Hydro	14.63	23.09	13.68	9.64	14.67	26.94	22.06	19.45	11.88
NT	Petroleum	9.99	8.37	16.71	11.12	9.37	27.41	10.41	8.03	9.54
SK	Coal and natural gas	6.29	8.16	1.77	2.81	5.97	23.00	10.07	12.52	8.62
MB	Hydro	17.93	27.06	22.94	11.20	17.69	29.07	24.38	25.42	12.78
ON	Uranium and hydro	15.07	24.28	23.89	10.99	15.34	28.85	21.42	22.29	7.22
QC	Hydro	18.76	**30.11**	**35.67**	**44.88**	18.87	**31.19**	26.40	**34.73**	13.04
NB	Uranium, coal and hydro	7.93	7.96	8.31	7.11	8.06	13.87	9.90	14.70	7.49
NF	Hydro	16.94	21.87	26.28	11.73	16.51	29.56	21.35	20.34	12.49
NS	Coal and natural gas	4.73	3.91	3.64	4.19	4.82	7.14	5.57	11.03	6.99
PE	Wind	10.16	10.92	11.19	7.81	10.26	16.12	12.78	16.51	8.87

Table 5
Environmental impact payback time across Canada following formula (2).

Provinces and territories	Primary electricity sources	Abiotic depletion	Acidification	Eutrophication	Freshwater aquatic ecotoxicity	Climate change	Land use	Photochemical oxidation	Terrestrial ecotoxicity	Cumulative energy use
AB	Natural gas and coal	6.53	8.63	1.45	2.48	6.08	66.41	12.19	16.46	10.74
BC	Hydro	28.54	100.25	25.13	14.20	28.72	264.31	83.37	55.33	19.67
NT	Petroleum	14.97	11.61	37.71	17.67	13.62	318.12	15.93	10.96	14.00
SK	Coal and natural gas	7.95	11.21	1.88	3.11	7.45	98.65	15.16	21.49	12.09
MB	Hydro	44.57	275.95	97.43	17.87	43.13	937.38	130.04	166.50	22.28
ON	Uranium and hydro	30.30	127.41	117.39	17.33	31.38	750.77	74.93	86.66	9.51
QC	Hydro	50.04	−8209.81	−188.85	−90.48	50.83	−788.46	219.92	−220.11	23.08
NB	Uranium, coal and hydro	10.79	10.83	11.49	9.32	11.02	25.79	14.78	28.80	9.98
NF	Hydro	38.92	80.71	212.14	19.26	36.73	2020.21	74.02	63.16	21.40
NS	Coal and natural gas	5.62	4.49	4.14	4.87	5.74	9.37	6.83	17.46	9.11
PE	Wind	15.35	17.16	17.85	10.56	15.58	34.85	22.25	36.70	12.59

Table 6
Sensitivity analysis of process parameters on the LCIA results for egg production in the NZE free run egg barn (**bold font** indicates the most sensitive parameters).

Impact category	Unit	Process parameter	Tin (±10%)	*Stone wool insulation (± 10%)*	Natural gas use (±10%)	Service life barn (±5 yr)	End-of-life (all landfill)
Abiotic depletion	kg Sb eq.	NZE barn	±0.86%	±0.39%	**±4.63%**	±7.72%	+0.02%
		non-NZE barn	±0.15%	±0.04%	**±2.11%**	**±15.51%**	+0.01%
Acidification	kg SO_2 eq.	NZE barn	**±3.42%**	±0.65%	±0.82%	±1.37%	+0.16%
		non-NZE barn	±0.76%	±0.09%	±0.47%	±13.91%	+0.08%
Eutrophication	kg PO_4-eq.	NZE barn	±1.57%	±0.56%	±0.63%	±1.04%	**+4.71%**
		non-NZE barn	±0.07%	±0.02%	±0.07%	**±16.18%**	+0.37%
Freshwater aquatic ecotoxicity	kg 1,4-DB eq.	NZE barn	±0.69%	±0.30%	±0.62%	1.03%	**+3.14%**
		non-NZE barn	±0.05%	±0.01%	±0.12%	±16.20%	+0.30%
Climate change	kg CO_2 eq.	NZE barn	±0.74%	±0.45%	**±4.39%**	±7.32%	+0.17%
		non-NZE barn	±0.12%	±0.05%	±1.88%	**±15.50%**	+0.05%
Land use	m^2a	NZE barn	**±4.01%**	±0.39%	±0.22%	±0.37%	+0.25%
		non-NZE barn	**±2.77%**	±0.18%	±0.39%	±6.67%	+0.22%
Photochemical oxidation	kg C_2H_4 eq.	NZE barn	±2.10%	±0.62%	±1.76%	±2.93%	+0.15%
		non-NZE barn	±0.61%	±0.11%	±1.29%	**±13.55%**	+0.09%
Terrestrial ecotoxicity	kg 1,4-DB eq.	NZE barn	±0.54%	±0.35%	±0.56%	±0.94%	+1.74%
		non-NZE barn	±0.19%	±0.08%	±0.51%	**±12.82%**	+1.50%
Cumulative energy use	MJ	NZE barn	±0.53%	±0.28%	**±3.32%**	±5.54%	+0.02%
		non-NZE barn	±0.14%	±0.05%	**±2.23%**	**±14.28%**	+0.01%

respectively. Estimated eutrophication, freshwater aquatic ecotoxicity, and terrestrial ecotoxicity impacts are sensitive to the recycling rates at end-of life. Impacts are not sensitive to the life cycle material implications of stone wool insulation usage (although this will clearly have an important influence on natural gas usage). It can be concluded that improving insulation is a win-win strategy.

3.4. Environmental impacts of the NZE barn using PV panels versus wind turbines

Table S7 and Fig. 8 report the comparative LCIA results for the three systems (conventional barn, NZE barn with PV panels and a scenario in which the NZE barn has wind turbines instead of PV). As depicted in Fig. 8, environmental impacts for egg production in the NZE barn with wind turbines are 3.71–12.87% lower than in the NZE barn with a PV system, except for land use and freshwater aquatic ecotoxicity. It can be concluded that, where sufficient wind resources are available, NZE barns with wind turbines are environmentally preferable to NZE barns with a PV system. The optimal selection of renewable energy generation system should, however, consider barn location, climate factors (such as solar and wind resource availability), and other financial factors, such as local electricity costs and farmers' budget.

3.5. Uncertainty analysis

A Monte Carlo simulation with 1000 runs was conducted using openLCA software in order to quantify the result uncertainty (Tables S8–S11). Many values were not significantly different, largely due to model (i.e. LCIA characterization factor) rather than data uncertainty - in particular, for toxicity category results. Estimated LCIA results for the NZE barn infrastructure were most uncertain for freshwater aquatic ecotoxicity (mean = 56.36, SD = 253.29), followed by terrestrial ecotoxicity (mean = 0.03, SD = 0.27) and eutrophication (mean = 0.12, SD = 0.18). In the non-NZE barn, freshwater aquatic ecotoxicity results were most uncertain (mean = 88.29, SD = 148.31), followed by terrestrial ecotoxicity (mean = 0.03, SD = 0.08). When direct energy inputs are included, the highest uncertainty was for freshwater aquatic ecotoxicity in the NZE barn (mean = 81.89, SD = 126.56) and for terrestrial ecotoxicity in the non-NZE barn (mean = 0.03, SD = 0.08). Per tonne of eggs produced, the LCIA results were most uncertain for freshwater aquatic ecotoxicity in both the NZE barn (mean = 577.24, SD = 2138.70) and non-NZE barn (mean = 459.71, SD = 10672). The high degree of uncertainty for ecotoxicity category results is largely related to uncertainty associated with the LCIA characterization models (Huijbregts et al., 2003). In addition, due to the combined uncertainty from background data and foreground data in the baseline

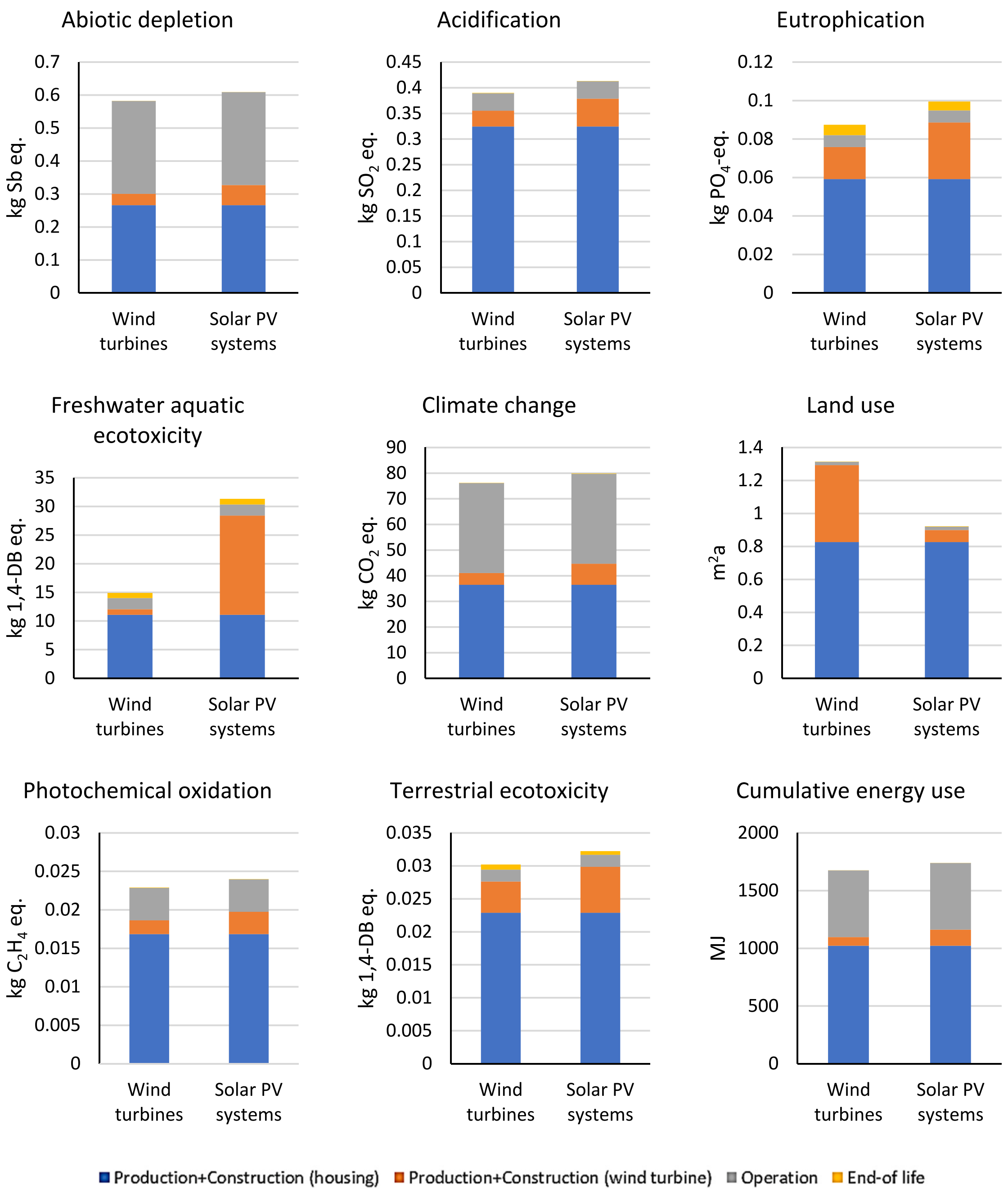

Fig. 8. Comparative LCIA results for egg production in 3 barn types (conventional barn, NZE barn with a PV system, NZE barn with a wind turbine system).

Canadian egg supply chain model and that of the solar PV system, the cradle-to-farm gate results for acidification, land competition, and photochemical oxidation were not significantly different for both the non-NZE and NZE barns. The data quality of these processes could be improved by updating the foreground LCI datasets with recently collected information, as well as the development of Canadian-specific life cycle inventory data for background system data sets. The significant differences between the means of two compared groups can be found in Table S11. "* mark" indicates that the differences between the compared groups are statistically significant. Estimated abiotic depletion, eutrophication and climate change impacts are statistically, significantly different in all three comparisons.

3.6. The mitigation potential of applying NZE technologies in poultry housing

The most environmentally relevant materials used in the poultry housing infrastructure are tin, plywood, and stone wool insulation in the roof and walls. The additional insulation used in the NZE barn led to only a small increment in infrastructure-related impacts. It did, however, contribute to substantially reducing the use of natural gas for heating the NZE barn, hence making a critical contribution to achieving NZE status. Indeed, the importance of an adequate thermal envelop is widely recognized in literature addressing residential and commercial NZEBs (Rodriguez-Ubinas et al., 2014). The current study confirms the relevance of this insight for poultry housing. Insulation beyond required levels, however, provides diminishing returns, and hence cannot be considered a stand-alone strategy.

Ventilation is also a key contributor to heating losses in layer barns (Baxevanou et al., 2014), as well as direct energy use for the operation of fans. Optimal design of integrated natural and mechanical ventilation is therefore important for designing NZE poultry housing. While HRVs are often used in commercial/residential NZEB applications (Liang et al., 2011), they are likely of even greater importance in NZE livestock housing systems. This is due to the need for large and continuous air flows to maintain air quality related to potentially high dust, moisture and ammonia levels in poultry houses (Cordeau and Barrington, 2010).

Despite increasing infrastructure-related impacts, the results of this study indicate that NZE housing for intensive, confined poultry production can nonetheless generate non-trivial benefits due to the overall reduction in direct energy use, and hence support sustainable intensification in this sector. This finding is generally consistent with research of commercial and residential NZEBs (Kannan et al., 2006). Nonetheless, a cautionary note regarding the importance of considering context instead of accepting generalizations with respect to the potential environmental benefits of NZE poultry housing is clearly warranted. The scenario analysis undertaken in the current study indicates that the environmental impact payback time of NZE poultry housing with PV systems will generally be shorter than the anticipated service life of 30 years of the barn in regions where fossil fuels dominate the electricity grid mix. This implies that the installation of the NZE infrastructure will provide net environmental benefits over time. However, this may not be the case for all impact categories in regions with “greener” electricity grids.

Interestingly, the eIPBT calculation suggested that the NZE barn with a PV system produced benefits even in a province with a primarily wind energy-based electricity grid (e.g. PEI). The reason could be that the impacts of electricity from grids largely provided by wind power can be higher than that of hydro-based or PV energy generation systems in some cases if there is a non-trivial share of fossil fuel generation in the grid mix to make up for the intermittent power (Wang et al., 2019; Varun and Prakash, 2009). This also likely reflects the environmental benefits of the NZE housing system that are conferred by having higher insulation levels and an HRV (Liang et al., 2011) to preheat inlet air (Cui et al., 2019), which reduces natural gas demands. Most often natural gas is used for heating in poultry housing (Alberta AgricultureForestry, 2006). Very efficient heating systems (Caslin, 2017) may also be an effective measure to reduce natural gas use – in particular, the use of ground-source geothermal systems for both heating and cooling poultry barns merits consideration.

3.7. Limitations

It should be noted that the scenario comparing inter-province eIPBTs considered in this study assumes *ceteris parabis*, and is hence overly simplistic. In reality, direct energy input levels will be influenced by climatic factors, which will vary province by province. In addition, while PV may present the best renewable energy system for an NZE barn in Alberta, availability of solar and other renewable energy resources varies within and between provinces. In some cases, other renewable energy systems (for example, wind turbines) may be more suitable for integration into NZE housing systems and provide greater environmental benefits. The optimal selection of a renewable energy generation system should consider barn locations (such as mountains or lowland) and local climates (such as wind speeds). For instance, a minimum 9 mph of annual wind speed is ideal for small-scale wind electric turbines, while 13 mph average wind speed is required for utility-scale wind power plants (Hasan et al., 2011).

In addition, environmental LCA does not enable consideration of other important sustainability issues such as economic feasibility and potential social benefits and impacts. In order to make appropriate recommendations for both egg farmers and policymakers about the feasibility and potential of applying NZE technologies in livestock production, these hence represent important areas for further research. This study suggests that NZE poultry housing may potentially represent an effective sustainable intensification strategy for the Canadian egg industry in many provinces and for many kinds of resource/environmental impacts, but careful attention to context is clearly necessary in order to provide nuanced decision support for egg farmers across the country.

4. Conclusions

Direct and embodied energy inputs contribute a substantial share of the resource and environmental burdens of industrial livestock production. The results of this LCA of NZE and non-NZE layer barns showed that housing infrastructure adds a small amount to total life cycle impacts of egg production. Average infrastructure-related impacts across all considered impact categories are around 4.34% and 1.94% for the NZE and non-NZE barns, respectively. The marginal impacts of the NZE barn infrastructure are, however, generally small relative to the gains associated with reduced direct energy use for heating. For this reason, the installation of NZE infrastructure for poultry housing will provide net environmental benefits over time – with the most rapid environmental impact paybacks achieved in areas with fossil fuel-based electricity grids. In areas with “greener” grids, payback may not be achieved for all impact categories within the anticipated lifespan of the housing system.

This study provides the first publicly available LCI model of an NZEB for poultry production, as well as an understanding of the potential viability of NZEB technology systems for sustainable intensification in livestock production. Efforts to encourage egg farmers to consider the adoption of new NZEB technologies should 1) target messages carefully regarding potential environmental, economic, and social costs and benefits and; 2) prioritize the development of additional pilot projects to showcase regionally-appropriate technologies. Facilitating development of a network for both research practitioners and farmers to exchange knowledge may be efficacious.

CRediT authorship contribution statement

Yang Li: Data collection, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Karen Allacker:** Supervision, Software, Modelling, Writing – review & editing. **Haibo Feng:** Software, Drawing. **Mohammad Davoud Heidari:** Writing – review & editing. **Nathan Pelletier:** Supervision, Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128014.

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