Journal of Building Engineering 37 (2021) 102160

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Framework for design and optimization of a retrofitted light industrial space with a renewable energy-assisted hydroponics facility in a rural northern canadian community

Artur Udovichenko, Brian A. Fleck, Tim Weis, Lexuan Zhong *

Department of Mechanical Engineering, University of Alberta, Edmonton, AB, T6G 1H9, Canada

ARTICLE INFO

Keywords:
Hydroponics
Controlled-environment agriculture
Hybrid energy system
Multi-objective optimization
Cold climate

ABSTRACT

The purpose of this study is to develop a design framework for retrofitting a light industrial building with a hybrid renewable energy-assisted hydroponics farming system for production of fresh food in rural north Canadian communities. This design protocol is targeted at facilities in rural areas of northern Canada, which could benefit from better access to fresh food, especially given the harsh climate as well as the long and limited transport routes. The process includes 1) a review of the existing building; 2) estimation of design loads for system sizing, such as temperature and humidity control, adequate lighting, airborne carbon, and water; 3) multi-objective genetic algorithm optimization of the hybrid renewable energy system for minimal operating cost and emissions; and 4) comparison of costs and greenhouse (GHG) emissions of the proposed farming operation with the traditional food supply chain. To demonstrate the proposed methodology, a case study building in a rural community in Alberta, Canada was evaluated for retrofit. The results showed that the GHG emissions generated from local hydroponic lettuce production, aided by a hybrid renewable energy system (HRES), are three times greater than those emitted by transporting an equivalent quantity of food from southern California, USA. On the other hand, the life cycle cost showed that the cost to produce lettuce from the case study facility is comparable to the price of lettuce available from traditional import, which shows a promising potential to provide fresh and cost-competitive food in the community, among other qualitative benefits gained from this empowering opportunity.

1. Introduction

Food insecurity in remote aboriginal families was reported to be as high as 65% in 2016 [1]. The various challenges experienced by the food supply chain; originating in warm growing climates and terminating at the hundreds of small communities scattered across Canada's north are partially responsible for this issue. The long transportation distances, some of which are not accessible year-round; not to mention the added supply chain disruptions caused by global pandemics [2–4], coupled with severe weather conditions, result in food waste, high retail costs, and decreased shelf life for commonly imported produce in northern provinces and territories [5]. A potential solution to this ongoing problem is installing medium-scale community indoor farms, such as greenhouses or plant factories, that provide fresh and cost-effective food.

Greenhouse and controlled-environment agriculture using hydroponics are becoming increasingly popular due to their capability of maintaining favourable microclimates as compared to open-field soil-based agriculture, which results in higher product quality and yield [6]. However, these production methods have higher energy demands than open field farming due to space conditioning, even in warm climates [7]. The territories and northern parts of the mainland provinces experience harsher heating seasons and higher energy costs [8], which can pose a problem for applying indoor farms. To overcome these challenges, greenhouse and hydroponic farms in northern rural communities must be designed and operated with sustainability in mind, particularly to address space heating and indoor climate control.

Various researchers have proposed unique and unconventional devices, or combinations thereof in a 'hybrid renewable energy system' (HRES), for use in greenhouses or growing facilities. Their goal was to improve the efficiency of the heating and cooling systems and reduce reliance on traditional fossil fuels. Since many greenhouses are

* Corresponding author.
E-mail address: lexuan.zhong@ualberta.ca (L. Zhong).

https://doi.org/10.1016/j.jobe.2021.102160
Received 19 October 2020; Received in revised form 23 December 2020; Accepted 30 December 2020
Available online 5 January 2021

traditionally designed to take advantage of passive solar gain and sunlight, solar energy systems are a common point of interest in existing research. Bambara and Athienitis [9] addressed the performance of greenhouses with roof-mounted solar PV to optimize simultaneous passive solar gain and electricity generation. Meanwhile, the case of a ground-source heat pump (GSHP) coupled with solar photovoltaics (PV) has seen success in heating greenhouses in both Turkey [10] and Italy [11]. Similarly, Esen and Yuksel [12] successfully demonstrated the potential of using biogas, ground, and solar energy HRES to heat a greenhouse through a full winter, also in Turkey. In these cases, the use of a GSHP has the added benefit of providing cooling during warmer periods, which further improves energy efficiency. Furthermore, the energy storage using phase change material (PCM) in mild climates, such as North Africa and Turkey, has been explored for night-time heating or capturing heat from a GSHP [13]. Overall, these studies are evidence of potential low energy consumptions of greenhouse design and operation solutions across various climates. However, three main gaps appear to be present in the research listed.

Firstly, the HRESs documented above are highly dependent on the mild climatic conditions of their locations; the cases listed were largely centred around the Mediterranean region. In the Canadian context, much less research has been found on this topic; only some passive greenhouse design technologies have been explored. For example, joining a greenhouse to a retail centre supplemented with on-site PV generation, waste heat recovery, and energy sharing was simulated to achieve net-zero performance in central Alberta [14]. Moreover, greenhouse envelope design for the extreme arctic was reviewed, and the researcher concluded that insulating the north wall of the building, thereby optimizing heat loss and solar gain, can extend the growing season by at least a month [15]. In general, research tends to be limited in colder climates applications.

Secondly, there is a lack of research that utilizes optimization to determine the optimal control strategy of an HRES, which would be critical in a hybrid system that includes multiple devices dedicated to satisfying specific demands [16]. While optimization has been seen used on indoor climate control of greenhouses and grow rooms [17]; with regards to ventilation and CO_2 injection, there has been a noticeable lack of studies relating to use of optimized HRESs in the realm of controlled-environment agriculture; most of the research on HRES optimization has been found applied on standard commercial and residential buildings [18–21].

Thirdly, to be compared with the base or traditional case, the cost and emissions savings, if any, of the proposed HRES must be quantified in terms of the plant product or crop yield, which has not been seen in the research outlined so far. In other words, a comparison between local production and import of a crop can aid in choosing the most economical and least emissions-intensive option for acquiring food [22,23]. To the best of the authors' knowledge, there is not enough research regarding local production as a method for import displacement, specifically targeting rural northern communities, where energy costs are higher, the climate is harsher, and transport operations are more limited.

The goal of this study is to address the lack of research regarding indoor farming performance and feasibility in northern rural communities. More explicitly, the objectives of this study are two-fold. Firstly, to present a methodology for design and optimization of renewable energy-assisted hydroponics retrofitted facilities. This procedure contains the steps to review the key requirements for a hydroponics facility, optimize the operation of a hybrid energy system such that annual operating emissions and costs are minimized, and evaluate the sustainable operation of the entire facility with the proposed system by comparing its costs and emissions to traditional import. The second objective is to showcase this procedure on a case study building in a rural community in northern Alberta, Canada.

2. Methodology

2.1. Hydroponics facility requirements

2.1.1. Heating and cooling

As with human-occupied buildings, plant growth facilities must be maintained at appropriate indoor temperatures for healthy plant growth, which tend to vary by crop type as well as the stage of growth [24]. This means that temperature control equipment must be capable of combating heat losses and gains. Heat transfer can occur through typical processes, such as conduction through the exterior surfaces (floors, walls, ceiling, doors, and windows), convection (ventilation and infiltration) of outdoor air into the space, and radiation from any lights and from the sun through fenestration [25]. In the case of plant facilities specifically, evaporative cooling is another energy loss to the plants that convert liquid water to vapour and must also be considered for heating system sizing [26,27].

2.1.2. Humidity

During photosynthesis, water taken up by the roots is used to carry nutrients through the plant's core and is then evaporated into the atmosphere by stomata on the leaf surface [28], which causes the evaporative cooling effect mentioned earlier. A carefully controlled vapor pressure deficit (VPD) drives the movement of water through the plant. A high indoor humidity means a low VPD that causes plants to evaporate water more slowly, slowing down their rate of photosynthesis. Meanwhile, a low indoor humidity (high VPD) can cause excessive evaporation and lead to significant dehydration [29]. As with temperature, the right VPD depends on crop type and stage of growth.

2.1.3. Carbon dioxide (CO_2)

Carbon dioxide (CO_2) consumption is the method by which plants obtain carbon for growth [28], and it is a crucial stage of the carbon cycle [30]. In open-field agriculture, this is not an issue as ambient outdoor air has an abundance of CO_2 that can be used to satisfy this demand. However, with indoor crop production, this resource can be quickly drained if adequate fresh air or supplemental carbon is not provided. In the case of CO_2 enrichment, elevated levels above the ambient concentration have been found to boost crop growth and yield, as well as improve quality [24].

2.1.4. Lighting

One of the main drawbacks of indoor facilities for farming is the lack of natural light due to the spaces having mostly opaque envelopes to combat the harsh climate. Even in transparent greenhouses at northern latitudes, the winter months see less than the optimal 14–16 h of light each day [24]. This issue is solved with specialized horticultural lighting options [31], which draw a considerable amount of power and create substantial heat.

2.1.5. Water

Water supply is the main form of nutrient transport through the plants and is an essential part of photosynthesis [28]. Hydroponics are well known for their incredible water use efficiency as compared with soil based traditional systems [32]. Nonetheless, water consumption is high even for a small system and must operate reliably.

2.2. Hybrid renewable energy system (HRES)

2.2.1. System sizing

If the existing equipment in the building cannot meet the identified requirements, new systems must be elected and sized according to appropriate design procedures and guidelines. It is also necessary to consider the available renewable energy options for the specific case. Factors such as energy availability and cost, local fuel options, available land area and resources may constrain the final selection of systems and their overall configuration.

2.2.2. System modelling

The goal is to estimate the operating costs and greenhouse gas (GHG) emissions by determining the actual space demands, modelling the selected energy systems, and considering local energy and resource prices and relevant emissions factors. However, given that certain operational parameters of the facility and the energy system have not been set, variability in the result can occur.

Heating, cooling, humidity control, and CO_2 availability are all tied to how much fresh airflow is occurring and given that there are no strict code requirements for minimum ventilation of plant growth spaces, this parameter can be adjusted to achieve the most minimal energy and resource consumption. Additionally, if more than one potential energy conversion device has been selected to satisfy certain energy demand, both devices can contribute to the total load through combined part-load energy supply at variable operating fractions based on the availability of natural resources, such as sunlight or warm weather. Therefore, the optimization of such variables is very critical in this application to achieve sustainable operation. The objective functions shall be set up as the monthly cost and emissions, and the decision variables are the ventilation flow rate and energy supply fractions for the individual demands.

2.2.3. Optimization of hybrid renewable energy system

Since this problem will contain multiple parameters desired to be minimized, multi-objective optimization serves as the appropriate tool to perform this task. Evolutionary algorithm optimization is one method by which many studies have found the optimal operating conditions for various HVAC systems [33]. These problems tend to have multiple objectives that conflict with each other, which means that a single solution cannot achieve all the goals [34]. Instead, the algorithm finds a range of potential non-dominated solutions along a 'Pareto-optimal front' that can be further analyzed by the user, a secondary algorithm, or other decision-making approach [35].

The 'gamultiobj' function in MATLAB, based on the NSGA-II algorithm [36], can be used to compute the Pareto front for each month defined by outdoor conditions. The algorithm configuration, comprised of population size, crossover fraction, Pareto fraction, and a convergence function tolerance, should be chosen to achieve a relatively quick convergence to a region near the optimal front. Followed by a secondary solver that searches more closely within the generated region to identify the best solution(s) [37]. In MATLAB, this secondary solver is the 'fgoalattain' hybrid function, a standard algorithm that can be used to solve goal attainment (e.g., minimization or maximization) but is hindered by the fact that it requires initial guessing. Since the genetic algorithm is extremely versatile, not requiring much input but is only useful for finding a collection of potential solutions, combining it with a more efficient local minimization function is a good strategy for achieving quick convergence at a global minimum.

The procedure of the custom MATLAB script, shown in Fig. 1, is outlined as follows. First, the month number is assigned from a loop ranging from 1 to 12. Next, the modelling data file, which contains the necessary equations and data, is provided. The decision variable vector and corresponding constraints, which are problem-specific, must be passed to the optimization function. The algorithm proceeds by generating the first population of input vectors and evaluating the fitness function and comparing it with the convergence tolerance value. The objective space continues to be populated with increasingly improved generations of points until this tolerance is met. At which point, the final generation containing the best Pareto front of solutions is passed as the initial guess to the secondary solver. The solver then attempts to minimize each point on the front further by generating additional guesses and evaluating the function value along a search direction generated by the genetic algorithm. Once a function tolerance is reached, and the same original constraints are satisfied, the solver stops and shows the final solution(s).

2.3. Comparison with traditional food import

The operating cost and greenhouse gas (GHG) emissions from the optimization procedure can be used in a comparative analysis to determine if production using this method is a viable replacement for traditional import, at least on a purely quantitative basis. It should be noted that techno-economic feasibility is only one of many factors that could affect decision making in northern Canadian communities. Ultimately, every rural hamlet or community, especially that of indigenous background, would be subject to a unique set of circumstances derived

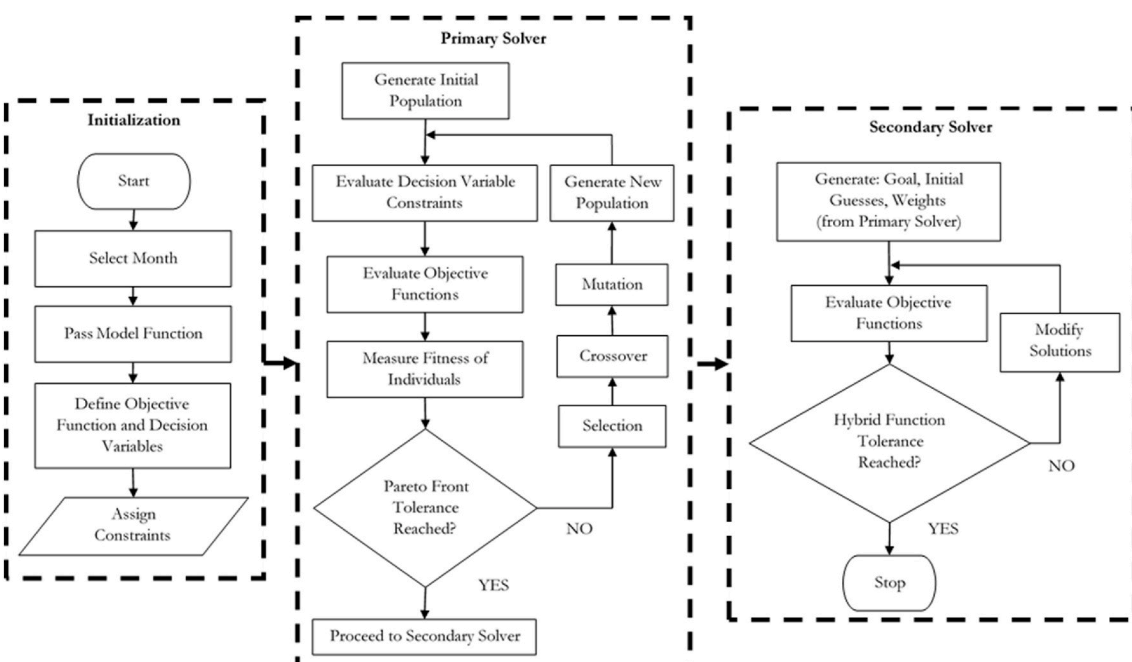

Fig. 1. The optimization process of the MATLAB script used in this study.

from a historical issue related to colonization, which would drive choice and behaviour. In other words, the optimal low-emissions solution obtained from optimization may not necessarily coincide with a solution that supports autonomy, local employment, and training.

2.3.1. Life cycle cost

The cost analysis involves accounting for all the cost components of retrofitting the facility as well as operating it over the course of its lifetime. More specifically, the costs associated with this analysis in the current application are: 1) capital costs of all major technologies involved in the retrofit, including the energy conversion devices and the hydroponics equipment; 2) operating costs associated with consumed resources, such as energies (fuel, electricity) and miscellaneous resources (water and supplemental carbon); and 3) any additional annual expenses, such as maintenance and labour. Meanwhile, estimating the amount of product yield over the same period can help establish a cost index per quantity of produce, which can be compared with the existing cost of the same food type at the local grocer.

2.3.2. Food-miles assessment

As for emissions, the 'food-miles' assessment has been seen in literature as a method of assessing the potential for import substitution by local production [22]. For the local production case, operating emissions from energy and resource use include the consumption of resources, fuels, and electricity required for the basic operation of the facility as obtained from the annual emissions results from optimization. On the other hand, the transport case only considers total emissions from fuel use during travel, which is based on the distance and size of the shipment [38]. The weight of the product to be transported is assumed to be equal to what is produced in a year at the local facility, which allows for a similar comparison between the two methods.

3. Case study

3.1. Existing building retrofit

The existing building (Supplementary Material: Figure A1) is a 270 m^2 commercial fish processing plant that is in Fort Chipewyan, Alberta (58.770 N, 111.120W) [89]. It is a steel-frame building with RSI-4 walls and RSI-7 roof and is almost entirely opaque with only three small windows on the south-eastern side. The main space makes up most of the floor space (31%) and was to be retrofitted with a commercial hydroponics vertical farming system designed to grow lettuce (*Lactuca sativa*). The building also included two chilled rooms, as a cooler and an ice room, as well as a food preparation area, a break room, and an office. 240 2.1 m growing towers and a combination of 24 75 W and 48,150 W variable RGB spectrum LED lights were used.

3.2. Load calculation

Indoor plant requirement analysis was performed by applying the fundamental energy and mass transfer equations outlined in ASHRAE Handbook – Fundamentals [25] to the case study building, and by taking into consideration the setpoints and specifications of each demand, as listed below.

3.2.1. Heating and cooling

For design load calculation, the outdoor temperature was set at the 99% and 1% worst-case dry-bulb temperatures as defined by climatic data for the weather station of Fort Chipewyan [25], and the main hydroponics space was set at 21 °C and 17 °C [39], for heating and cooling, respectively. For the other regularly occupied spaces, the temperature setpoint was 21 °C as a typical value for human occupancy [25]. The cooler and ice room were set at 5 °C and −5 °C, respectively. In conformance with ASHRAE standard 62.1 [40], the break room, prep area, and office were assigned ventilation flow rates in the range of 10–30 L/s, based on regular occupancy (two in the prep area and one in the office) and floor area. The flowrate of fresh ventilation air in the main growing space was set at 7 air changes per hour (ACH), as the typical maximum greenhouse ventilation rates in the winter, according to Chapter 24 of ASHRAE Handbook – HVAC Applications [41]. Meanwhile, infiltration was assumed negligible in this building based on the assumption that an indoor plant growth facility would need to be well sealed if its purpose were controlled environment agriculture [42]. Sensible energy loss due to evaporative cooling by plants was modelled as the product of the rate of evapotranspiration and the heat of vaporization of water. For the cooling load, the peak solar heat gain into the office and lunchroom (no windows in the main growing area) through fenestration during July was modelled based on the hourly solar irradiance estimates, which were obtained from a solar position calculator [43] and clearness index data for the target location [44]. Furthermore, the maximum lighting heat output of standard and hydroponics lighting in the building was also considered based on typical efficiencies for high performance grow LEDs and standard fluorescent ballasts [45,46]. A safety design factor of 20% was applied to the heating and cooling loads as a standard sizing procedure for industrial spaces.

For the performance modelling, the bin method was used to determine monthly loads based on ASHRAE provided hourly occurrence data in a typical meteorological year for the location. The actual hydroponics setpoint temperature was set to 17 °C and 20 °C for the winter and summer, respectively. The seasonal variation was introduced to ease the heating and cooling requirements, while still ensuring that the temperatures were appropriate for lettuce [24]. Meanwhile, the other spaces remained modelled at 21 °C, 5 °C, and −5 °C and the same healthy ventilation flowrates, for the regularly occupied, cooler, and ice room spaces, respectively. Flowrate of fresh air into the hydroponics space was chosen as a variable in the range of 0.1–7 ACH, based on the minimum ventilation for extracting contaminants generated by plants [42,47], and the maximum ventilation based on the design load. Actual lighting and solar heat gains were modelled as monthly averages based on hourly variations.

3.2.2. Humidity

The humidification and dehumidification requirements were determined using the 99% and 1% worst case outdoor humidity ratios, as listed in the climatic data for the local weather station [25], in combination with the corresponding worst-case air change flowrate of 7 ACH, and extreme indoor setpoints of 90% RH at 21 °C (VPD = 0.2 kPa) and 50% RH at 17 °C (VPD = 1.0 kPa) [48], respectively. Minimum humidifier and dehumidifier capacity were found by considering these conditions on a mass of water either removed or added per hour. This considered the approximate moisture supply to the air through plant transpiration, which was assumed equal to the watering rate; no irrigation loss or water consumption by the plants. For the other human-occupied spaces, humidity control was neglected since human comfort was not in the scope of the study.

During monthly performance modelling, the same logic was applied, except indoor setpoints of 60% RH at 17 °C (VPD = 0.8 kPa) for the winter and 80% RH at 20 °C (VPD = 0.45 kPa) for the summer were more realistic, and actual outdoor humidity was computed based on the hourly temperature occurrence data used in the bin method. Once again, this seasonal variation was introduced to reduce expected energy consumption by the humidity control systems, while still satisfying the requirements of the VPD.

3.2.3. Carbon dioxide (CO_2) supply

The CO_2 supply was simulated as only providing enough CO_2 to counter plant consumption and maintain a sufficient ambient concentration of approximately 400 ppm. This way, the concentration would always be constant regardless of CO_2 supply method. Plant consumption of CO_2 was taken as a value for a greenhouse 3 g/m^2 per hour [29,49], which conforms with values reported for plant factories in the literature

[32].

CO_2 consumption was modelled as inversely proportional to the average hourly indoor air change rate (ACH), such that, the time spent not ventilating the space, using a constant exhaust fan flowrate of 3780 L/s, would be supplemented by CO_2 injection, at the constant flowrate equal to plant consumption. Therefore, the higher the ventilation flowrate, the smaller the required CO_2 flowrate, and the lower the average consumption.

3.2.4. Water supply

Water supply was taken as a specification from the manufacturer of the hydroponics system as 220 L/day on average. Additional water demands for other spaces in the building were estimated based on fixtures layouts of one lavatory with a sink and two kitchen faucets, and the occupancy schedule. This also included water heating energy consumption, based on average temperature rise between municipal feed-water temperature of 8 °C and boiler supply temperature of 50 °C.

3.2.5. Lighting

120 growing lamps with a power consumption of 9 kW, were modelled as having a 60% efficiency with regards to heating gains used in heating and cooling loads. The operating schedule was set at 16 h/8 h photoperiod/dark period [50,51]. Similarly, the hydroponics equipment was modelled as operating 24 h per day, and any heat gain was neglected. In the rest of the building, lighting consisted of standard 32 W ballasts operating for a typical working schedule of 8 h a day in the occupied areas and intermittent use of 4 h a day in the freezer and cooler.

3.3. Hybrid renewable energy system (HRES)

3.3.1. System selection and sizing

A series of energy systems were considered, both renewable and traditional, for maintaining the temperature and humidity setpoints based on locally available resources. The forced air furnace and water heater were parts of the existing system of the building with a reliable fuel source (propane) that is available locally. Additionally, a biomass boiler was sized to be used as an alternative heating system because a review of the location revealed that cordwood is an abundant local resource. Investment in this technology can provide local employment and community development, which is a benefit that cannot be accurately captured through quantitative analysis.

It was found that this location is suitable for geothermal heat exchange [52,53], and it seemed logical to utilize a heating system that could use electricity instead of traditional fuels. Also, the high efficiency and dual functionality for summertime cooling of a heat pump were deemed as major advantages over conventional fossil fuel-fired equipment. Hence, the ground-source heat pump (GSHP) was selected as an alternative heating device and the only source of cooling. This was deemed a feasible option due to the significant amount of land area around this building, which would allow for a closed-loop vertical bore system with 20 bores of 40 m depth, 6 m separation, with 25 mm high-density polyethylene (HDPE) U-tubes in 127 mm diameter bores to be installed [54]. Data for ground conductivity, temperature, and thermal resistance was taken as an approximation from Alberta soil surveys [55].

Humidification and dehumidification systems for the hydroponics space were sized to meet the average daily moisture removal or addition loads operated under the worst-case design conditions, respectively. Although, the GSHP is a system capable of providing dehumidification, this process can only occur when the GSHP is in cooling mode. However, there was no guarantee that operation of dehumidification only when the GSHP was in cooling mode would have been the most cost- and emissions-friendly strategy. Therefore, the dehumidification and cooling systems were modelled independently from each other as separate units.

An indirect component of the HRES is a solar photovoltaic (PV) array, modelled as the primary source of renewable, reliable, and low maintenance electricity for the building. A total capacity of 60 kW was selected as a reasonable size for a light industrial building, for which there would be enough land area onsite. Table 1 lists the devices chosen to satisfy the computed loads, with details about capacity, efficiency, cost provided.

3.3.2. System modelling

The heating systems (furnace, boiler, GSHP) were set up in parallel as sources of thermal energy to the space satisfying the total monthly heating demand. Cooling, humidification, dehumidification, and water heating equipment were set up as single systems satisfying the total monthly loads. For the solar photovoltaics (PV) array installed onsite, the location-specific AC system output profile was simulated using the National Renewable Energy Laboratory's PVWatts® calculator on a monthly basis [57], using the location of the existing plant and the proposed system size. The primary source of electricity was the local community micro-grid, which fulfilled any electric demand of the HRES not covered by electric solar PV generation, such as lights, humidification equipment, or GSHP. In other words, the purpose of the PV system was to offset the monthly import of electricity. In addition to the energy systems, the water and supplemental CO_2 usage were modelled as a total monthly consumption based on the requirements described earlier. Fig. 2 shows the layout of the hybrid renewable energy system with energy flows from provided energy sources to the respective demands. Although the exhaust fan was not directly modelled in terms of energy use, it has been included because ventilation is a critical component of the operational strategy of the HRES.

The emissions and costs of each system were set up by using the local prices of the resource and consumption emissions factor. The general reporting guidelines listed in ASHRAE Standard 105 [58] were used to describe energy and resource use, which considered heat content values taken from the national inventory report in terms of primary thermal energy [59]. Table 2 shows the cost and emissions factors of the fuels used in the analysis. The electricity emissions factor was based on a conversion efficiency from diesel-fired generation in the community, and a value was assigned based on the average conversion efficiency found in the three Canadian territories, which most closely resemble the quality of infrastructure found in Fort Chipewyan [60,61]. For cordwood and propane, the emissions factors were taken from the national inventory report [59].

Meanwhile, the costs of electricity, cordwood, propane, and compressed CO_2 were found from estimates of local suppliers [62–66]. Similarly, the water supply (Table 3) was calculated based on the total monthly amount of water supply for the building, including hydroponics and typical fixtures. This was combined with the fixed monthly and variable flowrate fees for the existing meter size, 38 mm, in the local municipality [67].

3.3.3. Optimization of ventilation and HRES control

The objective functions used in the HRES system model acted to minimize the operating cost C_{op}^{i} and emissions GHG_{op}^{i} for each month, denoted by i, as shown below:

$$C_{op}^{i}=min\left\{m_{CO_2}^{i}*C_{CO_2}+m_{H_2O}^{i}*C_{H_2O}+E_{Wood}^{i}*C_{Wood}+E_{Prop}^{i}*C_{Prop}+E_{Elec}^{i}*C_{Elec}\right\} \tag{1}$$

$$GHG_{op}^{i}=min\left\{E_{Wood}^{i}*GHG_{Wood}+E_{Prop}^{i}*GHG_{Prop}+E_{Elec}^{i}*GHG_{Elec}\right\} \tag{2}$$

Table 1
Devices included in the HRES for the case study building.

Device	Fuel Type	Function	Efficiency	Capacity	System Capital Cost, CAD$
Boiler	Cordwood	Space Heating	80%	44 kW	$ 7000
Furnace	Propane	Space Heating	80%	35 kW	$ 0 (Existing)
GSHP (w/ground loop heat exchanger)	Electricity	Space Heating	COP = 4.0	16 kW	$ 45,800
		Space Cooling	EER = 13.7	23 kW	
Dehumidifier	Electricity	Dehumidification	2.9 L/kWh	30 L/h	$ 55,440
Humidifier	Electricity	Humidification	1.2 L/kWh	30 L/h	$ 3830
Water Heater	Propane	Water Heating	92%	17 kW	$ 0 (Existing)
Solar Photovoltaics	Electricity	Generation	Standard Module, Fixed Array, 20° tilt	60 kW DC	$ 132,600 [56]
Hydroponics	Electricity	Lettuce Farming	N/A	8440 kgs per year	$ 116,200

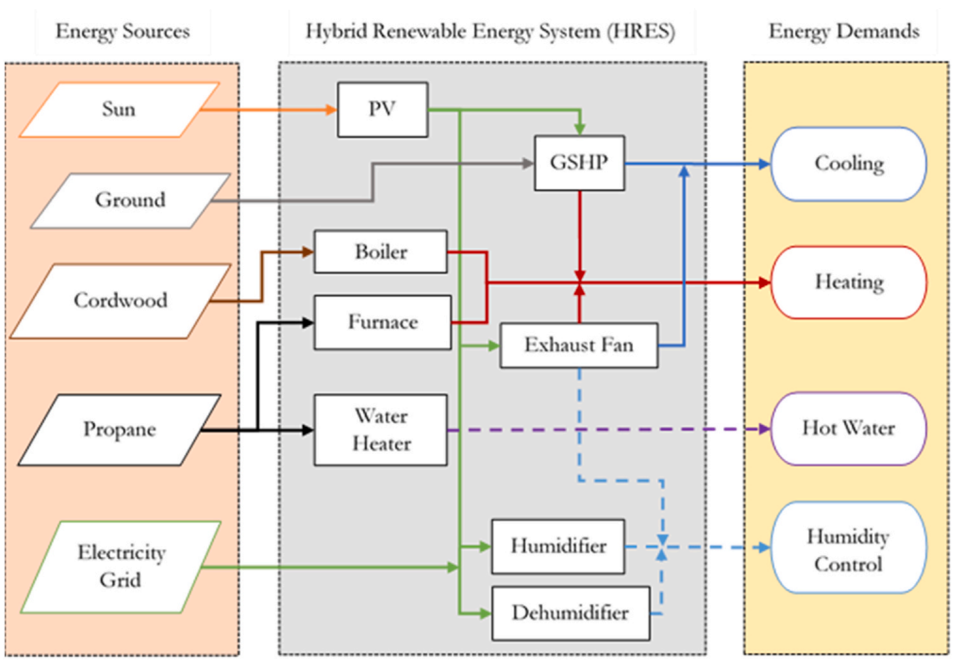

Fig. 2. Layout of the Hybrid Renewable Energy System (HRES) in the case study.

Table 2
Prices and emissions factors of fuel options used in the case study building.

Fuel Option	Emission factor gCO_2e/kWh	Fuel Cost, $/kWh
Cord Wood	2.33	0.031
Propane	220	0.127
Electricity	784	0.180

Table 3
Prices of material resources used in the case study building.

Fuel Option	Fixed Monthly Fee ($/mo)	Variable Cost, $/unit
Water Supply	$ 34.87	1.61$/m^3 [67]
CO_2 Supply	–	0.77 $/kg [66]

where, C refers to the unit cost, shown in Tables 2 and 3, of the various resources$m$, as defined by equations (3) and (4), and energies$E$, as defined by equations (5)–(8). Meanwhile,GHG represents the emissions factor of each energy source listed in Table 2. The consumption of each energy source or material resource is governed by the monthly demand, *Load*; such as heating, cooling, humidification, dehumidification, water supply, light use, or carbon dioxide supplementation, denoted with the subscripts *Heat*, *Cool*, *H*, *DH*, H_2O, *Lights*, and CO_2, respectively.

$$m^i_{CO_2} = Load^i_{CO_2}(ACH_i) \tag{3}$$

$$m^i_{H_2O} = Load^i_{H_2O,Hydroponics} + Load^i_{H_2O,Cold} + Load^i_{H_2O,Hot} \tag{4}$$

$$E^i_{Wood} = \frac{W_i * Load^i_{Heat}(ACH_i)}{80\%} \tag{5}$$

$$E^i_{Prop} = \frac{P_i * Load^i_{Heat}(ACH_i)}{80\%} + \frac{Load^i_{H_2O,Hot}}{92\%} \tag{6}$$

$$E^i_{Elec} = \frac{Load_{DH}(ACH_i)}{2.9L/kWh} + \frac{Load_H(ACH_i)}{1.2L/kWh} + E^i_{GSHP} + Load_{Lights} - E^i_{PV} \tag{7}$$

$$E^i_{GSHP} = \frac{G_i * Load^i_{Heat}(ACH_i)}{COP} + \frac{Load^i_{Cool}(ACH_i)}{EER} \tag{8}$$

As described earlier, some of these demands are dependent on the fresh air change rate, marked with ACH_i above. In addition, the three operating fractions of the heating systems (P = propane furnace, W = cordwood boiler, G = ground source heat pump in heating mode) distribute the heating requirement between the three systems. Together, these four parameters make up the decision variable x, defined by Equation (9), and subject to the constraint conditions shown in Equations 10–14.

$$x_i = (ACH_i, P_i, W_i, G_i)^T \tag{9}$$

$$0.1 < ACH_i < 7 \tag{10}$$

$$0 < P_i < P_{max}(ACH_i) \tag{11}$$

$$0 < W_i < W_{max}(ACH_i) \tag{12}$$

$$0 < G_i < G_{max}(ACH_i) \tag{13}$$

$$P_i + W_i + G_i = 1 \tag{14}$$

Constraint (10) ensures that the rate of fresh air change in the hydroponics space was limited by the minimum required ventilation flowrate for enclosed plant factories [42], and the maximum air change rate achievable for each month. Similarly, as shown in Equations 11–13, the operating fractions of the heating systems represented a fraction of the monthly heating load. However, these were constrained by the maximum, *max*, operational capacity, as defined by the monthly loads at a specific ventilation rate; they are variable based on the value of ACH_i. And, P_i, W_i, and G_i must add up to a value of one, such that the heating load in Equation (14) is satisfied.

For this problem, the algorithm configuration was defined by a population size of 100, a crossover fraction of 0.8, a Pareto fraction of 0.35, and a convergence function tolerance of 1e-4. Additionally, Excel was the software of choice to serve as the modelling function file, which was opened as a server within the MATLAB script outlined in Fig. 1.

3.4. Comparison with traditional import

3.4.1. Life cycle cost

The selection of costs to consider for life cycle cost (LCC) was taken from chapter 11 of the ASHRAE textbook [68]. The capital cost component of the analysis evaluated the sum of the costs of the individual units of the systems shown in Table 2. The capital cost of the GSHP system included only the main unit and the ground heat exchanger loop, based on common construction cost of 38 $/meter of bore length [54]. Additionally, the building already contained a propane furnace and a water heater, so these were not proposed as retrofit options. The boiler, humidifier, and dehumidifier were priced based on the manufacturers' suggested retail prices. The service lifetime analyzed was chosen to be 20 years, based on the average lifetime of many of the devices listed, as was seen in the literature [68]. A discounted cash flow analysis was performed to estimate the life cycle cost over the time period. A real discount rate of 4% was used to estimate the cost in 2020 dollars as per other cases found in the literature [69–71].

Annual operating costs were comprised of the total monthly operating costs from energy and resource consumption, as determined by the optimization procedure. Labour was estimated as $20 per hour, based on data for a typical Albertan farmer's wage [72], for two part-time workers doing a total of 16 h per week, for 50 weeks per year. More specifically, this labour was broken down into seed germination (2 h), transplanting seedlings into towers (6 h), harvesting (6 h), and routine maintenance (2 h). Hourly breakdown was averaged over a three-week growth cycle based on the system size as defined by the number of towers. Maintenance of the HRES was estimated as a 1% factor of the capital cost of the systems, an estimation method found in the literature [73–75]. Any other costs were excluded, and it was assumed that no profit was made from the operation.

3.4.2. Food-miles

For this case study, it was assumed that the point of origin is Napa, California, from which a 2780 km trip by road was taken to Fort McMurray by truck [76]. Since Fort Chipewyan has limited road access during warmer months of the year [77], it was assumed that from Fort McMurray the trip was completed by airfreight over a straight-lined distance of 222 km [78]. The trucking distance also included the 6 km from the regional Fort Chipewyan airport to the town centre. The emissions factors for combustion of fuel during transport by truck and airplane were taken as 0.25 ± 0.010 kg/tonne-km and 1.18 ± 0.0795 kg/tonne-km [22], respectively. Due to the emphasis on transport by road, the emissions factor for fuel combustion in trucks included emissions from energy used for refrigeration, including inefficiency due to refrigerant leakage of 15%, as found in the literature [79].

4. Results and discussion

4.1. Design loads

Design load calculations for heating, cooling, dehumidification, and humidification are shown in Table 4. Comparing the required capacities suggested that the combination of all heating equipment could satisfy this worst-case load. Similarly, the GSHP, humidifier, and dehumidifier have sufficient full-load capacities to satisfy their respective loads.

Table 4
Design loads of the case study building.

Heating	Cooling	Humidification	Dehumidification
87 kW	20 kW	26.8 L/h	27.8 L/h

4.2. Optimization

Table 5 shows the specific optimal values selected after the optimization process for each month. An example of the Pareto front of the objective space and the final hybrid function results is shown in Fig. 3 for January; points identified with the 'Gen' label refer to solutions identified in the main genetic algorithm and points marked with the blue diamonds refer to the final solutions determined by the secondary solver. It is important to note that while the algorithm had generated more than one unique numerical solution for many months, due to the software's extremely small numerical scale, these points can be observed to be clustered around a relatively narrow range of values. In practicality, these correspond to one general solution with some small range of uncertainty due to rounding error. As such, the error bars seen in Figs. 4–7 represent maximum and minimum values due to rounding error in air change (ACH) value from optimization procedure.

At first glance, it is evident that ventilation flowrates (ACH) have been set much lower than what was used for design load sizing and the maximum values on the operational constraints were one for all months except for January–March and November–December for the GSHP, which were still mostly constraint-free because only the GSHP was limited to capacities close to 0.6. Since the actual operating conditions draw much lower heating demands, the selected systems do not need to operate in conjunction to meet the worst-case loads; each system can be used independently without limitations to fulfil the demands. Therefore, it is immediately evident that the heating system designated for backup, the propane furnace, was never necessary since the cordwood boiler could always handle the heating demand.

In the wintertime, between months 1–3 and 9–12, ventilation flowrate was relatively low and experienced a steady increase as the months got warmer. This could be attributed to heating energy demand (Fig. 4) as a potential limitation for minimizing cost and emissions, especially since the low amount of solar PV generation (Fig. 5) does not allow for a significant contribution from the GSHP, which would otherwise provide emissions-free and inexpensive heat. As a result, the entirety of the heating demand was transferred to the cordwood boiler because it was less emitting and cheaper than the furnace and the grid imported electricity required to run the heat pump; a phenomenon that has been found to apply electric space heating systems in certain Canadian regions [80]. On the other hand, the dry outdoor air in winter, brought in at these moderate flowrates, caused an appropriate moisture removal from the plants, leading to reduced additional humidity control.

Optimal values for ventilation flowrate appear to peak for the spring months (4–6). Due to the excess of solar PV generation, the GSHP could be used for both heating and cooling. Plus, additional imported

Table 5
Optimization results of the HRES for the case study building.

Month	ACH (1/h)	F	W	GH
1	2.79	0.00	1.00	0.00
2	2.86	0.00	1.00	0.00
3	2.93	0.00	1.00	0.00
4	3.41	0.00	0.39	0.61
5	7.00	0.00	0.00	1.00
6	5.24	0.00	0.00	1.00
7	4.81	0.00	0.00	1.00
8	3.89	0.00	0.00	1.00
9	5.92	0.00	1.00	0.00
10	4.22	0.00	1.00	0.00
11	3.09	0.00	1.00	0.00
12	2.85	0.00	1.00	0.00

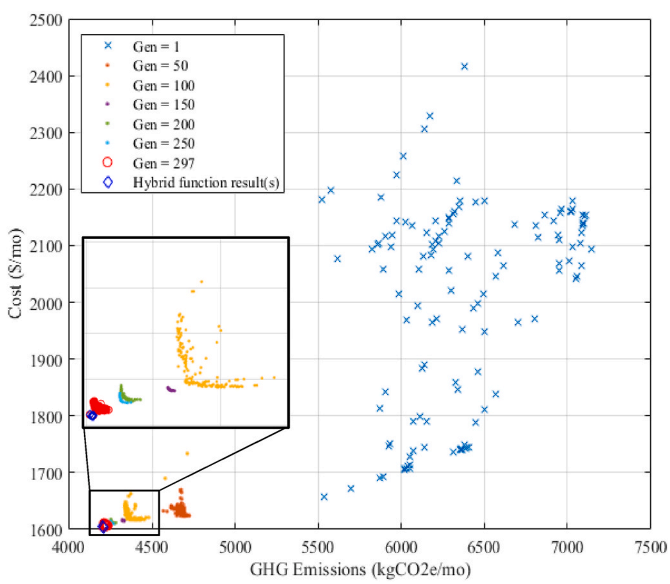

Fig. 3. Pareto plot and generation plot of the optimization procedure of the operation of the case study facility for January.

electricity was not needed for humidity control either. So, the ventilation flowrate peaked to prioritize natural CO_2 supply in May. As a result, the humidity control systems were forced to operate more to control the humidity of the greater amount of incoming outdoor air, as seen in Fig. 5.

During the summer months (7–8), the heating system operating fractions appear to have continued their trend of prioritizing the GSHP versus the boiler. However, given the fact that the heating loads were virtually non-existent, this ultimately, did not matter. Instead, electricity consumption by the heat pump increased due to the need for cooling during this time. However, cooling was less of a priority as compared to dehumidification, as evident by the fact that the ACH values experienced a noticeable decrease during this time, and the fact that electricity usage for dehumidification is at its maximum for the late summer months. This would suggest that the dehumidification system performance outweighed the natural CO_2 supply and cooling system electricity consumption because of greater electricity consumption for dehumidification of warmer, more humid outdoor air being introduced. (Fig. 5). As a result, the summertime months that were most ideal for taking advantage of ambient outdoor CO_2; due to minimal heating loss from larger ventilation were instead the most reliant on supplemental CO_2 supply.

These behaviours ultimately influenced the monthly cost distribution, shown in Fig. 6. Most notably, it is evident how greater solar PV generation during early summer months aided in reducing the import of grid electricity. Especially in April–June, the facility operated with net-zero grid electricity consumption. However, Fig. 5 also shows that lighting electricity usage was the most limiting factor, which could not be affected in this study. Since this facility is almost entirely opaque, increased summertime solar activity could not be used to reduce lighting electricity consumption. Furthermore, this design strategy would most surely affect energy consumption for heating during winter months, which are already the costliest months to operate the facility. Regardless, the electricity usage for humidity control is the highest monthly expense, which explains why the optimization procedures developed an operational strategy that varied so widely; as seen with the variation in ventilation flowrate, throughout the year in an attempt to utilize as much onsite PV generation and reduce electricity consumption for this process. Similarly, this trend is repeated in Fig. 7, which showcases the breakdown of monthly GHG emissions. Once again, the electricity import was by far the largest emitting component. The presence of onsite solar PV generation in combination with a variable operational strategy made a significant reduction of GHG emissions due to the import of grid electricity during the summertime. As such, the cost and emissions for a full annual cycle were found to be \$ 9393 $\pm$ 8 and 24,099 $\pm$ 30 kg CO_2e, respectively.

4.3. Life cycle cost

The life cycle cost of the proposed hydroponics facility is presented in Fig. 8. Error bars for the proposed case represent maximum and minimum values due to rounding error in air change (ACH) value from optimization procedure. Meanwhile, error bars for the existing case represent price variation across 2018–2019.

Since the optimization results showed that the furnace was not used, it had zero maintenance costs. And most importantly, since it was already existing, there was no loss of capital. To be fair, it could have potentially been resold or salvaged, but this was not considered in this study. As a result, the life cycle cost of the hybrid renewable energy system over a 20-year lifetime, including the hydroponics package,

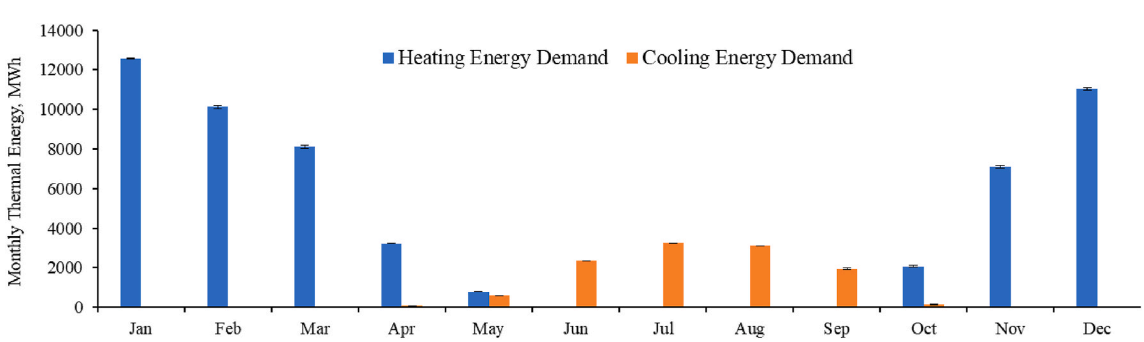

Fig. 4. Monthly heating and cooling thermal energy transfer requirements for the case study facility with the optimized HRES.

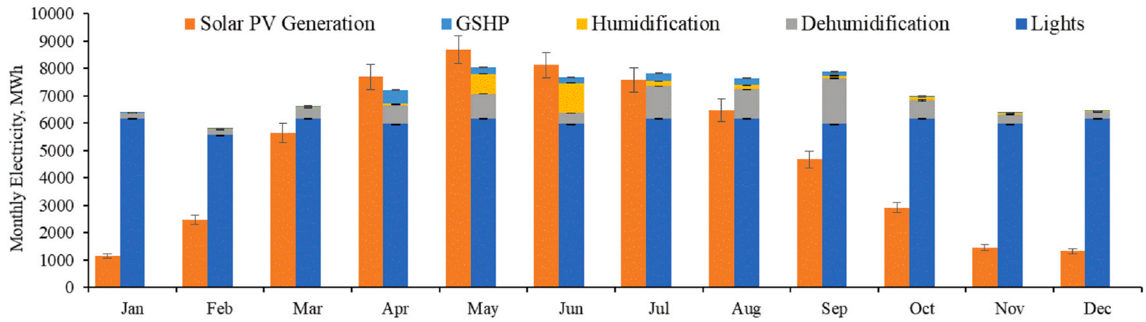

Fig. 5. Monthly electricity requirements and solar PV generation breakdown for the case study facility with the optimized HRES.

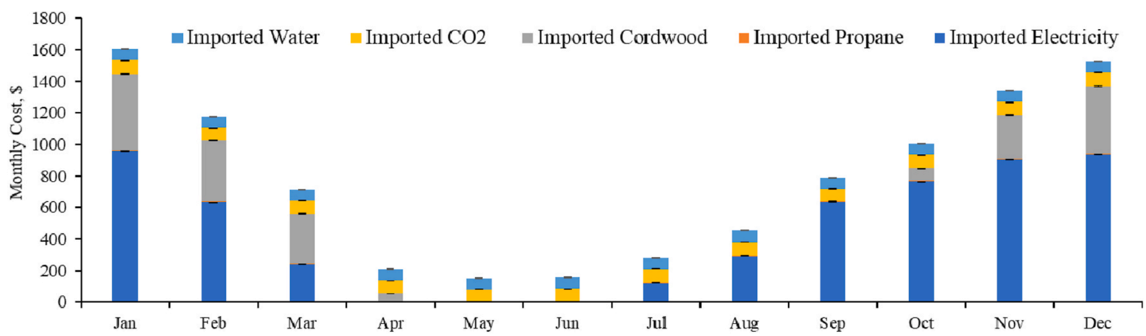

Fig. 6. Monthly cost breakdown for the case study facility with the optimized HRES.

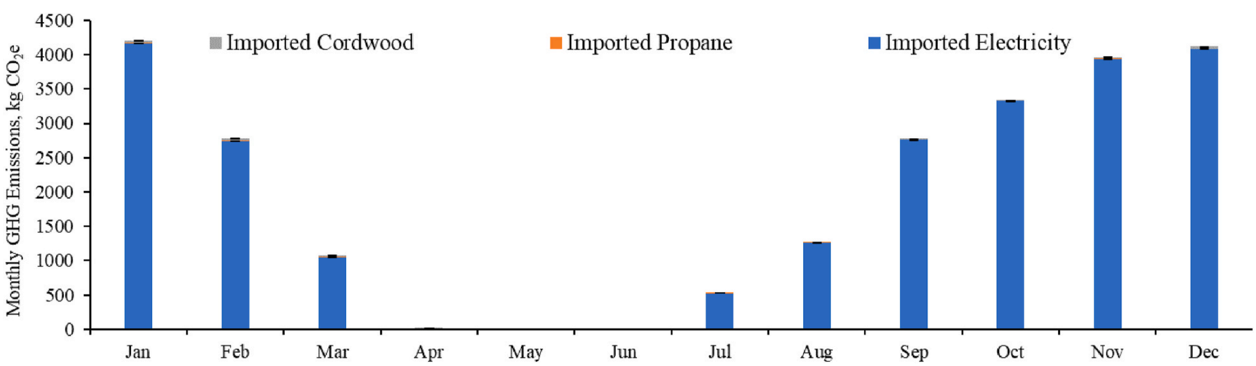

Fig. 7. Monthly GHG emissions breakdown for the case study facility with the optimized HRES.

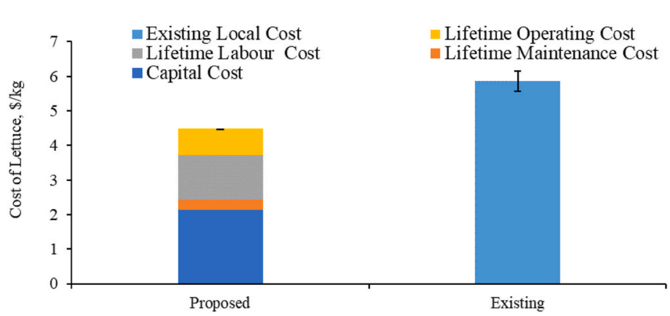

Fig. 8. Life cycle cost breakdown for the case study facility with the optimized HRES.

labour, maintenance, and operating resource and energy expenses came out to \$ 755,259 $\pm$ 110, in present 2020 value. Based on the production cycle of three weeks, which yields 2.5 kg per vertical hydroponic tower, the entire system of 240 towers operating for 50 weeks per year was estimated to produce 8440 kg of Romaine lettuce (Table 1), and 168,820 kgs over the 20-year period. The unit cost of lettuce produced from this facility was therefore 4.47 $\pm$ 0.01 \$/kg.

The local existing price of lettuce in the community was estimated as 5.86 $\pm$ 0.29 \$/kg. No direct data were available for Fort Chipewyan, so it was based on data extrapolated for the closest city of Fort McMurray and taking into account the costs in Alberta's capital of Edmonton; approximately 4.28 $\pm$ 0.41 \$/kg [81,82]. Comparing these two results, suggests that the proposed facility retrofit is competitive and could serve as a viable alternative to existing food prices caused by the long and limited supply chains. Although, the savings are not tremendous, it is important to remember that this alternate method would also provide lettuce of better quality since it does not have to endure a long transport stage. A closer look at the breakdown of costs, shown in Fig. 8, reveals that most of the expenses were attributed to the capital and labour costs. Although initial investment is relatively high, there is tremendous benefit from the operation of the optimized HRES; as witnessed by the reduced electricity and propane consumption, due to the solar PV onsite generation and the biomass boiler. This is especially important since fuel prices will continue to rise with carbon taxation. Moreover, Canada's north contains other communities that experience worse prices for vegetables, such as Kugaaruk (9.32 $/kg), Baker Lake (11.38 $/kg), Coral Harbour (8.52 $/kg), and Grise Fiord (7.97 $/kg) located in the territory of Nunavut [83], with which this type of facility could compete on an even greater scale.

4.4. Food-miles assessment

To deliver an annual equivalent quantity of lettuce (8440 kgs) to Fort Chipewyan from a traditional production location in southern USA, a total GHG emissions quantity of 8180 $\pm$ 285 kg CO_2e would be produced during fuel combustion for transport. Meanwhile, local production in the facility would result in 24,099 $\pm$ 30 kgs CO_2e due to fuel and energy use. More specifically, GHG emissions per unit of lettuce were approximately three times higher for local production than through import; 2.86 $\pm$ 0.004 kgs CO_2e/kg hydroponic lettuce and 0.97 $\pm$ 0.034 kgs CO_2e/kg imported lettuce. Therefore, despite the investment in renewable energy technologies for the retrofitted facility, this form of local production is not an environmentally friendly alternative to traditional transport and would fail at displacing current transport emissions. As mentioned previously, this can be attributed to the tremendous emissions from local electricity consumption. Despite the fact that the onsite solar PV array helped to reduce imported electricity, as seen during the summer months, there was still a significant reliance on wintertime grid electricity for powering lighting and equipment, and given that current Fort Chipewyan electricity is reliant on diesel combustion, as are most of Canada's remote communities [84], this contributed to many GHG emissions.

4.5. A note about Fort Chipewyan

Given that this is an indigenous community, which lives under conditions that can be traced back to colonization, there are additional qualitative factors at play in this case that would require special treatment but are outside of the quantitative assessment presented here. A recently proposed and currently undergoing federally funded construction project aims to improve the local electric grid by imbuing it with a 25% renewable electricity mix from a 2.2 MWh solar PV and storage array [85]. This would mean that a reliable, low-maintenance displacement of diesel-fired electricity could reduce the cost and emissions of power without the need for the local solar array modelled here. Similarly, there is the possibility of cordwood having much lower cost due to the logistics of the community's access to land and resources. The reliance on locally available fuels and resources can be beneficial in securing autonomy and community empowerment, which are concepts that ultimately lie outside of the authors' expertise.

5. Limitations

The analysis of the case study was simplified in several ways. Although care was taken to account for all climatic effects, wind speed and solar irradiance on opaque surfaces were neglected. During the design of the HRES, distribution equipment, such as ductwork, fans, pumps, CO_2 injection, sensors, and other equipment required for adequate climate control, were not within the scope of the analysis. For the modelling of the HRES on an annual operating basis, the emissions estimation was simplified by only considering GHG emissions expressed as equivalent CO_2 emissions. As such, biomass combustion was modelled under the assumption that it is carbon neutral when wood is regrown sustainably [59,86,87]. However, if a more thorough environmental impact assessment was performed, which was not within the scope of the study, land-use change and deforestation effects, as well as particle matter (PM) and volatile organic compound (VOC) emissions would be considered [88]. Other factors excluded in the environmental analysis were packaging and waste, disposal of the system, and transport of fuel and resources. In other words, since this analysis was not a full life-cycle assessment (LCA), many stages of the whole production process were neglected. The same was true for the traditional production case in the southern USA; the use of fertilizer or pesticides and machinery were not considered. Although, refrigerant leakage was considered for the effect of transport emissions, the actual environmental impact from refrigerant leakage was excluded because only combustion emissions were considered. For the financial analysis, any insurance, administrative, or disposal costs were not considered, and sensitivity analysis on any life cycle cost components was excluded from the scope. Export of electricity was not modelled, since there was no certainty that a net-metered connection would be realistic in this case. Plus, a monthly time basis was not detailed enough to accurately model the generation versus demand relationship anyway. Therefore, the analysis was limited to the case of 'net-zero' performance. Lastly, any wastewater fees were excluded as it was assumed that the water drainage from the hydroponics system was captured and reused in the community for local composting or outdoor plot farms.

6. Conclusion

Given the harsh conditions of northern climates, year-round horticulture can only be achieved with adequate environment control in enclosed spaces. This study has presented a detailed design and optimization protocol for retrofitting light industrial buildings in northern Canada with renewable energy-assisted hydroponics systems. Heating, cooling, humidity control, and sufficient levels of airborne carbon are all critical factors that must be accounted for during the design of the retrofit operation. Furthermore, once the requirements are determined, it is beneficial to explore renewable energy options to aim for sustainable operation and chosen systems must be sized according to appropriate design load evaluation procedures using in the building science industry. Depending on how complex the final system arrangement is, the operational strategy may not be trivial and therefore, optimization by way of numerical methods could be necessary. Regardless, the proposed retrofitted facility should be compared with traditional food production methods in terms of finances and environmental impact to determine feasibility. Conversely, it is essential to remember that this quantitative assessment does not have a capability to capture the decision-making values associated with the historical exploitation of northern communities due to colonization.

This procedure was performed on a 270 m^2 case study building in Fort Chipewyan, Alberta. A hybrid renewable energy system consisting of a ground-source heat pump, biomass boiler, propane furnace, solar photovoltaic array, humidifier, dehumidifier, water heater, and an exhaust fan was proposed for the building. As such, this study included the demonstration of the use of a genetic algorithm coupled with a goal attainment solver to optimize a multi-objective problem. In this case, the objectives were operating costs and greenhouse gas emissions, which were selected to ensure that the lettuce produced from the indoor commercial farm would be a viable alternative to traditional lettuce import. For economic analysis, life cycle cost was an adequate assessment that considered lifetime expenses and food production quantity and was compared with existing prices for the same food type. An environmental impact assessment was limited to an import displacement analysis that compared operating facility emissions against the transport of an equivalent quantity of food. It was found that although the optimized hybrid renewable energy system has the potential to improve annual operating performance, this specific facility design is only feasible in the realm of cost savings for its proposed function, with an average lettuce cost of 4.47 ± 0.01 \$/kg from the proposed facility. Meanwhile, the existing price of the crop, available in the local store, was estimated as 5.86 ± 0.29 \$/kg, which would make local production in the facility a competitive alternative. However, its emissions performance is unfavourable due to an excessively high reliance on imported, diesel-generated electricity. The facility would result in 2.86 ± 0.004 kg of CO_2e per kilogram of lettuce produced, as compared with 0.97 ± 0.034 kg of CO_2e per kilogram of imported lettuce, which would effectively triple the amount of greenhouse gases emitted by local production. Regardless, this protocol has proved to be a useful method of planning retrofit projects in northern Canada that experience food supply chain disruptions, especially those brought on by the current state of COVID-19.

CRediT authorship contribution statement

Artur Udovichenko: Conceptualization, Methodology, Writing - original draft, preparation. **Brian A. Fleck:** Writing - review & editing, Reviewing and Editing. **Tim Weis:** Visualization, Investigation. **Lexuan Zhong:** Supervision, Project administration, Writing - review & editing, Writing- Reviewing and 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.

Acknowledgements

The authors gratefully acknowledge the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC) Engage program. The authors also thank Mr. Rob Macintosh and Mr. Clayton Stafford for providing technical information on the facility design.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2021.102160.

References

[1] O. Leblanc-Laurendeau, Food insecurity in northern Canada: an overview, 2020, https://lop.parl.ca/sites/PublicWebsite/default/en_CA/ResearchPublications/201918E, 2019.
[2] Oecd, Food supply chains and COVID-19: impacts and policy lessons. http://www.oecd.org/coronavirus/policy-responses/food-supply-chains-and-covid-19-impacts-and-policy-lessons-71b57aea/, 2020.
[3] M.M. Queiroz, D. Ivanov, A. Dolgui, S. Fosso Wamba, Impacts of epidemic outbreaks on supply chains: mapping a research agenda amid the COVID-19 pandemic through a structured literature review, Ann. Oper. Res. (2020).
[4] Sophie Wirzba, COVID-19 is worsening food insecurity in Nunavut. https://www.mironline.ca/covid-19-is-worsening-food-insecurity-in-nunavut/, 2020.
[5] S. Mercier, M. Mondor, S. Villeneuve, B. Marcos, The Canadian food cold chain: a legislative, scientific, and prospective overview, Int. J. Refrig. 88 (2018), https://doi.org/10.1016/j.ijrefrig.2018.01.006. http://www.sciencedirect.com/science/article/pii/S0140700718300112.
[6] A. De Gelder, J.A. Dieleman, G.P.A. Bot, L.F.M. Marcelis, An overview of climate and crop yield in closed greenhouses, J. Hortic. Sci. Biotechnol. 87 (2012).
[7] H.S. Grewal, B. Maheshwari, S.E. Parks, Water and nutrient use efficiency of a low-cost hydroponic greenhouse for a cucumber crop: an Australian case study, Agric. Water Manag. (2011) 841–846, https://doi.org/10.1016/j.agwat.2010.12.010, 98, http://www.sciencedirect.com/science/article/pii/S0378377410003938.
[8] National Energy Board, Market Snapshot, Explaining the high cost of power in northern Canada, 2020, https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/snpsht/2017/02-03hghcstpwr-eng.html?=undefined&wbdisable=true, 2020.
[9] J. Bambara, A.K. Athienitis, Energy and Economic Analysis for the Design of Greenhouses with Semi-transparent Photovoltaic Cladding, Renewable Energy, 2019, p. 131, https://doi.org/10.1016/j.renene.2018.08.020. http://www.sciencedirect.com/science/article/pii/S0960148118309704.
[10] N. Yildirim, L. Bilir, Evaluation of a Hybrid System for a Nearly Zero Energy Greenhouse, Energy Conversion and Management, 2017, p. 148, https://doi.org/10.1016/j.enconman.2017.06.068. http://www.sciencedirect.com/science/article/pii/S0196890417306131.
[11] G. Russo, A.S. Anifantis, G. Verdiani, G.S. Mugnozza, Environmental analysis of geothermal heat pump and LPG greenhouse heating systems, Biosyst. Eng. (2014) 127, https://doi.org/10.1016/j.biosystemseng.2014.08.002. http://www.sciencedirect.com/science/article/pii/S1537511014001317.
[12] M. Esen, T. Yuksel, Experimental Evaluation of Using Various Renewable Energy Sources for Heating a Greenhouse, Energy Build, 2013, p. 65, https://doi.org/10.1016/j.enbuild.2013.06.018. http://www.sciencedirect.com/science/article/pii/S0378778813003563.
[13] S. Baddadi, S. Bouadila, W. Ghorbel, A. Guizani, Autonomous greenhouse microclimate through hydroponic design and refurbished thermal energy by phase change material, J. Clean. Prod. (2019) 360–379, https://doi.org/10.1016/j.jclepro.2018.11.192, 211, http://www.sciencedirect.com/science/article/pii/S0959652618335959.
[14] A.M. Syed, C. Hachem, Net-zero energy design and energy sharing potential of Retail - greenhouse complex, Journal of Building Engineering (2019) 24, https://doi.org/10.1016/j.jobe.2019.100736. http://www.sciencedirect.com/science/article/pii/S2352710218313159.
[15] P. Henshaw, Modelling changes to an unheated greenhouse in the Canadian subarctic to lengthen the growing season, Sustainable Energy Technologies and Assessments (2017) 24, https://doi.org/10.1016/j.seta.2016.12.004. http://www.sciencedirect.com/science/article/pii/S2213138816302399.
[16] D. Geleta, M. Manshahia, Optimization of renewable energy systems: a review, International Journal of Scientific Research in Science and Technology 3 (2017) 769–795.
[17] E. Iddio, L. Wang, Y. Thomas, G. McMorrow, A. Denzer, Energy efficient operation and modeling for greenhouses: a literature review, Renew. Sustain. Energy Rev. 117 (2020) 109480.
[18] M. Ko, Y. Kim, M. Chung, H. Jeon, Multi-objective optimization design for a hybrid energy system using the genetic algorithm, Energies 8 (2015) 2924–2949.
[19] Y. Xie, P. Hu, N. Zhu, F. Lei, L. Xing, L. Xu, Collaborative Optimization of Ground Source Heat Pump-Radiant Ceiling Air Conditioning System Based on Response Surface Method and NSGA-II, Renewable Energy, 2020, pp. 249–264, https://doi.org/10.1016/j.renene.2019.08.109, 147, http://www.sciencedirect.com/science/article/pii/S0960148119312960.
[20] A. Kusiak, F. Tang, G. Xu, Multi-objective optimization of HVAC system with an evolutionary computation algorithm, Energy 36 (2011) 2440–2449.
[21] R. Braun, M. Haag, J. Stave, N. Abdelnour, U. Eicker, System design and feasibility of trigeneration systems with hybrid photovoltaic-thermal (PVT) collectors for zero energy office buildings in different climates, Sol. Energy 196 (2020) 39–48.
[22] J.A. Dyer, R.L. Desjardins, Y. Karimi-Zindashty, B.G. McConkey, Comparing Fossil CO2 Emissions from Vegetable Greenhouses in Canada with CO2 Emissions from Importing Vegetables from the Southern USA, Energy for Sustainable Development, 2011, pp. 451–459, https://doi.org/10.1016/j.esd.2011.08.004, 15, http://www.sciencedirect.com/science/article/pii/S0973082611000664.
[23] M. Michalský, P.S. Hooda, Greenhouse gas emissions of imported and locally produced fruit and vegetable commodities: a quantitative assessment, Environ. Sci. Pol. (2015) 32–43, https://doi.org/10.1016/j.envsci.2014.12.018, 48, http://www.sciencedirect.com/science/article/pii/S1462901114002469.
[24] H. Resh, Hydroponic Food Production, CRC Press, Boca Raton, 2013.
[25] ASHRAE, ASHRAE Handbook - Fundamentals, 2017, 2017.
[26] L. Graamans, A. van den Dobbelsteen, E. Meinen, C. Stanghellini, Plant factories; crop transpiration and energy balance, Agric. Syst. (2017) 138–147, https://doi.org/10.1016/j.agsy.2017.01.003, 153, http://www.sciencedirect.com/science/article/pii/S0308521X16306515.
[27] M.K. McGowan, Solving growing problems: load calculations for cannabis grow facilities, ASHRAE J. 62 (2020).
[28] J.B. Jones, Hydroponics : a practical guide for the soilless grower. http://www.crcnetbase.com/isbn/9781420037708, 2005.
[29] N. Castilla, E. Baeza, A.P. Papadopoulos, Greenhouse Technology and Management, second ed., Greenhouse Technology and Management, 2012, pp. 1–335. Second Edition.
[30] D. Loustau, S. Rambal, The forest carbon cycle: generalities, definitions and scales, in: D. Loustau (Ed.), Forests, Carbon Cycle and Climate Change, 2010, pp. 19–26.
[31] C.A. Mitchell, F. Sheibani, Chapter 10 - LED advancements for plant-factory artificial lighting, in: T. Kozai, G. Niu, M. Takagaki (Eds.), Plant Factory, second ed., Academic Press, 2020, pp. 167–184.
[32] L. Graamans, E. Baeza, A. van den Dobbelsteen, I. Tsafaras, C. Stanghellini, Plant factories versus greenhouses: comparison of resource use efficiency, Agric. Syst. 160 (2018) 31–43.
[33] M. Fadaee, M.A.M. Radzi, Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms: a review, Renew. Sustain. Energy Rev. 16 (2012) 3364–3369.
[34] N. Gunantara, A review of multi-objective optimization: methods and its applications, Cogent Engineering 5 (2018).
[35] A. Konak, D.W. Coit, A.E. Smith, Multi-objective optimization using genetic algorithms: a tutorial, Reliab. Eng. Syst. Saf. (2006) 992–1007. 91, https://doi.org/10.1016/j.ress.2005.11.018. http://www.sciencedirect.com/science/article/pii/S0951832005002012.
[36] Mathworks, Gamultiobj Algorithm. https://www.mathworks.com/help/gads/gamultiobj-algorithm.html, 2020.
[37] Mathworks, Multiobjective genetic algorithm options. https://www.mathworks.com/help/gads/gamultiobj-options-effects.html, 2020.
[38] M. Kissinger, International trade related food miles – the case of Canada, Food Pol. 37 (2012) 171–178.

[39] M. Brechner, A.J. Both, C.E.A. Staff, Controlled Environment Agriculture - Hydroponic Lettuce Handbook, Cornell University, 2013. https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/8/8824/files/2019/06/Cornell-CEA-Lettuce-Handbook-.pdf.
[40] ASHRAE, Ashrae STD 62.1 - ventilation for acceptable indoor air quality. https://global.ihs.com/doc_detail.cfm?&item_s_key=00456163&item_key_date=800215&input_doc_number=ASHRAE%2062%2E1&input_doc_title=, 2019.
[41] ASHRAE, ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Applications, 2015, 2015.
[42] G. Niu, T. Kozai, N. Sabeh, Chapter 11 - Physical Environmental Factors and Their Properties, Plant Factory, second ed., 2020, pp. 185–195, https://doi.org/10.1016/B978-0-12-816691-8.00011-X. http://www.sciencedirect.com/science/article/pii/B978012816691800011X.
[43] National Oceanic, Atmospheric Administration, ESRL global monitoring laboratory - global radiation and aerosols, 2020, https://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html, 2020.
[44] H.O.M.E.R. Pro, Clearness Index, 2020, p. 2020. https://www.homerenergy.com/products/pro/docs/latest/clearness_index.html.
[45] B. Ahn, C. Jang, S. Leigh, S. Yoo, H. Jeong, Effect of LED lighting on the cooling and heating loads in office buildings, Appl. Energy (2014) 1484–1489, https://doi.org/10.1016/j.apenergy.2013.08.050, 113, http://www.sciencedirect.com/science/article/pii/S0306261913006946.
[46] R. Liu, X. Zhou, S.J. Lochhead, Z. Zhong, C.V. Huynh, G.M. Maxwell, Low-energy LED lighting heat gain distribution in buildings, part II: LED luminaire selection and test results, Science and Technology for the Built Environment 23 (2017) 688–708.
[47] H.- Daunicht, Gas turnover and gas conditions in hermetically closed plant production systems, in: E. Goto, K. Kurata, M. Hayashi, S. Sase (Eds.), Plant Production in Closed Ecosystems, Springer Netherlands, 1997, pp. 225–244.
[48] J.J. Hanan, Greenhouses: Advanced Technology for Protected Horticulture, CRC Press, 1998.
[49] E. Nederhoff, Effects of CO2 Concentration on Photosynthesis, Transpiration and Production of Greenhouse Fruit Vegetable Crops, Prof. Dr. Ir. H. Challa (Promotor), Landbouwuniversiteit Wageningen, 1994, p. 213, 1994.
[50] J.M. Frantz, G. Ritchie, N.N. Cometti, J. Robinson, B. Bugbee, Exploring the limits of crop productivity: beyond the limits of tipburn in lettuce, Journal of the American Society for Horticultural Science jashs 129 (2004) 331–338.
[51] R. Hiroki, H. Shimizua, A. Ito, H. Nakashima, J. Miyasaka, K. Ohdoi, Identifying the optimum light cycle for lettuce growth in a plant factory, Acta Hortic. 1037 (2014) 863–868.
[52] J.A. Majorowicz, S.E. Grasby, Heat transition for major communities supported by geothermal energy development of the Alberta Basin, Canada, Geothermics 88 (2020) 101883.
[53] S.B. Mahbaz, A. Dehghani-Sanij, M.B. Dusseault, J.S. Nathwani, Enhanced and integrated geothermal systems for sustainable development of Canada's northern communities, Sustainable Energy Technologies and Assessments (2020) 37, https://doi.org/10.1016/j.seta.2019.100565. http://www.sciencedirect.com/science/article/pii/S2213138819304096.
[54] S.P. Kavanaugh, K.D. Rafferty, Geothermal Heating and Cooling : Design of Ground-Source Heat Pump Systems, ASHRAE, Atlanta, 2014.
[55] M. Grobe, R.J.H. Richardson, K. Johnston, J. Quibell, H.S. Schillereff, B. Tsang, Importance of geoscience information in the implementation of closed-loop ground-source heat-pump systems (geoexchange) in Alberta , energy resources conservation board Alberta geological survey. https://ags.aer.ca/document/OFR/OFR_2009_09.pdf, 2009.
[56] National Energy Board, Neb – economics of solar power in Canada – appendix A: methods, 2020, https://www.cer-rec.gc.ca/nrg/sttstc/lctrct/rprt/cnmcsfslrpwr/ppndx-eng.html, 2020.
[57] NREL, NREL's PVWatts® Calculator, 2020, https://pvwatts.nrel.gov/pvwatts.php, 2020.
[58] ASHRAE, Standard methods of measuring, expressing and comparing building energy performance and greenhouse gas emissions. https://global.ihs.com/doc_detail.cfm?&item_s_key=00011540&item_key_date=850708&input_doc_number=ASHRAE%20105%20ERTA%20HTTPS%3A%2F%2FGLOBAL%2EIHS%2ECOM%2FDOC%5FDETAIL%2ECFM&input_doc_title=, 2014.
[59] Environment, Climate Change Canada, National inventory report 1990-2017: greenhouse gas sources and sinks in Canada, 2020, http://publications.gc.ca/collections/collection_2019/eccc/En81-4-2017-2-eng.pdf, 2019.
[60] Statistics Canada, Electric power generation, annual fuel consumed by electric utility thermal plants, 2020, https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=2510001701#timeframe, 2020.
[61] Statistics Canada, Electricity from fuels, annual generation by electric utility thermal plants, 2020, https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=2510001901#timeframe, 2020.
[62] NWT power corporation, business electrical rates. https://www.ntpc.com/customer-service/business-service/business-rates, 2020.
[63] Gwich'in Council International, Diverging from diesel. https://www.rncan.gc.ca/sites/www.nrcan.gc.ca/files/energy/energy-resources/Diverging_from_Diesel_-_Technical_Report_FINAL.pdf, 2017.
[64] Alberta Firewood, Cordwood prices, 2020, https://www.albertafirewood.ca/prices.html, 2020.
[65] Bluewave Energy, Propane, 2020, https://www.bluewaveenergy.ca, 2020.
[66] Praxair, Buy liquid carbon dioxide or compressed carbon dioxide gas (CO2), 2020, http://www.praxair.ca/en-ca/gases/buy-liquid-or-compressed-carbon-dioxide-gas, 2020.
[67] Regional municipality of wood buffalo, fees, rates and charges bylaw. https://www.rmwb.ca/Assets/Departments/Legislative+and+Legal+Services/Bylaws/Bylaw+19.010+Fees$!2c+Rates+and+Charges+Bylaw.pdf, 2019.
[68] R.H. Howell, Principles of Heating Ventilating and Air Conditioning, 8 ed., 2017.
[69] M. Panagiotidou, L. Aye, B. Rismanchi, Solar driven water heating systems for medium-rise residential buildings in urban mediterranean areas, Renew. Energy 147 (2020) 556–569.
[70] M. Moges, A review and recommendations for Canadian LCCA guidelines. https://www.tac-atc.ca/sites/default/files/conf_papers/ayed.a-a_review_and_recommendations_for_canadian_lcca_guidelines.pdf, 2017.
[71] C. Krus, Analysis of Life Cycle Cost Methods for Heating, Ventilation, and Air Conditioning Systems in Hospitals, 2004.
[72] Government of Alberta, Wages and salaries in Alberta. https://alis.alberta.ca/occinfo/wages-and-salaries-in-alberta/general-farm-workers/8431/, 2020.
[73] B. Dai, H. Qi, W. Dou, S. Liu, D. Zhong, H. Yang, V. Nian, Y. Hao, Life cycle energy, emissions and cost evaluation of CO2 air source heat pump system to replace traditional heating methods for residential heating in China: system configurations, Energy Convers. Manag. 218 (2020) 112954.
[74] Q. Tu, J. Mo, R. Betz, L. Cui, Y. Fan, Y. Liu, Achieving grid parity of solar PV power in China- the role of Tradable Green Certificate, Energy Pol. 144 (2020) 111681.
[75] Q. Zhang, L. Zhang, J. Nie, Y. Li, Techno-economic analysis of air source heat pump applied for space heating in northern China, Appl. Energy 207 (2017) 533–542.
[76] Google Maps, Napa to Fort McMurray, 2020, https://www.google.com/maps/dir/Napa,+California,+USA/Fort+McMurray,+AB/@47.1149278,-126.31764,5z/data=!3m1!4b1!4m14!4m13!1m5!1m1!1s0x8084ffe7f8f2deef:0xd6629f3a3384c725!2m2!1d-122.286865!2d38.2975381!1m5!1m1!1s0x53b03aeeff1a4459:0x5c8133330dca74b7!2m2!1d-111.3790441!2d56.7266598!3e0, 2020.
[77] Regional Municipality of Wood Buffalo, Fort Chipewyan Winter Roads, 2020, 2020, https://www.rmwb.ca/Municipal-Government/municipal_departments/Public-Operations/Roads/Winter-Roads/Fort-Chipewyan-Winter-Roads.htm.
[78] Distance calculator, distance from Fort McMurray to Fort Chipewyan. https://distancecalculator.us/search.php?from=fort+mcmurray&tcity1ll=&to=fort+chipewyan, 2020.
[79] S.A. Tassou, G. De-Lille, Y.T. Ge, Food transport refrigeration – approaches to reduce energy consumption and environmental impacts of road transport, Appl. Therm. Eng. 29 (2009) 1467–1477.
[80] A. Udovichenko, L. Zhong, Application of air-source heat pump (ASHP) technology for residential buildings in Canada, IOP Conf. Ser. Mater. Sci. Eng. 609 (2019), 052006.
[81] Government of Alberta, Alberta retail food prices: selected communities. https://open.alberta.ca/dataset/b4f477b4-a3a5-40cc-bd5f-b1e14e88e329/resource/2058319c-b3b5-4b3a-9567-b8da4809fbfa/download/af-alberta-retail-food-prices-selected-communities-2019-06.pdf, 2019.
[82] CBC News, How one Alberta First Nation addressed food security in an isolated, northern community. https://www.cbc.ca/news/canada/edmonton/fort-chipewyan-food-security-1.5469384, 2020.
[83] Nunavut Bureau of Statistics, Nunavut food price survey – price comparison per kilogram and litre, 2018, http://www.stats.gov.nu.ca/en/Economic%20prices.aspx, 2018.
[84] Government of Canada, Status of Remote/Off-Grid Communities in Canada, 2011.
[85] ATCO, Fort Chipewyan off-grid solar & storage, 2020, https://www.atco.com/en-ca/projects/fort-chipewyan-off-grid-solar.html, 2020.
[86] A. Evans, V. Strezov, T.J. Evans, Sustainability Considerations for Electricity Generation from Biomass, Renewable and Sustainable Energy Reviews, 2010, pp. 1419–1427, https://doi.org/10.1016/j.rser.2010.01.010, 14, http://www.sciencedirect.com/science/article/pii/S1364032110000183.
[87] US EPA, Wood residue combustion in boilers. https://www3.epa.gov/ttn/chief/ap42/ch01/index.html, 2003.
[88] C. Geng, W. Yang, X. Sun, X. Wang, Z. Bai, X. Zhang, Emission factors, ozone and secondary organic aerosol formation potential of volatile organic compounds emitted from industrial biomass boilers, J. Environ. Sci. (2019) 64–72, https://doi.org/10.1016/j.jes.2019.03.012, 83, http://www.sciencedirect.com/science/article/pii/S1001074218324665.
[89] Wikipedia, Fort Chipewyan. https://en.wikipedia.org/w/index.php?title=Fort_Chipewyan&oldid=945618750, 2020.