Chapter 61
Comparative Environmental Impact Assessment of Residential HVAC Systems

Nader Javani, Fadi Abraham, Ibrahim Dincer, and Marc A. Rosen

Abstract Residential energy use represents a considerable fraction of the total energy consumption in a region. Therefore, there is an increasing focus on reducing energy use and related greenhouse gas (GHG) emissions by improving the energy efficiency of building envelopes and major household appliances. The residential sector can benefit from the application of environmental impact assessment methods like life cycle assessment (LCA), which can be used to evaluate the environmental impacts of building materials, appliances, and heating, ventilation, and air conditioning (HVAC) units. Results of such assessments can identify and target important areas for improvement, to achieve optimal benefits. In this chapter, two residential HVAC systems in Canada are compared using the ReCiPe method. The systems are evaluated against a number of important environmental impact indicators. The results show that heat pumps present a good option for reducing household energy consumption and GHG emissions. Furthermore, areas for improvement are identified and suggestions are provided which aim at increasing residential energy efficiency and reducing related GHG emissions.

Keywords Efficiency • Environmental assessment • Greenhouse Gas • Heat Pump • Residential sector

Nomenclature

I_m Midpoint impact category
h Specific enthalpy (kJ/kg)
k Thermal conductivity (W/m C)

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$\dot{Q}$	Heat transfer rate (kW)
Q_{mi}	Characterization factor
R	Thermal Resistance (m^2.K/W)
T	Temperature (K or °C)
U	Overall heat transfer coefficient (W/m^2 K)

Subscripts

crit	Critical
en	Energy
g	Gas
i	Inventory

Acronyms

AFUE	Annual fuel utilization efficiency
A/C	Air conditioning
GHG	Greenhouse gas
GWP	Global warming potential
HVAC	Heating, ventilation, and air conditioning
LCA	Life cycle assessment
ODP	Ozone depleting potential
PCM	Phase change material
VOC	Volatile organic compound

61.1 Introduction

Residential greenhouse gas (GHG) emissions constitute 15 % of the total GHG emissions in Canada despite improvements in the energy efficiency of building materials, appliances, and heating, ventilating, and air conditioning (HVAC) systems [1]. This is mainly due to the steady increase of the average house size over the past few years, and is fostering improvements in energy efficiency in residential buildings. Various mature technologies for residential heating and cooling applications exist for consumers. Typically, the choice of technology is influenced by a number of factors such as: energy efficiency, initial investment, payback period, and reliability. In recent years the government of Ontario, the largest province in Canada, began efforts at raising public awareness about global warming and greenhouse gas emissions, and introduced various incentive programs to promote energy-efficient appliances and energy conservation practices [2].

The environmental impact of residential buildings has been investigated previously, including studies on key aspects such as embodied energy in construction materials, maintenance and operational energy usage. A study commissioned by the Canada Mortgage and House Corporation (CMHC) found that the building foundation and exterior envelope account for 40 % of the initial embodied energy of building systems, while 74 % of the overall life cycle energy use of the building is consumed during the operation phase [3]. Kassab et al. estimated the embodied energy of a modern, energy efficient house with a floor area of 310 m^2 located in Montreal, Canada as 2,280 MJ/m^2 [4]. Several other studies address similar themes for various locations and weather conditions around the world [5–7].

Fewer studies have shed light on residential HVAC applications. The environmental impact of hot water and forced air heating systems has been evaluated for a house located in Quebec, Canada [8]. The concepts of expanded cumulative exergy consumption (ECExC) and embodied energy were used as indicators of the environmental impact of the systems, and the authors concluded that the hot water heating system has the lowest ECExC. Another study compared a vapor compression unit and desiccant cooling device using EPS2000 method [9], and found that the energy consumed during the operation phase was the dominant contributor to the environmental impact of both systems. An ABB EU 2000 air handling unit also has been analyzed with respect to nine environmental impact categories and nine resource depletion categories [10]. Areas for improvement were identified such as increasing efficiency and avoiding galvanizing unit surfaces. The Eco-indicator 95 method has been applied to examine the environmental impact of the manufacturing stages and processes for three residential heating systems [11]: convection system, floor heating system, and radiator unit with pipes. The results of the study showed that the radiator unit has the highest environmental impact followed by the floor heating and the convection system, respectively.

In the present study, a comparative environmental impact assessment of two HVAC systems for a house located in Toronto, Ontario is performed, to improve understanding of the benefits of the options. The two systems considered are: (1) hot-air furnace combined with an air-conditioning unit, and (2) air-to-air heat pump unit. The ReCiPe method [12] is used to assess the environmental impact of the systems, and serves as a tool to assist home owners and builders in making informed decisions when purchasing or installing residential HVAC equipment.

61.2 System Description

61.2.1 Features of Residential Buildings

A typical modern detached house is selected for analysis. The total living space of the two-story building is 185 m^2 (2,000 sq. ft). The main floor comprises the kitchen, the family room, and the laundry area, while the second floor includes bedrooms and bathrooms. A two-car garage is attached to the house and considered to be part of the building envelope. Furthermore, the area of the basement is equal to

Table 61.1 Thermal resistance of building components (adapted from [14])

Building component	Thermal resistance [m^2 K/W]
Ceiling with roof space	7.00
Roof (no roof space)	5.00
Wall	3.35
Foundation wall	2.12
Concrete floor/slab	1.41
Window (fixed)	0.63
Glass door (sliding)	0.30
Exterior door	0.63

the area of the main floor [13]. The hot water heater and the HVAC equipment are located in the basement. The air distribution system consists of non-insulated galvanized metal ducts properly sized to handle the required volumetric air flow rates. The construction of the house conforms to the Ontario Building Code and the municipal code of Toronto [14, 15]. Because of the airtight construction of the house, natural air infiltration is taken to be 1.5 air changes per hour (ACH) at 50 Pa. The thermal resistances of the building components are listed in Table 61.1.

Additionally, the following assumptions are made in this study:

1. The front of the house faces East
2. The house is occupied by a family of four (two adults and two children)
3. The internal heat gain from occupants and appliances accounts for 15 % of the total energy supplied to the house

61.2.2 HVAC Equipment and System Boundaries

A regional study conducted by Natural Resources Canada (NRC) revealed that 76 % of households in the province of Ontario use a hot-air furnace (HAF) as the main heating system, mainly because affordability and availability in developed communities make natural gas the preferred fuel choice [16]. For summer cooling, window-type air conditioning units are available in a variety of sizes, but add-on central air conditioning (AC) units are usually more popular. Different heating systems and their market share in Canada have been listed in Table 61.2. The combination of HAF/AC shown in Fig. 61.1 forms the boundary of system “A” in this study.

Alternatively, a heat pump (HP) can replace the HAF/AC combination system, with the advantage that such a device can provide heating during winter and cooling during summer (dual mode). This is achieved using a reversing valve contained within the heat pump which allows for switching the direction of the refrigerant thus changing the mode of operation [16]. The heat pump is designated as system “B” with a system boundary as reflected in Fig. 61.2.

Table 61.2 Market share of various heating systems in Canada (adapted from [16])

Region	Heating system	Market share [%]
Atlantic	Electric baseboard	33
Quebec	Electric baseboard	61
Ontario	Hot-air furnace	76
Prairies	Hot-air furnace	82
British Columbia	Hot-air furnace	50

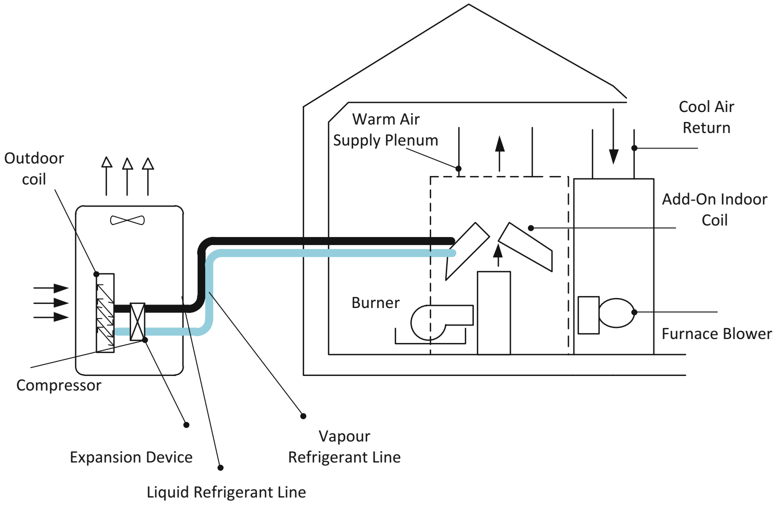

Fig. 61.1 Boundary definition of HAF/AC system (System "A") (Modified from [16])

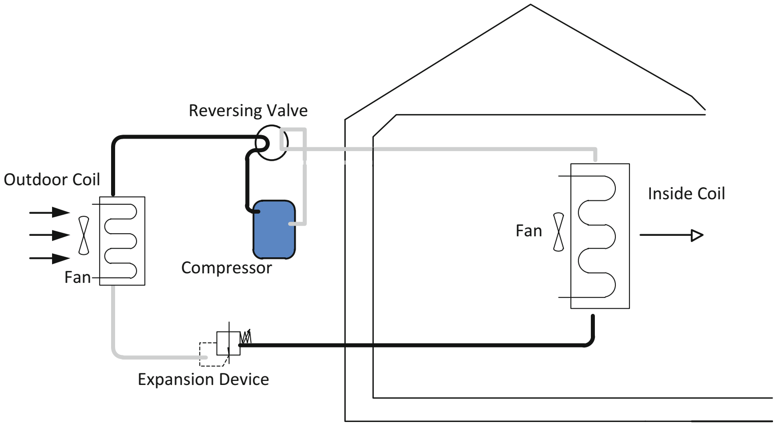

Fig. 61.2 Boundary definition of heat pump (HP) system (System "B") (Modified from [16])

Table 61.3 Rated capacities and efficiencies of subsystems (adapted from [18])

System	Subsystem	Capacity [kW]	Efficiency
A	HAF	19.35	AFUE = 93 %
	AC	7.00	SEER = 14
B	HP	17.60	SEER = 14

Table 61.4 Compositions and weights of materials for subsystems

Subsystem	Material	Weight [kg]
Furnace	Cold-rolled steel	36.21
	Galvanized steel	14.17
	Aluminum	7.08
	Copper	–
	Total	63.95
Air-conditioner	Cold-rolled steel	33.79
	Galvanized steel	15.16
	Aluminum	7.36
	Copper	7.36
	Total	63.68
Heat pump	Cold-rolled steel	84.84
	Galvanized steel	26.88
	Aluminum	5.88
	Copper	8.40
	Total	126.00

The program HOT2000 and the CSA standard (CAN/CSA F280) are used to size HVAC equipment [17]. The capacities of the systems are determined as shown in Table 61.3. To determine component distributions, compositions, and relative weights, units manufactured by Lennox International are selected. The units used for the base case study are energy-star rated and certified by the Air-Conditioning and Refrigeration Institute (ARI), and their capacities and efficiencies are listed in Table 61.3 [18]. The electronic components of the units are neglected in order to simplify this analysis without unreasonably compromising accuracy. Table 61.4 lists the material compositions and weights.

61.2.3 Weather Characteristics

Toronto is located in southern Ontario on the north shoreline of Lake Ontario. The lake serves to moderate the city's weather and renders it somewhat mild for Canada. The Degree-Days (DD) method provides a simplified representation of the historical weather data pertaining to a specific area or region. For this study, weather data are obtained from the weather station at Toronto's Pearson International Airport (CYYZ), located about 20 km northwest of Toronto city center [19]. The heating degree-days (HDD) and cooling degree-days (CDD) for Toronto are depicted in

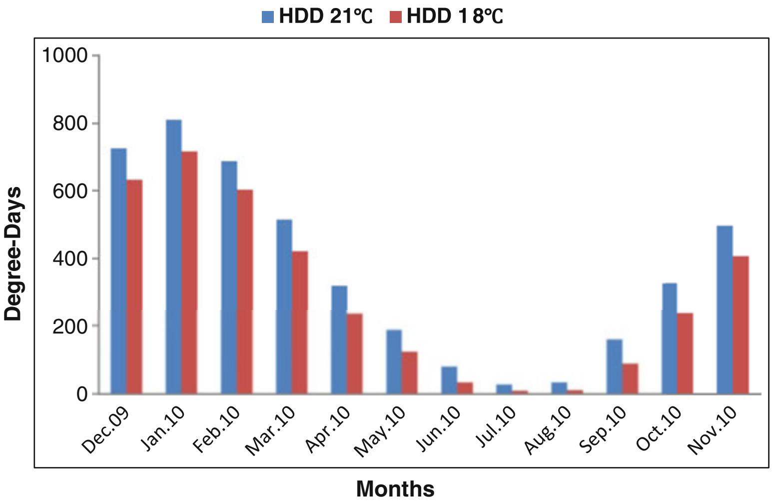

Fig. 61.3 Heating Degree-Days (HDD) for the city of Toronto for a typical year

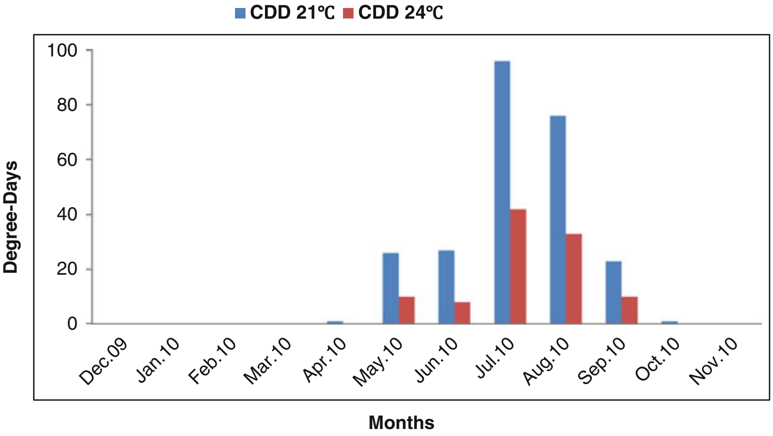

Fig. 61.4 Cooling Degree-Days (CDD) for the city of Toronto for a typical year

Figs. 61.3 and 61.4, respectively. The significant heating loads in comparison to the cooling loads can be clearly construed from the figures. A software application developed by CanmetENERGY (HOT2000) was used to estimate the heating and cooling requirements and to calculate the energy consumption of the residential building under study.

Data such as the building design characteristics, specifications of construction materials, number and type of appliances as well as internal heat gains can be specified by a user in detail. The current version of the software (version 10.51) has a great deal of flexibility that allows for the examination of multiple scenarios and comparative studies [20], which are presented in subsequent sections.

61.3 Methodology: ReCiPe Method

Since the inception of life-cycle assessment (LCA), efforts have been dedicated to improving the method. The International Standards Organization introduced the framework of LCA under the ISO 14040 series which aims at standardizing the process at an international level [12]. Various LCA methods based on ISO standards have been developed over the years. Although there are some differences among these methods in terms of determining the impact factors of various processes and substance, the majority of the methods follow the scheme of midpoint and endpoint evaluation indicators. The ReCiPe method uses midpoint indicators with environmental mechanisms like acidification, climate change, and ecotoxicity and endpoint indicators like human health and resource depletion [12].

Some researchers believe that there should be a harmonization between these two groups of indicators and consequently attempt to develop models with a harmonized structure [12, 21]. Some of the methods convert environmental hazardous substances and the effects of resource depletion to the midpoint level while other methods relate them to more generalized impacts at the endpoint level. Life cycle impact (LCI), midpoint and endpoint indicators are shown in Fig. 61.5, from left to right, respectively. Eighteen impact categories for midpoint level are considered in this method. These midpoint impact indicators can be linked to the endpoint level through environmental mechanisms. The endpoints are: (1) damage to human health (HH), (2) damage to ecosystem diversity (ED), and (3) damage to resource availability (RA).

It is useful to apply global rather than regional impacts since some environmental mechanisms are limited regionally in scope and can be ignored in a comprehensive list of mechanisms. Mechanisms like acidification, eutrophication, photochemical ozone formation, toxicity, wastewater and land use are dependent on regional conditions. This method is also suitable for developed countries. The impact categories are considered as design tools for sustainable engineering and policy making. Therefore, the endpoint level is selected based on important protection issues: human health, ecosystem quality, and availability of resources.

61.3.1 Impact Categories for Midpoint and Endpoint levels

For midpoints, the equivalent impact of different substances is shown in Table 61.5. Substances obtained from the life cycle inventory are categorized by their equivalent impact on the midpoint indicators. For example, CO_2 is generally agreed to be responsible for climate change and other substances may be expressed by their equivalent of CO_2, to show their effect on climate change. Although endpoints assign score points to each system, they are not considered since the midpoint can be normalized to show the relative environmental impact of the systems under investigation.

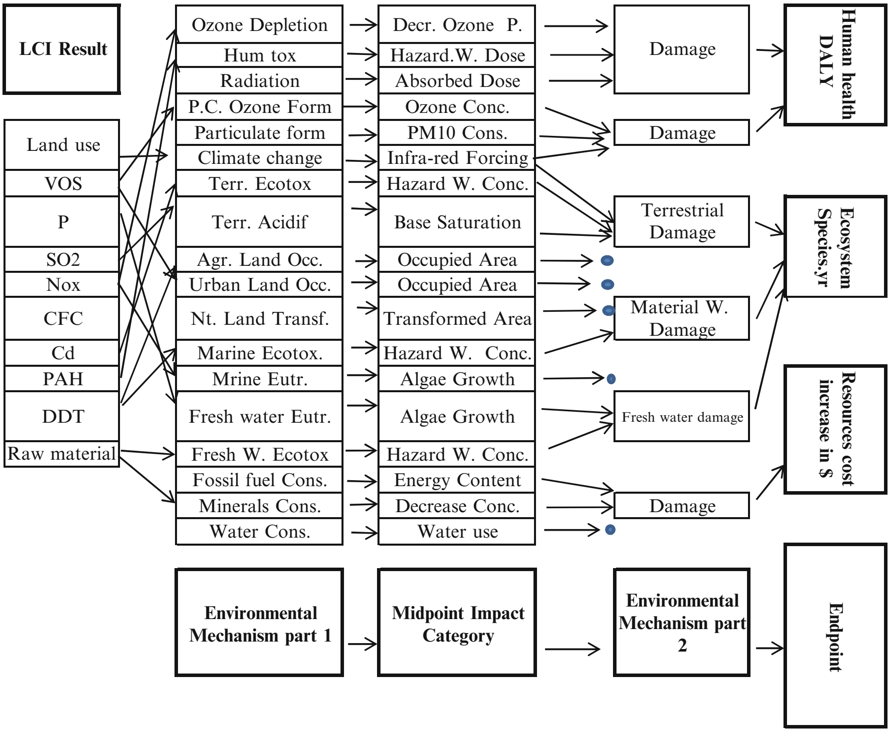

Fig. 61.5 Relationship between LCI, and midpoint and endpoint levels. (Modified from [12])

61.3.2 Midpoint Level in ReCiPe Method

For the midpoint level, this method uses the following relation:

$$I_m = \sum_{i}^{n} Q_{mi} mi$$

Here, m_i is the amount of considered intervention i, like the amount of CFC-11 released to atmosphere for ozone depletion impacts. Q_{mi} is a factor that connects midpoint impact category m to the intervention of i (Characterization Factor), and I_m represents midpoint impact category obtained for intervention i

Referring to ReCiPe database, there are three classifications in developing the impacts: (1) Individualist (I) as short-term time frame, (2) Hierarchist (H), and (3) Egalitarian (E) which uses a long-term schedule with a more conservative approach. In this study, we selected the Hierarchist class that uses 100 years as a time-frame of impact. As some researchers show, 50 years is rather more realistic, but the ReCiPe method does not consider such time frame [22].

Table 61.5 Midpoint, endpoint categories and characterization factors [12]

	Characterization factor name	Unit	Abbreviation
Midpoint Impact	Global warming potential	kg (CO_2 to air)	GWP
	Ozone depletion potential	kg (CFC-115 to air)	ODP
	Terrestrial acidification potential	kg (SO_2 to air)	TAP
	Freshwater eutrophication potential	kg (P to freshwater)	FEP
	Marine eutrophication potential	kg (N to freshwater)	MEP
	Human toxicity potential	kg (14DCB to urban air)	HTP
	Photochemical oxidant formation potential	kg (NMVOC6 to air)	POFP
	Particulate matter formation potential	kg (PM10 to air)	PMFP
	Terrestrial ecotoxicity potential	kg (14DCB to industrial soil)	TETP
	Freshwater ecotoxicity potential	kg (14DCB to freshwater)	FETP
	Marine ecotoxicity potential	kg (14-DCB7 to marine water)	METP
	Ionizing radiation potential	kg (U235 to air)	IRP
	Agricultural land occupation potential	m^2 × year (agricultural land)	ALOP
	Urban land occupation potential	m^2 × year (urban land)	ULOP
	Natural land transformation potential	m^2 (natural land)	NLTP
	Water depletion potential	m^3 (water)	WDP
	Mineral depletion potential	kg (Fe)	MDP
	Fossil depletion potential	kg (oil)	FDP
Endpoint Impact	Indicator Name	Impact Category Name	Unit
	Damage to human health	Damage to human health	Year
	Loss of species during a year	Damage to ecosystem diversity	Year
	Increased cost	Damage to resource availability	$

61.3.3 Life Cycle Inventory Assessment (LCIA)

After identifying the material composition of the HVAC units, a life cycle inventory is constructed using the materials database provided by the National Renewable Energy Laboratory (NREL) [23]. The NREL database provides individual "cradle-to-gate" accounting of the energy and material inputs and outputs relative to the production of materials and substances. While populating and analyzing specific inventories, it came to our attention that some emissions to nature were assigned negative values. No clarification is provided in the NREL inventory user manual, so we assume there is a net gain (positive impact) resulting from such emissions; however, these values are not considered in our final results. The NREL database is not comprehensive and does not contain information regarding the production of copper tubing. Consequently, the copper life cycle inventory is obtained from the European Copper Institute [24]. Although the inventory resources and methods of preparations are potentially different, this represents the best available information for this study. Note that LCA software is not used in this study. Instead, all relevant inventories are manually processed to develop a better understanding of the environmental impact assessment stage.

61.3.4 Assumptions and Limitations

All life cycle assessment methods have inherent limitations which may differ from one method to another [22]. The following assumptions and limitations are invoked in the current study:

1. Due to the lack of reliable data, only the energy consumption is considered for the manufacturing stage for the units.
2. Maintenance, reduction in system efficiency, and waste disposal are neglected since these factors are assumed comparable for both systems.
3. Environmental impact results are influenced by operating conditions.
4. The electricity generation profile in a given region remains the same for the duration of the study.
5. At the stage of production of raw materials, the ratio of scrap–virgin materials is 52:48, 31:69, 30:70, and 50:50 for aluminum, cold rolled steel, galvanized steel, and copper, respectively.

61.4 Results and Discussion

The impact assessment is divided over the three life stages of the HVAC devices: production of metals from raw materials, manufacturing/assembly of HVAC units, and operation. Using the midpoint factors from the ReCiPe method, the impact of raw materials production for each system is depicted in Fig. 61.6. The results are normalized by selecting system “A” as the reference system. In general, the environmental impact of system “A” is similar to that of system “B.” This result is primarily dictated by the large amount of raw materials required by system “B,” which has a total mass of 140 kg in comparison to the combined mass of system “A” (64 kg for HAF and 71 kg for AC).

HVAC units are manufactured using proprietary processes. An extensive search for the environmental impact of such processes yielded unreliable data. However, Yang et al. were able to estimate the energy consumption during the manufacturing stage using the manufacturing cost of the respective unit which is approximately equal to 1.8 MJ/$ [8, 25]. The cost of each unit was then estimated to be equal to $1400, $2000, and $3500 for the AC, HAF, and HP, respectively [26]. Figure 61.7 shows the energy consumption during the production of raw materials

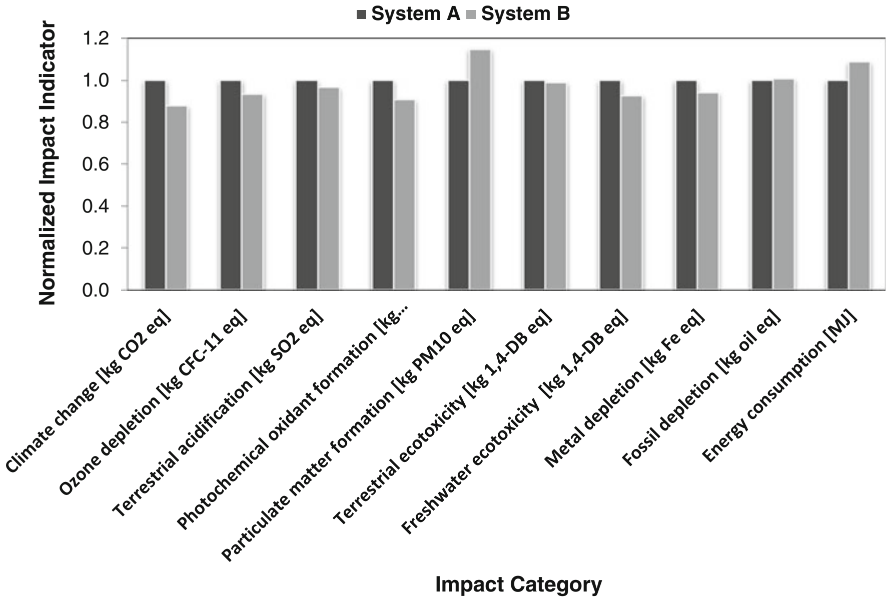

Fig. 61.6 Normalized impact of the production of raw materials for both systems

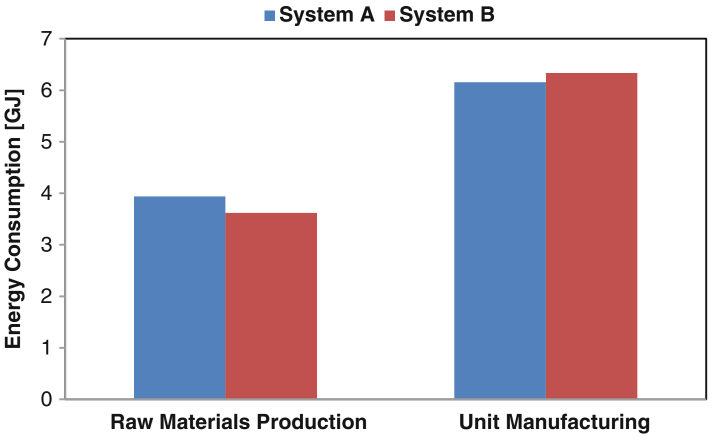

Fig. 61.7 Energy consumption during the raw material production and manufacturing

along with the estimated consumption of energy during the manufacturing stage. Although the energy consumption of both systems is comparable in both stages, the consumption during the manufacturing stage appears to be about 50 % higher. The uncertainty associated with the method of estimating the energy consumption during manufacturing may have contributed to the final values.

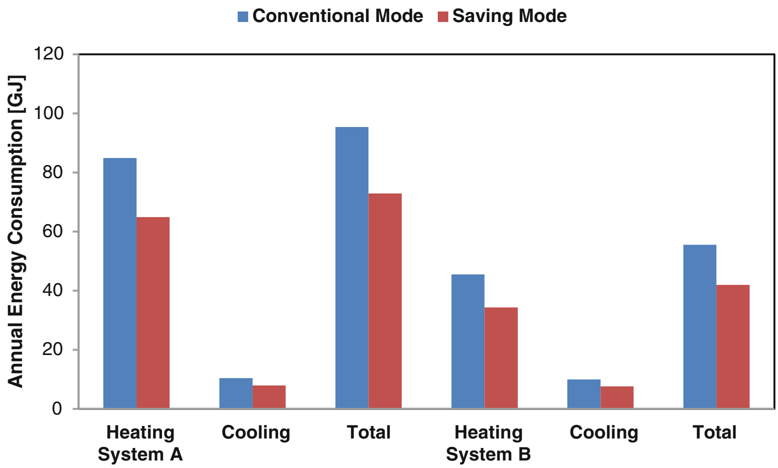

Fig. 61.8 Annual energy consumption for systems

The operational life of the system represents the longest life stage. These systems may last between 15 and 25 years depending on a number of factors like initial quality, operating environment and maintenance. Two operating modes are considered to evaluate their impact on the energy consumption during the heating and cooling seasons. The conventional mode assumes that the thermostat heating and cooling set points are equal to 21 °C. The saving mode assumes that some ventilation cooling may be achieved during mild weather by opening the house windows while lower heating requirements may be met by reducing the setting temperature on the thermostat. Accordingly, the thermostat heating and cooling set points are 18 °C and 24 °C, respectively.

The annual energy consumption is depicted in Fig. 61.8 which compares both systems and reflects the benefit on the saving mode of operation. The reduction of energy consumption amounts to 5–25 % using the saving mode. Furthermore, 30–40 % of additional energy savings may be realized during the heating season by using the heat pump while minimal energy saving is achieved during the cooling season due to the comparable energy efficiency of the air-conditioning unit and the heat pump (cooling mode).

Greenhouse gas emissions are an important aspect in assessing the environmental impact of the systems under consideration. Carbon dioxide is considered to be a major greenhouse gas, so much effort is being expended to mitigate its production and release to the environment [27]. The impact assessment performed on the stage of raw materials production takes into account CO_2 release and its effects on climate change as depicted in Fig. 61.6. However, the CO_2 emissions during the unit manufacturing stage may be estimated by assuming that the units are manufactured at Lennox facilities in Texas, USA (Lennox Headquarters) and that electricity is the primary fuel used during the process. The CO_2 emission factor for

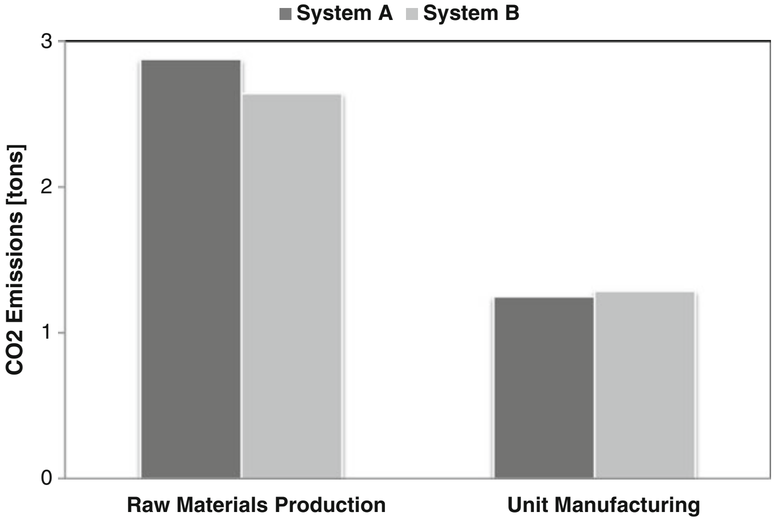

Fig. 61.9 CO_2 emissions during the raw material and unit manufacturing stages

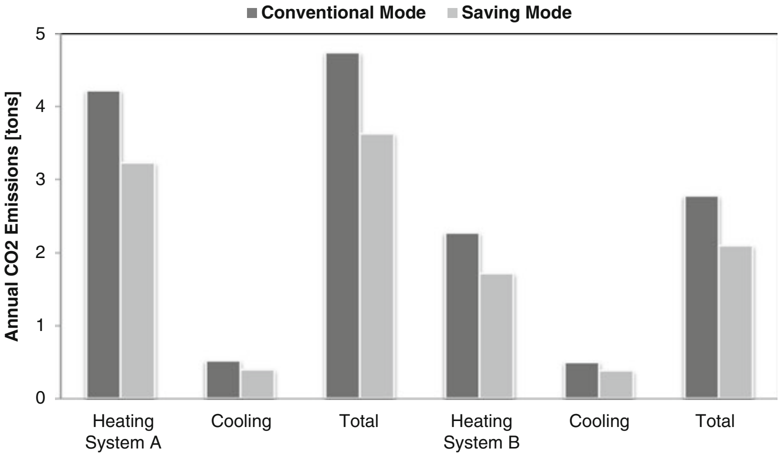

Fig. 61.10 Annual CO_2 emissions

electricity produced in the State of Texas is 0.73 ton_{CO2}/MWh [28]. The CO_2 emissions based on the energy consumption only (effects of chemical emissions are not considered) are shown in Fig. 61.9.

On the other hand, the operation phase of the systems occurs in Ontario, Canada which has CO_2 emission factors of 0.18 ton_{CO2}/MWh and 0.0497 ton_{CO2}/GJ for electricity and natural gas consumption respectively [29, 30]. The annual CO_2 emissions during the operation phase are reflected in Fig. 61.10. By comparing

Figs. 61.9 and 61.10, it can be seen that emissions during the annual operation phase are higher than those during the production of raw materials and unit manufacturing combined. The results also show that there is an environmental benefit from using the heat pump system for heating and cooling throughout the year.

61.5 Conclusions

A comparative life cycle assessment of two residential HVAC systems is demonstrated. LCA methods normally consider a set of assumptions which can highly influence the final outcome of the assessment. Our results show that weather characteristics and geographic location can heavily impact the environmental assessment of residential HVAC systems since their performances and efficiencies are weather dependent. A sensitivity analysis may be incorporated within the LCA to address the effects of uncertainty associated with various input data and life cycle inventories on the final results. While using heat pumps for heating and cooling may yield energy savings and reductions in greenhouse gas emissions, financial savings are difficult to realize by the end user. This is mainly due to the higher specific cost of electricity (per unit energy) compared to natural gas, which leads to long payback periods if a heat pump is to be selected for use. Some financial factors such as inflation rate, interest rate, and rise of commodity prices can also alter the LCA outcome and the benefits of using one system over the other. Further research and development is merited to improve the energy efficiency of building envelops, materials, and major home appliances, and local governments should consider endorsing energy-efficient appliances through incentive programs and end-user education.

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