Techno- Economic Analysis of Combined Solar Water Heating Systems in Cold Climate Regions

by

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ABSTRACT

Traditional furnaces and gas-based tank water heaters are pervasive in residential buildings in cold climate regions such as in Alberta, Canada, despite the availability of alternative heating systems with higher efficiencies, lower noise production, reduced pollution emission, and which occupy less space. The aim of this study was to perform a techno-economic analysis to consider alternative heating systems as an investment, using the traditional heating system as a benchmark. The alternative heating plants examined were conventional (non-condensing) and condensing boilers and condensing tankless water heaters that were coupled to forced air hydronic air handling units. In this study, a model was created in which a set of similar houses with identical domestic hot water heating load and different floor areas were used to determine the effect of the space heating load on the suitability of the alternative units as a function of the size of the building. A comparison between the annual natural gas consumption, GHG emissions, and mitigation, and annual cost savings for different houses indicated that the tankless water heaters economically attractive and has higher potential for CO_2 mitigation of all the systems that were studied. This suggests that tankless water heaters are potentially useful for residential applications for the purpose of garnering energy savings and enabling CO_2 mitigation. Moreover, this study considers a techno-economic analysis of a solar water heating system (SWHS) with evacuated tube solar collectors for different solar loads, ranging in size from 20% to 100% of the total roof area of a typical residential building located in Edmonton, Alberta, Canada. The SWHS is combined with different alternative heating systems that are compared to a traditional heating system, consisting of a conventional boiler, applied to houses of various gross floor areas. A comparison among the alternative heating systems for annual natural gas consumption, GHG emissions, and mitigation in various house sizes indicated that the combined solar heating system can reduce the natural gas consumption and CO_2 emissions, and increase CO_2 mitigation for all the systems that were studied. The results illustrated that solar water heating systems are beneficial for residential heating system usage in terms of energy savings and GHG mitigation. However, because of the values of annual cost savings, and annual GHG abatement costs, combined SWHS would not be suitable as an economic option in Edmonton, Canada, based on the large capital costs of the SWHS.

PREFACE

Section 2.7of the thesis document was developed in collaboration with Mr. Alberto Palomino.

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"The true sign of intelligence is not knowledge but imagination."

Albert Einstein

TABLE OF CONTENTS

ABSTRACT i

PREFACE……………………………………………………………………………………..iv

ACKNOWLEDGMENTS iv

LIST OF FIGURES viii

LIST OF TABLES xi

NOMENCLATURE xii

1. INTRODUCTION 1

1.1 EXISTING HEATING SYSTEMS………………………………………………..1

1.2 COMBO HEATING SYSTEMS AND COMBO ECONOMIC ANALYSIS………… 2

1.3 SOLAR WATER HEATING SYSTEMS 6

1.3.1 SYSTEM COMPONENTS AND OPERATION……………………………………..6

1.3.2 SOLAR THERMALCOLLECTORS…………………………………………………9

1.3.3 RESEARCH STUDIES……………………………………………………………..11

1.3.4 TECHNO- ECONOMIC ANALYSIS………………………………………………15

1.4 OBJECTIVES………..……………………………………………………………..19

1.5 THESIS ORGANIZATION 21

2. THEORY AND ASSUMPTIONS 22

2.1 MODEL HOUSE.. 22

2.2 EQUIPMENT SELECTION 23

2.3 ANNUAL HEATING PERIOD……………………..……………………………..24

2.4 PERFORMANCE ANALYSIS………..……………………………………….……...28

2.5 ECONOMIC ANALYSIS…………………………………………………..……30

2.6 EXTRAPOLATION OF SPACE HEATING LOAD………..………………………..31

2.7 MATHEMATICAL MODEL………………………………..……………………..32

2.8 SWHS TECHNICAL ASSUMPTIONS……..…………………………………….…..37

2.9 SWHS ECONOMIC ASSUPTIONS………..…………………………………………...38

2.10 SWHS COMBINED SWHS PERFORMANCE ANALYSIS…………..…………...39
2.11 COMBINED SWHS ECONOMIC ANALYSIS………..………...…………………40
3. RESULTS AND DISCUSSION…………………………….....…………………………..41
3.1 NATURAL GAS CONSUMPTION AND CO_2 MITIGATION……..……………….41
3.2 ECONOMIC ANALYSIS………..…………………………….….……….………43
3.3 EFFECT OF HOUSE FLOOR AREA………………………...…….….…….……….47
3.4 SENSITIVITY ANALYSIS FOR THE MODEL HOUSE…..………….……….……..52
3.5 NATURAL GAS (NG) CONSUMPTION IN THE COMBINED SWHS…..…...…..56
3.6 CO_2 EMISSION IN THE COMBINED SWHS………………….....…….……..……..60
3.7 CO_2 MITIGATION IN THE COMBINED SWHS…………………………...…….63
3.8 ANNUAL COST SAVINGS IN THE COMBINED SWHS………..….……….……66
3.9 GHG ABATEMENT COST (GAC) IN THE COMBINED SWHS…..………..…….69
3.10 ANNUAL COST SAVINGS (ACS) WITH THE CO_2 TAX……...……..………...72
3.11 GHG ABATEMENT COST (GAC) WITH THE CO_2 TAX…….……….….……...75
3.12 POSSIBILITY OF THE USE OF SWHS IN THE FUTURE………...…………..…78
4. CONCLUSIONS…………………………………………………………...……..82
5. REFERENCES 85

LIST OF FIGURES

Figure 1-1: Schematic of a typical combo heating system……………………………………4

Figure 1-2: Solar collectors' orientation angels [23]………………………………………8

Figure 1-3: Glazed flat plate collector [29]………………………………………………..9

Figure 1-4: Evacuated tube collectors' components [31]……………………………………10

Figure 2-1: The floor plan of the model house ……………………………………...…22

Figure 2-2: Flow chart for the subdivision of heating time by application……….……….25

Figure 2-3: Schematic of the gas tank water heater ……………………………………….33

Figure 3-1: GHG abatement cost (GAC) curve for the model house ………………………..45

Figure 3-2: Annual NG consumption ……………………………………………………...…47

Figure 3-3: Annual CO_2 mitigation …………………………………………………………48

Figure 3-4: Annual cost savings (ACS)………………………………..………………49

Figure 3-5: GHG abatement cost (GAC)……………………………………………….....50

Figure 3-6: GHG abatement cost (GAC) curve for 1000 ft^2 house ……………….……...51

Figure 3-7: Sensitivity analysis for ACS based on the gas price changes …………………..53

Figure 3-8: Sensitivity analysis for GAC based on the gas price changes…………………...54

Figure 3-9: Sensitivity analysis for ACS based on thermal efficiency changes …………….55

Figure 3-10: Sensitivity analysis for GAC based on thermal efficiency changes ……………56

Figure 3-11: Annual Natural gas consumption for 20% solar coverage……………………...57

Figure 3-12: Annual Natural gas consumption for 40% solar coverage ……………………..58

Figure 3-13: Annual Natural gas consumption for 60% solar coverage ……………………..58

Figure 3-14: Annual Natural gas consumption for 80% solar coverage ……………………..59

Figure 3-15: Annual Natural gas consumption for 100% solar coverage ……………………59

Figure 3-16: Annual CO_2 emissions for 20% solar coverage ………………………………...60

Figure 3-17: Annual CO_2 emissions for 40% solar coverage ………………………………...61

Figure 3-18: Annual CO_2 emissions for 60% solar coverage …………………………………61

Figure 3-19: Annual CO_2 emissions for 80% solar coverage…………………………………62

Figure 3-20: Annual CO_2 emissions for 100% solar coverage……………………………......62

Figure 3-21: Annual CO_2 mitigation for 20% solar coverage ……………………………..….63

Figure 3-22: Annual CO_2 mitigation for 40% solar coverage ………………………………...64

Figure 3-23: Annual CO_2 mitigation for 60% solar coverage ………………………………...64

Figure 3-24: Annual CO_2 mitigation for 80% solar coverage ………………………………...65

Figure 3-25: Annual CO_2 mitigation for 100% solar coverage ……………….………………65

Figure 3-26: Annual cost savings (ACS) for 20% solar coverage ……………………………66

Figure 3-27: Annual cost savings (ACS) for 40% solar coverage ……………………………67

Figure 3-28: Annual cost savings (ACS) for 60% solar coverage…………………..………67

Figure 3-29: Annual cost savings (ACS) for 80% solar coverage ……………………………68

Figure 3-30: Annual cost savings (ACS) for 100% solar coverage …………………………..68

Figure 3-31: Annual GHG abatement costs (GAC) for 20% solar coverage …………..……70

Figure 3-32: Annual GHG abatement costs (GAC) for 40% solar coverage…………………70

Figure 3-33: Annual GHG abatement costs (GAC) for 60% solar coverage ………………...71

Figure 3-34: Annual GHG abatement costs (GAC) for 80% solar coverage…………………71

Figure 3-35: Annual GHG abatement costs (GAC) for 100% solar coverage …………..….72

Figure 3-36: Annual cost savings (ACS) with CO_2 tax for 20% solar coverage …………….73

Figure 3-37: Annual cost savings (ACS) with CO_2 tax for 40% solar coverage …………….73

Figure 3-38: Annual cost savings (ACS) with CO_2 tax for 600% solar coverage …………..74

Figure 3-39: Annual cost savings (ACS) with CO_2 tax for 80% solar coverage …….……...74

Figure 3-40: Annual cost savings (ACS) with CO_2 tax for100% solar coverage …………...75

Figure 3-41: Annual GHG abatement costs (GAC) with CO_2 tax for 20% solar coverage….76

Figure 3-42: Annual GHG abatement costs (GAC) with CO_2 tax for40% solar coverage…..76

Figure 3-43: Annual GHG abatement costs (GAC) with CO_2 tax for 60% solar coverage….77

Figure 3-44: Annual GHG abatement costs (GAC) with CO_2 tax for 80% solar coverage….77

Figure 3-45: Annual GHG abatement costs (GAC) with CO_2 tax for 100% solar coverage…78

LIST OF TABLES

Table 2-1: The values used to calculate the heating time for the cycle of the gas tank water heater………………………………………………………………………… 27

Table 2-2: The values of the properties of CO_2 and NG (CH_4)…………………………….28

Table 2-3: The values of the properties used to compute the estimate of the cooling time in the gas tank water heater cycle ……………………………………………........36

Table 3-1: The values used to calculate heat load and annual heating time for space heating

……………………………………………………………………………………………..41

Table 3-2: Natural Gas Input Requirements for Heating Systems …………………………42

Table 3-3: Annual NG Consumption and CO_2 Mitigation ………………………………...43

Table 3-4: Annuity and Operating Costs ……………………………………………………..44

Table 3-5: ACS and GAC for Different Heating Systems…………………………………45

Table 3-6: Economic cost of SWHS in the model house (1000 ft^2) with 20% solar coverage ……………………………………………………………………………………………..79

Table 3-7: Economic cost of SWHS in the model house (1000 ft^2) with 40% solar coverage ………………………………………………………………………………………………80

Table 3-8: Economic cost of SWHS in the model house (1000 ft^2) with 60% solar coverage 80

Table 3-9: Economic cost of SWHS in the model house (1000 ft^2) with 80% solar coverage80

Table 3-10: Economic cost of SWHS in the model house (1000 ft^2) with 100% solar coverage81

NOMENCLATURE

A_s	surface area (m^2)
ACH	air change rate (hr^{-1})
Cap	capacity factor
c_p	specific heat capacity of air ($kJkg^{-1}K^{-1}$)
D	diameter of gas water heater (m)
g	acceleration due to gravity (ms^{-2})
G_h	recovery rate (m^3s^{-1})
h	heat transfer coefficient ($Wm^{-2}K^{-1}$)
i	interest rate (%)
k	thermal conductivity ($Wm^{-1}K^{-1}$)
L	height of the mass of water in the gas tank water heater (m)
n	the number of compounding periods
P	present value of original capital costs
Pr	Prandtl number

Q energy transferred as heat (kJ)

$\dot{Q}$ rate of heat transfer (W)

$\dot{Q}_{\text{SWHS}}$ the amount of heat provided by the SWHS

$\dot{q}$ Specific rate of heat transfer (W/kg)

r the radius from the center of the mass of water inside the gas tank water heater (m)

R radius of gas water heater (m)

$R''_{\text{Insulation}}$ thermal resistance due to insulation on tank (Km^2W^{-1})

Ra_{D_o} Rayleigh number, $\text{Ra}_{D_o} = g\beta\left(T_s - T_o\right)D_o^3\,\text{Pr}/\upsilon^2$

SWHS solar water heating system

t time (s)

T temperature (^oC)

TWH tankless water heater

U overall heat transfer coefficient ($Wm^{-2}K^{-1}$)

V volume of the interior of the building (m^3)

$\dot{V}$ volumetric flow rate (m^3s^{-1})

Greek Symbols

α thermal diffusivity (m^2s^{-1})

β Reciprocal of temperature

$\delta_{insulation}$ thickness of insulation (m)

ε_{tank} Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$)

η thermal efficiency

λ_n eigenvalues

υ kinematic viscosity (m^2s^{-1})

ρ density (m^3kg^{-1})

Subscripts

a air

ave average

DHW corresponding to domestic hot water heating

e emitted

h high

i initial

in inside

ind individuals

l low

o outer

out outside

ref reference

w corresponding to water at mean temperature

WH water heater

1. INTRODUCTION

1.1 EXISTING HEATING SYSTEMS

Nowadays, a large variety of different heating systems are used in residential applications. Furnace- based heating systems, in- floor hydronic heating systems, electric heating systems, steam heating systems, and heat pumps are the most common heating systems used in different residential applications. Forced- air furnaces are the most common heating systems in Canada. To achieve a higher efficiency from a furnace, condensing technology is typically used that absorbs heat from the water vapour and decreases the heat loss. There are different types of furnaces, including wood- electric combination furnaces, oil- electric combination furnaces, oil-fired furnaces, and gas- fired furnaces [1]. Besides, in- floor hydronic heating systems consist of plastic pipes that are installed under the floor. The piping system circulates water through the house and transfers the heat into the floor surface. By dispersing the heat through the floor surface, the water cools down; therefore, the water is transferred into the heat source to heat up at the same rate. It is important to know that the heat needed for the residential application is determined by the floor covering, the flow rate, water temperature, and the distances between the pipes [2]. Electric heaters are also used in many residential and commercial applications in Canada. There are different types of electric heating systems, including electric furnaces, radiator- like units, portable plug- ins, decorative fireplaces, and powerful air- curtain heaters. In these systems, thermostats are utilized to control energy use, and the temperature [3]. Steam heating is one of the oldest heating systems used for residential applications as well. It is typically difficult to control the heat distribution in such a system due to the fact that there is always a long delay of the steam distribution between the boiler and the radiators. Therefore, steam heating system is less efficient than modern heating systems. There are two types of steam radiators, including a one- pipe system, and a two- pipe system. In one- pipe system, the pipe that transfers the steam also returns condensate, however, in two- pipe system, a separate pipe is utilized to return the condensate [4]. Moreover, a heat pump is an electrical system that absorbs heat from somewhere and transfers it to another place. The place can be the ground or the air. In winter, they absorb the heat from the air or the ground and move it into the house. However, in summer, the same happens in reverse. In cold climate regions, heat pumps are typically combined to another heat source in order to supplement the heat needed for the residential application [5].

1.2 COMBO HEATING SYSTEMS AND TECHNO-ECONOMIC ANALYSES

In recent years, integrated water heating and hydronic space heating systems, commonly known as combo heating systems, have begun to permeate the commercial and residential building markets because they have lower maintenance and installation costs and usually require less space. It has been shown that well-designed integrated water heating systems can have a noticeable effect on energy savings compared to separate water heating systems [8]. These systems provide thermal energy through fan coils or under-floor heating, and use radiators for space heating. Similarly, domestic hot water is supplied by means of a single source. The systems utilize oil, gas, pellets, or solid wood fuel, or a combination of any of these fuel sources [8], while other systems may be fuelled by electricity or solar energy [8, 9]. Combo heating systems have a large variety of configurations which can be divided into three groups: (1) reversible-cycle heat pump systems, which provide both space and water heating, (2) domestic hot water (DHW) heaters with indirect space heating, and (3) space heating systems with indirect DHW heating [10, 11].

Instantaneous or tankless water heaters can be used for residential applications [8, 13]. They can provide uninterrupted, "on demand" supply of hot water because of their modulating function, where the water flow rate is adjusted to heat the water to the temperature that is required by the present demand [14]. Tankless water heaters have been retrofitted for residential applications, and are available in combo units that can supplement space heating as well as DHW heating [12, 13]. In tankless water heaters, the heating rate varies with the temperature rise and the change of water flow rate. Most modern tankless water heaters have advanced multistage burners to control the outlet temperature of the water. Moreover, they have a flow switch which can control the burner and a modulating flow rate valve which controls the fuel flow. Some tankless water heaters also have electronic control units that reduces the standby energy losses in comparison to minimum-efficiency tank types which provide the same loads [15].

Combination space and tankless domestic hot water heating systems (combo heating systems) are used in residential applications. In these systems, the same water heating equipment is used for both domestic water heating and space heating. Therefore, it has a positive impact on space saving and capital costs .The combo heating systems have some noticeable advantages, including the compact space- size, low initial costs, high heating capacity, high water heating efficiency, and low standby losses [7]. The components of a typical combo heating system are shown in Fig. 1.1. As it can be seen in Fig. 1.1, the tankless water heater is combined to the air handler unit. The hot water provided by the tankless water heater (TWH) is used for both domestic hot water, and space heating. The water produced by the TWH is utilized by the air handler unit (AHU) to heat up the air, and then the heated air is used for space heating.

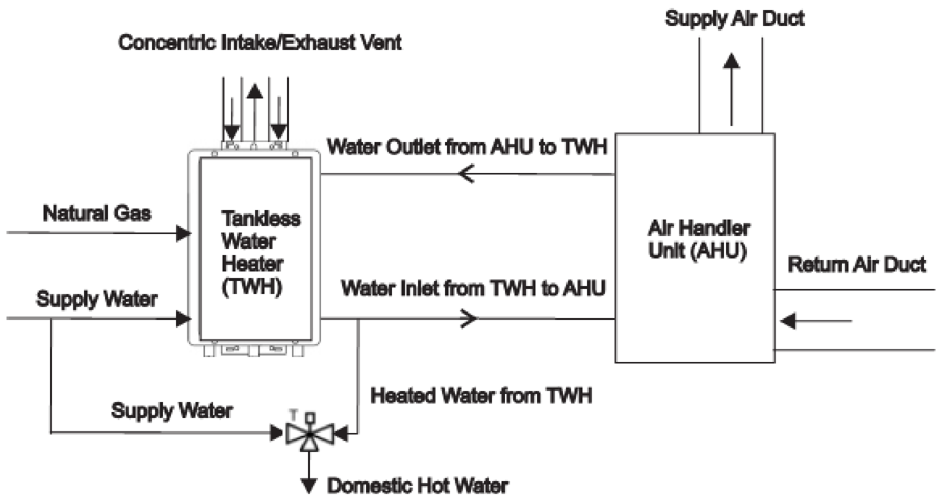

Fig1-1: Schematic of a typical combo heating system [6]

In 2007, the main kind of heating fuel utilized in Alberta was natural gas, with 88% of residential households using this fuel [16]. The natural gas components have a bad effect on air pollution and global warming [18]. It is found that the use of fossil fuels for the purpose of generating heat is noticeably responsible for producing GHG emissions [17]. Canada is one of the highest per capita GHG emissions producers among all the G8 countries with a 22% increase from 1990 to 2006 [19]. Therefore, improvements in the efficiency of heating systems for residential applications can result in potentially large energy savings and reduced pollution emission, which can contribute to reducing the carbon footprint of the residential housing sector.

Bohm and Danig [20] analyzed data on the performance of heating systems in buildings. Space and water heating systems for a residential apartment in a district heating scheme in Denmark was studied in an effort to analyze heat loads, energy consumption, and energy efficiency of pumps and heat exchangers. Cholewa and Siuta-Olcha [21] presented the results of an experiment that investigated heat use in a residential building that used residential thermal stations (RTS). The study showed that the use of RTS for producing hot water and heat for space heating is characterized by a high annual efficiency of 67%. Cholewa *et al*. [22] presented the results of an experimental study for three commonly available heating systems used for space and DHW heating in buildings. It was shown that the efficiency of the system was reduced when the system was producing hot water only, rather than when the system was operating during the heating season to provide space heating.

A number of studies have been performed on the economic and technical analysis of different energy systems to determine and assess energy savings, GHG mitigation, and GHG abatement costs. Dembo *et al*. [23] explored energy savings and GHG mitigation during heating of a building. A model of a typical single-family detached home was considered as the baseline. Three separate energy efficient options were considered and modeled using home energy simulation software to compare both energy savings and carbon dioxide reduction for space and domestic hot water energy use. Miller *et al*. [24] developed a techno-economic model to generate curves that indicate the typical annual energy savings, rate of return, and payback period for retrofitting aerial coolers with variable frequency drives (VFDs). Hang *et al*. [25] evaluated the economic and environmental life cycle of solar water heating systems for the U.S. market. The solar water heating systems were also compared with common conventional systems that utilized either electricity or natural gas. The sensitivity analysis showed that the daily hot water use had the most significant effect on energetic, environmental, and economic performance. Blum *et al*. [26] investigated the technical and economic factors that have an effect on the performance of vertical ground source heat pump (GSHP) systems. Bakos *et al*. [27] studied the installation, technical features, and economic performance of a grid-connected building integrated photovoltaic system (BIPV) installed in Northern Greece. Ren and Gao [28] analyzed two typical micro-combined heat and power (CHP) alternatives, including gas engine and fuel cell for residential buildings. The results of the analysis showed that, from both economic and environmental aspects, the fuel cell system was a better option for the residential building. Saban and Erdem [29] presented a techno-economic model for district heating systems. The fundamental parameters used in the model were area, number of buildings and dwellings, annual heat demand, and peak heat load. The results of the model were useful to predict the effect of the parameters on the cost of district heating systems. Although many of these studies on the techno-economic analysis of heating systems have been conducted to analyze energy consumption, GHG mitigation, GHG abatement cost, and other economic parameters of different energy systems, no studies have focused on a techno-economic analysis of combo heating systems for residential building applications in cold weather climates.

1.3 SOLAR WATER HEATING SYSTEMS (SWHS)

1.3.1 SYSTEM COMPONENTS AND OPERATION

Solar water heating systems (SWHS) collect the solar radiation and convert it to the heat used for different residential applications. The heat is transferred to water, and then the heated water is stored in the storage tank water heating system for the future use. Since the maximum solar radiation is not always reachable, notably in the late evening, an SWHS is combined to a conventional system that supplements the additional heat that can be used for the domestic usage. In general, SWHS consist of five basic components [30]:

1. Auxiliary hot water system to supplement the heat when the solar radiation is not enough. The auxiliary system can be a natural gas storage tank water heater or a tankless water heating system.
2. Control system to manage the distribution of thermal energy, the storage, and the collection.
3. Storage system to store the thermal energy provided by the solar collectors.
4. Heat transfer system that includes pumps, fans, piping and valves, and heat exchangers, if needed
5. Solar thermal collectors that are generally evacuated tube or flat plate collectors

The global market for solar water heating systems is increasing. However, the amount of energy provided by solar thermal systems varies in different countries. For instance, the capacity in China is 61%, Asian countries excluding China are 4.8%, Europe is 18.4%, and the United States and Canada is 8.2% [30]. Moreover, the solar thermal growth on a global scale has been increasing with an average of about 21% yearly from 2000 to 2010 [31].

The density of solar energy that is absorbed by the earth's atmosphere is approximately an average of 1,367 W-m^{-2}, which is absorbed or reflected and results in diffuse and direct solar radiation [32]. Diffuse and direct radiation can be used by different solar collectors. The amount of solar energy that can be absorbed by a solar collector depends on the orientation of the collector and the available solar radiation [32]. The orientation of a solar collector is defined by two different angles, including the tilt angle (β) and the Azimuth angle (α) [33]. The former is the angle between the horizontal surface and the collector and the latter is the angle of the collector from due north.It is really important to install a solar collector in the most optimal orientation. However, due to the availability of roof space, installing a solar collector in an optimal orientation is not always possible. In general, for solar collectors, an azimuth angle of within 60º of due South and a tilt angle of between 5º to 60º are suggested [33]. Solar collector orientation angles are shown in Fig. 1-1.

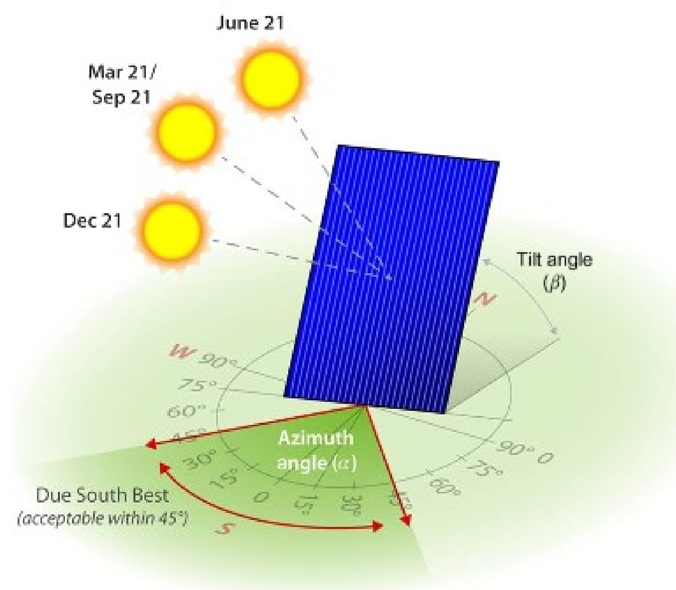

Fig1-2: Solar collectors' orientation angles [30]

Solar water heater is the most common type of solar energy utilization due to technological feasibility comparing to other types of solar energy utilization [34]. Solar water heating systems (SWHS) collect solar radiation from the sun and convert it to heat. The heat is transferred to water for the domestic use. Since hot water needed for residential applications is usually more during a day, an SWHS is typically coupled to a conventional system to provide the needed heat when the solar radiation is not available [30].

1.3.2 SOLAR THERMAL COLLECTORS

Generally, there are two types of solar collectors, including flat plate solar collectors (FPSCs) and evacuated tube solar collectors [35]. Typical applications of FPSCs consist of pool heating, residential space and water heating, and industrial process heat [30]. Fig. 1-2 shows the glazed one. As shown in Fig 1-2, the glazed FPSCs consist of different components. The sun heats the absorber plate that is covered by a coating and increases its temperature. When water enters the insulated metal box, the heat flows through the pipes and increases the water temperature inside the pipes. As shown in Fig. 1-2, the flat plate collector also consists of a glass cover to achieve a higher temperature and reduce the heat loss. It should not be left unmentioned that unglazed flat plate collectors are not covered by a glass or a plastic cover; therefore, due to the high heat losses, they are often utilized for low temperature applications [30].

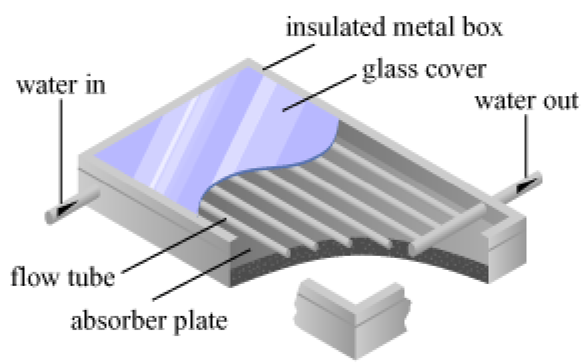

Fig. 1-3: Glazed flat plate collector [36]

On the other hand, unglazed FPSCs do not have a cover; therefore, they can absorb more of the solar radiation compared to the glazed ones, however, because of the increased heat losses, they cannot be used for high temperature applications.

Evacuated tube solar collectors (ETSCs) are utilized for residential and commercial space and water heating applications. ETSCs are usually as parallel rows of twin glass tubes. The inner surface of each tube is coated with different materials [30]. To keep heat inside the inner tubes, the both outer and inner pipes have the minimum reflection. The two tubes are joined together on the top side while pumping out the air which creates a vacuum. The created vacuum has a positive effect on absorbing the solar radiation without losing the heat [37]. Fig 1-3 shows the components of a typical ETSC.

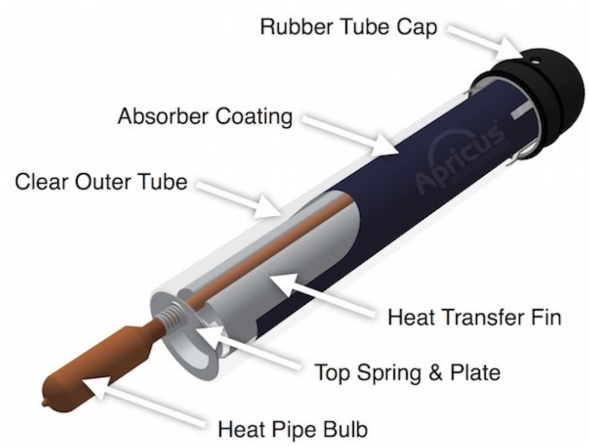

Fig. 1-4: Components of an evacuated tube solar collectors [38]

Many researchers have proved that ETSCs have greater efficiencies than flat plate solar collectors (FPCs), notably in cold climates owing to the fact that the efficiency of evacuated tube solar collectors does not drop as quickly when the outside air temperature decreases [39, 40]. For ETSCs and FPSCs, under similar environmental conditions, the collector efficiencies are 60.7% and 46.1% respectively for domestic water heating systems [41]. Also, ETSCs are so beneficial in terms of collecting both diffuse and direct radiation, ease of transport, convenient installation, and reasonable thermal performances [37]. Moreover, the maintenance of ETSCs is easy and cheap whereas FPSCs have higher maintenance and repair costs. For the former, when a tube is damaged, it can be repaired without stopping the system. However, for the latter, the entire system must be shut down in order to accommodate repair; therefore, the shutdown period is high in FPSCs [42]. Besides, they can be combined with other high temperature heating systems. For instance, boost tank incorporated solar preheaters, boost element integrated single solar tank system, and instantaneous gas heaters [43].

1.3.3 RESEACH STUDIES

In recent years, solar energy is one of the most indispensable resources of renewable energy systems in all over the world. Solar energy is renewable, clean, and widely available in comparison to traditional energy including fossil fuel and nuclear fuel [44]. Also, availability of large- scale solar energy resources can reduce building energy consumptions [45, 46]. Therefore, studying the possibility of applying different solar energy systems to buildings has a good effect on energy savings.

Many studies have focused efforts on improving and maximizing the utilization and collection of solar energy [47]. A variety of studies have investigated the domestic use of solar water heating systems for the purpose of energy savings. Kjellsson *et al*. [48] studied the utilization of ground-source heat pumps with solar collectors for heating and domestic hot water. They concluded that the optimal design was when solar collector provides domestic hot water during hot weather conditions and recharges the borehole during cold climate conditions. Ayompe and Duffy [49] presented the thermal evaluation of a solar water heating system with flat plate solar collectors in Dublin, Ireland. The annual average daily energy collected was 19.6 MJ/day, energy delivered by the solar coil was 16.2 MJ/day, and the collector efficiency was 45.6%. Jie *et al*. [50] studied the thermal characteristics of a building-integrated dual-function solar collector for water heating and space heating in winter. The results showed that when the system was working in the water heating mode, it performed well to provide hot water without causing overheating problems in the summertime. Bourke and Bansal [51] presented a new test method to determine the annual energy consumption of a domestic solar water heater incorporating a gas booster on the storage vessel outlet to supplement auxiliary heating. They found that the tested condensing gas booster was able to maintain a noticeable performance advantage over the non-condensing model for a range of solar water heaters. Bakirci *et al*. [52] investigated the performance of a solar-ground source heat pump system in Erzurum. The system had different components, including a ground heat exchanger (GHE), a liquid-to-liquid vapor compression heat pump, water circulating pumps, solar collectors, and other measurement equipment. The coefficient of performance of the system was found to be in the range of 2.7–3.0. Western and Benseman [53] measured the thermal performance of solar water heating systems in the New Zealand. They compared the electrical energy used by a conventional heated tank with the electrical energy utilized by the solar-assisted systems. Measurements were based on the electrical energy input, water quantity delivered, solar radiation, ambient temperatures, temperature of water delivered, and wind speed. Hobbi and Siddiqui [54] modeled and analyzed an indirect forced circulation solar water heating system using a flat-plate solar collector for domestic hot water application in Montreal, Canada. They showed that by using solar energy, the system could provide 30 – 62% and 83 – 97% of the hot water in winter and summer, respectively. Greening and Azapagic [55] studied life cycle environmental sustainability of solar water heating systems in UK conditions. The results showed that solar thermal systems decrease environmental effects, specially, compared to gas boilers. Therefore, they have much lower harmful emissions impact than different fossil-based options. Gastli and Charabi [56] investigated the potential of solar water heater usage in Oman .They used a mathematical model to evaluate the energy production, and emission reductions for different kinds of renewable-energy technologies. They showed that solar water heating systems have good environmental benefits to Oman. Wang *et al.* [57] provided a comprehensive review for SWHS regarding to their applications. Therefore, they analyzed different research questions including environmental performance assessment, energy savings, exploitation strategies, thermal and dynamic performance evaluation, sizing, and optimization. This study helped to understand the current barriers regarding to solar water heating systems in order to improve the systems performance and solar global market. Zeghib and Chaker [58] studied the modeling of a domestic solar water heating system operated in Constantine (Algeria). The system included a water storage tank, solar flat plate collectors, radiators, and a source of auxiliary energy. They examined the effect of the thermosiphon-flow rate on the solar water heating system performance. The presented analysis was an efficient model to design and analyze the solar systems under thermosiphon flow conditions. Liu *et al.* [59] presented the thermal evaluation of solar desalination system with evacuated tube solar collectors. They established mathematical models in order to examine the impact of the collector area and collector outlet water temperature on the system performance. Ayompe *et al.* [60] analyzed the thermal performance of a solar water heating system with the use of evacuated tube solar collectors over a year. They reported that the temperature at the bottom of the hot water tank was 59.5°C and the maximum collector outlet fluid temperature was 70.3 °C. Besides, the solar collector efficiency was 63.2%, and the solar fraction was 33.8%. Liangdong *et al.* [61] investigated the thermal performance of an evacuated tube solar collector by an analytical method. They also studied the effect of air layer and solar radiation on the heat efficiency value. They concluded with the increase of synthetical conductance, the fluid temperature and the solar collector efficiency increases as well. Hayek *et al.* [62] investigated the thermal performance of two types of evacuated solar collectors, including the heat pipe designs and the water-in glass designs under eastern Mediterranean weather conditions. The collectors were made of 20 evacuated tube solar collectors and the experiment was done from November to January. The results showed that the heat pipe collectors had better performance than the water-in-glass designs since their efficiency was 15 to 20% higher. Zheng *et al.* [63] studied the influence of the receiver's back surface radiative characteristics on the evaluation of a heat pipe evacuated tube solar collector. The results showed that with the increase of the back surface emissivity, the heat loss of the ETSC increased. They also tested two solar water heaters, including roughness-treated tubes and six ETSCs. The results indicated that when the water temperature was below 60°C, the two solar water heaters had similar temperature changes. However, when the water temperature is over 80°C, the solar roughness-treated tube had lower temperature increase compared to ETSCs tube. Kabeel *et al.* [64] studied the heat transfer process and the absorbed solar radiation in evacuated tube solar collectors. They compared different tilt angles operating in Egypt and indicated that 10°, 30° and 45° tilt angle ETSCs provide the maximum used solar energy over a year. Besides, they showed that the vertical evacuated tube solar collectors had the worst performance in the course of a year. Tang *et al.* [65] developed a mathematical model to calculate the total incidence radiation on evacuated tube solar collectors. The results showed that the yearly radiation on solar evacuated tubes is affected by different factors, including size of solar tubes, central distance between tubes, collector type, and tilt and azimuth angles. They also indicated that for increasing the annual energy collection by the solar collectors, the annual optimal solar tube collectors tilt angle should be less than the site latitude. Shah and Furbo [66] studied a theoretical model to examine the thermal performance of evacuated tube solar collectors in Denmark. The results showed that the highest thermal performance can be achieved when the collector azimuth was around 45 – 60º towards the west and the tube centre distance was around 0.2 m. Moreover, they compared the thermal performance of evacuated solar collectors to flat plate solar collectors. They determined that the thermal performance of evacuated tube collectors achieved the highest amount. Kim and Seo [67] investigated the thermal performance of an evacuated tube solar collector experimentally and numerically. According to the comparison of the calculated results, they concluded that the numerical analysis can accurately estimate the thermal performance. Also, they carried out that changing collector tube center distances can result in a different thermal performance owing to the fact that increasing the center distances of tubes, decreases the number of tubes and the absorbing area. Ucar and Inalli [68] studied and compared the thermal performances of three kinds of central solar heating systems, including underground storage tank without insulation, ground storage tank without insulation, and storage tank with insulation on ground. The results showed that the higher solar fraction was achieved for the system with underground storage. Therefore, solar saving of the system with underground storage was the most in comparison to the other systems. However, the higher heat loss was reported for a storage tank without insulation on ground.

1.3.4 TECHNO- ECONOMIC ANALYSIS

A variety of studies were focused on the economic analysis of different solar heating systems as well. Sreekumar [69] studied an economic analysis of a roof-integrated solar air heating system for drying fruit and vegetables by three methods, including present worth of cumulative savings, annual cost, and present value of annual savings. The solar air heater was with the area of 46 m^2

and maximum temperature of 76.6 °C. The results showed that the payback period was almost 0.5 year and the cost of dehydrating 1 Kg of pineapple by the solar system was almost half of an electric dryer. Faiza *et al*. [70] studied energy, and economic analysis of metal oxides nanofluid of a flat plate solar collector for a solar water heating system. They concluded that increasing the heat transfer area increased the output temperature. However, it increased the cost. They also examined the possibility of decreasing the size of solar collectors with the use of nanofluid as working fluid for the same desired output temperature. Huang *et al.* [71] studied the economic analysis of a solar-assisted heating system to find an economical design. In order to reduce the energy consumption of the air conditioner, a solar coolingbsystem was utilized to provide part of the cooling load. The economic analysis indicated that the payback period of the system decreases by the increase of cooling capacity. Buonomano *et al*. [72] presented economic analysis of geothermal–solar trigeneration systems in Ischia. The results showed that the system was very beneficial when high temperature geothermal sources were available. Besides, the system performance was more affected by the availability of the geothermal energy than the solar system. In the best case, the payback period was 2.5 years. However, in the worst case, the payback period was almost 7 years. Shatat *et al.* [73] studied an economic analysis of a small solar powered water desalination system for the purpose of calculating different economic parameters. The results indicated that the cost of potable water provided by a solar desalination compact unit was nearly 11 US$/m^3. However, by using an evacuated tube solar collector with an area of 3 m^2 the cost could reduce to 8 US$/ m^3. Sahnoune *et al.* [74] studied a comparative economic research between solar and conventional heating in an individual house in Algerian weather conditions. The results showed that in countries such as Algeria, solar heating system cannot be competitive with natural gas owing to fact that the conventional energy cost is mostly subsidized in such countries. Cassard *et al.* [75] studied the economic performance of residential solar water heating systems in the U.S. The results showed that the SWH decreased the water heating energy request from 50 to 85%. They also carried out that the use of SWHS would result in the annual bill savings of $100 to over $300 in comparison to the use of electricity for water heating. Hawlader *et al.* [76] evaluated an economic analysis of a solar water heating system in Singapore. They used internal rate of return analysis to study the economic analysis. The results showed that the minimum payback period was almost 14 years. Abou-Zeid and Hawas [77] evaluated the possibility of using solar water heating systems for providing domestic space and water heating in Libya. They calculated the solar collector costs, fuel cost, and the systems costs. Besides, based on the average equivalent cost, they compared 324 cases and determined the optimum collector area for each case. Arsalis and Alexandrou [78] studied the cost analysis of a solar heating system for detached single family households in hot weather conditions in Nicosia, Cyprus. The system consisted of different components, including absorption chiller, hot water storage tank, flat plate solar collectors. The results indicated that the solar heating system would not be suitable as an economic option if the solar collector cost is more than $\$360/m^2$.

While previous studies have examined the performance and economic analysis of different solar heating systems, there was no published record of the evaluation of combined SWHS in terms of both technical and economic analyses for the sake of energy savings, CO_2 mitigation, and customers' satisfaction in cold climate regions. Moreover, the combination of the SWHS with different heating systems would help the government and individuals to realize the both technical and economic aspects of a variety of SWHS, individually, including the annual natural gas consumption, annual GHG emissions, annual cost savings, annual GHG abatement costs in order to choose the best heating system in terms of energy and cost savings, simultaneously. Besides, this research thesis would clarify whether the use of combined SWHS is a practical option for Edmonton in the near future or not. Also, the possibility of use of different combined SWHS as a future choice would definitely have a positive impact on the future governmental projects to figure out the rebate values as possible incentives in each combined SWHS.

1.4 OBJECTIVES

The overall objectives of this study were to:

1. Perform a comparative technical, economic, and greenhouse gas (GHG) emissions assessment of combo heating systems for residential applications:

    i. Study the annual natural gas consumption for typical residential buildings located in Edmonton, Alberta, Canada.

    ii. Study the carbon dioxide (CO_2) mitigation, and emissions for typical residential buildings located in Edmonton, Alberta, Canada.

    iii. Study the impact of floor areas on annual natural gas consumption, carbon dioxide (CO_2) mitigation, and CO_2 emissions

    iv. Compare the annual cost savings and annual GHG abatement cost in different alternative heating systems using a traditional furnace-water heater system as a benchmark.

    v. Study the effect of NG price, and thermal efficiency on annual cost savings, and annual GHG abatement cots according to a sensitivity analysis.

2. Develop a techno- economic study of the impact of SWHS on residential buildings located in Edmonton, Alberta, Canada:

    i. Study the effect of solar load on natural gas consumption, carbon dioxide (CO_2) mitigation, and CO_2 emissions.

ii. Study the impact of floor areas on NG consumption, carbon dioxide (CO_2) mitigation, and CO_2 emissions for different solar loads.

iii. Examine the effect of floor areas on annual cost savings and annual GHG abatement

iv. Examine the effect of solar load on annual cost savings and annual GHG abatement with the consideration of carbon dioxide (CO_2) tax for Alberta.

1.5 THESIS ORGANIZATION

This thesis document is divided into the following chapters. Chapter 2 describes the theory and assumptions used to calculate technical, economic, and greenhouse gas (GHG) emissions assessment of combo heating systems and combined solar water heating systems for residential applications, using a traditional furnace-water heater system as a benchmark. Chapter 3 presents the results and discussion of the technical, and greenhouse gas (GHG) emissions assessment of different alternative heating systems. Also, this chapter describes the technical assumptions of the SWHS that is combined to different alternative heating systems. The results and analysis from the evaluation of the economic aspects of the use of combined solar water heating systems are also presented. Chapter 4 shows the conclusions of this study.

2. THEORY AND ASSUMPTIONS

2.1 MODEL HOUSE

A 195 m^2 (2099 ft^2) single-family, detached bungalow house (without basement) with the floor plan shown in Fig. 2-1 [79] was used as a model house. It is important to notice that with the consideration of a basement in the model house, it would likely have an effect on heat load marginally because of the insulation provided by the ground. Besides, the layout of the model house is not necessarily ubiquitous to Edmonton. The model house is used as a benchmark layout to study the models that are developed in the thesis research work.

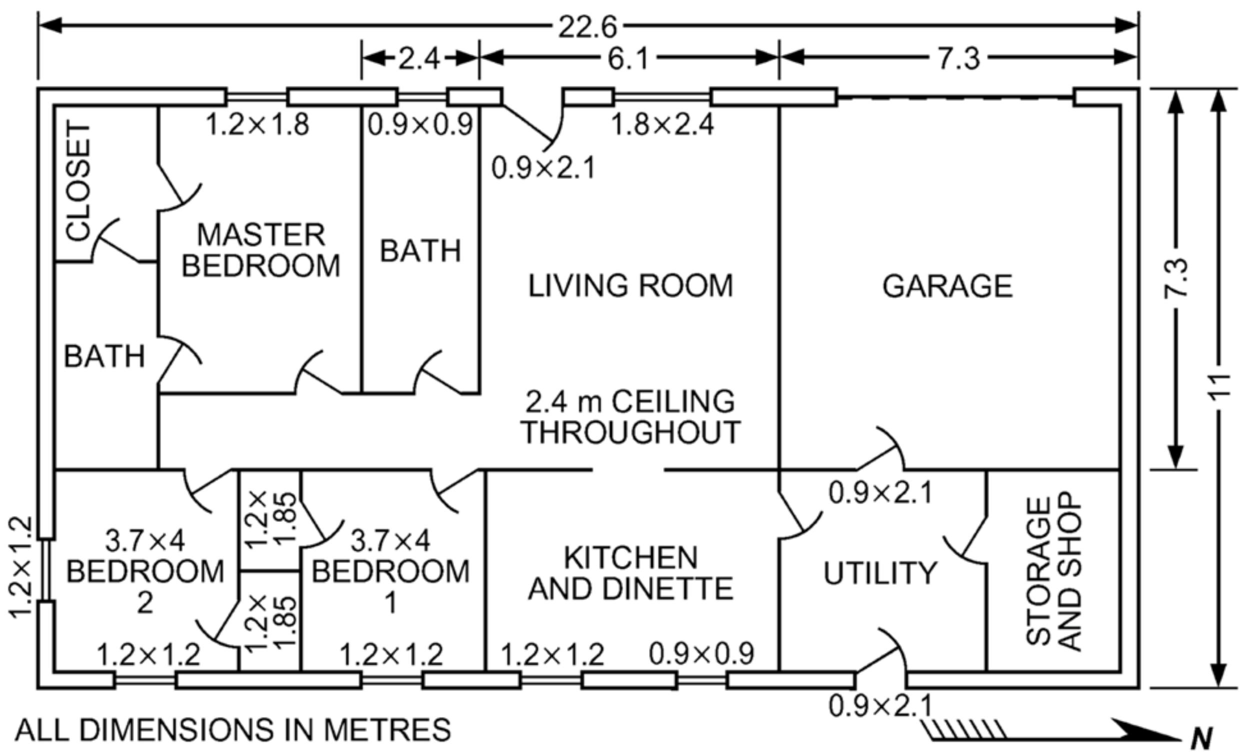

Figure 2-1: The floor plan of the model house.

It was assumed that the house was located in Edmonton, Alberta, Canada. The construction characteristics were based on the minimum requirements of ASHRAE Standard 90.1 for Zone 7 [80]. Garages are not usually heated. Therefore, the garage was assumed to have the same conditions as that of the outdoor environment. It was also assumed that the indoor comfort conditions were 21.2°C (70°F)/50% RH [81] with T_{in} = 21.2°C as the design dry bulb temperature. The outdoor design dry bulb temperature, T_{out} = -29.6°C (-21.3°F), was chosen for Edmonton [79]. The heat load was calculated based on the indoor and outdoor design temperatures and the relevant thermal properties. An estimate of the heat load for the model house was determined by using Newton's law of cooling, $\dot{Q} = UA(T_{in} - T_{out})$, to calculate the rate of heat loss from the building through the walls, roof, windows, doors, floor, and by way of infiltration, which is given by the air-change method as $\dot{Q} = \rho c_p V(ACH)(T_{in} - T_{out})$.

2.2 EQUIPMENT SELECTION

The domestic hot water (DHW) load was used to calculate the required input of natural gas to any combination heating equipment as well as the thermal size of the equipment. The thermal size of the water heater, $\dot{Q}_{WH}$, was calculated by using

$$\dot{Q}_{WH} = \frac{G_h \rho_w c_p (T_{out} - T_{in})}{\eta}, \qquad (2\text{-}1)$$

where the thermal efficiency, η is as stated by the manufacturer.

It was assumed that there were 4 persons living in the house, and they required a minimum of 454 L (120 gal) of water per day [82]. The minimum water requirement defines the useable storage capacity of the tank of a tank-based water heater. The maximum possible volumetric flow rate was based on the fixture unit method [15], and was used to calculate the required recovery rate, G_h, for the heating systems. All models of heating plant were chosen so as to provide the required recovery rate.

2.3 ANNUAL HEATING PERIOD

The annual natural gas (NG) consumption can be determined from the rate of NG input to the heating plants and the annual heating time. The NG consumption is the product of the rate of NG input and the annual heating time. The annual heating time can be subdivided into the time required for space heating and that for DHW heating. For DHW heating, the heating time corresponds to the time for "on-demand" heating or to the heating phase of a gas tank water heater cycle in a traditional tank-based system. "On-demand" heating occurs when a high-efficiency heat exchanger is used to provide hot water instantaneously. The subdivision of the heating period by application is presented in Fig 2-2.

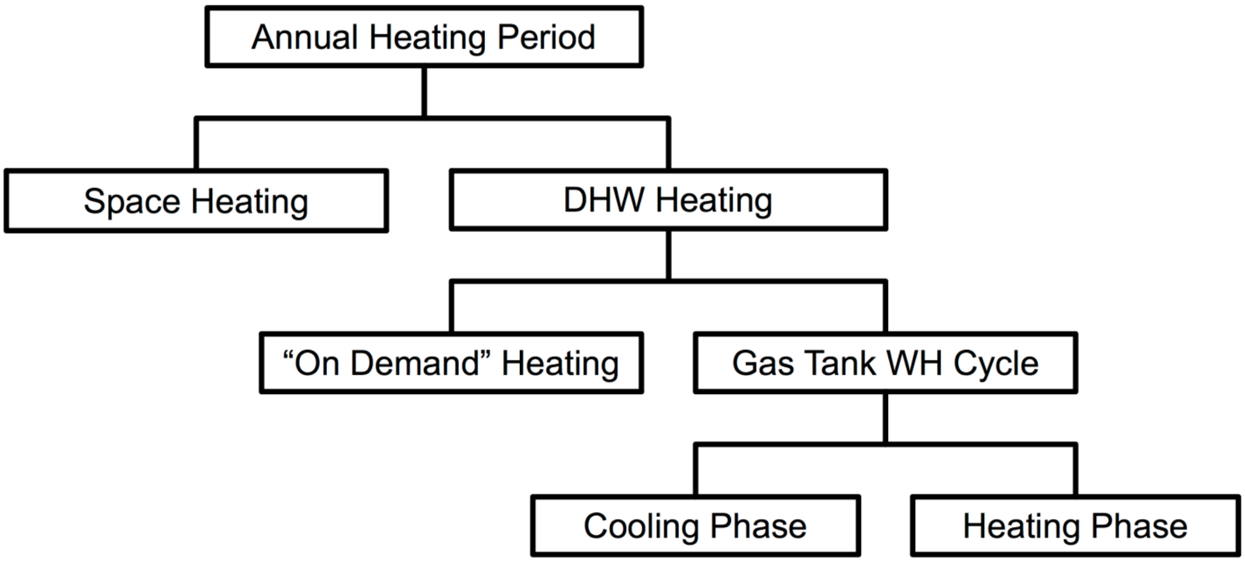

Figure 2-2: Flow chart for the subdivision of heating time by application.

The annual heating time for space heating can be determined by using the heating degree-days (HDD) method, which compares the daily mean temperature for every day in the heating season to a reference temperature, T_{ref} [80]. Only days during which heating is required are considered and when the daily mean temperature is less than the reference temperature. Therefore,

$$\mathrm{HDD} = \sum_{m=1}^{N} \left(T_{\mathrm{ref}} - \overline{T}_{\mathrm{m}} \right), \tag{2-2}$$

where N is the number of days in the heating season and $\overline{T}_{\mathrm{m}}$ is the mean daily temperature on the m^{th} day of the season. Thus, the heating period is calculated as follows:

$$t_{\mathrm{AnnualHeating}} \approx \frac{\mathrm{HDD}_{18}}{T_{\mathrm{indoor}} - T_{\mathrm{outdoor}}}, \tag{2-3}$$

where the subscript on HDD indicates that the reference temperature was taken to be 18.3°C (65°F).

On the other hand, to calculate the heating time for "on-demand" hot water usage, the daily consumption of water was estimated by multiplying the daily consumption per person by the number of people living in the house. The total volume flow rate of water consumed was calculated based on the fixture unit method [15]. The heating time for "on-demand" hot water usage, $t_{\mathrm{DHW,on\,demand}}$ can be determined by using the daily water consumption and the volumetric flow rate obtained from the fixture unit method as follows:

$$t_{\mathrm{DHW,on\,demand}} = \frac{(365\ \mathrm{days/year}) \times V_{\mathrm{Daily}}}{\mathrm{Demand\ Factor} \times \dot{V}_{\mathrm{Hourly}}} . \tag{2-4}$$

The demand factor is used to obtain the water demand that is most likely to occur for a given application. The demand factor is used to adjust the possible maximum demand of water to the most probable demand of water. The demand factor was chosen as 0.3 for a residential application [15].

The heating time of the cycle for a typical gas tank water heater can be determined by using the heating input rate to find

$$t_{\mathrm{cycleheating}} = \frac{Q_{\mathrm{heatingrequired}}}{\dot{Q}_{\mathrm{heatinginput}}} = \frac{\rho_w V_{\mathrm{tank}} c_{p,w} (T_h - T_1)}{\dot{Q}_{\mathrm{heatinginput}}} . \tag{2-5}$$

The heating cycle consists of the time during which the water in the heater is heated to its maximum set-point temperature (when the burner turns OFF), and then the time during which it cools to its minimum set-point temperature (when the burner turns ON); and then these phases repeat indefinitely. The heating time was calculated based on the heating load and the rate of heat transferred to the fluid from the combustion gases leaving the burner. The values used to calculate the heating time in the gas tank water heater cycle are presented in Table 2-1.

Table 2-1: The values used to calculate the heating time for the cycle of the gas tank water heater.

Property	Value
V	246.05 (L) (65 (gal.))
$\rho_{\text{w@48.9°C(120°F)}}$	988.5 (kg/m^3) (61.71 (lb$_m$/ft^3))
$c_{p,\text{w@48.9°C(120°F)}}$	4.181 (kJ/kg-K) (0.999 (Btu/lb$_m$-R))
T_h	54.4°C (130°F)
T_l	46.1°C (115°F)
$\dot{Q}_{\text{heating input}}$	19,050 W (65,000 Btu/hr)

The time required to complete the gas tank water heater cycle is as follows:

$$t_{\text{cycletotal}} = t_{\text{cycleheating}} + t_{\text{cyclecooling}}. \qquad (2\text{-}6)$$

It was assumed that the duration of the cycle was always the same and that the cycle was repeated continuously throughout the entire year. For a gas tank water heater cycle, it was also assumed that the water temperature reached a maximum of 54.4°C (130°F) to prevent scalding from occurring and the low set-point temperature (the temperature at which the heater turns on) was 46.1°C (115°F) to avoid the risk of growth of Legionella bacteria [82].

2.4 PERFORMANCE ANALYSIS

In this study, the GHG emissions are causative of pollution and the mass of CO_2 is assumed to be representative of the amount of GHG emissions that are produced by the heating units. It is expected that the emissions from the heating units will constitute other gases, including NO_X and water vapor; however, since the GHG emission is the difference between the emissions produced by the traditional or conventional heating systems, it is expected that the difference would be approximately the same whether or not the other gases in the flue gas emissions from the heating units were considered.

The rate of carbon dioxide (CO_2) emission was found by considering a balanced stoichiometric combustion reaction that

$$CH_4(g) + 2(O_2(g) + 3.76N_2(g)) \xrightarrow{\Delta H \uparrow} CO_2(g) + 7.52N_2(g) + 2H_2O(g). \quad (2\text{-}7)$$

The equation shows the stoichiometric combustion of methane (CH_4). It was assumed that NG is 100% CH_4, which is justified because the composition of NG is approximately 95% CH_4 [83]. The heat loss by way of the combustion (flue) gases is neglected in this model. The lower heating value (LHV) was used to calculate the rate at which CO_2 was emitted from the non-condensing heater systems and the higher heating value (HHV) was used in the case of the condensing systems. The values of the properties of CO_2 and (NG) CH4 are shown in Table 2-2.

Table 2-2: The values of the properties of CO_2 and NG (CH_4)

Property	Value
CH_4	
Molar Mass	16.043 (kg/kmol)
$HHV_{@25□C(77□F)}$	55,530 (kJ/kg)
$LHV_{@25□C(77□F)}$	50,050 (kJ/kg)
CO_2	
Molar Mass	44.009 (kg/kmol)

The rate of NG consumption was determined as follows:

$$\left(\text{kg CH}_4/\text{hr}\right) = \left(\frac{1\,\text{kJ}}{0.94782\ \text{Btu}}\right) \times \frac{\dot{Q}_{\text{input}}}{\text{HHV}_{\text{CH}_4}}. \tag{2-8}$$

It was assumed that the furnace and gas tank water heater operate at the maximum capacity (with the correct fan setting for the furnace). For the tankless water heating systems, the heat input was calculated from the thermal efficiency of the system and the required NG input as

$$\dot{Q}_{\text{INPUT}} = \frac{\dot{Q}_{\text{REQUIRED}}}{\eta}. \tag{2-9}$$

The annual NG consumption and CO_2 emission was calculated by multiplying the rate of NG consumption and CO_2 emission by the annual heating time. The annual CO_2 mitigation was calculated by multiplying the annual heating time by the difference in the hourly rate of emission of CO_2 between the traditional and alternative systems as

$$\left(\frac{\text{kg CO}_2}{\text{year}}\right)_{\text{mitigation}} = \left[\left(\dot{m}_{\text{CO}_2}\right)_{\text{Traditional}} - \left(\dot{m}_{\text{CO}_2}\right)_{\text{Alternative}}\right] \times t_{\text{Annual}}. \tag{2-10}$$

2.5 ECONOMIC ANALYSIS

An economic analysis was conducted in order to determine the impact of the performance of the different heating systems on annual costs. The economic analysis included an estimation of the gas cost per kilogram of NG, which was determined by using the gas cost per GJ and the higher heating value in

$$\left(\frac{\$}{\text{kg NG}}\right) = (\text{HHV}) \times \left(\frac{\$}{\text{GJ}}\right) \times \left(\frac{1\,\text{GJ}}{1{,}000{,}000\ \text{kJ}}\right). \tag{2-11}$$

The annual gas cost of NG was determined by multiplying the gas cost per kilogram by the annual NG consumption. Electricity is required for operation of auxiliary equipment such as pumps and fans in the heaters. The annual electricity cost for the heating units and plants was included in the total energy cost. The annual operating costs were determined by the annual labor cost of each heating system, the total average cost of gas based on reference prices in province of Alberta, and the average regulated rates of electricity from a local electricity provider (Direct Energy Regulated Services) [98] during the months where the mean temperature was below the reference temperature, T_{ref}.

To calculate the annual original capital costs including the equipment and installation costs [84-87], the original capital costs are distributed over the 10-year lifetime. Thus, the annual capital costs were determined by representing the principal costs as an annuity as,

$$A = P \times \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right), \tag{2-12}$$

The annual costs were the total of the annual operating costs and the annual original capital costs. In order to show the reduction of the annual costs of the alternative heating systems in comparison to the traditional or conventional heating system, the annual cost savings (ACS) was determined and is given as

$$ACS = (\text{AnnualCost})_{\text{traditional}} - (\text{Annual Cost})_{\text{alternative}} \tag{2-13}$$

It is expected that, the alternative heating systems may produce less emissions than the traditional or conventional heating systems. The effort to reduce emissions, and ultimately pollution, may have an associated cost. In general, GHG abatement cost (GAC), in \$/tonnes of CO_2 /year, is a quantitative measure of the cost required to reduce one more unit of pollution. Equation (2-14) shows the expression for the GAC as

$$\text{GAC} = \frac{(\text{Cost})_{(\text{alternative} - \text{traditional})}}{\left(\frac{\text{GHG emissions}}{\text{year}}\right)_{(\text{traditional} - \text{alternative})}}. \tag{2-14}$$

2.6 EXTRAPOLATION OF SPACE HEATING LOAD

The floor area of the model house was varied in order to determine the effect of the space heating load on the annual NG consumption, CO_2 mitigation, GAC, and ACS. It is typical that the floor area of similarly constructed houses will correlate positively with the space heating load. It goes without saying that with the increase of house sizes, the efficiency of the heating plants used for different house sizes decreases, however, when the heating plants are modulated, the efficiency of the heating plants increases.

The houses in the model study were chosen to have a square-shaped floor plan with the floor areas of 65, 93, 139, 186, and 232 m^2 (700, 1000, 1500, 2000, and 2500 ft^2, respectively). It was assumed that the same number of inhabitants resided in each of the houses; therefore, the DHW load was assumed to be the same in all of the houses. The window area was assumed to be 20% of the wall area in order to conform to the ASHRAE model house of Fig. 2-1. The percentage of window area in the model houses was less than that stipulated in ASHRAE Standard 90.1 at 40% of the total wall area [80]. It was assumed that the volume of air in the houses was enclosed by the exterior walls, ceiling, and floor of the building). All other design parameters are the same as those used with the model house of Fig. 2-1.

2.7 MATHEMATICAL MODEL [100]

This model described in this section was prepared in collaboration with another student, Mr. Alberto Palomino. The water in the tank-based water heater loses energy to the ambient surroundings, prompting the need to reheat it to the desired set-point temperature. The time required for the water to cool from the set point temperature can be estimated by considering a one-dimensional radial transient heat conduction model in cylindrical co-ordinates for the cooling of the stagnant water. Figure 2-3 shows a schematic of the cylindrical tank of the model.

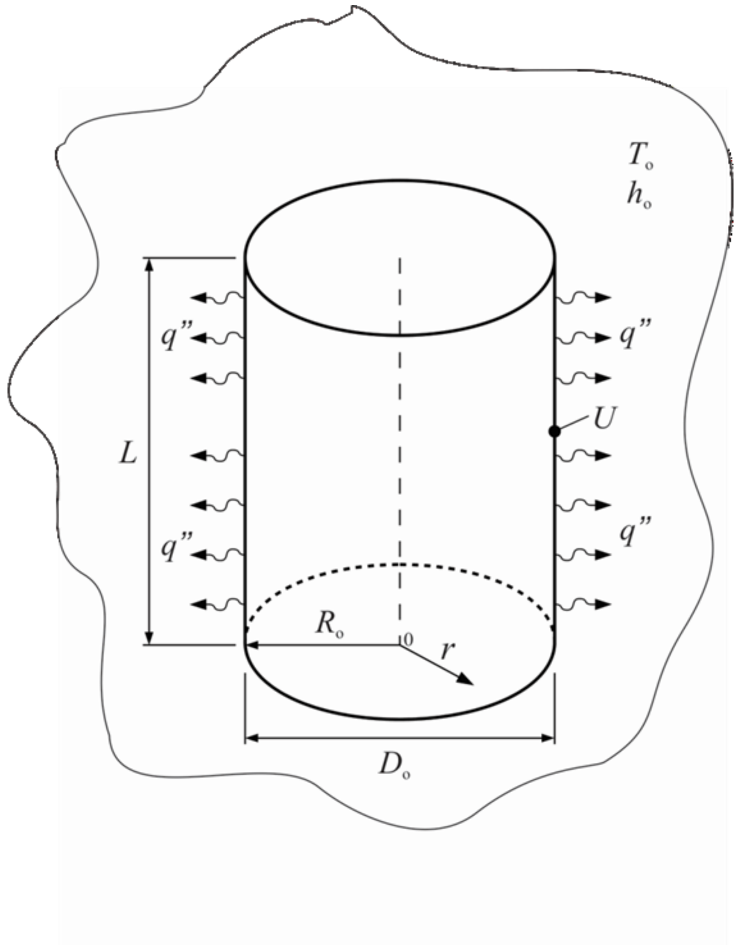

Figure 2-3: Schematic of the gas tank water heater.

It was assumed that heat loss from the top and bottom of the tank was small compared to that lost radially. Further assuming constant properties, the governing equation is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r^2}\right)=\frac{1}{\alpha_w}\frac{\partial T}{\partial t}, \qquad 0\le r\le R_o. \tag{2-15}$$

The boundary and initial conditions are:

$$\frac{\partial T(0,t)}{\partial r}=0, \tag{2-16}$$

$$-k_{\mathrm{w}} \frac{\partial T(R_{\mathrm{o}},t)}{\partial r} = U\left[T(R_{\mathrm{o}},t) - T_{\mathrm{o}}\right], \tag{2-17}$$

$$T(r,0) = T_{\mathrm{i}} - T_{\mathrm{o}}. \tag{2-18}$$

Özişik [88] has solved Eq. (2-15) with the boundary and initial conditions of Eqs. (2-16) - (2-18) to give

$$T(r,t) = T_{\mathrm{o}} + \frac{2u(T_{\mathrm{i}} - T_{\mathrm{o}})}{R_{\mathrm{o}}} \sum_{n=1}^{\infty} \frac{J_0(\lambda_n r)}{(\lambda_n^2 + u^2) J_0(\lambda_n R_{\mathrm{o}})} \exp(-\alpha_{\mathrm{w}} \lambda_n^2 t), \tag{2-19}$$

where $u = \frac{U}{k_{\mathrm{w}}}$ and the eigenvalues are

$$\frac{\lambda_n J_1(\lambda_n R_{\mathrm{o}})}{J_0(\lambda_n R_{\mathrm{o}})} = u. \tag{2-20}$$

Values of the final temperature, $T(r,t)$, at $r = R_{\mathrm{o}}$ was used to estimate the cooling time, t_{c} of the water in the tank.

The overall heat transfer coefficient (U) at the external surface of the tank was estimated by utilizing correlation equations that are available from the work of others. In general,

$$\frac{1}{U} = \frac{1}{\bar{h}_{\mathrm{o,convection}}} + \frac{1}{h_{\mathrm{o,radiation}}} + R''_{\mathrm{Insulation}}. \tag{2-21}$$

Free convection and radiation will occur at the outer surface of the tank. The free convective heat transfer coefficient for vertical cylinders is given by Nagendra, *et al*. [89] as

$$\bar{h}_{\mathrm{o,convection}} = \frac{k_{\mathrm{air}}}{D_{\mathrm{o}}} \begin{cases} 0.6\left(\mathrm{Ra}_{D_{\mathrm{o}}} \frac{D_{\mathrm{o}}}{L}\right)^{0.25}, & \mathrm{Ra}_{D_{\mathrm{o}}} \frac{D_{\mathrm{o}}}{L} \geq 10^4 \\ 1.37\left(\mathrm{Ra}_{D_{\mathrm{o}}} \frac{D_{\mathrm{o}}}{L}\right)^{0.16}, & 0.05 \leq \mathrm{Ra}_{D_{\mathrm{o}}} \frac{D_{\mathrm{o}}}{L} \leq 10^4 \\ 0.93\left(\mathrm{Ra}_{D_{\mathrm{o}}} \frac{D_{\mathrm{o}}}{L}\right)^{0.05}, & \mathrm{Ra}_{D_{\mathrm{o}}} \frac{D_{\mathrm{o}}}{L} \leq 0.05 \end{cases}. \tag{2-22}$$

Under stagnant air conditions, the approximate radiation heat transfer coefficient is [90]

$$\bar{h}_{\mathrm{o,radiation}} \approx \frac{\varepsilon_{\mathrm{tank}}\sigma\left[T^4\left(R_{\mathrm{o}},t\right)-T_{\mathrm{o}}^4\right]}{T\left(R_{\mathrm{o}},t\right)-T_{\mathrm{o}}}, \tag{2-23}$$

where the Stefan-Boltzmann constant is σ = 5.67 x 10^{-8} W/m^2-K^4 and T is in Kelvin.

The thermal resistance of the insulation is given approximately as

$$R''_{\mathrm{Insulation}} \approx \frac{\delta_{\mathrm{insulation}}}{k_{\mathrm{insulation}}}. \tag{2-24}$$

Given the typically large thermal conductivities of metals [91], it is expected that the resistance to heat transfer of the metal tank will be negligible compared to that of the insulation. The values of the properties used in the calculation of the cooling time of the water in the gas tank water heater are presented in Table 2-3.

Table 2-3: The values of the properties used to compute the estimate of the cooling time in the gas tank water heater cycle.

Property	Value
k_{w}	0.644 (W/m-K)
R_{o}	0.305 (m)
ρ_{w}	985.2 (kg/m^3)
$c_{p,\mathrm{w}}$	4138 (J/kg-K)
V	0.2461 (m^3)
A_s	1.61 (m^2)
T_h	54.4□C (130□F)
T_l	46.1□C (115□F)
$T_{\square}$	18.3□C (65□F)
For Convection	
D_{o}	0.610 (m)
L	0.843 (m)
T_{o}	18.3□C (65□F)
T_i	54.4□C (130□F)
β	3.40(10)$^{-3}$ (K^{-1})
g	9.81 (m/s^2)
υ_{air}	1.516(10)$^{-5}$ (m^2/s)
$\mathrm{Pr}_{\mathrm{air}}$	0.7306
For Radiation	
$\varepsilon_{\mathrm{tank}}$	1.0
σ	5.67(10)$^{-8}$ (W/m^2-K^4)
For the Overall Heat Transfer Coefficient	
$R''_{\mathrm{Insulation}}$	2.818 (K-m^2/W)
$\bar{h}_{\mathrm{o,convection}}$	3.84 (W/m^2-K)
$\bar{h}_{\mathrm{o,radiation}}$	6.48 (W/m^2-K)
U	0.3105m^2-K)

2.8 SWHS TECHNICAL ASSUMPTIONS

In this Section, the technical assumptions of combined solar water heating systems with evacuated tube solar collectors for different solar loads, ranging from 20% to 100% of the total roof area of a typical residential building located in Edmonton, Alberta, Canada are presented. The alternative heating systems were conventional (non-condensing) and condensing TWH and condensing boilers, as we discussed in the beginning of Chapter 2, that were coupled to solar water heating systems. The technical performance of different alternative heating systems was compared to a conventional boiler, consisting of a traditional boiler, applied to houses of different gross floor areas, ranging from 800 to 2500 ft^2. A comparison between the traditional heating systems and combined SWHS was based on the annual natural gas consumption, GHG mitigation, and emissions for the various house sizes.

The same assumptions presented in the previous Sections were considered for different heating systems in different house sizes. However, in the combined SWHS, the amount of heat provided by the SWHS was subtracted from the input heat transfer rate in order to indicate the influence of solar energy on all of the heating systems. Moreover, it was assumed that the roof area has the rectangular shape and the same area as the floor area of different house sizes. Besides, in regards to solar irradiation, for Edmonton, the average solar radiation is 47.152 Btu/hr-ft^2 [95]. It should not be left unmentioned that if the hourly variation of solar radiation was considered, the solar loads value would be different because the solar loads depend on the orientation and location of the building. The lack of solar irradiation data is the main reason of the use of average values. For evacuated tube solar collectors, the average efficiency was as assumed to be 61% based on work from Ayompe and Duffy [96]. The useful energy provided by evacuated tube solar collectors is given as follows:

$$Q_u = \eta A_c I_T \qquad (2\text{-}25)$$

where Q_u is the useful energy provided by the ETSCs, η is the efficiency, A_C is the collector area, and I_T is the solar radiation incident on the collector plate.

2.9 SWHS ECONOMIC ASSUMPTIONS

The annual cost of each combined SWHS consists of the annual capital costs, and the annual operating costs, including the maintenance (labor) costs, gas costs, and electricity costs:

$$C_{total} = C_{op} + C_{capital} \qquad (2\text{-}26)$$

Where the capital costs includes the installation and equipment costs:

$$C_{capital} = C_{installation} + C_{equipment} \qquad (2\text{-}27)$$

According to natural resources Canada [97], the capital cost of an evacuated tube solar collector system is approximately $700/m^2. Also, the average maintenance cost is almost $300/ yr. Similarly, as it was discussed in Section 2.3, the average gas price for the last four years was chosen as 3.07 ($/GJ) [92] based on the mean value of the monthly gas prices over the months where heating was required over a recent 4- year time period. Based on the average gas price, the gas cost can be determined by Eq. (2-11). The gas cost was 0.1705 ($/kg NG) for condensing systems (the HHV is used), and 0.1537 ($/kg NG) for non-condensing systems (where the LHV is used). Moreover, to determine the electricity cost, the pump motor and the fan power ratings were assumed to be 246 W and 373 W, respectively. Also, the annuity was calculated using Eq. (2-12) based on the assumption of an interest rate of 10% [93] and a lifetime of 10 years for the systems based on the warranty of the systems [94].

2.10 COMBINED SWHS PERFORMANCE ANALYSIS

To evaluate the performance analysis of the combined SWHS in terms of the annual natural gas consumption, carbon dioxide (CO_2) mitigation, and emissions for different heating systems, the same methods presented in Section 2.4 were used. However, the amount of heat provided by the SWHS was subtracted from the input heat transfer rate in order to show the impact of solar energy on the annual natural gas consumption, carbon dioxide (CO_2) mitigation, and emissions for different house sizes. Therefore, for the combined SWHS, the rate of NG consumption was determined as follows:

$$\left(\text{kg CH}_4/\text{hr}\right) = \left(\frac{1\,\text{kJ}}{0.94782\ \text{Btu}}\right) \times \frac{(\dot{Q}_{\text{input}} - \dot{Q}_{\text{SWHS}})}{\text{HHV}_{\text{CH}_4}}. \tag{2-28}$$

Similarly, as it was discussed in Section 2.4, the annual NG consumption and CO_2 emission was calculated by multiplying the rate of NG consumption and CO_2 emission by the annual heating time. The annual CO_2 mitigation was calculated by multiplying the annual heating time by the difference in the hourly rate of emission of CO_2 between the traditional and combined SWHS as

$$\left(\frac{\text{kg CO}_2}{\text{year}}\right)_{\text{mitigation}} = \left[\left(\dot{m}_{\text{CO}_2}\right)_{\text{Traditional}} - \left(\dot{m}_{\text{CO}_2}\right)_{\text{Combined SWHS}}\right] \times t_{\text{Annual}}. \tag{2-29}$$

2.11 COMBINED SWHS ECONOMIC ANALYSIS

As it was discussed earlier in Section 2.5, the annual costs were the summation of the annual operating, and the annual original capital costs. For the combined SWHS, the annual operating costs, and the annual capital costs of the SWHS were added to the annual cost of each heating system. To calculate the annual original capital costs of the combined SWHS, the original capital costs of the SWHS were added to the original capital costs of each heating system, including the equipment and installation costs [84- 87] in order to distribute the total initial costs over the 10-year lifetime. Thus, the annual capital costs were determined by representing the principal costs as an annuity as it was presented in Eqn. 2-12. In order to show the change of the annual costs of the combined SWHS in comparison to the traditional or conventional heating system, the annual cost savings (ACS) was determined and is given as

$$ACS = (\text{AnnualCost})_{\text{traditional}} - (\text{Annual Cost})_{\text{Combined SWHS}} \tag{2-30}$$

It is expected that, the combined SWHS produce less emissions than the traditional or conventional heating systems. The reduction in emissions, and ultimately pollution, may have an associated cost. Thus, in general, GHG abatement cost (\$/tonnes of CO_2) is a measure of the cost required to reduce one more unit of pollution. Therefore, in order to show the expression for the GAC in the combined SWHS, Eq. (2-14) would be modified as

$$\text{GAC} = \frac{(\text{Cost})_{(\text{combinedSWHS} - \text{traditional})}}{\left(\frac{\text{GHG emissions}}{\text{year}}\right)_{(\text{traditional} - \text{combinedSWHS})}} \tag{2-31}$$

3. RESULTS AND DISCUSSION

3.1 NATURAL GAS (NG) CONSUMPTION AND CO_2 MITIGATION

In order to determine the NG consumption and CO_2 mitigation in the model house, the heat load, and the annual heating time for both space and water heating was calculated based on the equations that were presented in Section 2.3.

For space heating, the heat load due to infiltration was calculated by using the air change method, and the building construction was assumed to be tight. Also, the annual heating time for space heating was found by using the HDD method with a reference temperature of18.3 ^{o}C. The values used to calculate the annual heating time and heat load for space heating are shown in Table 3-1.

Table 3-1: The values used to calculate heat load and annual heating time for space heating

Property	**Value**
Air change per hour *(ACH)*	0.40/hr
T_{ref}	18.3 °C (65 °F) [72]
HDD	6,124 °C-day [73]

Upon employing Eq. (2-3), the annual heating time was calculated to be 3066 hours. With regards to the domestic hot water heating (DHW), the annual heating time was calculated using the "on demand" criterion, and it was found to be 1,281 hours of DHW/year (see Eq. (2-4)). In addition, the maximum possible volumetric flow rate was based on the fixture unit method, and was used to calculate the required recovery rate, G_h, for the heating systems, such that G_h = 2.16 L/min (0.57 GPM) and the tank capacity was calculated to be 227 L (60 gal).

The different heating systems that were explored in this study had varying requirements. Eq. (2-1) was used to calculate the natural gas input requirements for DHW in different heating systems. The values calculated are summarized in Table 3-2.

Table 3-2: Natural Gas Input Requirements for Heating Systems.

Water Heater	η [a]	**Input Required** W (Btu/hr)
Conventional TWH	0.82	9,133.6 (31,165)
Condensing TWH	0.96	7,801.6 (26,620)
Condensing Boiler	0.965	7,761.1 (26,482)
Gas Tank	0.57	13,139.5 (44,834)

As shown in Table 3-2, the gas tank had the highest input gas requirement, and the condensing boiler had the lowest gas requirement. This behavior was due to the fact that the thermal efficiency of the gas tank was much lower than that of the condensing boiler.

Similar to space heating, an annual heating time can also be determined for the water heaters. Tank-based water heaters may operate in a cycle of heating-no heating in order to maintain the DHW in the tank at a predetermined set-point temperature. For the gas tank water heater cycle, Eq. (2-5) was used to calculate the heating time of the tank cycle, and it was found to be as 0.17 hours. Further, the analytical model of Eq. (2-6) was used to determine that the cooling time of the water in the insulated tank was 5.5 days. Therefore, the annual heating time for the water from the alternative systems was 4347 hours and 4356 hours for heating water from the traditional system. The difference in heating times between the two systems was due to the time required by the gas tank water heater cycle.

The annual NG consumption was calculated by multiplying the rate of NG consumption by the annual heating time. Eq. (2-10) was also utilized for calculating the CO_2 mitigation. The calculated results are presented in Table 3-3.

Table 3-3: Annual NG Consumption and CO_2 Mitigation.

System	Annual NG Consumption	Annual CO_2 Mitigation
	kg NG/year (lb_{mass} NG/year)	**kg CO_2/year (lb_{mass} CO_2/year)**
Traditional System	6936 (15292)	-
Conventional TWH	5855 (12908)	2971 (6550)
Condensing TWH	4507 (9937)	6666 (14695)
Condensing Boiler	4507 (9937)	6666 (14695)

As shown in the table, the largest natural gas consumption rate corresponds to use of the traditional system, whereas the lowest consumption corresponds to use of the condensing TWH and condensing boiler systems. The condensing TWH and condensing boiler also had the highest value of annual CO_2 mitigation, whereas the conventional TWH had the lowest mitigation value of annual CO2 mitigation. This was due to the fact that the condensing TWH and condensing boiler have the lowest value of NG consumption and CO_2 emissions. According to Eq. (2-7), 2.74 kg of CO_2 was emitted per kg of CH_4 input, which illustrates that there is a linear relationship between NG consumption and CO_2 emissions.

3.2 ECONOMIC ANALYSIS

In this study, the economic analysis was used to determine the effect of the performance of the different heating systems that were explored on the annual costs. The original capital costs included the equipment and installation costs that were used in Eq. (2-12) to calculate the annuity (see Table 3-4).

Table 3-4: Annuity and Operating Costs

System	Annuity	Annual Operating Costs
	($)	**($/year)**
Furnace	871	891
Gas Tank WH	609	271
Traditional System	1480	1162
Conventional TWH	1278	1157
Condensing TWH	1381	1021
Condensing Boiler	2691	1048

It should be mentioned that the equipment costs included the heating plant, air handler, and miscellaneous costs such as vent pipe fittings, roof flashing, and a termination kit. On the other hand, operating costs were estimated to be the annual labor cost of each heating system, the average cost of gas in the province of Alberta, and the average of the regulated rates of electricity from a local electricity provider during the months where the mean temperature was below the reference temperature, T_{ref} of 18.3°C. The average gas price for the last four years was selected to be 3.07 ($/GJ) based on the mean value of the monthly gas prices over the months where heating was required over a recent 4- year time period [92]. Knowing the average gas price, the gas cost can be determined by using Eq. (2-11). The gas cost was $0.1705 per kg of NG for condensing systems (the HHV is used), and $0.1537 per kg of NG for non-condensing systems (where the LHV is used). Moreover, to determine the electricity cost (8.509¢/kWh), the pump motor and the fan power ratings were assumed to be 246 W and 373 W, respectively.

To determine the annual costs, the annuity was calculated by using Eq. (2-12) based on the assumption of an interest rate of 10% [93] and a lifetime of 10 years based on the warranty of the systems [94]. The annuity and annual operating costs are presented in Table 3-4. The ACS, and GAC were determined by comparing the cost of the alternative systems to the cost of the traditional system using Eqs. (2-13) and (2-14). The ACS and GAC are presented in Table 3-5.

Table 3-5: ACS and GAC for Different Heating Systems

System	ACS ($/year)	GHG Abatement Cost ($/Mg CO_2)
Conventional TWH	207.72	-69.91
Condensing TWH	241.22	-36.19
Condensing Boiler	-722.30	108.36

As shown in Table 3-5, the annual cost savings is negative for the condensing boiler due to the fact it is more costly than the traditional system. In addition, the values of the GAC for the conventional and TWH systems are negative since the alternatives cost less than the traditional system and they also emit less CO_2. Figure.3-1 shows the graph of GAC versus the annual abatement potential corresponding to the model house.

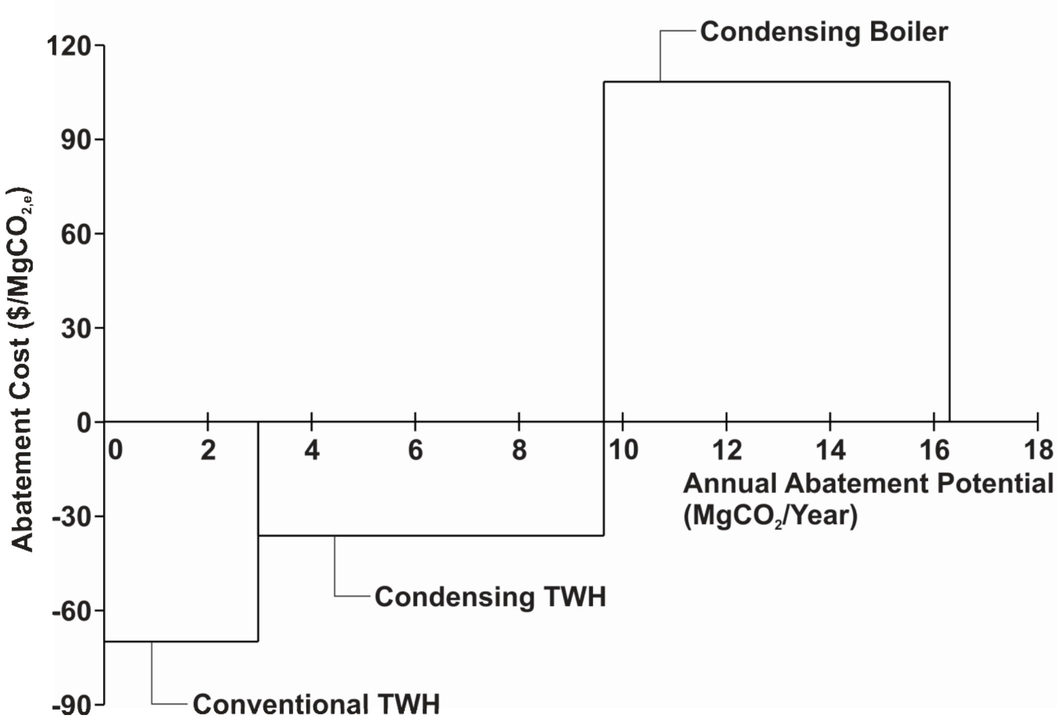

Figure 3-1: GHG abatement cost (GAC) curve for the model house

The monetary values presented in Fig. 3-1 may be interpreted as the value of a rebate that the government could provide to individuals in order to incentivize the purchase of the alternative systems and to compensate for the additional cost of adopting the alternative over the traditional system. The rebate value in this case is equivalent to the negative value of the cost savings based on how the rebate value was calculated. The value of the GAC in Fig. 3-1 is negative for the tankless water heating systems that indicates they provide net positive return on investment. This occurs because the TWH systems cost less and emit less CO_2 than the traditional system. However, the GAC of the condensing boiler is positive because it costs more than the traditional system, even though it mitigates CO_2 production as shown in Table 3-3.

3.3 EFFECT OF HOUSE FLOOR AREA

For the traditional system, furnaces of ubiquitous sizes were chosen according to the heating load for the model homes corresponding to each floor area. The annual NG consumption, annual CO_2 mitigation, and the annual abatement costs were calculated in the same manner as with the first model home and are presented. The annual NG consumption is shown in Fig. 3-2.

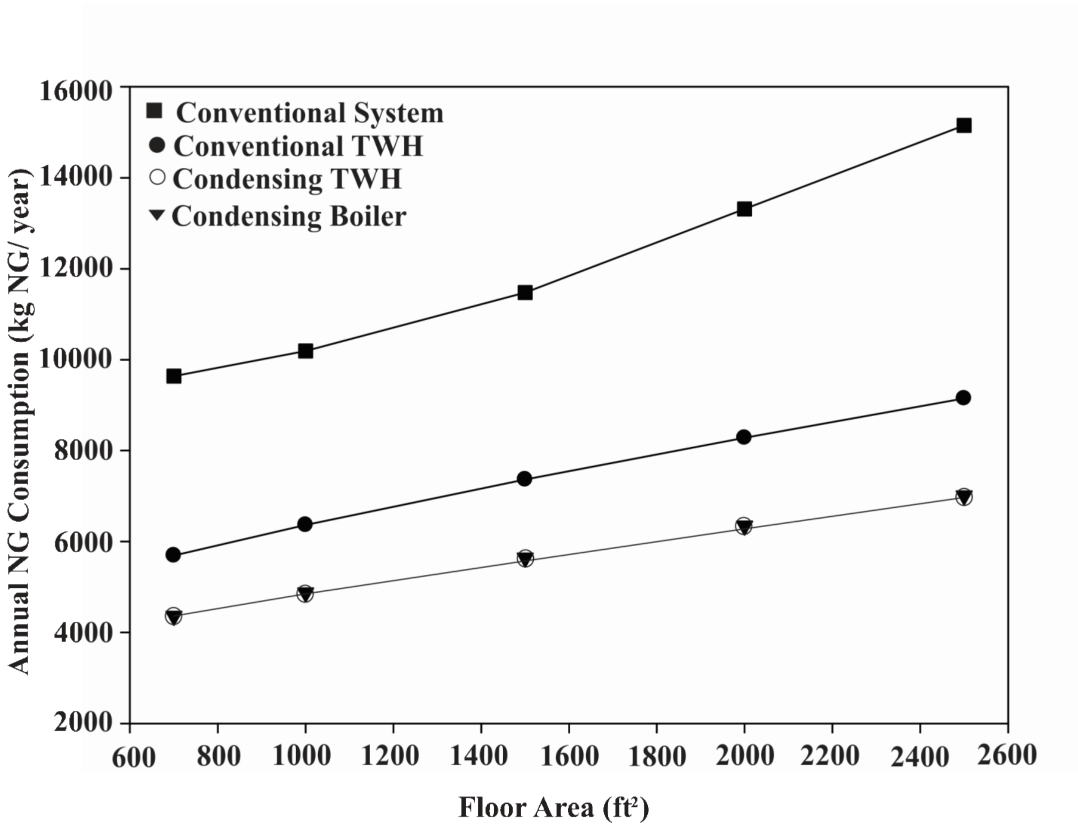

Figure 3-2: Annual NG consumption.

As shown in Fig. 3-2, as the floor area of the residential building increases, the annual NG consumption increases. The largest natural gas consumption rate corresponds to use of the conventional system, whereas the lowest consumption corresponds to use of the condensing boiler, and condensing TWH.

The annual CO_2 mitigation is presented in Fig. 3-3.

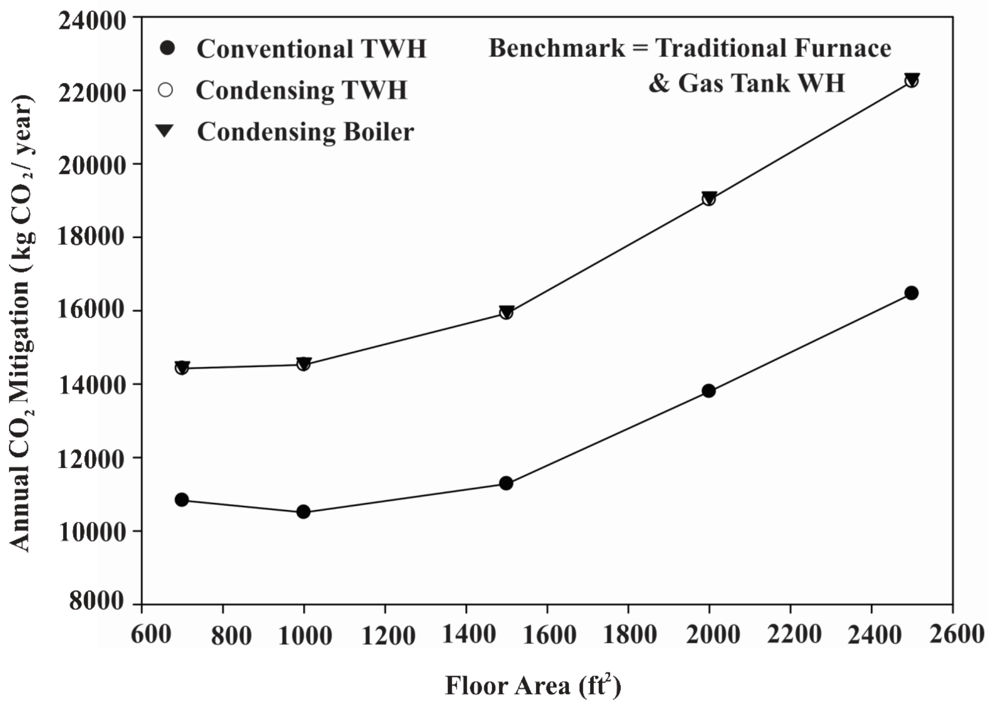

Figure 3-3: Annual CO_2 mitigation.

As it can be seen in Fig. 3-3, the condensing boiler, and the condensing TWH have the highest value of annual CO_2 mitigation owing to the fact that they have the lowest value of CO_2 emissions and NG consumption. Moreover, the values for the annual CO_2 mitigation in Fig. 3-3 increase linearly with increasing house size after the 139 m^2 (1500 ft^2) house for all of the alternative systems. It should not be left unmentioned that the condensing systems consistently have a higher value of CO_2 mitigation than the conventional tankless water heater. The results of the economic analysis are shown in Fig. 3-4. The figure shows that the annual cost savings generally increases with the space heat load and it appears to do linearly for houses with floor areas larger than 139 m^2 (1500 ft^2) house. Due to the higher capital costs of the condensing boiler, it was shown to have the lowest value in annual cost savings, whereas the condensing

TWH yielded the greatest annual cost savings.

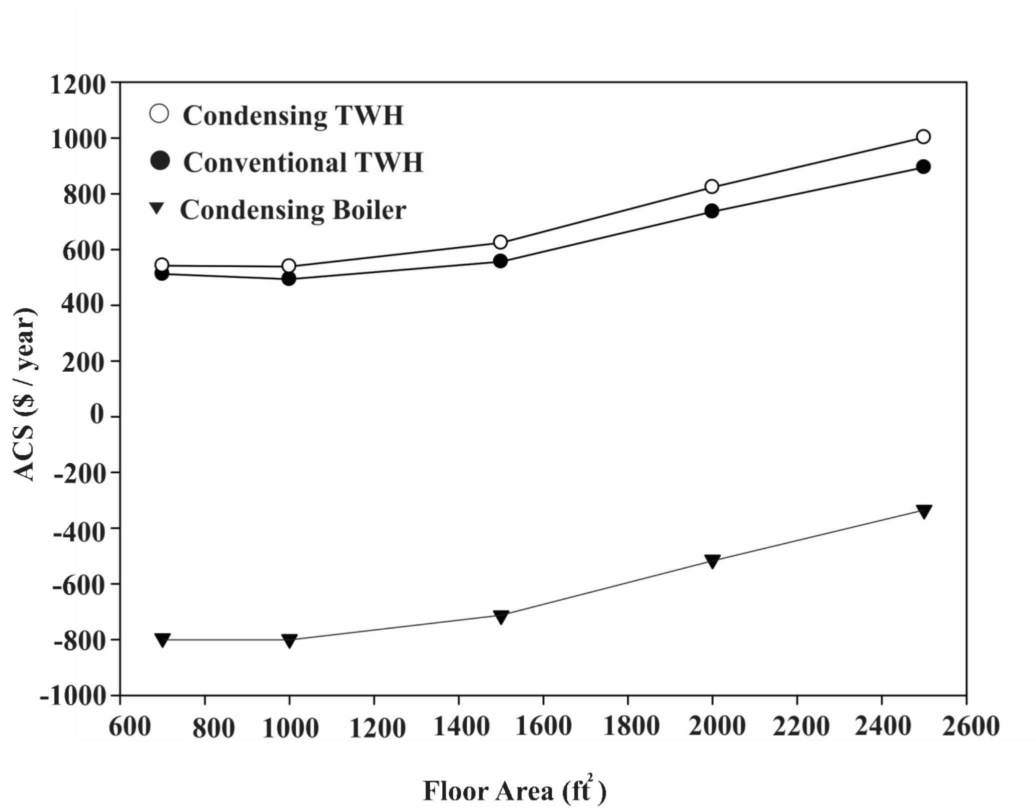

Figure 3-4: Annual cost savings (ACS)

The GAC is depicted in Fig. 3-5. According to the figure, both TWH systems and the condensing boiler have similar behavior; however, in the condensing boiler, the changes are noticeable because it has higher annual original and capital costs compared to the two TWH systems. Since the condensing boiler is more costly than the traditional system, it has negative annual cost savings and positive GAC for the houses with floor areas less than 232 m^2 (2500 ft^2).

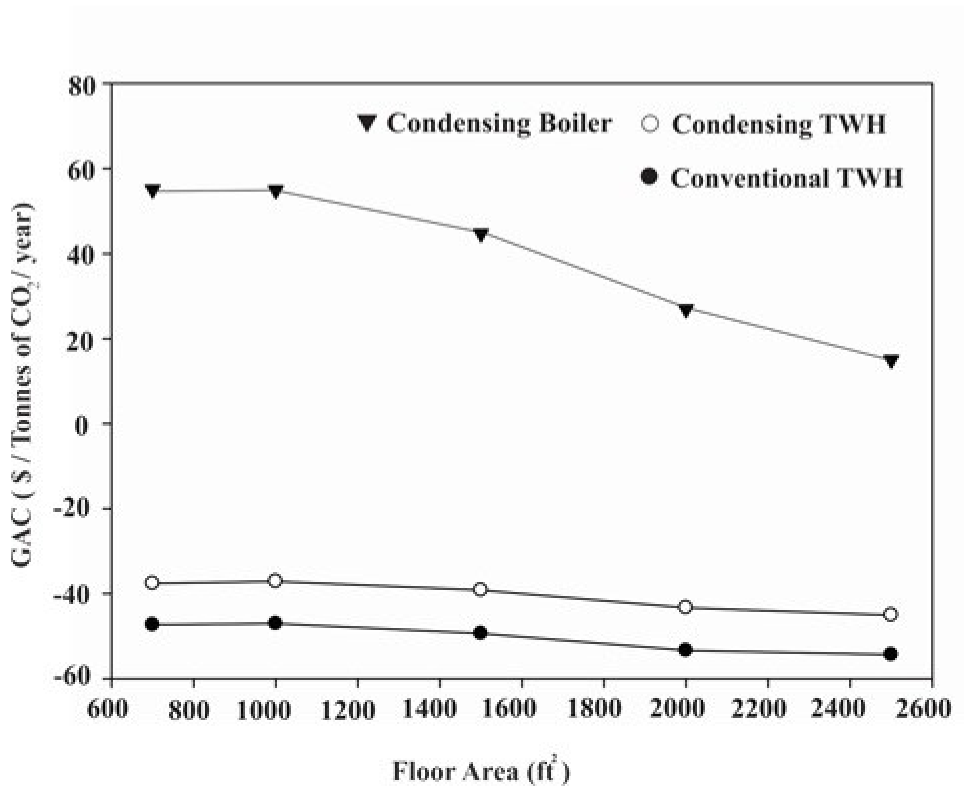

Figure 3-5: GHG abatement cost (GAC)

The abatement potential of the alternative systems for the 93 m^2 (1000 ft^2) house are presented in Fig. 3-6.

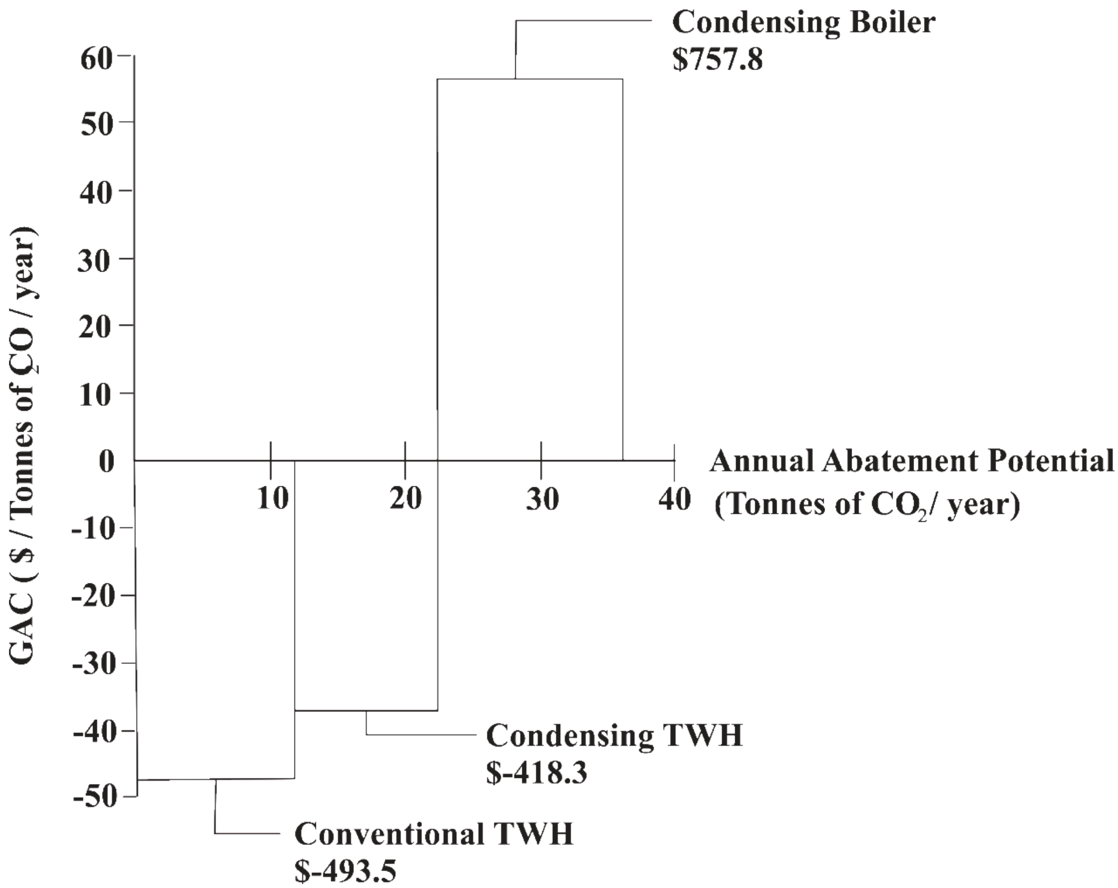

Figure 3-6: GHG abatement cost (GAC) curve for 1000 ft^2 house

The rebate values presented for this house are different from those for the original model house because of the smaller space heat load, and different geometries of the heated space, which is not based in a square floor area. For this house, the conventional tankless water heater had the lowest monetary value which is indicative of the greatest positive return on investment. This result is different from the ASHRAE model house because of the space heat load. It should be noted that while different configurations are possible, the preferred alternative for residential applications is the tankless water heaters, with regards to the abatement costs. This is due to the negative amount of GHG abatement costs, as indicated in Fig. 3-6.

Since there were no studies concentrating on a techno-economic analysis of combo heating systems for residential building applications, it is clear that the presented results have a positive impact on the selection of the heating system. Therefore, it is potentially beneficial for residential heating system applications in terms of energy savings, CO_2 mitigation, and annual costs due to the fact that for suggesting the best option based on the customer satisfaction, both technical and economic analysis should be always considered.

3.4 SENSITIVITY ANAYSIS FOR THE MODEL HOUSE

For the model house (1000 ft^2), a sensitivity analysis was conducted based on the gas price and the thermal efficiency of different alternative heating systems in order to show the impact of the gas price and the changes in thermal efficiency on ACS and GAC. Figure 3-7 shows the sensitivity analysis of ACS based on the gas price. As is shown in Fig 3-7, the percentage of gas price changes from -40% to 40%. This figure shows the ACS as a function of the percentage of changes in gas price. As shown in the figure, as the gas price increases, the ACS increases. The largest ACS rate corresponds to use of the condensing TWH, whereas the lowest rate corresponds to use of condensing boiler. Moreover, the TWH systems have a positive impact on ACS when the gas price increases. Given this fact, with the increase of gas price, the conventional TWH and the condensing TWH are the best economic options compared to the condensing boiler.

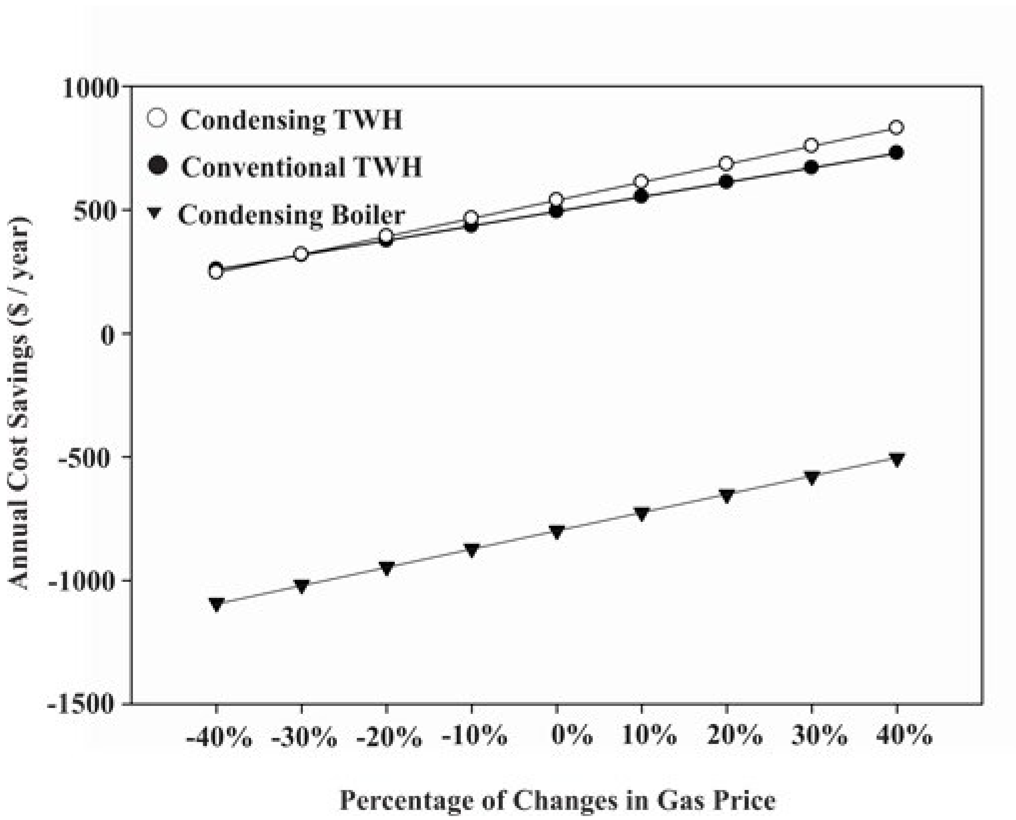

Figure 3-7: Sensitivity analysis for ACS based on the gas price changes

Similarly, Fig 3-8 shows the sensitivity analysis of GAC based on the gas price. As shown in Fig 3-8, the largest GAC rate corresponds to use of the condensing boiler; however, the lowest rate corresponds to use of conventional TWH. In addition, as can be seen in Figs 3-8, with the increase of gas price, the GAC decreases in all of the heating systems owing to the fact that there is a negative correlation between GAC and ACS. It means that with the increase of gas price, the tankless water heating systems have a better effect on GAC in comparison to the condensing boiler.

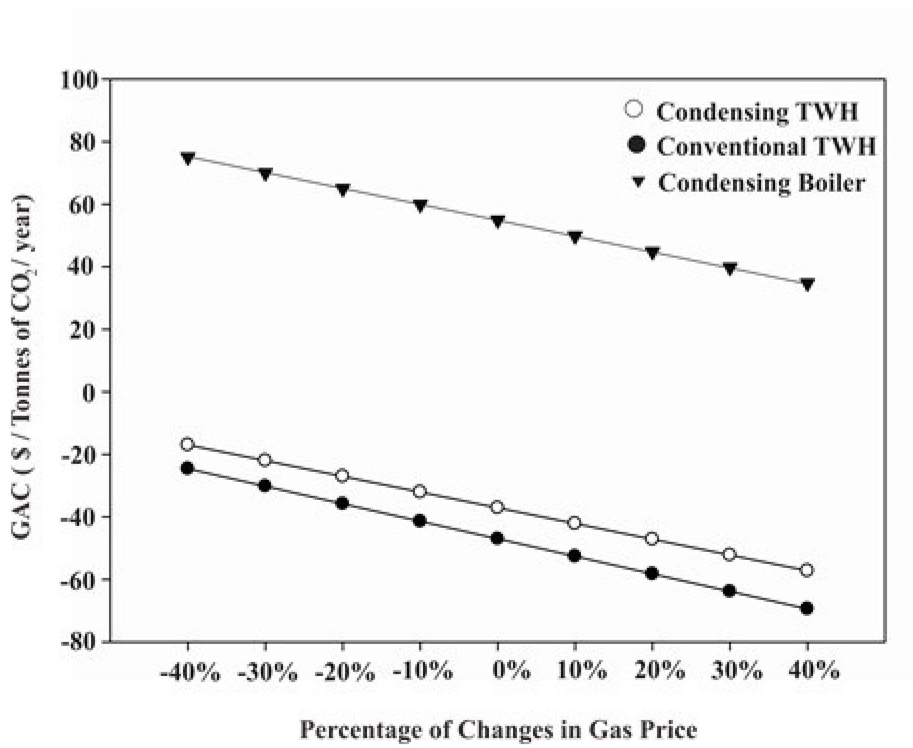

Figure 3-8: Sensitivity analysis for GAC based on the gas price changes

Figure 3-9 shows the sensitivity analysis of ACS based on the thermal efficiency. As shown in Fig 3-9, the change in thermal efficiency ranges from -30% to 0%. This figure shows the ACS as a function of the percentage change in thermal efficiency. As shown in the figure, as the thermal efficiency decreases, the ACS decreases. Thus, the reduction of thermal efficiency has a negative impact on ACS. Further, the largest ACS rate corresponds to use of the condensing TWH, whereas the lowest rate corresponds to use of condensing boiler.

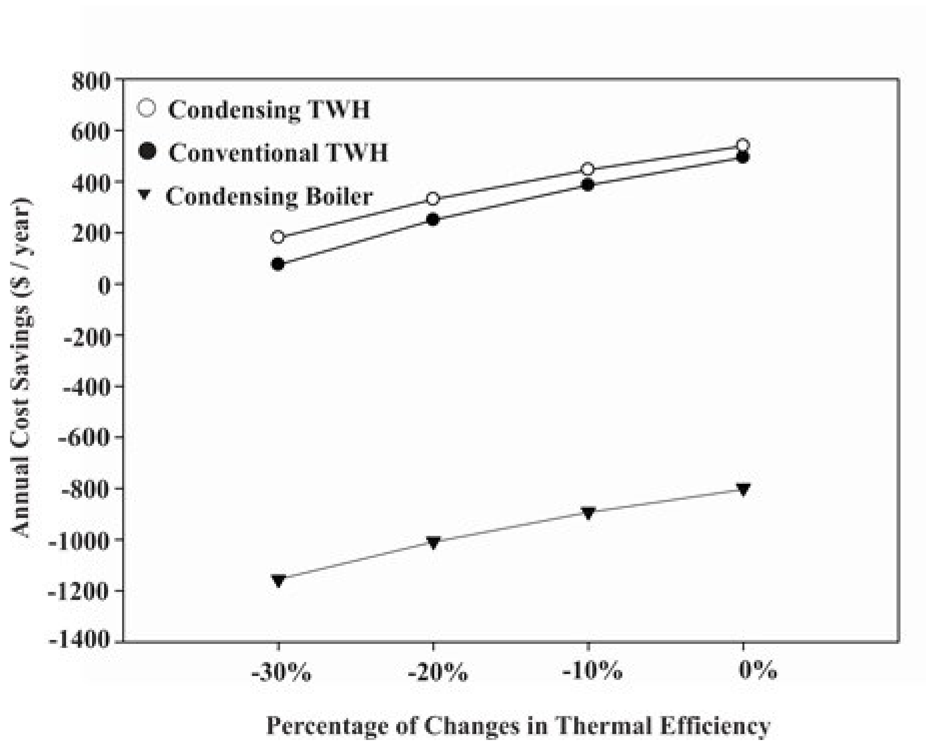

Figure 3-9: Sensitivity analysis for ACS based on thermal efficiency changes

Figure 3-10 shows the sensitivity analysis of GAC based on the thermal efficiency. As seen in Fig 3-10, the changes in thermal efficiency ranges from -30% to 0%. As shown in the figure, as the thermal efficiency decreases, the GAC increases since there is a negative correlation between GAC and ACS. Given this fact, the reduction of thermal efficiency has a negative impact on GAC. Also, the largest GAC rate corresponds to use of the condensing boiler, whereas the lowest rate corresponds to use of conventional TWH. Therefore, the both TWH systems have a better influence on GAC in comparison to the condensing boiler.

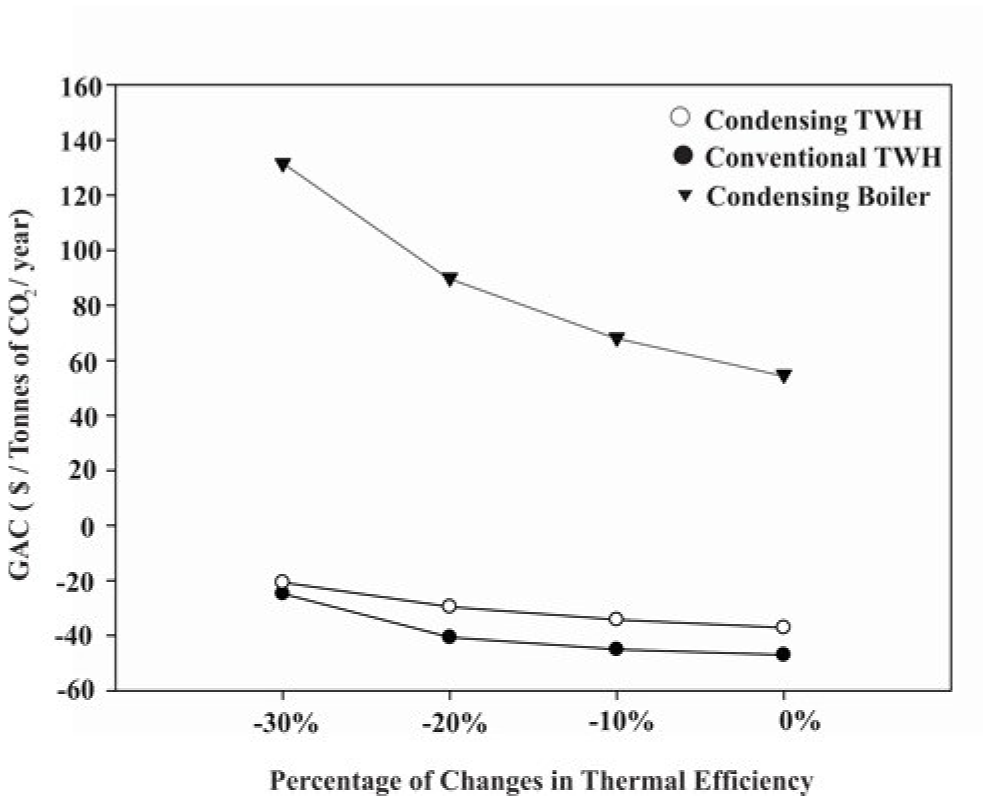

Figure 3-10: Sensitivity analysis for GAC based on thermal efficiency changes

3.5 NG CONSUMPTION IN THE COMBINED SWHS

The results of annual NG consumption for different solar loads, ranging from 20% to 100% coverage of the roof with solar collectors have been shown in Figs. (3-11) - (3-15), respectively. These figures show the annual NG consumption as a function of floor area. As shown in the figures, as the floor area of the residential building increases, the annual NG consumption increases. The largest natural gas consumption rate corresponds to use of the conventional boiler alone, whereas the lowest consumption corresponds to use of the two combined SWHSs, including the condensing boiler with SWHS and condensing tankless water heater (TWH) with

SWHS. The use of the SWHS has resulted in reduction of the annual NG consumption. In addition, as can be seen in Figs. 3-11 and 3-15, with the increase of solar coverage from 20% to 100%, the reduction of annual NG consumption is noticeable in all of the heating systems due to the fact that the more solar radiation is available due to the larger solar coverage. The increased solar energy supplements the energy required for space and water heating. It should be noted that the curves shown in the figures are approximately linear since it was assumed that the doors area, windows area, and other appurtenances of the buildings change linearly with the increase of floor are. However, in practice, these curves may not necessarily be linear due to the fact that owners of the buildings may prefer not to change the fenestrations, and other appurtenances of the buildings linearly with the increase of floor area.

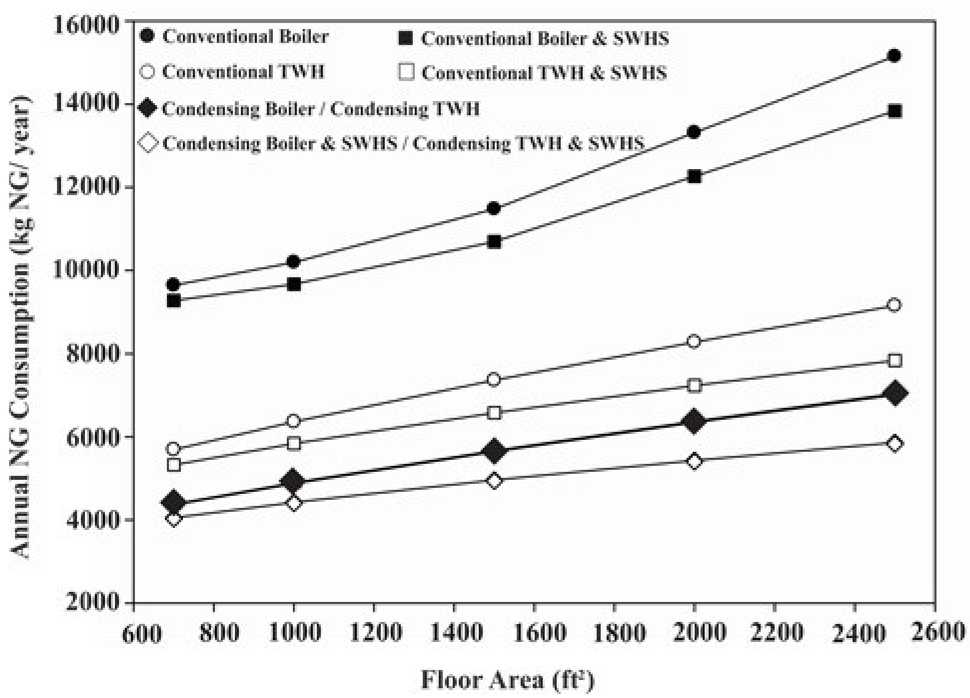

Figure 3-11: Annual natural gas consumption for 20% solar coverage

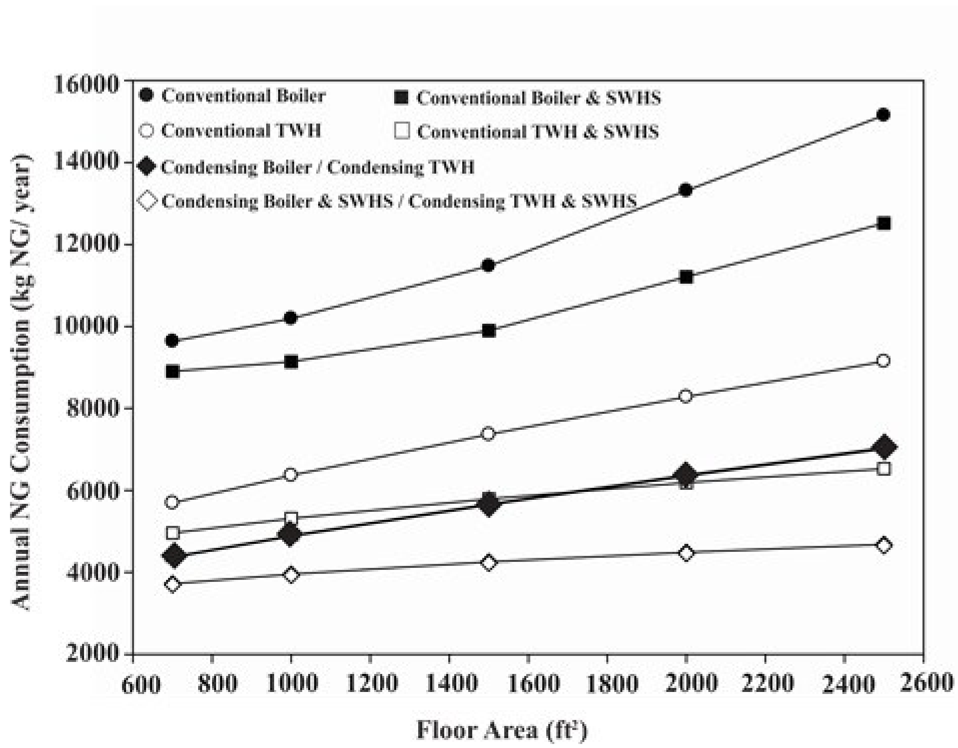

Figure 3-12: Annual Natural gas consumption for 40% solar coverage

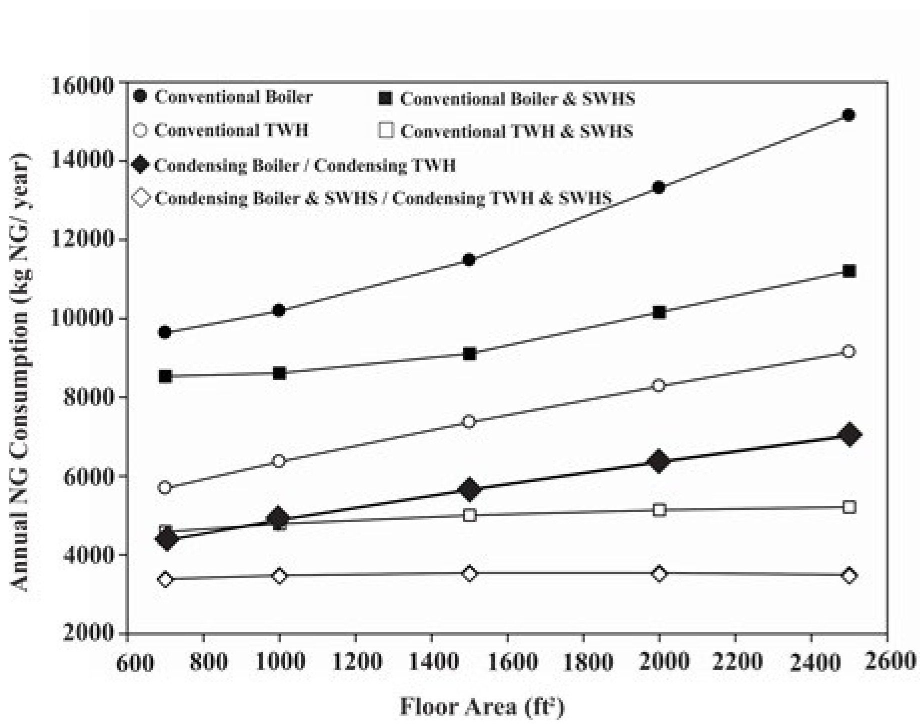

Figure 3-13: Annual Natural gas consumption for 60% solar coverage

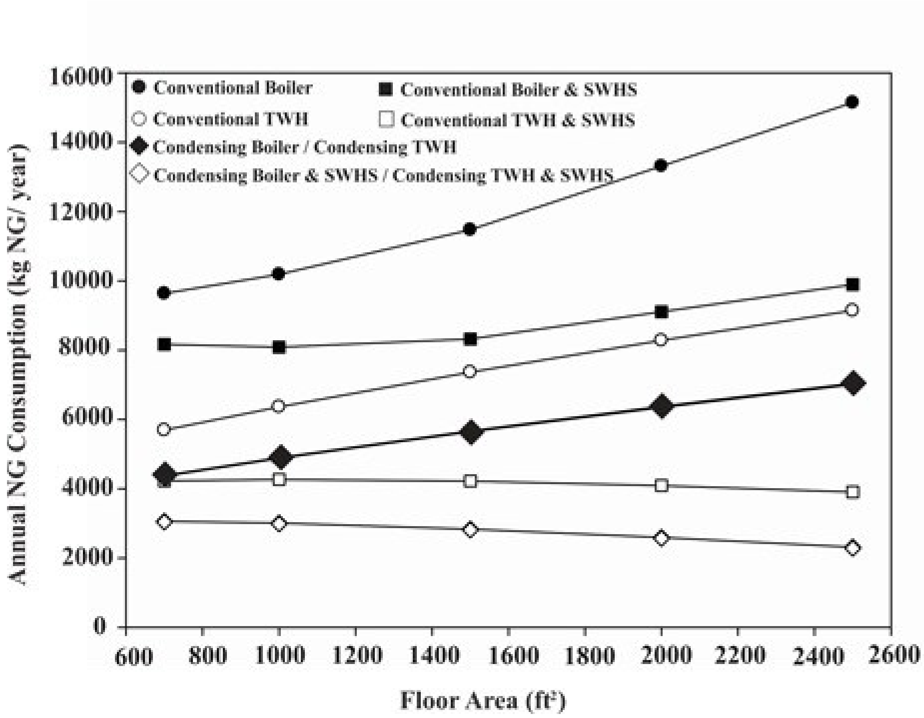

Figure 3-14: Annual Natural gas consumption for 80% solar coverage

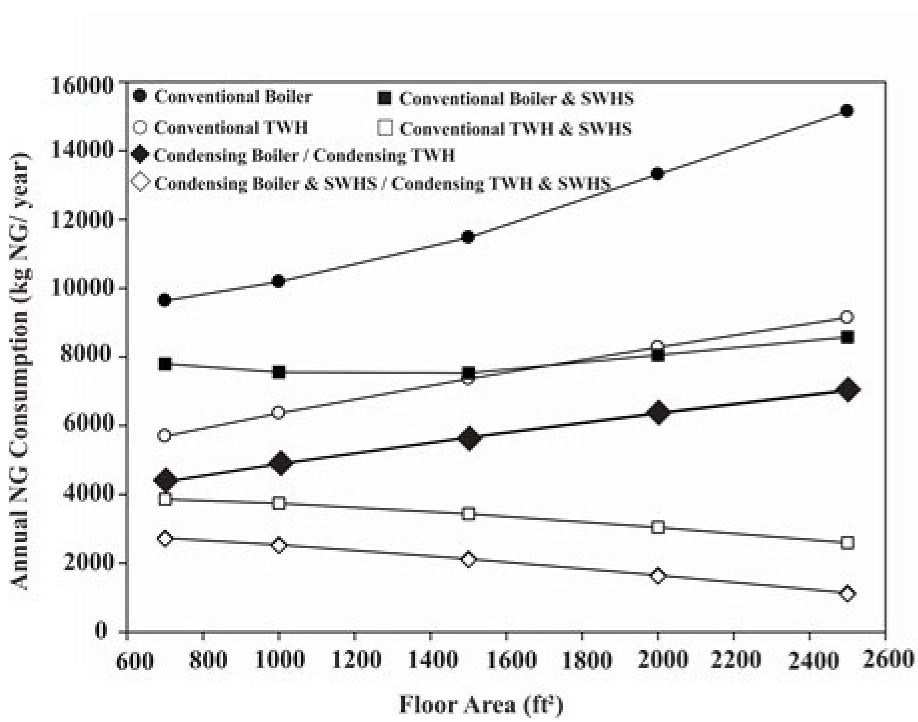

Figure 3-15: Annual Natural gas consumption for 100% solar coverage

3.6 CO_2 EMISSIONS IN THE COMBINED SWHS

The results of annual CO_2 emissions for different solar loads, ranging from 20% to 100% have been shown in Figs (3-16) - (3-20), respectively. These figures show the annual CO_2 emissions as a function of floor area. As shown in the figures, the increase in the floor area results in an increase in the annual CO_2 emissions for the different heating systems. In addition, as can be seen in Figs. (3-16) – (3-20), with the increase of solar coverage from 20% to 100%, the reduction of annual CO_2 emissions is noticeable in all of the heating systems because the more solar radiation is available due to the larger solar coverage. It should be noted that based on Eq. (2-7), 2.743 kg CO_2 is emitted per kg CH_4 input which obviously shows that there is a linear relationship between NG consumption and CO_2 emissions. Therefore, as seen in the below figures, the trend of the curves for different solar loads are similar to the trend of the curves for NG consumption in different solar loads.

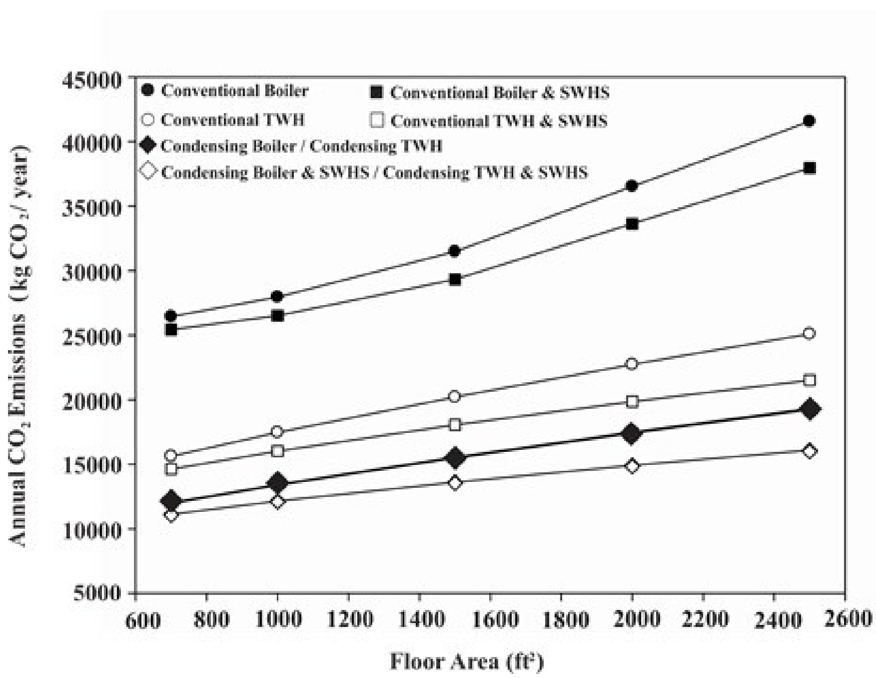

Figure 3-16: Annual CO_2 emissions for 20% solar coverage

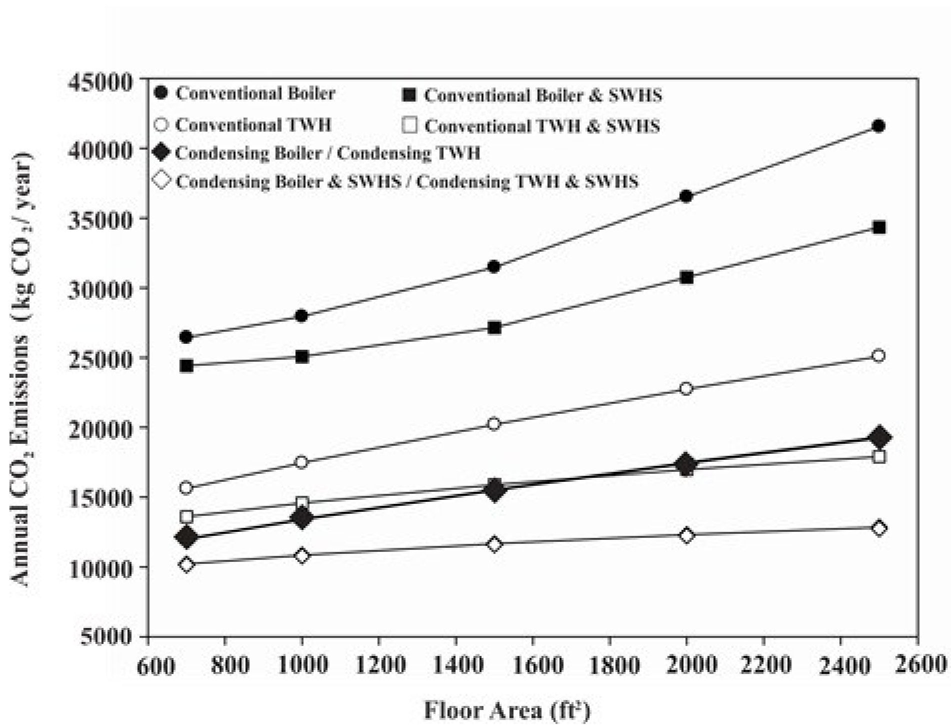

Figure 3-17: Annual CO_2 emissions for 40% solar coverage

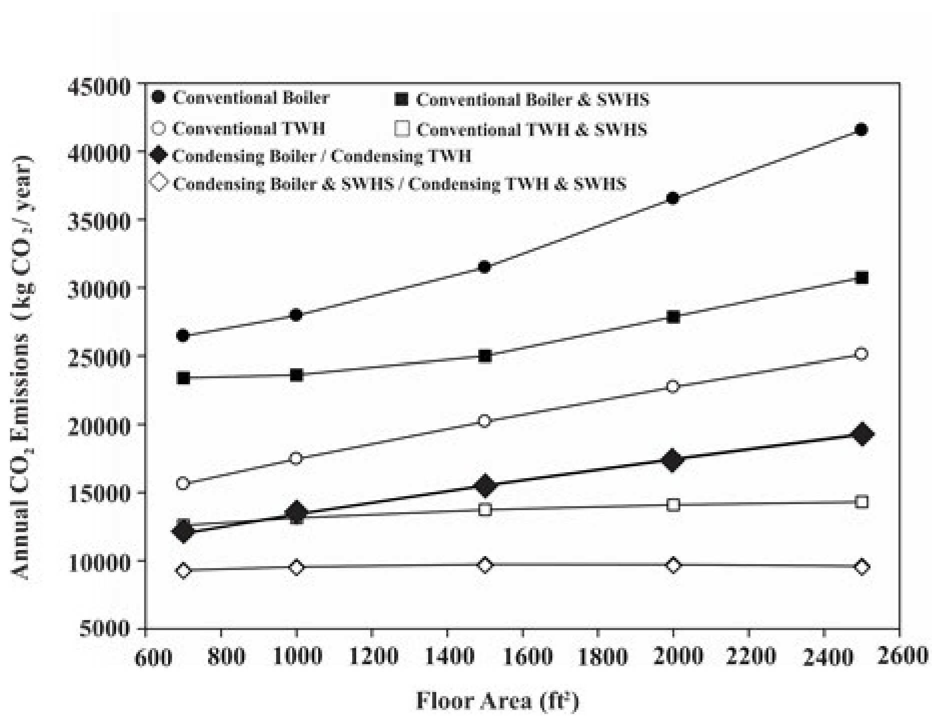

Figure 3-18: Annual CO_2 emissions for 60% solar coverage

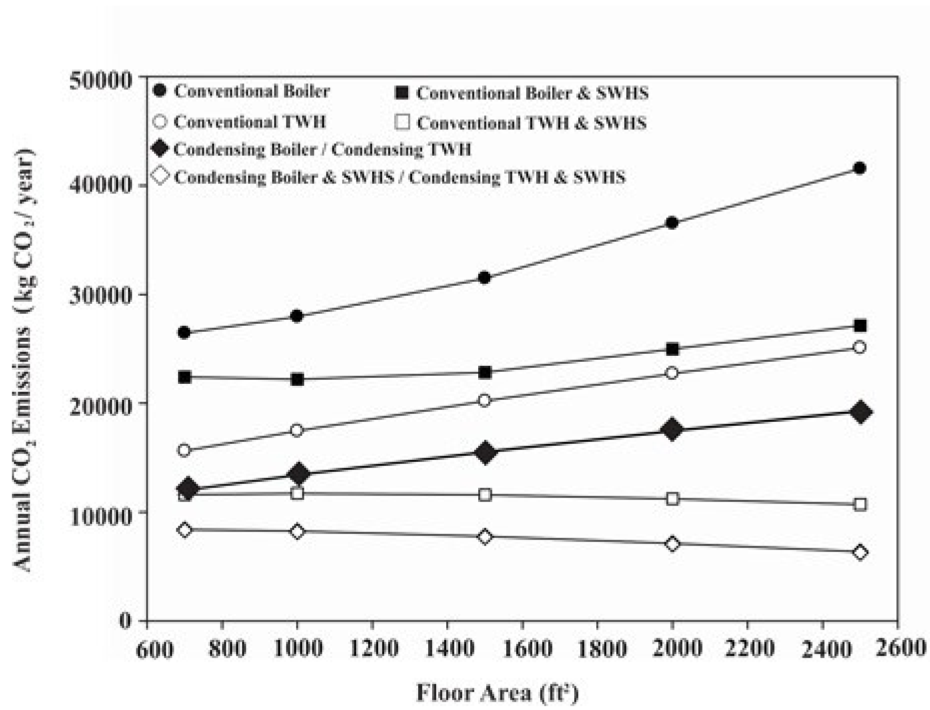

Figure 3-19: Annual CO_2 emissions for 80% solar coverage

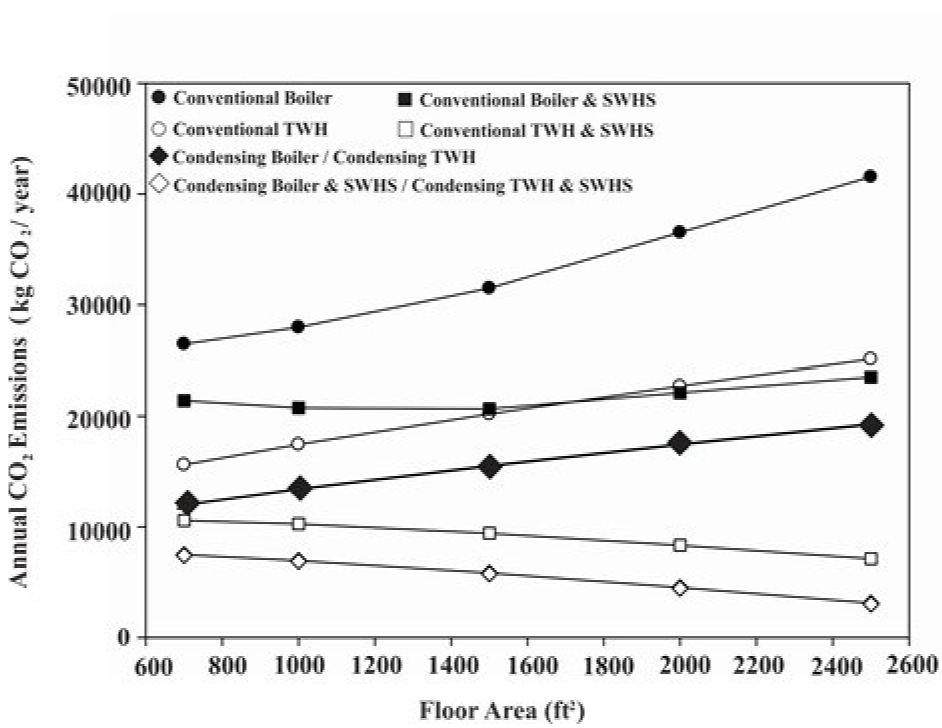

Figure 3-20: Annual CO_2 emissions for 100% solar coverage

3.7 CO_2 MITIGATION IN THE COMBINED SWHS

The results of annual CO_2 mitigation for different solar loads, ranging from 20% to 100% have been shown in Figs. (3-21) – (3-25), respectively. These figures show the annual CO_2 mitigation as a function of floor area. According to Eq. (2-29), the annual CO_2 mitigation is calculated by multiplying the annual heating time by the difference in the hourly rate of emission of CO_2 between the conventional boiler (benchmark system) and the combined SWHS. Thus, by decreasing the annual CO_2 emissions, the annual CO_2 mitigation increases. As it can be seen in Fig. (3-21)- (3-25), the condensing boiler with SWHS, and condensing TWH with SWHS have the highest value of annual CO_2 mitigation owing to the fact that they have the lowest value of CO_2 emissions as shown in Figs. (3-15) – (3-20). A similar trend is observed for the other systems. The increase of solar coverage from 20% to 100% resulted in a noticeable increase of the annual CO_2 mitigation for all of the heating systems. This was due to the reduced CO_2 emissions from the systems that were coupled with the SWHSs for space and water heating.

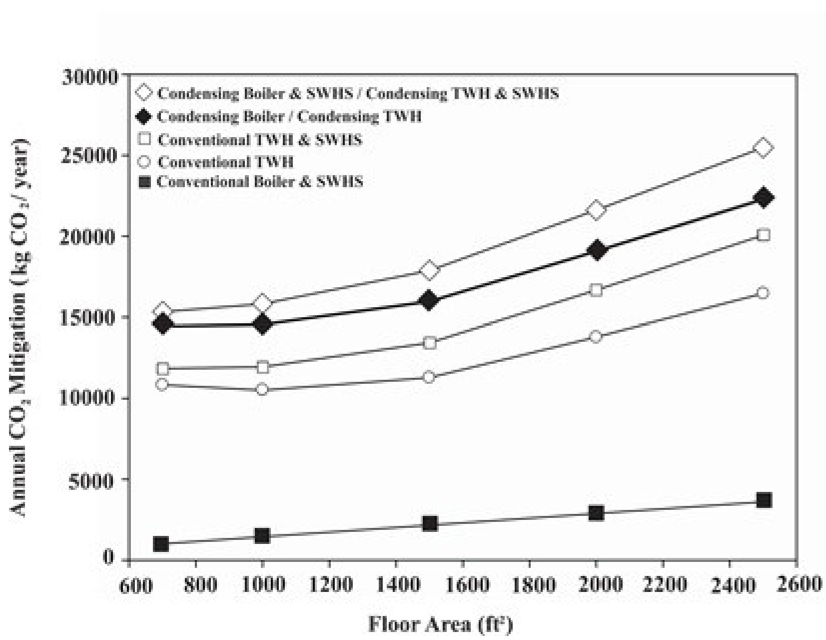

Figure 3-21: Annual CO_2 mitigation for 20% solar coverage

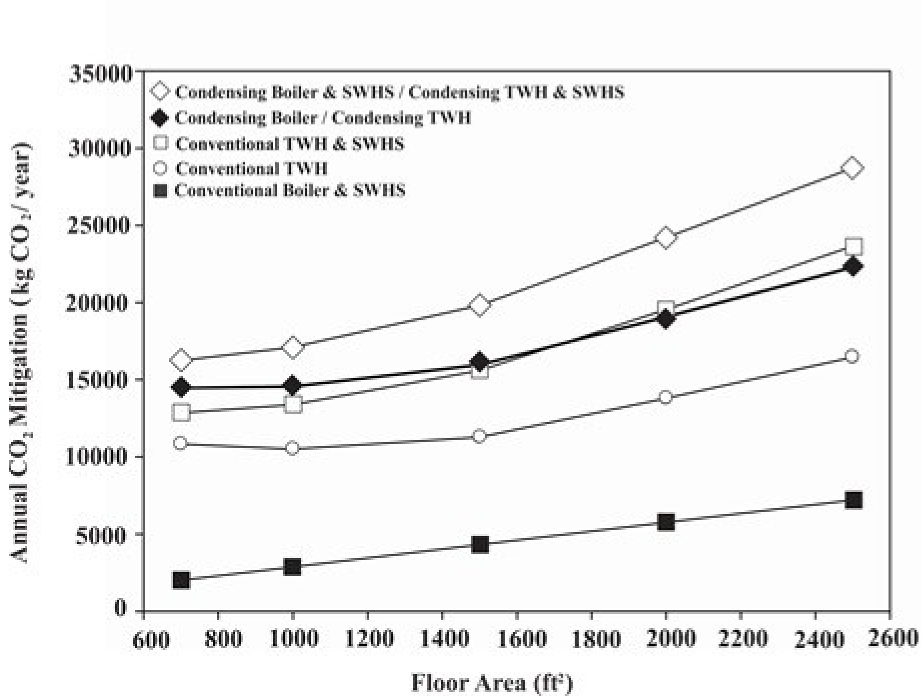

Figure 3-22: Annual CO_2 mitigation for 40% solar coverage

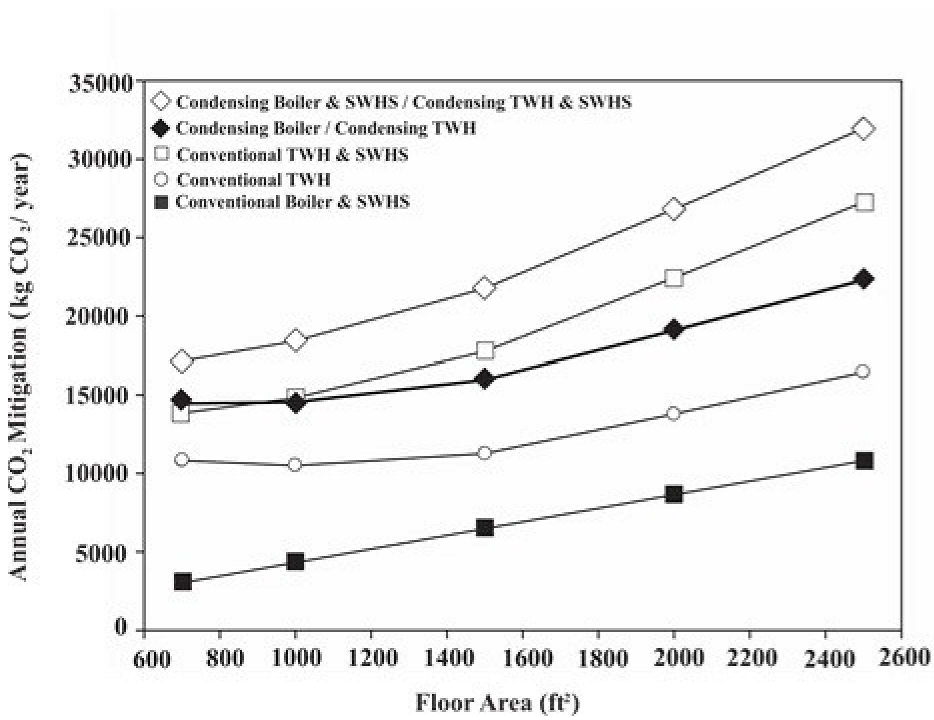

Figure 3-23: Annual CO_2 mitigation for 60% solar coverage

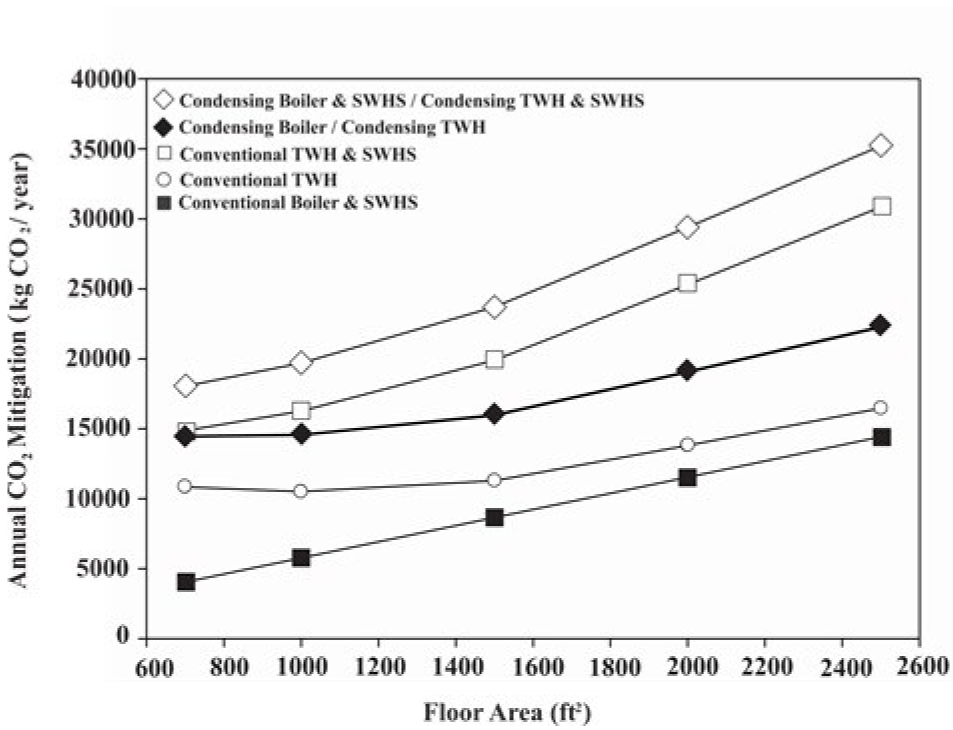

Figure 3-24: Annual CO_2 mitigation for 80% solar coverage

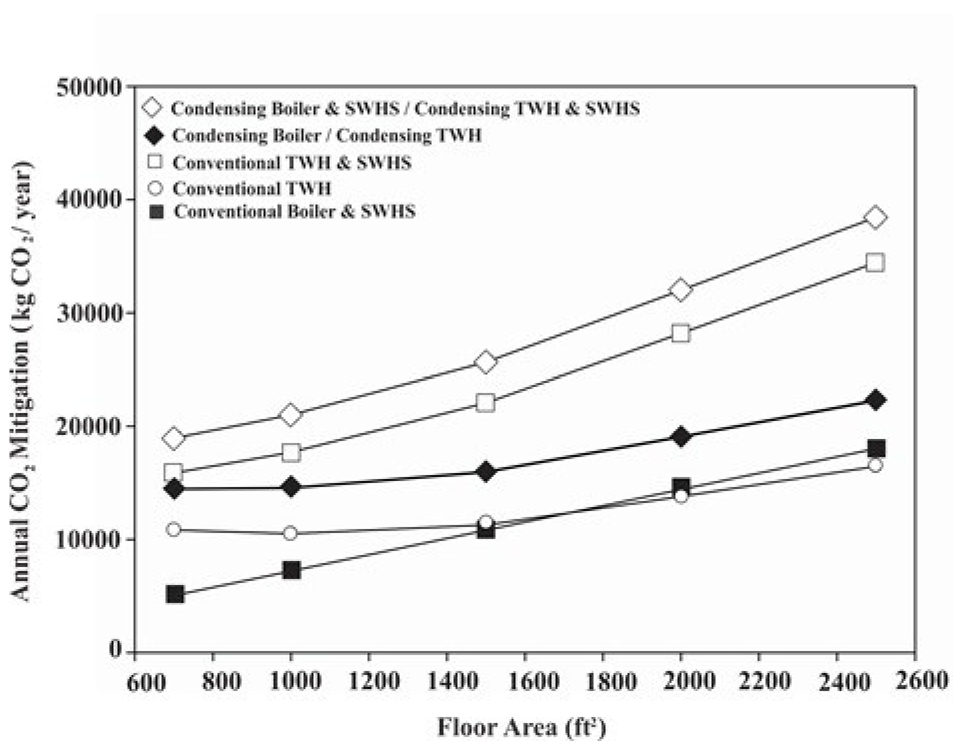

Figure 3-25: Annual CO_2 mitigation for 100% solar coverage

3.8 ANNUAL COST SAVINGS (ACS) IN THE COMBINED SWHS

The results of the economic analysis of the combined SWHS for different solar loads, ranging from 20%to 100% of the roof with solar collectors shown in Figs. (3-26) – (3-30). The figures show that the annual cost savings (ACS) generally decreases with the use of SWHS. Moreover, with the increase of solar loads, the reduction of ACS is noticeable in all of the combined SWHS due to the higher annual costs of the combined SWHS. These results show that the combined SWHS cannot be an economic option for Edmonton, Alberta, Canada although they decrease NG consumption and CO_2 emissions. In other words, the annual costs of the SWHS are much more than the price of the gas reduced by the use of the SWHS. Furthermore, the condensing boiler and the SWHS have the lowest value of ACS, whereas the tankless water heating systems yield the greatest ACS, compared to other combined SWHS in different solar loads.

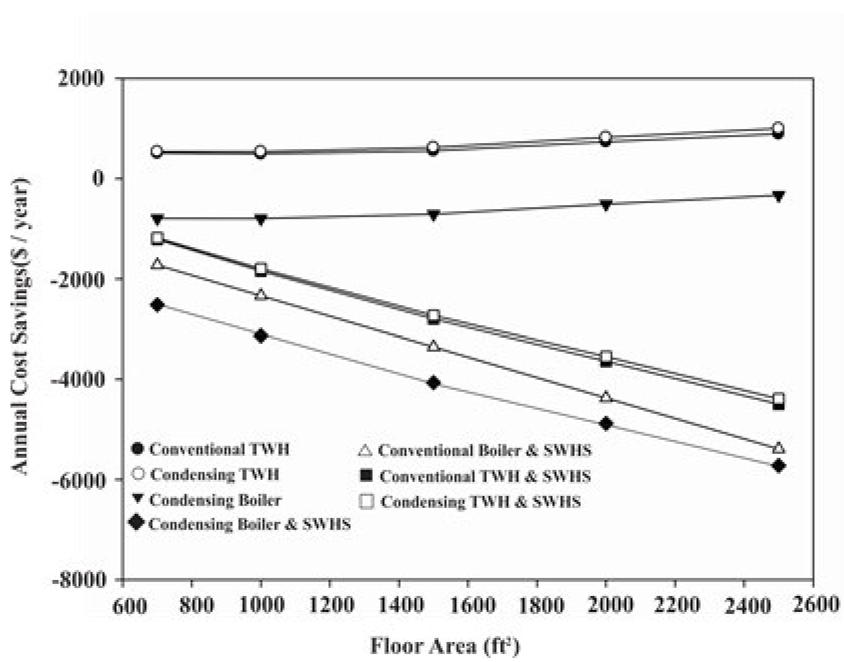

Figure 3-26: Annual cost savings (ACS) for 20% solar coverage

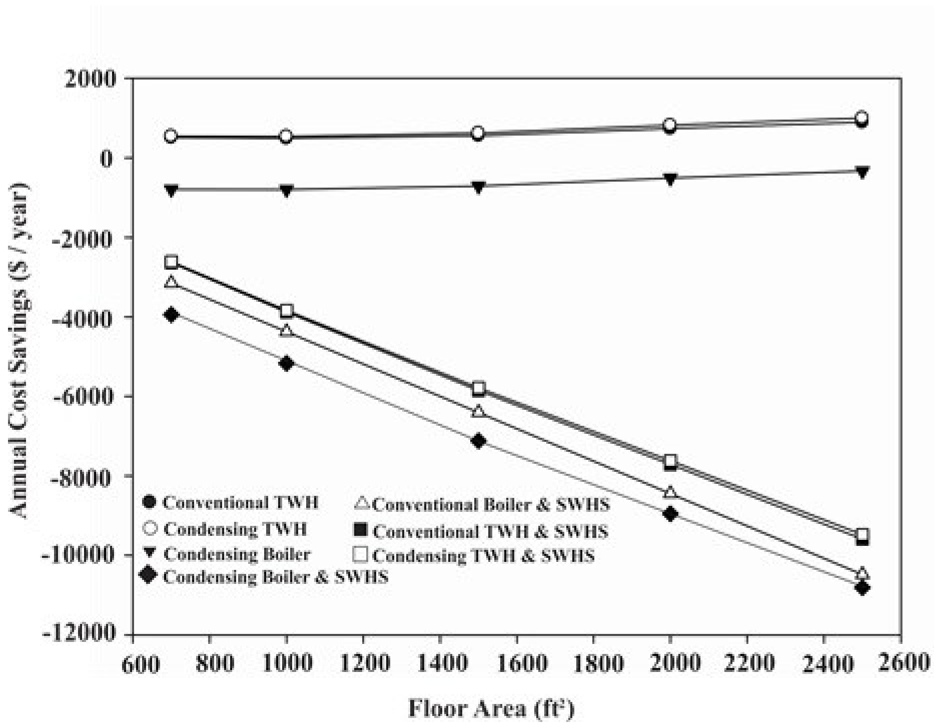

Figure 3-27: Annual cost savings (ACS) for 40% solar coverage

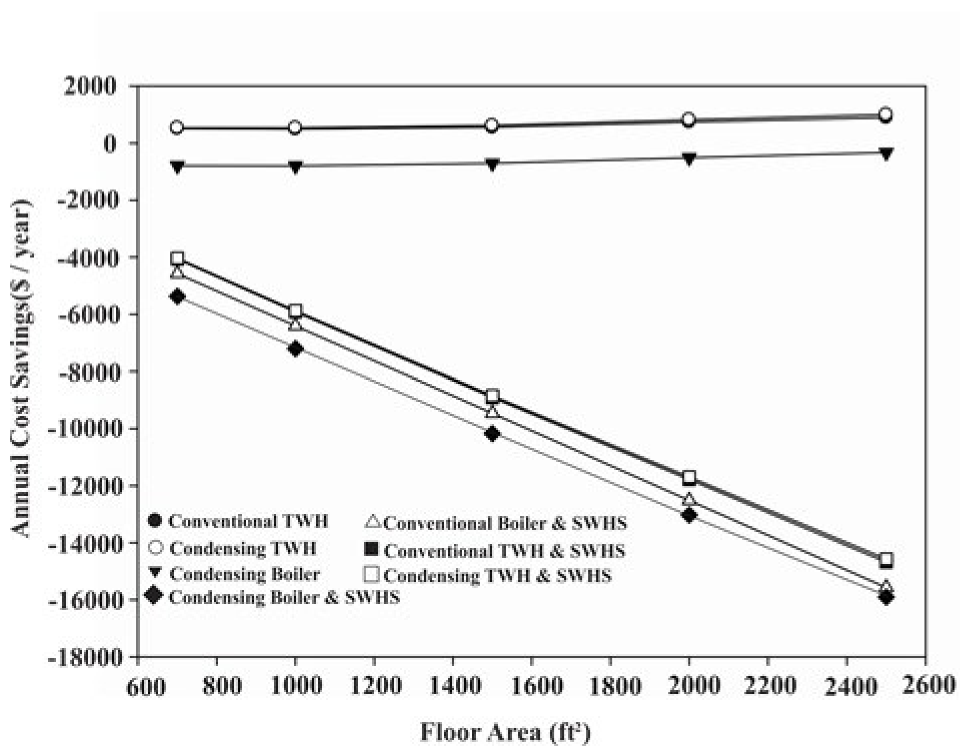

Figure 3-28: Annual cost savings (ACS) for 60% solar coverage

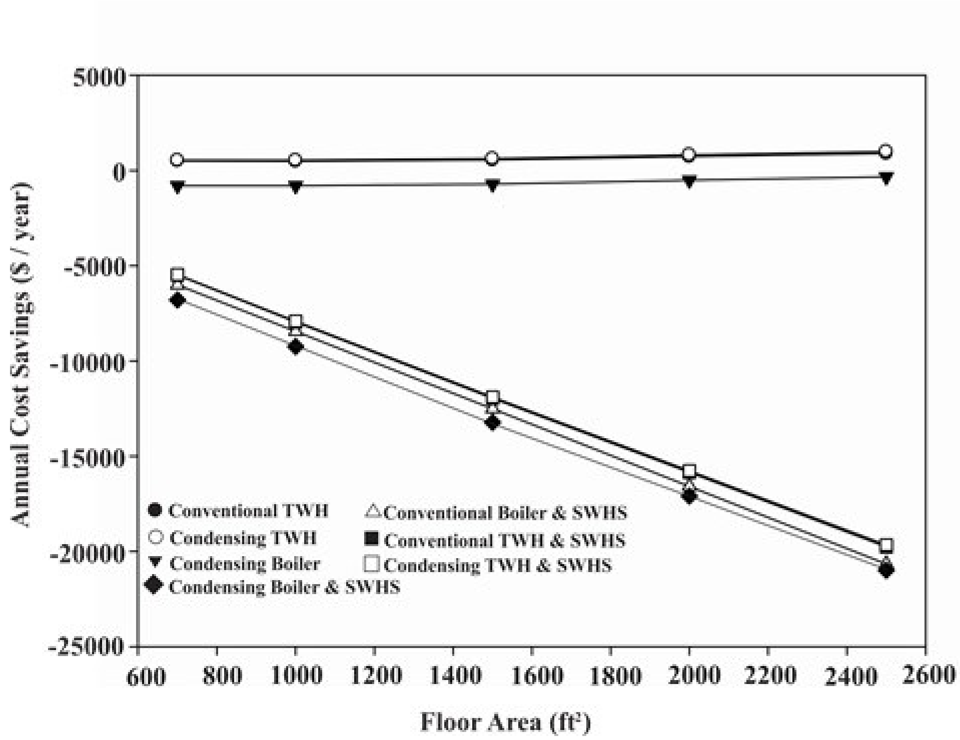

Figure 3-29: Annual cost savings (ACS) for 80% solar coverage

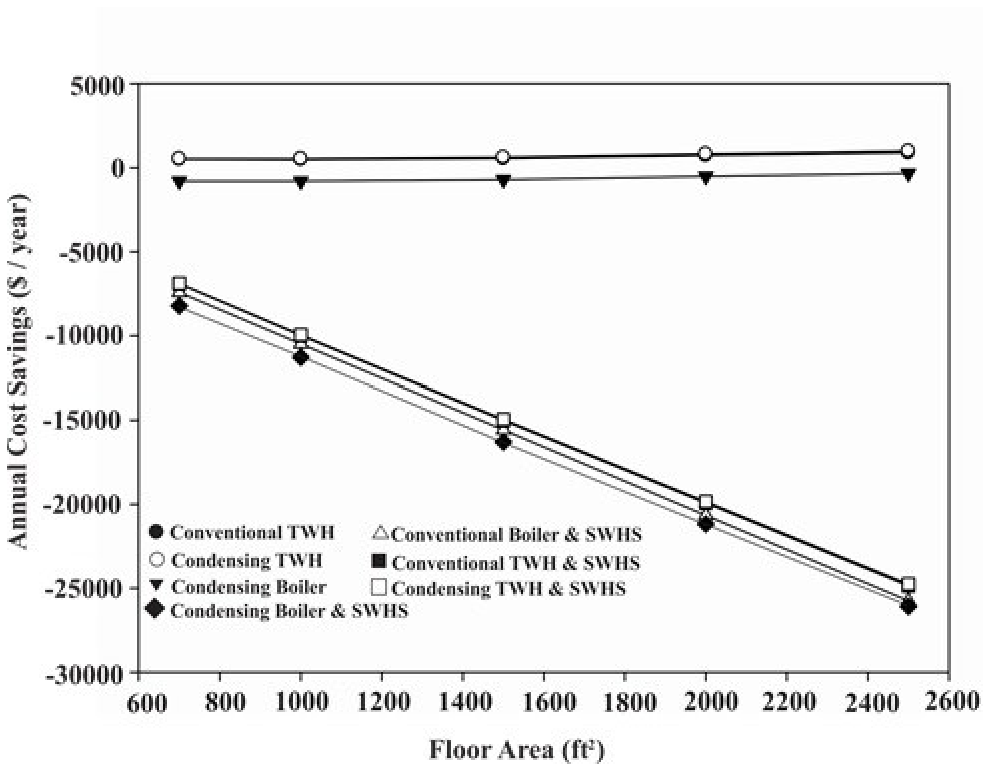

Figure 3-30: Annual cost savings (ACS) for 100% solar coverage

3.9 GHG ABATEMENT COST (GAC) IN THE COMBINED SWHS

The GAC was determined by comparing the cost of the combined SWHS to the cost of the traditional system using Eq. (4-7). The GAC is depicted in Figs. (3-31) – (3-35), and according to the figures, all combined SWHS have positive GAC since the combined SWHS are more costly than the non-combined SWHS. Furthermore, with the increase of solar loads from 20% 100%, the changes are noticeable because the combined SWHS have more annual costs compared to non- combined SWHS. As can be seen in the figures, the traditional system and the combined SWHS have the highest value of GAC, whereas the TWH systems have the lowest amount. Therefore, the combined SWHS cannot be an economic option owing to the fact that GAC is positive in different combined SWHS and wit the increase of solar loads, the value of GAC leads to an ascent. The values presented in the figures mean the value of a rebate that the government could provide to the customers in order to incentivize the purchase of SWHS. The GAC of the combined SWHS is positive in all of the following figures because of the high cost of the solar collectors per square meter of collector. It clearly illustrates that the government should provide the high rebate value of a rebate to incentivize the purchase of the combined SWHS compared to the other alternative heating systems. However, based on the GAC of the combined SWHS, it is unlikely possible to provide a high rebate value to the consumers.

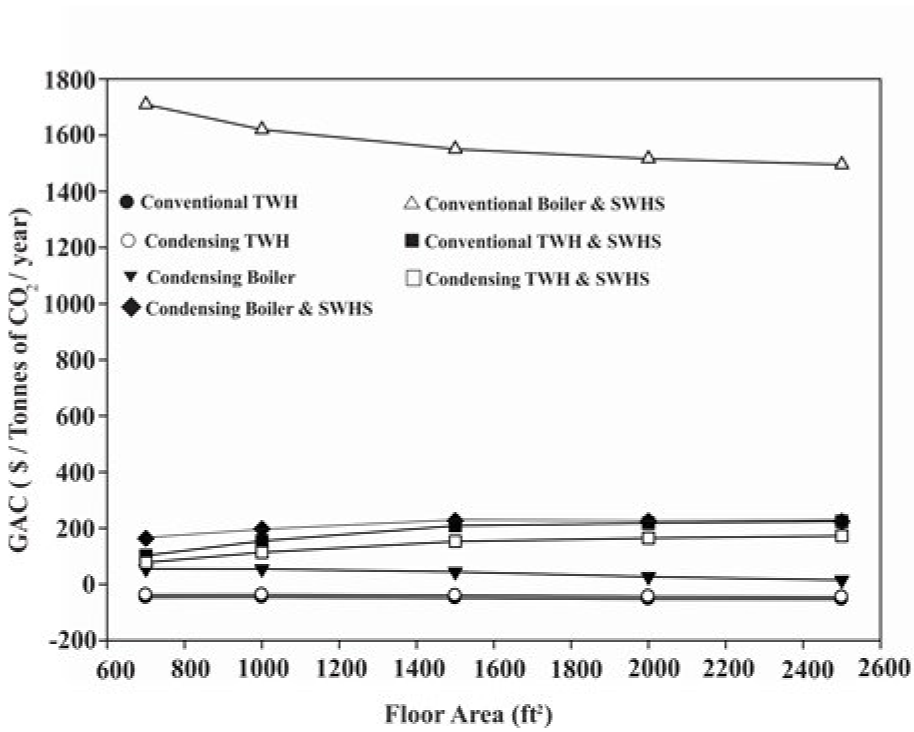

Figure 3-31: Annual GHG abatement costs (GAC) for 20% solar coverage

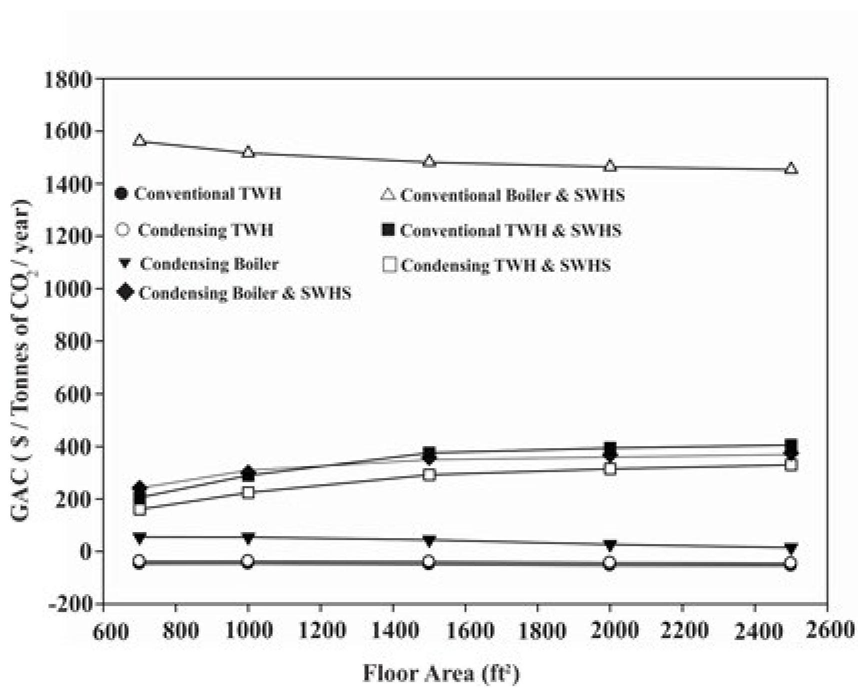

Figure 3-32: Annual GHG abatement costs (GAC) for 40% solar coverage

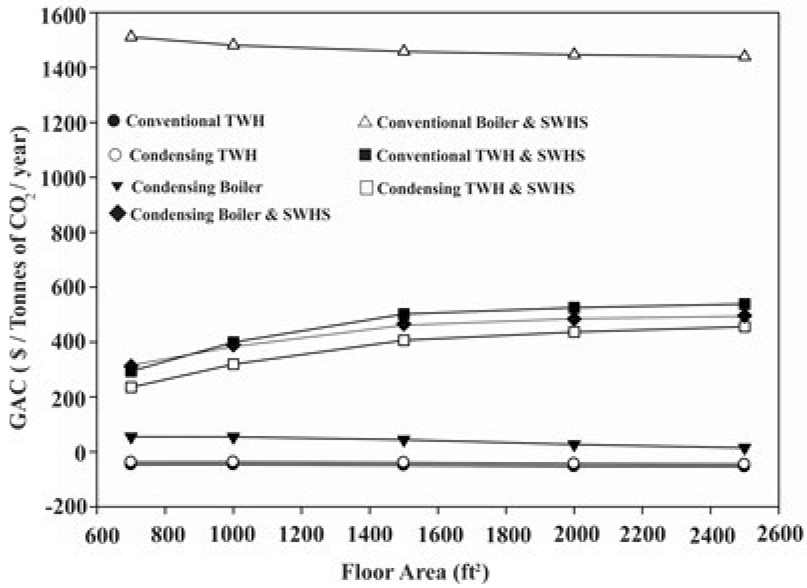

Figure 3-33: Annual GHG abatement costs (GAC) for 60% solar coverage

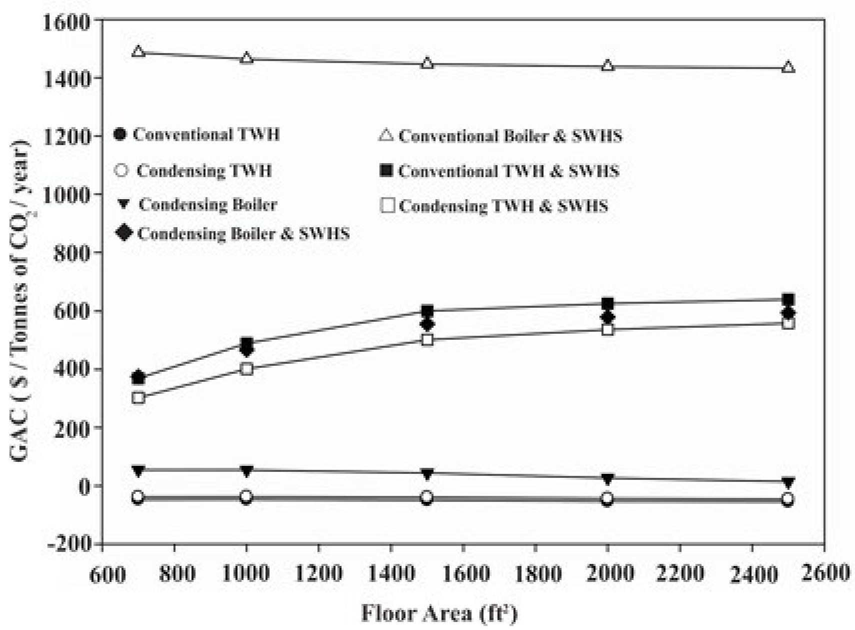

Figure 3-34: Annual GHG abatement costs (GAC) for 80% solar coverage

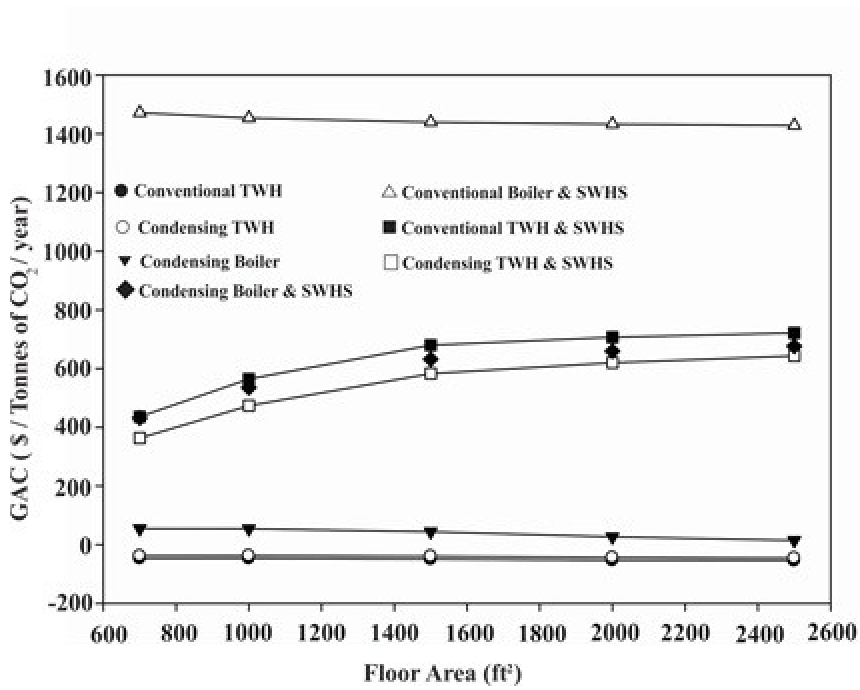

Figure 3-35: Annual GHG abatement costs (GAC) for 100% solar coverage

3.10 ANNUAL COST SAVINGS (ACS) WITH THE CO_2 TAX

It should be noted that the Alberta government has launched its plan to implement a tax of $20 per tonne on carbon dioxide in 2017 [99]. Therefore, considering the effect of the carbon dioxide tax will have an impact on the outcome of the evaluation of the economic analysis. This will inform whether or not the use of SWHS with the consideration of CO_2 tax is an economically viable option. Figures (3-36) – (3-40) show the annual cost savings for different solar loads, ranging from 20% to 100%. As can be seen in the figures, with the increase of the solar loads, the annual cost savings (ACS) noticeably decreases. Also, the effect of the carbon dioxide tax is not that noticeable on the ACS compared to the results of the Section 5.4 because the ACS of the combined SWHS is still negative. Therefore, the combined SWHS cannot be an economically viable option even if the carbon dioxide tax was implemented.

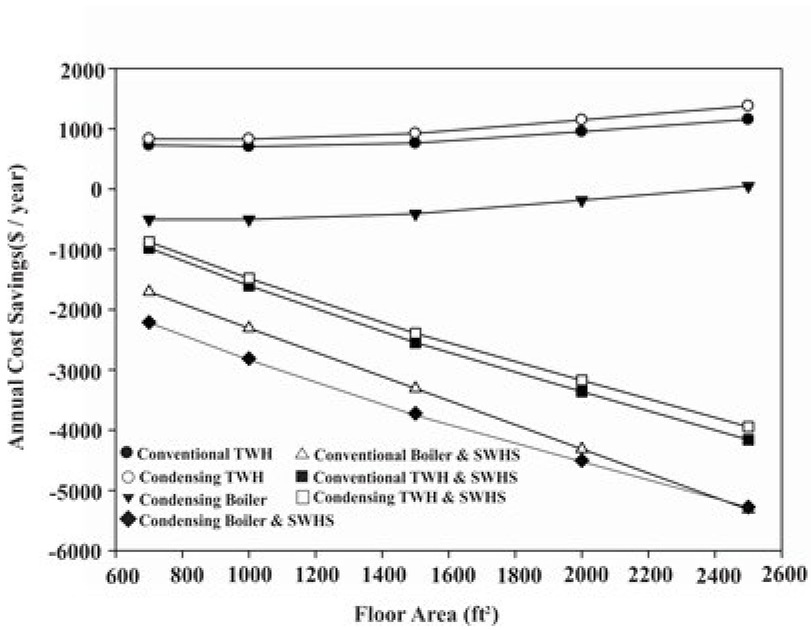

Figure 3-36: Annual cost savings (ACS) with CO_2 tax for 20% solar coverage

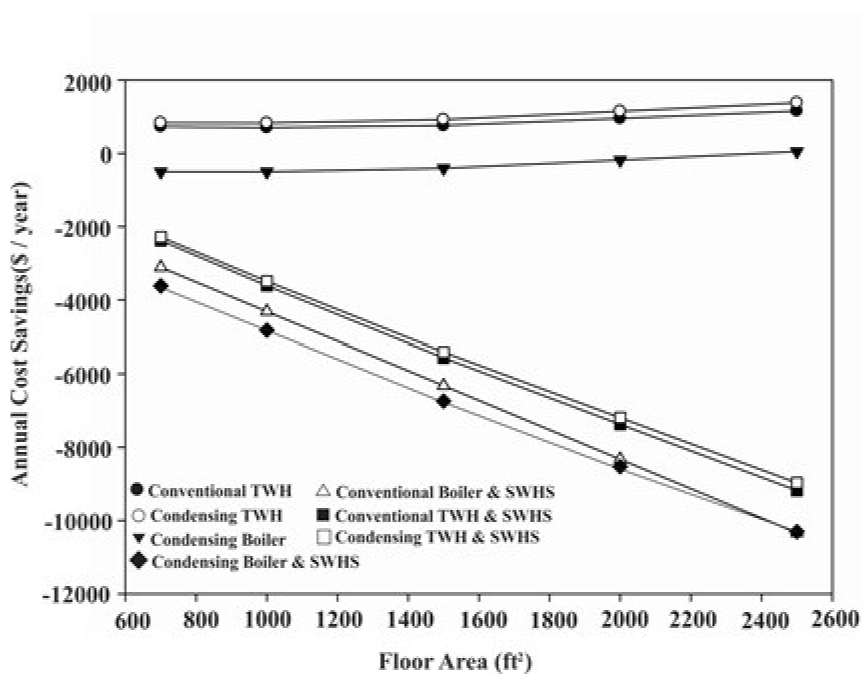

Figure 3-37: Annual cost savings (ACS) with CO_2 tax for 40% solar coverage

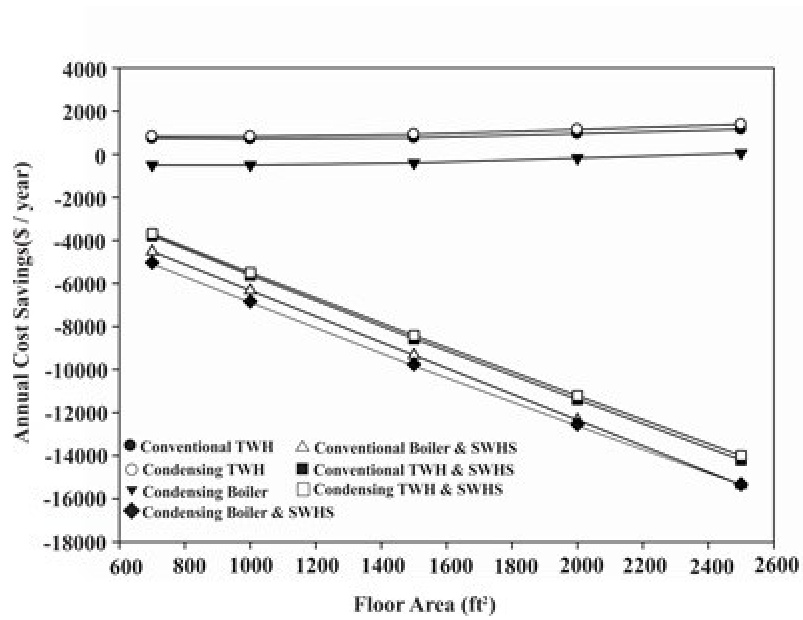

Figure 3-38: Annual cost savings (ACS) with CO_2 tax for 60% solar coverage

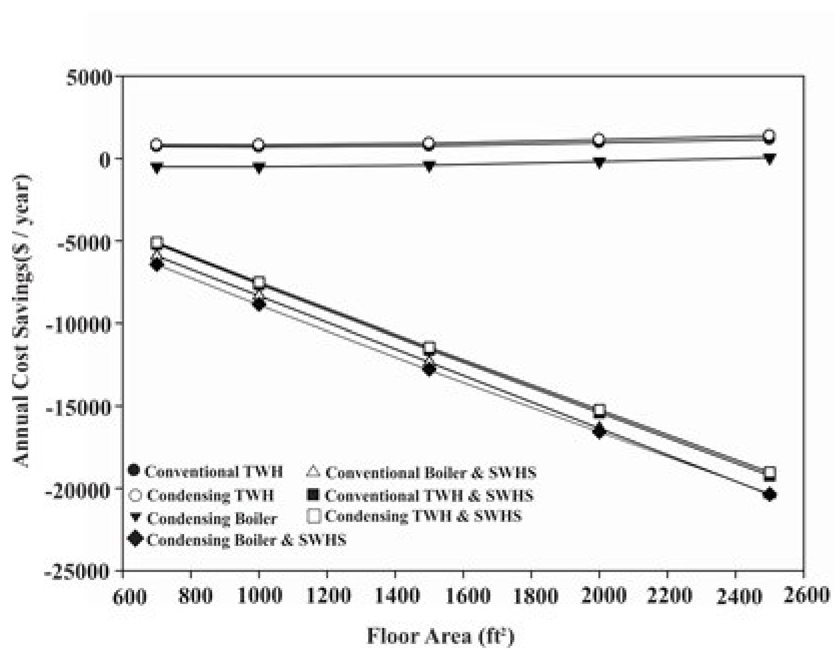

Figure 3-39: Annual cost savings (ACS) with CO_2 tax for 80% solar coverage

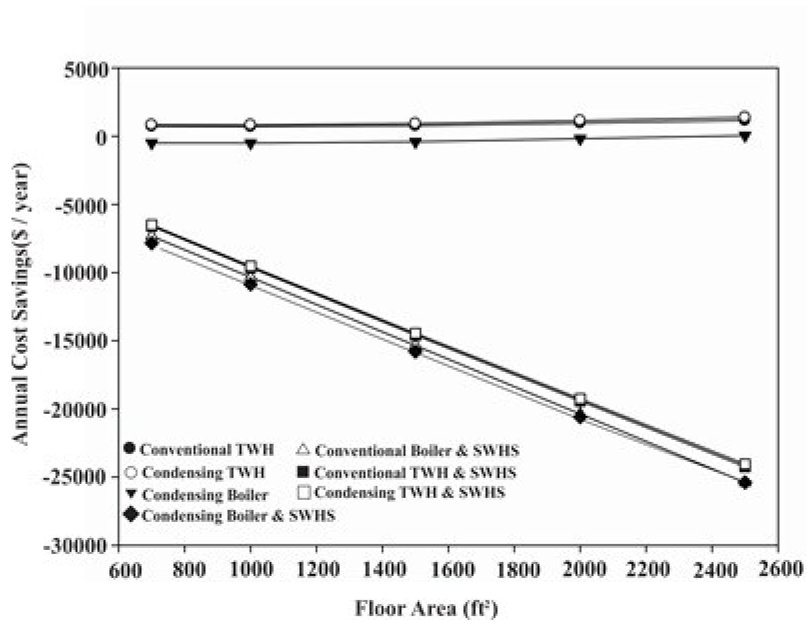

Figure 3-40: Annual cost savings (ACS) with CO_2 tax for 100% solar coverage

3.11 GHG ABATEMENT COST (GAC) WITH THE CO_2 TAX

Similarly, the effect of the carbon dioxide tax on the evaluation of GAC was studied in order to determine whether the use of SWHS with the consideration of CO_2 tax is an economic option or not. Figs (3-41) – (3-45) show the GHG abatement cost (GAC) for different solar loads, ranging from 20% to 100%. As can be seen in the figures, with the use of SWHS, the GAC increases. Furthermore, as the solar load increases, the increase of the GAC value gets more noticeable in different combined SWHS. Also, the influence of the carbon dioxide is not that noticeable on the GAC compared to the results of the Section 5.5. It means that by applying the carbon dioxide tax, the SWHS would likely not be an economically viable option for different solar loads, especially when the solar load increases.

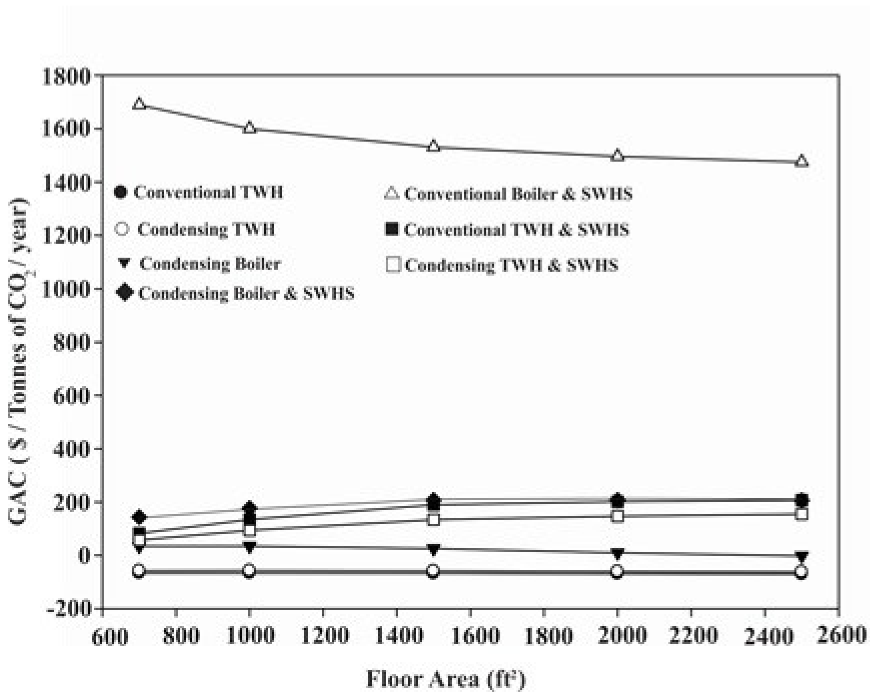

Figure 3-41: Annual GHG abatement costs (GAC) with CO_2 tax for 20% solar coverage

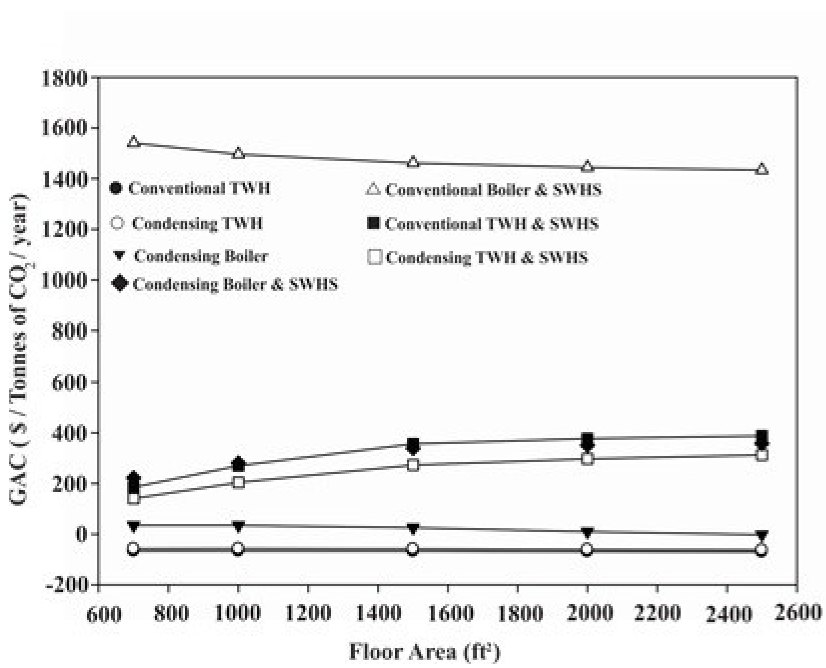

Figure 3-42: Annual GHG abatement costs (GAC) with CO_2 tax for 40% solar coverage

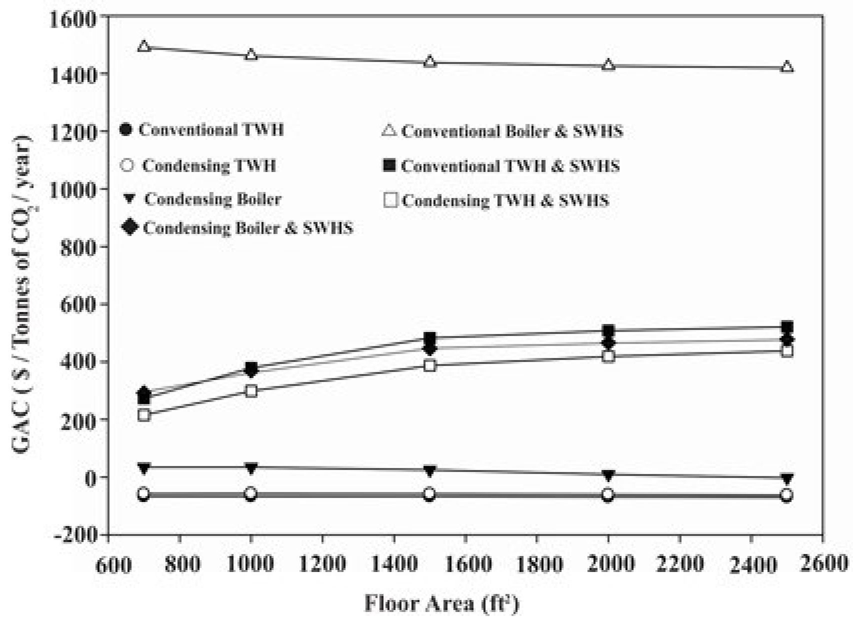

Figure 3-43: Annual GHG abatement costs (GAC) with CO_2 tax for 60% solar coverage

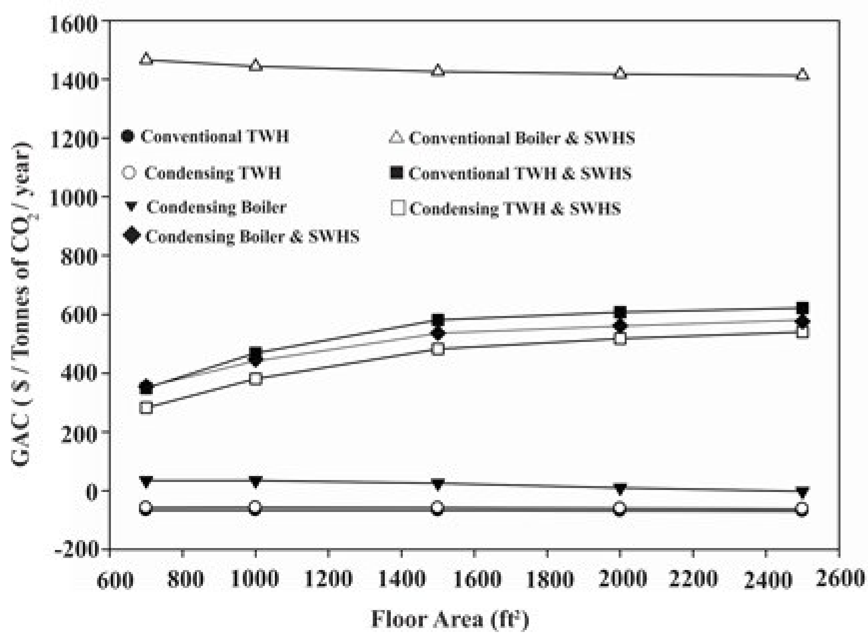

Figure 3-44: Annual GHG abatement costs (GAC) with CO_2 tax for 80% solar coverage

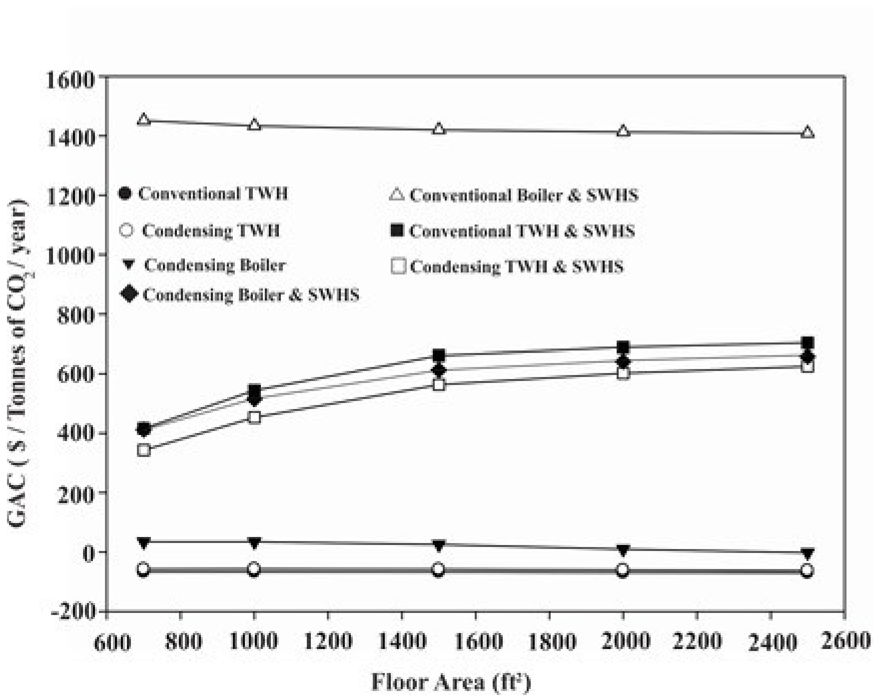

Figure 3-45: Annual GHG abatement costs (GAC) with CO_2 tax for 100% solar coverage

3.12 POSSIBILITY OF USE OF SWHS IN THE FUTURE

According to the results presented in Sections 3.5, and 3.6, the combined SWHS had a positive effect on NG consumption and CO_2 emissions. However, the economic results showed that they likely would not be economically viable options due to the high annual costs of the SWHS. Since the combined SWHS do not supplement the whole space and water heating and part of the heating is provided by the natural gas, with the increase of gas price, the ACS decreases; therefore, economic results become worse. In other words, combined SWHS cannot be an economic option in Edmonton, Alberta, Canada even though the gas price increases. Therefore, by decreasing the capital costs, the combined SWHS can be an economic option in the future. To take aim at the demand, using high technology and cheap materials will be the best solution. To suggest the economic price of the evacuated tube solar collectors as a future option, the maximum price of the SWHS with evacuated tube solar collectors for different combined SWHS based on the solar loads, ranging from 20% to 100% in the model house (1000 ft^2) are presented in Tables 3-6 to 3-10. In other words, the economic price is the maximum price in which the annual cost saving (ACS) would be equal to zero in each combined SWHS. As shown in the below tables, with the increase of solar loads, the economic price of the SWHS increases in each combined SWHS. Therefore, for higher solar loads, the economic costs of SWHS are more than the lower solar loads. Moreover, as shown in the below tables, for solar loads less than 100%, the combined SWHS (condensing boiler and SWHS) have negative prices. It is obvious that the combined SWHS cannot be an economic option at all because the amount of energy provided by the combined SWHS (condensing boiler and SWHS) does not have a positive effect on the economic analysis and do not cover the systems costs. In other words, since the annual costs of the condensing boiler and the SWHS are high, they cannot be a suitable combined SWHS.

Table 3-6: Economic cost of ETSCs in the model house (1000 ft^2) with 20% solar coverage

Combined SWHS Type	Economic Cost of Solar Collectors ($\$/m^2$)
Conventional Boiler & SWHS	7.248
Conventional TWH & SWHS	53.793
Condensing TWH & SWHS	61.886
Condensing Boiler& SWHS	-26.230

Table 3-7: Economic cost of ETSCs in the model house (1000 ft^2) with 40% solar coverage

Combined SWHS Type	Economic Cost of Solar Collectors ($\$/m^2$)
Conventional Boiler & SWHS	14.497
Conventional TWH & SWHS	61.026
Condensing TWH & SWHS	68.931
Condensing Boiler& SWHS	-19.184

Table 3-8: Economic cost of ETSCs in the model house (1000 ft^2) with 60% solar coverage

Combined SWHS Type	Economic Cost of Solar Collectors ($\$/m^2$)
Conventional Boiler & SWHS	21.746
Conventional TWH & SWHS	68.260
Condensing TWH & SWHS	75.977
Condensing Boiler& SWHS	-12.138

Table 3-9: Economic cost of ETSCs in the model house (1000 ft^2) with 80% solar coverage

Combined SWHS Type	Economic Cost of Solar Collectors ($\$/m^2$)
Conventional Boiler & SWHS	28.994
Conventional TWH & SWHS	75.492
Condensing TWH & SWHS	83.022
Condensing Boiler& SWHS	-5.093

Table 3-10: Economic cost of ETSCs in the model house (1000 ft^2) with 100% solar coverage

Combined SWHS Type	Economic Cost of Solar Collectors ($\$/m^2$)
Conventional Boiler & SWHS	36.243
Conventional TWH & SWHS	82.726
Condensing TWH & SWHS	90.067
Condensing Boiler& SWHS	1.951

4. CONCLUSIONS

In this study, a techno-economic analysis was used to assess the suitability of combo heating systems for residential applications in Alberta, Canada a city with cold climate. System performance and economic benefits of alternative heating systems were compared to those of benchmark conventional traditional furnace and gas tank water heater. The results showed that the highest value of NG consumption corresponded to the conventional system, whereas the lowest value corresponded to the condensing boiler and condensing TWH. Carbon dioxide mitigation for the condensing systems was higher in the alternative systems that were studied than for the conventional tankless water heater by almost 3.7 Mg CO_2/year.

However, with the use of SWHS, the lowest value of NG consumption corresponded to the condensing boiler & SWHS and the condensing TWH & SWHS. It is important to know that by increasing the solar load from 20% to 100%, the reduction of annual NG consumption was noticeable in all of the alternative heating systems due to the fact that the more solar radiation is available due to the larger solar coverage. The increased solar energy supplement, to a greater extent, the energy required for space and water heating. Also, with the use of SWHS, carbon dioxide mitigation for the SWHS & condensing systems was higher than conventional TWH systems. It is clear that with the increase of solar load, this amount increases since the NG consumption decrease as the solar load increases.

On the other hand, without using SWHS, it was noted from the ACS that the condensing TWH was the most economically favourable investment, based on savings accrued relative to the traditional system. The conventional tankless water heater was the next best alternative based on the ACS. However, the condensing boiler was the most expensive alternative and was the least well-suited alternative for this residential application because it was more costly than the traditional system. The condensing boiler had negative cost savings for different floor areas.

The GAC can be used to quantify incentives that serve to promote the implementation of the alternative systems in Alberta for the purposes of emissions reduction. These incentives may be in the form of rebates. The monetary values presented in the GHG abatement cost curve can be interpreted as the value of the rebate. The values for the tankless water heaters were both negative, which means that they are less costly than the traditional system and do not require an incentive; whereas, the condensing boiler has positive marginal abatement cost. Therefore, purchase and installation of the condensing boiler plant would require rebate. The monetary values presented in the GHG abatement cost curves for the ASHRAE model house and for the house with a 93 m^2 (1000 ft^2) floor plan are different for the alternative systems, which means that the better alternative is dependent on the geometry of the heated area. However, the condensing and conventional tankless water heaters had very similar rebate values for each of the different house sizes. Therefore, the condensing TWH was the preferred investment because of the amount of CO_2 that was mitigated. The rebate values provide an estimate of the possible incentives for abatement of air pollution that would be provided by the alternative heating systems.

However, with the use of SWHS, the results showed that the annual cost savings (ACS) generally leads to the reduction with the use of SWHS. Moreover, with the increase of solar loads, the reduction of ACS is noticeable in all of the combined SWHS, notably when the solar load increases because of the higher annual costs of the combined SWHS. Therefore, the combined SWHS cannot be an economic option for Edmonton, Alberta, Canada although they decrease NG consumption and CO_2 emissions. Besides, all combined SWHS had positive GAC because the combined SWHS are more expensive than the non-combined SWHS. Furthermore, with the increase of solar coverage from 20% 100%, the changes are noticeable since the combined SWHS have much more original and capital costs compared to non- combined SWHS. In other words, the combined SWHS cannot compensate the high annual costs even though the reduction of NG consumption has a positive impact on the annual NG bills. According to the results, the traditional system and the combined SWHS had the highest value of GAC, whereas the TWH systems had the lowest amount. Therefore, as it was discussed earlier, the combined SWHS cannot be an economic option. However, by the reduction of the annual costs, the combined SWHS can be an economic option in the future. Thus, using high technology and cheap materials will be the best solution. To present the economic price of the evacuated tube solar collectors in Edmonton, Alberta, Canada as a future option, the maximum price of the evacuated tube solar collectors for different combined SWHS based on the solar loads, ranging from 20% to 100% were studied in this study. It goes without saying that presenting the maximum price of evacuated solar collectors will ultimately affect the study of the possibility of the reduction of the SWHS costs.

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