بسم الله الرحمن الرحيم

Palestine Polytechnic University

College of Engineering and Technology
Mechanical Engineering Department

Graduation Project

Technical-economic Analysis of a Solar Heating System for Hebron Climatic Region

Project Team

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In accordance with the recommendations of the project supervisor, and the acceptance of all examining committee members, this project has been submitted to the Department of Mechanical Engineering in the College of Engineering and Technology in partial fulfillment of the requirements of the Bachelor's degree in Air-conditioning and Refrigeration Engineering.

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ABSTRACT

A solar heating system under the climatic conditions of Hebron/Palestine is studied from both technical and economics points of view. The analysis of the solar heating system which obeys the *f*-chart model, is performed by using a developed computer program. The results are presented for a common prototype building (house) with an estimated heating load located in the climatic region of Hebron.

In the economic analysis, cumulated cost flows of the selected system is compared throughout the lifetime of the system by using the present worth value technique. Optimum design magnitudes such as collector area, yearly solar heating fraction, etc., are determined for the maximum life-cycle savings. Total savings and solar heating fraction are found for the optimum conditions. Variation of the system performance is studied within the forecastable range of changes of the most influential unstable economic parameters.

In the technical analysis, effects of the primary design parameters such as collector (tilt angle, $F_R(\tau\alpha)$ and F_RU_L), storage tank (its volume per square meter of collector area), heat-exchanger (effectiveness, and the flow rate of primary and secondary working fluids), and the design heating load (building overall heat loss coefficient and area product, and the number of heating hours per day), on the system performance are studied within the valid range of changes. Finally, the economics of the solar heating systems in Palestine as general are discussed.

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a_0, a_1: annuity for CI and SI, respectively.

A: the collector area, surface area $[m^2]$.

A_z: collector azimuth angle $[Degree]$.

$c_{p,w}$: water specific heat, $[kJ/kg.\text{℃}]$.

C_0, C_1: percent of yearly increase rate of conventional and auxiliary fuel price $[\%\ year]$.

C_c: total present cost for CI.

C_s: total present cost for SI.

d: the discount rate.

$\bar{D}$: monthly average daily diffuse radiation $[kJ/m^2.day]$.

DD: the number of degree-days in a month $[℃\text{-}day]$.

$DD_{17/17}$: the degree-days of a given month based on 17^{o}C $[℃\text{-}day]$.

e_0, e_1: percent of total initial investment assumed to be paid at year zero of CI and SI, respectively.

E: the total auxiliary energy required during the month $[kJ]$.

f : the fraction of the monthly total heating load supplied by solar energy.

F: the future cash flow.

$\bar{F}$: yearly solar heating fraction.

F_R: the collector heat removal factor.

F'_R: the collector-heat exchanger efficiency factor.

G_0, G_1: guaranty period for CI and SI, respectively.

H_{in}: indoor enthalpy.

H_{out}: outdoor enthalpy

$\bar{H}$: total radiation on horizontal plane $[kJ/m^2\ .day]$.

$\bar{H}_0$: monthly mean daily extraterrestrial radiation $[kJ/m^2.day]$.

$\bar{H}_b$: monthly mean beam radiation $[kJ/m^2]$..

$\bar{H}_T$: monthly average daily radiation $[kJ/m^2.day]$.

I_c: initial investment for CI.

I_s: Initial capital cost of SI.

I_{sc}: solar constant $[W/m^2]$, solar collector costs.

I_{sf}: fixed solar system costs.

I_{ss}: storage tank cost.

k_1: thermal Conductivity, $[W/m.^0C]$.

$\bar{K}_T$: the clearness index.

L: monthly total heating load $[kJ]$.

L_s: the monthly space heating load.

L_{st}: the storage tank heat loss $[kJ]$.

L_w: the monthly water heating load $[kJ]$.

m_0, m_1: maintenance and operation costs fraction of the initial investment for CI and SI, respectively.

$(\dot{m}c_p)_c$: flow rate times specific heat of fluid circulating through the collector $[W/°C]$.

$(\dot{m}c_p)_{min}$: the minimum flow rate times specific heat of the fluid in the heat exchanger $[W/°C]$.

M: the actual storage capacity in liters per square meter of collector area.

n: number of days in a year, number of years, number of days in a month.

n_0, n_1: number of credit years for CI and SI, respectively.

N_m: numbers of days in month.

N_p: the number of persons.

P: the present worth or present value.

P_0: the actual conventional fuel price at year zero$[NIS/GJ]$.

P_1: the actual auxiliary fuel price at year zero$[NIS/GJ]$.

P_a: the present value of annuity.

$P(e, d, n)$: the present-worth factor.

Q: the annual heating load $[kJ]$.

Q_c: conduction heat loss $[W]$.

Q_f: infiltration heat loss $[W]$.

Q_t: total heat loss $[W]$.

Q_T: the total useful solar energy delivered during the month $[kJ]$.

r_0, r_1: credit interest rate for CI and SI, respectively.

$\bar{R}$: total radiation tilt factor $[Dimensionless]$.

R_0, R_1, R_2: yearly increment decrease in the efficacy of CI, $\mathcal{F}$, and efficacy of auxiliary installation, respectively [% $year$].

$\bar{R}_b$: ratio of the average beam radiation on the tilted surface to that on the horizontal surface for each month $[Dimensionless]$.

R_{th}: thermal Resistance, $[m^2.^0C/W]$.

S: life-cycle saving.

S_1, S_1': present value of the initial investment for CI and SI, respectively.

S_2, S_2': present value of fuel costs for CI and SI, respectively.

S_3, S_3': present value of combined maintenance and operation costs for CI and SI, respectively.

$T_{a,d}$: the daily mean ambient temperature $[\,^0C]$.

$\bar{T}_a$: monthly average ambient temperature $[\,^0C]$.

T_c: the temperature of the cold water must be heated $[\,^0C]$.

T_w: the temperature of the hot water supply $[\,^0C]$.

T_i: inside dry bulb temperature$[\,^0C]$.

T_{out}: outside dry bulb temperature $[\,^0C]$.

T_{ref}: a reference temperature determined to be 100 °C.

T_{st}: storage tank water temperature $[{}^{0}C]$.

U: overall heat transfer coefficient, $[W/m^2.{}^{0}C]$.

UA: the building overall energy loss coefficient-area product $[W/°C]$.

$(UA)_{st}$: storage tank overall heat transfer coefficient-area product $[W/{}^{0}C]$.

U_c: unit collector price.

U_L: the collector overall energy loss coefficient $[W/m^2°C]$.

U_s : the storage tank cost per square meter of storage tank surface.

V_f: the infiltration rate $[m^3/s]$.

V_w: volume of hot water required per person, assumed to be 30 $[liter/day]$.

x_i: layer thickness, $[m]$

X: dimensionless parameter.

X_L: the storage tank volume per square meter of collector area.

Y: dimensionless parameter.

z: load heat exchanger size.

GREEK LETTERS

α: absorptance of collector cover.

β: tilt angle of the surface from the horizontal.

δ: declination angle.

Δt: the total number of seconds in the month.

ΔT: temperature difference $[{}^{0}C]$.

ΔT_{adj}: temperature difference for unheated adjacent rooms.

ΔU: the energy change in the storage unit $[kJ]$.

ε: the primary heat exchanger effectiveness.

ε_L: the load heat exchanger effectiveness.

$\bar{\theta}_b$: monthly average incidence angle of beam radiation $[Degrees]$.

θ_i: incidence angle $[Degrees]$.

ρ: ground reflectance $[Dimensionless]$.

ρ_o: outside air density $[kg/m^3]$

ρ_w: the density of water, $[kg/liter]$.

τ: transmittance of collector cover.

$(\overline{\tau\alpha})$: the monthly average transmittance-absorptance product.

ϕ: latitude $[Degrees]$.

ϕ_o: outside relative humidity.

ω: hour angle.

ω_s: sunset hour angle for a horizontal surface.

ω_s': sunset hour angle for a tilted surface.

CHAPTER ONE

INTRODUCTION

INTRODUCTION

1.1 General Introduction

The ultimate source of energy the planet Earth may has is the sun. It produced energy for billions of years, providing our planet about 3850 zettajoules ($ZJ=10^{21}$) per year[1]. However, oceans absorb about 285 ZJ, leaving 3565 ZJ. While the worldwide energy consumption of energy reached[2] 0.471 ZJ in 2004.

Resources of energy are divided into non-renewable energy and renewable energy. Non-renewable resource is called so because it exists in a fixed amount or is used up faster than it can be made (by nature). We also use the name "fossil fuels" for non-renewable resources since they are hydrocarbons found within the top layer of the earth's crust[3]; such as coal, petroleum and natural gas. It was estimated that in 2004, 86% of human-produced energy came from burning fossil fuels[4]. Burning of fossil fuels produces around 6.3 gigatons of carbon dioxide per year (worldwide), while natural processes can only absorb about half of that amount[5].

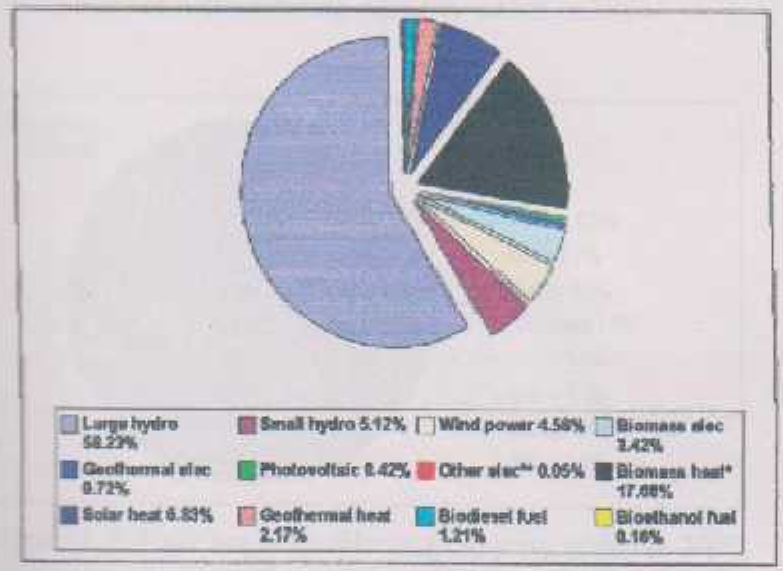


Figure 1.1: Worldwide renewable energy 2005

Renewable resources of energy are effectively utilizes natural resources such as tides sunlight, wind and geothermal heat, which are naturally replenished, and are known to be clean resources of energy.

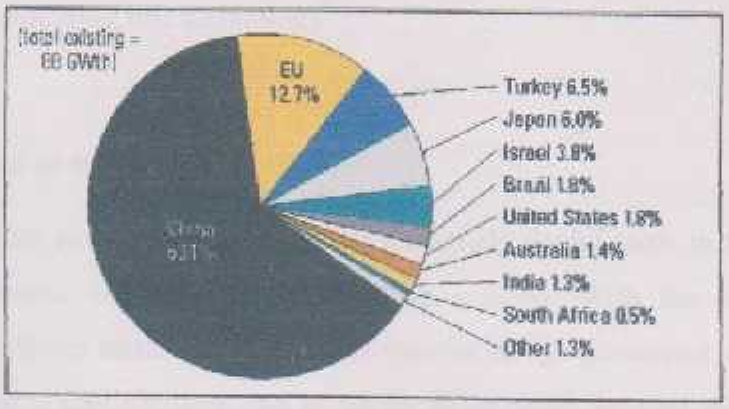


Figure 1.2: Solar hot water/heating capacity existing in 2005

Figure 1.1 shows[6] the worldwide percentage of renewable energy resources of usage during the year 2005. This case study is interested in solar heating which is 6.83% of the total use. Figure1.2 shows[6] solar hot water/heating capacity existing in 2005, and Figure 1.3 shows[6] Solar hot water/heating capacity added in 2005.

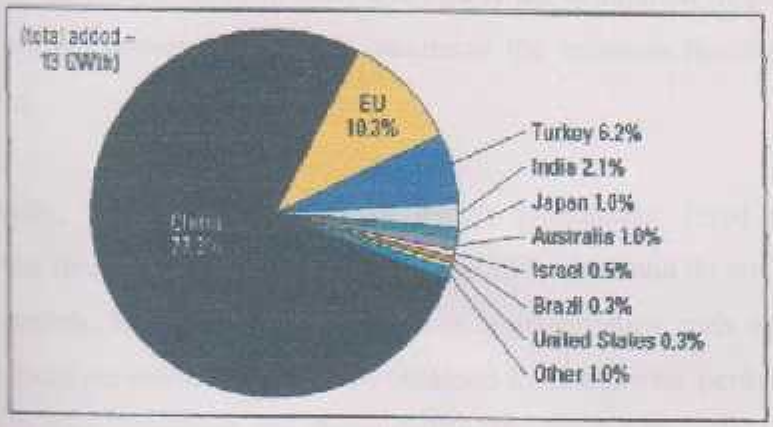


Figure 1.3: Solar hot water/Heating capacity added in 2005

As seen in the last two figures, 13 gigawatts-thermal (GWth) were added to the 88 GWth of worldwide heat capacity exist in 2005. That means it's increased by about 14% each year[6]. China leads the deployment of solar hot systems, while Israel (including Palestine) is the per capita leader in the use of solar hot water with 90 percent of homes using this technology[6].

1.2 Description of the Project

Computer simulation programs are extremely useful tools in the design and technical-economic analysis of solar heating systems. With the aid of a valid computer simulation model, the effects of various design parameter changes on the performance of a given system can be easily determined, as well as the economic feasibility of the solar system in comparison with a conventional alternative.

Economic optimization procedure in a particular solar heating design is based on the estimation of the size of a solar system that will yield the highest economic benefit on behalf of the solar system. This is usually made by comparing the cost flows recurring throughout the lifetime of the solar and conventional alternative system. One of the major tasks in such analysis is the estimation of the best set of values for design parameters that will maximize the criterion function in a solar heating system.

Generally, there are two types of design parameters: fixed and variable parameters. The fixed design parameters have specific values and do not change for a given solar system. For instance, the collector characteristics such as $F_R(\tau\alpha)$ and F_RU_L are the fixed parameters, and can be obtained from collector performance tests. The variable design parameters are dependent on the size of the solar system, their optimum values are found from technical-economic analysis. Among these, collector area, storage value, and load heat-exchanger size or capacity can be accounted.

Although, a criteria such as minimum payback period, maximum internal rate of return, etc. may be chosen, the maximum saving produced on behalf of the solar heating system during its lifetime is often chosen as a criterion function for the optimization.

ECO-COLLECTOR computer program is developed to serve for the needs of this technical-economic analysis. The basic climatic data needed for the analysis which are related to the concerned climatic region are fed to the program, then several different communicating modes with the computer are introduced to obtain the required specific data which are used to perform the technical-economic analysis.

The main focus of this project is on the economics of solar heating systems under the conditions of Hebron region. Also, this may be extended to any climatic region or any prototype building in Palestine. In addition, the effects of some important design parameters are considered in order to evidence the fundamental relation between the technical and economic aspects of solar heating systems.

The major contributions and studies made in each chapter can be resumed as follows:-

Chapter two briefly explains the classical methodology for the calculation of solar radiation incident on inclined surfaces. The estimation of the monthly mean diffuse radiation are explained. Basic equations used in the calculation procedure are given and their relations are described.

Calculation of the building heating load using the degree-day method is introduced in the third chapter, monthly degree-day values on the base of 17°C are also estimated. The characteristics of the selected climatic region (Hebron) and building prototype are resumed.

One of the mostly used design methods in solar heating systems is the f-chart method. The fourth chapter accounts for the use of this model, system configuration, characteristics and the modifications which can be made for some special cases.

Chapter five discusses the life cycle costing technique using the present value method. Basic economic concepts and criterion used in the technical-economic analysis of solar heating systems are described. A number of comparisons are made between the conventional systems using fuel oil and liquefied petroleum gas (LPG) and the solar energy heating system.

The following chapters account for the economical and technical results of comparison studies for the selected region and prototype building, discussion of the economic feasibility of solar heating systems under the climatic conditions of Hebron. Conclusions and recommendations are made in the final chapter.

The appendices give the details of the tables and heating load calculations, $(\tau\alpha)$ calculations and the details of the inputs and outputs of the program.

1.3 Project's Feasibility, Benefits and Industry Correlation

Today's sky-rocketing of the fuel price make such a study necessary and worth to search for and find any possibility of reducing the cost of energy, especially in the heating sector which constitutes a considerable portion of the national as well as the per-capita budget. Solar energy is considered as the most clean and friendly to the environment. Fortunately, the sun is available in our country Palestine in a better manner compared to other countries, which increases and encourages the feasibility of such a study.

There are several factories producing the solar collectors in our country Palestine. And Hebron city has the biggest contribution in this sector. Thus, a competitive price of such product is always available, and in case of getting a reasonable results from the study, the industry sector would benefit in two ways; their production capacity would increase and the quality of their products would also be increased by trying to enhance and develop their products towards the best.

Although this analysis can be extended to all climatic regions in Palestine, another reason for choosing Hebron city is due to the colder winter of this city so as to make the analysis more feasible.

The results of this analysis are presented in a wide range change of unstable economic parameters, and the correct future panorama would most probably be one of the expected cases presented in this analysis. Despite the fact that, prediction of the future success or failure of the solar heating in Palestine would require knowledge of the future price fluctuations of conventional fuels, all the worldwide seen and given indications or panoramas emphasize that (at least for the next coming future), the situations of fuel price would not be better than today's situations.

1.4 Timetable

Week	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30	31 32
Choosing The Project Subject	■															
Study solar geometry, calculating heating load		■	■	■	■	■										
Study about f-chart model and economic analysis						■	■									
Documentation and submitting the proposal							■	■								
Learning Visual Basic and developing ECO-COLLECTOR program									■	■	■	■	■			
Data collection and analyzing												■	■	■	■	
Documentation and submitting the project														■	■	■

Table 1.1: Timetable

CHAPTER TWO
SOLAR RADIATION

SOLAR RADIATION

2.1 Introduction

The operating efficiency of a solar system should be judged on its long-term performance rather than on its instantaneous virtue. The design of a solar system requires a knowledge of long-term, say monthly, average solar radiation data for the locality under consideration.

Solar radiation potential is dependent on the latitude, time, and the position of solar energy collectors. For many locations in the world the average daily radiation on a horizontal surface can be looked up. However, solar energy collectors are often located with an inclination from the horizontal surfaces so as to receive more radiation. For a more accurate indication of how much energy is falling on such tilted collectors, a series of calculations must be done. This present chapter briefly explains the classical methodology to estimate the monthly average daily total radiation on tilted surfaces, and explains the angles we are interested in.

2.2 Solar Geometry

The angles and position of solar energy collector are important to gain the maximum amount of solar radiation. In this study we are interested in three angles: collector tilt (slope) angle (β), azimuth angle (A_z) and incidence angle (θ_i). However, to find these angles, other angles should be known.

Tilt angle (β), is the angle between the plane of the collector aperture and the horizontal. It can be a monthly average values, but we will take it as a fixed value. Tilt angle is be given by[7]:

$$\beta = \emptyset - \delta \tag{2.1}$$

where,

$\emptyset$: latitude.

δ: solar declination angle.

Latitude angle ($\emptyset$) is the angle between the line from the collector to the center of the Earth and the line from the center of the Earth to the equator. Declination angle (δ) is the angle between the earth-sun line and the equatorial plane. Solar declination varies throughout the year, and can be approximated by[8]:

$$\delta = 23.45 \sin\left[\frac{360}{365.25}(284 + n)\right] \tag{2.2}$$

where n is the number of the days in the year.

Table 2.1: Recommended average days for months and of n by months[9]

Month	**n for i^{th} Day of Month**	**For the Average Day of the Month**		
		Date	**n, Day of Year**	**δ, Declination**
January	i	17	17	-29.9
February	$31 + i$	16	47	-13.0
March	$59 + i$	16	75	-2.4
April	$90 + i$	15	105	9.4
May	$120 + i$	15	135	18.8
June	$151 + i$	11	162	23.1
July	$181 + i$	17	198	21.2
August	$212 + i$	16	228	13.5
September	$243 + i$	15	258	2.2
October	$273 + i$	15	288	-9.6
November	$304 + i$	14	318	-18.9
December	$334 + i$	10	344	-23.0

The day of the year (n) can be conveniently obtained by the help of Table 2.1.

Azimuth angle (A_z), is the angle between collector axis and south, east negative, west positive.

Hour angle (ω) is the angle on a horizontal plane between the local solar noon (meridian which contains the south-north line) and the horizontal projection of the sun's rays and given by: $[15^0 \times (hours\ from\ solar\ noon)]$, being afternoons positive, mornings negative.

Incidence angle (θ_i), is the angle between the sun's rays irradiated on a surface and the line normal to this surface. θ_i is given by[9]:

$$\begin{aligned}\cos\theta_i = {} & \sin\delta\sin\emptyset\cos\beta - \sin\delta\cos\emptyset\sin\beta\cos A_z \\ & + \cos\delta\cos\emptyset\cos\beta\cos\omega + \cos\delta\sin\emptyset\sin\beta\cos A_z\cos\omega \\ & + \cos\delta\sin\beta\sin A_z\sin\omega \end{aligned} \tag{2.3}$$

2.3 Total Radiation Tilt Factor

Monthly average daily radiation ($\bar{H}_T$) on a tilted surface is given by[8]:

$$\bar{H}_T = \bar{R} \times \bar{H} \quad [kJ/m^2] \tag{2.4}$$

where,

$\bar{H}$: total radiation on horizontal plane $[kJ/m^2]$.

$\bar{R}$: total radiation tilt factor $[Dimensionless]$.

Both are written on monthly mean (average) daily basis. Total radiation tilt factor is the ratio of the total radiation on tilted surface to that on a horizontal surface. It can be written on monthly average daily basis by the following equation[8]:

$$\bar{R} = \left(1 - \frac{\bar{D}}{\bar{H}}\right)\bar{R}_b + \frac{(1+\cos\beta)}{2}\frac{\bar{D}}{\bar{H}} + \frac{(1-\cos\beta)\rho}{2} \tag{2.5}$$

where,

$\bar{D}$: monthly average daily diffuse radiation $[kJ/m^2]$.

$\bar{R}_b$: ratio of the average beam radiation on the tilted surface to that on the horizontal surface for each month $[Dimensionless]$.

β: tilt angle of the surface from the horizontal.

ρ: ground reflectance $[Dimensionless]$.

The ground reflectance (ρ) varies between 0.2 and 0.7 depending upon the extent of snow cover[10]. However, in our study, ρ is taken as 0.2. The ratio $(\bar{R}_b)$ is given by[8]:

$$\bar{R}_b = \frac{\cos(\emptyset - \beta)\cos\delta\sin\omega_s' + \frac{\pi}{180}\,\omega_s'\sin(\emptyset - \beta)\sin\delta}{\cos(\emptyset)\cos\delta\sin\omega_s + \frac{\pi}{180}\,\omega_s\sin(\emptyset)\sin\delta} \tag{2.6}$$

Where,

$\emptyset$: latitude.

δ: declination angle.

ω_s: sunset hour angle for a horizontal surface and is given by[8]:

$$\omega_s = \cos^{-1}[-\tan\emptyset\tan\delta] \tag{2.7}$$

ω_s': sunset hour angle for a tilted surface and is given by[8]:

$$\omega_s' = min\{\omega_s, \cos^{-1}[-\tan(\emptyset - \beta)\tan\delta]\} \qquad (2.8)$$

2.4 Estimation of Diffuse Radiation

The measurements of monthly mean diffuse radiation are rarely available at a given location. It should be estimated from the measurements of monthly mean total radiation. The ratio $(\overline{H}/\overline{H}_0)$ has been correlated as a function of clearness index $\overline{K}_T$. Clearness index is the ratio of the monthly mean daily radiation received by a horizontal surface on the ground to that of the extraterrestrial radiation $\overline{H}_0$. So, clearness index is given by[8]:

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_0} \quad [Dimensionless] \qquad (2.9)$$

Monthly mean daily extraterrestrial radiation is given by[8]:

$$\overline{H}_0 = \frac{86400}{\pi} I_{sc}\left[1 + 0.034\cos\left(\frac{360\,n}{365.25}\right)\right] \times \left[\cos\emptyset\cos\delta\sin\omega_s + \left(\frac{2\pi\,\omega_s}{360}\right)\sin\emptyset\sin\delta\right] \quad [J/m^2] \qquad (2.10)$$

where I_{sc}: solar constant (approximately equals to 1367 W/m^2)[11]. Note that "86400" is the number of seconds in 24 hours.

$\overline{K}_T$ values calculated in equation (2.9) are valid in the range[8] $0.3 \leq \overline{K}_T \leq 0.8$ between $\emptyset = \pm 55°$. $\overline{K}_T$ can be used to find the monthly average daily diffuse radiation$(\overline{D})$[8]:

$$\bar{D} = \bar{H}(1 - 1.13\bar{K}_T) \tag{2.11}$$

Monthly mean total radiation is the sum of the beam ($\bar{H}_b$) and diffuse ($\bar{D}$) components.

$$\bar{H} = \bar{H}_b - \bar{D} \tag{2.12}$$

Introducing the above fact in equation (2.4), $\bar{H}_T$ becomes:

$$\bar{H}_T = \bar{H}\left(1 - \frac{\bar{D}}{\bar{H}}\right)\bar{R}_b + \frac{\bar{D}}{2}(1 + \cos\beta) + \frac{\bar{H}}{2}(1 - \cos\beta)\rho \quad [kJ/m^2] \tag{2.13}$$

Using tabulated values of monthly mean (average daily) solar radiation on a horizontal surface, to the solar radiation on tilted surfaces (collectors) can be calculated by the aid of equation (2.13)

CHAPTER THREE

DEGREE-DAY METHOD AND HEATING LOAD CALCULATIONS

DEGREE-DAY METHOD AND HEATING LOAD CALCULATION

3.1 Introduction

Unlike conventional heating systems, both the efficiency and the economics of solar heating depend greatly upon the size of the solar heating system in relation to the size of the space and/or water heating loads. For conventional systems, it is sufficient to estimate the design heating load (i.e., the maximum probable heating load) in order to size the heating equipment. In contrast, estimates of the long-term average heating load for each month are required to design solar heating systems.

Different factors affect the heating load of a building, such as the geographic location, its architectural design, orientation, construction quality, and the particular lifestyle of the occupants. Many different methods of calculating space loads have been developed, ranging in complexity from the simple degree-day method to detailed computer simulations using hourly meteorological data. All of these methods involve some degree of uncertainty[12].

3.2 The Degree-Day Method

In general, a degree-day is defined as a measure of the departure of the mean temperature for a day from a given base temperature. The accumulation of such departures over a season or up to any day can be used as an indication of past temperature effect on some quantity[13]. The degree-day method of estimating the space heating load of a building is based upon the fact that the amount of heat required to maintain a comfortable indoor temperature is primarily dependent upon the difference between the indoor and outdoor temperatures.

The monthly space heating load (L_s) for a building maintained at a comfort temperature is assumed to be proportional to the number of degree-day during the month[12].

$$L_s = UA \times DD \tag{3.1}$$

where,

DD: the number of degree-days in a month [°C-day].

UA: the building overall energy loss coefficient-area product [$W/°C$].

The number of degree-days in a single day is the difference between the selected base temperature and the daily mean temperature (calculated as the average of the maximum and minimum daily temperatures). If the daily mean temperature is above comfort temperature, the number of degree-day is taken to be zero. The number of degree-days for a month is the sum of daily degree-days.

For instance, for 17/17 base, the degree-day of a given month will be the sum of the differences between 17 °C and the daily mean ambient temperature. When the daily mean ambient temperature is greater than or equal to 17 °C, this day will not be considered in the summation process.

$$DD_{17/17} = \sum_{r=1}^{N_m} \left(17 - t_{m,r}\right), \text{when } t_{m,r} < 17°C \tag{3.2}$$

where,

$DD_{17/17}$: the degree-days of a given month based on 17°C.

$t_{m,r}$: the daily mean ambient temperature.

3.3 Domestic Hot Water and Heating Load

The actual water heating load is the amount of energy required to heat water for domestic purposes. The monthly water heating load (L_w) can thus be estimated as:

$$L_w = N_m \times N_p \times V_w \times \rho_w \times C_{p,w}(T_h - T_c) \tag{3.3}$$

where,

N_p: the number of persons.

V_w: volume of hot water required per person, assumed to be 30 $[liter/day]$.

ρ_w: the density of water, 1 $[kg/liter]$.

$C_{p,w}$: water specific heat, 4.18 $[kJ/kg.°C]$.

T_h: the temperature of the hot water supply, approximately 60 $[\,^{o}C]$.

T_c: the temperature of the cold water must be heated (main supply water).

One of the important parameters that need to be used is the water main supply temperature T_c. The British standards (BS5918) of 1982 referenced correlation for computing this temperature, and the correlation modified to suit the Palestine climatic[14], and reads:

$$T_c = 18 - 5.5\, cos\left[\left(\frac{2\pi}{365.5}\right) \times (n + 11.25)\right] \tag{3.4}$$

where n is the number of day in the year.

So, the monthly total heating load (L), is the sum of the space and domestic hot water heating loads:

$$L_t = L_s + L_w \tag{3.5}$$

The losses from the storage tank L_{st} are considered in calculating the solar fraction using the following equation[9]:

$$L_{st} = (UA)_{st}(T_{st} - \bar{T}_a) \tag{3.6}$$

where

$(UA)_{st}$: storage tank overall heat transfer coefficient-area product $[W/^0C]$.

T_{st}: storage tank water temperature $[^0C]$.

$\bar{T}_a$: monthly average ambient temperature $[^0C]$.

3.4 Selection of Prototype Building

A 150 m^2 flat apartment in the second floor of a building was chosen as a prototype for the analysis. The overall heat transfer coefficient of the building UA are calculated as in Appendix A.

The monthly average daily climatic data in Hebron, are shown in Table 3.1.

Table (3.1): Monthly average daily climatic data.[15, 16]

Month	$\bar{T}_a$ [^{0}C]	$\varnothing_o$ [%]	$\bar{H}$ [MJ]
January	9.35	65	10.165
February	5.40	72	11.939
March	7.75	70	18.255
April	12.20	50	18.894
May	20.15	38	26.645
June	21.20	51	27.326
July	22.65	49	27.597
August	21.25	60	24.416
September	19.95	52	19.941
October	19.45	50	14.727
November	15.15	58	11.906
December	10.15	70	10.017

where $\varnothing_o$ is the outside relative humidity.

CHAPTER FOUR

F-CHART METHOD

F-CHART METHOD

4.1 Introduction

Using the software simulation programs in design of solar heating systems became more common in system design procedures. Simplified analysis methods have many advantages as computational speed, low cost, rapid turnaround, and ease of use by persons with little technical experience. There are many simulation programs which are developed to design solar water heating systems such as: *f*-chart, TRANSYS, WATSUN, EMPG2... etc.

A Developed program based on the *f*-Chart method is used to evaluate space heating and service water heating under Hebron region climates and conditions. The results of these analyses correlate the fraction *f* of the heat load met by solar energy. The correlations give the fraction *f* of the monthly heating load (for space heating and domestic hot water) supplied by solar energy as a function of collector characteristics, heating loads, and weather.

Two principle categories of solar heating systems are used in the *f*-Chart method; the first one is the active systems, which use pumps to move the liquid through the collector, and the second one is the passive systems which use the gravity and tendency for water to circulate it naturally. Combine elements of both active and passive systems are called Hybrid systems.

4.2 Water Storage Space and Domestic Water Heating System

This study deals with water storage space and domestic water heating system which use flat plate collectors to heat a fluid, storage unit to store solar energy until it's needed , and distribution equipment to provide solar energy for both domestic hot water and space heating.

A solar heater includes a solar collector that absorbs solar radiation and converts it to heat, which is then absorbed by a heat transfer fluid (water, a nonfreezing liquid, or air) that passes through the collector. The heat transfer is stored or used directly. In the active systems heat transfer fluid is transported by forced circulation, whereas forced circulation uses pumps or fans, that means of course these systems need electrical power (or may be from another power source) to drive these motors during the operation of the system for the recirculation process.

Air heating systems circulate air through ducts to and from an air heating collector , and use a pebble bed to store heat . However air systems are effective for space heating applications (because a heat exchanger is not required and the collector inlet temperature is low throughout the day), do not need protection from freezing, overheat, or corrosion. Also air costs nothing and does not cause disposal problems, but the use of air ducts and air-handling equipment in the collector array require more space than pipes and pumps.

Liquid heating systems circulate a liquid, often a water-based fluid, through a solar collector, and it uses a storage tank to store energy as a sensible heat. In Figure 4.1, a liquid-to-liquid heat exchanger is used to transfer heat from the collector array to the storage tank. Two distributions are used, one for a direct circulation of the liquid in the storage tank to the space heating coil and the other is a liquid-to-liquid heat exchanger which used to transfer energy from the main storage tank to the domestic hot water. A conventional heating unit (furnace, heat pump, or a burner) is used to meet the space-heating and domestic hot water (DHW) loads when the energy in the storage tank is depleted.

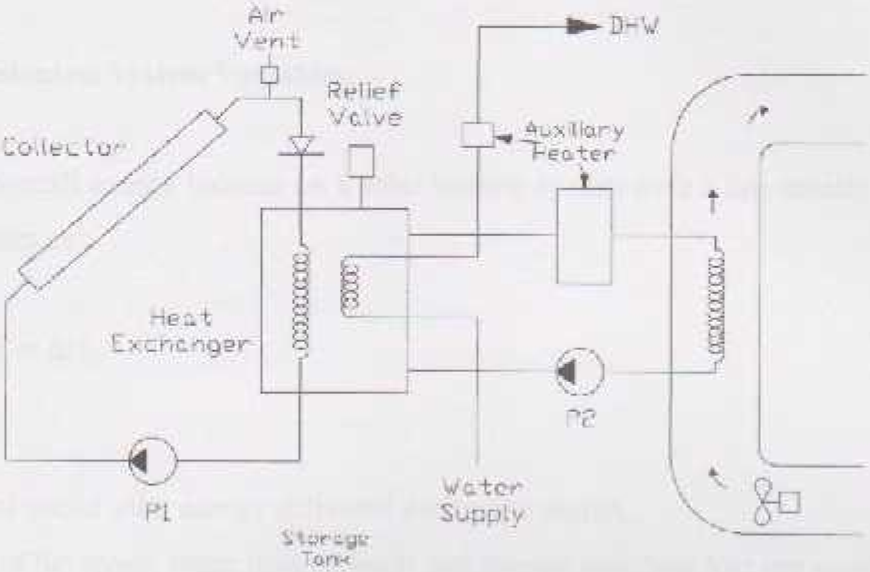


Figure 4.1: Solar collection, storage, and distribution system for space heating and DHW

The liquid in solar collectors must be protected against freezing, which could damage the system. Freezing is the principal cause of liquid system failure. For this reason, freeze tolerance is an important factor in selecting the heat transfer fluid and equipment in the collector loop. A solar collector radiates heat to the cold sky and freezes at air temperatures well above 0°C[17].

In this system, antifreeze heat transfer fluid is assumed to circulate through the closed collector loop of the collector array. The most commonly used heat transfer fluids are water/ethylene glycol and water/propylene glycol solutions.

To protect the collector against excessive pressure and temperature, a relief valve is placed on the line between the heat exchanger and the storage tank. A check valve should be installed in the return line to prevent reverse thermosiphon action during cold nights.

4.3 Dimensionless System Variables

An overall energy balance on a solar heating system over a one month period can be written as[9]:

$$Q_T - L + E = \Delta U \tag{4.1}$$

where,

Q_T: the total useful solar energy delivered during the month.

L: the sum of the space, water heating loads and storage tank heat loss per month.

E: the total auxiliary energy required during the month.

ΔU: the energy change in the storage unit.

For the storage sizes commonly used in solar heating systems, ΔU for a month is small with respect to Q_T, L and E and it can be rearranged so that[9]:

$$f = \frac{Q_T}{L} = \frac{(L - E)}{L} \tag{4.2}$$

where f is the fraction of the monthly total heating load supplied by solar energy.

Equation 4.2 cannot be used to calculate f directly since Q_T is complicated function of the incident radiation, the ambient temperature, and the heating load. However, by considering the parameters on which Q_T depends, equation 4.2 suggests that f may be empirically related to the two dimensionless groups[9]:

$$X = \frac{collector\ heat\ loss}{heating\ load} = \frac{A\,F_R'\,U_L\,\left(T_{ref} - \bar{T}_a\right)\Delta t}{L} \tag{4.3}$$

$$Y = \frac{absorbed\ insolation}{heating\ load} = \frac{A\,F_R'\,U_L\,(\overline{\tau\alpha})\,\bar{H}_T N_m}{L} \tag{4.4}$$

where,

A: the collector area $[m^2]$

U_L: the collector overall energy loss coefficient $[W/m^{2}{}^{\circ}C]$.

Δt: the total number of seconds in the month.

T_{ref}: a reference temperature determined to be 100 °C.

$\bar{T}_a$: the monthly average ambient temperature [°C].

L: the monthly total heating load $[J]$.

$\bar{H}_T$: the monthly average total radiation incident on the collector surface per unit area $[J/m^2]$.

N_m: numbers of days in month.

$(\overline{\tau\alpha})$: the monthly average transmittance-absorptance product.

F_R': the collector-heat exchanger efficiency factor which is expressed as[9]:

$$F_R'/_{F_R} = \left\{1 + \left[\frac{F_R U_L A}{\left(\dot{m}c_p\right)_c}\right]\left[\frac{\left(\dot{m}c_p\right)_c}{\varepsilon\left(\dot{m}c_p\right)_{min}} - 1\right]\right\}^{-1} \tag{4.5}$$

where,

$\left(\dot{m}c_p\right)_c$: flow rate times specific heat of fluid circulating through the collector $[W/{}^{\circ}C]$.

$\left(\dot{m}c_p\right)_{min}$: the minimum flow rate times specific heat of the fluid in the heat exchanger $[W/{}^{\circ}C]$.

F_R: the collector heat removal factor.

ε: the heat exchanger effectiveness.

As mentioned above, these dimensionless groups have some physical significance. X is related to the ratio of a reference collector energy loss to the total heating load during the month. Y is related to the ratio of the total energy absorbed on the collector plate surface to the total heating load during the month. For convenience in calculation, equations 4.3 and 4.4 can be rewritten as[9]:

$$X = F_R U_L \times \left(\frac{F_R'}{F_R}\right) \times \left(T_{ref} - \bar{T}_a\right) \times \Delta t \times \frac{A}{L} \tag{4.6}$$

$$Y = F_R(\tau\alpha)_n \times \left(\frac{F_R'}{F_R}\right) \times \left(\frac{(\overline{\tau\alpha})}{(\tau\alpha)_n}\right) \times \frac{\bar{H}_T A}{L} \tag{4.7}$$

$F_R U_L$ and $F_R(\tau\alpha)_n$ are obtained from collector test results. F_R'/F_R corrects for various temperature drops between the collector and the storage tank and is calculated by the aid of equation 4.5. $\bar{T}_a$ is obtained from meteorological records for the month and location desired. $\bar{H}_T$ is found from $\bar{H}$ and $\bar{R}$ by the methods of Chapter 2. The monthly loads, L, are determined as noted in chapter 3. Values of A, the collector area, are selected for the calculation.

4.4 Liquid-Based Solar Space Heating System

A correlation was obtained between the f-factor and the dimensionless parameter X and Y for both liquid and air based systems. In this study a liquid-based system is considered. The relationship between X and Y and f can be expressed as[9]:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \tag{4.8}$$

For $0 < Y < 3$ and $0 < X < 18$

The graphical representation of equation 4.8 is shown in Figure 4.2. The correlation is valid for the following range of design parameters:

$$0.6 \le (\tau\alpha)_n \le 0.9$$

$$5 \le F_R' A \le 120 \quad m^2$$

$$2.1 \le U_L \le 8.3 \quad W/m^2.°C$$

$$30 \le \beta \le 90 \quad degrees$$

The energy contribution for the month is the product of the monthly fraction supplied by solar energy f_i and the monthly total heating load L_i. The fraction of the heating load supplied by solar fraction $\mathcal{F}$ is[9]:

$$\mathcal{F} = \frac{\sum f_i L_i}{\sum L_i} \tag{4.9}$$

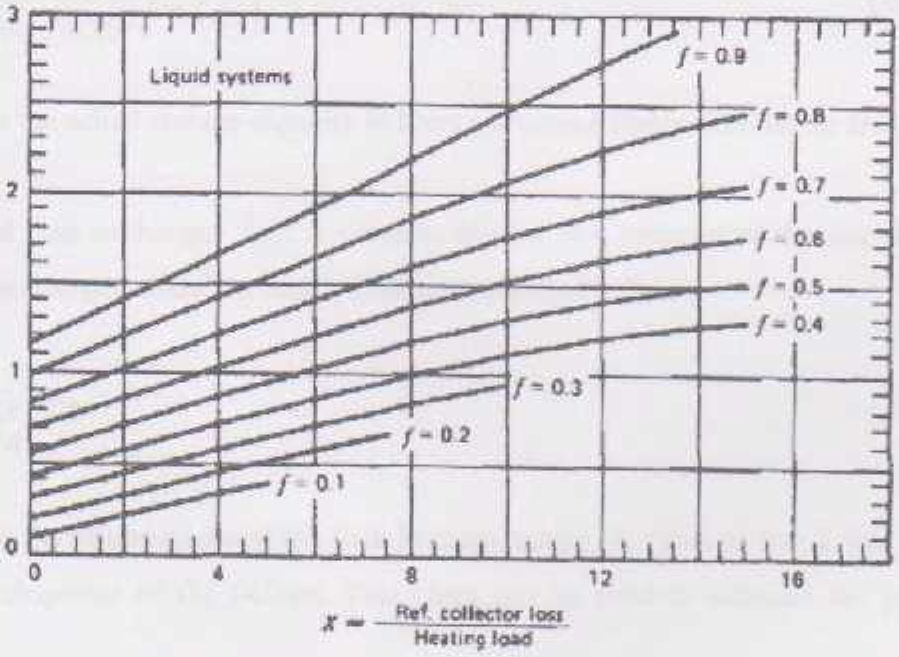


Figure 4.2: *f*-Chart for Liquid Systems[9]

4.5 Modifications on the *f*-Chart Model

f-Chart curves were numerically generated using fixed nominal values for storage capacity per unit collector area [75 $liters/m^2$], collector liquid flow rate per unit collector area [0.015 $liters/s.m^2$], and load heat exchanger size relative to space heating load[9]. In practical design of solar heating systems it is important to take into account the sensitivity of these design parameters on the long-term performance of the system and to make correlations when necessary. The following corrections were developed for the dimensionless parameters X and Y.

Storage capacity: the method was developed for a storage capacity of 75 liters of stored water per square meter of collector and can also be used to estimate the yearly performance of the systems with storage capacities in the range of 37.5 to 300 liter per square meter of collector we must multiplying the dimensionless parameter X by the following correction factor[9]:

$$\left(\begin{matrix} Storage\ size \\ correction\ factor \end{matrix}\right) = \left(\frac{M}{75}\right)^{-0.25} \tag{4.10}$$

where M is the actual storage capacity in liters per square meter of collector area.

Load heat exchanger size: A dimensionless z is a measure of the size of the load heat exchanger needed to supply heat to a specified building.

$$z = \frac{\varepsilon_L (\dot{m}c_p)_{min}}{UA} \tag{4.11}$$

where ε_L is the effectiveness of the load heat exchanger. A value of $z = 2$ was used in the development of the *f*-Chart. This chart can be used to estimate the yearly performance of systems having other values of z by multiplying the dimensionless parameter Y by the following correction factor[9]:

$$\begin{pmatrix} \textit{Load heat exchanger} \\ \textit{correction factor} \end{pmatrix} = 0.39 + 0.65 \exp\left(-\frac{0.139}{z}\right) \tag{4.12}$$

$$for \quad 0.5 < z < 50$$

To use system in Figure 4.1 for domestic hot water heating only using the f-Chart model, X must be multiplied by following correction factor[9]:

$$\begin{pmatrix} \textit{Service water heating} \\ \textit{correction factor} \end{pmatrix} = \frac{11.6 + 1.18T_c + 3.86T_h - 2.32\bar{T}_a}{100 - \bar{T}_a} \tag{4.13}$$

CHAPTER FIVE

ECONOMIC ANALYSIS

ECONOMIC ANALYSIS

5.1 Introduction

Economic viability of solar energy heating systems are usually the lifetime of the solar (SI) and conventional (CI) installations. The analysis estimate the best set of values for design parameters that will minimize the criterion function in a solar installation. The criterion function here taken to be the maximum saving produced on behalf of the solar installation during its lifetime. Economic optimization procedure in a particular solar heating design is oftenly based on the estimation of the size of a solar system in terms of collector area, as it is the most costly design component.

5.2 Time Value of Money

A sum of money at hand is worth more than the same sum in the future; because the money at hand can be invested at some compounding interest to generate a bigger sum in the future. Conversely, a sum of money or cash flow in the future must be discounted and is worth less as the present-day value. Cash flow occurring n years from now can be reduced to its present value by equation[17]:

$$P = \frac{F}{(1+d)^n} \tag{5.1}$$

where,

P: the present worth or present value.

F: the future cash flow.

d: the discount rate.

Meanwhile, during inflationary times the amount of money needed to purchase a certain item is increasing because the value of money is decreasing. A future cost F at year n according to the relation[17]:

$$F = E(1+e)^n \tag{5.2}$$

where,

E: the purchase cost.

e: yearly increase rate.

The future value F as given by equation 5.2 is also subjected to discount, resulting in present-worth as expressed by[17]:

$$P = \frac{E(1+e)^n}{(1+d)^n} \tag{5.3}$$

The above equation gives present worth of a single future payment. Summing up all the present worth of n such future payments results in the total present worth[17]:

$$Total\ present\ worth = E\sum_{i=1}^{n}\left(\frac{1+e}{1+d}\right)^i = EP(e,d,n) \tag{5.4}$$

where $P(e,d,n)$ is the present-worth factor and is given by[17]:

$$P(e,d,n) = \begin{cases} \dfrac{1+e}{d-e}\left[1-\left(\dfrac{1+e}{1+d}\right)^n\right] & for\ e \neq d \\ n & for\ e = d \end{cases} \tag{5.5}$$

5.3 Life Cycle Savings Analysis

Life-cycle savings is the net present worth, representing the difference of life-cycle costs between a SI and CI[18]. The life-cycle cost of the system is determined by discounting each required annual cash flow or net payment to its present worth and finding the sum of these present worth. For a series of regularly varying yearly cash flow, the life-cycle cost can be calculated by using equation 5.4. In a life-cycle saving analysis, the present worth of all costs, present or future, is determined for each of the alternative systems under condition, including nonsolar and different combination of solar-auxiliary systems.

In this study, primarily the initial investment, fuel and maintenance costs are considered. If the total capital cost of the system is not paid at the purchasing time, the mortgage payments at annuities are also considered. Mortgage payments include initial investment and interest on loans for the purchase of the systems. Fuel expenses are fossil-fuel energy purchase for CI and the auxiliary part of SI. Maintenance is the cost needed to keep the system in operating conditions.

5.4 Conventional System Costs

1. Initial Investment: For the general case, percent of total initial investment I_c, is assumed to be paid at year zero and the rest of the loan with equal annuities.

Annuity is the equal mortgage payments or receipts paid in equal time periods. The annuity (a_0), can be expressed as[19]:

$$a_0 = P_d \frac{r_0(1+r_0)^{n_0}}{(1+r_0)^{n_0}-1} \tag{5.6}$$

where,

P_d: the present value.

r_0: credit interest rate.

n_0: number of credit years.

The amount of each equal annual installments of the rest of the initial investment becomes[19]:

$$a_0 = (1 - e_0) I_c \frac{r_0 (1 + r_0)^{n_0}}{(1 + r_0)^{n_0} - 1} \tag{5.7}$$

where e_0 is percent of total initial investment assumed to be paid at year zero.

Considering these annuities paid at the end of each period, the present value of the initial investment for CI can be written as[19]:

$$S_1 = e_0 I_c + \frac{a_0}{1 + d} + \frac{a_0}{(1 + d)^2} + \dots + \frac{a_0}{(1 + d)^{n_0}}$$

$$S_1 = e_0 I_c + \sum_{i=1}^{n_0} \frac{a_0}{(1 + d)^i} \tag{5.8}$$

Substituting equation 5.7 in to equation 5.8, S_1 becomes:

$$S_1 = e_0 I_c + \sum_{i=1}^{n_0} (1 - e_0) I_c \frac{r_0 (1 + r_0)^{n_0}}{(1 + r_0)^{n_0} - 1} \times \frac{1}{(1 + d)^i}$$

and in terms of function P from equation 5.5:

$$S_1 = e_0 I_c + \sum_{i=1}^{n_0} (1 - e_0) I_c \frac{r_0(1 + r_0)^{n_0}}{(1 + r_0)^{n_0} - 1} \times P(0, d, n_0) \tag{5.9}$$

2. Fuel costs: Annual fuel consumption cost is $P_0(i)Q(i)$.

where,

$P_0(i)$: the conventional fuel price at year i $[NIS/GJ]$.

C_0: percent of yearly increase rate.

Thus:

$$P_0(i) = P_0(1 + C_0)^i \tag{5.10}$$

where P_0 is the actual fuel price at year zero.

Decrease of the installation efficiency by the time is equivalent to an increment of percent in the annual heating load. Thus the annual heating load[19]:

$$Q(i) = \frac{Q}{(1 - R_0)^i} \tag{5.11}$$

where,

R_0: percent decrease of the installation efficiency.

Q: the annual heating load at the year zero.

Thus the total fuel cost throughout the system life time, can be written as[19]:

$$S_2 = P_0Q + \frac{P_0(1+C_0)}{(1+d)}\frac{Q}{(1-R_0)} + \frac{P_0(1+C_0)^2}{(1+d)^2}\frac{Q}{(1-R_0)^2} + \dots + \frac{P_0(1+C_0)^\ell}{(1+d)^\ell}\frac{Q}{(1-R_0)^\ell}$$

$$S_2 = P_0Q + P_0Q\sum_{i=1}^{\ell}\left(\frac{1+C_0}{1-R_0}\right)^i\frac{1}{(1+d)^i} \tag{5.12}$$

where ℓ is the system life time $[years]$.

and in terms of function P:

$$S_2 = P_0Q\left[1 + P\left(\frac{C_0+R_0}{1-R_0}, d, \ell\right)\right] \tag{5.13}$$

3. Maintenance and operation costs: Combined yearly cost for maintenance and operation is expressed as a determined proportion of the initial investment of installation in the year considered[19]:

$$S_3 = \sum_{i=G_0}^{\ell}\frac{m_0I_c(1+d)^i}{(1+d)^i} = m_0I_c(\ell - G_0) \tag{5.14}$$

where

m_0: maintenance and operation costs fraction of the initial investment of CI.

G_0: guaranty period of CI.

Thus the total cost for CI is:

$$C_c = S_1 + S_2 + S_3$$

$$C_c = e_0 I_c + a_0 P(0, d, n_0) + P_0 Q + P_0 Q P\left(\frac{C_0 + R_0}{1 - R_0}, d, \ell\right) + m_0 I_c(\ell - G_0) \qquad (5.15)$$

5.5 Solar System Costs

Analogously, the costs for SI are as follows:

1. Initial Investment: Initial capital cost of SI, (I_s), consists of:

(a) fixed solar system costs (I_{sf}) including auxiliary heating system, piping, ducts, pumps and controls,

(b) solar collector costs (I_{sc}).

(c) storage tank cost (I_{ss}).

$$I_s = I_{sf} + I_{sc} + I_{ss} \qquad (5.16)$$

Fixed solar system costs are assumed to be independent of collector area, and solar costs are proportional with the collector area is.

$$I_{sc} = U_c A \qquad (5.17)$$

where U_c is the unit collector price.

Storage tank price is considered to be a function of collector area[20].

$$I_{ss} = 10\pi\left(\frac{AX_L}{4000\pi}\right)^{2/3} U_s \qquad (5.18)$$

where,

U_s : the storage tank cost per square meter of storage tank surface.

X_L: the storage tank volume per square meter of collector area.

Percent of total initial investment I_s is assumed to be paid at year zero and the rest of the loan with equal annuities, so the present value of the initial investment for CI is given by:

$$S_1' = e_1 I_s + a_1 P(0, d, n_1) \tag{5.19}$$

where

e_1 : percent of total initial investment I_s is assumed to be paid at year zero.

n_1: number of credit years:

a_1: the equal annuities of the rest loan, expressed as:

$$a_1 = (1 - e_1) I_s \frac{r_1 (1 + r_1)^{n_1}}{(1 + r_1)^{n_1} - 1} \tag{5.20}$$

where r_1 is the credit interest rate.

2. Fuel costs: Efficiency loss due to aging in SI is considered from two points of view: decrease of yearly solar heating fraction $\mathcal{F}$, due to depreciation of the components, and decrease of the efficiency of the auxiliary part of SI. Thus, the annual auxiliary heating load at year i is:

$$\text{[illegible]} = Q\left[1 - \mathcal{F}(1 - R_1)^i\right] \frac{1}{(1 - R_2)^i} \tag{5.21}$$

where,

R_1: percent decrease of solar heating fraction.

R_2: percent decrease of the efficiency of auxiliary part of SI.

The cost of auxiliary fuel consumption per GJ is:

$$P_1(i) = P_1(1 + C_1)^i$$

where,

C_1: yearly increase of the auxiliary fuel price.

P_1: the actual auxiliary fuel price at the year zero.

Thus the cost of auxiliary fuel consumed is:

$$S_2' = P_1Q(1 - \mathcal{F}) + \sum_{i=1}^{\ell} P_1Q \frac{(1 + C_1)^i}{(1 + d)^i} \frac{1}{(1 - R_2)^i} - P_1Q\mathcal{F} \sum_{i=1}^{\ell} \frac{(1 + C_1)^i}{(1 + d)^i} \frac{(1 - R_1)^i}{(1 - R_2)^i}$$

and in terms of function P:

$$S_2' = P_1Q(1 - \mathcal{F})P_1Q\left\{P\left(\frac{C_1 + R_2}{1 - R_2}, d, \ell\right) - \mathcal{F}P\left[\frac{(1 + C_1)(1 - R_1) - (1 - R_2)}{(1 - R_2)}, d, \ell\right]\right\} \quad (5.22)$$

3. Maintenance and operation costs: If combined yearly costs for maintenance and operation are expressed as a determined fraction of the initial investment, the present value of the yearly maintenance and operation cost is:

$$S_3' = m_1 I_s(\ell - G_1) \tag{5.23}$$

where,

m_1: maintenance and operation costs fraction of the initial investment of SI.

G_1: guaranty period for SI.

Thus the total cost for SI is:

$$C_s = S_1' + S_2' + S_3'$$

$$\begin{aligned} C_s = {} & e_1 I_s + a_1 P(0, d, n_1) + m_1 I_s(\ell - G_1) + P_1 Q(1 - \mathcal{F}) \\ & + P_1 Q \left\{ P\left(\frac{C_1 + R_2}{1 - R_2}, d, \ell\right) - \mathcal{F} P\left[\frac{(1 + C_1)(1 - R_1) - (1 - R_2)}{(1 - R_2)}, d, \ell\right] \right\} \end{aligned} \tag{5.24}$$

Finally the life-cycle saving will be:

$$S = C_c - C_s \tag{5.25}$$

Substituting for equation 5.25 gives:

$$\begin{aligned} S = {} & e_0 I_c - e_1 I_s + a_0 P(0, d, n_0) + a_1 P(0, d, n_1) + P_0 Q - P_1 Q(1 - \mathcal{F}) \\ & + P_0 Q P\left(\frac{C_0 + R_0}{1 - R_0}, d, \ell\right) + m_0 I_c(\ell - G_0) - m_1 I_s(\ell - G_1) \\ & + P_1 Q P\left(\frac{C_1 + R_2}{1 - R_2}, d, \ell\right) + P_1 Q \mathcal{F} P\left[\frac{(1 + C_1)(1 - R_1) - (1 - R_2)}{(1 - R_2)}, d, \ell\right] \end{aligned} \tag{5.26}$$

CHAPTER SIX

ECONOMICAL AND TECHNICAL RESULTS

ECONOMICAL AND TECHNICAL RESULTS

6.1 Introduction

System design parameters and life-cycle economic analysis were explained in chapters 4 and 5, respectively.

Under the first section of this chapter, life-cycle economic analysis is used to determine the effects of economical parameters (for the optimum design conditions) on the system performance. The study is performed by changing economical parameters in a wide range.

The effects of the most important design parameters when they deviate from the optimum conditions (within their accepted ranges given in chapter 4) on the system performance are issued under the second section of this present chapter.

6.2. Economical Results

Both the conventional heating system (CI) and the solar heating system (SI) purchasing cost and fuel prices are determined from the present market conditions. The lifetime of the systems is assumed to be 20 years.

6.2.1 System Purchasing and Fuel Costs

The design of conventional fuel using system for a given building is based on the total heating load of that building at the design conditions. Hundred percent of this load should be covered by the heating system. Total space heating load for the this load should be covered by the heating system. Total space heating load for the selected region and prototype building is calculated as shown in Appendix A. The domestic hot water heating load is calculated by the program using equation 3.3.

An average cost of conventional heating system in the market is determined. Similar inquiry is also made for the determination of conventional boilers costs (fuel oil and fuel gas) and the control system devices costs, too. Finally, the cost of conventional systems for the prototype building and climatic region is determined in accordance with the present actual market conditions (see Table 6.1).

Purchasing cost of solar energy system includes; fixed solar system costs which is the conventional installation with the additional pump, and control devices needed (see Table 6.1). Also the cost of solar collectors and storage units.

A similar inquiry is also made among the various companies producing solar energy equipment in order to determine the unit collector and storage prices. These are determined to be 300 NIS per meter square of collector area and 2500 NIS per square meter of surface area of storage tank[22].

Table (6.1): Fixed costs of solar and conventional installations $[NIS]$[21]

	Conventional Installment	Solar Installment
Fuel Oil	29,000	31,000
Fuel Gas	30,500	32,500

Fuel oil and fuel gas heating values' are 41.8 and 49.3 MJ/m^3, respectively[23], with 88% and 90% of boiler burning efficiency cost, respectively[21]. The actual price for fuel oil is 5.75 $NIS/Liter$, whereas the price of fuel gas (LPG) is 4.6 NIS/kg[24]. The unit fuel prices then becomes 156 and 104 NIS/GJ for fuel oil and fuel gas, respectively. The maintenance and operating costs of CI and SI are around 5% and 4%, respectively, from their initial cost[21].

6.2.2 Economical Results Under the Optimum Conditions

The study at first aims to determine the optimum collector area under the given technical, economic and climatic conditions, which makes the total life saving maximum. Optimum collector area, optimum solar heating fraction and maximum saving are then calculated using the developed computer program. In accordance with the actual economic of the country an average of 15% discount rate[25] and 11% average fuel price increment throughout the past twelve years[26]. The results for the calculated parameters are shown in Table 6.2.

Table (6.2): Results under the optimum conditions

	Optimum Collector Area $[m^2]$	Solar Fraction [%]	Total Saving [NIS]
Fuel Oil	46	70.52	41,060
Fuel Gas	28	55.30	15,384

6.2.3 Graphical Representation of Economical Results

The most economic results compiled in this study are presented in the form of graphs which can ease the understanding of their contents just by visualizing. Almost all results are given for the prototype building using fuel oil and fuel gas systems in the climatic region of Hebron. This will lead the reader to make future comparison studies between the chosen systems.

6.2.3.1 Optimum Collector Area and Solar Heating Fraction

In the graph of Figure 6.1, the variations of solar heating fraction and the total saving versus the collector are shown. In the preparation of this graph, all design parameters are kept fixed as in the actual conditions, and the collector area is varied. Optimum collector area corresponds to the maximum saving. For instance, when solar installation is compared with fuel oil in the prototype building, the optimum collector area becomes approximately 46 m^2 corresponding to yearly solar heating fraction of 70.52% and a maximum saving of 41,060 *NIS*. Figure 6.2 shows that the optimum area for fuel gas becomes approximately 28 m^2 corresponding to yearly solar heating fraction of 55.3% and a maximum saving of 15,384 *NIS*.

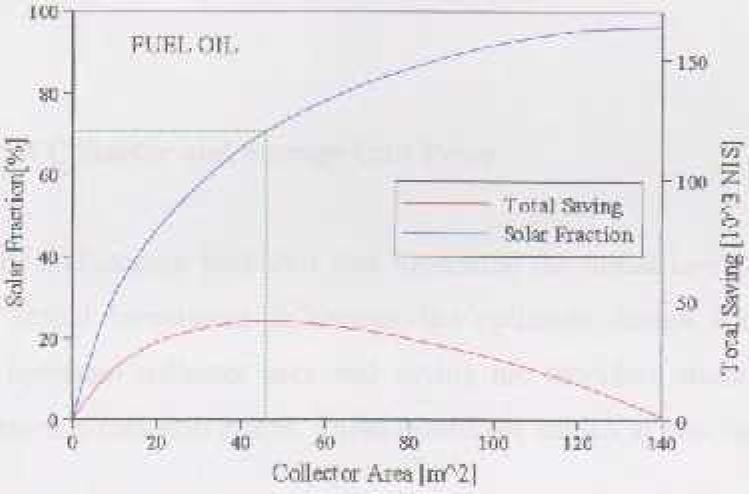


Figure 6.1: Variations of solar heating fraction and total saving versus the collector area for fuel oil using system

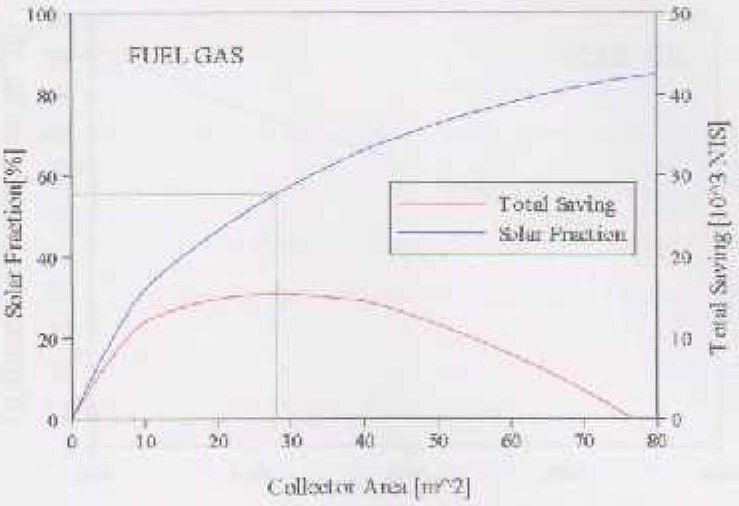


Figure 6.2: Variations of solar heating fraction and total saving versus the collector area for fuel gas using system

6.2.3.2 Effect of Collector and Storage Unit Price

Collector and storage tank unit cost determine the initial investment of a SI. The level of initial investment influences the optimum design conditions. The variations of optimum collector area and saving are therefore studied versus the collector and storage tank unit prices. These results are shown in two figures.

Figures 6.3 and 6.4 show the variations of optimum collector area versus storage tank and collector prices, respectively. Optimum collector area decreases with the increase in unit price. High unit price of main solar system components results in an expensive SI. From economic point of view, lower collector areas have to be used to compensate the high unit price of storage tank (Figure 6.3). The cost of unit collector area is the most influential parameter as seen from Figure 6.8, there is a sharp decrease in the optimum collector area by increasing the collector unit price.

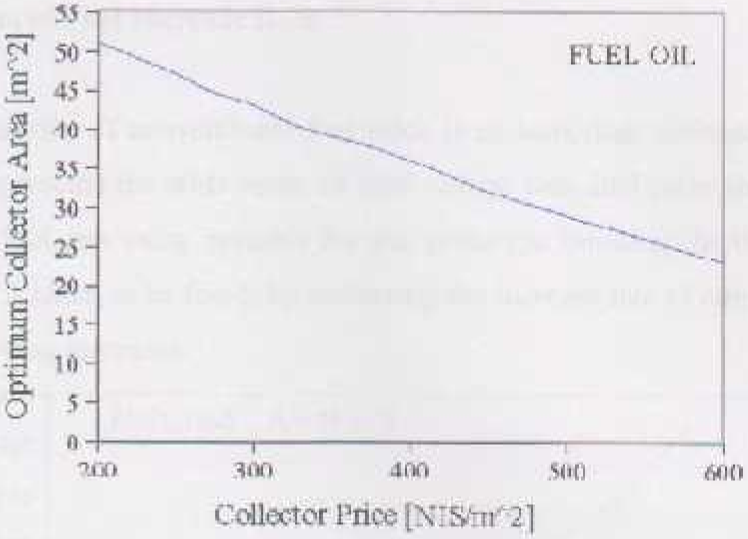


Figure 6.3: Variation of optimum collector area versus unit price of the collector for fuel oil

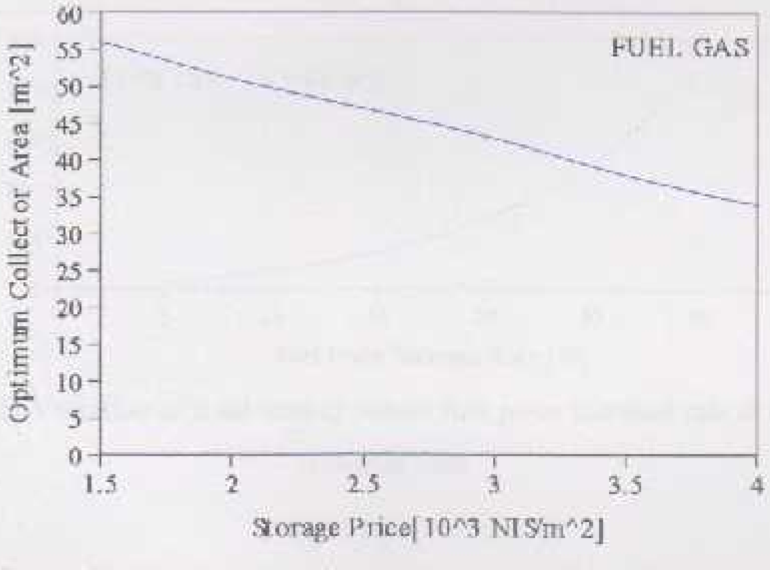


Figure 6.4: Variations of optimum collector area versus the storage tank per square meter of collector area for fuel gas

6.2.3.3 Effects of Fuel Increase Rate

Increase rate of conventional fuel price is an important economic parameter. Figure 6.5 represents the wide range of total saving with fuel price increase rate in fuel oil and fuel gas using systems for the prototype building. In this curve, the discount rate is taken to be fixed, by increasing the increase rate of conventional fuel price, total saving increases.

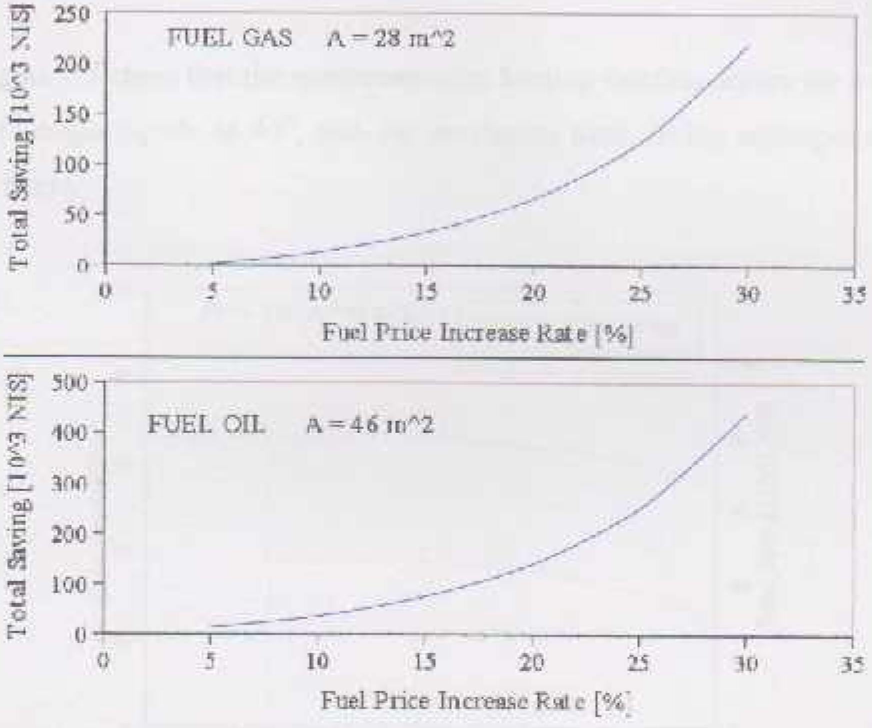


Figure 6.5: Variation of total saving versus fuel price increase rate at optimum collector area

6.3 Technical Results

Collector tilt angle, characteristics ($F_R(\tau\alpha)_n$ and F_RU_L), storage tank volume, primary and secondary fluids' flow rate, and the number of heating hours per day were used to test their effects on total saving and solar heating fraction.

6.3.1 Tilt Angle

Optimum tilt angle of the collector is the angle with which the solar heating system provides the largest fraction of the annual heating load. This doesn't necessarily correspond to a tilt with which the annual solar radiation on the collector is maximum. The relative time distribution of the solar radiation and heating loads are important factors.

Figure 6.6 show that the maximum solar heating fraction occurs for a collector tilted with angle equals to 43^0, and the maximum total saving corresponds to the same tilt angle.

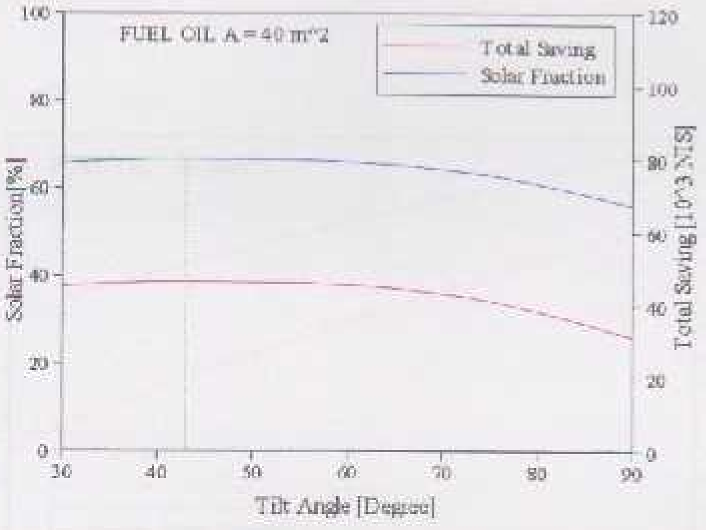


Figure 6.6: Variations of total saving and solar heating fraction versus collector tilt angle

6.3.2 Collector Characteristics

The parameters $F_R(\tau\alpha)_n$ and F_RU_L represents the operating efficiency of solar collector. In Figure 6.7 effects of $F_R(\tau\alpha)_n$ are shown. An increase in the transmittance-absorptance product will sharply increase the solar heating fraction, since this factor represents the amount of energy absorbed by the collector. By changing $F_R(\tau\alpha)_n$ from 0.5 to 0.9, a 28% of increase on the solar heating fraction is observed. The value of the parameter $F_R(\tau\alpha)_n$ for a flat-plate collector is between[9] 0.60 to 0.70. However, throughout the analysis the value of $F_R(\tau\alpha)_n$ is assumed to be 0.65.

The effect of $F_R U_L$ are shown in Figure 6.8. Since this parameter indicates the energy losses from the collector, by increasing its value, both useful energy gain and the solar heating fraction along with the total saving will decrease. For $F_R U_L$ ranging from 1 to 7.3 $W/m^2.{}^0C$, the decrements are about 20% in solar heating fraction and 32,000 NIS in total saving. The actual value for this parameter is taken to be 4.7 $W/m^2.{}^0C$ [27].

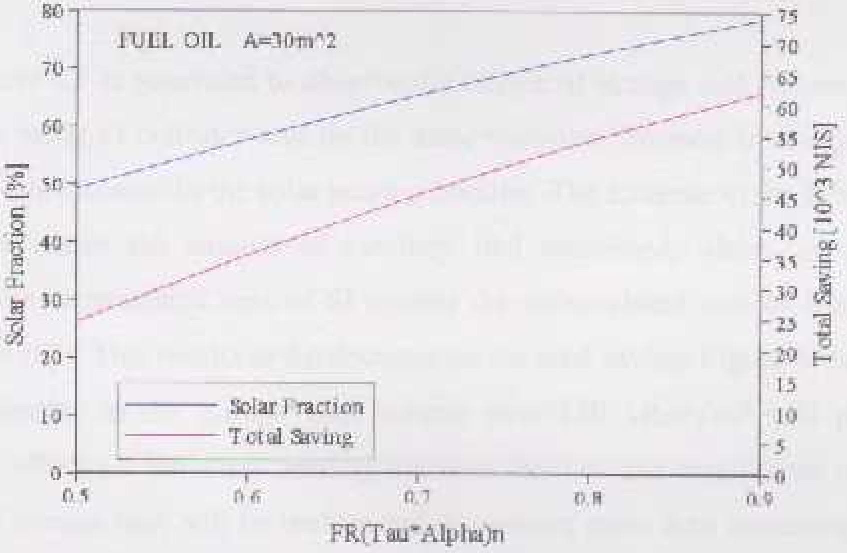


Figure 6.7: Variations of total saving and solar heating fraction versus $F_R(\tau\alpha)_n$

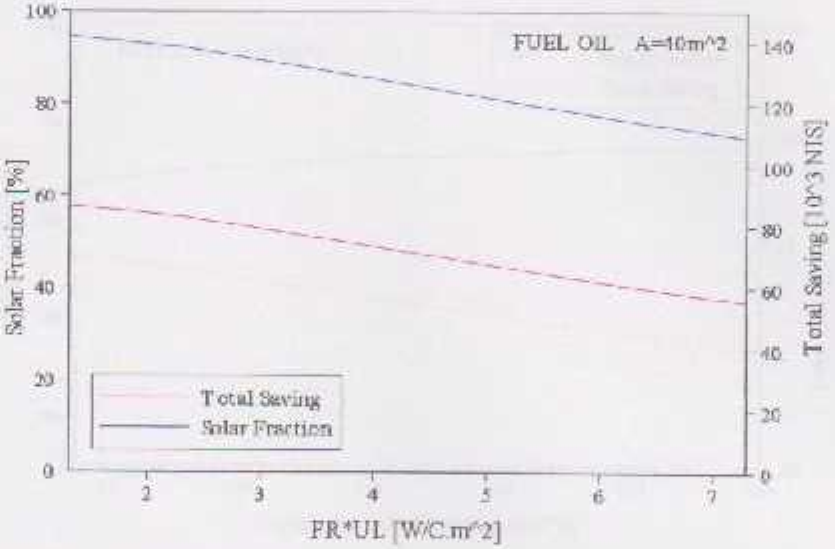


Figure 6.8: Variations of total saving and solar heating fraction versus $F_R U_L$

6.3.3 Storage Tank Volume

Figure 6.9 is generated to observe the effects of storage tank volume in liters per square meter of collector area on the same variables. Increase in storage volume draws a slight increase in the solar heating fraction. The increase in the solar heating fraction decreases the amount of auxiliary fuel consumed, which, in turn, will decrease the accumulated cost of SI against the accumulated cost of conventional installation (CI). This results in the decrease on the total saving. Figure 6.9 evidences that an increase in the storage tank volume over 150 $Liter/m^2$ will produce a negligible effect on the solar heating fraction. So that, the installation of a large volume of storage tank will be useless and do nothing more than increasing the cost of SI. The actual value for the storage tank volume is 37.5 $Liter/m^2$ which corresponds the maximum saving.

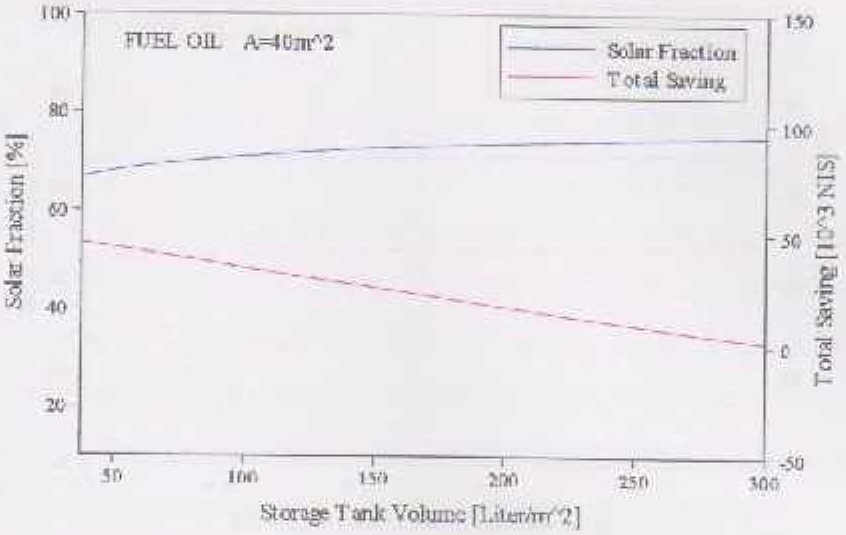


Figure 6.9: Variations of total saving and solar heating fraction versus storage tank volume per square meter of collector area

6.3.4 Heat Exchanger

As it's explained in chapter 3, an *f*-Chart design for liquid-based collectors heating system has one heat exchanger. This heat exchanger is characterized by its effectiveness and the flow rate of the fluid. Thus, the variations of the same variables with the effectiveness of the heat exchanger and the flow rate of the fluid as shown in Figure 6.10. Effects of the both are negligible when compared to the other design parameters studied. The actual values used in this study are 0.7 and 0.015 $kg/s.m^2$ for heat exchanger effectiveness and the flow rate, respectively.

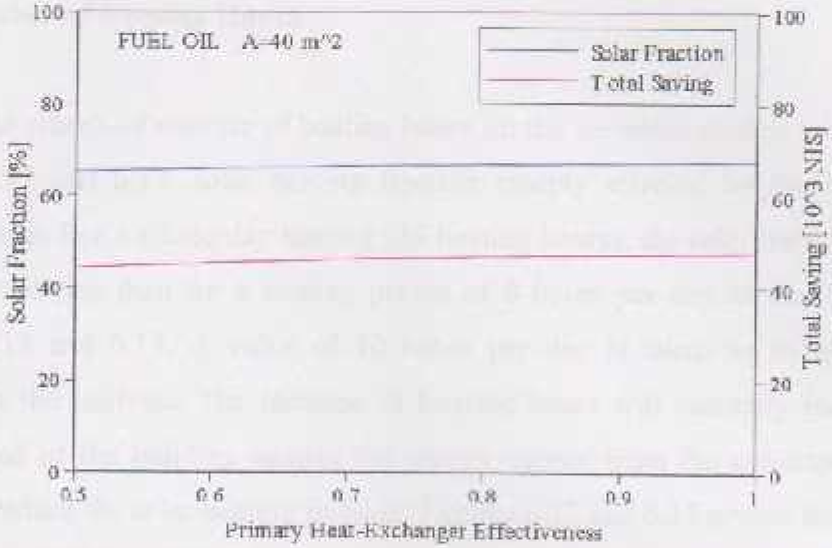


Figure 6.10: Variations of total saving and solar heating fraction versus the primary heat-exchanger effectiveness

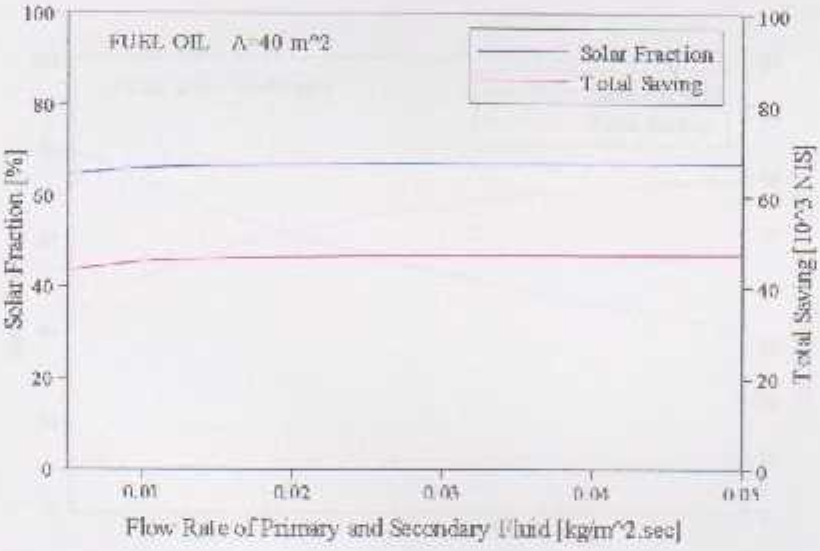


Figure 6.11: Variations of total saving and solar heating fraction versus the flow rate of primary and secondary fluid

6.3.5 Number of Heating Hours

The effects of number of heating hours on the variables studies are shown in Figures 6.12 and 6.13. solar heating fraction sharply affected by the number of heating hours. For a whole day heating (24 heating hours), the solar heating fraction is about 30% less than for a heating period of 8 hours per day as can be seen in Figures 6.12 and 6.13. A value of 10 hours per day is taken as an actual case throughout the analysis. The increase of heating hours will naturally increase the heating load of the building against the energy supply from the collectors, and in turn, will reduce the solar heating fraction. Figures 6.12 and 6.13 proves that the total saving is indeed increasing by increasing the number of heating hours. This is actually due to the higher increase in the building heating load when higher heating hours are applied. However, higher heating hours also in higher optimum collector areas.

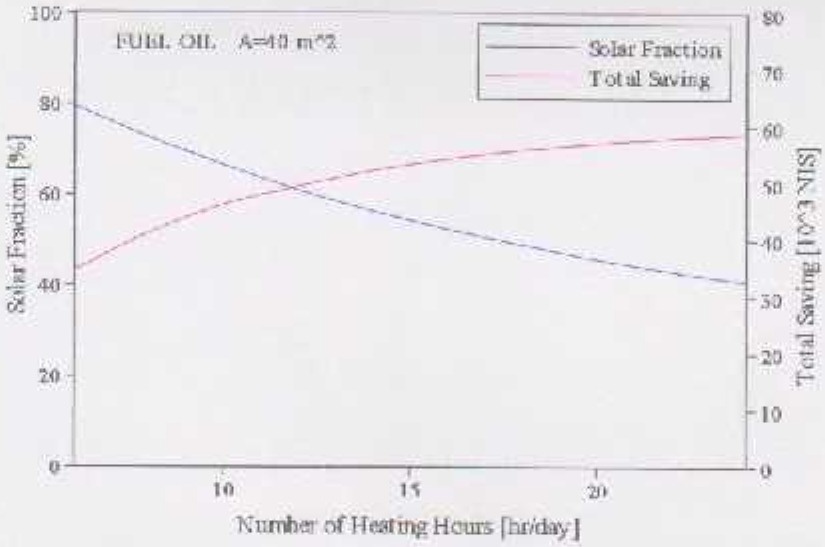


Figure 6.12: Variations of total saving and solar heating fraction versus number of heating hours for fuel oil using system

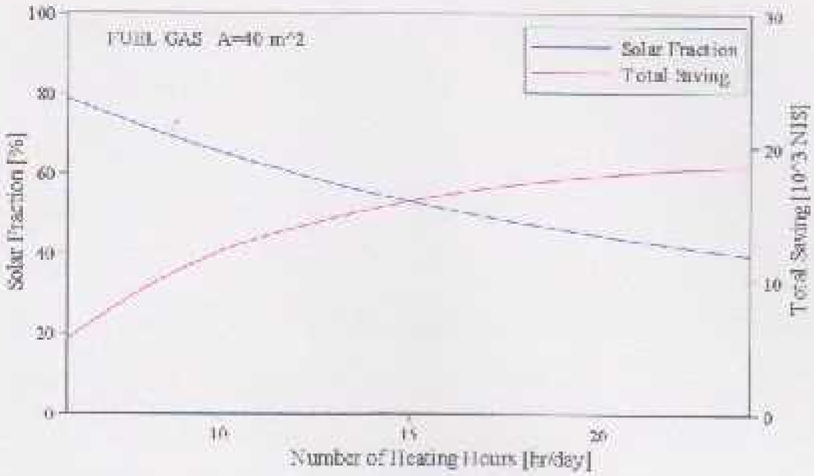


Figure 6.13: Variations of total saving and solar heating fraction versus number of heating hours for fuel gas using system

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This project aims to open a discussion on the economic feasibility of solar energy heating system against the common conventional heating systems in Palestine. To this end, the performance of a selected solar energy heating system operating in climatic region of Hebron is investigated. The effects of the primary design parameters on the system operating performance and the economics are studied. These are the collector (slope, $F_R(\tau\alpha)_n$ and F_RU_L), storage tank (its volume per square meter of collector area), heat-exchanger (effectiveness and the mass flow rate of primary and secondary fluid) and the design heating load (building overall heat loss coefficient-area product, and the number of heating hours per day).

The most important economic parameters such as life-cycle savings, fuel price increase rate, collector area and storage volume for the expected range of changes. economic feasibility of the solar energy heating system versus the conventional heating system using either fuel oil and fuel gas is analyzed under the climatic region of Hebron.

In this chapter, the main conclusions are taken within the elaboration of the results from chapter 6. Energy demand per square meter of the collector area for the studied system is normalized for the conditions of Hebron. The solar energy cost for heating is also discussed. Finally, some general conclusions about the feasibility of solar energy heating system are expressed under the last section.

7.2 Elaboration of Economical Results

From the results of the economical analysis under section 2 in chapter 6, the following points can be concluded:

1- Optimum collector area is found to be very sensitive to the type of fuel consumed. Increments on the collector area over the optimum values result in few increments on the solar heating fraction. So, it's clear uneconomic to install more collectors in the system.

2- Increase of conventional fuel price is found to be a dominant parameter for choosing the solar energy system, which exponentially increases the life-cycle savings and the optimum collector area.

3- Collector and storage tank unit price are the determinant parameters of the initial investment of a solar energy system. Collector price per square meter is found to be an effective parameter as well as the conventional fuel price, especially in the determination of optimum collector area.

7.3 Elaboration of Technical Results

From the results of the technical analysis under section 3 in chapter 6, the following points can be concluded:

1- Collector characteristics $F_R(\tau\alpha)_n$, F_RU_L and slope are the most critical parameters on the system economics, since the absorbed solar radiation potential by the collectors can be maximized with the optimum values of these parameters. Deviation from the optimum values sharply decrease the total saving and solar heating fraction. The changes of these design parameters within the accepted ranges may unfavorably change the solar heating fraction and total saving up to about 27%.

2- Valid range change of storage tank volume from a low of 37.5 $Liter/m^2$ to a high of 300 $Liter/m^2$ sharply decreases the total saving and slightly increases the solar heating fraction.

3- The changes of number of heating hours per day from 6 to 24 hours strongly drop the solar heating fraction about an average of 35%. This change clearly increases the heating load of the building, thus, sharply reduce the fraction of solar energy utilization.

4- Against the other design parameters studied, the effects of heat-exchanger efficiency and flow rate are negligible in the valid range.

7.4 Cost of Solar Energy

Solar energy cost can be defined by:

$$\text{Solar energy cost} = \frac{\begin{pmatrix}\text{Extra Expenses for Using Solar}\\ \text{Space Heating System}\end{pmatrix}}{\begin{pmatrix}\text{Total energy consumption}\\ \text{during the life time}\end{pmatrix} \times \begin{pmatrix}\text{Solar heating}\\ \text{fraction}\end{pmatrix}} \qquad (7.1)$$

$$\text{Solar energy cost} = \frac{43{,}543}{20 \times 54.268 \times 0.7052} = 57\ [NIS/GJ]$$

Actual conventional fuel costs are compared with the solar energy cost for heating in Table 7.1.

Table (7.1): Comparison of conventional fuel costs with solar energy cost [NIS/GJ]

Fuel Oil	Fuel Gas	Solar Energy
156	104	57

7.5 Discussion Recommendations

Although the maintenance and operating cost of solar heating systems (SI's) are generally low, the initial cost for such system is about twice as much as to the common conventional heating systems (CI's) used in Palestine. On the other hand. the life-cycle savings due to the low consumption of conventional fuel in the auxiliary part of SI are observed to be about 1.2 times the initial cost of the same SI. This shows that solar energy use can be an attractive decision from economics point of view.

Table 7.1 shows that using CI with fuel gas is economically cheaper than using fuel oil by about 33%. However, the use of SI with fuel oil costs less than CI with the same fuel by about 63%, while the use of SI with fuel gas costs less than CI with same fuel by about 45% under the same conditions.

When SI's become more common in the community, their initial costs might well decrease, especially when it comes to collector unit price; since every SI needs a number of collectors to reach the optimum collector area. For instance, if the collector price per meter square dropped by 20%, life-cycle savings would increase by about 12% in this case study.

Due to the lack of tests on the flat-plate collectors in Palestine, this study used testing results for only one factory taken from previous study[27]. It's highly recommended to make more tests for at the other factories producing such type of collectors to get more accurate results for system parameters, and to trigger the competition between the various manufactures. The competition will lead the manufacturers to improve their production quality. Thus, production capacity would increase and the quality of their products would also be increased by trying to enhance and develop their products towards the best.

SI is not restricted to water storage and domestic hot water, it can also be used in pool heating systems as an example. Swimming pool season usually begins with spring; when the sun shines almost during the hole day, which makes such system of heating very useful. However, another study should be done to insure the feasibility for SI as a pool heating system.

Passive solar heating (PSH) was not considered in this study. The use of PSH improves comfort, permits smaller heating plant, reduces heating costs, and thus, can increase the total saving[28].

APPENDIX A

UA-VALUE CALCULATIONS FOR THE BUILDING

UA-VALUE CALCULATIONS FOR THE BUILDING

A.1 Design Conditions

The useful outside design conditions are shown in Table 3.1. The inside design conditions are assumed to be: 20 $[^{0}C]$ inside dry bulb temperature and 50% inside relative humidity.

Table (A.1): Dimensions of windows

Window	Type	Width $[cm]$	Height $[cm]$
W1	Al, single glass	100	120
W2	Al, single glass	200	120
W3	Al, single glass	140	120
W4	Al, single glass	140	100
W5	Al, single glass	60	60
W6	Al, single glass	160	100

Table (A.2): Dimensions of doors

Window	Type	Width $[cm]$	Height $[cm]$
D1	Al, single glass	100	200
D2	Al, single glass	90	200
D3	Wood, 40 mm	80	200

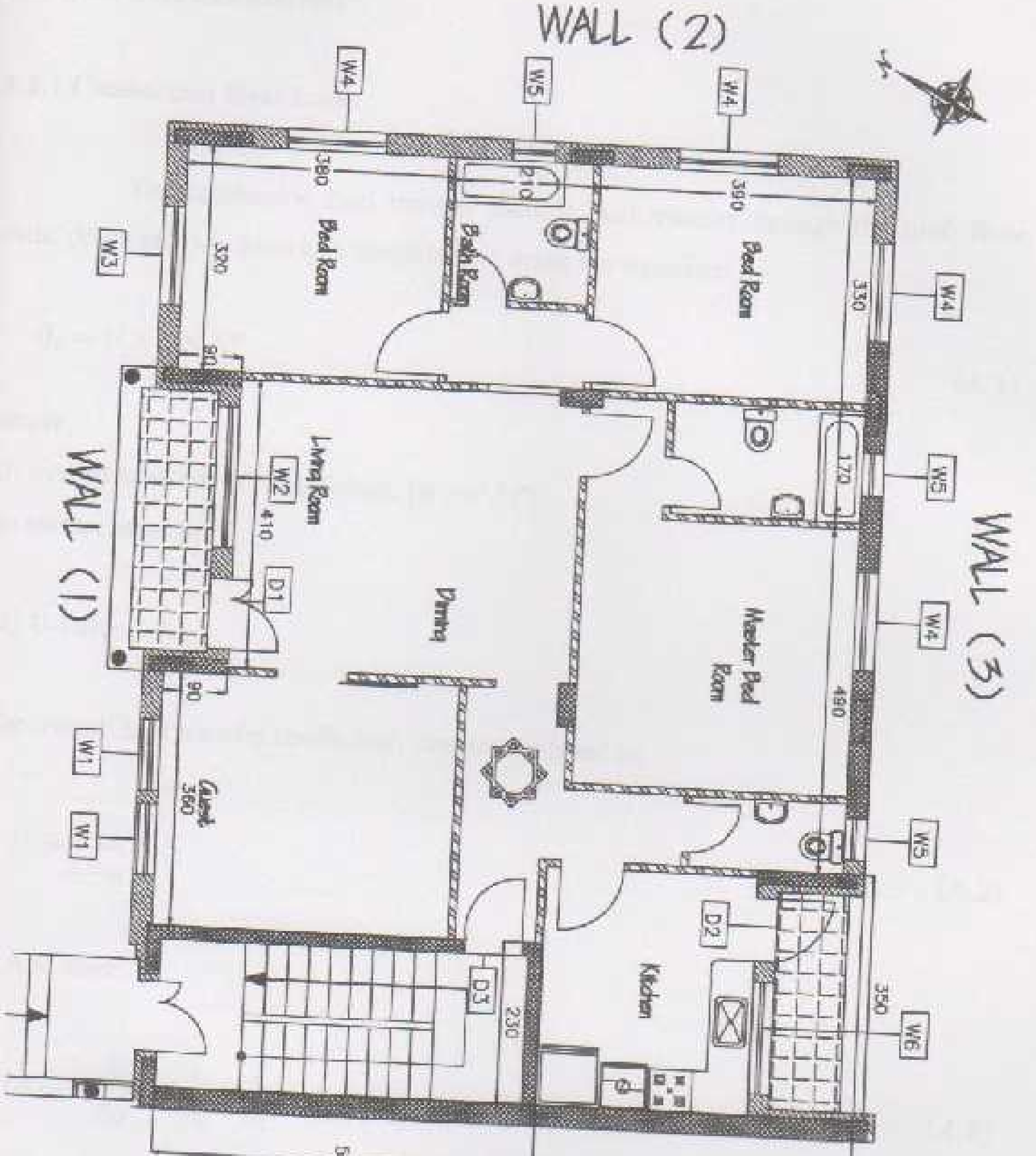


Figure A.1: A prototype building

A.2 Heat Loss Calculations

A.2.1 Conduction Heat Loss

The conduction heat transfer include heat transfer through the roof, floor, walls, doors and windows as a sensible heat using the equation:

$$Q_c = U \times A \times \Delta T \qquad (A.1)$$

where,

U: overall heat transfer coefficient, $[W/m^2.^0 C]$.

A: surface area, $[m^2]$.

(i) U-value

The overall heat transfer coefficient, can be expressed as:

$$U = \frac{1}{\Sigma R_{th}} \qquad (A.2)$$

And also:

$$\Sigma R_{th} = \frac{1}{h_O} + \Sigma \frac{x_i}{k_i} + \frac{1}{h_i} \qquad (A.3)$$

where,

R_{th}: thermal Resistance, $[m^2.^0 C/W]$.

x_i: layer thickness, $[m]$

k_i: thermal Conductivity, $[W/m.^0 C]$.

- **U-value for the roof**

Figure A.2 shows a section in the roof. The construction of the roof and their U-values are shown in Table A.3.

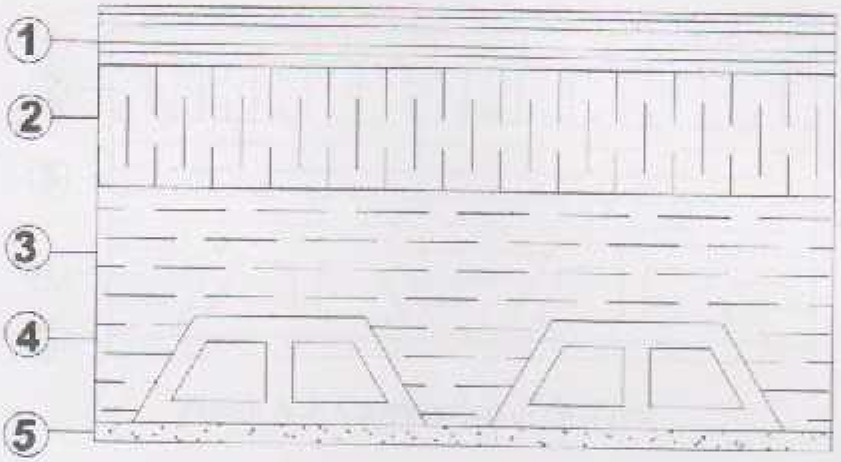


Figure A.2: Construction of the roof

Table A.3: Overall heat transfer coefficient for the roof[16]

Material	k $[W/m.^0C]$	x $[m]$	$[m^2.^0C/W]$
Outside air film	--	--	0.060
(1) Mastic asphalt	0.10	0.02	0.200
(2) Cement	1.75	0.08	0.046
(3) Reinforced concrete	1.75	0.07	0.040
(4) Cement brick	1.1	0.18	0.163
(5) Plaster	1.2	0.02	0.017
Inside Air film	--	--	0.120
	$U = 1.55[W/m^2.^0C]$		

- **U-value for the floor**

Figure A.3 shows a section in the floor. The construction of the floor and their U-values are shown in Table A.4.

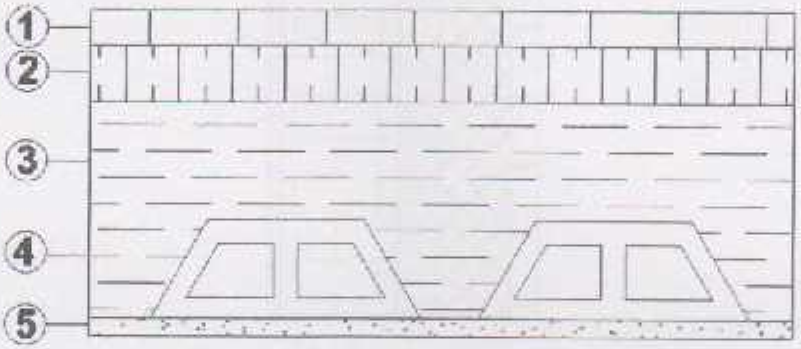


Figure A.3: Construction of the floor

Table A.4: Overall heat transfer coefficient for the floor[16]

Material	$[W/m.^0C]$		$[m^2.^0C/W]$
Inside air film	--	--	0.120
(1) Tiles	1.10	0.02	0.018
(2) Cement	0.54	0.05	0.092
(3) Reinforced concrete	1.75	0.06	0.034
(4) Cement brick	0.95	0.18	0.190
(5) Plaster	1.2	0.02	0.017
Outside Air film	--	--	0.060
	$U = 1.88[W/m^2.^0C]$		

- **U-value for the walls**

Figure A.4 shows a section in the wall, The construction of the walls and their U-values are shown in Table A.5.

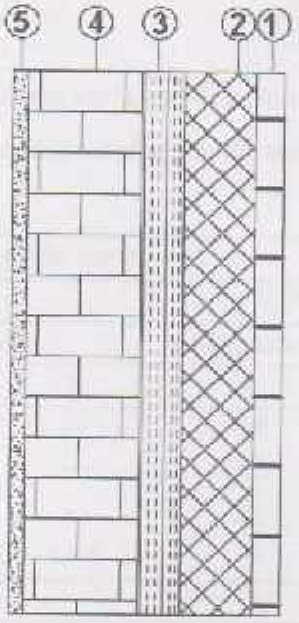


Figure A.4: Construction of walls

Table A.5: Overall heat transfer coefficient for the walls[16]

Material	$[W/m.^0C]$	$[m]$	$[m^2.^0C/W]$
Outside air film	--	--	0.060
(1) Stone	1.70	0.07	0.040
(2) Concrete	1.75	0.15	0.09
(3) Air gap	--	0.03	0.18
(4) Cement brick	0.09	0.07	0.080
(5) Plaster	1.2	0.02	0.020
Inside Air film	--	--	0.120

$$U = 1.70[W/m^2.^0C]$$

- **U-value for the windows and doors**

Table A.6: Overall heat transfer coefficient through windows and doors[29]

Material Type	$U\ [W/m^2.^0C]$
Aluminum windows with single glass	5.6
Wood doors 40 mm (without wood storm door)	1.5
Aluminum doors	7.0

(*ii*) A-value

The inside area for both the surfaces adjacent to the atmospheric outside air (a), and the surface adjacent to the unheated space (b) are listed in Table A.7.

Table A.7: Area of the heat transfer surfaces

Wall	A [m^2]				
	Walls		Windows	Doors	
	a	b	a	a	b
(1)	32	---	6.4	2.0	----
(2)	26	---	3.2	---	---
(3)	35	---	5.1	1.8	---
(4)	12.3	13.8	---	---	1.6
Roof and Floor			88		

(*iii*) ΔT-value

The temperature difference for the roof, and the walls which are exposed to the atmosphere expressed as:

$$\Delta T = T_i - T_o \qquad (A.4)$$

Also temperature difference for unheated adjacent rooms is given by[29]:

$$\Delta T_{\text{adj}} = \frac{T_i - T_o}{2} \qquad (A.5)$$

The months in which we need to calculate space heating load are in which the dry bulb temperature is less than 17 ^{0}C. the ΔT in these months are listed in Table A.8.

Table A.8: Monthly average outside dry bulb temperatures, $T_{DB,o}$ [°C]

Month	$T_{DB,o}$ [°C]	ΔT [°C]	ΔT_{adj} [°C]
January	4.4	15.6	7.80
February	2.4	17.6	8.80
March	6.5	13.5	6.75
April	7.8	12.2	6.10
November	12.5	7.5	3.75
December	7.8	12.2	6.10

(*vi*) Total Conduction Heat Loss

Table A.9: Monthly conduction heat loss

Conduction Surface	Conduction heat loss [**W**]					
	Month					
	Jan.	Feb.	March	April	Nov.	Dec.
Wall (1)	849	957	734	664	408	664
Wall (2)	690	778	597	539	332	539
Wall (3)	928	1047	803	726	446	726
Wall (4)	509	575	438	398	343	398
Roof	2128	2401	1841	1664	1664	1664
Floor	1290	1456	1117	1009	620	1009
Windows	1284	1449	1014	1004	617	1004
Doors	434	481	375	339	209	339
Total Q_c	**8112**	**9144**	**6919**	**6343**	**4639**	**6343**

A.2.2 Infiltration Heat Loss:

Air change method is a simple method to find the infiltration load, building which assumes that air volume in a space is replaced by outside air at certain number of times per hour. The number of air changes depend on the type of space, which is given in the Tables of air changes [29].

Table A.10: Air change per hours in residences and commercial application[29]

Kind of Room or Building	ACH per Hour
Rooms with no widows or exterior doors	0.5
Rooms with widows or exterior doors on one side only	1.0
Rooms with widows or exterior doors on two sides	1.5
Rooms with widows or exterior doors on three sides	2.0
Entrance halls	2.0
Classrooms, dining rooms, lounges, toilets, hospital	2.0
Rooms, kitchens, laundries, ballrooms, bathrooms. Toilets, auditorium	3.0

The total heat loss due to infiltration Q_f is given by[29]:

$$Q_f = \rho_0 V_f (H_{in} - H_{out}) \qquad (A.6)$$

where,

H_{in}: indoor enthalpy, can be obtained from the psychometric chart.

H_{out}: outdoor enthalpy, can be obtained from the psychometric chart.

ρ_0: outside air density $[kg/m^3]$.

V_f: the infiltration rate $[m^3/s]$, expressed by:

$$V_f = \left(\frac{No.\ of ACH}{hr}\right) \times Room\ Volume \qquad (A.7)$$

the values of the used parameters are shown in Table A.11.

Table A.11: The values of infiltration parameters

Parameter	Value
ρ_0 [kg/m^3]	1.18
$No. of ACH$/hr	2.0
$Rooms\ Volume$ [m^3]	262.5
V_f [m^3/hr]	525
Outdoor RH [%]	65
H_{in} [kJ/kg]	38.5

the total heat loss due to infiltration have a monthly values shown in Table A.12.

Table A.12: Monthly enthalpy and total heat loss due to infiltration

Month	**H_{out} [kJ/kg]**	**Q_f [W]**
January	7	5421
February	1	6505
March	10	4904
April	18	3528
November	29	1635
December	18	3528

A.2.3 Total Heat Loss and UA-values

Total heat loss is the sum of conduction, and infiltration heat loss. And the overall heat transfer coefficient-area product is the design heating load per design temperature difference, and the results are in the Table A.13.

Table A.13: Monthly total heat loss and UA-values

Month	Q_c $[W]$	Q_f $[W]$	Q_t $[W]$	UA $[W/{}^0C]$
January	8112	5421	13533	868
February	9144	6505	15649	889
March	6919	4904	11823	876
April	6343	3528	9871	809
November	4639	1635	6274	837
December	6343	3528	9871	809

APPENDIX B

AVARAGE TRANSMITANCE-ABSORPTANCE PRODUCT

AVARAGE TRANSMITANCE-ABSORPTANCE PRODUCT

Transmittance and absorptance of collector depend on the incidence angle of solar radiation on the collector surface. It is not possible to determine their separate values from the collector test. The product of F_R, τ, and α determined from the collector tests corresponds to the transmittance and absorptance values for radiation at normal incidence, $F_R(\tau\alpha)_n$. Depending on the collector orientation and the time of the year, the monthly average values of transmittance and absorptance can be significantly lower than the values for radiation at normal incidence. The ratio of the monthly average transmittance-absorptance product, $(\overline{\tau\alpha})$, to the transmittance-apsorbtance product at normal incidence, $(\overline{\tau\alpha})_n$, can be calculated as a function of weighted average for the beam, diffuse, and reflected components of the radiation[9].

$$\frac{(\overline{\tau\alpha})}{(\tau\alpha)_n}=\frac{\overline{H}_b\overline{R}_b}{\overline{H}_T}\frac{(\overline{\tau\alpha})_b}{(\tau\alpha)_n}+\frac{\overline{D}}{\overline{H}_T}\frac{(\overline{\tau\alpha})_d}{(\tau\alpha)_n}\left(\frac{1+\cos\beta}{2}\right)+\frac{H\,\rho}{\overline{H}_T}\frac{(\overline{\tau\alpha})_g}{(\tau\alpha)_n}\left(\frac{1-\cos\beta}{2}\right) \qquad (B.1)$$

where $(\overline{\tau\alpha})_b$, $(\overline{\tau\alpha})_d$, and $(\overline{\tau\alpha})_g$ are the monthly average values of transmittance-apsorbtance product corresponding to beam, diffuse, and ground-reflected radiation.

The ratio of transmittance for radiation at a known incidence angle to the transmittance for radiation at normal incidence is given as a function of incidence angle[20]:

$$\left(\frac{\tau}{\tau_n}\right)_{\theta_i} = 0.9998530947 + 2.77399\times10^{-3}\,\theta_i - 2.8993\times10^{-4}\,\theta_i^{\,2}$$

$$+ 8.02554\times10^{-6}\,\theta_i^{\,3} - 7.21636\times10^{-8}\,\theta_i^{\,4} \qquad (B.2)$$

In a same manner, the ratio of the collector plate apsorbtance for radiation at a known incidence angle to the apsorbtance for radiation at normal incidence is given by:

$$\left(\frac{\bar{\alpha}}{\alpha_n}\right)_{\theta_i} = 0.989501758 + 7.34668 \times 10^{-3}\,\theta_i - 6.30122 \times 10^{-4}\,\theta_i^{\,2} + 1.52771 \times 10^{-5}\,\theta_i^{\,3} - 1.16131 \times 10^{-7}\,\theta_i^{\,4} \qquad (B.3)$$

So, in order to determine $(\overline{\tau\alpha})/(\tau\alpha)_n$ it is necessary to specify the monthly average incidence angle for beam, diffuse and reflected radiation. For surfaces facing directly to words the equator[30], the average incidence angle for beam radiation $\bar{\theta}_b$ is approximately the angle at which radiation strikes the collector surface 2.5 hours from solar noon on a day in the middle of the month. $\bar{\theta}_b$ is given by:

$$cos\bar{\theta}_b = sin\,\delta\,sin\,\emptyset\,cos\,\beta - sin\,\delta\,cos\,\emptyset\,sin\,\beta + cos\,\delta\,cos\,\emptyset\,cos\,\beta\,cos\,(37.5\,^0) + cos\,\delta\,sin\,\emptyset\,sin\,\beta\,cos\,(37.5\,^0) \qquad (B.4)$$

The average angle of incidence for diffuse and ground reflected radiation is taken to be 60 ^{0}. So:

$$\frac{(\overline{\tau\alpha})_b}{(\tau\alpha)_n} = \left(\frac{\tau}{\tau_n}\right)_{\bar{\theta}_b} \times \left(\frac{\alpha}{\alpha_n}\right)_{\bar{\theta}_b} \qquad (B.5)$$

and

$$\frac{(\overline{\tau\alpha})_d}{(\tau\alpha)_n} = \frac{(\overline{\tau\alpha})_g}{(\tau\alpha)_n} = \left(\frac{\tau}{\tau_n}\right)_{60} \times \left(\frac{\alpha}{\alpha_n}\right)_{60} \qquad (B.6)$$

After being calculated the above values, the monthly average transmittance-absorptance product $(\overline{\tau\alpha})/(\tau\alpha)_n$ can be found from equation B.1.

APPENDIX C

STORAGE TANK UA-VALUE AND LOAD HEAT-EXCHANGER SIZE

STORAGE TANK UA-VALUE AND LOAD HEAT-EXCHANGER SIZE

C.1 Storage Tank Overall Heat Transfer Coefficient Area Product $(UA)_{st}$

Overall heat transfer coefficient is taken to be[27] 0.59 $W/m^2.^0C$, and the surface area of the storage tank was found to be 5.5 square meter per cubic meter of storage tank volume. Thus, the storage volume needed for fuel oil system is 1725 $Liter$, and the storage volume needed for fuel gas system 1050 $Liter$. So, $(UA)_{st} = 5.6\ W/^0C$ for fuel oil system, and $(UA)_{st} = 3.3\ W/^0C$ for fuel gas system.

C.2 Load Heat-Exchanger Size (z)

The load heat-exchanger size depends on the minimum fluid flow rate and specific heat. Primary and secondary fluids' flow rate are taken to be $0.015 kg/m^2.s$, which is vary according to the optimum collector area, and it's 0.7 and 0.42 kg/s for fuel oil and fuel gas, respectively. The primary fluid specific heat for 10% ethylene glycol with water is equal to 3.94 $kJ/kg.^0C$ [31]. Also it depends on the effectiveness of load heat exchanger, which is assumed to be 0.75 and the average value of the overall heat transfer coefficient area product of the building calculated in Appendix A is 845 $W/^0C$.

$$z = \frac{\varepsilon_L (\dot{m}c_p)_{min}}{UA}$$

Using equation 4.11 the load heat exchanger size is about 2.5 and 1.5 in the fuel oil and fuel gas systems, respectively.

APPENDIX D

ECO-COLLECTOR PROGRAM

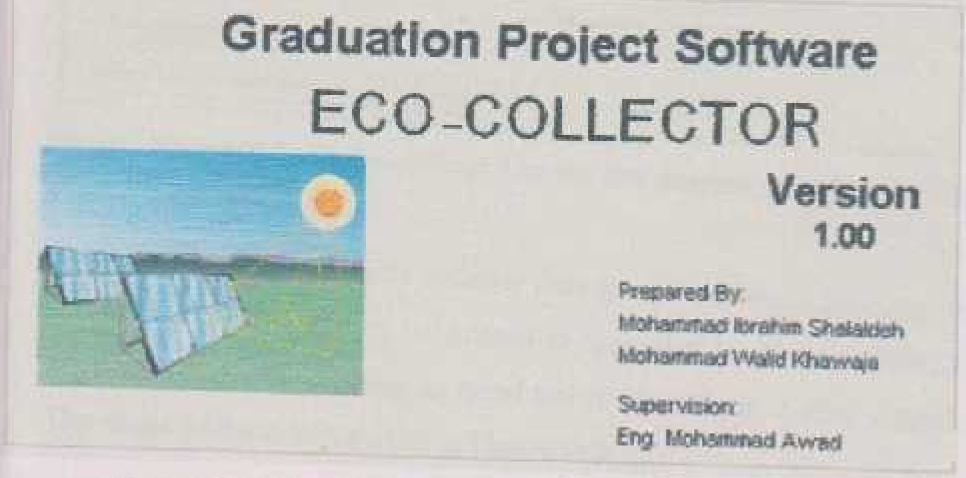
ECO-COLLECTOR PROGRAM

D.1 ECO-COLLECTOR Program

This program aims to find life-cycle savings throughout system effective life, which is assumed to be 20 years as a maximum value. The program is developed using Microsoft Visual Basic 6.0, due to its simplicity to learn and use. The main input data consist of the technical, economical and meteorological parameters.

The structure of the main program consists of five forms and a splash screen. The forms are arranged as follows;

Splash Screen: It pops-up whenever the program is launched, it shows the name of the program and the other information about it. The user must press on the splash screen to start the program. The splash screen of the first version of ECO-COLLECTOR is shown in Figure D.1.



Graduation Project Software

ECO-COLLECTOR

Version
1.00

Prepared By:
Mohammad Ibrahim Shalaldeh
Mohammad Walid Khawaja

Supervision:
Eng. Mohammad Awad

Figure D.1: Splash screen in the first version of ECO-COLLECTOR

Form 1: This is the first and the most important form in ECO-COLLECTOR, it contains all the input parameters needed to calculate the outputs mentioned later under this section. After setting all input values, the user can press "Click To Calculate" button, or he/she can press "Click Here to Change Weather Data" button to change weather data for his/her location. Form 1 shape is shown in Figure D.2.

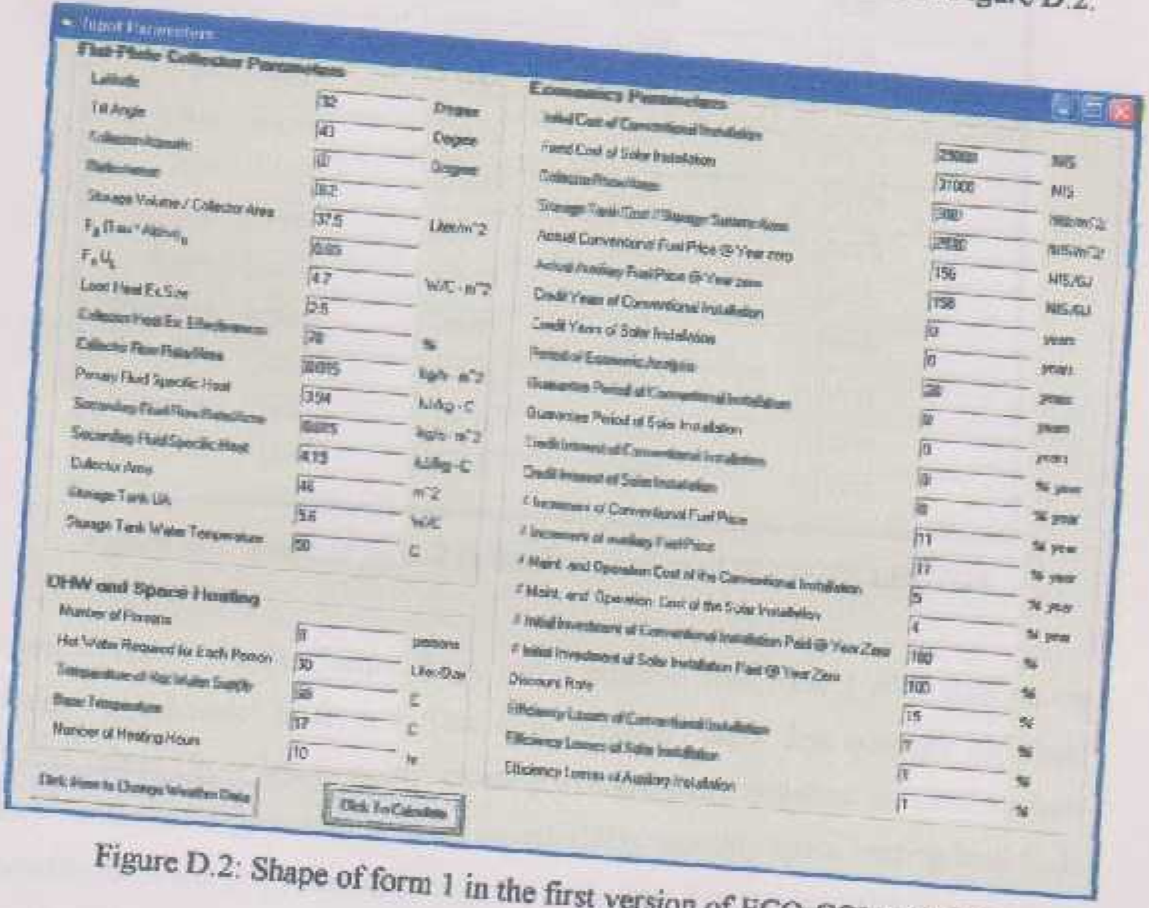
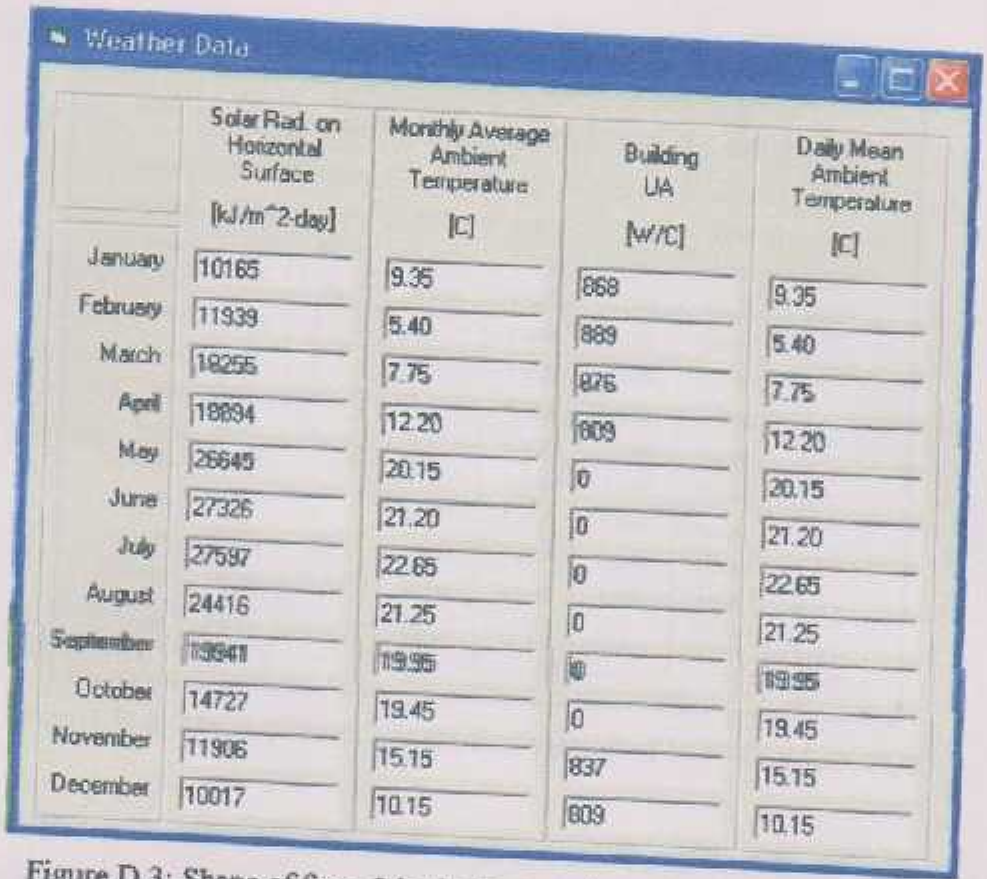


Figure D.2: Shape of form 1 in the first version of ECO-COLLECTOR

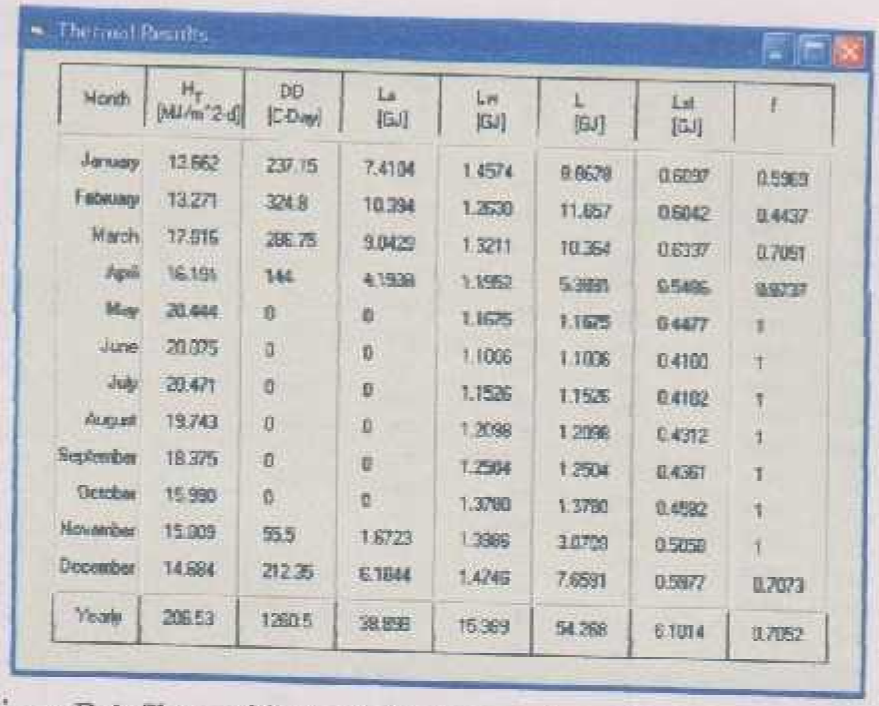
Form 2: This form contains weather data given in chapter 3, along with the overall UA values of the building calculated in appendix A. These values can be changed anytime as needed, keeping in mind not to close form 2 after changing the values. The shape of Form 2 is shown in Figure D.3.



	Solar Rad. on Horizontal Surface [kJ/m^2-day]	Monthly Average Ambient Temperature [C]	Building UA [W/C]	Daily Mean Ambient Temperature [C]
January	10165	9.35	868	9.35
February	11939	5.40	889	5.40
March	18255	7.75	876	7.75
April	18894	12.20	809	12.20
May	26645	20.15	0	20.15
June	27326	21.20	0	21.20
July	27597	22.65	0	22.65
August	24416	21.25	0	21.25
September	19841	19.95	0	19.95
October	14727	19.45	0	19.45
November	11906	15.15	837	15.15
December	10017	10.15	809	10.15

Figure D.3: Shape of form 2 in the first version of ECO-COLLECTOR

Form 3: This is the first output form, and it pops-up with form 4 after clicking on "Click To Calculate" in form 1. This form contains output data columns and their annual values (from left to right); monthly average daily radiation on tilted surface (H_T), number of degree days in every month (DD), monthly space heating load (L_s), monthly domestic hot water demand load (L_w), total heating load (L), storage tank heat loss (L_{st}) and monthly solar fraction (f). The shape of form 3 is shown in Figure D.4.

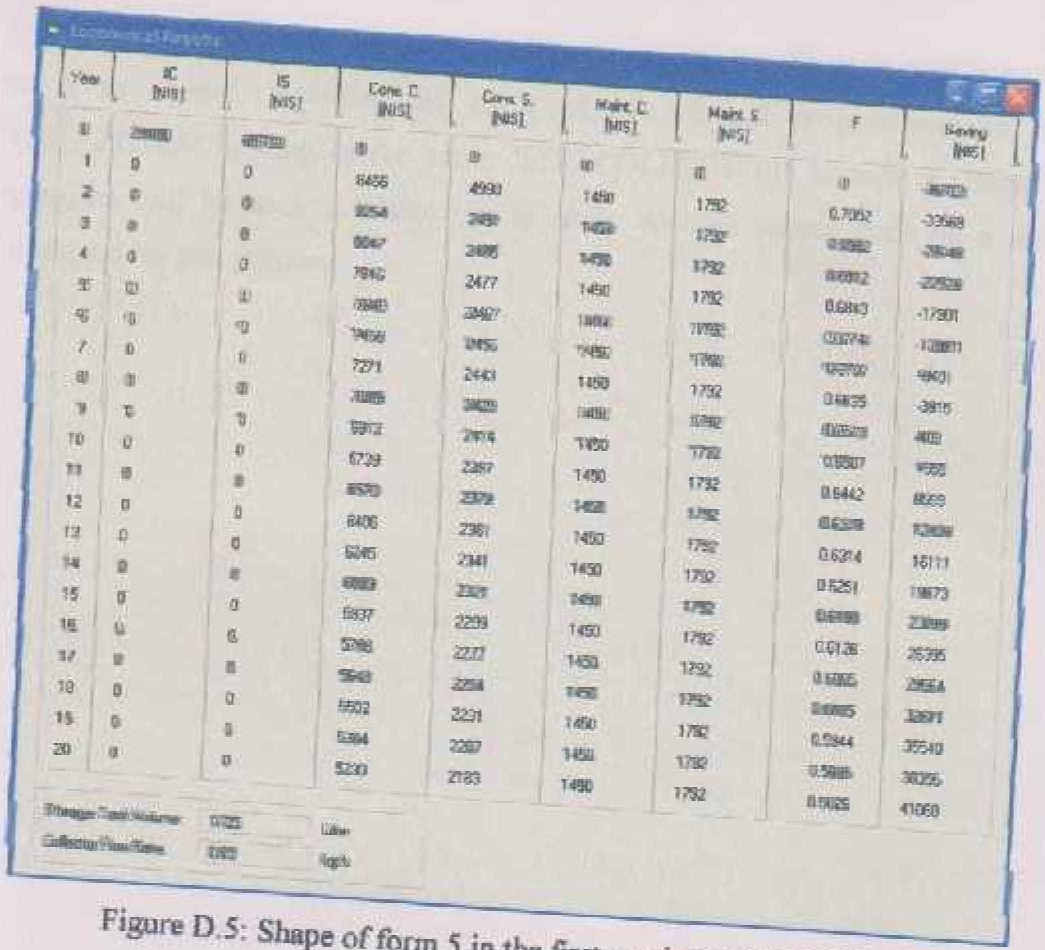


Month	H_T [MJ/m^2-d]	DD [C-Day]	La [GJ]	Lw [GJ]	L [GJ]	Lst [GJ]	f
January	12.662	237.15	7.4104	1.4574	8.8678	0.6097	0.5969
February	13.271	324.8	10.394	1.2630	11.657	0.6042	0.4437
March	17.916	286.75	9.0429	1.3211	10.364	0.6337	0.7051
April	16.191	144	4.1938	1.1952	5.3890	0.5486	0.9737
May	20.444	0	0	1.1675	1.1675	0.4477	1
June	20.075	0	0	1.1006	1.1006	0.4100	1
July	20.471	0	0	1.1526	1.1526	0.4182	1
August	19.743	0	0	1.2098	1.2098	0.4312	1
September	18.375	0	0	1.2504	1.2504	0.4361	1
October	15.990	0	0	1.3780	1.3780	0.4582	1
November	15.009	55.5	1.6723	1.3986	3.0709	0.5058	1
December	14.684	212.35	6.1844	1.4746	7.6591	0.5977	0.7073
Yearly	206.53	1260.5	38.898	15.369	54.268	6.1014	0.7052

Figure D.4: Shape of form 3 in the first version of ECO-COLLECTOR

Form 4: This is the last form of outputs, it shows the annual cash flows according to the parameters were input in form 1. Output columns are arranged (from left to right) as follows; initial cost of conventional installation (IC), initial cost of solar installation (IS), yearly consumption of conventional installation (Cons. C.), yearly consumption of solar installation (Cons. S.), yearly maintenance and operation of conventional installation (Maint. C.), yearly maintenance and operation of solar installation (Maint. S.), yearly solar heating fraction (F) and the accumulated total saving throughout the effective life of the system. Also, two more outputs are shown in the bottom of this form; storage tank volume and collector flow rate. The shape of form 4 is shown in Figure D.5.

Form 5: Although this form is hidden, it's used to make calculations haven't space in their original forms.



Year	IC [NIS]	IS [NIS]	Cons. C [NIS]	Cons. S [NIS]	Maint. C [NIS]	Maint. S [NIS]	F	Saving [NIS]
0	[illegible]	[illegible]	0	0	0	0	0	[illegible]
1	0	0	8456	4930	1450	1792	0.7052	-33569
2	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
3	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
4	0	0	[illegible]	2477	1450	1792	0.6843	-17301
5	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
6	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
7	0	0	7271	2441	1450	1792	0.6635	-3815
8	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
9	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
10	0	0	6739	[illegible]	1450	1792	0.6442	8569
11	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
12	0	0	6406	2361	1450	1792	0.6314	16111
13	0	0	6245	2341	1450	1792	0.6251	19673
14	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
15	0	0	5937	[illegible]	1450	1792	0.6126	26395
16	0	0	[illegible]	2277	1450	1792	[illegible]	[illegible]
17	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
18	0	0	5502	2231	1450	1792	0.5944	35540
19	0	0	[illegible]	[illegible]	1450	1792	[illegible]	[illegible]
20	0	0	5230	2183	1450	1792	[illegible]	41060

Storage Tank Volume [illegible] Liter
Collector Flow Rate [illegible] Kg/h

Figure D.5: Shape of form 5 in the first version of ECO-COLLECTOR

D.2 Future Developments

Despite the fact that ECO-COLLECTOR was developed especially for this graduation project, development process shouldn't stop after version 1.00 was released. hopefully, more developments in the near future will be made.

The next version will hopefully contain at least one more economical output; such as payback period, internal rate of return and/or the optimum collector area using mathematical iteration methods. The new interface will be more interesting than the current classic interface.

This program was set to be free for everyone to benefit or to modify any part of it as needed, including the name of the original programmers of ECO-COLLECTOR as long as the name "ECO-COLLECTOR" is kept the same. The program will be soon available online along with its source code on a website designed for that purpose.

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