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THE AMERICAN UNIVERSITY IN CAIRO  
SCHOOL OF SCIENCES AND ENGINEERING

*A Techno-Economic Study for Heating Poultry Houses Using  
Renewable Energy*

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B.Sc. Mechanical Engineering, 2009  
The American University in Cairo

A thesis submitted in partial fulfillment of the requirements for the degree of  
**Master of Science in Mechanical Engineering**

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January, 2015

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## ABSTRACT

In any broilers poultry house, fuel-based heating systems are commonly used to maintain the targeted temperatures for successful breeding of chicken. A considerable amount of fuel is consumed for this application, which leads to high running cost and contributes to the increase of air pollutant emissions. Given the current energy crisis and the urge to use renewable energy, this research studies the application of a solar heating system (SHS) for a poultry house. It includes the technical and economic study for the SHS and the integration of biogas produced from chicken manure as an auxiliary source of heat.

The heating demand of a broilers poultry house of capacity 24000 birds located in Al Menia governorate in Egypt is calculated hourly over a complete year using TRNSYS simulation tool. Accordingly, a SHS is designed to cover part of this demand besides a fuel based auxiliary source. The system consists of: evacuated tubes, water storage tanks and fan coil units. The two main design variables of the SHS are the area of the solar collector ( $A_{SC}$ ) and the volume of the storage tanks ( $V_{tank}$ ). An economical study of the SHS is carried out, where the net present value (NPV) is calculated.

A solution space consisting of 65 different designs is explored, where the NPV is calculated at each solution to select the best economical design within the solution space. The calculation is performed twice, once using the Egyptian local fuel price, where the SHS is found to be economically feasible using certain designs only. The other calculation is performed using the international minimum benchmark price of diesel fuel, where the NPV of all designs is found to be significantly higher and thus, the use of SHS is more appealing at this fuel price. Other parameters such as the infiltration rate of the building and the usage of latent heat storage technique are examined to explore their effect on the performance of the SHS.

Finally, an all-green heating solution is introduced, where bio-digesters are used to produce biogas from the waste of the poultry house in order to complement the SHS by covering the auxiliary energy needed. The economics of the all-green solution is examined and found to be bettered.

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## ACRONYMS

$A_{sc}$	Area of the Solar Collectors ( $m^2$ )
ACH	Air Changes per Hour
BW	Bird Weight (kg)
CM	Chicken manure
$C_t$	Tax deductible expense
$D_t$	Tax Deduction
DHW	Domestic Hot Water
F	Fuel Savings
F.C	Fan Coil
FCR	Feed Conversion Ratio
GHP	Geothermal Heat Pump
KPI	Key Performance Indices
LCS	Life Cycle Savings
LHP	Latent Heat Produced
LHS	Latent Heat Storage
N	Cash Flow Period
NPV	Net Present Value
$P_{Load}$	Load Pump
PCM	Phase Change Materials
PID	Proportional-integral-derivative
PW	Present Worth Factor
$Q_{aux}$	Auxiliary Energy Needed
$Q_{FC}$	Total Heating Rate for the 5 fan coil units (kJ/hr)
$Q_{Heat}$	Heat Demand(kJ/hr)
SHC	Solar Heating and Cooling System
SHP	Sensible Heat Produced
SHS	Solar Heating System
t	Income Tax
$T_{ambient}$	Ambient Temperature / Outside Temperature ( $^{\circ}C$ )
$T_{House}$	Temperature inside the poultry house “Zone 2” ( $^{\circ}C$ )
$T_{Roof\&\ Ceiling}$	Temperature between the ceiling and roof of the building “Zone 1”

$T_{Set}$	Set Temperature ( $^{\circ}C$ )
$T_{Tank}$	Average temperature of the storage tank ( $^{\circ}C$ )
$T_{tank-load}$	Water temperature exiting the tank to the load ( $^{\circ}C$ )
$T_{out SC}$	Outlet temperature of the collector ( $^{\circ}C$ )
THP	Total Heat Produced
TRNSYS	Transient System Simulation Tool
$V_{Tank}$	Volume of Storage Tanks ( $m^3$ )
VBA	Visual Basic Application
WACC	Weighted Average Cost of Capital

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# CHAPTER 1

## INTRODUCTION

### 1.1 Background Information

Poultry industry is one of the energy intensive industries that consume large quantities of fuel, especially for the Broilers sector. Broiler poultry houses- producing chicken meat- heavily consume diesel fuel, gasoline or gas for their heating systems in order to maintain the temperatures required for the breeding of the chicks. The required temperature of any broiler house ranges from 22°C to 32°C depending on the birds' age. At each stage of the birds' development there is one optimum temperature zone in which the birds make the best performance in terms of the use of feed energy for growth and meat yield. If the birds are kept at a temperature that is lower than the targeted optimum temperature, the birds increase their feed intake and use more of the feed energy to keep their bodies warm, which increases the production cost and decreases the meat yield. While, if they were kept at a temperature that is higher than the targeted optimum temperature, they reduce their feed intake to limit heat production, which also results in lower meat yield [1]. Therefore, an efficient heating system is necessary for any broiler house to maintain the required temperatures all around the year.

Currently, the heating systems used depend either on electricity, gas, diesel fuel, kerosene or other non-renewable sources. The equipment widely used in poultry houses is either direct hot air generators or indirect hot air generators-with external exhaust. The principle of operation of a hot air generator is having a pump that drives fuel under pressure to a burner nozzle. The fuel is sprayed into the combustion chamber, where it is burnt. The produced hot exhaust gases are used to heat an air stream that is supplied by a motor fan. The running cost of the aforementioned equipment is high and affects the economic efficiency of poultry houses.

In addition to its high running cost, conventional fuel-based heating systems contribute to the increase of air pollutant emissions. CO<sub>2</sub> emission is one of the main sources of global warming that the world is suffering. CO<sub>2</sub> emissions in Egypt have drastically increased by a percentage of 140.3% from 1990 till 2011, where it reached 188.4 million tons of CO<sub>2</sub> [2]. Globally, space heating and cooling systems consume 30–50% of global energy consumption, which is 5.6x10<sup>10</sup> MWh year<sup>-1</sup> corresponding to the emission of 1.4 x10<sup>10</sup> tons CO<sub>2</sub> per year [3]. A study made on the greenhouse gas emissions in EU countries showed that poultry produces 1.6 kg CO<sub>2</sub>-eq per kg of chicken [4].

Clearly, the amount of CO<sub>2</sub> emitted per chicken varies from case to case depending on the amount of fuel used.

The amount of fuel used for heating a poultry house depends on many factors. One of the main factors is the climatic conditions [5]. The location of the house defines the annual mean air temperature and the lowest air temperatures reached during winter time, and thus determines the amount of space heating needed inside the house. Also, the level of insulation of the poultry house building indicates the amount of heat leakage to the outer atmosphere. Another factor affecting the amount of fuel used is the amount of heat produced by the chicken within the space to be heated. Chicken produce latent and sensible heat depending on their weight, age and brooding temperature[6]. Thus, the number of birds housed per volume and their weight affects the amount of heat needed to maintain a certain set temperature at this volume.

According to the FAO<sup>1</sup> report about poultry in Egypt, in 2005 “the total number of broiler Exotic "Commercial" and improved native "Balady"houses was reported to be 25,935 houses with an estimated annual production potential of 962 million broilers” [7]. However, only 80% of these houses were operative and the actual production reported for year 2005 was 415 million birds [7]. To get an updated tangible figure for the current production of broilers in Egypt, an interview was conducted with Dr. Khaled Mostafa, a board member of the Egyptian Poultry Association and the General Manager of the Grand Parent Sector at Cairo Poultry Group, which is the biggest producer of Broilers in Egypt. He stated that the number of broilers produced in Egypt in 2013 was 876,135,247 broilers[8]. For a live chicken weight of 1.8 kg and excluding the carcass and by-products (bones, blood, feathers... etc), he estimated the net broilers meat production in Egypt to exceed 1 million tons. According to his data, the yearly average heating consumption of diesel fuel in a commercial well insulated broiler house in Egypt is 0.44 liters/bird [8]. This number may vary drastically from one house to another depending on the location and insulation of the house and the density of birds per house. However, from the beforehand mentioned numbers, it can be concluded that the broilers poultry sector in Egypt consumes about 350,000 tons of fuel per year for heating purposes. By questioning some of the Egyptian poultry farmers, it was found that they are suffering from the scarcity of diesel fuel and/or butane gas cylinders needed to heat their broiler houses. In many cases, they are obliged to resort to the black market to fulfill their needs.

Egypt started to experience an energy crisis over the past few years. According to the World Factbook produced by the Central Intelligence Agency of the US, Egypt consumes 816,300 barrels of refined petroleum products per day, among which it imports 164,200 barrels per day[9]. The

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<sup>1</sup> Food and Agriculture Organization of the United Nations

percentage of electricity that is produced from fossil fuels is 87.6%, while that produced from hydroelectric plants is 10.4% and the contribution of other renewable sources is only 2% [9]. Thus, there is an urge to reduce the usage of fossil fuels as the main source of energy and replace it by introducing renewable energy solutions.

Many fields of research have been explored for utilizing different states of renewable energy including, geothermal, wind, solar and biomass energy. Solar energy is considered one of the most promising sources of renewable energy. The total annual solar radiation received on earth is approximately 3,400,000 EJ, which is tremendously greater than all other discovered and undiscovered non-renewable energy resources worldwide and is thousands of multiples of the world's total annual primary energy consumption of 450 EJ [10]. Egypt is privileged to be in one of the best locations to receive huge amount of these solar radiations as shown in Figure 1. Being the most abundant source of energy, there is a great opportunity to utilize solar energy for space heating of poultry houses in Egypt. Solar energy is extensively investigated worldwide to be used in different thermal applications such as solar water heaters, driers (air heaters), cookers, ponds, architecture, air-conditioning, chimneys & power plants [10]. Space heating of poultry houses can be achieved using the developed solar air or water heating techniques.

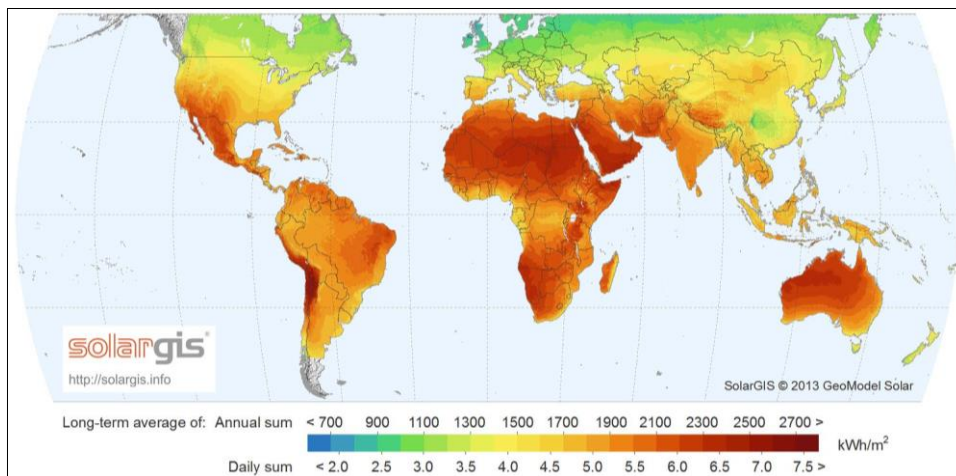


Figure 1: World Map of Global Horizontal Irradiation [11]

Source: SolarGIS © 2015 GeoModel Solar

However, it has to be noted that one of the main challenges of using solar energy is the energy storage method. Generally, for thermal energy storage, energy is stored by the change in the internal energy of a material by sensible heat, latent heat or thermo-chemical heat [12]. Sensible heat storage depends on raising the temperature of a certain material, whether solid or liquid, to utilize the heat capacity of this material. It depends on the change in temperature, specific heat of the material and

the amount of the storage material as the amount of heat stored is:  $Q = \int_{T_i}^{T_f} mC_p dT$  where,  $T_i$  and  $T_f$  are the initial and final temperatures;  $m$  is the mass of the material and  $C_p$  is its specific heat [13]. As for the latent heat storage (LHS), it depends on the heat absorption or release of a material when it changes from solid to liquid or liquid to gas or vice versa. That material used for latent energy storage is called phase change material (PCM). When the temperature rises, the chemical bonds within the PCM break up as the change of phase occurs; this can be described as an endothermic process absorbing heat. When the phase change temperature of the PCM is reached, the material starts to melt and the temperature is kept constant until the melting process is completed. The heat stored during the melting process is called the latent heat [12]. The amount of heat storage is shown by Equation 1:

$$Q = ma_m \Delta h_m + \int_{T_i}^{T_m} mC_p dT + \int_{T_m}^{T_f} mC_p dT \quad (1)$$

where  $a_m$  is the fraction melted;  $\Delta h_m$  is the heat of fusion per unit mass and  $T_m$  is the melting temperature [13]. Sensible heat storage is the widely used method in most common applications like domestic hot water, where insulated water storage tanks are used as the storage medium. Sensible heat storage will also be mainly used in this research; nevertheless LHS will be tackled as well.

A secondary source of renewable energy that can be explored for the application of heating poultry houses is biogas. Poultry houses produce a considerable amount of manure as a byproduct of the production cycle. Each bird, in addition to meat or eggs, produces a waste mainly composed of manure, litter and feathers, with a weight ranging from 4.5 to 45 kg per year depending on the sector of poultry whether it is Broilers sector producing meat, or Layers sector producing eggs or others [14]. In many countries, chicken manure is classified as waste material and generally it is a burden on the farm owners to dispose. However, when observed from a different point of view, chicken manure is a source of carbon, nitrogen and hydrogen that can be used to produce the heating gas, methane. To produce methane, the chicken manure is put into a bio-digester, which uses bacteria without oxygen to degrade the organic matter and capture methane released by the bacteria in a process called anaerobic fermentation [15]. The remaining solid waste can further be used as fertilizers for agricultural applications. The produced methane can be used back again in the poultry houses as a heating fuel.



## 1.2 Problem Statement

Given the energy problem that Egypt is facing and the commencement of its negative effect on energy intensive industries such as the poultry industry, it is crucial to find a renewable source of energy to serve as a substitute for fossil fuel based poultry heating systems. Being used as an alternative energy source for numerous industrial and domestic applications, solar energy is intended to be investigated in this research for space heating of poultry houses. One of the main challenges of this application is the storage of the harvested heat to cover the heating demand all over the day and night. Therefore, it is required to determine the amount of energy that is needed for this application and design a suitable storage system to ensure the supply of this amount.

In addition to solar energy, one of the promising sources of non-fossil fuel energy that can be incorporated in this research is biogas. Since chicken manure is a free byproduct produced in any poultry house, this research will study the application of biogas produced from chicken manure as an auxiliary heating fuel for the poultry house besides the solar heating system.

## CHAPTER 2

### LITERATURE REVIEW

In this chapter, different researches related to the topic of this research work are presented. That includes several researches that have tackled the topic of heating poultry houses with focus on the energy aspect. A study made on Broiler houses in Iran to analyze the energy inputs and outputs by collecting data from different farms is presented. Another study that investigated the heating demand for poultry houses in Syria is mentioned. Then, an interesting study about using geothermal heat pumps as a renewable source of energy for heating broiler houses is discussed. Finally, an experiment on a primitive solar-roof heater for chicken brooders in a Peruvian village is presented. Then, a review on the literature of solar heating systems shows the different techniques currently used for space heating for various applications such as solar heating for drying fruits, vegetables, tea and coffee. The integration of latent heat storage in solar heating systems is explored. Then, a series of researches done on solar heating & cooling systems is traced to observe the different ideas and advancements of this field. Other than exploring solar energy solutions for heating poultry houses, the utilization of chicken manure as a source of renewable energy is also investigated. That includes the applications of using biomass boilers, ammonia stripping and anaerobic digestion. A practical application of an anaerobic digester that is located in a Broilers farm in south-central Mississippi is presented. Finally, a simple anaerobic digester that is introduced by an international non-governmental organization (NGO) in Egypt is reviewed.

#### 2.1 Heating Poultry Houses

Heidari et al. [16] studied the energy inputs and outputs in broiler farms in Yazd province, Iran. Their main objective was to determine the energy use efficiency (EUE) per 1,000 birds. Data was collected from farmers through face-to-face interviews across 44 farms over the period between January and February 2010. The average capacity of the surveyed farms was 18,142 birds per farm, while the average meat production was 2,601 kg per 1,000 birds [17]. According to their study, the “input energy sources included human labor, machinery, diesel fuel, electricity, chicken (chick) and feed; while output energy sources were broiler and manure”.

Table 1 shows the tabulated result of their study by stating the total energy equivalent for each input and output per 1,000 birds. It also shows the constituting percentage of each item from the total input and output energy.

Table 1: Energy Equivalents of Inputs and Outputs in Broiler Production in Yazd, Iran[17]

Inputs/Outputs	Unit	Quantity per unit (1000 bird)	Total energy equivalent MJ (1000 bird) <sup>-1</sup>	Percentage
<b>A. Inputs</b>				
1. Chick	kg	51.50	531.96	0.28
2. Human labor	h	65.27	127.93	0.07
3. Machinery	kg	3.54	196.06	0.10
4. Diesel fuel	L	2314.49	11,0632.79	59.20
5. Feed	kg	5501.49	59,311.40	31.74
6. Electricity	kW h	4468.26	16,085.73	8.61
<b>B. Outputs</b>				
1. Broiler	kg	2601.82	26,876.78	97.87
2. Manure	kg	1948.11	584.43	2.13

It was found that diesel fuel was the highest energy consumption with 59.2% of the total input energy. According to the results of the study, an average of 2,314.49 liter of diesel fuel was consumed for the heating of 1,000 birds during one production cycle. The share of each input energy in percentages is shown in Figure 2.

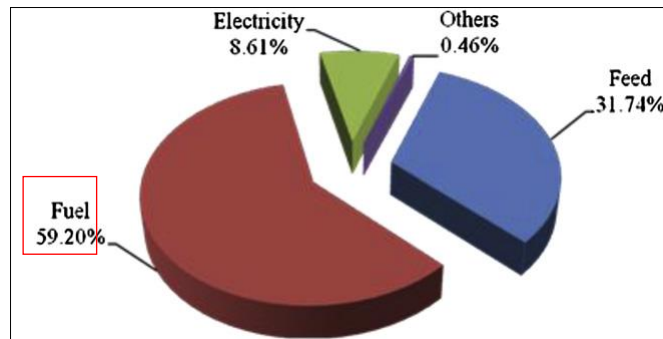


Figure 2: The Share of Energy Inputs in Broiler Production in Yazd, Iran[17]

In another research, “Sustainable heating and cooling systems for agriculture”, Kharseh and Nordell investigated the heating demand for poultry houses in Syria [3]. They mentioned that for the production of 172,000 ton of meat, 13,000 chicken farms in Syria consume 1,196 GW.hr as an estimated annual heating demand [3].

In an attempt to use renewable energy for space heating systems, Choi et al. used a geothermal heat pump (GHP) for the economic heating of a broiler house in Korea[18]. They carried out an investigation to evaluate the effect of using the GHP on the performance and housing environment of a broiler house in comparison with that of a conventional diesel fuel heated house. The comparative analysis was performed on two environmental-controlled commercial broiler

houses each of capacity 17,000 birds divided on 5 replicates. The experiment was carried out on a production cycle of 35 days long during winter time, where the outside temperature reached -10.8°C. The conventional house was equipped with 3 oil heaters (Power Heater, Samsung, Seoul, Korea) each with a capacity of 116.3 kW. The other broiler house was equipped with a GHP with a capacity of 210.9 kW (Ten Co., Seoul, Korea) in addition to 3 oil heaters with the same capacity that were used only when the GHP couldn't maintain a suitable brooding temperature for chicks at the first stage of the production cycle. The birds' weight (BW) gain was observed in both houses. The O<sub>2</sub>, CO<sub>2</sub>, and NH<sub>3</sub> gas concentrations were measured inside the two houses. Also, the electricity and fuel consumption of both houses were recorded.

The results showed that replacing the diesel fuel heating system with the GHP, enhanced the air quality inside the house as fresh air was supplied, which caused the average BW to increase by 6.8% in the GHP house more than the conventional house. The record of the gas emissions showed that the O<sub>2</sub> content was not affected by the heating system but the CO<sub>2</sub> and NH<sub>3</sub> contents significantly decreased in the GHP house relative to the conventional house as shown in Table 2 below.

Table 2: The O<sub>2</sub>, CO<sub>2</sub>, and NH<sub>3</sub> Contents Comparison [18]

Wk	O <sub>2</sub> content (%)		CO <sub>2</sub> content (ppm)		NH <sub>3</sub> content (ppm)	
	GHP System	Conventional System	GHP System	Conventional System	GHP System	Conventional System
1	20.6	20	4500	6500	1	3
2	20.7	20.4	3281	4304	4	14
3	20.6	20.8	2803	3967	10	25
4	20.5	20.6	3299	4945	11	20
5	20.4	20.6	3967	3866	15	21

The consumption of fuel was reduced from 2,813 Liter per 35d cycle per 3,400 birds in a conventional house to 160 liter in the GHP house. From the results of the fuel and electricity consumption and the total energy cost calculated for each house (shown in Table 3), it was found that the GHP house was more economical than the conventional house. According to Choi et al., "GHP house saved about 92% of the energy cost compared with the conventional house" [18].

Table 3: Energy Consumption and Costs of Heating using GHP vs. Conventional System [18]

Item	GHP system <sup>1</sup>	Conventional System
Fuel consumption (L)	160	2,813
Electricity consumption (kWh)	1,905	292
Total energy cost for heating (won) <sup>2</sup>	222,363	2,711,217

<sup>1</sup>GHP = geothermal heat pump.  
<sup>2</sup>One US dollar = 1,159.87 won (as of January 2010); diesel price = 960 won/L; and electricity price = 36.1won/kWh (as of January 2010).

In 1976, Benard et.al carried out an interesting experiment of using solar-roof to solve the problem of heating traditional chicken brooders in a Peruvian village[19]. The installation is 4.9×2.8m and divided into a patio with asbestos roof and a heated enclosure of lower height than the patio as shown in Figure 3[19]. Two semi-circular tanks with transparent glass covers containing 42kg of paraffin wax each were installed below the glass roof of the heated enclosure. Mobile mirrors were used to direct the sun rays to increase the radiation on the paraffin.

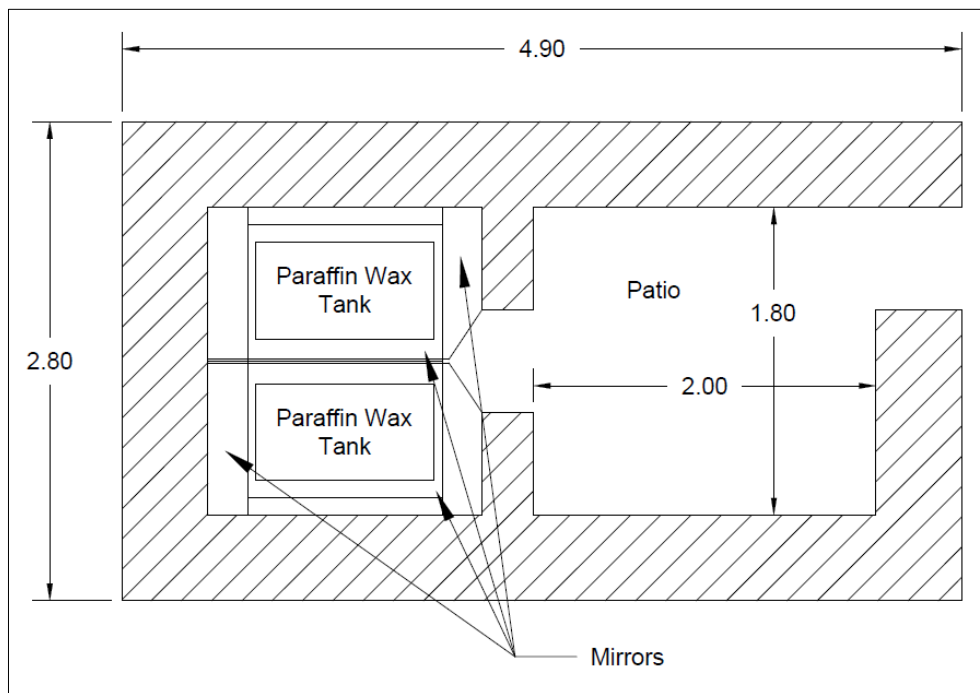


Figure 3: Benard et. al Solar Roof Experimental Setup[19]

During night, a polyurethane insulator of 10cm thickness was used to isolate the paraffin tanks from the glass roof. The paraffin wax had a melting temperature of 58-60°C. It was used to

collect and store the radiation at daytime. Then, the heat stored was exchanged during night time through radiation of the blackened tanks to the walls and floors of the enclosure. The aim of the system is to regulate the enclosure temperature between 22-30°C. The first version of the installation yielded daily mean variation of temperatures from 16-33°C. The following enhancements were carried out:

- The glass roof was changed to avoid air leakage
- The mirrors were remade to avoid direct radiation into the enclosure in order to lower the maximum enclosure temperature
- The patio was covered with the asbestos roof (it was not roofed during the 1<sup>st</sup> experiment)
- The ventilation of the installation was enhanced by adding four ventilators; two Trombe walls and two wind ventilators. This was done to bring fresh air into the installation and push hot air from above the tanks into the lower region of the enclosure (i.e.: better circulation of air).

The modifications resulted in the following:

- A higher minimum temperature of around 22°C
- A lower maximum temperature of around 30°C
- Greater stability during bad weather sequences
- Better ventilation

Then, the experiment was carried out at four different periods of the year and was repeated at two periods with the chickens housed. According to the local climate, the solar daily total irradiation ( $I$ ) varies from  $2.1 \times 10^4$  kJ/m<sup>2</sup>/day to  $2.7 \times 10^4$  kJ/m<sup>2</sup>/day. The result of the experiment at Period I show that  $T_m$  is not correlated to the outside temperature  $T_{eM}$  but to the daily variations of  $I$  with a 1-day delay. However, the variations in  $T_m$  are much smoother than that of  $I$ [19].

The storage gives back a total average of 14,500 kJ. The expected loss of heat from the upper glass surface was calculated over the 15 hours to be around 2,000 kJ. Thus, the useful heat  $Q_U$  was 12,500 kJ. The radiative night losses  $Q_R$  that take place between the storage and the enclosure was calculated assuming black body radiation and was found to be around 7,300 kJ. This proved that the natural ventilation created a non-negligible, even significant, heat transfer by convection.

## 2.2 Solar Heating Systems

Currently, there are different types of solar collectors used for the different applications such as: evacuated tubes, flat plate, single or double glazed, parabolic troughs and other types of collectors. Any thermal solar system usually consists of five interrelated constituents: solar collector, heat transfer fluid, thermal storage system, heat distribution system and control system. The heat transfer fluid, named as the working heating system fluid, can be either air, water or oil [20].

One of the interesting applications of thermal solar energy is solar heating for drying fruits, vegetables, tea and coffee. According to Palaniappan and Subramanian[21], a 25% annual reduction of fossil fuel usage could be achieved by using a solar collector area of 212 m<sup>2</sup> in an average capacity tea industry in South India. The major disadvantage of using solar air heaters as solar driers is the dependency on local weather conditions which causes case hardening, shrinkage and over burning of the dried products due to the peak temperature rise at noon[22]. Thus, thermal storage systems are incorporated in solar driers to overcome this problem. According to Esakkimuthu et al.[22], “latent heat storage is particularly attractive, because of its ability to provide high energy storage density and its ability to store energy at a constant temperature, corresponding to the phase transition temperature of the energy storage substance” but the low thermal conductivity of the PCM is a drawback. There have been different researches for enhancing the thermal conductivity of the PCM such as using nano particles, graphite embedding, fin and honey comb structure and encapsulated PCM based packed bed thermal storage unit, which was the focus of Esakkimuthu et al. research study[22]. In their study, Esakkimuthu et al. used 500 spherical balls each filled with 250g of PCM and kept in the thermal storage system to store 31,250KJ of heat. They conducted different experiments to study the charging and discharging behavior of the PCM storage unit. They constructed an experimental set up that consists of a solar air collector, a centrifugal blower to supply hot air to the storage tank, a cylindrical shaped packed bed type PCM thermal storage unit to store the excess thermal energy, and a drier as shown in Figure 4.

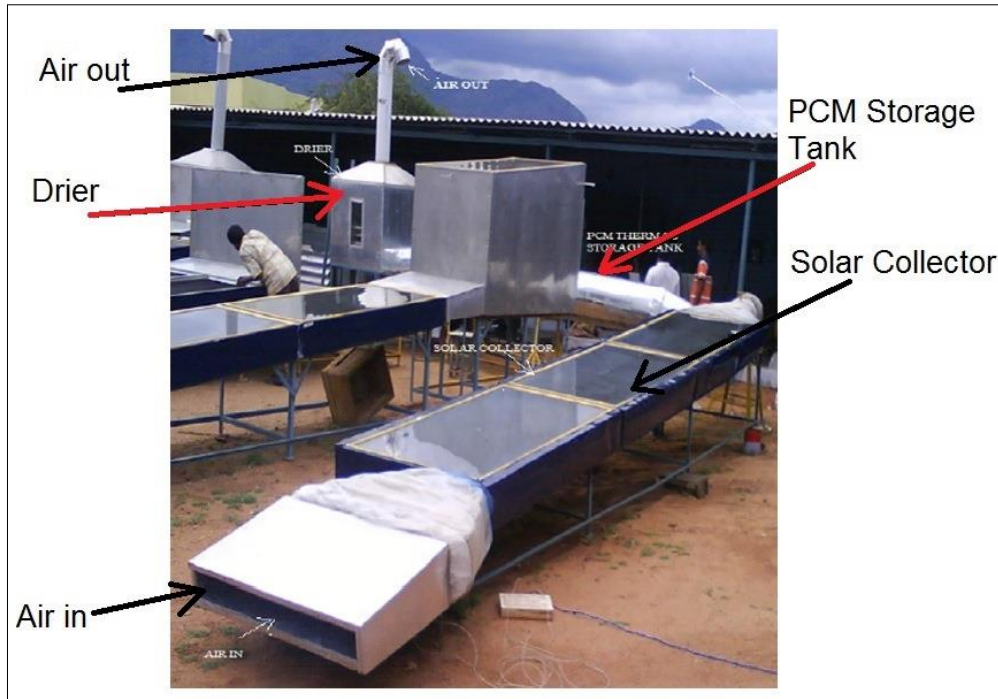


Figure 4: Esakkimuthu et al. Experimental Setup for a Solar Drier[22]

A blower of capacity  $500\text{m}^3/\text{hr}$  is used to draw hot air from the solar collector to the PCM thermal storage unit. Five auxiliary electric heaters each of capacity 1 kW are installed immediately after the blower to maintain the inlet air temperature to the PCM unit at  $70\text{ }^\circ\text{C}$  during the charging experiments. The discharging experiments were carried out by supplying ambient air at the inlet. Three different air mass flow rates: 200, 300 & 400 kg/hr, were used in both the charging and discharging experiments.

It was observed from the experimental results that the approximate heating rate of PCM during the solid sensible heating is around  $2.5\text{ }^\circ\text{C}/\text{min}$  and it was found that the phase change occurs in the PCM between the temperature range of  $58\text{--}64\text{ }^\circ\text{C}$ . The temperature of the ambient air that enters the inlet of the collector varied from  $28\text{--}33\text{ }^\circ\text{C}$ . The temperature of the air at the outlet of the collector reached  $45\text{ }^\circ\text{C}$  with a mass flow rate of 200 kg/h, and  $36\text{ }^\circ\text{C}$  with a mass flow rate of 400 kg/h. However, “at higher mass flow rates, the collector efficiency is higher due to the reduction in the heat losses associated with the decrease of the average temperature of the collector, in addition to the increase in the value of the heat transfer coefficient at a higher mass flow rate”.

The cumulative energy contribution made by the electric heaters to reach the  $70\text{ }^\circ\text{C}$  at the inlet of the PCM storage during the charging experiments was found to be 40%, while that of the solar collector was 60%. During the discharging process at a mass flow rate of 200 kg/h, a near uniform instantaneous heat transfer is achieved for a longer duration due to the higher thermal resistance inside the PCM balls due to the lower thermal conductivity of the PCM. It was concluded that “the



lower mass flow rate of 200 kg/h is able to provide uniform charging and discharging, and also utilizes the maximum capacity of the storage system”[22].

For the PCM to be used in LHS systems, there are certain thermal, physical, kinetic, chemical and economical properties that are required. These properties include: suitable phase transition temperature, according to the application, high latent heat of transition, high specific heat, good thermal conductivity, small volume changes, high nucleation rate to avoid super cooling, high rate of crystal growth, chemical stability, no degradation after a large number of freeze / melt cycles, compatibility with the material of construction, non-toxic, non-flammable, non-explosive materials, cost effective and abundant material[12]. The PCM materials can be classified into: organic PCM such as Paraffins, in-organic PCM such as salt hydrates and eutectic PCM which is a composition of two or more components[13]. Choosing the suitable PCM is very important to build an advantageous LHS, however, there are two other important factors, which are: having a suitable heat exchange surface and a suitable container compatible with the PCM. A LHS system has two main advantages over the other systems. First, it facilitates the storage of large amounts of heat with only small temperature changes and therefore to have a high storage density. Second, it smooths the temperature variations as the change of phase at a constant temperature takes some time to be accomplished[12].

At the Institute of Thermal Engineering within the framework of the European Project PAMELA (2004), the IEA SHC TASK 32 has developed a simulation model called Type 840 within the simulation environment of TRNSYS[23]. The model facilitates the simulation of water tanks with integrated PCM modules of different geometries such as cylinders, spheres and plates. Salt hydrate with embedded graphite is used as the phase change material. Schranzhofer et al. presented the simulation model and its validation using experimental data obtained from different experiments[16]. The comparison between the simulation results and the experimental result showed very good correlation. The developers of the model were contacted in person to acquire their model to be used as part of this research.

Another series of interesting researches on solar heating & cooling systems were done by a group of researchers from the University of Naples in Italy. They simulated different solar energy systems producing hot water for cooling by absorption chillers and/or heating by heat exchangers for residential or office buildings. In 2008, Calise et al. [24] developed a dynamic model of a prototype of solar assisted absorption refrigeration system simulated using TRNSYS. The simulated system consisted of: evacuated solar collectors, circulation pumps, variable speed pump, water storage tanks, auxiliary heater, single-stage H<sub>2</sub>O-LiBr absorption chiller, cooling tower, feedback controller, on/off hysteresis controller, single lumped capacitance building and controllers.

A sensitivity analysis was performed to determine the set of design and operational parameters that maximize the performance of the system. The following parameters were varied each at a time: area of the solar collectors ( $A_{sc}$ ), volume of the storage tank, set-point temperatures and mass flow rate [24].

In 2010, Calise et al. published their paper "Maximization of primary energy savings of solar heating and cooling systems by transient simulations and computer design of experiments" [25]. In this research, they analyzed 3 different configurations of the solar assisted absorption refrigeration system. The first configuration included an electric water-cooled chiller that is activated in case of insufficient solar radiation. The second configuration is the same as the first but covering about 30% of the building cooling load. The third configuration is similar to the first but using a gas fired heater instead of the electric water-cooled chiller. They developed a case study for an office building located in South Italy using the 3 configurations. The monthly operating costs and energy savings were calculated for the three configurations. The simulation results showed that the first configuration achieved the best energetic performance. It also showed that suitable flow rates of the solar collectors pump and volumes of the system storage tank are mandatory to achieve the best energy efficiency and satisfactory economic performance [25].

As an extension to this work, Calise F. presented a dynamic simulation and economic assessment for a solar heating and cooling system (SHC) in 2012. However, he used Parabolic Trough Collectors instead of the evacuated tubes to be coupled with a double-stage LiBr-H<sub>2</sub>O absorption chiller. He used a biomass-fired heater to supply the auxiliary energy for both heating and cooling. The model simulated a one year long space heating and cooling and domestic hot water supply for a small university hall in seven Mediterranean cities in Italy, Spain, Egypt, France, Greece and Turkey. The results of the study showed that concentrating solar heating and cooling systems, like the one simulated, are generally profitable, especially in hot climates like Cairo. However, the full development of this technology - high temperature heating and cooling - is limited by the scarce commercial availability of concentrating solar collectors, like the parabolic trough collectors [26].

Reverting to the previously researched solar heating and cooling system with evacuated tubes, Buonomano et al. investigated different control strategies for the thermal storage management in SHC [27]. In this research, the simulated system included a variable volume storage system of three separate tanks and a number of mixers and diverters managed by novel control strategies based on combinations of series/parallel charging and discharging approaches to facilitate the variation of the thermal storage capacity as a function of the combinations of solar radiation availability and user energy demands. This configuration was also compared with a constant-volume storage system from

the energy and economic points of view. For the case study of an office building in Naples, it was found that the multi tank system did not show any significant improvement in the economic or energetic efficiency of the SHC system. Among the important observations of this study, it was mentioned that the higher surfaces of the tanks in case of multi tanks system caused more thermal losses during the cold months of the winter [27].

### 2.3 Utilizing Chicken Manure for Heating Poultry Houses

Aside from solar energy solutions, two of the largest broiler producers in Great Britain have invested in a different renewable energy solution for heating their poultry houses, which is using biomass boilers [28]. They installed biomass boilers that are capable of burning chicken litter to produce hot water using fluidized bed combustion chamber. The hot water is then circulated to the poultry houses for heating at a temperature of 82 °C. According to a published article, the first farmer achieved a “50% cost saving compared with using gas, and has calculated a seven-year payback on the £1.8m investment” [28]. While the second farmer produces 300kWh of thermal energy to eliminate any requirement for gas for heating, which saved him £65,000 a year.

Chicken manure (CM) produced from poultry farms contains 25% or more of dry matter rich in nitrogen. The higher nitrogen content of poultry waste compared to manure from other farm animals makes CM a difficult substrate for anaerobic digestion[29]. The excess of ammonia can inhibit the anaerobic microbial groupings necessary for the production of methane[30]. There have been several attempts to avoid the accumulation of ammonia during methane fermentation. CM diluted with water could be treated anaerobically either in a semi-solid form containing 10–11.5% total solid (TS), or in a wet form containing 0.5–3% TS. Co-digestion of CM with other types of livestock manure such as cattle manure, hog wastes and anaerobically digested sludge improves biogas production. Both of these methods result in larger volumes of waste, which, increase the cost of storage and transportation[31].

A new approach for utilizing CM that has high total solid content is ammonia stripping. Previous studies used ammonia stripping only for the removal of the ammonia produced, as a separate step. Further improvements were necessary to reduce the cost and the time consumed by the multi-step process of ammonia stripping during dry fermentation of CM. This could be achieved only through ammonia removal during the production of ammonia and methane. In this process, “a sludge obtained after thermophilic anaerobic digestion of excess activated sludge was used as a seed sludge to initiate anaerobic digestion of CM”[31]. However, ammonia stripping approach is still under research and not widely applied yet.

On the other hand, anaerobic digestion of chicken manure is practically in application in different places around the world. An anaerobic digester is located in south-central Mississippi and is considered to be the first on-farm unit of its kind in North America. US Patent No: 7,785,467 [32]. Chicken litter is moved from the chicken house to dry-stack-litter storage. Solar panels, or fuel-wood cut from the farm, heat up to 2,500 gallons of fresh water per day from the farm's reservoir or well. Chicken litter is mixed with the 140°F (60°C) water and moved into the anaerobic digester (AD), where it is mixed with the precise strain of bacteria needed to output methane and a highly concentrated liquefied fertilizer. The bacteria are concerned only with carbon, but taking the hydrogen sulfide out of the gas eliminates the odor in the fertilizer. The methane passes through scrubbers and is compressed into the gas storage tank or directly fuels generators, where it can be used for on-farm heat and electricity. Excess power may be transferred to the electric grid for commercial sale. The entire system is computer-controlled with remote monitoring and manual overrides [33]. The AD is capable of covering all the heat demand of the chicken houses. Figure 5 below summarizes the process that is followed in Brinson's farm.

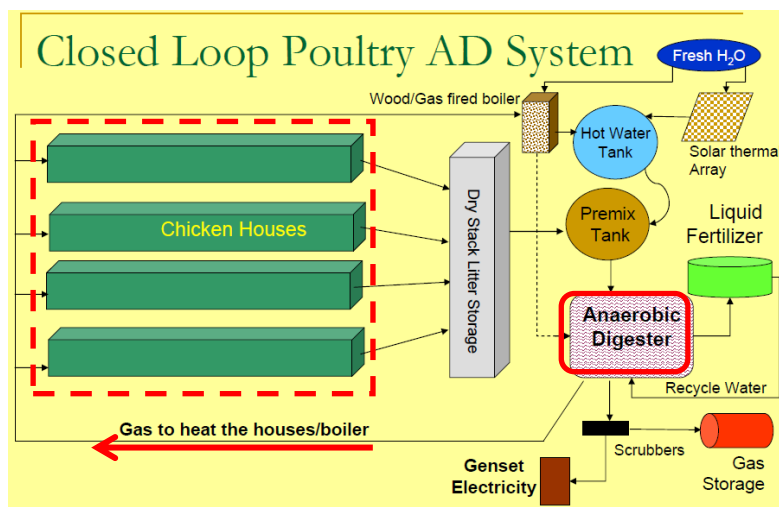


Figure 5: Closed Loop Poultry Anaerobic Digester System[33]

A nonprofit organization focused on Sustainable Energy and Solid Waste Management, an NGO called SKG Sangha, introduced a simple anaerobic digester to utilize litter, animal manure, or wastes in general for the production of biogas in some villages in Upper Egypt [34]. They introduced a biodigester model called Deenbandhu, shown in Figure 6[35]. The manure or dung is mixed with water at a ratio of 1:1 to create slurry that is fed into the biodigester. At the first operation, biogas, a combination of methane and carbon dioxide, will be generated after about 10 days inside the dome. The variation of slurry heights between the slurry in the dome and that in the displacement tank will create pressure that drives the gas outside of the digester to be consumed.

When the gas is consumed, the pressure drops inside the dome and the slurry in the displacement tank will flow back to the digester. Also, new slurry is fed into the dome during operation. Thus, new gas will be produced and the production continues. Excess slurry will be discharged through the exit hole at the displacement tank [35].

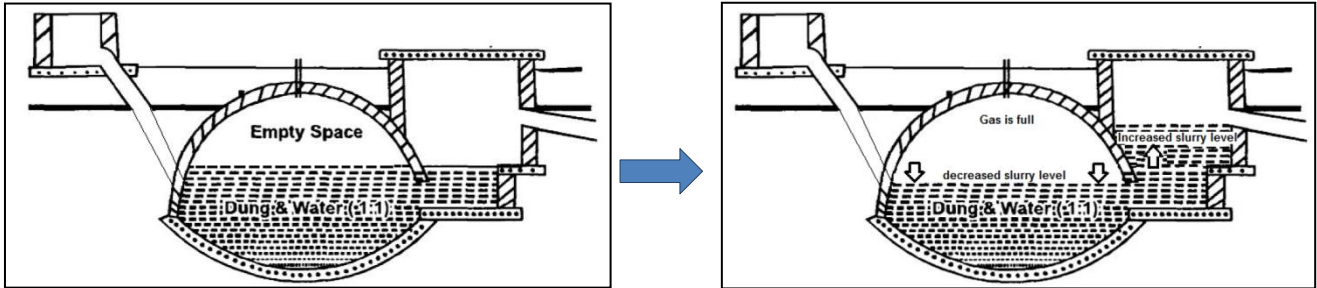


Figure 6: Deenbandhu Biodigester Model[35]

The model is designed to store 1/3 of its daily gas production capacity, where it is available in different capacities starting from 2m<sup>3</sup> till 6 m<sup>3</sup> units[35][34]. According to SKG Sangha foundation in Egypt, the 6 m<sup>3</sup> bio-digester unit produces daily 6 m<sup>3</sup> of biogas, which is equivalent to the consumption of 6 LPG cylinders per month.

## 2.4 Research Objective

Many researches have been done for renewable energy heating solutions including solar systems. However, very few have tackled the needs of poultry houses in terms of heating energy. This study has taken an initiative to fill this gap and to take the responsibility to investigate the application of a solar heating system for a poultry house. The investigation includes a technical and economic study for a solar heating system and the integration of biogas from chicken manure as an auxiliary source of heat.

## 2.5 Methodology

To pursue the stated objective, first it is necessary to identify the amount of heat needed to fulfil the requirements of heating a poultry house. Therefore, an exemplary poultry Broiler house is chosen as a model to calculate the heat demand. The calculation is done using TRNSYS simulation. Then, a solar heating system design is developed using a solar collector, thermal storage system & a heat distribution system to fulfil the calculated heat demand. An economic study is made to select the best design variables of the system based on the highest calculated net present value (NPV). Further economic studies are made to evaluate the performance of the solar system by varying different parameters. Then, the byproduct chicken manure of the modeled poultry house is considered to generate biogas using biodigestors. The produced biogas is used as heating fuel to cover the auxiliary amount of energy needed for the designed solar heating system.

To summarize, the following procedures are performed to accomplish the objective of this research:

- Modeling an exemplary poultry house
- Calculating the heat demand of the poultry house throughout the year
- Designing a solar heating system to fulfill the calculated heat demand
- Economically studying the designed SHS
- Evaluating the performance of the system under different parameters
- Integrating Biogas solution to the design

## CHAPTER 3

### CALCULATING THE HEAT DEMAND FOR A BROILER HOUSE

This section of the thesis describes the procedures followed to calculate the heat demand of a broiler poultry house. An exemplary broiler house is selected as a case study to be modeled. The house is located at Al Menia governorate in Egypt. It is considered an advanced closed system poultry house that is well insulated, mechanically ventilated and carries a capacity of 24,000 birds.

#### 3.1 Production Cycle Requirements

Before simulating the broiler house and calculating the heat demand, the production cycle of broilers and its requirements has to be well understood. In a broiler house, the production cycle starts with the housing of one day old chicks. The cycle lasts for 36-42 days when the chickens' weight reach the targeted weight for selling or slaughtering. After the 42 days, the house is evacuated from all birds to be cleaned out and then disinfected. Also, the equipment is being inspected in case any maintenance is needed. Then, the house is prepared to receive the new flock of birds and start the second production cycle. The number of production cycles per year depends on the length of the cleaning and maintenance period. Usually, it ranges between 6-7 cycles per year. In the simulated model, the cleaning and maintenance period is set to be 14 days. This information is obtained from the farm manager of the modeled house in Al Menia.

The flock performance is measured by the growth rate, feed conversion ratio (FCR), livability and meat yield[36]. These are considered the main key performance indices (KPIs) for the broiler industry. To achieve the best efficiency of converting feed into meat, birds have to live in consistent optimum environmental conditions, with temperature being the most critical factor [1]. Thus, to achieve the required KPIs these environmental conditions have to be maintained within the broiler house. These conditions change daily depending on the age and weight of the birds and may slightly vary from one breed of chicken to another. In this research, the management guide for the "Arbor Acres" breed, which is one of the widely used breeds in the commercial broiler houses in Egypt, is used as a reference for the chicken requirements at every age.

### 3.2 Methodology

A one year simulation is carried out using TRNSYS software to model the hourly performance of the poultry house throughout the year. In order to model the thermal behavior of the poultry house, TRNSYS MULTIZONE BUILDING MODELING (Type56) is utilized [37]. The “energy rate” method is used to calculate the temperature inside the poultry house ( $T_{\text{House}}$ ) every hour. The hourly weather data represented by the ambient temperature ( $T_{\text{ambient}}$ ) of the selected location – Al Menia – is fed into the simulation using a TRNSYS component. Heat gains and inputs to the broiler house is calculated and transmitted to the TRNSYS building component either using an excel sheet with Visual Basic Application (VBA) add-in or directly through the building component interface. The heat gains calculated using the excel sheet are the convective and radiant heat produced by the birds and this will be explained in section 3.5.1 *Birds Heat Production*. The other inputs calculated hourly, using the excel sheet, are the set temperature ( $T_{\text{Set}}$ ) required to be maintained inside the house and the ventilation rate applied for the chicken. The heat gains, the ventilation rate and  $T_{\text{Set}}$  are determined based on the age of the birds,  $T_{\text{ambient}}$  and  $T_{\text{House}}$ . Other heat gains introduced to the building are the heat generated from the lighting and the movement of the workers inside the house. The geometry of the building is defined using a Google SketchUp<sup>2</sup> drawing as described in section 3.3.1. The specifications of the building in terms of the materials used and infiltration rate are defined within the building component interface. A flow chart explaining the simulation structure is presented in Figure 7. To determine the heat demand ( $Q_{\text{Heat}}$ ), the calculated  $T_{\text{House}}$  is compared to the  $T_{\text{Set}}$  every hour. If  $T_{\text{House}}$  is found to be lower than the required  $T_{\text{Set}}$ , then  $Q_{\text{Heat}}$  is calculated and supplied to reach the targeted temperature. If  $T_{\text{House}}$  is found to be higher than the required  $T_{\text{Set}}$ , then cooling should be applied but this is out of the scope of this research. The desired outputs of the simulation, including  $T_{\text{House}}$  and  $Q_{\text{Heat}}$ , are plotted and wrote into an external output excel file.

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<sup>2</sup> Google Sketchup Version 8: <http://www.sketchup.com/>



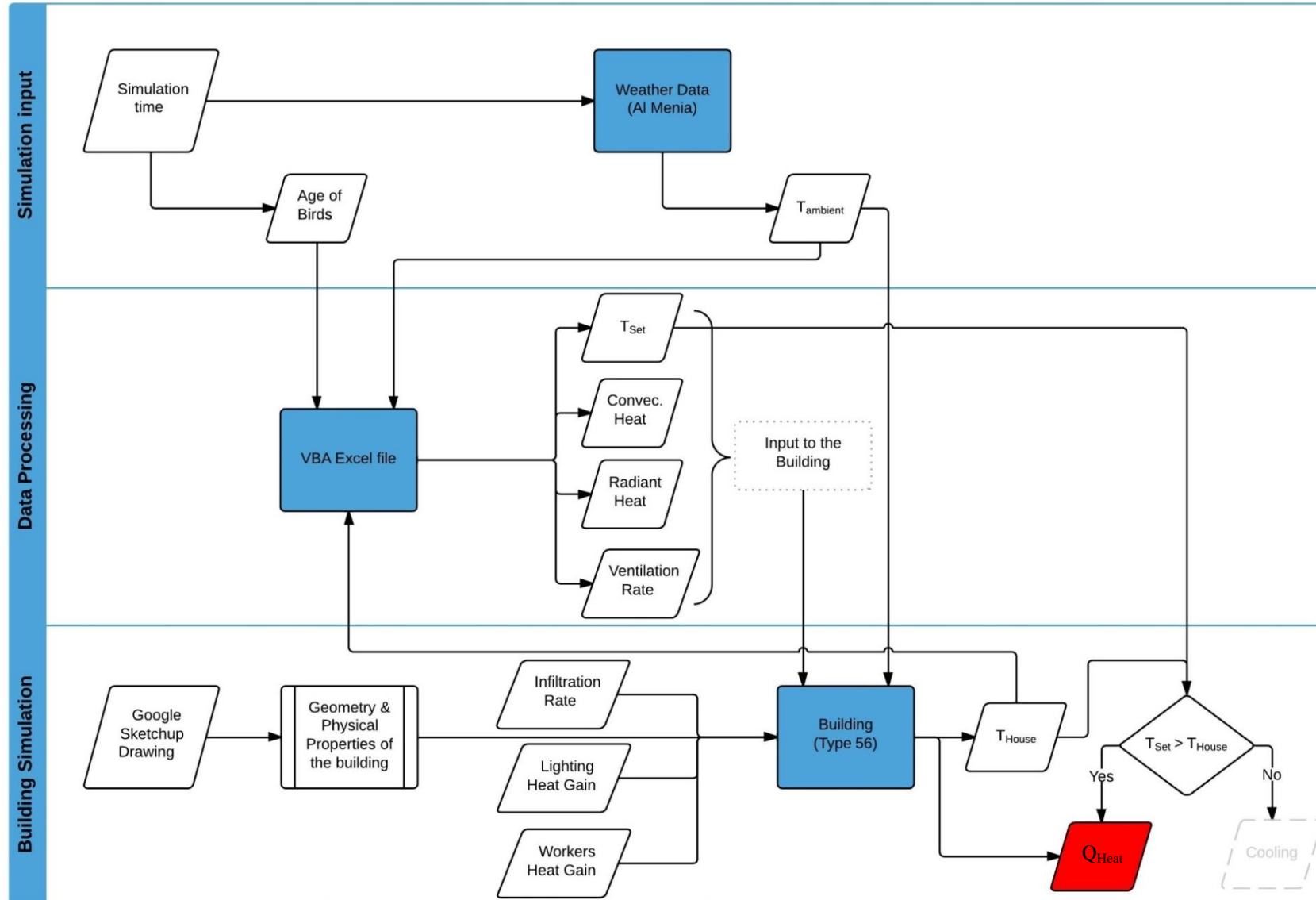


Figure 7: Simulation Flow Chart for Heat Demand Calculation

### 3.3 Modeling the house

To set up a multizone building project in TRNSYS, the three dimensional building geometry was imported from a Google Sketchup drawing using the TRNSYS3d plug-in for Google SketchUp program [38]. The TRNSYS3d file is imported to the building component in TRNSYS program (TYPE56). The orientation of the building is manually defined in TRNSYS. Then, the materials of all geometrically described surfaces are defined.

#### 3.3.1 Geometric Model

The Google SketchUp drawing included the dimensions of the house, its location on Google map and the geometric definition of the different thermal zones within the house. Also, the location and dimensions of the windows (openings) of the house are defined in this drawing. An image of the model is exported from Google SketchUp and shown in Figure 8.

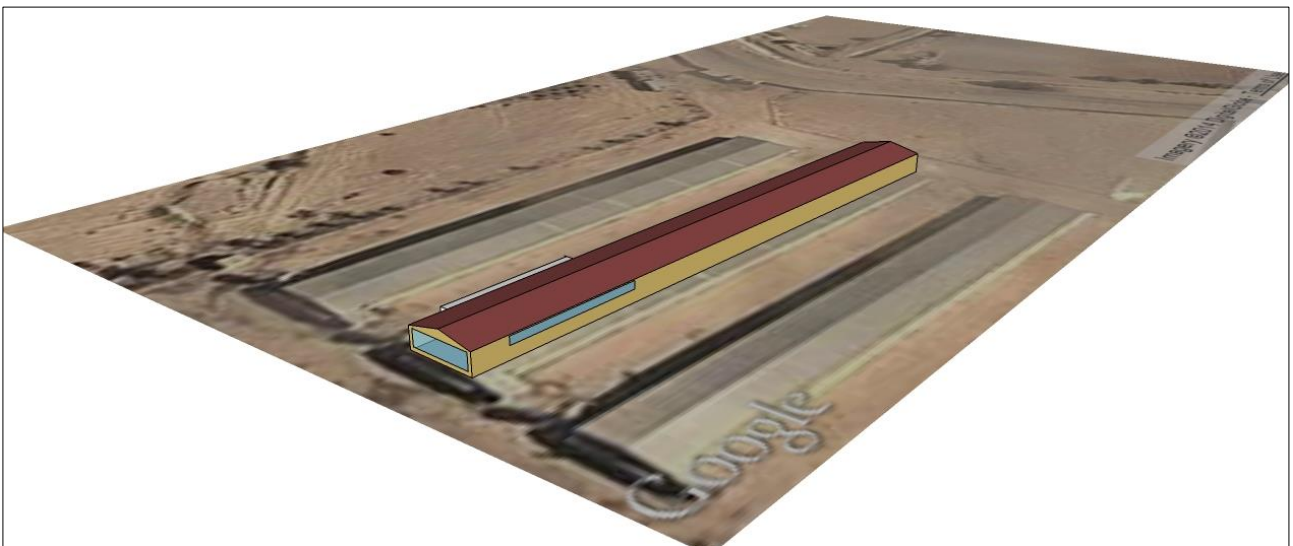


Figure 8: House Model using Google SketchUp

The modeled building is divided into two different thermal zones:

- Zone 1: Starting from the ceiling up till the roof
- Zone 2: Below the ceiling, which is the utilized volume of the poultry house

The ceiling is the common surface connecting the two zones and it contains a thermally insulating material. The house is divided into two zones to be able to distinguish between the average temperature of the air above the insulation layer and that below it, which is the average temperature of the air of the utilized volume. This division facilitated the calculation of a more accurate average

temperature for the air affecting the chicken. The terminology used to describe the geometry of the house is labeled in Figure 9. The width of the house is 14 m, its length is 108 m and its eave height is 3 m. The roof is sloped by an angle of  $12^\circ$ . Thus, the total area utilized by the chicken is  $1,512 \text{ m}^2$  and the volume is  $5,564 \text{ m}^3$ .

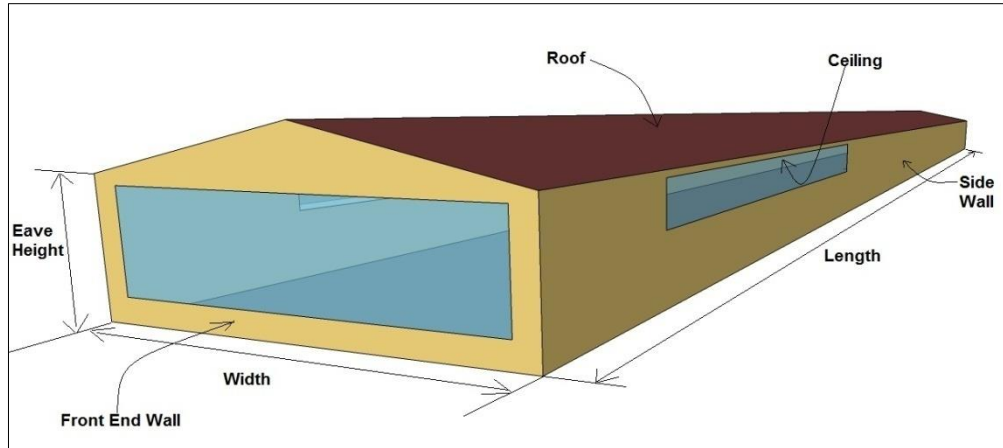


Figure 9: Modeled House Geometry

The front end wall has an opening of 13m wide by 2m height. The right and left side walls have an opening of 24m length and 1m height. These openings are used to install a cooling system that will not be modeled as it is out of the scope of this research. The openings are closed from inside of the house using an air inlet controlled device that will be referred to as “window” hereinafter.

### 3.3.2 Building Specifications

The walls are made of limestone bricks of thickness 20 cm covered by a layer of lime mortar from the outside and a layer of cement mortar from the inside. All the inside walls are painted with a layer of gypsum plastic. The ceiling consists of corrugated pre-painted galvanized sheets carrying a 10 cm thickness fiberglass insulation. Then an air gap of about 40 cm isolates between the fiberglass & a roof made of corrugated pre-painted galvanized sheets. Since it is a special type of window that is related to the poultry application, it is not available within the library of TRNSYS. According to the commercial supplier’s technical data sheet, the U-value for the 4 cm thick polyurethane panels that are used for the windows of the house is  $0.5 \text{ W/m}^2 \text{ K}$ [39]. Therefore, an approximation is done by choosing a window with the nearest heat transfer coefficient (U-value). Accordingly, as a substitute, a window type of  $0.59 \text{ W/m}^2 \text{ K}$  is selected from the TRNSYS library.

### 3.3.3 Infiltration

According to the ASHRAE handbook, “infiltration is determined by the extent and distribution of leaks over the building envelope and the pressure differences across these leaks” [40]. To determine its value, the air exchange rate must be measured over a range of weather and equipment operation [40]. Being a well-insulated building and a closed system poultry house, it is expected to have low infiltration rates for the modeled house. However, it is found that the fans (air extractors) used in the poultry industry are a major source of air leakage. The modeled house is equipped with 13 fans each of dimension 140×140 cm. The fans have shutters that open when the fan is running and close by gravity when it is idle. An example of the installed fans in the modeled house is shown in Figure 10.



Figure 10: Example of Fans used in Poultry Houses [41]

Recent tests have shown that even in high quality and new fans, these shutters do not close tightly, which allows for air leakage that costs several hundreds of dollars in heat losses per house [1]. To evaluate the amount of air leakage, agricultural engineers from Auburn University in Alabama have tested different types of high-quality fans in a laboratory under different negative static pressures [42]. The results of their test are summarized in Table 4 below. The results of the tested fans show that the amount of air leakage per fan is significant. For the modeled house, the air leakage amount is estimated to be equivalent to that of the Aluminum shutters at 0.1 inch static pressure. The total air leakage is calculated to be 6714 m<sup>3</sup>/hr which is equivalent to 1.19 air changes per hour.

Table 4: Fan Shutter Air Infiltration Test Results [42]

48-inch Shutter Type	Static Pressure (inches)	Measured Air Leakage per shutter (cfm)
Aluminum	0.08	270
	0.10	304
PVC	0.08	301
	0.10	351

### 3.4 Birds Requirements

As mentioned beforehand, there are certain indoor environmental conditions that have to be maintained in a broiler house. These conditions are changing daily throughout the production cycle depending on the requirements of the chicken. These requirements may slightly vary from one breed to another. In this research, the management guide for the “Arbor Acres” breed, which is one of the widely used breeds in the commercial broiler houses in Egypt, is used as a reference for the chicken requirements at every age. In order to run the simulation, the targeted environmental conditions at every hour are defined.

#### 3.4.1 Set Temperature

For the Arbor Acres breed, the recommended optimum target temperature at every age is tabulated in their management guide and is shown below in Table 5. The target temperatures are given for the age from 1 day old till 27 days old with an interval of 3 days. However, the target temperature should be set to decrease gradually during these 3 days. The required input to the TRNSYS simulation is the hourly set temperature of the house. Therefore, the targeted temperature was interpolated from the values recommended by the broilers management guide to have the daily set temperature as shown in Appendix 1. From 27 days old till the end of the cycle, 42 days old, the temperature is required to be kept at 20°C[36].

Table 5: Arbor Acres Recommended Target Temperatures [36]

Age (Days)	Target Temperature
Day Old	30°C
3	28°C
6	27°C
9	26°C
12	25°C
15	24°C
18	23°C
21	22°C
24	21°C
27	20°C

### 3.4.2 Minimum Ventilation Rate

The minimum ventilation rate is “the quantity of air required per hour to supply sufficient oxygen to the birds and maintain air quality”[36]. The main sources that pollute the air quality in broiler houses are the feed, litter and the chicken themselves [43]. The chicken produces carbon dioxide and ammonia by respiration and manure excretion, respectively. Therefore, the minimum ventilation is required to extract the unwanted pollutants from the house or reduce their concentration and introduce fresh air for the birds at the early age and during cold weather. At older age or during hot weather, more ventilation is used to maintain lower temperatures inside the house. Consequently, lower pollutant concentrations will be maintained. The minimum ventilation rate needed in a broiler house to maintain acceptable concentrations of ammonia and inhalable dust is 360-400 m<sup>3</sup>/hr per 500 kg live weight broilers [43]. A more specific and weight dependent minimum ventilation rates are recommended by the Arbor Acres management guide as shown in Appendix 2. To calculate the corresponding minimum ventilation rate per bird at every age, the daily weight of the birds is determined from Arbor Acres Broiler Performance Objectives manual [44]. Then, to calculate the total number of birds in house, the mortality rate is considered throughout the production cycle. Generally, one of the lowest rates of mortality for broilers can be 2.5% [45]. However, this figure may vary from one farm to another. Seeking accuracy, the mortality rate records of the modeled poultry house of Al Menia is obtained from the farm manager. The mortality rate for this house reached 3.7% [46]. So, at the beginning of the cycle, the number of birds start with 24000 birds and the cycle ends with 23112 birds. The results of the calculations of the total daily required minimum ventilation are tabulated in Appendix 3.

### 3.5 Heat Gains

In order to calculate the heat demand of a broiler house, it is crucial to define the internal heat gains within the volume of the house. The main effective heat gain is that produced by the birds inside the house. The other calculated heat gains are that produced from the internal lighting and from the workers entering the house. The heat produced from electric appliances inside the house is neglected as the only appliances found are small motors for the feeding system. All the heat gains are calculated inside “Zone 2”, which is the house zone. The roof and ceiling zone, “Zone 1”, has no internal heat gains. The internal heat gains are defined in the building component using the gains input window shown in Figure 11. The heat gain produced by the birds are calculated hourly using the VBA excel sheet and fed into the building component as an input called “BIRDSGAIN”.

Type	Scale	Geo Position
BIRDSGAIN	1	0

Figure 11: Heat Gains Input Window

### 3.5.1 Birds Heat Production

According to the Broilers management guide, the normal body temperature of a broiler chicken is 41°C and it regulates its body temperature by two methods; sensible and insensible heat loss [36]. When the ambient temperature is between 13–25°C, sensible heat loss occurs as physical radiation and convection to the cooler environment. When the ambient temperature rises above 30°C, insensible heat loss occurs through evaporative cooling and panting and increased respiration rate” [36]. Also, part of the heat loss that is considered from broilers chicken is released by the litter. Therefore, the heat produced from broilers can be classified as heat and moisture, or sensible heat and latent heat. The ASHRAE handbook refers to the data of a research done in 1982 to show the heat produced by broilers and it states that the data is outdated due to the continued improvement in genetics, nutrition and housing of poultry [40]. It also, refers to the research done by Gates et. al. in 1996 as a more recent research. In their literature review about heat and moisture production of poultry, Chepete and Xin [47] carried out a comparative analysis of different researches from 1968 till 2000. For year 1968, the total heat produced (THP) is calculated as shown in equation 2 below [47]:

$$THP \left( \frac{W}{kg} \right) = 8.31 M^{-0.29} \quad (2)$$

where, M is the body mass of the bird. From 1982 till 2000, the total heat produced (THP) is modified to be as show in equation 3 below [47]:

$$THP \left( \frac{W}{kg} \right) = 10.60 M^{-0.26} \quad (3)$$

In 1996, Gates et al. presented more recent empirically derived mathematical relationships which described broiler heat production as a function of age with adjustments for partitioning of sensible and latent heat production (SHP & LHP) at different brooding temperatures [6]. Different equations are derived for different brooding temperatures. To be able to select the suitable equations, the temperature corresponding to every age is matched to the set temperature calculated in section 3.4.1. Given  $x$  is the bird age in days and  $K=0.64631$  for W/kg units, the equations used are as follows:

For all brooding temperatures [6], equations from 4 to 8 are used:

$$SHP = K \exp(-6.5194 + 2.9186x - 0.24162x^2) \quad 3 \leq x \leq 5 \quad (4)$$

$$SHP = K \exp(1.8662 + 0.054213x - 0.00161x^2) \quad 6 \leq x \leq 19 \quad (5)$$

$$LHP = K(-42.961 + 27.415x - 2.84344x^2) \quad 2 \leq x \leq 5 \quad (6)$$



$$LHP = K(36.424 - 2.8998x + 0.08676x^2) \quad 6 \leq x \leq 15 \quad (7)$$

$$LHP = K(15.812 - 0.22611x) \quad 16 \leq x \leq 19 \quad (8)$$

For temperature  $t = 21.1^\circ\text{C}$ [6], equations 9 and 10 are used:

$$SHP = K(36.070 - 2.3107x + 0.058862x^2 - 0.00051x^3) \quad 20 \leq x \leq 39 \quad (9)$$

$$LHP = K(11.221 + 0.40495x - 0.02727x^2 - 0.000353x^3) \quad 20 \leq x \leq 43 \quad (10)$$

Considering the different set temperature at every age and the number of birds, the value of sensible heat produced (SHP) and latent heat produced (LHP) by the birds at each day is calculated using the set of equations developed by Gates et al and summed up to give the total heat produced (THP). The results of these calculations are tabulated in Table 25 and plotted in Figure 23 as shown in Appendix 4.

### 3.5.2 Lighting

The modeled house is equipped with four longitudinal lines of lighting. Each line is of 108m length and has a 60 W incandescent lamp placed every 4 meters. Therefore, the total number of lamps is 108 lamps, which is equivalent to 6480 W. The related floor area is equivalent to 1512 m<sup>2</sup>. Thus, it is approximated to have an artificial lighting of total heat gain of 5 W/ m<sup>2</sup>. According to the broilers management guide, the lighting program for the first 7 days of the cycle is 23 hours of light and one hour of dark. Afterwards, the “EU Broiler Welfare Directive requires a total of 6 hours darkness, with at least 1 uninterrupted period of darkness of at least 4 hour” [36]. However, by surveying a group of farm managers in Egypt, it is found that most of them apply a 24 hour light program to stimulate the birds to eat more. Thus, artificial lighting is set to be on continuously.

### 3.5.3 Workers Heat Production

For the modeled broiler poultry house, daily inspection is done by workers throughout the broiler cycle. The inspection is done by walking around the house to collect any dead birds and check on the feeding and drinking systems. Using schedule type manager, the inspection schedule is defined such that starting 6 a.m. every 6 hours one worker will enter the house to do the routine inspection work. The rate of heat gain from the occupants inside the house depends on the level of activity done. It is assumed that the inspection work in a poultry house is equivalent to walking at a speed of 1.3m/s or doing light machine work activity as defined by the ASHRAE standards. At this level of activity, the sensible heat is equal to 100 W and the latent heat is equal to 205 W.



time-step so that the final  $T_{\text{House}}$  just reaches  $T_{\text{set}}$ . Similarly, simplified cooling is imposed to avoid  $T_{\text{House}}$  higher than  $T_{\text{set}}$ .

By this technique,  $Q_{\text{Heat}}$  is calculated in kJ/hr at every time-step of the simulation (i.e. every hour). The output results of the simulation is exported to an excel file showing the hourly  $Q_{\text{Heat}}$ ,  $T_{\text{ambient}}$ ,  $T_{\text{House}}$  at “Zone 2” and  $T_{\text{Roof\&Ceiling}}$  at “Zone 1”. The output results are plotted using Excel to be observed. The first plot is for the  $T_{\text{ambient}}$ ,  $T_{\text{House}}$  at “Zone 2” and  $T_{\text{Roof\&Ceiling}}$  at “Zone 1” during the one year simulation as shown in Figure 13.

Since a simplified heating is used by TRNSYS to generate the required heat, the  $T_{\text{House}}$  is ideally representing the  $T_{\text{set}}$ . At the beginning of each production cycle,  $T_{\text{House}}$  reaches the required set temperature equal to 33 °C then it gradually decreases to reach the 20 °C at the end of the cycle. The plot showed that  $T_{\text{Roof\&Ceiling}}$ , which is the temperature at “Zone 1” between the roof and the ceiling, is following the trend of the ambient temperature. This confirms the significance of having two separate zones during the simulation. The ceiling in “Zone 1” insulates between the air inside the house and the atmosphere.

A closer look at the temperature results is shown in Figure 14. The first cycle is plotted separately to be focused upon. The peak difference in temperature between  $T_{\text{House}}$  and  $T_{\text{ambient}}$  is at the first day of the cycle. The small fluctuations in  $T_{\text{House}}$  are within the heating region, where the heating temperature  $T_{\text{Heat}}$  is equal to  $T_{\text{set}} - 0.5$  °C.

The supplied heat demand ( $Q_{\text{Heat}}$ ) by the simulated heating equipment is plotted in Figure 15. This represents the amount of heat needed for  $T_{\text{House}}$  to reach  $T_{\text{set}} - 0.5$  °C. The plot shows that the first cycle in the year starting on the 1<sup>st</sup> of January requires the highest demand. Cycle 4 and 5 are the summer cycles operated from June to August, thus they require the least heat demand. Only at the beginning of the cycle it is always needed to supply heat in order to maintain the 33 °C set temperature. The maximum  $Q_{\text{Heat}}$  is observed on the 1st day of the cycle, 1st of January, and is equal to 581000 kJ/hr. This amount is needed to raise the house temperature to the required 33 °C. This peak value is equivalent to about 161 kW.

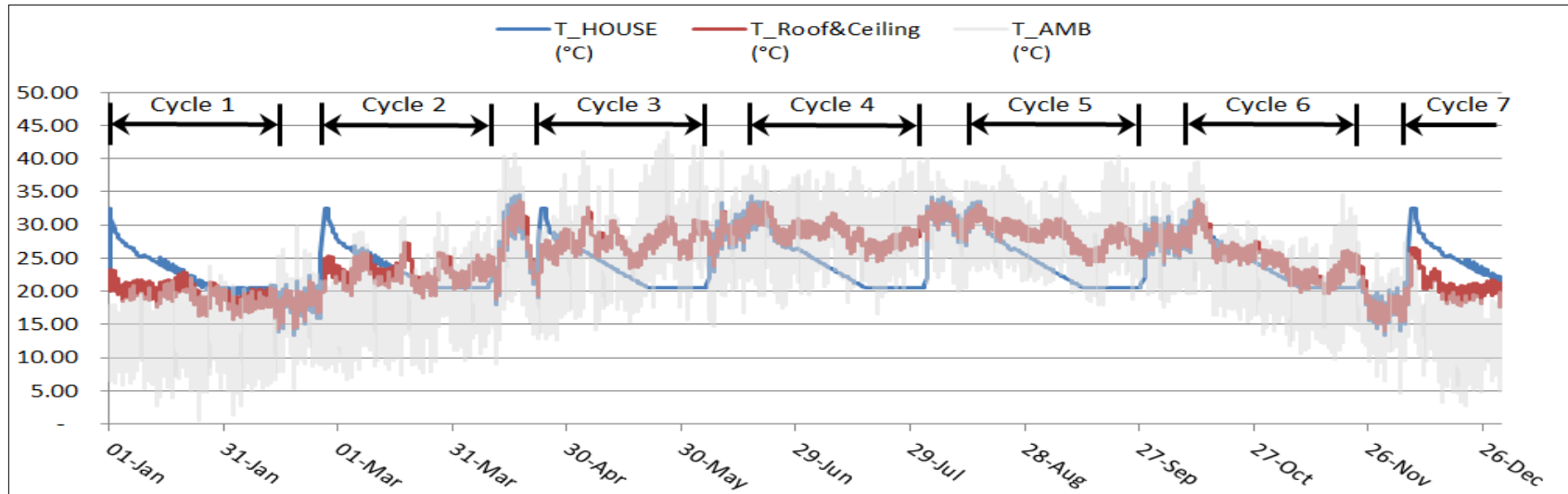


Figure 13: One Year Heat Demand Simulation Temperatures

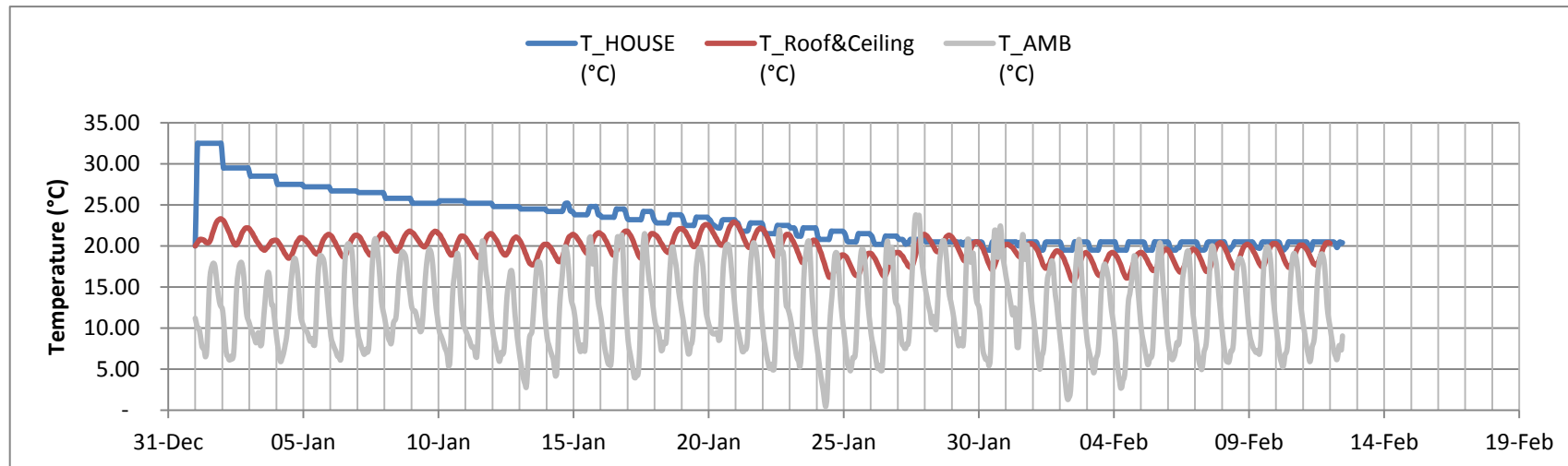


Figure 14: Cycle 1 Heat Demand Simulation Temperatures

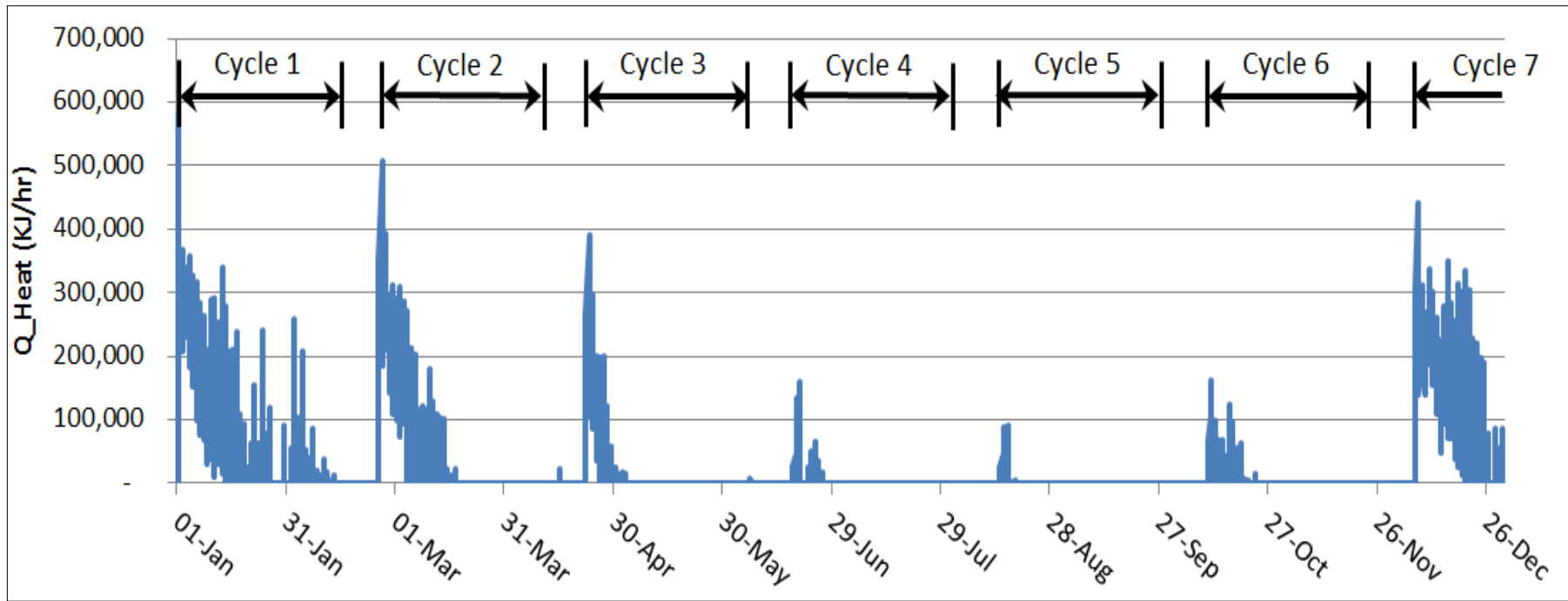


Figure 15: One Year Heat Demand Simulation  $Q_{Heat}$

## CHAPTER 4

### DESIGNING A SOLAR HEATING SYSTEM

The objective of this chapter is to present a valid economical heating system for the modeled house using renewable energy. It is intended to use solar thermal energy as the main source of heating energy in the designed system. The results obtained from chapter 3 are taken as the benchmark for the heat quantity needed to fulfil the targeted set temperatures of the house. Thus, it is required to design a solar heating system (SHS) that economically provides the required heating demand with the aid of an auxiliary source, if needed. To evaluate the designed SHS economically, the running cost of the traditional fuel-based heaters is determined and all the finances of the SHS are analyzed.

#### 4.1 The Structure of the Solar Heating System

To deliver heat to the broiler house using solar energy, the system is designed to consist of the following three linked subsystems: solar thermal collector, thermal storage system and heat distribution system, as illustrated in Figure 16. The solar thermal collector is where the solar radiation is received and transmitted into the system via the heat transfer fluid. The thermal storage sub-system is where the solar energy produced from the collectors in the form of heat is stored to be available for the varying all-day demand of the house. The heat distribution system is where the heat is extracted from the heat transfer fluid and delivered to the broiler house. The described SHS consists of two fluid closed loops. The first is the solar loop where the heat transfer fluid flows between the solar collector and the thermal storage system. The second is the heat distribution loop where the heat transfer fluid is circulated between the thermal storage system and the heat distribution system. The details of each subsystem are explained in the following section.

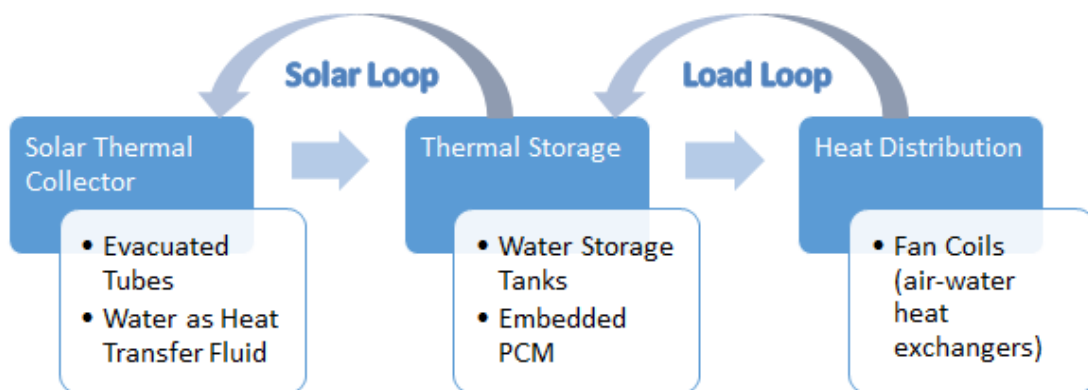


Figure 16: SHS Designed Structure

## 4.2 Designing the Solar Heating System (SHS)

The design of the SHS starts by the selection of a suitable heat distribution system to provide the final product, which is heat, to the house. According to the requirements of the selected system, the remaining sub-systems, which are the solar thermal collector and the thermal storage system, are designed. The design variables of the system are defined to be the area of the solar collector ( $A_{SC}$ ) and the volume of the storage tanks ( $V_{\text{tank}}$ ). TRNSYS simulations are run for each set of design variables to calculate the output of the SHS. Then, an economical study is performed to evaluate the performance of the system for different design variables.

### 4.2.1 Heat Distribution System

There are two general heat transfer methods that can be used to deliver the heat from the fluid of the SHS to the house, which are convection and radiation. Heat transfer by radiation will require installing a large amount of radiators distributed over the area of the house to maintain homogeneous temperatures within the whole volume of the house. Therefore, it is preferred to transfer the heat by convection using fan coils. A fan coil unit consists of a heat exchanger that transfers the heat from hot fluid to air. Using the fan, it can generate hot air with considerable heat throw to cover a larger area. Also, additional equipment like ducts and air jet diffusers can be installed on the fan coils to achieve better hot air distribution. The capacity of the fan coil units is selected based on the maximum heat required according to the results of chapter 3. The maximum amount of energy is needed at the beginning of the cycle in January, as shown in section 3.6 and is equivalent to 161 kW.

Based on this number, it is decided to use five fan coil units each of capacity 34.35 kW. As a result, the total rated fan coils capacity is about 172 kW. The fan coil unit is selected based on its performance data sheet produced by Modine Manufacturing Company as shown in Appendix 6[48]. The data of the selected model, unit size 014, is shown in Table 6. The data mentioned in Table 6 is the rated performance at standard conditions of entering hot water at 93.33°C water and 15.5°C of entering air.

Table 6: Fan Coil Data in SI units [48]

High Fan Speed Data				Low Fan Speed Data				Water Data	
m <sup>3</sup> /hr	kW	*WTD (°C)	*FAT (°C)	m <sup>3</sup> /hr	kW	*WTD (°C)	*FAT (°C)	m <sup>3</sup> /hr	*WPD (m)
2,429.59	33.23	- 3.22	56.67	1,554.59	25.50	- 6.61	64.44	2.04	0.79
	33.97	- 5.56	57.78		26.08	- 8.39	65.56	2.50	1.13
	34.35	- 6.67	58.33		26.38	- 9.22	66.11	2.77	1.37
	35.02	- 8.56	58.89		26.90	- 10.72	66.67	3.41	1.98
	35.34	- 9.56	59.44		27.14	- 11.50	67.22	3.86	2.50
*WTD: Water Temperature Drop *FAT: Final Air Temperature *WPD: Water Pressure Drop									

#### 4.2.2 Solar Thermal Collector

As mentioned beforehand, there are several types of solar collectors such as flat plate, evacuated tubes, parabolic troughs or other types that can be used in a SHS. Also, there are different working fluids that can be used for heat transfer which are: water, oil or air. According to the application in hand, and after selecting the fan coils as the method for heat distribution to the house, it is compulsory to use water as the heat transfer fluid. This is because, first, the selected fan coil is designed to work with water as the heat transfer fluid. Second, water is more accessible than oil and requires no special pumps or piping accessories.

In order to match the rated capacity of the fan coil, it is required to supply the fan coils with water at temperature of about 90°C. Based on this information, the evacuated tubes solar collector is selected to be the type of solar thermal collector to be used in the design. While flat plate collectors are usually used for Domestic Hot Water (DHW) applications with operating temperature around 60°C and parabolic trough collectors are usually used to generate very high temperatures of water and steam, evacuated tubes are considered the best to operate at this range of 90°C temperature.

The specifications and performance data of the evacuated tubes solar collector used in the design is based on that of the certified OVSOL 5 – 16 evacuated tube collector produced by Oventrop Company [49]. The data, shown in Appendix 7, is obtained from the solar collector certification and rating report produced by the Solar Rating and Certification Corporation [49]. The collector's gross area is equal to 4.097 m<sup>2</sup>. The number of collectors to be used will determine the total area of solar collectors, which is one of the main variables in the design.



To find an initial estimate for the required solar collector area, the following calculation is carried on. From the results of Chapter 3, the total accumulated thermal energy needed for the broiler house over the year is equal to 68422 kWh. Thus, an average of 187.5 kWh of energy per day is required. From the collector's thermal performance rating, it is found that each solar panel can produce 8.5 kWh per day at high radiation for water or space heating at a temperature difference of 50°C [49]. Therefore, 22 solar collector panels, which are equivalent to 90.13 m<sup>2</sup>, can fulfill the daily estimated energy requirement of the house. However, the design cannot be based on this roughly estimated value because the way of calculation doesn't take into account the daily variations in the heat demand, the actual difference in temperature and the actual radiation.

### 4.2.3 Thermal Storage System

The purpose of this system is to maintain the heat within the heat transfer fluid – water – as long as possible to cover the heating demand of the house. In this design, the main energy storage technique used is sensible heat storage. This is done by feeding the hot water produced from the evacuated tube solar collector into an insulated water storage tank. The water is circulated from the tank to the collector in a closed loop, named as the solar loop. Similarly, the hot water is fed from the tank into the fan coils and circulated back to the tank in a closed loop, named as load loop. The volume of the tank is considered a design variable that is to be determined based on the economic study of the system.

For high volumes of water storage, multiple tanks can be used in different configurations of charging and discharging. According to a study by Buonomano et. al, one of the efficient storage configurations is charging in series and discharging in parallel as shown in Figure 17[27].

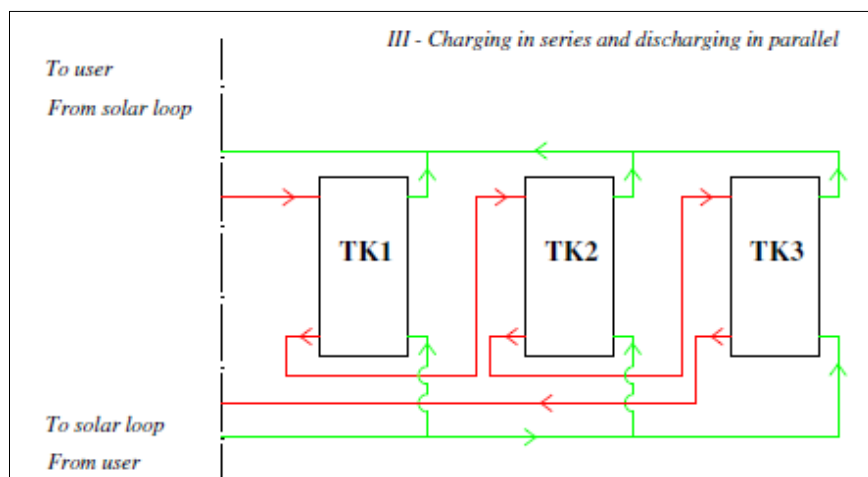


Figure 17: A Storage Technique using Series Charging and Parallel Discharging[27]

However, it is found that the difference between the results of energy savings of the multi-tank system with different configurations and that of using a single storage tank is not significant [27]. One of the factors affecting the results is the total surface area of the storage tanks, because it contributes to the heat losses to the ambient. So, for the design in this research, it is decided to install the storage tanks inside the poultry house. In this case, the heat losses from the tanks surface area are recoverable to the heated space. Also, it is decided to use a single tank configuration for the simulation regardless of the volume of the tank. However, for practical application of the design, a multi-tanks system can be used as a replacement for the single tank to accommodate for the space constraints. After the completion of the design phase of the SHS, a further study is done on using latent heat storage technique by embedding phase change materials (PCM) into the water storage tanks.

#### **4.2.4 TRNSYS Simulation of the Designed SHS**

To observe the outcome of the SHS with any selected design variables, it is required to run a TRNSYS simulation. The TRNSYS project is set up to plug in the values of the design variables and run the simulation for a complete year to read the results. The previously built TRNSYS project that is used in this research to calculate the required heat demand is used as the starting point for building the SHS simulation. As mentioned beforehand, in the previous simulation, the heating of the house is set to be automatic with unlimited energy to fulfil the target temperature. However, for the design simulation, this theoretical automatic heating is de-activated and replaced by the heat supplied by the five fan coil units.

##### Fan Coil Units:

The fan coil units are simulated by a performance map fan coil type 996. The hot water inlet is supplied from the storage tanks. The air to be heated is the return air from inside the house and its temperature is taken from the calculation of the house temperature at the previous hour. The heating rate of each fan coil unit, which is the rate at which energy is added to the heated air across the heating coil, is summed up together and fed as an input to the building – Type 56. The outlet water leaving the fan coil is returned back to the storage tanks.

##### Fan Coil Units Controller:

The fan coil units are operated by a 5-stage aquastat, which is a controller used to output the ON and OFF signals at 5 different conditions depending on the set temperature of each stage. With a dead band of 2°C, the first fan coil unit is operated when the temperature of the house is less than

the set temperature by 0.5°C. The next fan coil units are operated by increments of 0.5°C from each other. As an additional control, whenever the temperature of the water in the storage tank is less than 40.5°C, the fan coil units are turned OFF to avoid feeding the fan coils with water at lower temperature than its performance range. The 5-stage aquastat controls the operation of the fan only.

#### Load Loop Pump:

The circulation of the water between the storage tank and the fan coil units is done by a pump named as the load pump ( $P_{Load}$ ). The operation of  $P_{Load}$  depends on two conditions. First, at least one fan coil unit has to be ON. Second, the  $P_{Load}$  controller signal has to be ON. The  $P_{Load}$  controller is an ON/OFF differential controller that works according to difference between the air temperature of the house ( $T_{House}$ ) and the water temperature exiting the tank to the load ( $T_{tank-load}$ ). The controller works with upper and lower dead bands equal to 10°C and 5°C respectively such that:

When  $P_{Load}$  is ON:

If  $T_{Tank-Load} - T_{House} > 5^{\circ}C \rightarrow P_{Load}$  stays ON

If  $T_{Tank-Load} - T_{House} < 5^{\circ}C \rightarrow P_{Load}$  turns OFF

When  $P_{Load}$  is OFF:

If  $T_{Tank-Load} - T_{House} < 10^{\circ}C \rightarrow P_{Load}$  stays OFF

If  $T_{Tank-Load} - T_{House} > 10^{\circ}C \rightarrow P_{Load}$  turns ON

$P_{Load}$  suction side is connected to the hot side outlet of the storage tank, while  $P_{Load}$  outlet is pumping the hot water into the fan coil units.

#### Storage Tanks:

The storage tank is simulated by a stratified sensible energy storage tank with fixed inlet and outlet positions, where the hot fluid flows in or out of the top of the tank and the cold fluid flows in or out of the bottom of the tank. The volume of the storage tank is one of the variables of the design that can be changed for the different simulations. The tank's heat loss coefficient is input per unit area of the tank. According to the European standard EN 15316-4-3 for calculating system energy requirements, if the heat loss coefficient of the storage tank is unknown, the equation 11 is used [50]:

$$UA = 0.16 \times V_S^{0.5} \quad (11)$$

where  $UA$  is the overall heat loss coefficient of the storage tank in (W/K) and  $V_S$  is the solar storage tank volume in (liters). Using this equation,  $UA$  for a tank of volume  $8m^3$  is calculated and then the average tank loss coefficient per unit area is calculated to be  $0.64 \text{ W/m}^2 \cdot \text{K}$ .

### Solar Collector:

The hot fluid inlet of the tank is fed by the water circulating from the thermal solar collector. The collector is simulated as an evacuated tube solar collector of unit gross area equals  $4.097 \text{ m}^2$ . The number of collectors connected in series, thus the total gross area of the collector is a design variable that can be changed for each simulation. The hourly ambient temperature and all the solar radiations and angles are fed into the solar collector from the weather data file of Al Menia.

### Solar Loop Pump:

The solar pump, which is simulated within the solar collector, modulates the flow rate and keeps the outlet temperature as close as possible to the target temperature of  $95^\circ\text{C}$  as long as the collector is gaining energy. However, if the collector is losing energy, it turns OFF.

An overview of the simulation's layout showing all the components connected together is shown in Figure 18. More details about the simulation connections are shown in Appendix 8.

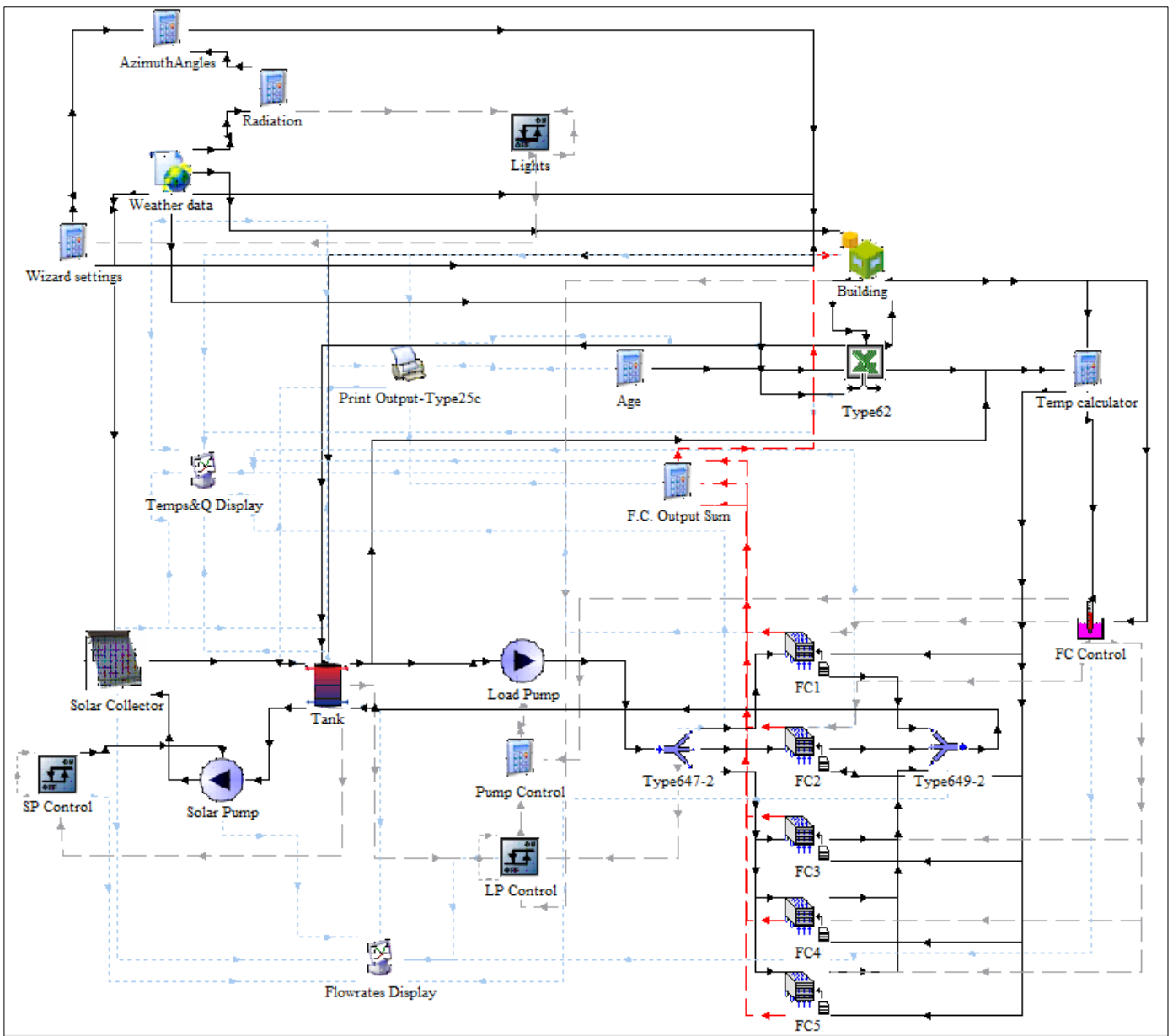


Figure 18: SHS Simulation using TRNSYS

### Output of the simulation:

The outputs that are selected to be read hourly from the simulation are as follows:

- Air temperature of the house in °C ( $T_{House}$ )
- Average temperature of the water in the storage tank in °C ( $T_{Tank}$ )
- Outlet temperature of the collector in °C ( $T_{out SC}$ )
- The sum of total heating rate for the 5 fan coil units in kJ/hr ( $Q_{FC}$ )

An example of the output file is shown in Appendix 9. The most significant output of the simulation is  $Q_{FC}$ , where it is used to determine the auxiliary energy needed  $Q_{aux}$  to be supplied by the non-solar system to cover the heat demand of the house  $Q_{Heat}$  which is calculated in chapter 3. The

hourly auxiliary energy needed is calculated by subtracting  $Q_{FC}$  from the hourly  $Q_{Heat}$  obtained from the previous simulation in chapter 3 based on the following conditions:

$$Q_{aux} = \begin{cases} Q_{Heat} - Q_{FC}, & Q_{Heat} > Q_{FC} \text{ or } T_{Set} > (T_{airhouse} + 2) \\ 0, & Q_{FC} > Q_{Heat} \text{ or } ProductionCycleisOFF \end{cases}$$

These conditions are put to avoid calculating false auxiliary energy which may occur if the production cycle is not running and to accommodate for the response of the fan coils controller, where there is a dead band temperature of 2°C. The accumulated auxiliary energy needed over the year is calculated by summing up  $Q_{aux}$ . Then, it is expressed as percentage of the total heat demand of the house by dividing it by the accumulated  $Q_{Heat}$ . So, the aftermath of the simulation is the percentage of auxiliary energy needed relative to the overall heat demand of the house.

### 4.3 Pricing of the Solar Heating System

To be able to assess the investment value of the system, a research is done to collect the prices of the different components. A detailed quotation for a solar water heating system of storage capacity of 2 m<sup>3</sup> is prepared by a specialized local company, TAQAMISR<sup>3</sup>, and is used as guidance for the pricing. The breakdown prices are shown in Appendix 10. Also, several international suppliers are contacted to obtain financial offers for the different components.

#### 4.3.1 Fan Coils

A specialized supplier of fan coils for poultry houses is selected. The supplier produces a range of air-water heat exchangers with the different accessories for mounting and hot air distribution. An example of the supplier's products is shown in Figure 19. From within the product range, a suitable model is selected to match the capacity of the simulated fan-coil. Based on the supplier's information, the heating capacity of this model is about 40 kW at 30°C. The heating medium (water) rated flow and return temperatures are 80/60°C [51]. The supplier is contacted to get an estimated price. Each fan coil with its suspension system is calculated to be equivalent to \$2,800.

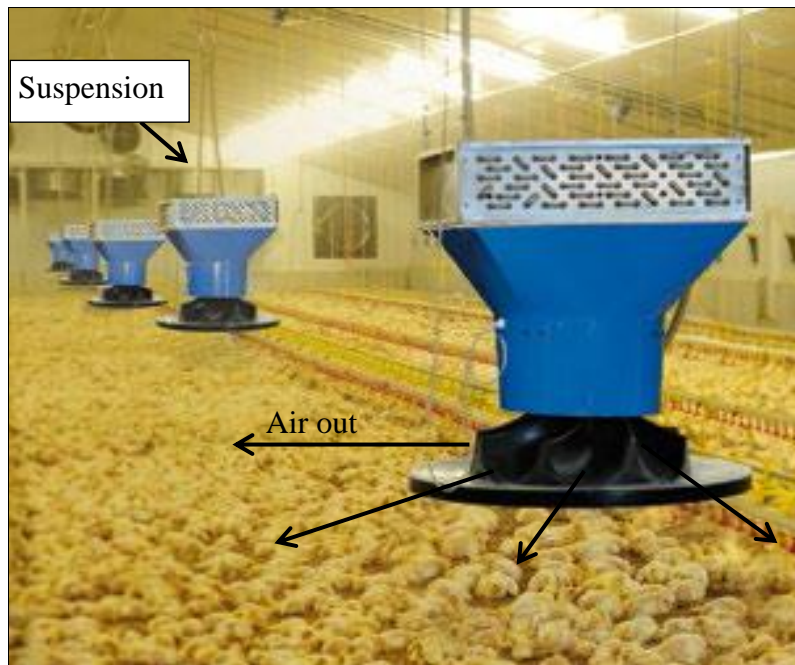


Figure 19: REVENTA Heat X-3H Fan Coil [51]

<sup>3</sup>[www.taqamisr.com](http://www.taqamisr.com)

### 4.3.2 Water Storage Tank

In the DHW application, which is the widely used application, the storage tanks usually have one or two heating coils categorized as single or double coiled storage tanks. However, in this research the tank used in the simulation is categorized as insulated buffer tank rather than a standard storage tank as there are no coils used as shown in Figure 20. The tank is selected from a recent detailed price list for solar heating systems provided by a specialized company called SOLARFOCUS [52]. The price list includes a wide range of tanks with different storage capacities. The average price per 1 m<sup>3</sup> volume is calculated to be \$1,400.

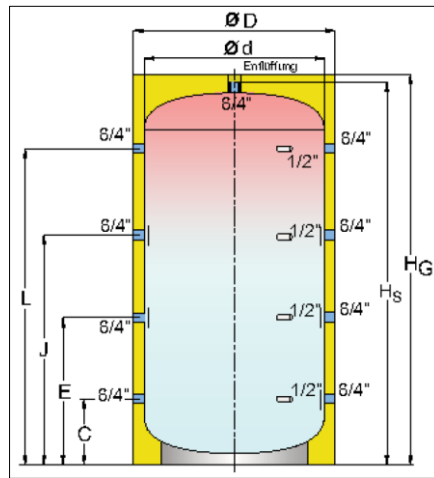


Figure 20: Example of SOLAR FOCUS Storage Buffer Tank [52]

### 4.3.3 Solar Collector

Different prices from different suppliers are encountered for evacuated tubes solar collectors starting from \$270 to \$500 USD per m<sup>2</sup> area. An APRICUS solar collector [53] is selected from the quotation presented in Appendix 10. It is a vacuum tube solar collector with heat pipes and standard frame and manifold. The price of the evacuated tubes solar collector is calculated to be about \$375 per m<sup>2</sup> area.

### 4.3.4 Pumps

A wide range of solar pumps designed for solar water heating applications are available in the market. Their prices range from \$150 to \$1,000 depending on the specifications of the pump and the accessories supplied with it such as flow regulators, thermometers and valves. For the pump used in the solar loop, between the solar collectors and the tank, an estimated price of \$850 is obtained from SOLARFOCUS price list [52].



The pump used in the load loop, between the storage tank and the fan coils, is required to supply a specified water flow rate to the fan coils that matches its rated value in order to maintain the best heat exchange performance. Therefore, the number of fan coils installed in the system will affect the selection of the pump. The rated flow rate and the water pressure drop of the fan coil were obtained from the performance data sheet of the fan coil. Having suspended fan coils, additional pressure head is considered due to the difference in height between the tank outlet and the fan coil inlets. Also, the flow resistance within the piping and elbows used for the connection will cause an addition in the pressure head.

Based on the pressure head and the required flow rate, the pump is selected to be as close as possible to the highest efficiency operating region. The circulating pump is selected from the product range of CALPEDA in-line pumps [54]. Table 7 summarizes the calculation done to select the suitable pump: The performance curve of the selected pump is presented in Appendix 11. The price of this model is in the range of \$ 1,000. Therefore, the item of pumps in the pricing is set to be \$ 1,850.

Table 7: Pump Selection Calculation

No. of Fan coils	5	Units
Pressure drop per Fan Coil	0.44	bar/F.C.
Total Pressure drop (in m)	22.44	m
Additional pressure head ( $\Delta H$ + Piping)	5	m
Total Pressure Head in (m)	27.4	m
Rated Flow rate per Fan Coil	2.77	m <sup>3</sup> /hr
Total Required Flow rate	13.85	m <sup>3</sup> /hr
Selected Pump Model	NR 40/160A	
Pump Power	3 HP	

### 4.3.5 Others

In addition to the main constituents mentioned beforehand, the following are essential expenses that have to be considered when pricing the system:

i. Piping and Accessories

This item includes the piping network interconnecting the solar collectors together to the storage tank as a closed loop as well as the other loop connecting the storage tank to the fan coils. All the pipes connecting the solar collectors up till the tank have to be well insulated. The network includes all connections and safety equipment such as ball valves, relief valves, air vents, non-return valves ...etc. The cost of this item is estimated from the quotation presented in Appendix 10 to be \$600 as fixed cost undependable of the size of the system in addition to \$35 per 1 m<sup>2</sup> of solar collectors.

ii. Liquid Additive

To increase the lifetime of the system and protect the components, anti-rust additives are used. An estimated cost that depends on the storage volume is obtained from the quotation presented in Appendix 10. It is considered to be \$410 per 1 m<sup>3</sup> of storage tanks.

iii. Electric material

For any solar heating system, regardless of its size, cables, cable trays and a control unit will be installed to operate the system. The cost of the electric material and wiring of this system is also estimated from the quotation presented in Appendix 10 to be \$1,000.

iv. Installation Fees

For the installation of the system, it is estimated to have a fixed cost of \$1,000 in addition to a size dependent cost of \$15 for every m<sup>2</sup> of solar collectors.

In most of the solar heating systems quotations, there is a considerable cost for the construction of the supports for mounting the solar collectors. However, in this research, the solar collectors are mounted on the existing roof of the poultry house. Thus, this cost is saved as the roof is readily inclined to fulfill the requirements of the collectors' installation instructions.

### 4.3.6 Summary of Prices

For illustration, the summary of prices of an example SHS is tabulated below:

**Table 8: Summary of Investment Cost**

Item	Description	Unit	QTY	Unit Price (USD)	Total Price (USD)
Fan Coils	40 kW Fan Coils	N.	5	\$2,800	\$14,000
Storage Tanks	2m <sup>3</sup> Buffer Tanks	m <sup>3</sup>	6	\$1,400	\$8,400
Solar Collectors	Evacuated tubes	m <sup>2</sup>	70	\$375	\$26,250
Pumps	Solar + Circulating	N.	2		\$1,850
Others:					
Piping & Accessories					\$3,050
Liquid Additives					\$2,460
Electric material					\$1,000
Installation Fees					\$2,050
Total Investment					\$ 59,060

For further calculations, equation 12 is used to calculate the total cost:

$$InvestmentValue(\$) = 4450 + 2800F.C. + 1810V_{Tank} + 425A_{sc} \quad (12)$$

where,  $F.C$  is the number of fan coils,  $V_{Tank}$  is the storage volume of the tanks and  $A_{sc}$  is the area of the solar collectors.

## 4.4 Traditional Heaters Running Cost

### 4.4.1 Fuel Consumption in Poultry Houses

To calculate the running cost of the conventional diesel fired heaters for the modeled house, it is necessary to know the consumption of fuel over the year. The farm manager of the modeled house in Al Menia is contacted to collect the required data. Unfortunately, exact figures are not available. However, according to his information, the modeled house consumes 600 liters of diesel fuel per day during the winter season to maintain the required set temperatures [46]. Using the results obtained in Chapter 3, the accumulated energy needed for each production cycle is calculated in terms of percentage and the data obtained for the consumption of the 1<sup>st</sup> cycle (winter cycle) is used as a reference for the remaining cycles as shown in Table 9. From this data, it is concluded that the yearly consumption of the house is about 61,000 liters of diesel fuel per year.

Table 9: Estimated Fuel Consumption Calculation for Al Menia Farm

Cycle No.	Calculated $Q_{\text{heat}}$ (kJ/cycle)	Normalized Percentages (%)	Fuel Consumption (Liters)
1st Cycle	87,018,020	100%	21,600
2nd Cycle	51,870,291	60%	12,875
3rd Cycle	18,708,700	21%	4,644
4th Cycle	3,045,030	3%	756
5th Cycle	1,672,980	2%	415
6th Cycle	6,403,806	7%	1,590
7th Cycle	77,518,737	89%	19,242

To confirm the data collected from Al Menia farm, another source is sought-after. Dr. Khaled Mostafa, a member of the Egyptian Poultry Association board and the General Manager of Grand Parent Sector at Cairo Poultry Group provided more accurate data about the fuel consumption for a traditional heating system. His data is based on the management analysis of cost per bird for the Cairo Poultry Group broiler houses, which are very similar to the modeled house. The analysis showed that the average consumption of diesel fuel per bird over the year, summer and winter seasons, is 0.44 liters per bird [8]. Thus, for the modeled house of capacity 24,000 birds and having 6.54 production cycles per year, the total consumption of diesel fuel for the modeled house is calculated to be about 69,000 liters per year.

The average of both fuel consumption rates is calculated to be about 65,000 liters. This figure is used to determine the yearly running cost of a traditional diesel fired heaters for the modeled house in Egypt.

#### 4.4.2 Fuel Prices

According to the Egyptian Cabinet Decree no. 1160 of 2014 for modifying fuel prices that is published in the Egyptian Official Gazette on 5<sup>th</sup> of July 2014, the price of diesel fuel is 1.8 Egyptian pounds per liter [55]. Using the current official exchange rate, the price is calculated to be equivalent to 0.25 USD per liter. According to the German Agency for International Cooperation (GIZ) GmbH, Egypt lies in the category of the high subsidies countries, where the retail price of diesel is below the price for crude oil on the world market [56]. The ranking of diesel fuel price in Egypt among 171 countries of the world is shown in Appendix 12 [56]. To have a deeper look at the diesel fuel price in Egypt, Figure 21 shows the prices from year 1991 till 2012 with comparison to the international prices [56]. The red benchmark line represents the price of crude oil on world market. The green benchmark line represents the retail price of diesel fuel in the United States of America, which may be considered as the international minimum benchmark price for a non-subsidized policy. The grey benchmark line represents the retail price of diesel fuel in Luxembourg, which is recorded in November 2012 as the lowest in the European Union countries.

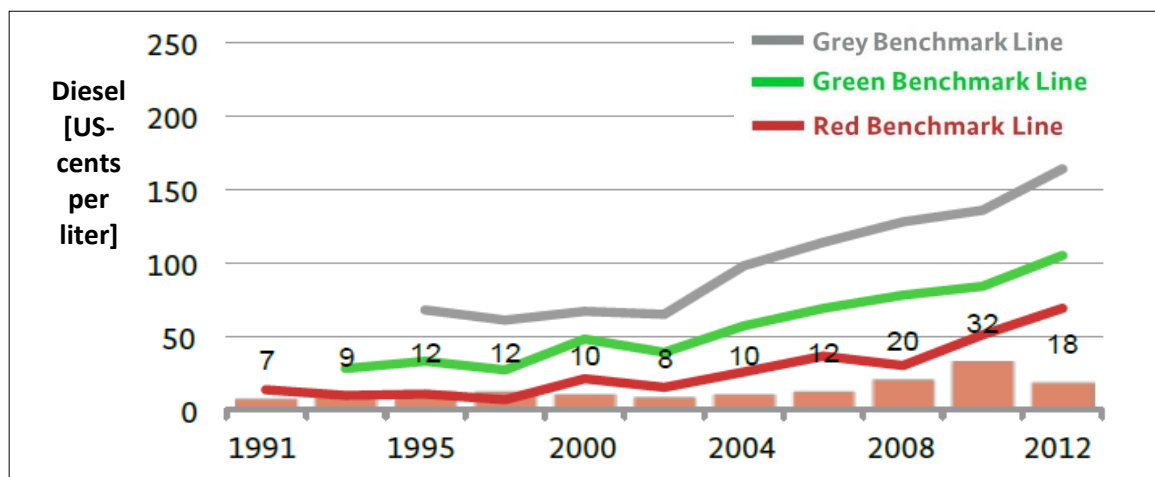


Figure 21: Time Series of Fuel Prices in Egypt (1991-2012) [56]

In this research, the equivalent for the Egyptian local official price of diesel fuel in USD is used for the economic study of the designed SHS. Thus, the price is considered to be 0.25 USD/liter. A further comparative study is carried out using the international minimum benchmark price, which is equal to 1.05 USD/liter as of November 2012.

## 4.5 Economic Study

Given a set of values for the design variables: an area of the solar collector  $A_{SC}$  and a volume of the storage tanks  $V_{\text{tank}}$ , it is possible to:

- Run the TRNSYS simulation to know the percentage of auxiliary energy needed to cover the heat demand of the house
- Calculate the value of the yearly fuel savings
- Calculate the cost of investment

To be able to select the best economical values of the design variables,  $A_{SC}$  and  $V_{\text{tank}}$ , it is required to carry on an economical study to find the best trade-off between the cost of investment and the amount of fuel saved by the system. Among the different economic evaluation criteria, the Life Cycle Savings (LCS) is selected for this study. LCS is defined as “the difference between the life-cycle costs of a conventional fuel-only system and the life-cycle cost of the solar plus auxiliary energy system” [57]. The life cycle cost method is considered “the most complete approach to solar process economics” because it facilitates the comparison of future costs with today’s costs [57]. This is done by calculating a discounted cash flow using the present worth method. This method converts all the anticipated cash flows, expenses and savings, to a single sum equivalent at time zero [58]. This single value is the Net Present Value (NPV). Any study yielding a positive NPV means the investment under study is economically acceptable. When comparing different investment alternatives, the greatest value of NPV is for the most recommended investment. To calculate the NPV, it is required to know the discount rate at which the present worth factor (PW) is calculated over a certain period of time using the equation 13[57]:

$$PW = \frac{1}{(1 + d)^N} \quad (13)$$

where,  $d$  is the market discount rate and  $N$  is the cash flow period. The market discount rate takes into account the percentage of the investment that is financed by a bank loan versus that covered as equity (paid by the owner or shareholders). While calculating the NPV, the inflation rate and tax deductions are taken into consideration. The following sections explain the method of calculation of the NPV.

### 4.5.1 Life-time of the System

The cash flow period ( $N$ ) represents the life-time of the system on which the analysis will be made. To determine this period, it is important to evaluate the lifetime of the main components of the SHS. For the selected APRICUS evacuated tubes solar collector, their lifetime is found to be

from 15-20 years [53]. As for the fan coil units, they were found to have 20 years of service life time [59]. The remaining main component, storage tanks, is estimated to have a lifetime of 20 years as well. Based on these figures, the system lifetime of the analysis is selected to be 15 years.

#### 4.5.2 Loans

As mentioned above, part or even all of the investment can be financed through a bank or an institution against a certain interest rate. The interest rate of lending from the central bank of Egypt is found to be 10.25% as of July 2014 [60]. By surveying different commercial banks, the average lending interest rate is found to be 12%. Thus, given the total investment cost, the percentage of this cost that is to be financed by a loan, the interest rate of 12% and the number of payment years  $N=15$ , the annual loan payment is calculated. The loan payment is a fixed installment that is constant over the 15 years. However, it can be analyzed into two varying payments: the interest expense and the principal re-payment. The interest expense is reduced every year as the principal payment grows.

Renewable energy projects can be financed by special funds that are concerned with environmental aspects and sustainable development. These funds may be giving grants or loans at very low interest rates. However, for this research, a conservative approach is taken by considering the commercial banks as the only source of financing.

#### 4.5.3 Maintenance

The cost of maintenance of the system is divided into two types: operational costs and materials (spare parts) costs. The operational cost is the extra cost of general maintenance and cleaning of the solar system in comparison to that of the conventional fuel based system. It is estimated to be \$100 per month. So, a yearly expense of \$1200 is included in the cash flow starting from year one.

The materials or spare parts cost is usually considered as a fraction of the capital cost. However, it is related to the warranty and lifetime of the different components of the SHS. Thus, a price breakdown is done to divide the components into 4 categories: Collectors, Tanks, Fan Coil units and others. The others category includes all other components such as the pipes, valves, accessories, electric material and liquid additives. The cost of maintenance for the four categories is considered to be a fraction of 2% from their capital cost. This cost will inflate yearly by 8.47%, which is the core inflation rate announced by the Central Bank of Egypt as of October 2014 [60]. However, the expense of each category will be actuated after the end of its warranty period. The

solar collectors price includes a warranty period of 10 years, thus its maintenance expense will start from year 11. The tanks warranty is valid for 5 years, so its expense starts at year 6. The fan coils units life time is 20 years, thus it is expected to start its maintenance expenses at year 11. For the others category, the maintenance starts at the first year of operation.

#### 4.5.4 Parasitic energy

The parasitic energy is the power needed to run the components of the SHS, which are mainly the pumps and fan coil units. Table 10 summarizes their values as follows:

Table 10: SHS Parasitic Power

Item	Rated Power	Units
Pumps	4.47	kW
Fan Coils	2.65	kW
Total Parasitic Power	7.12	kW

Using the normalized heat demand percentages shown in section 4.4.1 and referring to the number of operating hours of the conventional fuel system, the maximum total number of operating hours per year is estimated to be 2268 hours. The parasitic consumption of the SHS is calculated based on the solar fraction of the operating hours (depending on the auxiliary energy needed) multiplied by the total parasitic power.

According to the Egyptian law no. 1257 of 2014, the electricity tariff is subjected to an annual increase for the next five years [61]. To estimate the tariff after the 5 years period, an inflation of 10% is used. The tariff of interest, which is for low voltage 380V applications as shown in Appendix 13 is multiplied by the parasitic consumption to calculate the yearly parasitic expenses in USD as per the current official currency exchange rate.

#### 4.5.5 Fuel Savings

The Egyptian government has been announcing since 2011 that it will lift the energy subsidies on industries, which is causing a lot of controversy within the business sector [62]. However, by observing the historical time series of the fuel prices in Egypt and putting in consideration the social and political pressures against the reduction in subsidies, a conservative inflation rate for diesel fuel equal to 2% is considered for this study. So, the price at the first year is set to be \$0.25/liter as concluded in section 4.4.2. The fuel savings (F) at this year is calculated based on the amount of fuel



saved. The amount of fuel saved is calculated by multiplying the total yearly fuel consumption concluded in section 4.4.1, which is 65000 liters, by the percentage of energy saved by the SHS. Thus, the fuel saving for year 1 is calculated using equation 14 as follows:

$$F_1 = \text{Price of Fuel} \times \text{Yearly Fuel Consumption} \times (1 - \% \text{Aux. Energy Needed}) \quad (14)$$

Then, to account for the inflation rate starting the second year, for each year N,  $F_N$  is calculated based on equation 15 as follows:

$$F_N = F_1(1 + i)^{N-1} \quad , \text{ where } i=2\% \quad (15)$$

#### 4.5.6 Tax Savings

By law, some of the expenses are tax deductible from the Income Tax that is paid by any entity. Therefore, for an income tax ( $t$ ) and a tax deductible expense  $C_t$ , the tax deduction  $D_t$  is extracted from the life-cycle cost as shown in equation 16 below [59]:

$$D_t = t \times C_t \quad (16)$$

According to the income tax law of Egypt,  $t=25\%$  [63]. For this research, where the house is a producing unit and not a residential home, the expenses that are tax deductible are: the loan interest expense, the maintenance cost and the parasitic energy expense.

#### 4.5.7 Discount Rate

The discount rate is used to determine the present value of future cash flows, where it is considered “a consequence of the productivity of capital” [59]. It takes into account the time value of money, and also the risk or uncertainty of future cash flows. In this research, the weighted average cost of capital (WACC) is used to determine the discount rate, and is calculated using equation 17 as follows [64]:

$$WACC = \frac{E}{E + D} \times k_E + \frac{D}{E + D} \times k_D \quad (17)$$

where,  $E$  is the amount of equity used in financing the project,  $k_E$  is the after tax equity rate of return,  $D$  is the amount of debt (loan) used in financing the project and  $k_D$  is the after tax debt interest rate.  $k_E$  takes into account the risk of the investment and the alternative of depositing the amount in a risk free depository. The 10-year bond yield of 15.28% -as per the ministry of finance, is considered as the risk free rate [65]. Considering a risk premium of 8% and a security factor  $\beta=1$ , the  $k_E$  is calculated to be 19.5% after tax deduction.

Based on the central bank's loan rates [60] and by surveying the commercial banks' rates, the loan interest rate is set to be 12%. Thus, the after tax rate  $k_D$  is calculated to be 9%. In this study, it is assumed that 90% of the investment will be financed through a bank loan, while the remaining 10% will be paid by the owner or shareholders. Based on this percentage, the discount rate is calculated to be 10.05%.

#### 4.5.8 Salvage Value

The economic study is made on a period of 15 years as verified beforehand. At the last year,  $N=15$ , a re-sale value of the SHS is estimated to be 10% of the total capital cost.

## CHAPTER 5

### RESULTS AND DISCUSSION

#### 5.1 Fuel Saver System

In this section, the SHS is dealt with as a fuel saver system that is complementing an already existing conventional fuel based heating system. Therefore, the economic study takes into account only the additional cost of the SHS and deducts the fuel savings achieved by the SHS.

As mentioned beforehand, the solar area collector  $A_{SC}$  and the volume of storage tanks  $V_{tank}$  are the two design variables of the SHS. To examine the magnitude and direction of the effect of each variable on the performance of the SHS, a  $2^2$  factorial experiment is carried out. The evaluation of the performance of the system is done based on the NPV, which is the outcome of the economic study. A solution space is explored to search for the best design, which yields the maximum NPV. The effect of adding latent heat storage to the designed sensible heat water storage tanks is explored. Also, the effect of reducing the infiltration rate of the building is examined.

##### 5.1.1 Effect of the Design Variables on the NPV

Based on the literature, a solar system performance is much more sensitive to collector area than to any other variable[57]. A  $2^2$  factorial experiment is carried out to confirm this statement. The two factors to be experimented are the  $A_{SC}$  and the  $V_{tank}$ . Using the initial estimate of  $A_{SC}=90m^2$  mentioned in section 4.2.2, the high and low values of each variable are selected to be multiples of the single collector area of  $4.097 m^2$  and single storage tank of volume  $2 m^3$ . The selected values are as follows:

Table 11: Low&High Values of the Design Variables

Variable	Low Value (-1)	High Value (+1)	Unit
$A_{SC}$	40.97	139.29	$m^2$
$V_{tank}$	4	12	$m^3$

Using the high and low values of the design variables, four different SHS designs are simulated using TRNSYS for a complete year. From the results of the simulations the percentage of the needed auxiliary energy is calculated as explained beforehand in section 4.2.4. The cost of the investment is calculated using equation 12 in section 4.3.6. Then, using the resulted percentage of

auxiliary energy needed, the fuel saving is calculated using equation 14 in section 4.5.5, where the local fuel price is used and set to be \$0.25/liter. The results of the simulations and the subsequent calculations are shown in Table 12.

Table 12: Preliminary Results of the 2<sup>2</sup>Factorial Experiment Simulations

	$x_1$	$x_2$			
Run #	$A_{SC}$ (m <sup>2</sup> )	$V_{tank}$ (m <sup>3</sup> )	Aux. Energy %	Investment USD	Fuel Savings USD
1	40.97	4	75%	\$ 43,102	\$ 4,032
2	139.29	4	19%	\$ 84,892	\$ 13,292
3	40.97	12	58%	\$ 57,582	\$ 6,846
4	139.29	12	10%	\$ 99,372	\$ 14,829

Then, for each design, the economic study is performed to calculate the response of the numerical experiment, which is the NPV of the system. The details of the economic study for the fourth run only, where  $A_{SC}=139.29$  m<sup>2</sup> and  $V_{tank}= 12$  m<sup>3</sup>, are shown below.

#### Loan Calculation:

Given the following parameters:

- Total investment: \$99,372
- Financed percentage: 90% (refer to section 4.5.7)
- Loan interest rate: 12% (refer to section 4.5.7)
- Loan period (N): 15 years (refer to section 4.5.1)

The loan value is calculated to be \$89,434 with a yearly payment of \$13,131. The loan cash flow is calculated as explained in section 4.5.2.

#### Maintenance Calculation:

At the given run no. 4, where  $A_{SC}=139.29$  m<sup>2</sup> and  $V_{tank}= 12$  m<sup>3</sup>:

- Price of collectors: \$ 52,237
- Price of storage tanks: \$ 16,800
- Price of fan coil units: \$ 14,000
- Price of others: \$ 16,335

Given that the spare parts fraction of capital is 2% with inflation rate of 8.47%, the maintenance expenses cash flow are calculated as explained in section 4.5.3 and the results are shown in Table 13.

Table 13: Maintenance Cash Flow for  $A_{SC}=139.29 \text{ m}^2$  &  $V_{\text{tank}}= 12 \text{ m}^3$

Years	Materials (spare parts) Costs				Operational Costs	Total Yearly Maintenance
	Collectors	Storage Tanks	Fan Coils Units	Others	General Maint. & Cleaning	
1	0	0	0	\$326.70	\$1,200.00	-\$1,526.70
2	0	0	0	\$354.37	\$1,200.00	-\$1,554.37
3	0	0	0	\$384.38	\$1,200.00	-\$1,584.38
4	0	0	0	\$416.94	\$1,200.00	-\$1,616.94
5	0	0	0	\$452.26	\$1,200.00	-\$1,652.26
6	0	\$336.00	0	\$490.56	\$1,200.00	-\$2,026.56
7	0	\$364.46	0	\$532.11	\$1,200.00	-\$2,096.57
8	0	\$395.33	0	\$577.18	\$1,200.00	-\$2,172.51
9	0	\$428.81	0	\$626.07	\$1,200.00	-\$2,254.88
10	0	\$465.13	0	\$679.10	\$1,200.00	-\$2,344.23
11	\$1,044.74	\$504.53	\$280.00	\$736.62	\$1,200.00	-\$3,765.88
12	\$1,133.22	\$547.26	\$303.72	\$799.01	\$1,200.00	-\$3,983.21
13	\$1,229.21	\$593.62	\$329.44	\$866.69	\$1,200.00	-\$4,218.95
14	\$1,333.32	\$643.90	\$357.34	\$940.10	\$1,200.00	-\$4,474.66
15	\$1,446.25	\$698.44	\$387.61	\$1,019.72	\$1,200.00	-\$4,752.02

Parasitic Energy Calculation:

For an auxiliary energy coverage of 10%, the yearly operating hours of the SHS is estimated to be 2052 hr. Given the power of 7.12 kW, the estimated parasitic consumption is 14,610kWh/year. The cash flow of the parasitic energy expenses is calculated as explained in section 4.5.4 and the results are shown in Table 14.

Table 14: Parasitic Energy Cash Flow for  $A_{SC}=139.29 \text{ m}^2$  &  $V_{\text{tank}}= 12 \text{ m}^3$

Years	Price per kWh Egyptian Piaster	Price per kWh (equivalent) USD	Total Yearly cost of Parasitic Energy USD
1	36.6	\$0.05	-\$747.88
2	43.5	\$0.06	-\$888.87
3	52.5	\$0.07	-\$1,072.78
4	58.6	\$0.08	-\$1,197.43
5	66.5	\$0.09	-\$1,358.85
6	73.2	\$0.10	-\$1,494.74
7	80.5	\$0.11	-\$1,644.21
8	88.5	\$0.12	-\$1,808.64
9	97.4	\$0.14	-\$1,989.50
10	107.1	\$0.15	-\$2,188.45
11	117.8	\$0.16	-\$2,407.29
12	129.6	\$0.18	-\$2,648.02
13	142.5	\$0.20	-\$2,912.83
14	156.8	\$0.22	-\$3,204.11
15	172.5	\$0.24	-\$3,524.52

#### Discounted Cash Flow:

For the design under study, which is run no. 4, the total energy saved is 90% of the conventional system's consumption, which is equivalent to \$14,828 of fuel savings at the first year. Using the fuel inflation rate of 2%, the calculated discount rate of 10.05% (refer to section 4.5.7) and the salvage value at  $n=15$  of \$9,937 (refer to section 4.5.8), the discounted cash flow (DCF) is developed as shown in Table 15. The NPV is found to be equal \$11,704, which indicates that the design is economically accepted.

Table 15: DCF Calculating NPV for  $A_{SC}=139.29 \text{ m}^2$  &  $V_{\text{tank}}= 12 \text{ m}^3$

Year	Investment Payment	Fuel savings	Parasitic energy Cost	Maintenance Cost	Loan payment	Interest expense	Tax savings	Salvage value at n=15	Net cash flow	Discount factor	NPV of cash flow
0	-\$9,937								-\$9,937	1.00	-\$9,937
1	0	\$14,829	-\$748	-\$1,527	-\$13,131	-\$10,732	\$3,252	0	\$2,675	0.91	\$2,431
2	0	\$15,125	-\$889	-\$1,554	-\$13,131	-\$10,444	\$3,222	0	\$2,775	0.83	\$2,291
3	0	\$15,428	-\$1,073	-\$1,584	-\$13,131	-\$10,122	\$3,195	0	\$2,837	0.75	\$2,129
4	0	\$15,736	-\$1,197	-\$1,617	-\$13,131	-\$9,761	\$3,144	0	\$2,938	0.68	\$2,004
5	0	\$16,051	-\$1,359	-\$1,652	-\$13,131	-\$9,356	\$3,092	0	\$3,005	0.62	\$1,862
6	0	\$16,372	-\$1,495	-\$2,027	-\$13,131	-\$8,903	\$3,106	0	\$2,832	0.56	\$1,594
7	0	\$16,699	-\$1,644	-\$2,097	-\$13,131	-\$8,396	\$3,034	0	\$2,869	0.51	\$1,468
8	0	\$17,033	-\$1,809	-\$2,173	-\$13,131	-\$7,828	\$2,952	0	\$2,881	0.46	\$1,340
9	0	\$17,374	-\$1,989	-\$2,255	-\$13,131	-\$7,191	\$2,859	0	\$2,866	0.42	\$1,211
10	0	\$17,721	-\$2,188	-\$2,344	-\$13,131	-\$6,479	\$2,753	0	\$2,820	0.38	\$1,083
11	0	\$18,076	-\$2,407	-\$3,766	-\$13,131	-\$5,680	\$2,963	0	\$1,746	0.35	\$609
12	0	\$18,437	-\$2,648	-\$3,983	-\$13,131	-\$4,786	\$2,854	0	\$1,541	0.32	\$489
13	0	\$18,806	-\$2,913	-\$4,219	-\$13,131	-\$3,785	\$2,729	0	\$1,285	0.29	\$370
14	0	\$19,182	-\$3,204	-\$4,475	-\$13,131	-\$2,663	\$2,585	0	\$972	0.26	\$254
15	0	\$19,566	-\$3,525	-\$4,752	-\$13,131	-\$1,407	\$2,421	\$9,937	\$10,531	0.24	\$2,505
<b>NET PRESENT VALUE (NPV)</b>											<b>\$ 11,704</b>

The same procedure is followed to calculate the NPV value for the 3 other experimental conditions. The results are tabulated in Table 16.

Table 16: Response Values of the 2<sup>2</sup> Factorial Experiment

(a) Design Variables Values

	$x_1$	$x_2$	<b>Response y</b>			
<b>Run #</b>	<b>A<sub>SC</sub> (m<sup>2</sup>)</b>	<b>V<sub>tank</sub> (m<sup>3</sup>)</b>	<b>Aux. Energy %</b>	<b>Investment USD</b>	<b>Fuel Savings USD</b>	<b>NPV USD</b>
1	40.97	4	75%	\$ 43,102.25	\$ 4,031.64	-\$ 17,630
2	139.298	4	19%	\$ 84,891.65	\$ 13,291.96	\$ 14,508
3	40.97	12	58%	\$ 57,582.25	\$ 6,846.15	-\$ 10,436
4	139.298	12	10%	\$ 99,371.65	\$ 14,828.50	\$ 11,704

(b) Coded Variables

$x_1$	$x_2$	$x_1 x_2$	$y$	<b>Response Symbol</b>
-1	-1	1	-\$ 17,630	(1)
1	-1	-1	\$ 14,508	a
-1	1	-1	-\$ 10,436	b
1	1	1	\$ 11,704	ab

where, the coded variables are as follows:

$$x_1 = \frac{A_{SC} - 90.13}{49.16} \text{ and } x_2 = \frac{V_{tank} - 8}{4}$$

The symbols (1), a, b and ab are used to represent the response of the runs from 1 to 4 respectively.

The contrast or the total effect of each variables is calculated based on the following equations [66]:

$$Contrast_A = ab + a - b - (1) \quad (18)$$

$$Contrast_B = ab + b - a - (1) \quad (19)$$

$$Contrast_{AB} = ab + (1) - a - b \quad (20)$$

where A represents the first variable A<sub>SC</sub>, B represents the second variable V<sub>tank</sub> and AB represents the effect of the interaction of both variables. Then, the sum of squares are calculated by equation 21 shown below [66]:

$$SS = \frac{[Contrast]^2}{4n} \quad (21)$$



where  $n$  is the number of replicates, which is equal to 1 because running the same simulation for certain design variables will always yield the same response (no random effect). The contribution of each design variable and their interaction effect on the response is shown in Table 17.

Table 17: The  $2^2$  Factorial Experiment Results

Variable	Sum of Squares	% Contribution
$x_1$	736525321	96.1%
$x_2$	4818025	0.6%
$x_1x_2$	24990001	3.3%

From the results of, it is confirmed that the effect of variable  $x_1$  ( $A_{SC}$ ) is the most dominant on the response with a percentage of 96.1%.

### 5.1.2 Solution Space

In the search for the most economical design, a solution space is explored by setting the design variables to the values shown in Table 18. Starting from the design center, the area of solar collectors,  $A_{SC}$ , is chosen to vary between the high and low values used in the  $2^2$  Factorial experiment with an increment of  $8.194 \text{ m}^2$ , which is equivalent to two solar collectors. Similarly, the volume of the storage tanks,  $V_{\text{tank}}$ , will vary between the high and low values but with an increment of  $2 \text{ m}^3$ .

Table 18: Selected Design Variables for the Solution Space

$A_{SC}$ ( $\text{m}^2$ )	$V_{\text{tank}}$ ( $\text{m}^3$ )
40.97	4
49.164	6
57.358	8
65.552	10
73.746	12
81.94	
90.134	
98.328	
106.522	
114.716	
122.91	
131.104	
139.298	

The 13 values of  $A_{SC}$  and 5 values of  $V_{tank}$  will yield a total of 65 combinations; in other words 65 solutions are to be explored. The objective is to find the maximum NPV within the selected solution space. The 65 TRNSYS simulations are run to calculate the auxiliary energy needed, investment cost and the fuel savings. Then, the economic study is performed for the 65 solutions to calculate the NPV. The results of this process are tabulated in Table 19.

The best design is found to be at solution number 46, where  $A_{SC}=114.7m^2$  and  $V_{tank}=4 m^3$ . The investment cost of this design is \$74,444. At this design, the SHS covers 77% of the heat demand of the house, leaving 23% to be covered by an auxiliary source. The fuel savings at the first year is \$12,631. The net present value for the investment in this design is \$19,428. A graphical display of the tabulated solution space results is shown in Appendix 14.

Table 19: Solution Space Results

Sol #	$A_{SC}$ (m <sup>2</sup> )	$V_{tank}$ (m <sup>3</sup> )	Aux. Energy %	Investment USD	Fuel Savings USD	NPV USD
1	40.97	4	75%	\$ 43,102.25	\$ 4,031.64	-\$ 17,630.00
2	40.97	6	69%	\$ 46,722.25	\$ 5,117.91	-\$ 12,834.00
3	40.97	8	63%	\$ 50,342.25	\$ 6,005.87	-\$ 9,593.00
4	40.97	10	60%	\$ 53,962.25	\$ 6,481.03	-\$ 9,583.00
5	40.97	12	58%	\$ 57,582.25	\$ 6,846.15	-\$ 10,436.00
6	49.164	4	70%	\$ 46,584.70	\$ 4,906.90	-\$ 14,141.00
7	49.164	6	54%	\$ 50,204.70	\$ 7,475.04	\$ 2,252.00
8	49.164	8	51%	\$ 53,824.70	\$ 8,104.61	\$ 3,472.00
9	49.164	10	48%	\$ 57,444.70	\$ 8,577.56	\$ 3,467.00
10	49.164	12	46%	\$ 61,064.70	\$ 8,853.08	\$ 1,916.00
11	57.358	4	59%	\$ 50,067.15	\$ 6,700.65	-\$ 3,460.00
12	57.358	6	46%	\$ 53,687.15	\$ 8,782.97	\$ 9,128.00
13	57.358	8	44%	\$ 57,307.15	\$ 9,221.31	\$ 8,854.00
14	57.358	10	41%	\$ 60,927.15	\$ 9,681.29	\$ 8,744.00
15	57.358	12	39%	\$ 64,547.15	\$ 10,043.49	\$ 7,871.00
16	65.552	4	41%	\$ 53,549.60	\$ 9,604.39	\$ 15,908.00
17	65.552	6	39%	\$ 57,169.60	\$ 10,044.56	\$ 15,644.00
18	65.552	8	38%	\$ 60,789.60	\$ 10,230.04	\$ 13,386.00
19	65.552	10	36%	\$ 64,409.60	\$ 10,423.79	\$ 11,193.00
20	65.552	12	34%	\$ 68,029.60	\$ 10,772.72	\$ 10,216.00
21	73.746	4	42%	\$ 57,032.05	\$ 9,532.83	\$ 11,986.00
22	73.746	6	37%	\$ 60,652.05	\$ 10,349.08	\$ 14,666.00
23	73.746	8	33%	\$ 64,272.05	\$ 11,052.20	\$ 16,458.00
24	73.746	10	32%	\$ 67,892.05	\$ 11,205.73	\$ 13,952.00
25	73.746	12	30%	\$ 71,512.05	\$ 11,427.89	\$ 11,981.00
26	81.94	4	38%	\$ 60,514.50	\$ 10,123.52	\$ 13,246.00
27	81.94	6	31%	\$ 64,134.50	\$ 11,353.45	\$ 19,166.00

Table 19: Solution Space Results (cont'd)

Sol #	A <sub>SC</sub> (m <sup>2</sup> )	V <sub>tank</sub> (m <sup>3</sup> )	Aux. Energy %	Investment USD	Fuel Savings USD	NPV USD
28	81.94	8	29%	\$ 67,754.50	\$ 11,702.43	\$ 18,186.00
29	81.94	10	27%	\$ 71,374.50	\$ 12,029.73	\$ 17,040.00
30	81.94	12	28%	\$ 74,994.50	\$ 11,751.00	\$ 11,151.00
31	90.134	4	34%	\$ 63,996.95	\$ 10,773.53	\$ 14,972.00
32	90.134	6	29%	\$ 67,616.95	\$ 11,601.71	\$ 17,744.00
33	90.134	8	29%	\$ 71,236.95	\$ 11,597.62	\$ 14,005.00
34	90.134	10	25%	\$ 74,856.95	\$ 12,304.64	\$ 15,830.00
35	90.134	12	23%	\$ 78,476.95	\$ 12,603.10	\$ 14,459.00
36	98.328	4	29%	\$ 67,479.40	\$ 11,601.59	\$ 18,089.00
37	98.328	6	28%	\$ 71,099.40	\$ 11,724.64	\$ 15,344.00
38	98.328	8	27%	\$ 74,719.40	\$ 12,018.81	\$ 13,941.00
39	98.328	10	23%	\$ 78,339.40	\$ 12,631.39	\$ 15,026.00
40	98.328	12	20%	\$ 81,959.40	\$ 13,063.14	\$ 14,696.00
41	106.522	4	28%	\$ 70,961.85	\$ 11,862.05	\$ 16,766.00
42	106.522	6	24%	\$ 74,581.85	\$ 12,446.96	\$ 17,635.00
43	106.522	8	22%	\$ 78,201.85	\$ 12,838.84	\$ 16,995.00
44	106.522	10	20%	\$ 81,821.85	\$ 13,123.87	\$ 15,519.00
45	106.522	12	20%	\$ 85,441.85	\$ 13,181.25	\$ 12,259.00
46	114.716	4	23%	\$ 74,444.30	\$ 12,631.42	\$ 19,428.00
47	114.716	6	20%	\$ 78,064.30	\$ 13,074.33	\$ 19,183.00
48	114.716	8	18%	\$ 81,684.30	\$ 13,411.87	\$ 18,120.00
49	114.716	10	16%	\$ 85,304.30	\$ 13,838.28	\$ 17,749.00
50	114.716	12	17%	\$ 88,924.30	\$ 13,577.55	\$ 11,998.00
51	122.91	4	22%	\$ 77,926.75	\$ 12,796.60	\$ 17,358.00
52	122.91	6	18%	\$ 81,546.75	\$ 13,359.90	\$ 18,058.00
53	122.91	8	17%	\$ 85,166.75	\$ 13,651.23	\$ 16,631.00
54	122.91	10	15%	\$ 88,786.75	\$ 13,941.18	\$ 15,193.00
55	122.91	12	13%	\$ 92,406.75	\$ 14,337.86	\$ 14,589.00
56	131.104	4	19%	\$ 81,409.20	\$ 13,216.81	\$ 17,286.00
57	131.104	6	16%	\$ 85,029.20	\$ 13,791.93	\$ 18,077.00
58	131.104	8	15%	\$ 88,649.20	\$ 13,970.69	\$ 15,766.00
59	131.104	10	13%	\$ 92,269.20	\$ 14,189.27	\$ 13,769.00
60	131.104	12	10%	\$ 95,889.20	\$ 14,799.42	\$ 14,839.00
61	139.298	4	19%	\$ 84,891.65	\$ 13,291.95	\$ 14,508.00
62	139.298	6	14%	\$ 88,511.65	\$ 14,023.34	\$ 16,526.00
63	139.298	8	15%	\$ 92,131.65	\$ 13,997.59	\$ 12,617.00
64	139.298	10	11%	\$ 95,751.65	\$ 14,530.72	\$ 13,081.00
65	139.298	12	10%	\$ 99,371.65	\$ 14,828.50	\$ 11,704.00

### 5.1.3 Applying International Fuel Prices

The results of the economic study of the 65 solutions, shown in Table 19, are based on the local diesel fuel price in Egypt, which is \$0.25/liter. As mentioned in section 4.4.2, the local price in Egypt is far below the international fuel price. Therefore, in this section a comparative study is carried out using the international minimum benchmark price, which is equal to \$ 1.05/liter. The economic study is repeated for the 65 solutions and the NPV is calculated at each case based on the international fuel price. The results of the calculations are shown in Table 20.

Table 20: Solution Space Results using International Fuel Prices

Sol #	$A_{sc}$ ( $m^2$ )	$V_{tank}$ ( $m^3$ )	Aux. Energy %	Investment USD	Fuel Savings USD	NPV USD
1	40.97	4	75%	\$ 43,102.25	\$ 16,815.34	\$ 90,384.00
2	40.97	6	69%	\$ 46,722.25	\$ 21,346.01	\$124,283.00
3	40.97	8	63%	\$ 50,342.25	\$ 25,049.56	\$151,315.00
4	40.97	10	60%	\$ 53,962.25	\$ 27,031.38	\$164,055.00
5	40.97	12	58%	\$ 57,582.25	\$ 28,554.22	\$172,984.00
6	49.164	4	70%	\$ 46,584.70	\$ 20,465.94	\$117,324.00
7	49.164	6	54%	\$ 50,204.70	\$ 31,177.25	\$202,522.00
8	49.164	8	51%	\$ 53,824.70	\$ 33,803.09	\$220,609.00
9	49.164	10	48%	\$ 57,444.70	\$ 35,775.67	\$233,275.00
10	49.164	12	46%	\$ 61,064.70	\$ 36,924.82	\$239,105.00
11	57.358	4	59%	\$ 50,067.15	\$ 27,947.40	\$176,062.00
12	57.358	6	46%	\$ 53,687.15	\$ 36,632.41	\$244,439.00
13	57.358	8	44%	\$ 57,307.15	\$ 38,460.66	\$255,909.00
14	57.358	10	41%	\$ 60,927.15	\$ 40,379.17	\$268,123.00
15	57.358	12	39%	\$ 64,547.15	\$ 41,889.86	\$276,954.00
16	65.552	4	41%	\$ 53,549.60	\$ 40,058.42	\$273,227.00
17	65.552	6	39%	\$ 57,169.60	\$ 41,894.31	\$284,756.00
18	65.552	8	38%	\$ 60,789.60	\$ 42,667.90	\$287,467.00
19	65.552	10	36%	\$ 64,409.60	\$ 43,476.04	\$290,465.00
20	65.552	12	34%	\$ 68,029.60	\$ 44,931.34	\$298,837.00
21	73.746	4	42%	\$ 57,032.05	\$ 39,759.95	\$267,387.00
22	73.746	6	37%	\$ 60,652.05	\$ 43,164.43	\$291,937.00
23	73.746	8	33%	\$ 64,272.05	\$ 46,097.03	\$312,566.00
24	73.746	10	32%	\$ 67,892.05	\$ 46,737.36	\$314,173.00
25	73.746	12	30%	\$ 71,512.05	\$ 47,663.98	\$318,155.00
26	81.94	4	38%	\$ 60,514.50	\$ 42,223.66	\$284,473.00
27	81.94	6	31%	\$ 64,134.50	\$ 47,353.47	\$323,345.00
28	81.94	8	29%	\$ 67,754.50	\$ 48,809.03	\$331,715.00
29	81.94	10	27%	\$ 71,374.50	\$ 50,174.14	\$339,338.00

Table 20: Solution Space Results using International Fuel Prices (cont'd)

Sol #	A <sub>SC</sub> (m <sup>2</sup> )	V <sub>tank</sub> (m <sup>3</sup> )	Aux. Energy %	Investment USD	Fuel Savings USD	NPV USD
30	81.94	12	28%	\$ 74,994.50	\$ 49,011.61	\$325,981.00
31	90.134	4	34%	\$ 63,996.95	\$ 44,934.73	\$303,613.00
32	90.134	6	29%	\$ 67,616.95	\$ 48,388.96	\$328,574.00
33	90.134	8	29%	\$ 71,236.95	\$ 48,371.89	\$324,726.00
34	90.134	10	25%	\$ 74,856.95	\$ 51,320.75	\$345,493.00
35	90.134	12	23%	\$ 78,476.95	\$ 52,565.58	\$352,118.00
36	98.328	4	29%	\$ 67,479.40	\$ 48,388.45	\$328,917.00
37	98.328	6	28%	\$ 71,099.40	\$ 48,901.68	\$329,468.00
38	98.328	8	27%	\$ 74,719.40	\$ 50,128.61	\$335,946.00
39	98.328	10	23%	\$ 78,339.40	\$ 52,683.57	\$353,443.00
40	98.328	12	20%	\$ 81,959.40	\$ 54,484.35	\$364,680.00
41	106.522	4	28%	\$ 70,961.85	\$ 49,474.79	\$334,571.00
42	106.522	6	24%	\$ 74,581.85	\$ 51,914.36	\$351,112.00
43	106.522	8	22%	\$ 78,201.85	\$ 53,548.83	\$360,971.00
44	106.522	10	20%	\$ 81,821.85	\$ 54,737.63	\$367,131.00
45	106.522	12	20%	\$ 85,441.85	\$ 54,976.94	\$365,408.00
46	114.716	4	23%	\$ 74,444.30	\$ 52,683.70	\$357,846.00
47	114.716	6	20%	\$ 78,064.30	\$ 54,531.02	\$369,468.00
48	114.716	8	18%	\$ 81,684.30	\$ 55,938.86	\$377,448.00
49	114.716	10	16%	\$ 85,304.30	\$ 57,717.35	\$388,501.00
50	114.716	12	17%	\$ 88,924.30	\$ 56,629.85	\$375,765.00
51	122.91	4	22%	\$ 77,926.75	\$ 53,372.66	\$360,202.00
52	122.91	6	18%	\$ 81,546.75	\$ 55,722.10	\$375,994.00
53	122.91	8	17%	\$ 85,166.75	\$ 56,937.18	\$382,372.00
54	122.91	10	15%	\$ 88,786.75	\$ 58,146.50	\$388,702.00
55	122.91	12	13%	\$ 92,406.75	\$ 59,801.00	\$398,725.00
56	131.104	4	19%	\$ 81,409.20	\$ 55,125.26	\$371,387.00
57	131.104	6	16%	\$ 85,029.20	\$ 57,524.03	\$387,587.00
58	131.104	8	15%	\$ 88,649.20	\$ 58,269.58	\$390,065.00
59	131.104	10	13%	\$ 92,269.20	\$ 59,181.24	\$393,925.00
60	131.104	12	10%	\$ 95,889.20	\$ 61,726.12	\$411,341.00
61	139.298	4	19%	\$ 84,891.65	\$ 55,438.69	\$370,623.00
62	139.298	6	14%	\$ 88,511.65	\$ 58,489.19	\$392,236.00
63	139.298	8	15%	\$ 92,131.65	\$ 58,381.80	\$387,638.00
64	139.298	10	11%	\$ 95,751.65	\$ 60,605.39	\$402,384.00
65	139.298	12	10%	\$ 99,371.65	\$ 61,847.39	\$408,985.00

The NPV calculated using the international fuel prices is found to be positive and of large value for the 65 solutions, which shows that all solutions are economically feasible and profitable. The best design is found to be at solution number 60, where A<sub>SC</sub>=131.1m<sup>2</sup> and V<sub>tank</sub>=12 m<sup>3</sup>. The investment

cost of this design is \$95,889. At this design, the SHS covers 90% of the heat demand of the house, leaving 10% to be covered by an auxiliary source. The fuel savings at the first year is \$61,726. The net present value for the investment in this design is \$411,341. A graphical display of the tabulated solution space results using the international fuel price is shown in Appendix 15.

#### 5.1.4 Effect of Infiltration Rate

According to the calculation made in section 3.3.3, the infiltration in the modeled house is found to be 1.19 air changes per hour (ACH). The broilers house under study is a closed system poultry house, which means that a high level of air tightness should be maintained. Referring to ASHRAE handbook[40], air leakage during winter time can be expressed as 0.45 ACH for a tight building with outside temperature of  $-1^{\circ}\text{C}$ . The effect of infiltration on the performance of the SHS is explored. Three different designs are selected from the solution space, including the best economical design which is solution number 46. The performance of the three designs, solutions number 12, 29 and 46, are evaluated by running TRNSYS simulation and calculating the NPV at 3 different levels of infiltration: 0.45, 1.19 and 2 ACH. The results are summarized in Table 21.

Table 21: Results of Varying Infiltration

Solution #	Infiltration ACH (1/hr)	Aux. Energy Needed (%)	NPV (USD)
Solution 12	0.45	33%	\$26,322.00
	1.19	46%	\$ 9,128.00
	2	55%	-\$ 1,900.00
Solution 29	0.45	23%	\$21,647.00
	1.19	27%	\$17,040.00
	2	36%	\$ 4,967.00
Solution 46	0.45	17%	\$27,021.00
	1.19	23%	\$19,428.00
	2	33%	\$ 6,492.00

By observing the tabulated results, it is clear that reducing the infiltration yields significant savings in the auxiliary energy needed given the same design variables. Thus, it yields an increase in the NPV of the investment. For the best selected design from within the solution space, solution

46, the NPV increases by a value of \$7,600 (about 39% increase) when reducing the infiltration rate from 1.19 to 0.45 ACH.

### 5.1.5 Effect of adding Latent heat Storage using PCM

According to the literature, latent heat storage technique should enhance the performance of the storage system due to its ability of storing energy at a constant temperature. To explore the effect of using latent heat storage on the designed SHS, the model developed by the IEA SHC TASK 32 [23], mentioned in section 2.2, is used as a replacement for the water storage tank of the SHS. The developed model, Type 840, is a TRNSYS component that simulates water tanks with integrated PCM modules of different geometries such as cylinders, spheres and plates. One of the developers of the model, Dr. Hermann Schranzhofer, is contacted to acquire the model and he responded by sending all the required files to run the model using TRNSYS.

The effect of using latent heat storage on the performance of the SHS is explored only on the design of solution 46, where  $A_{SC}=114.7\text{m}^2$  and  $V_{\text{tank}}=4\text{ m}^3$ . A  $5\text{ m}^3$  water storage tank with embedded PCM solid cylinders is used as a replacement for the stratified sensible energy storage tank described in section 4.2.4. The extra  $1\text{ m}^3$  of volume, from  $4$  to  $5\text{ m}^3$  is used to accommodate for the addition of the PCM cylinders volume. For clarification, a sketch for the cross section of a storage tank with embedded PCM cylinders is shown in Figure 22. In this study,  $D_i$  shown in the figure is equal to zero. The parameters of the model, TYPE 840, are set as follows:

- Tank Volume:  $5\text{ m}^3$
- Tank Height:  $2.2\text{ m}^3$
- Number of PCM modules (cylinders): 270
- Diameter of PCM modules (cylinders):  $D_o=50\text{mm}$
- PCM % of cross section area from the tank: 23%
- Overall heat loss coefficient of the storage tank:  $11.31\text{ W/K}$  (calculated using equation (11))

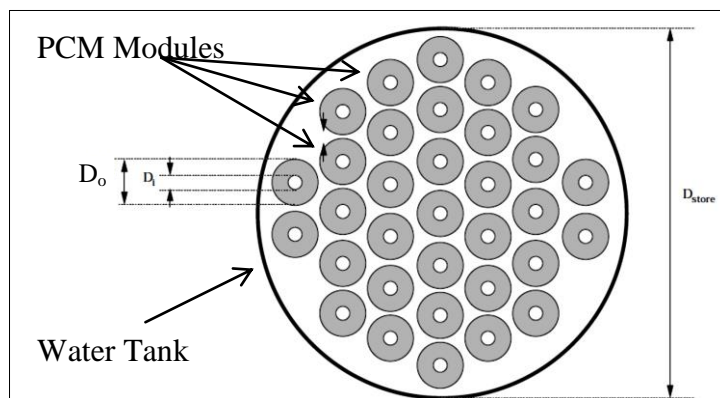


Figure 22: Sketch for Storage Tank Cross Section with Embedded PCM [67]

The validation of the model done by Schranzhofer et al [16] is carried out using Sodium Acetate Trihydrate with embedded graphite as the PCM material. The melting temperature of this material is between 56 and 60 °C as per the material data file supplied by the author, Dr. Hermann Schranzhofer. The same material is used for the simulation of this research.

TRNSYS simulation is run using the above mentioned parameters. The results are obtained for the design of solution 46. The percentage of auxiliary energy needed is calculated by the method shown in section 4.2.4 to be 21%. Thus, the replacement of the storage tanks from sensible water storage tanks to latent heat water storage tanks with embedded PCM resulted in a reduction of 2% of the auxiliary energy needed.

To evaluate the feasibility of using PCM, the NPV of the SHS after adding the PCM is calculated. First, the extra cost of adding PCM to the storage tanks is calculated. A supplier [68], is contacted to get a quotation for PCM material of similar specifications to the modelled one. The price is found to be £ 2.5/kg of capsulated PCM, which is equivalent to \$3.9/kg. According to the material data file, the density of the modelled PCM is 1100 kg/m<sup>3</sup>. Thus, the weight of the PCM used is calculated to be 1,155kg, which is equivalent to an extra cost of \$4,500. An additional cost of \$1,000 is estimated for the containers of the PCM. Therefore, the total extra cost for embedding PCM modules is calculated to be \$5,500. Second, the economic study is carried out using the local fuel price of \$0.25/liter to calculate the NPV. The fuel savings at the first year is calculated to be \$12,945. The total investment increased to be \$79,944. Following the same procedures done in section 5.1.1, the NPV value is calculated to be \$15,801 as shown in Appendix 16.

By comparing the calculated NPV to that of the SHS with sensible storage system, it is found that the NPV decreased by a value of \$3,627. In other words, for solution 46, it is more economical to use sensible water storage tanks than using latent heat storage tanks.



## 5.2 All-Green Solution: Bio-digesters as an Auxiliary Source of Energy

In this section, the SHS is complemented with a bio-digester to build a complete renewable all-green solution that can replace the traditional fuel based heating system of poultry houses. As mentioned in section 2.3 of the literature review, the anaerobic bio-digesters are used to produce biogas from litter, manure or any waste in general. The bird production of manure in a broilers house is calculated to be 1.95 kg/bird per production cycle [17]. Thus, the modeled house of capacity 24,000 broilers in this research produces 46,754 kg of manure per cycle, which is equal to about 306 tons of manure per year.

### 5.2.1 Modeled HouseWaste to Energy Production

According to El-Haggar[69], 7.7 kg of dry chicken manure can produce 1 m<sup>3</sup> of biogas and the calorific value of 1 m<sup>3</sup> of biogas is equivalent to that of 0.6 liter of kerosene (or diesel fuel). The educational manual of SKG Sangha [35] states that the broilers chicken manure moisture content is 25%. From this information, it can be concluded that 10.3 kg of moist chicken manure can produce 1 m<sup>3</sup> of biogas. Therefore, the modeled house of capacity 24,000 broilers is capable of producing 29,800 m<sup>3</sup> of biogas, which is equivalent to 17,877 liters of kerosene (or diesel fuel) per year.

Returning to the results of calculations in section 5.1.2, it is found that the auxiliary energy needed for the design of solution 46 is 23%. Thus, 23% of the total yearly consumption of fuel, which is equal to about 15,000 liters, is needed to complement the SHS. This being said, it is clear that the amount of fuel that can be produced from the waste of the chicken per year is sufficient to cover the auxiliary energy needed to complement the SHS design of solution 46.

Based on the above, an all green solution for heating the modelled poultry house is presented by integrating the simple anaerobic bio-digesters model Deenbandhu that is introduced by SKG Sangha organization in Egypt with the designed SHS of solution 46. The 23% of auxiliary energy needed for this design is equivalent to 24,950 m<sup>3</sup> of biogas per year. Thus, it is required to produce daily 68.3 m<sup>3</sup> of biogas. The largest available unit that SKG Sangha currently establishes in Egypt is a 6 m<sup>3</sup> bio-digester unit. Therefore, 12 units of 6 m<sup>3</sup> of daily production each are needed to cover the auxiliary heating demand of the modeled poultry house. It has to be noted that the produced biogas have to be stored to be used at different times of the day and the year depending on the varying heat demand.

## 5.2.2 Economic Study of the All-Green Solution

To evaluate the performance of the all green solution, an economic study is carried out to calculate the NPV of the investment. First, the extra cost of establishing the bio-digesters is calculated. According to SKG Sangha in Egypt, the cost of establishing the 6 m<sup>3</sup> unit is L.E 10,000 [34]. Thus, the total cost for establishing the 12 units is calculated to be about \$16,800. By adding this value to the cost of the SHS of solution 46, the total investment cost becomes \$91,244. The auxiliary energy needed in this case will be equal to zero since all the auxiliary energy will be supplied by the bio-digesters. Therefore, 100% of the yearly fuel consumption will be saved. Using the local fuel price of Egypt of \$0.25/liter, the fuel savings at the first year becomes \$16,387. Following the same procedures of section 5.1.1, the NPV value is calculated to be \$30,237 as shown in Appendix 17. Therefore, an additional value of \$10,800 is added to the NPV when using bio-digesters as the auxiliary source of energy instead of diesel fuel.

## 5.2.3 Space Constraint

However, it has to be noted that the space required for the establishment of a 6 m<sup>3</sup> bio-digester is 4.6×4.6m (21.16 m<sup>2</sup>) per bio-digester unit. Therefore, a total area of 254 m<sup>2</sup> should be available around the poultry house to be able establish the required bio-digester units. Also, the bio-digesters require a suitable setting for mixing the manure and waste of the poultry house with water before being fed into the bio-digesters. Finally, the handling of the discharged excess slurry and residuals of the bio-digesters has to be put into consideration.

## CHAPTER 6

### CONCLUSIONS

#### 6.1 Research Outcomes

In this work, the heating demand of a broilers poultry house of capacity 24000 birds located in Al Menia governorate in Egypt is calculated hourly over a complete year using TRNSYS simulation. The highest heating demands were found to be at the beginning of the 1<sup>st</sup> and 7<sup>th</sup> (last) production cycle, where the peak value reached 161 kW at the first day of the 1<sup>st</sup> cycle. To obtain these results, the house is modeled in full details and all the heat gains were calculated and fed as an input to the model.

Knowing the heating demand of the house, a solar heating system (SHS) is designed to cover part of this demand. The system consists of: Evacuated tubes as solar thermal collectors, water storage tanks as a storage system and fan coil units as heat distribution system. The two main design variables of the SHS are the area of the solar collector ( $A_{SC}$ ) and the volume of the storage tanks ( $V_{tank}$ ). The pricing of the system is calculated for each component and summarized using equation 12 in section 4.3.6. To evaluate the performance of the SHS under different design variables, the Life Cycle Savings (LCS) economic evaluation criteria is used, where the difference between the life-cycle costs of a conventional fuel-only system and the life-cycle cost of the SHS plus auxiliary energy source is calculated and presented in a discounted cash flow to determine the NPV.

The fuel consumption of the modelled house using traditional fuel-based heating system is found to be about 65000 liters per year. The local price of diesel fuel in Egypt is found to be \$0.25/liter, while the international minimum benchmark price is \$1.05/liter. The fuel savings achieved by the SHS is calculated based on the percentage of auxiliary energy needed using equation 14 in section 4.5.5. The life-time of the SHS upon which it will be economically studied is 15 years. The SHS is assumed to be 90% financed by a loan with an interest rate of 12%. The maintenance expense is defined as operational costs and materials (spare parts) costs and calculated yearly with an inflation rate of 8.5%. The parasitic energy expense is estimated yearly based on the operational hours of the system. The tax savings are calculated based on the Egyptian tax law and the discount rate is concluded to be 10.05%. A re-sale value of the SHS is set to be 10% of its cost after 15 years.

A  $2^2$  Factorial experiment is carried out to examine the magnitude and direction of the effect of each variable on the performance of the SHS. The high and low values of the two design variables were set to be  $139 \text{ m}^2$  and  $40 \text{ m}^2$  and  $12 \text{ m}^3$  and  $4 \text{ m}^3$  respectively. The NPV is calculated for the 4 experimental conditions. It is found that increasing the  $A_{SC}$  had 96% of the contribution to the increase in the NPV.

To determine the most economical design, a solution space consisting of 65 solutions is created by varying the design variable  $A_{SC}$  from 40 to  $139 \text{ m}^2$  and  $V_{\text{tank}}$  from 4 to  $12 \text{ m}^3$ . The NPV is calculated at each solution using the local fuel price in Egypt, which is \$0.25/liter. The best solution with highest NPV of \$19,428 is found to be at solution 46, where  $A_{SC}=114.7 \text{ m}^2$  and  $V_{\text{tank}}=4 \text{ m}^3$ . The investment cost of this design is \$74,444 and it covers 77% of the heat demand of the house, leaving 23% to be covered by an auxiliary source.

The economic study is repeated for the 65 solutions using the international minimum benchmark price, which is equal to \$ 1.05 /liter. The highest NPV is found to be \$411,341 at solution number 60, where  $A_{SC}=131.1 \text{ m}^2$  and  $V_{\text{tank}}=12 \text{ m}^3$ . The investment cost of this SHS design is \$95,889 and it covers 90% of the heat demand of the house, leaving 10% to be covered by an auxiliary source. It has to be noted that increasing the fuel price to match the minimum international value, which is almost 4 times the local price, caused a tremendous increase in the NPV. The highest NPV using the international fuel price is 21 times the highest NPV calculated using the local prices.

Thus, it can be concluded that if the fuel prices in Egypt increased to reach the minimum international fuel price, then heating the modelled poultry house using the SHS will be vital and extremely profitable in comparison to the conventional fuel-based heating system. Yet, given the current local fuel price, it is still economically acceptable to use the SHS for heating the modelled house when selecting the suitable design.

A study is done to evaluate the effect of the house's infiltration rate on the performance of the SHS. The modelled house under study is estimated to have an infiltration rate of 1.19 ACH, which is a very high value compared to the standard ASHRAE value of 0.45 ACH for a tight building. The value of infiltration rate of the modeled house is varied to be 0.45 ACH and 2 ACH to check the effect of increasing and decreasing its value. The economic study is repeated using these 2 values for 3 different designs. The 3 designs were selected from the solution space to be solution 12, 29 and 46 to cover different regions of the solution space and to include the best economic solution, which is solution 46. The NPV for each solution is found to increase with decreasing the infiltration rate. For the best economic design, solution 46, the NPV can increase by a value of \$7600 when

reducing the infiltration rate from 1.19 to 0.45 ACH, where the auxiliary energy needed drops from 23% to 17%. Enhancing the infiltration rate to be 0.45, will increase the fuel savings for the first year by a value of \$1000. Therefore, it is recommended to enhance the tightness of the building to reach a lower infiltration rate for better economic results.

A further study is done to check the effect of using latent heat storage technique on the performance of the SHS. The water storage tank used in the SHS is replaced by a water tank with embedded PCM modules. The new tank is modelled using TYPE 840 TRNSYS component, which is developed by the IEA SHC TASK 32 and is obtained from one of the authors, Dr. Hermann Schranzhofer. The PCM used is Sodium Acetate Trihydrate with embedded graphite of melting temperature between 56 and 60 °C. The NPV calculated for the SHS with embedded PCM is found to be less than that of the SHS with sensible heat storage by a value of \$3,627. Therefore, given the cost of the PCM modules, using the described latent heat storage technique yielded a negative effect on the economic performance of the system. However, it has to be noted that the fan coil unit performance is rated at inlet water temperature of 90°C, which is much higher than the phase change temperature of the material used.

In an attempt to build a completely green heating solution for poultry houses, bio-digesters are introduced to produce biogas from the waste/manure of the birds. From the calculations, it is found that 12 units of a simple anaerobic bio-digester model called Deenbandhu of capacity 6 m<sup>3</sup> each are capable of covering the auxiliary energy needed by the SHS design of solution 46. The total cost for establishing the 12 units as per SKG Sangha foundation in Egypt is found to be \$16800. An economic study is carried out for the all-green heating system, where the bio-digesters are used as the auxiliary source for the SHS design of solution 46. The NPV value is calculated to be \$30,237, which is much higher than that of using diesel fuel as the auxiliary source of energy. The 6m<sup>3</sup> of biogas produced daily from the bio-digesters are stored to be used as the auxiliary source of energy for the SHS all over the year. Therefore, it can be concluded that the modelled poultry house produces enough manure that can be transformed into biogas using the bio-digesters to complement the SHS in covering the full heating demand of the house economically. However, it has to be noted that the bio-digesters require an area of 254 m<sup>2</sup> to be established. Also, the complexity of mixing the waste with water before entering the bio-digester and handling the excess discharge of the bio-digester has to be put into consideration when applying the suggested all-green heating solution.

## 6.2 Future Work

For future work on this research, there are several recommendations that are suggested as stated below:

- Modeling the litter:

For any broilers house, there is a layer of straw, wood shavings or other dry organic material that is spread on the floor of the building to be used as bedding for the birds. This layer is not included in the TRNSYS model created in this research. It is expected that this layer will have a certain heat capacity that should be included in the energy balance of the model. Therefore, it is recommended to model the litter layer for more accurate results.

- Including piping heat losses:

There is a network of pipes connecting the solar collectors to the storage tanks, which are the pipes of the solar loop. These pipes should be well insulated. However, still there should be heat losses occurring by convection to the atmosphere. Thus, for more accurate results, it is recommended to add the heat losses from the pipes and connections to the model.

- Using PID controllers:

The controllers used in this research to activate the pumps and fan coils are ON-OFF controllers. It is recommended to replace them with proportional-integral-derivative controller (PID controllers) to have more accurate and stable control of temperatures.

- Introducing minimum ventilation through the fan coil units:

To achieve the required minimum ventilation rate for the poultry house, certain quantity of fresh air is introduced into the house through air inlets. At cold weather, the low temperature of the incoming air may have negative impact on the birds inside the house. Since the SHS designed in this research includes fan coil units, it is recommended to introduce the fresh air through the fan coil units so that the incoming air temperature be suitable for the birds.

- Using PCM with higher melting temperature:

The result of embedding PCM modules in water storage tanks is not satisfactory. It is recommended to study the effect of embedding PCM with higher melting temperature that matches the operating temperature range of the SHS.

- Exploring the environmental aspect:

In this research work, the SHS is studied economically, but, its environmental effect is not tackled. The SHS and the all-green heating solution are expected to contribute to the reduction of gas emissions with a considerable amount that is worth studying. In addition to its environmental benefit, the reduction of the CO<sub>2</sub> footprint for poultry houses using the SHS could result also in financial benefits. Several international organizations offer grants and funds for projects that contribute to the reduction of CO<sub>2</sub> footprint. Therefore, it is recommended to investigate the environmental aspect of the SHS and the all-green solution and explore its effect on the economics of the system.

- Integrating cooling to the SHS:

Since the poultry houses require high cooling capacity during the summer time, it is recommended to integrate a renewable source of cooling to the system. This can be done by adding a chiller that feeds the fan coil units with cold water during summer time. Also, the idea of adding a geothermal pump to the SHS can be explored.

- Validating the results

The amount of heat required for a poultry house and the economical study of the SHS design is based on the results obtained from TRNSYS simulations. It is recommended to validate these results by carrying out an experimental investigation to compare the TRNSYS simulation results with the experimental results.

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## APPENDIX 1: BROILERS HOUSE SET TEMPERATURES

Based on the recommended target temperatures mentioned in Table 5, the following is interpolated:

Table 22: Interpolated Set Temperatures

Age (days)	Temp (°C)
0	33
1	30
2	29
3	28
4	27.67
5	27.17
6	27
7	26.33
8	25.67
9	26
10	25.67
11	25.33
12	25
13	24.67
14	24.33
15	24
16	23.67
17	23.33
18	23
19	22.67
20	22.33
21	22
22	21.67
23	21.33
24	21
25	20.67
26	20.33
27-42	20

## APPENDIX 2: RECOMMENDED MINIMUM VENTILATION

Table 23: Arbor Acres Minimum Recommended Ventilation Rates [36]

Live Weight kg (lbs)	Minimum Ventilation Rate m <sup>3</sup> /hour (ft <sup>3</sup> /min)	Maximum Ventilation Rate m <sup>3</sup> /hour (ft <sup>3</sup> /min)
0.050 (0.110)	0.074 (0.044)	0.761 (0.448)
0.100 (0.220)	0.125 (0.074)	1.280 (0.754)
0.200 (0.441)	0.210 (0.124)	2.153 (1.268)
0.300 (0.661)	0.285 (0.168)	2.919 (1.719)
0.400 (0.882)	0.353 (0.208)	3.621 (2.133)
0.500 (1.102)	0.417 (0.246)	4.281 (2.522)
0.600 (1.323)	0.479 (0.282)	4.908 (2.891)
0.700 (1.543)	0.537 (0.316)	5.510 (3.245)
0.800 (1.764)	0.594 (0.350)	6.090 (3.587)
0.900 (1.984)	0.649 (0.382)	6.653 (3.919)
1.000 (2.205)	0.702 (0.413)	7.200 (4.241)
1.200 (2.646)	0.805 (0.474)	8.255 (4.862)
1.400 (3.086)	0.904 (0.532)	9.267 (5.458)
1.600 (3.527)	0.999 (0.588)	10.243 (6.033)
1.800 (3.968)	1.091 (0.643)	11.189 (6.590)
2.000 (4.409)	1.181 (0.696)	12.109 (7.132)
2.200 (4.850)	1.268 (0.747)	13.006 (7.661)
2.400 (5.291)	1.354 (0.798)	13.883 (8.177)
2.600 (5.732)	1.437 (0.846)	14.42 (8.683)
2.800 (6.173)	1.520 (0.895)	15.585 (9.180)
3.000 (6.614)	1.600 (0.942)	16.412 (9.667)
3.200 (7.055)	1.680 (0.990)	17.226 (10.146)
3.400 (7.496)	1.758 (1.035)	18.028 (10.618)
3.600 (7.937)	1.835 (1.081)	18.817 (11.083)
3.800 (8.377)	1.911 (1.126)	19.596 (11.542)
4.000 (8.818)	1.986 (1.170)	20.365 (11.995)
4.200 (9.259)	2.060 (1.213)	21.124 (12.442)
4.400 (9.700)	2.133 (1.256)	21.874 (12.884)

## APPENDIX 3: MINIMUM VENTILATION CALCULATIONS

Table 24: Calculated Required Minimum Ventilation (c)

Age (Days)	Body Weight (Kg)	No. of Birds	Total Min. Vent. (m <sup>3</sup> /hour)	Total Min. Vent. (Kg/hour)
0	0,042	24000	1.776,00	2.131,20
1	0,056	23928	1.770,67	2.124,81
2	0,07	23904	1.768,90	2.122,68
3	0,087	23880	2.985,00	3.582,00
4	0,106	23880	2.985,00	3.582,00
5	0,128	23760	2.970,00	3.564,00
6	0,152	23616	2.952,00	3.542,40
7	0,179	23544	4.944,24	5.933,09
8	0,208	23520	4.939,20	5.927,04
9	0,241	23520	4.939,20	5.927,04
10	0,276	23472	6.689,52	8.027,42
11	0,315	23472	6.689,52	8.027,42
12	0,357	23472	8.285,62	9.942,74
13	0,402	23472	8.285,62	9.942,74
14	0,45	23448	9.777,82	11.733,38
15	0,501	23448	9.777,82	11.733,38
16	0,555	23400	11.208,60	13.450,32
17	0,612	23376	11.197,10	13.436,52
18	0,672	23376	12.552,91	15.063,49
19	0,734	23376	12.552,91	15.063,49
20	0,8	23376	13.885,34	16.662,41
21	0,868	23376	15.171,02	18.205,23
22	0,938	23376	15.171,02	18.205,23
23	1,011	23352	16.393,10	19.671,72

Table 24: Calculated Required Minimum Ventilation (cont'd)

Age (Days)	Body Weight (Kg)	No. of Birds	Total Min. Vent. (m <sup>3</sup> /hour)	Total Min. Vent. (Kg/hour)
24	1,086	23304	16.359,41	19.631,29
25	1,164	23304	18.759,72	22.511,66
26	1,243	23304	18.759,72	22.511,66
27	1,323	23280	21.045,12	25.254,14
28	1,406	23280	21.045,12	25.254,14
29	1,49	23280	23.256,72	27.908,06
30	1,575	23256	23.232,74	27.879,29
31	1,661	23256	23.232,74	27.879,29
32	1,748	23256	25.372,30	30.446,76
33	1,836	23256	25.372,30	30.446,76
34	1,924	23232	27.436,99	32.924,39
35	2,013	23208	27.408,65	32.890,38
36	2,102	23184	29.397,31	35.276,77
37	2,192	23160	29.366,88	35.240,26
38	2,281	23136	29.336,45	35.203,74
39	2,37	23136	31.326,14	37.591,37
40	2,459	23136	31.326,14	37.591,37
41	2,548	23112	33.211,94	39.854,33
42	2,637	23112	33.211,94	39.854,33



## APPENDIX 4: BIRDS HEAT PRODUCTION

Using Gates et al. [6] empirical equations, Arbor Acres birds weights [44], and knowing the set temperatures calculated in section 3.4.1 at each bird's age, the SHP and LHP are calculated and the results are summarized in Table 25 below:

Table 25: Calculated Sensible, Latent and Total Heat Produced by the birds (cc)

Age (Days)	Body Weight (g)	SHP (W/KG)	LHP (W/KG)	THP (W/KG)	SHP (W/Bird)	LHP (W/Bird)	THP (W/Bird)
0	42			-			-
1	56			-			-
2	70		0,32	0,32	-	0.02	0.02
3	87	0,69	8,85	9,54	0.06	0.77	0.83
4	106	2,35	13,70	16,05	0.25	1.45	1.70
5	128	4,94	14,88	19,82	0.63	1.91	2.54
6	152	5,46	14,31	19,77	0.83	2.18	3.01
7	179	5,64	13,17	18,81	1.01	2.36	3.37
8	208	5,81	12,14	17,95	1.21	2.52	3.73
9	241	5,97	11,22	17,19	1.44	2.70	4.14
10	276	6,12	10,41	16,52	1.69	2.87	4.56
11	315	6,24	9,71	15,95	1.97	3.06	5.02
12	357	6,35	9,13	15,48	2.27	3.26	5.52
13	402	6,44	8,65	15,09	2.59	3.48	6.07
14	450	6,51	8,29	14,80	2.93	3.73	6.66
15	501	6,56	8,05	14,60	3.29	4.03	7.32
16	555	6,59	7,88	14,47	3.66	4.37	8.03
17	612	6,59	7,74	14,33	4.04	4.73	8.77
18	672	6,58	7,59	14,17	4.42	5.10	9.52
19	734	6,54	7,44	13,99	4.80	5.46	10.27
20	800	6,02	7,26	13,29	4.82	5.81	10.63
21	868	5,67	7,09	12,76	4.93	6.15	11.08

Table 25: Calculated Sensible, Latent and Total Heat Produced by the birds (cont'd)

Age (Days)	Body Weight (g)	SHP (W/KG)	LHP (W/KG)	THP (W/KG)	SHP (W/Bird)	LHP (W/Bird)	THP (W/Bird)
22	938	5,36	6,91	12,27	5.03	6.48	11.51
23	1011	5,08	6,72	11,80	5.13	6.80	11.93
24	1086	4,83	6,54	11,36	5.24	7.10	12.34
25	1164	4,60	6,34	10,95	5.36	7.39	12.74
26	1243	4,41	6,15	10,56	5.48	7.65	13.13
27	1323	4,24	5,96	10,20	5.60	7.89	13.49
28	1406	4,09	5,77	9,86	5.75	8.11	13.86
29	1490	3,96	5,58	9,54	5.90	8.32	14.22
30	1575	3,85	5,40	9,25	6.06	8.51	14.57
31	1661	3,76	5,22	8,98	6.24	8.68	14.92
32	1748	3,68	5,06	8,73	6.43	8.84	15.27
33	1836	3,61	4,89	8,51	6.63	8.99	15.62
34	1924	3,56	4,74	8,30	6.85	9.13	15.97
35	2013	3,51	4,60	8,12	7.07	9.27	16.34
36	2102	3,47	4,48	7,95	7.30	9.41	16.71
37	2192	3,44	4,36	7,80	7.54	9.57	17.11
38	2281	3,41	4,27	7,68	7.78	9.73	17.51
39	2370	3,38	4,19	7,57	8.01	9.92	17.93
40	2459	3,37	4,12	7,50	8.30	10.14	18.43
41	2548	3,37	4,08	7,45	8.60	10.39	18.99
42	2637	3,37	4,06	7,43	8.90	10.70	19.60

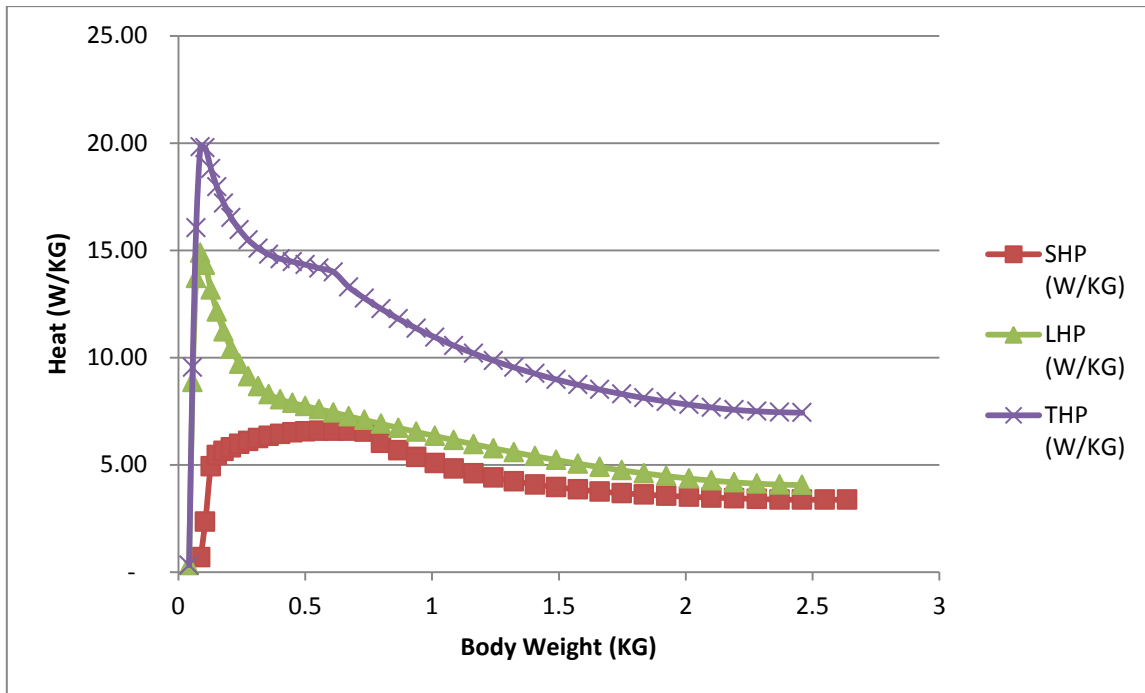


Figure 23: Plotted Sensible, Latent and Total Heat Produced by the birds

## APPENDIX 5: TRNSYS SIMULATION FOR HEAT DEMAND CALCULATION DETAILS

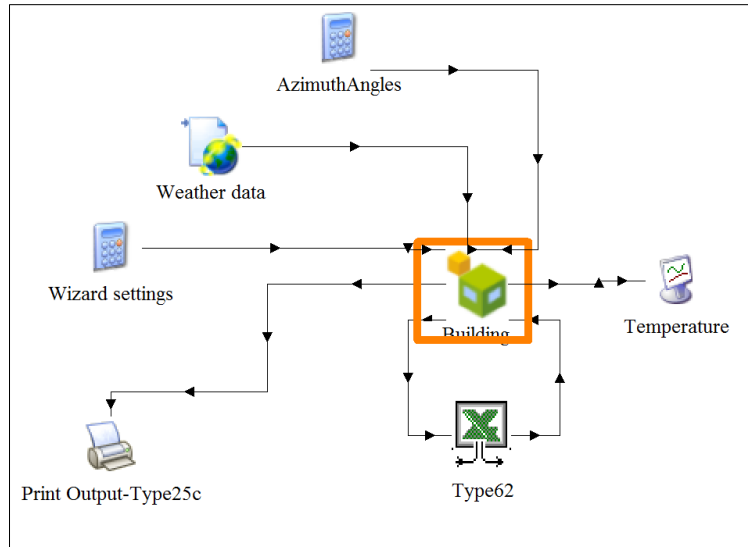


Figure 24: Building Component "Type 56" Connections

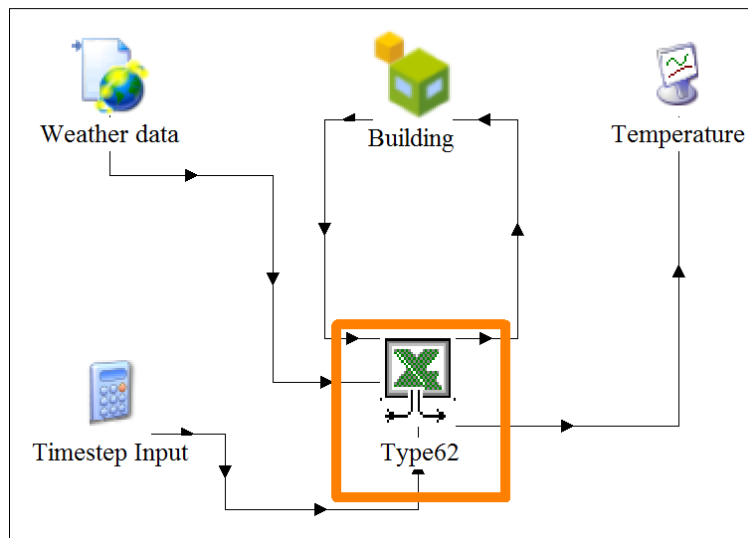


Figure 25: VBA Excel File "Type 62" Connections

## APPENDIX 6: FAN COIL PERFORMANCE

High Capacity Two Row Coil at Standard Conditions  
(200°F Entering Water / 60°F Entering Air) [48]

Unit Size	High Fan Speed Data				Low Fan Speed Data				Water Data	
	CFM	Btu/hr	WTD	FAT	CFM	Btu/hr	WTD	FAT	GPM	WPD (ft)
002	250	20,200	42.0	134	140	13,000	27.1	146	1	0.7
		21,600	30.1	140		13,900	19.4	152	1.5	152.0
		22,700	23.7	144		14,600	15.2	156	2	1.8
		<b>23,400</b>	<b>20.0</b>	<b>146</b>		<b>15,000</b>	<b>12.9</b>	<b>159</b>	<b>2.4</b>	<b>2.7</b>
		23,700	16.5	148		15,300	10.6	161	3	4.3
003	330	31,100	32.4	148	195	21,000	21.9	159	2	1.4
		31,900	26.6	151		21,600	18.0	162	2.5	2.1
		32,600	22.6	152		22,000	15.3	164	3	2.8
		<b>33,000</b>	<b>20.0</b>	<b>154</b>		<b>22,300</b>	<b>13.5</b>	<b>166</b>	<b>3.4</b>	<b>3.5</b>
		33,300	17.4	155		22,500	11.7	167	4	4.5
004	450	41,200	43.0	146	270	28,300	29.4	156	2	1.5
		42,600	35.3	149		29,000	24.2	159	2.5	2.4
		43,300	30.1	151		29,700	20.6	161	3	2.9
		44,500	23.2	153		30,500	15.9	164	4	5.0
		<b>44,900</b>	<b>20.0</b>	<b>154</b>		<b>30,800</b>	<b>13.7</b>	<b>165</b>	<b>4.7</b>	<b>8.7</b>
006	620	49,700	51.7	134	370	34,600	36.0	146	2	1.4
		53,600	37.2	140		37,300	25.9	153	3	2.8
		56,500	29.5	145		39,300	20.5	158	4	4.8
		58,400	24.3	148		40,600	16.9	161	5	7.2
		<b>59,300</b>	<b>20.0</b>	<b>149</b>		<b>41,200</b>	<b>13.9</b>	<b>163</b>	<b>6.2</b>	<b>10.7</b>
008	840	66,800	27.9	134	540	50,500	21.1	146	5	1.0
		70,900	21.1	138		53,600	15.9	151	7	1.7
		<b>71,700</b>	<b>20.0</b>	<b>139</b>		<b>54,200</b>	<b>15.1</b>	<b>152</b>	<b>7.5</b>	<b>1.9</b>
		74,900	15.6	143		56,600	11.8	157	10	3.2
		76,100	13.2	144		57,500	10.0	158	4.3	
010	1050	79,400	28.0	130	680	61,600	21.4	144	6	1.4
		83,000	21.6	134		64,500	16.8	147	8	2.2
		<b>84,200</b>	<b>20.0</b>	<b>135</b>		<b>65,400</b>	<b>15.5</b>	<b>149</b>	<b>8.8</b>	<b>2.5</b>
		87,600	15.2	138		68,000	11.8	152	12	4.3
		88,500	13.2	138		68,700	10.2	153	14	5.8
012	1240	99,000	29.4	135	790	76,400	22.7	149	7	1.7
		102,300	23.7	137		78,900	18.3	152	9	2.6
		<b>104,800</b>	<b>20.0</b>	<b>139</b>		<b>80,800</b>	<b>15.4</b>	<b>154</b>	<b>10.9</b>	<b>3.7</b>
		106,800	17.1	141		82,400	13.2	156	13	5.0
		107,900	15.0	142		83,300	11.6	157	15	6.5
014	1430	113,400	26.2	134	915	87,000	20.1	148	9	2.6
		115,900	22.0	136		89,000	16.9	150	11	3.7
		<b>117,200</b>	<b>20.0</b>	<b>137</b>		<b>90,000</b>	<b>15.4</b>	<b>151</b>	<b>12.2</b>	<b>4.5</b>
		119,500	16.6	138		91,800	12.7	152	15	6.5
		120,600	14.8	139		92,600	11.3	153	17	8.2

## APPENDIX 7: SOLAR COLLECTOR PERFORMANCE

### SOLAR COLLECTOR CERTIFICATION AND RATING[49]

SUPPLIER: Oventrop Corporation

29 Knipes Road

East Granby, CT 06026 USA

MODEL: OV 5-16 AS/AB

COLLECTOR TYPE: Tubular

CERTIFICATION#: 2006027B

COLLECTOR THERMAL PERFORMANCE RATING							
Kilowatt-hours (thermal) Per Panel Per Day				Thousands of Btu Per Panel Per Day			
Climate ->	High Radiation (6.3 kWh/m <sup>2</sup> .day)	Medium Radiation (4.7 kWh/m <sup>2</sup> .day)	Low Radiation (3.1 kWh/m <sup>2</sup> .day)	Climate ->	High Radiation (2000 Btu/ft <sup>2</sup> .day)	Medium Radiation (1500 Btu/ft <sup>2</sup> .day)	Low Radiation (1000 Btu/ft <sup>2</sup> .day)
Category (Ti-Ta)				Category (Ti-Ta)			
A (-5 °C)	12.5	9.4	6.4	A (-9 °F)	42.6	32.2	21.8
B (5 °C)	11.8	8.7	5.7	B (9 °F)	40.2	29.8	19.4
C (20 °C)	10.6	7.6	4.6	C (36 °F)	36.3	26.0	15.7
D (50 °C)	8.5	5.5	2.6	D (90 °F)	29.0	18.6	9.0
E (80 °C)	6.3	3.5	0.8	E (144 °F)	21.6	12.0	2.8

A- Pool Heating (Warm Climate) B- Pool Heating (Cool Climate) C- Water Heating (Warm Climate)  
D- Space & Water Heating (Cool Climate) E- Commercial Hot Water & Cooling

COLLECTOR SPECIFICATIONS					
Gross Area:	4.097 m <sup>2</sup>	44.10 ft <sup>2</sup>	Dry Weight:	105 kg	231 lb
Net Aperture Area:	1.304 m <sup>2</sup>	14.04 ft <sup>2</sup>	Fluid Capacity:	1.0 liter	0.3 gal
Absorber Area:	0.000 m <sup>2</sup>	0.00 ft <sup>2</sup>	Test Pressure:	1000 kPa	145 psi

TECHNICAL INFORMATION			Tested in accordance with:		
ISO Efficiency Equation [NOTE: Based on gross area and (P)=Ti-Ta]					
SI UNITS:	$\eta = 0.489 - 1.58550(P/G) - 0.00524(P^2/G)$	Y Intercept:	0.492	Slope:	-1.924 W/m <sup>2</sup> .°C
IP UNITS:	$\eta = 0.489 - 0.27943(P/G) - 0.00051(P^2/G)$	Y Intercept:	0.492	Slope:	-0.339 Btu/hr.ft <sup>2</sup> .°F

Transverse Incident Angle Modifier							Longitudinal Incident Angle Modifier at 50°:			
$\theta$	10	20	30	40	50	60	70	Test Fluid:	Water	
K $\tau\alpha$	1.01	1.06	1.12	1.19	1.19	0.87		Test Mass Flow Rate:	0.0202 kg/(s m <sup>2</sup> )	14.91 lb/(hr ft <sup>2</sup> )

## APPENDIX 8: TRNSYS SIMULATION FOR SHS DETAILS

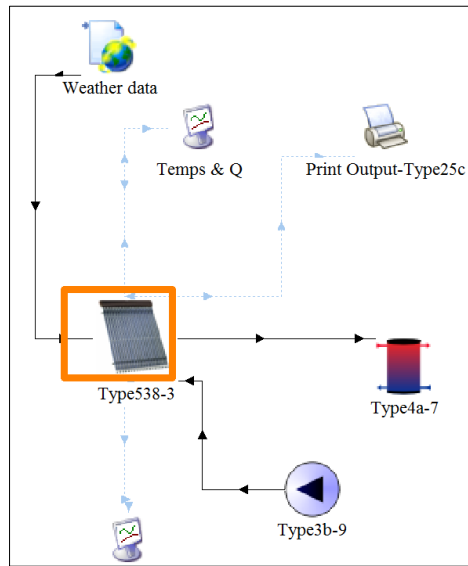


Figure 26: Solar Collector "Type 538" Connections

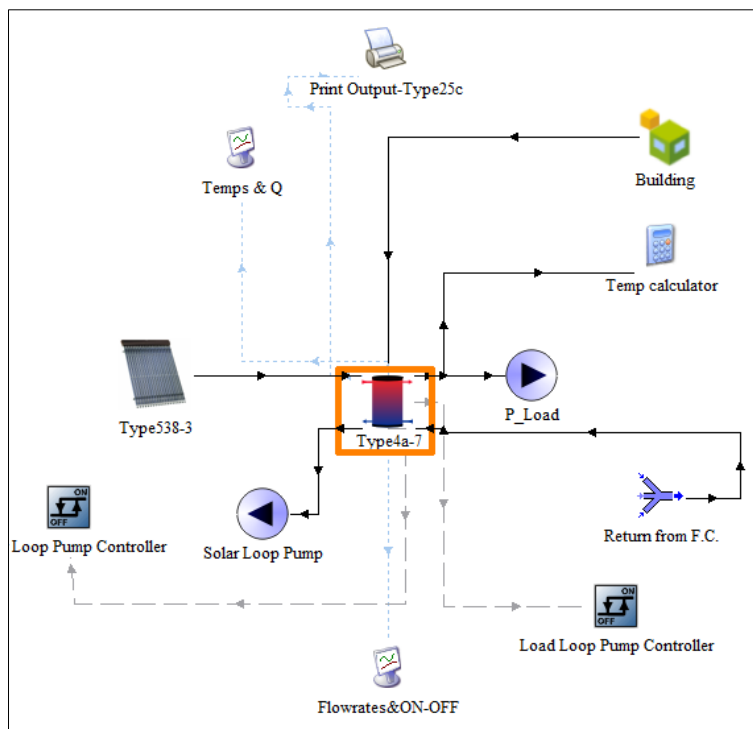


Figure 27: Storage Tank "Type 4a" Connections

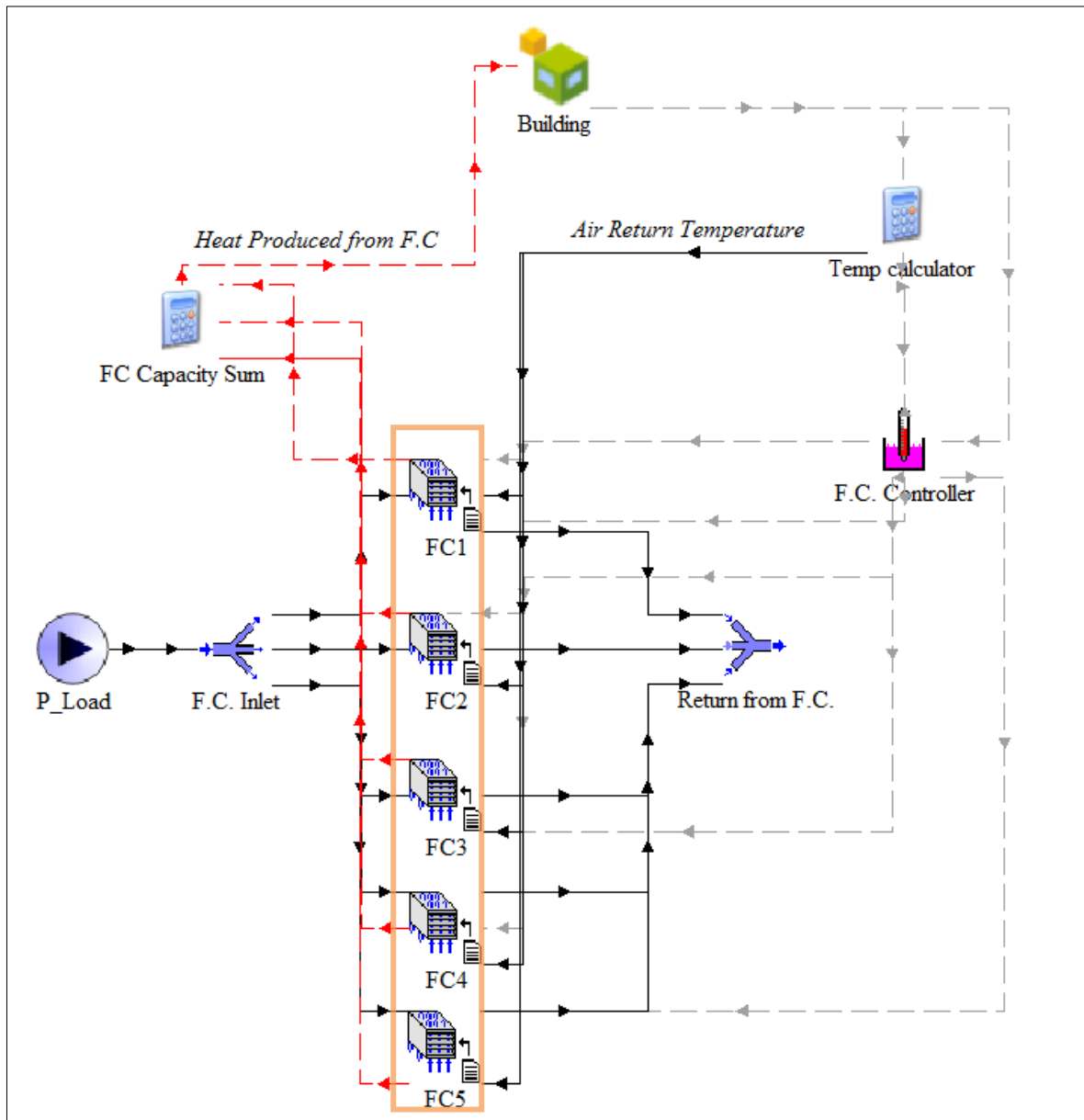


Figure 28: Fan Coil Units "Type 996" Connections



## APPENDIX 9: TRNSYS SIMULATION RESULTS

An example of the data exported from TRNSYS to the output excel file is shown in Table 26, where the outputs of the simulation are tabulated hourly over one complete year.

Table 26: Sample of Results obtained from TRNSYS SHS Simulation (cc

Time	Day	T <sub>amb</sub> (°C)	T <sub>set</sub> (°C)	T <sub>House</sub> (°C)	Q <sub>FC</sub>	T <sub>out SC</sub> (°C)	T <sub>tank</sub> (°C)
1	0	6.20	33.00	24.91	210,932.47	45.41	44.94
2	0	5.90	33.00	24.48	211,149.66	45.32	44.59
3	0	6.30	33.00	24.21	213,229.48	45.51	44.55
4	0	6.70	33.00	24.07	216,961.79	45.78	44.71
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
175	7	6.55	26.33	23.19	233,679.21	52.22	50.48
176	7	6.45	26.33	22.98	234,453.40	51.75	43.71
177	7	8.50	26.33	22.58	182,733.91	53.17	38.84
178	7	12.35	26.33	20.17	-	57.20	39.79
179	7	16.25	26.33	22.03	159,188.66	61.95	36.22
180	8	18.95	26.33	22.84	-	67.14	37.79
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
458	19	8.35	22.67	22.03	-	8.37	68.64
459	19	7.50	22.67	21.51	-	7.52	68.56
460	19	6.65	22.67	21.71	90,815.66	6.67	65.81
461	19	6.20	22.67	22.15	84,664.21	6.21	63.22
462	19	5.95	22.67	21.90	80,111.60	5.95	60.78
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
573	24	16.35	21.33	21.83	-	16.37	92.28
574	24	15.25	21.00	21.67	-	15.27	92.17
575	24	14.35	21.00	21.50	-	14.37	92.05
576	24	13.65	21.00	21.50	-	13.66	91.94

Table 26: Sample of Results obtained from TRNSYS SHS Simulation (cont'd)

Time	Day	T <sub>amb</sub> (°C)	T <sub>set</sub> (°C)	T <sub>House</sub> (°C)	Q <sub>FC</sub>	T <sub>out SC</sub> (°C)	T <sub>tank</sub> (°C)
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
1370	57	12.55	33.00	30.47	261,685.26	59.24	57.70
1371	57	11.25	33.00	30.16	273,711.43	60.87	58.81
1372	57	9.95	33.00	30.00	285,649.99	62.32	59.84
1373	57	9.75	33.00	29.88	293,785.88	63.20	60.52
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
5482	228	30.30	33.00	32.50	134,913.04	95.32	91.86
5483	228	31.10	33.00	32.50	134,913.04	95.25	92.92
5484	229	31.75	33.00	32.57	134,913.04	95.00	92.56
5485	229	33.65	33.00	33.07	131,867.52	95.00	90.43
5486	229	35.40	33.00	33.50	-	95.00	91.39
5487	229	35.85	33.00	33.50	-	95.00	91.65
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
8747	364	11.60	21.67	22.17	-	90.27	78.10
8748	365	13.20	21.67	22.17	-	91.63	78.72
8749	365	14.95	21.67	22.17	-	91.76	79.33
8750	365	16.30	21.67	22.17	-	91.72	87.62
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
8760	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.

## APPENDIX 10: SOLAR WATER HEATER QUOTATION

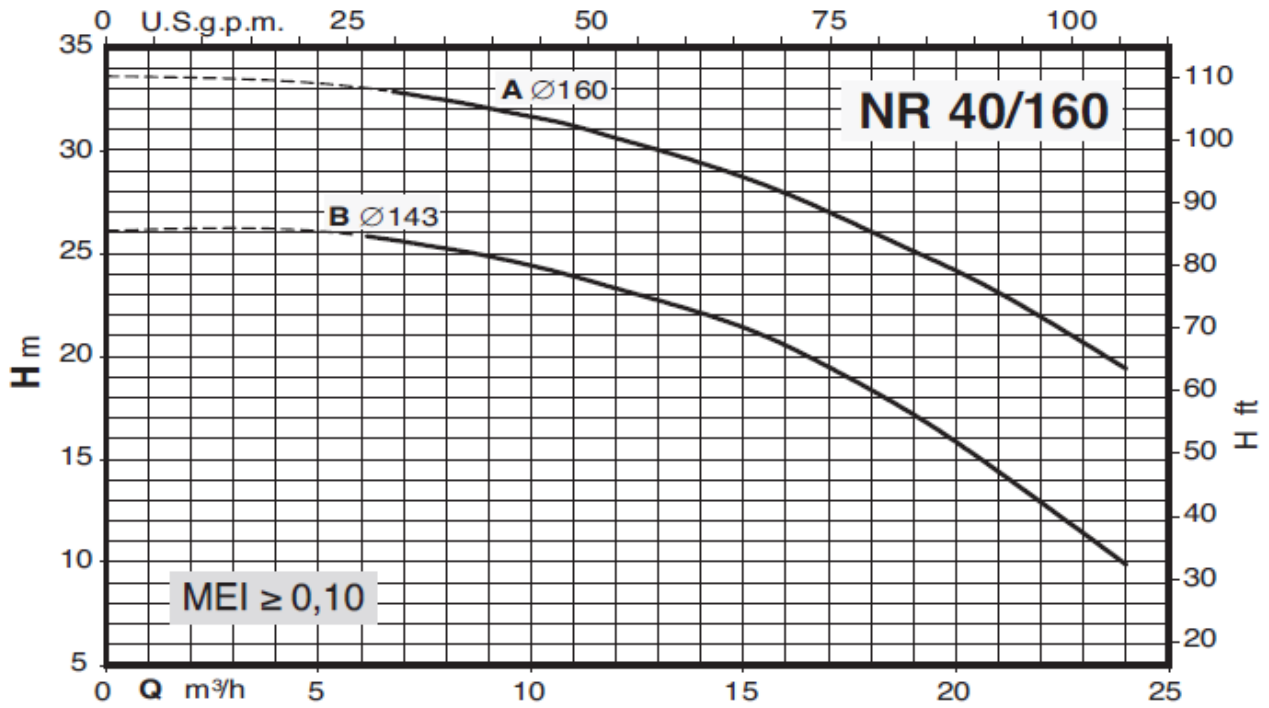
TAQA MISR: (2 cubic meter) Hot Water Solar Water Heating Offer[70]

Ref	Item Hardware	Description	Quantity	Unit Price (USD)	Total Price (USD)
1	Appricus Vacuum Tube Solar Collectors	1 x APSE-30-KIT (Manifold and standard frame) 3 x BOX-ET/HP-10/10 (Tubes and heat pipes)	8	1,568	12,544
2	Tanks	2000 liter Pressurized with Single Coil	1	3,450	3,450
3	Solar Work Station	0.5HP Circulation Pump,220 v.+Manometer+Controller	1	612	612
4	Expansion Tank	60 liter Expansion Tank	1	165	165
5	<b>Pipes &amp; Fittings</b>				-
5.1	Pipes & Fittings	Black metal steel pipes between collectors and tanks with accessories60m Ø1"inch	35	35	1,225
5.2	Pipes & Fittings	B.R pipes Return loop with accessories60m Ø3/4 "inch	0	21	-
6	Pipes & Fittings	workmanship	1	1,423	1,423
7	Thermal Insulation	Glass Wool Insulation for Steel pipe & Fitting only + 5mm Aluminum Cladding	35	15	525
8	Electical Material				-
8.1	Cable Tray	Cable Tray Stainless Steel (5x15)1.25mm,with cover	36	18	648
8.2	El Swedy Cables	Electric Cable 4 x 10 Thermo	18	10	180
8.3	El Swedy Cables	Electric Cable 4 x 6 Thermo	18	7	133
8.4	El Swedy Cables	Electric Cable 2 x 6 Thermo	18	4	76
9	Civil Work & Others	Pipe Line Supports & Metal Support for other equipment	Lump Sum	563	4,000
10	Safety instruments	Relief Valve, Air Vent , Check Valves ,Balance Valves	1	573	573
11	Liquid	Anti Freeze + Anti Rust	20	41	820
<b>Total Hardware</b>					<b>26,374</b>

## APPENDIX 11: PUMP PERFORMANCE CURVE

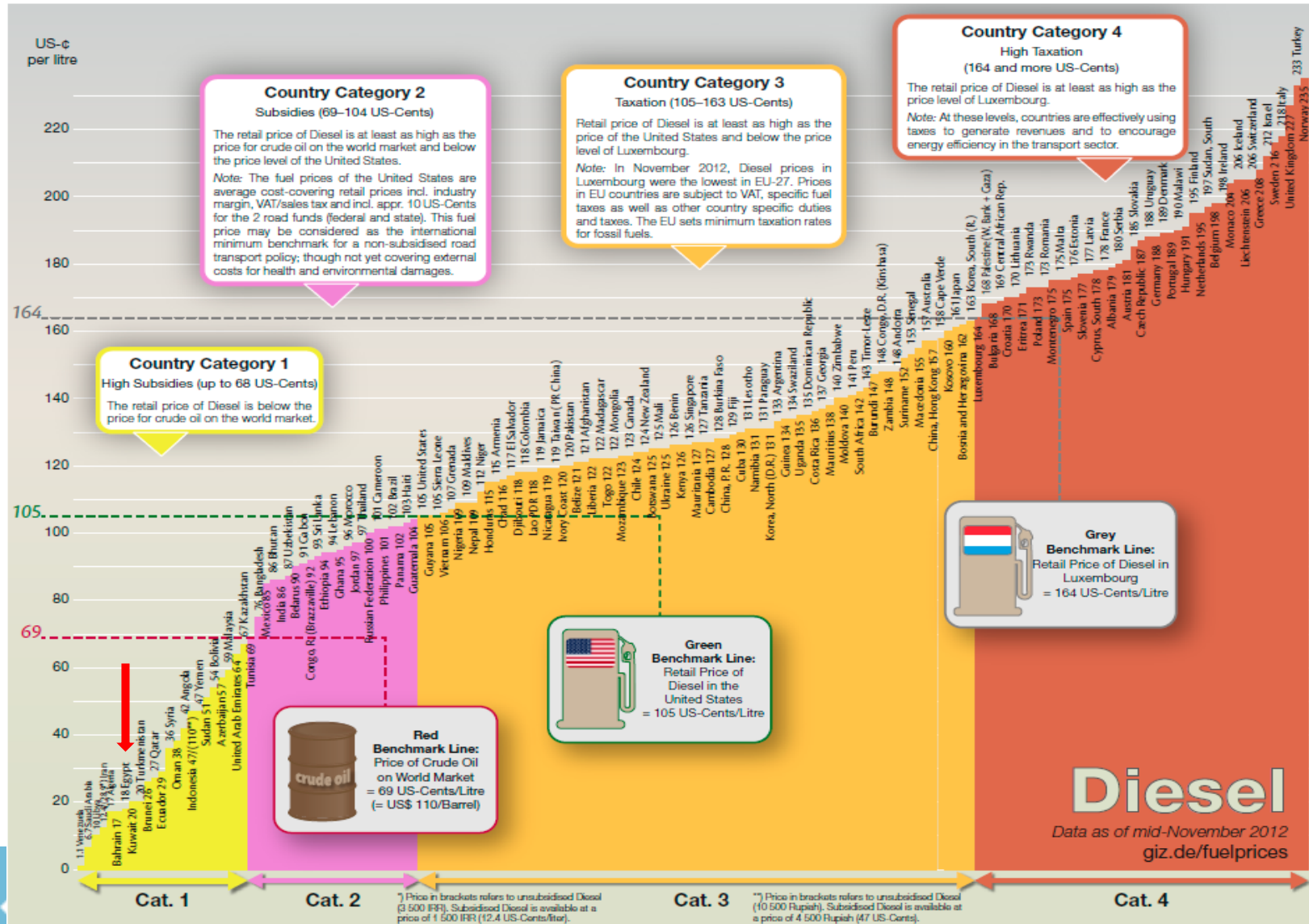
Selected Pump Performance Curve [54]

Calpeda Model NR40/160A



# APPENDIX 12: DIESEL FUEL PRICES

The Retail Price of Diesel in 171 Countries as of November 2012 [56]



## APPENDIX 13: EGYPT'S ELECTRICITY TARIFF

Egypt's Electricity Tariff for Low Voltage (380V) Applications

Law n. 1257 of 2014 [61]

Year	Price Piaster per kWh
2014/2015	36.6
2015/2016	43.5
2016/2017	52.5
2017/2018	58.6
2018/2019	66.5

Note: Prices are in Egyptian currency

### APPENDIX 14: SOLUTION SPACE RESULTS USING LOCAL FUEL PRICE

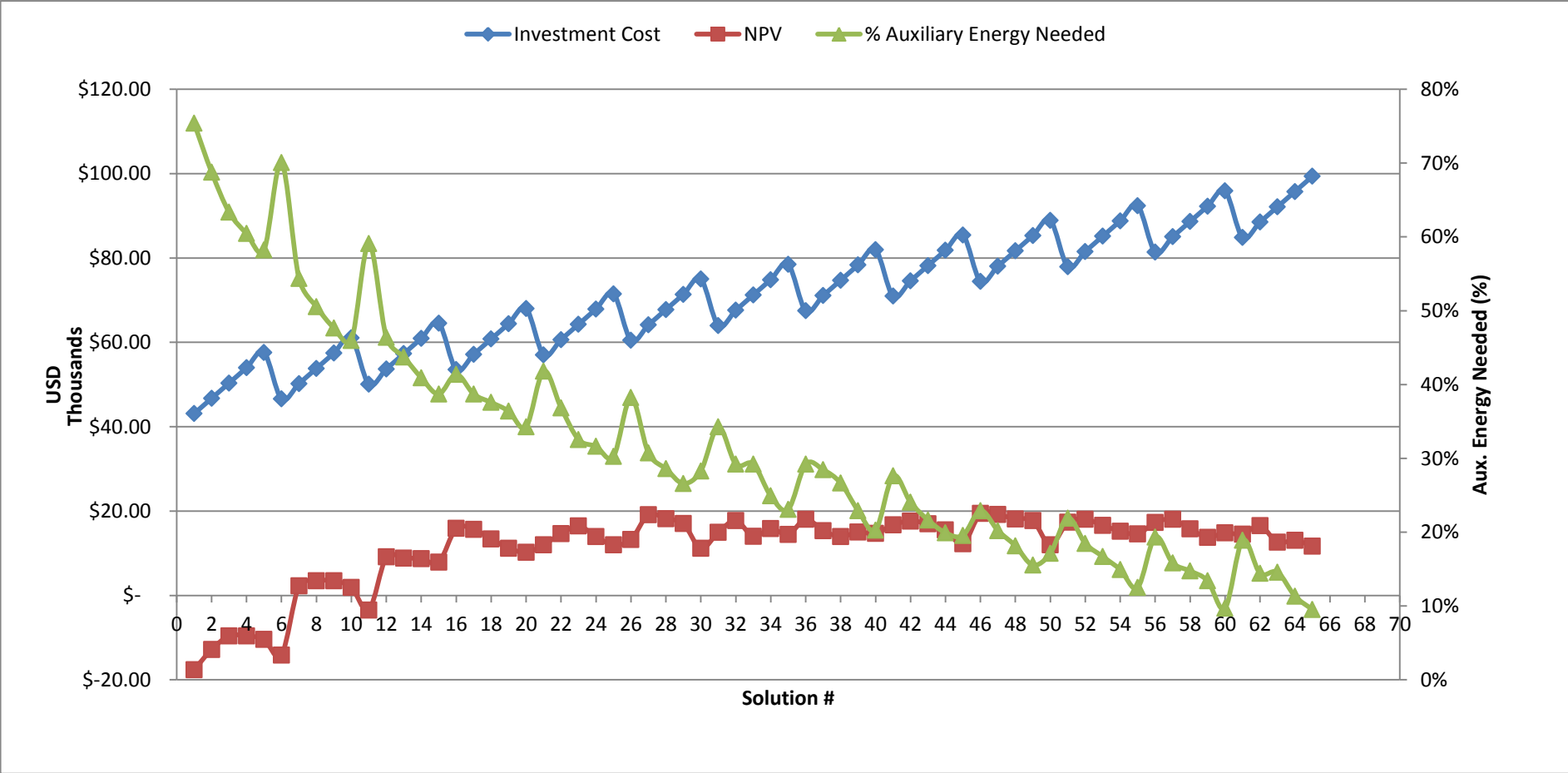


Figure 29: Graphical Display of Solution Space Results using the Local Fuel Price

## APPENDIX 15: RESULTS USING INTERNATIONAL FUEL PRICES

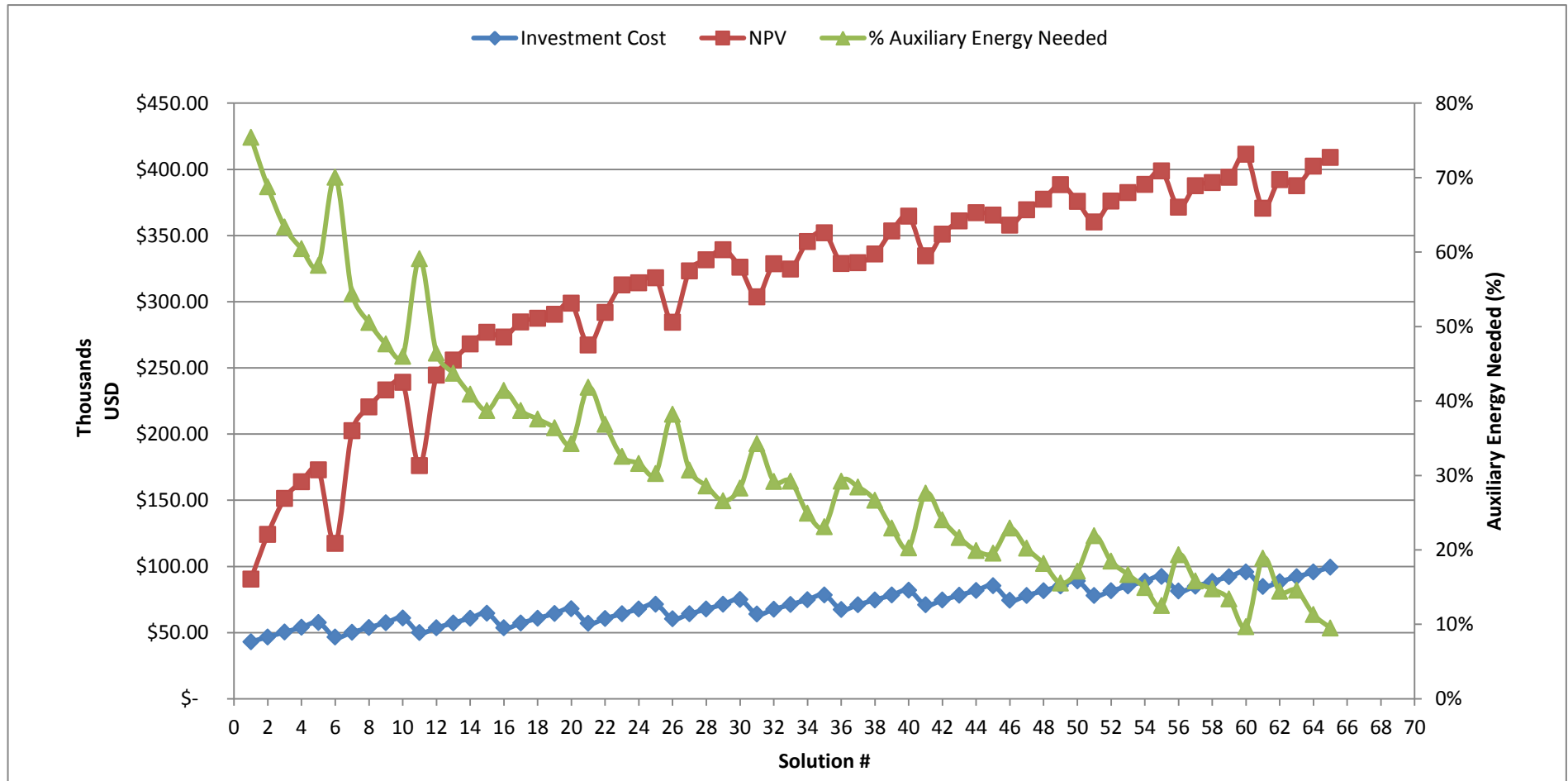


Figure 30: Graphical Display of Solution Space Results using International Fuel Prices



## APPENDIX 16: NPV CALCULATION FOR SOLUTION 46 WITH LATENT HEAT STORAGE

Table 27: DCF Calculating NPV for Solution 46 with Latent Heat Storage

Year	Investment Payment	Fuel savings	Parasitic energy Cost	Maintenance Cost	Loan payment	Interest expense	Tax savings	Salvage value at n=15	Net cash flow	Discount factor	NPV of cash flow
0	-\$7,994.40								-\$7,994.40	1.00	-\$7,994.40
1	0	\$12,945.73	\$-653.12	-\$1,546.51	-\$10,563.95	-\$8,633.95	\$2,708.40	0	\$2,891.55	0.91	\$2,627.59
2	0	\$13,204.64	-\$776.25	-\$1,575.86	-\$10,563.95	-\$8,402.35	\$2,688.62	0	\$2,979.21	0.83	\$2,460.11
3	0	\$13,468.74	-\$936.85	-\$1,607.69	-\$10,563.95	-\$8,142.96	\$2,671.88	0	\$3,035.12	0.75	\$2,277.50
4	0	\$13,738.11	-\$1,045.71	-\$1,642.23	-\$10,563.95	-\$7,852.44	\$2,635.09	0	\$3,125.33	0.68	\$2,131.10
5	0	\$14,012.87	-\$1,186.68	-\$1,679.68	-\$10,563.95	-\$7,527.06	\$2,598.36	0	\$3,185.92	0.62	\$1,974.11
6	0	\$14,293.13	-\$1,305.35	-\$1,832.31	-\$10,563.95	-\$7,162.64	\$2,575.07	0	\$3,172.60	0.56	\$1,786.40
7	0	\$14,578.99	-\$1,435.88	-\$1,885.87	-\$10,563.95	-\$6,754.48	\$2,519.06	0	\$3,219.36	0.51	\$1,647.25
8	0	\$14,870.57	-\$1,579.47	-\$1,943.96	-\$10,563.95	-\$6,297.34	\$2,455.19	0	\$3,246.39	0.46	\$1,509.45
9	0	\$15,167.99	-\$1,737.42	-\$2,006.98	-\$10,563.95	-\$5,785.35	\$2,382.44	0	\$3,251.08	0.42	\$1,373.64
10	0	\$15,471.35	-\$1,911.16	-\$2,075.33	-\$10,563.95	-\$5,211.92	\$2,299.60	0	\$3,230.52	0.38	\$1,240.35
11	0	\$15,780.77	-\$2,102.28	-\$3,289.84	-\$10,563.95	-\$4,569.68	\$2,490.45	0	\$2,326.16	0.35	\$811.60
12	0	\$16,096.39	-\$2,312.50	-\$3,466.85	-\$10,563.95	-\$3,850.37	\$2,407.43	0	\$2,172.52	0.32	\$688.80
13	0	\$16,418.32	-\$2,543.75	-\$3,658.85	-\$10,563.95	-\$3,044.74	\$2,311.83	0	\$1,976.60	0.29	\$569.47
14	0	\$16,746.68	-\$2,798.13	-\$3,867.11	-\$10,563.95	-\$2,142.43	\$2,201.92	0	\$1,733.41	0.26	\$453.82
15	0	\$17,081.62	-\$3,077.94	-\$4,093.02	-\$10,563.95	-\$1,131.85	\$2,075.70	\$7,994.40	\$9,431.81	0.24	\$2,243.90
<b>NET PRESENT VALUE (NPV)</b>											<b>\$15,801</b>

## APPENDIX 17: NPV CALCULATION FOR THE ALL-GREEN SOLUTION

Table 28: DCF Calculating NPV for All-Green Solution

Year	Investment Payment	Fuel savings	Parasitic energy Cost	Maintenance Cost	Loan payment	Interest expense	Tax savings	Salvage value at n=15	Net cash flow	Discount factor	NPV of cash flow
0	-\$9,124.40								-\$9,124.40	1.00	-\$9,124.40
1	0	\$16,387.00	-\$826.61	-\$1,772.51	-\$12,057.15	-\$9,854.35	\$3,113.37	0	\$4,845.10	0.91	\$4,402.81
2	0	\$16,714.74	-\$982.44	-\$1,821.00	-\$12,057.15	-\$9,590.02	\$3,098.36	0	\$4,954.51	0.83	\$4,091.25
3	0	\$17,049.03	-\$1,185.70	-\$1,873.60	-\$12,057.15	-\$9,293.96	\$3,088.32	0	\$5,023.90	0.75	\$3,769.84
4	0	\$17,390.02	-\$1,323.47	-\$1,930.65	-\$12,057.15	-\$8,962.38	\$3,054.13	0	\$5,136.87	0.68	\$3,502.73
5	0	\$17,737.82	-\$1,501.89	-\$1,992.54	-\$12,057.15	-\$8,591.01	\$3,021.36	0	\$5,212.59	0.62	\$3,229.91
6	0	\$18,092.57	-\$1,652.08	-\$2,171.67	-\$12,057.15	-\$8,175.07	\$2,999.70	0	\$5,217.38	0.56	\$2,937.76
7	0	\$18,454.42	-\$1,817.29	-\$2,253.97	-\$12,057.15	-\$7,709.22	\$2,945.12	0	\$5,278.14	0.51	\$2,700.67
8	0	\$18,823.51	-\$1,999.02	-\$2,343.24	-\$12,057.15	-\$7,187.47	\$2,882.43	0	\$5,314.54	0.46	\$2,471.06
9	0	\$19,199.98	-\$2,198.92	-\$2,440.07	-\$12,057.15	-\$6,603.11	\$2,810.52	0	\$5,323.37	0.42	\$2,249.22
10	0	\$19,583.98	-\$2,418.81	-\$2,545.11	-\$12,057.15	-\$5,948.62	\$2,728.14	0	\$5,301.05	0.38	\$2,035.33
11	0	\$19,975.66	-\$2,660.69	-\$3,799.41	-\$12,057.15	-\$5,215.60	\$2,918.92	0	\$4,388.34	0.35	\$1,531.09
12	0	\$20,375.17	-\$2,926.76	-\$4,019.58	-\$12,057.15	-\$4,394.61	\$2,835.24	0	\$4,218.93	0.32	\$1,337.61
13	0	\$20,782.68	-\$3,219.44	-\$4,258.40	-\$12,057.15	-\$3,475.11	\$2,738.24	0	\$3,998.93	0.29	\$1,152.12
14	0	\$21,198.33	-\$3,541.38	-\$4,517.44	-\$12,057.15	-\$2,445.26	\$2,626.02	0	\$3,722.38	0.26	\$974.55
15	0	\$21,622.30	-\$3,895.52	-\$4,798.43	-\$12,057.15	-\$1,291.84	\$2,496.45	\$9,124.40	\$12,507.05	0.24	\$2,975.52
<b>NET PRESENT VALUE (NPV)</b>											<b>\$ 30,237</b>