APPLICATION OF SOLAR ENERGY AT OHIO HIGHWAY REST AREAS

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by

Lankajith C. Pannila
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Finally, I would like to thank my wife, Indra for her assistance and encouragement.
As an alternative energy source, solar energy can be used to produce hot water and electricity in public rest areas. To investigate performance and economics of such applications, two solar systems were instrumented at high way rest areas in Lake and Butler county in I-90 and I-75 respectively. From the data collected, average annual solar contributions were calculated as 52% for Lake county and 72% for Butler county. Both solar systems were modeled using TRNSYS subroutines and validated results. This program could be used in designing solar domestic hot water systems for other highway rest facilities.
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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

As an alternative energy source, solar energy is more promising as it’s free availability and dependability. Solar energy is widely used for water heating, air conditioning, building heating and to generate electricity. Ohio Department of transportation uses solar energy for water heating and as an emergency source of power at several highway rest facilities.

There are many advantages in using solar energy at highway rest areas. For example, since rest areas are completely dependant on electricity for water heating and lighting, solar energy may be an economical alternative energy source. Ohio department of transportation has installed solar water heating systems in seventeen rest facilities and sixteen emergency lighting systems to examine the performance and economics of solar energy systems.
1.2 LITERATURE REVIEW

In 1981, James C. Huggings, James D. Poland and T.F. Tiedemann investigated performance improvements of flat plate solar collectors[1]. They performed such as static pressure tests, thirty day exposure tests, thermal shock / water spray tests, collector time constant tests, incident angle modifier tests, and thermal performance tests on more than 400 collectors. The thermal performance tests were conducted according to the ASHRAE standard (93-77). They found that collector performance dramatically increased (approximately 37%) from 1977 to 1981. Average maximum collector ratings increased from 723 to 994 in the same period.

In 1984, C.J. Cromer, K.C. Conrath and W.R. Cromer studied the back siphoning effect of hot water systems[3]. They compared performances of a half length insulated heat trap, a full length insulated heat trap and a ball valve. They determined that the insertion of a ball valve minimizes the back siphoning compared to other heat traps. Also they showed that a well insulated half length heat trap is more efficient than the full length heat trap.

In 1983, David L. Block presented four years of field data on a solar domestic hot water system located at 28.4° latitude in Florida[2]. Results showed that an average of 140 kwh/month can be saved by using SDHS at that latitude. He compared the experimental results with the FCHART 4.0 and FCHART 4.1 simulated predictions and found that experimental data under predicts solar fraction by 16%. (.61 compared to .51 from FCHART)
Charles J. Cromer, (1984) studied the possibility of using solar power to run the circulating pump[9]. He compared the performance of four pumps, March 12v and 24v brush type and Hartwell 24v (brushless), and, Hartwell 24 v brush type motors and found that Hartwell performed better. Also he pointed out that the characteristic of pump should exactly match with pv cells for a smooth start for these pumps.

J. Prakash, H. P. Gary, R. Jha and D. S. Hrishikesan in 1991 studied the performance of transparent insulations[4]. They used Methyl Methacrylate transparent insulation in solar collectors, shallow solar ponds, and collector storage systems. Results were compared with similar systems without insulation on top, and found that the efficiencies of systems were not improved.

The best developed application of solar energy is to heat water. For this purpose, flat plate collectors in thermo-syphon systems are in widespread use. In these systems, after tank temperature reaches it’s maximum value, the direction of the flow in the collector may reverse, and therefore, the hot water in the tank may be cooled. To eliminate this disadvantage a two-phase thermo-syphon system was developed. The first comprehensive study of this system was carried out by Soin in 1979. T. Yalmaz in 1989, modelled a two phase flow thermosyphon solar water heating system[5]. He considered the heat transfer in the collector as well as in the condenser and assumed the flow as nonhomogeneous with two phases. Using a computer model he showed there is an optimum value for collector pipe diameter. Further he proved that since the flow is always around the transient region, it is important to choose the right parameters of
Optimum collector flow rates in solar water heating systems have been broadly established; the existence of an optimum flow rate was determined for systems having a heat exchanger.

In contrast, Fanney and Klein in 1988 found that there is no optimum flow rate for solar systems with heat exchanges. Hollands K.G. and Bruger A. P. (1991) also arrived at the same conclusion. He also found that collector side flow rate should be $(1 + \delta)/\delta$.

where $e = (UA)_s / (F'U_L A_c)$

$(UA)_s = \text{overall conductance of the heat exchanger}$

$F' = \text{collector efficiency factor}$

$(U)_L = \text{collector heat loss coefficient}$

$(A)_c = \text{collector area}$

Bopshetty S.V., Nayak J.K., and Sukhatme (1991) carried out a performance analysis of a concrete solar collector[7]. They embedded PVC pipes inside a reinforced concrete slab and painted the absorber surface with ordinary black board paint. In order to reduce collector surface losses an ordinary window glass was fixed using a wood frame and a rubber gasket. They found that the concrete collectors are 10-15 % less efficient (37% at 50°C inlet temperature and 1.21 gal/min flow rate) when compared with a flat plate collector. Although these collectors are less efficient, such collectors integrated with building structures, are likely to be more cost effective than conventional flat plate collectors using metal absorber plates.
In 1983, New Jersey Department of Transportation research engineers studied the appropriateness of solar energy for hot water heating in highway rest areas[19]. They instrumented and monitored a solar hot water system in New Jersey and showed that solar fraction is high as 0.71.

In addition to solar heating, solar photovoltaic power generation is also becoming increasingly popular. Becquerel E. (1839), a French physicist, discovered the photovoltaic effect. He noticed that shining a light on one of two identical electrodes in a weak conducting solution would produce a voltage. Einstein A. (1884) earned a Nobel Prize in physics in 1921 for enplaning this effect in early 1905. In 1954, Bell laboratories researchers made key discoveries that led to the first practical solar cell - a crystalline silicon device with a conversion efficiency of 4%.

Numerous DOE and industry funded research projects have been conducted to improve efficiency of PV cells and lower the manufacturing costs. Improvements in processing and production technology, along with greater effort in marketing, have reduced PV electricity production cost to $0.30-0.50 per kilowatt-hour, though still not competitive with today's utility grid power costs. US Department of Energy's (DOE) goal for the 1995-2000 time period is about $0.12-0.20 per kilowatt-hour[8].

Florida Solar Energy Center is one of the leading institutions doing research on photovoltaics. At its PV research facility, Paul D.F. has compared the performance of four matched 500 peak watt photovoltaic systems operating on following tracking modes: two axis, single axis azimuth tracking (i.e., rotation about a vertical axis at fixed orientation (south facing at latitude tilt).
They found that D.C. energy enhancement ratios of 1.19 for the single axis, 1.22 for the azimuth and 1.39 for the two axis tracking arrays compared to the fixed axis array. Output power variation of photovoltaic cells due to rise in cell temperature was compared in 1984 by David R.W. for three cell types. He used Mobil, Solarex and Photowatt modules with different mounting methods in order to expose back surface of modules to wind. He concluded that the Solarex module performed better than other modules for zero wind velocity (approximately 25% more efficient).
CHAPTER 2

Scope of The Study

2.1 Introduction

To date, the most efficient way to utilize solar energy is for water and space heating, since electrical power generation with photovoltaic cells operates at low efficiency (6-15%).

Solar systems were installed in 17 highway rest areas in Ohio (Figure 2.1). Sixteen PV systems were also installed to provide emergency lighting. Since these installations represented a substantial investment, the Ohio Department of Transportation (ODOT) was interested in determining economic viability and operational characteristics of the solar facilities installed. Major objectives of this project were[11]:

1. Determine the proportions of heat gain derived from the solar collectors and
electrical elements in hot water heating.

2. Determine seasonal variation of solar systems.

3. Examine the energy utilization as a function of operational characteristics.

4. Examine the validity of empirical design equations available in the literature for the estimation of heat gain and thermal efficiency by comparing them with field observations.

5. Compare energy cost at the instrumented facilities and examine the other facilities for consistent operations.

6. Compare experimental results with simulated results.

The most basic solar water heating has two major components: solar collector and water storage tank. Additional components found in most systems are circulating pump, controller and a heat exchanger. Efficiency may be improved considerably with proper design. Solar water heaters are widely used in low latitudes where as Ohio extends from -35° to -45° latitudes where experience with solar collectors is limited.
Figure 2.1 Locations of rest areas with solar facilities
Photovoltaic systems, although not efficient as hot water systems, are widely used for backup power and to power remote equipments such as telecommunication transmitters, etc.

Solar hot water systems were installed with backup electrical heater so that an uninterrupted hot water supply was assured. PV power was stored for emergency lighting. Emergency lighting consists of 4, 30 watt fluorescent lights.

Sixteen solar systems are basically similar with six solar collectors, a tank with a heat exchanger, circulating pump, controller, expansion value, PV array, charge controller and batteries. Two of the above were instrumented during construction in order to determine economic viability and performance data. Flow meters and BTU meters were installed to measure water flow and energy use. Four thermistors were installed to measure temperatures at different locations and consequently to determine energy entering the water heater from collector and energy exiting the heater.

2.2 Solar Collectors

Solar collectors are basically heat exchangers that use solar radiation to heat a working fluid, a liquid or air. Collectors are usually classified in three groups. The first group consist of flat plate collectors that use no optical concentration of sunlight. Generally the
output temperature of these collectors is below 225°F. The second group is focusing collectors which follow the sun and generally utilize only direct radiation. They are capable of producing high temperatures. Intermediate between these two are non-imaging concentrators which are capable of producing temperatures up to 350°F[12].

Under steady state conditions, the useful heat delivered by solar collector is equal to the energy absorbed minus the heat losses directly and indirectly to the surroundings (Figure 2.2)

\[
Q_u = A_c \left[ I_t \tau \alpha - U_L (t_p - t_a) \right]
\]

Where;

- \( Q_u \) - is useful energy collected (Btu/h)
- \( A_c \) - total collector area, (ft²)
- \( I_t \) - is the solar energy received on the upper surface the sloping collector structure (Btu/h - ft²)
- \( \tau \) - transmissivity
- \( \alpha \) - absorptivity
- \( U_L \) - is the overall heat loss coefficient (Btu/h - ft² . °F)
- \( t_p \) - is average temperature of the upper plate of the absorber plate (°F)
- \( t_a \) - is atmospheric temperature (°F)
In order that the performance of a collector be economically practical, design and operating factors that increase the value of $I - \tau a$ in the above equation and that reduce the value of $U_L (t_p - t_c)$ are selected. Specially, in colder climates, as ambient temperature ($T_a$) is low, heat losses are generally high. To reduce these heat losses, more than one cover plate can be used. Overall heat loss coefficient can be reduced by this method. Since Cleveland also has the highest average wind speed in of Ohio, two plates may significantly improve collector efficiency.
Radiation losses can be decreased by other techniques also. For example, collector cover plates can be coated with a thin transparent tin oxide coating on it's back surface to reflect thermal radiation to the absorber plate. Or collectors can be fabricated with transparent honeycomb between the bottom cover plate and the absorber plate.

Heat losses also occur through the sides and back of the collector which should be adequately insulated. Materials used must be stable at the high temperatures occasionally encountered when collector flow is interrupted.

**Flat Plate Collectors**

Flat plate collectors are commonly used for space heating, swimming pool heating and domestic hot water applications. A typical flat plate collector consist of a absorber plate, flow passages, cover plate, insulation and enclosure (Figure 2.3).

![Figure 2.3 Cross sectional view of a flat collector][12].
Absorber plates are usually made out of copper, steel or plastic and may have a selective coating that maximizes the absorptance of solar energy and minimizes the radiation emitted by the plate.

In the liquid collectors the flow passage generally does not extend over the entire absorber plate surface and therefore heat has to be conduct along the absorber plate to reach the fluid. In such an installation, tubes are placed several inches apart and the absorber plate acts as a fin. Tube spacing is determined by a trade-off between the fin efficiency of the collector plate and the cost of the tubes. For a 0.02" thick copper plate with 1/2 inch diameter tubes spaced 6" apart in good thermal contacts with the plate has a fin efficiency close to 97%. Generally, copper, which has high conductivity and corrosion resistivity, is the best choice for absorber plates and tubes. However, as copper is expensive, steel is also widely used.

**Cover plates**

Cover plates must have high transmittance for solar radiation and must not deteriorate with time. Most commonly used material for cover plates is tempered glass. A 1/8 inch thick cover sheet of window glass with iron content of 0.12% transmits about 85% of solar energy at normal incidence. If the iron content is reduced to 0.05% the transmittance increases to about 92%.
Plastic materials also can be used as collector glazing. They are cheaper and lighter, but not as durable as glass. Also transparent insulation sheets are used as cover plates to minimize heat losses. However, collector efficiency doesn’t improve as these cover plates have low transparency. Some collectors, operating in cold climates, have two cover plates to reduce heat losses.

Enclosure and Insulation

Enclosures of collectors are fabricated of aluminum, steel or fiberglass. The frames are designed so that the absorber plate is shaded as little as possible. Enclosure boxes should be well sealed to exclude moisture. Insulation is used to prevent heat losses from the back and sides of the absorber. Materials are generally nonflammable. Most commonly used insulations are fiberglass and polyurathane. High temperatures limits are 350°F and 250°F respectively. With different binders, these insulations will have higher temperature limits.

2.3 Storage Tank

Although thermal storage adds expenses and complexity to solar thermal systems, it is almost always required due to fluctuations of energy collection and demand. Solar systems are normally sized so that they can supply hot water even when energy is not
being collected. Although there are different types, a storage system necessarily consists of a heat storage material, a container and provision for adding and removing heat.

Both I-75, Cincinnati and I-90, Cleveland have 120 gallons thermal storage tanks with an auxiliary heating element. The heat exchanger was installed in the water tank.

2.4 Heat Transfer Fluid

In thermo syphon systems, water can be used as the heat transfer fluid except in colder climates. To avoid this difficulty a separate liquid loop with a heat exchanger may be introduced. An antifreeze liquid (poly propylene) was used as the heat transfer media. A 20-30 psi pressure was maintained to ensure flow. Pressure should be examined regularly. If pressure is low the system must purged and recharged or repaired when necessary.

2.5 Pump

A high head low capacity pump is used in solar systems to circulate the antifreeze liquid. The pump circulates fluid in the collector loop where heat is transferred from the collector to the tank. An electronic circuit with adjustable temperature settings controls the pump. If the collector temperature reaches a pre determined value than the tank temperature, pump is started automatically. Similarly, it shuts off when the collector and
tank temperature difference reaches a set value or the high temperature limit of the tank is achieved. At both systems under investigation, off temperature was set at 5°F, on temperature was set at 16°F, and the high temperature was set at 180°F.

2.6 Thermal Expansion and Safety Values

Since the temperature of antifreeze liquid goes as high as 250°F, for expansion a thermal expansion valve is incorporated in the solar system. In thermo-syphon systems, expansion valves are not used, instead, a pressure relief valve in the tank releases the high pressure developed due to thermal expansion. In closed loop solar systems a pressure relief valve is included to prevent accidents from high pressures.

2.7 Photovoltaic Cells

Photovoltaic is a descriptive name for a technology in which radiant energy from the sun is converted into dc electrical energy. A photovoltaic system consist of an array of solid state devices called solar cells. These cells are made from semiconducting materials, typically silicon, doped with special additives. The most usual configuration for a solar cell is shown in Figure 2.3.
A junction made out of p-type and n-type materials provides an inherent electrical field which separates the charges created by the absorption of sun light. The positive and negative charges created drift to the front and back of the solar cell. The back is completely covered by a metallic contact to remove the charges to the electrical load. The collection from the front of the cell is aided by a fine grid of narrow metallic fingers. The surface coverage of conducting collectors is typically about 5% to allow as much light as possible to reach the active junction area. Generally, each solar cell produces power about 0.5V with the current directly proportional to the cell’s area. Cells
are connected in series-parallel combinations to meet voltage, power and reliability requirements of a particular application.

Most commonly available cells are rated at 15V to be used with 12V batteries. Electrical characteristics of such a module is shown in Figure 2.4. Maximum power is generated when these cells are operated on the "knee" of the curve.

![Figure 2.4 A Typical Graph of Current vs Voltage](image)
2.8 Battery Storage

Batteries are used to store electrical energy generated by the modules during sunny periods and to deliver energy whenever the modules are not active. Batteries discharge at night or during cloudy weather. If load exceeds the array output, the batteries will supplement the energy supplied by modules. No single component in a PV system is more affected by the size and load usage than storage batteries. If a charge controller is not included in the system, excessive charge can damage the batteries. A battery system should be sized carefully to match the load and an appropriate protection and control system should be included.

Performance of Batteries

The performance of batteries can be described in two ways;

(i) Ampere hour capacity

(ii) The Depth of Cycling

The first method, the number of amp-hours a battery can deliver, is simply the number of amps of current it can discharge in time, i.e. 200 amps for 1 hour. Automotive batteries are designed for short period of rapid discharge without damage. Thus, automotive batteries are not appropriate for PV systems.
Another factor that influences the amp-hr capacity is the temperature of the battery and its surroundings. Batteries are rated for performance at 80° F. Lower temperatures reduce amp-hr capacity significantly. Higher temperatures result in a slightly higher capacity will decrease number of cycles of the battery (Figure 2.5)

![Figure 2.5 Storage battery characteristics](image-url)

Figure 2.5 Storage battery characteristics[16]
Depth of Discharge

Depth of Discharge describes how much of the capacity of the battery is used during a charge - recharge cycle. Shallow cycle batteries are designed to discharge from 10% to 25% of their total amp-hr capacity during each cycle. In contrast most deep cycle batteries designed for PV applications, are designed to discharge up to 80% of their capacity without damage. Manufacturers of deep cycle Ni-Cad batteries claim the capacity of total discharged without damage.
CHAPTER 3

INSTRUMENTATION

3.1 INTRODUCTION

Two rest areas from Northeast and Southwest regions of Ohio were chosen for instrumentation. In the Northeast region, a rest area on I-90, West, Lake Co. near Mentor, Cleveland (latitude 43.5N) was selected, and in Southwest, a rest area near Cincinnati (latitude 35.4N) on I-75, North, Butler Co. was instrumented.

Both rest areas were equipped with solar hot water heating and emergency lighting systems. Designed and construction of these systems was completed in 1988. Both facilities consist of six 3ft by 8ft solar collectors, storage tank with a heat exchanger, circulating pump and a pump controller. Emergency lighting systems have a collector module, battery storage and a charge controller. A schematic diagram of these systems are shown in Figure 3.1. Other than the equipment positioning in the mechanical room, both systems are identical.
Figure 3.1 View of the Lake county (I 90) Rest Area.

Figure 3.2 Schematic Diagram of the Solar System
Solar domestic hot water system and PV system at Cleveland has been monitoring since December 1991. Routine monitoring and data collection has been done at a three week interval. The following measurements were recorded.

1. Water in temperature
2. Hot Water out temperature
3. Hot Water out temperature after mixing
4. Solar water in temperature
5. Solar water out temperature
6. Hot water tank bottom temperature
7. Collector water temperature
8. Hot water flow
9. Solar(heat exchanger fluid) flow
10. Pump status
11. Heater element status
12. Hot water BTU
13. Solar BTU
14. Ambient temperature
15. PV voltage
16. PV current
Instruments were installed in the system to measure above readings and they were connected to a data acquisition system, in order to collect and store data every 15 minutes.

Temperature sensors 1 and 3 (Figure 3.3) were installed in water lines to get the water temperatures entering and leaving the storage tank, respectively. Sensor 2 was placed before the mixing valve. Also, there was a visual thermometer to indicate the temperature of hot water leaving the tank. Temperature sensors(7&6) placed at the

Figure 3.3 Sensor placement.
collector panel and the tank bottom to give the collector and tank temperatures. These two sensors were directly connected to the pump controller which activate the pump when the set differential temperature temperatures condition is met. To measure the ambient temperature a sensor was placed outside the rest area. There were two flow meters and two BTU meters installed during construction to measure BTUs supplied by the solar system. The solar BTU meter was connected to the solar flow meter and to two sensors located at heat exchanger inlet and out flow (4&5) positions. Therefore the BTU meter measures the net heat transfer from the heat exchanger to the hot water storage tank. Similarly, water BTU meter indicates the net heat transfer from hot water tank to the load.

3.2 Instruments

Thermistors:

A thermistor is a semiconductor that varies in resistance in a predictable way as temperature changes. Thermistors are usually inexpensive ceramic compounds which are extremely sensitive to temperature changes. Thermistors are stable and but respond non-linearly to temperature changes. They are commonly used for temperature control and switching in the range of -100 to 500° F.
For all temperature measurements in this investigation, thermistors were used. The thermistors used, have an accuracy of \( \pm 1\degree C \) for a range of 0 to 150\degree C.

**BTU METERS:**

BTU meters manufactured by D K Enterprises of California were used in both solar systems. These BTU meters, by comparing inlet, outlet temperatures of the fluid and the flow rate, electronically calculate the BTU. Each BTU meter is connected to two thermistors and a flow meter to monitor above parameters to calculate BTUs. Each meter has two resettable electro-mechanical counters, one of which shows BTU \( \times 10^4 \) and the other indicator shows the flow rate \( \times 10 \) in gallons. Figure 3.4 shows the BTU meters used in the Cleveland rest area.

![BTU Meters Image](image.png)

**Figure 3.4** Hot water and solar BTU meters.
Data Acquisition system used in Cleveland rest area.

In addition to BTU meters a complete data acquisition system was installed to accumulate data. An ADAC Direct Connect 5508 MF data acquisition interface board with Labtech Note-Book software was used as the data acquisitor. The interface card was installed to a 386, 16 MHz Personnel computer with a hard drive of 40Mb for data collection and storage. An uninterrupted power supply was also used to supply power to the computer in order to minimize system shut offs owing to power fluctuations and short time period failures.

5508MF Data Acquisition Card

The 5508MF is a half size IBM PC/X/386 compatible data acquisition module. This board supports 16 channels of 12 bit resolution analog inputs, 8 channels of digital I/O, and three 16 bit timer/counters. Interrupts and DA transfers are also supported. Analog input range of this board can be set for -10 to 10, -5 to 5 or 0 to 10 volts. The 5508MF has a maximum conversion time of 40 μs (25 kHz) aggregated. Block diagram of this board is shown is shown in Figure 3.5.
Figure 3.5 Block Diagram of the data acquisition board.

One important feature of this board is that it could be directly installed internally to PC's serial port, as the 5508MF board's front and back shields provide a significant reduction in radiated noise pickup from other boards in the system. Inputs to the data acquisition system were wired to a separate connector which could be plugged separately into the 5508MF board.
Notebook software was used as the interface between the instruments and the user. This software is menu driven, and a flexible software which can be programmed according to specific data collection requirements. The data collection was programmed to collect data every 15 minutes and store to the hard drive.

3.3 Temperature Measurements.

As the data acquisition system can only measure voltages, to measure the change of resistance were recorded as a voltage and later converted into temperatures. All thermistors were connected with a resistor in series and to voltage supply as shown in the Figure 3.6.

![Thermistor wiring diagram](image)

Figure 3.6 Thermistor wiring diagram.
3.4 Flow Measurements.

To measure the flow, pulses generated by the analog flow meters were converted into voltage levels. Then, the pulses coming from the flow meter was stepped down and conditioned using a debouncing circuit. The signal was then sent to a counter where number of pulses were counted. After counting 16 pulses, the output voltage was raised by an one level. There were only ten such voltage levels. Once the indicator reached the last level it reset to the initial voltage. Voltage levels and the corresponding flow rates for the circuit used in Cleveland is shown in Table 3.1.

<table>
<thead>
<tr>
<th>Level</th>
<th>Solar Voltage</th>
<th>Water Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84</td>
<td>0.98</td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
<td>1.22</td>
</tr>
<tr>
<td>3</td>
<td>1.16</td>
<td>1.41</td>
</tr>
<tr>
<td>4</td>
<td>1.30</td>
<td>1.49</td>
</tr>
<tr>
<td>5</td>
<td>1.36</td>
<td>1.57</td>
</tr>
<tr>
<td>6</td>
<td>1.44</td>
<td>1.65</td>
</tr>
<tr>
<td>7</td>
<td>1.63</td>
<td>1.82</td>
</tr>
<tr>
<td>8</td>
<td>1.87</td>
<td>2.12</td>
</tr>
<tr>
<td>9</td>
<td>2.56</td>
<td>2.76</td>
</tr>
<tr>
<td>10</td>
<td>3.21</td>
<td>3.16</td>
</tr>
</tbody>
</table>

Table 3.1  Flow measurement and voltage levels.
3.5 PV Module Current Measurements.

As the data acquisition system could not measure the current directly, current was converted to a voltage. The circuit used for this purpose is shown in the Figure 3.8. Basically in this system, a low resistance wire is connected in series with the PV circuit. The voltage across the wire is amplified and calibrated to show current as a voltage.

![PV Current Measuring Circuit](image)

**Figure 3.8** PV Current Measuring Circuit.
3.6 Other Measurements

In addition to above measurements, circulating pump and electrical heater element on-off status were also observed. Two step-down transformers and AC to DC convertors were used to obtain a 5-6 V DC output signal when either the pump or the hot water heating the element were on. These DC output signals were directly connected to data acquisition system.
CHAPTER 4

DATA ANALYSIS

4.1 INTRODUCTION

The solar, domestic hot water systems installed in the highway rest areas on I-90 W in Lake county and I-75N in Butler county were monitored for a 12 month period July 1992 to June 1993.

Data collected during this time period were analyzed to determine daily and seasonal variations of temperature in the storage tank, collector panels and water in and out of tank and panel, respectively. Also, solar energy, total energy of hot water delivered and photovoltaic power were also calculated from measured values in order to give solar contribution percentage and economic viability.

Field data were stored in computers and retrieved for analysis at 3-4 weeks intervals. All data were recorded as voltages and later converted to temperatures and the flow measurements.
All rest areas with solar facilities including the Lake and Butler county rest areas were inspected annually during the period 1991 - 1993. Nine solar systems were found with low or zero pressure in the collector heat transfer fluid, during the 1993 visits.

4.2 CALCULATION OF THE DATA

4.2.1 CALCULATION OF TEMPERATURES

Figure 4.1 shows the wiring diagram of thermistors. To calculate temperature, the change in resistance of the thermistor was determined, and then the corresponding temperature was obtained from the characteristics curve (Figure 4.2).

Figure 4.1 Thermistor wiring diagram
Resistance of the thermistor $R_T$, is written as,

$$R_T = \frac{V_T \cdot R}{V - V_T}$$

Where

- $V_T$ - Voltage across the thermistor
- $V$ - Open circuit voltage
- $R$ - Fixed resister

**Figure 4.2** Thermistor characteristic curve.
Collector and tank temperature sensing thermistors were connected to a larger voltage sources and a fixed resistors than the other thermistors. Voltages sources and fixed resistor values used are given below.

<table>
<thead>
<tr>
<th>Collector thermistor</th>
<th>Tank thermistor</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R = 8.8 , k\Omega )</td>
<td>( R = 9.82 , k\Omega )</td>
<td>( R = 3.24 , k\Omega )</td>
</tr>
<tr>
<td>( V = 11.2 , V )</td>
<td>( V = 11.2 , V )</td>
<td>( V = 5 , V )</td>
</tr>
</tbody>
</table>

Thermistor characteristic curve was presented by following equations.

When \( R > 19380 \)

\[
T = (3.137 \times 10^{-8}) \, R^2 - (3.049 \times 10^3) \, R + 98.21
\]

When \( 19380 > R > 4200 \)

\[
T = (-1.64 \times 10^{-11}) \, R^3 + (7.848 \times 10^{-7}) \, R^2 - (1.494 \times 10^{-2}) \, R + 164
\]

When \( R < 4200 \)

\[
T = (-3.578 \times 10^{-9}) \, R^3 + (3.3002 \times 10^{-5}) \, R^2 - (1.146 \times 10^{-1}) \, R + 275.5
\]

When the thermistor instantaneous resistance is measured, temperature at that time is determined using the applicable equation.
For energy calculations, the following equation was used,

\[ Q = C \times m (T_2 - T_1) \]

Where

- \( Q \) = Energy (BTU)
- \( C \) = Specific heat constant (BTU/gal. °F)
- \( m \) = mass flow rate
- \( T_1 \) = Inlet Temperature(°F)
- \( T_2 \) = Outlet Temperature(°F)

### 4.2.2 Calculation of Solar and Hot Water Flows

Three methods were used to calculate the solar and hot water flow of the solar system. Electronic counters were designed to be used with the data acquisition system. When ten gallons passed through the flow meter, the output of the counter advanced one voltage level. Voltage levels were converted back into gallons. During visits to the sites, mechanical flow meter readings and digital flow meter readings on BTU meters were also recorded. These flow meter readings gave an independent estimate of daily flow rate.

A computer was used to carry out above calculations and to separate data to a daily basis. This program is shown in Appendix A.
4.3 Results

After converting data into temperatures and flow rates, five graphs were produced for each day. The variations in temperatures, energy and pump and heating element status with respect to time were plotted.

**Figure 4.3** Solar loop temperatures across the water tank on 09.04.92
Figure 4.3 shows the solar in and solar out temperatures for an sunny day. Collector temperature rises as sun falls on collectors. The circulating pump starts when the pre-set temperature is reached and the energy from collectors is transported to the storage tank (Figure 4.4).

Figure 4.5 Hot water tank temperature and heating element status on 09.04.92 for 190 rest area.
Figure 4.5 shows the variation of temperature for water in, water out, and final mixed temperatures; and the heating element status. Water out temperature increased from 125°F to 140°F around noon due to the solar energy delivered to the tank from 8:00 to 11:00 am. Temperature of hot water delivered to rest rooms also increases for the same reason. Water in temperature also fluctuates with time due to the heat transfer from the hot water storage and when there is a water flow, water in temperature show actual temperature. From midnight till 5:00 am there was very little hot water usage.

Figure 4.6 System energy balance 09.04.92 for I-90 rest area.
Solar energy delivered to the hot water tank and total energy delivered to rest rooms are shown in Figure 4.6. Total energy points are scattered as the hot water flow was recorded at periods of peak usage.

Voltage, current and power generated by the photovoltaic (PV) panel are shown in Figure 4.7. When the batteries are fully charged, power generated by the panel is dissipated through a resistor in the charge controller. Voltage drops to zero, since voltage was monitored after the charge controller. However, the current curve continues as it was monitored before the charge controller.

Figure 4.7 Photovoltaic characteristic 09.04.92 for I-90 rest area.
Figure 4.8 shows solar in and solar out temperatures for a typical hot summer day. Collector heat transfer fluid temperature reached 225°F around noon on this day. Tank temperature also increased gradually to 180°F (Figure 4.9) and the temperature of water delivered to rest rooms is too hot (155°F) during these days. Pump worked continuously from 7:00 am to 3:00 pm as shown in Figure 4.10.

Figure 4.8 Solar loop characteristic across the hot water tank 08.22.92 for I 90 rest area.
Figure 4.9 Hot water tank characteristics on 08.22.92 for I 90 rest area.

Figure 4.10 Solar system characteristics on 08.22.92 for I 90 rest area.
From Figures 4.11 to 4.14 show graphs for a cloudy/rainy day in summer. Pump was not on. Heating element was not activated as the tank temperature did not fall below 120°F. Solar energy stored during the previous day was used in this day. Photovoltaic panels too, did not generate sufficient power to charge the batteries (Figure 4.14).

**Figure 4.11** Solar loop characteristic across the hot water tank on 08.28.92 for I-90 rest area.
Figure 4.12 Hot water delivered on 08.28.92 for I 90 rest area.

Figure 4.13 Solar system characteristics on 08.28.92 for I-90 rest area.
Figure 4.14 Photovoltaic characteristic on 09.04.92 for I-90 rest area.

Figure 4.15 shows water temperatures and the element status for a cool day with no sunlight. Water out temperatures fall around 3:30 am due to heavy hot water consumption. (Figure 4.16). The heating element was needed on this day to maintain the tank temperature. (Figure 4.17).
Figure 4.15 Hot water tank characteristic on 11.04.92 for I-90 rest area.

Figure 4.16 Energy used on 11.04.92 for I-90 rest area.
Figure 4.17 Typical hot water tank characteristic on 08.02.92 for I-90 rest area.

Figure 4.18 Solar contribution to hot water on 08.02.92 for I-90 rest area.
During the summer there were a few days when the collector temperature was higher than the tank temperature at night. In Figure 4.17, around 10:00 pm the collector temperature started to increase and the tank temperature decreased. This may be due to the heat transfer on solar in pipe in the opposite direction. In Figure 4.18, solar in temperature increased at night. Although the heat losses are in the range of 75-125 Watts depending on the system configuration, there is a possibility that the circulating pump may start if the temperature difference is sufficient. However, during the period of this research, no data points were recorded when the circulating pump was activated at night. Figures 4.19 also shows a similar occurrence.

Figure 4.19 Solar system characteristic on 08.23.92 for I-90 rest area.
Average solar out temperatures during different hours of the day for Lake and Butler county are shown in figures 20 and 21.

Figure 4.20 Average solar exit temperature for Lake county.
Figure 4.21 Average solar exit temperature for Butler county[18].
4.3.1 Comparison of Cleveland Solar System with Cincinnati and New Jersey System

The Cleveland(I-90) solar system results are compared with both the Cincinnati(I-75) Solar system and the results of the study reported by New Jersey department of transformation.

There are a few differences when the New Jersey solar system and its instrumentation is compared with Ohio solar systems: Four collector panels with total area of 84ft² were used in New Jersey system where as six panels with 138ft² were used in Cleveland and Cincinnati. A two tank storage system was used initially in New Jersey, however towards the end of the study it was converted to one tank system which is similar to the systems located near Cleveland and Cincinnati. Also, the New Jersey rest area was not equipped with an emergency PV lighting system.

![Figure 4.22 Hot Water Consumption During 12 Months](image-url)

Figure 4.22 Hot Water Consumption During 12 Months
Analysis of operating parameters on monthly basis are illustrated from Figure 4.22 to Figure 4.28. These results are based on data collected from July 1992 to June 1993. Figure 4.22 shows the total volume of hot water supplied to rest rooms in I-90 and I-75 rest areas. New Jersey data was not available for comparison in the report. The I-90 rest area consumes slightly more hot water than the I-75 rest area. An average 30% drop occurs for hot water consumption in summer months when compared to winter months.

**Figure 4.23 Energy supplied to Rest Facilities during a Year**

Figure 4.23 illustrates energy consumption in MBTU s for Cleveland(I-90), Cincinnati(I-75) and New Jersey rest areas.
Solar energy gained by the storage tank is shown in Figure 4.24. Although the New Jersey solar system had 4 collector panels, solar energy gain is considerably higher than for the Ohio rest areas. Also, the solar circulating pump operates much larger than for the Ohio rest areas. These differences may be due to smaller collector surface or different pump controller and tank temperature settings.

![Figure 4.24 Energy supplied by the solar systems to the Storage Tank](image-url)
Figure 4.25 Total Pump Operating Time During a Year

Figure 4.26 Solar Contribution
Solar contribution for Cleveland, Cincinnati and New Jersey are graphed in Figure 4.26. Since solar energy gain is a function of hot water consumption and collector parameters, solar contribution is not proportional to solar energy availability at these locations. New Jersey rest area’s solar contribution is 100% from June to October. Only in August and September did the Cleveland (I-90) rest area have 100% solar contribution. The average contribution for these rest areas are as follows:

- Cleveland (I-90) - 52.1%
- Cincinnati (I-75) - 78.8%
- New Jersey - 58.1%

**Figure 4.27 Photovoltaic Power used by Storage Batteries**
Photovoltaic power stored in the storage batteries is illustrated in Figure 4.27. This figure does not give an indication of availability of solar energy or total power generated by the PV panel. When the batteries are fully charged, the power generated by the PV panel is dissipated through a resistor. Only actual power stored by batteries are illustrated in this figure. Hours of photovoltaic system in operation is also graphed in Figure 4.28 which indicates the hours of sunlight available at these locations and collector orientation. The average PV system operating time for Cleveland (I-90) is 10.5 hrs and for Cincinnati (I-75) is 11.35 hrs. Based on these values, PV system in Cleveland could produce 0.84 kwh a day. But, only an average of 0.25 kwh (30%) is utilized to charge the storage batteries.
4.4 Economic Analysis

Economic viability of solar systems at Cleveland(I-90) and Cincinnati(I-75) solar facilities were investigated by preparing life cycle cost analysis. All calculations were carried out which was in accordance with the USDOT Federal Highway Administration’s solar demonstration project guidelines similar to New Jersey final report[19]. The following criteria were used in the Cleveland and Cincinnati solar systems economic analysis.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar system components life</td>
<td>15-20 years</td>
</tr>
<tr>
<td>Other components life</td>
<td>20 years</td>
</tr>
<tr>
<td>Rate of return on investment</td>
<td>10 %</td>
</tr>
<tr>
<td>Fuel price escalation rate</td>
<td>10 %</td>
</tr>
<tr>
<td>Inflation rate(other than fuel)</td>
<td>7 %</td>
</tr>
</tbody>
</table>

In this analysis, total cost of the solar hot water system with the backup heater is compared with the conventional electric heating system. Cost of equipment, installation, electricity and maintenance were considered in the analysis. Cost of each item was compared after calculating the present value of the cost. Detail cost analysis for Cleveland(I-90) solar system is shown in this section and cost analysis for Cincinnati (I-75) is shown in Appendix D.

4.4.1 Cost of Solar Hot Water System

Cost of solar system is defined as all costs of solar heating equipment with back up heating system, design and installation cost, maintenance and operating cost over a period of 20 years.
Detail cost of engineering and design, equipment and installation are as follows for Cleveland (I-90) and Cincinnati (I-75) rest areas.

Supply and Install Solar Domestic hot water system  -  $6228.50
Extra Collector  -  $879.00
Extra collector frame base  -  $102.00
Fabricate and Erect collector 100ft mount  -  $218.50
Extra material  -  $220.00
Extra lacing  -  $535.00
Solar tank  -  $950.00
Total  

$10133.00

4.4.2 Electricity Cost

Electrical cost of both solar hot water system were estimated using solar and hot water BTU meter reading.

Total Hot Water Demand per Anum  =  23.78 MBTU
Total Solar contribution per Anum  =  12.39 MBTU
Heat Supplied by the heating element  =  11.39 MBTU
=  3337.25 kWh
Cost of electricity per Anum  (@ 0.10/kWh)  =  $333.72

It was assumed in the calculations, that the hot water demand will increase by 5% annually over
next 20 years.

Present worth of the electricity cost can be calculated from the following equation.

\[
\text{Present worth} = \text{Future worth} \times \frac{1}{(1+i)^n}
\]

where \(i\) = Rate of return on investment

\(n\) = no. of years

Table 4.1 shows the present worth of the back up electricity cost for Cleveland (I-90)solar hot water system.
Table 4.1 Electricity cost for solar system with electric backup for a period of 20 years.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>FUTURE WORTH</th>
<th>PRESENT WORTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>333.72</td>
<td>333.72</td>
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<tr>
<td>1993</td>
<td>385.45</td>
<td>350.41</td>
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<tr>
<td>1994</td>
<td>445.19</td>
<td>367.93</td>
</tr>
<tr>
<td>1995</td>
<td>514.20</td>
<td>386.32</td>
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<tr>
<td>1996</td>
<td>593.90</td>
<td>405.64</td>
</tr>
<tr>
<td>1997</td>
<td>685.95</td>
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<td>1998</td>
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<td>447.22</td>
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<tr>
<td>1999</td>
<td>915.07</td>
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<td>2000</td>
<td>1056.91</td>
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<tr>
<td>2001</td>
<td>1220.73</td>
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<td>2002</td>
<td>1409.94</td>
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</tr>
<tr>
<td>2003</td>
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<tr>
<td>2004</td>
<td>1880.90</td>
<td>599.31</td>
</tr>
<tr>
<td>2005</td>
<td>2172.44</td>
<td>629.28</td>
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<tr>
<td>2006</td>
<td>2509.17</td>
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<td>2007</td>
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<td>2008</td>
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<td>728.47</td>
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<tr>
<td>2009</td>
<td>3866.13</td>
<td>764.89</td>
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<tr>
<td>2010</td>
<td>4465.38</td>
<td>803.14</td>
</tr>
<tr>
<td>2011</td>
<td>5157.51</td>
<td>843.29</td>
</tr>
</tbody>
</table>

Total present worth of electricity cost = $1034.77
4.4.3 Maintenance Cost

The annual maintenance cost estimated by the Ohio Department of Transportation for the solar domestic hot water system is $250. To estimate the total present value of maintenance cost for 20 years, 7% inflation rate and 10% rate of return on investment were used. This shown in Table 4.2.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>FUTURE WORTH</th>
<th>PRESENT WORTH</th>
</tr>
</thead>
<tbody>
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<td>250.00</td>
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<tr>
<td>1993</td>
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<td>236.55</td>
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<tr>
<td>1995</td>
<td>306.26</td>
<td>230.10</td>
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<td>1996</td>
<td>327.70</td>
<td>223.82</td>
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<td>1997</td>
<td>350.64</td>
<td>217.72</td>
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<td>1998</td>
<td>375.18</td>
<td>211.78</td>
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<td>2001</td>
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<td>2002</td>
<td>491.79</td>
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<tr>
<td>2006</td>
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<tr>
<td>2007</td>
<td>689.76</td>
<td>165.12</td>
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<tr>
<td>2008</td>
<td>738.04</td>
<td>160.62</td>
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<tr>
<td>2009</td>
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<td>2010</td>
<td>844.98</td>
<td>151.98</td>
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<tr>
<td>2011</td>
<td>904.13</td>
<td>147.83</td>
</tr>
</tbody>
</table>

Total present worth of maintenance cost = $ 3893.96

Table 4.2 Present worth of maintenance cost for solar system with backup heating element
4.4.4 Cost of Conventional Heating System

The cost of a conventional electrical water heating system is defined as the present worth of the existing equipment including installation, electricity and maintenance cost for 20 years.

Equipment required for the conventional water heating system is a 120 gallon hot water storage tank with a 4.5 kW heating element and a thermostat. The cost of this tank is about $950. Engineering, design and installation cost used in the New Jersey report[19] is used in this analysis.

\[
\text{Engineering design and installation cost} = 800 \ $ \\
\text{Cost of the storage tank} = 950 \ $ \\
\text{Total equipment cost} = 1750 \ $
\]

4.4.5 Electricity cost

\[
\text{Total hot water demand} = 23.78 \text{ MBTU} \\
= 6967.5 \text{ kWh} \\
\text{Cost (@ 10cts. per kWh)} = 696.75 \ $
\]

Table 4.3 shows the total present worth of electricity cost for a period of 20 years.
<table>
<thead>
<tr>
<th>YEAR</th>
<th>FUTURE WORTH</th>
<th>PRESENT WORTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
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<td>2008</td>
<td>6988.58</td>
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<td>2009</td>
<td>8071.81</td>
<td>1596.96</td>
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<tr>
<td>2010</td>
<td>9322.94</td>
<td>1676.81</td>
</tr>
<tr>
<td>2011</td>
<td>10767.99</td>
<td>1760.65</td>
</tr>
</tbody>
</table>

Total present worth of electricity cost \(=\) $23038.70

Table 4.3 Present worth of electricity cost for the conventional heating system.
4.4.6 Maintenance Cost

Only routine maintenance cost are considered for the conventional electric hot water system. This routine maintenance such as draining the storage tank yearly is estimated as 4 hours of labor at 25$ an hour for a total cost of 100$ a year. 7% inflation rate was added to calculate the maintenance cost for a period of 20 years. Present worth of maintenance cost is shown in table 4.4.
### Table 4.4 Present worth of maintenance cost for the conventional system.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>FUTURE WORTH</th>
<th>PRESENT WORTH</th>
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</thead>
<tbody>
<tr>
<td>1992</td>
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<td>64.25</td>
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<td>2009</td>
<td>315.88</td>
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<tr>
<td>2010</td>
<td>337.99</td>
<td>60.79</td>
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<tr>
<td>2011</td>
<td>361.65</td>
<td>59.13</td>
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</table>

Total present worth of electricity cost = $1557.59
Summary

<table>
<thead>
<tr>
<th></th>
<th>Conventional system</th>
<th>Solar system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment cost($)</td>
<td>1,750.00</td>
<td>10,133.00</td>
</tr>
<tr>
<td>Electricity cost($)</td>
<td>23,038.70</td>
<td>11,034.77</td>
</tr>
<tr>
<td>Maintenance cost($)</td>
<td>1,557.59</td>
<td>3,893.96</td>
</tr>
<tr>
<td>Total cost($)</td>
<td>26,346.29</td>
<td>25,060.96</td>
</tr>
</tbody>
</table>

Table 4.5 Summary of the cost analysis of Cleveland (I-90) solar system.

The above table summarizes the cost analysis for Cleveland solar hot water system. $1285 difference in cost between the evaluated systems shows that the solar system with electric backup is an economical alternative to conventional hot water heating system.
CHAPTER 5

SIMULATION

5.1 INTRODUCTION

Solar hot water systems can be represented as a computer model. Once an accurately modeled and tested for a known system, the model can be used to design more economical and efficient solar systems. Also, these models can be used to examine the performances of similar systems at different locations. Therefore, results of these models can be used in decision making.

Solar hot water systems at I-90 East in Lake county and I-75 North in Butler county were modeled using TRNSYS version 13.1 simulation program. Using physical parameters to describe the systems, weather data and hot water demand; then theoretical quantities for solar energy gain, energy delivered to rest rooms, energy losses, energy supplied by heating element and parasitic power draw were estimated.

These simulated results were then compared with field measurements. Performance characteristics of the solar systems were calculated and compared as parameters of the collector array and the pump controller were modified.
5.2 TRNSYS SIMULATION PROGRAM

TRNSYS is a TRaNsient SYStems simulation program, with a modular structure[17]. The program was developed at Solar Energy Laboratory of University of Wisconsin. The modular structure of TRNSYS gives the program tremendous flexibility, but it demands from the user some degree of expertise.

TRNSYS consists of 55 subroutines for the different components used in solar systems. A solar system Relevant subroutines can be assembled together to model a solar system. As the system consist of components, it is possible to simulate the performance of the system by collectively simulating the performance of the interconnected components.

All subroutines in TRNSYS are written in fortran and therefore, modify or add new components conveniently. TRNSYS can be run on Sun machines or IBM compatible PC’s with a math co-processor.

The I-90 and I-75 rest areas were modeled by assembling subroutines for collector, pump, pump controller, storage tank, heat exchanger and the auxiliary heater. Weather data at each location was read from the weather data file in the program.
Major subroutines of TRNSYS used to simulate the solar system at I-90 and I-75 were as follows:

1) Solar Collector
2) Pump and Pump Controller
3) Heat Exchanger
4) Main Storage Tank
5) Weather Generator
6) Radiation Processor
7) Profile Generator

In addition to above, utility subroutines such as data reader, integrator, printer, plotter etc. were also used.

5.2.1 Solar Collector

This component models the thermal performance of flat plate collectors by using standard test data of collectors. The thermal performance of the total collector array is determined by the number of modules in series and the characteristic of the each module. At both locations, collector array consisted of six collectors connected three in each series. The following collector test parameters, consist with these issued by Solar Rating and Certificate Corporation (SRCC), were used for the simulation.

1) Collector test flow rate - 1.50 gal/min
This is the flow rate at which the collector was tested. Necessary corrections are applied in the model if the collector flow rate was different.

2) Collector test fluid density - 62.40 lb/ft³

3) SRCC y intercept of \( \eta \) vs \( \Delta T/I_T \) curve - 0.743

General expression for collector efficiency as given by Hottel-Whillier equation[17].

\[
\zeta = \frac{Q_u}{A I_T} = F_{\tau \alpha} - F_{R L} \frac{(T_T - T_a)}{I_T}
\]

Therefore, the y intercept of \( \eta \) vs \( \Delta T/I_T \) plot represents the value of \( F_{\tau \alpha} \).

4) SRCC first order loss coefficient - 0.726

5) First order incident angle modifier - 0.8600

The physical measurements and other parameters used are listed below.

Collector panel gross area - 23.32 ft²
Total number of panels - 6
Number of panel in series - 3
Collector array flow rate - 2.00 gal/min
Collector fluid specific heat - 1.00 Btu/lb-F
Collector fluid density - 62.40 lb°/ft³
Collector Slope - 45°
Collector azimuth angle - -14°
Ground reflectance - 0.20
Collector pipe outside diameter - 0.65 in
Insulation thickness - 0.50 in
Pipe Insulation R value - 3.0 hr-ft²°F/BTU

Rate of energy gain by collectors, \( Q_u \) is evaluated from this solar collector subroutine. When the pump is on \( Q_u \) can be written as[17]

\[
Q_u = r \cdot A \left[ F_R (\tau \alpha) \frac{\tau \alpha}{(\tau \alpha)_n} \cdot I_T - F_R U_L (T_i - T_A) \right]
\]

5.2.2 Pump

The pump Model computes the mass flow rate and the power consumed. In this model pump control function constantly checks the temperatures in collector and storage tank models and turns on the pump when collector and tank temperature difference reaches the set value. Parameter used are as given below:

Pump Capacity - 1.42 gal/min
Power Consumption - 60 W
Turn on dead band - 16° F
Turn off dead band - 5° F
Pump controller power consumption - 10W
5.2.3 Heat Exchanger

Cross flow type heat exchanger was used for the modeling. Effectiveness of the heat exchanger, inlet fluid temperature and fluid flow rate input parameters were used for this model. Total heat transfer across the heat exchanger was obtained from

\[ Q_T = \varepsilon \ c_{\text{min}} \ (T_{hi} - T_{ci}) \]

Effectiveness of the heat exchanger, \( \varepsilon \) was used as 0.40 for both locations. The other two inlet parameters, flow rate and inlet temperature were taken as 1.42 gallon/min and the outlet temperature of the collector array wheel was calculated in the collector model, respectively.

5.2.4 Hot Water Storage Tank

Thermal performance of the storage tank was modeled by assuming that the tank consist of \( N \) (\( N < 15 \)) fully mixed equal volume segments. as shown in Figure 5.1. The degree of satisfaction is determined by the value of \( N \), which is calculated from tank parameters. The storage tank was modeled with an electrical resistance heating element. A temperature and time controller was also included in the program to compare the tank temperature and the tank set temperatures to determine the necessity of the auxiliary heater.
Parameter used for this model were as follows:

- **Tank Value**: 120 gal
- **Tank Height**: 6 ft
- **Tank R-value**: 10.0 hr-ft²°F / BTU
- **Element Capacity**: 4500 W
- **Tank Set temperature**: 120°F
5.2.5. Weather Data Generator.

This component generates hourly weather data, given the monthly average values of solar radiation, dry bulb temperature, humidity ratio and wind speed. The data are generated in a manner such that their associated statistics are approximately equal to the long term statistics at the specified location. The purpose is to generate a single typical year data, similar to a Typical Meteorological Year.

For the simulation, weather data is stored from an external data file. In this file, data is supplied in the following format.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12</td>
<td>W1 W2 W3 W4 W5 W6 W7 W8 W9 W10 W11 W12</td>
</tr>
<tr>
<td>T1 T2 T3 T4 T5 T6 T7 T8 T9 T10 T11 T12</td>
<td></td>
</tr>
</tbody>
</table>

Where

- Location - the name of the city (max 32 characters)
- Latitude - Latitude of the location (between -90.0 and 90.0 starts at column 33)
- I1 - I12 - Monthly average daily global horizontal radiation (kJ/m²)
- W1 - W12 - Monthly average humidity ratio time 10⁴ (kg Water/kg air)
- T1 - T12 - Monthly average ambient temperature (C°)
In TRNSYS these weather data for 329 locations are placed in a separate file named WDATA.DAT. Therefore, the user can add or modify weather data for a specific location[17].

5.2.6 Solar Radiation Processor

Insolation data is generally taken at one hour intervals and on a horizontal surface. In this simulation, estimate of radiation in every five minutes period are needed. Solar radiation processor interpolate the radiation data, calculate quantities related to the position of the sun and estimates insolation on four surfaces of either a fixed or variable orientation.

5.2.7 Profile Generator

This component was used to generate the actual hot water delivery profile based on the average daily hot water demand, and the water temperature profiles.

Input daily flow rate by the user was distributed over the day according to this profile. This profile was prepared by observing actual flow patterns of the I-90 rest area. Figure 5.2 shows the hot water load profile used for the simulation.
Figure 5.2 Hot water load profile for Cleveland rest area.

All these components were assembled in the TRNSYS deck file. A complete listing of the deck file (File Name.dck) is given in the Appendix B.

5.3 SIMULATION OF THE LAKE COUNTY (I-90) REST AREA SOLAR SYSTEM

The above system was simulated using TRNSYS based on the average daily hot water consumption for every month. Values of solar energy gained by collectors, solar energy delivered to the storage tank, energy loss to the environment, energy supplied by the heating element, total energy (hot water) delivered to rest rooms and parasitic power...
Where

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qu</td>
<td>Solar energy gain by collectors in MBTU</td>
</tr>
<tr>
<td>QSOTN</td>
<td>Net solar energy delivered to the tank in MBTU</td>
</tr>
<tr>
<td>QLSOTN</td>
<td>Energy loss to the environment in MBTU</td>
</tr>
<tr>
<td>QAUX</td>
<td>Energy supplied by the heating element in MBTU</td>
</tr>
<tr>
<td>QDEL</td>
<td>Total hot water energy delivered to rest rooms in MBTU</td>
</tr>
<tr>
<td>QPA</td>
<td>Parasitic power draw in MBTU</td>
</tr>
</tbody>
</table>

5.3.1 Comparison to Lake county I-90 Rest Area

Simulation output of net solar energy delivered to the tank is compared with the experimental values in Figure 5.3. In this figure, solar energy delivered in October is higher than the month of September as the hot water consumption was higher in October compared to September. There was a significant increase in solar energy gain by collectors with higher water consumption. Figure 5.4 shows the TRNSYS estimate of net solar energy delivered for different hot water flow rate.
Figure 5.3 Experimental and theoretical net solar energy delivered to the storage tank at I-90 rest area.

Figure 5.4 TRNSYS output of solar energy gain by collectors for two different flow rates.
Figure 5.5 shows the simulated output of hot water delivered and measured values. Solar energy contribution for I-90 rest areas is shown in Figure 5.6.

![Graph showing theoretical and experimental hot water energy delivered to rest rooms]

**Figure 5.5** Experimental and theoretical energy (hot water) delivered to rest rooms

TRNSYS output of energy loss to the environment shown in Figure 5.7. During summer months energy losses are high due to higher tank temperature and longer pump operating time.
Figure 5.6 Experimental and theoretical solar energy contribution for I-90 rest area.

Figure 5.7 Theoretical energy loss to the environment at I-90 rest area.
Figure 5.8 Energy supplied by the heating element at I-90 rest area.

Figure 5.9 Parasitic power draw at I-90 rest area
Energy consumption by the heating element and the parasitic power draw are shown in Figures 5.8 and 5.9. Parasitic power is the power consumed by the circulating pump and the pump controller.

5.3.2 Examination of Modifications to I-90 Rest Areas

Performance of a solar domestic hot water system depend on many parameters such as collector array area, azimuth angle, slope of collectors, storage tank size, temperature settings, pipe & insulation dimensions and hot water load. Without changing the hot water load, effects on the system performance can be examined by changing the collector size, azimuth angle, pump controller settings etc.

5.3.2.1 Performance of Three Collector Systems

Performance of the solar system with 3 collectors was compared with six collectors using TRNSYS. The same daily hot water load was used for both simulations. Analysis show an average of 40% drop in solar energy collected when the collector area is reduced by 50% (Figure 5.10). Energy losses are also less in the three collector system as a lesser amount of energy was transported from the collector array and stored in the tank(Figure 5.11).
Figure 5.10 Solar energy gain by collectors at I-90 rest area

Figure 5.11 Energy loss to the environment with three and six collectors
More energy was supplied by the heating element to compensate for the loss of three collectors (Figure 5.12). Figure 5.13 shows the parasitic power draw was also slightly higher. This may be due to the circulating pump, which runs larger in the three collector system.

**Figure 5.12** Energy provided by the heating element for six and three collector systems
Figure 5.13 Parasitic power draw for six and three collector systems

Figure 5.14 Solar contribution by six and three collectors
Solar energy contribution by three collectors is much less during Spring and Summer months, but in Winter months is very close to heat calculated by six units (Figure 5.14).

5.3.2.2 Change in Azimuth Angle

At the I-90 rest area, the collector array was installed with an azimuth angle of 14° towards east. The system performance was estimated for 0° azimuth and is shown in Figures 5.15 to 5.18. A significant improvement of solar collection was not shown when collectors were modeled at 0° azimuth.

Figure 5.15 Solar energy gain by collectors for azimuth angles -14 and 0 degrees.
Figure 5.16 Solar contribution for azimuth angles -14 and 0 degrees.

Figure 5.17 Energy provided by the heating element azimuth angles -14 and 0 degrees.
Figure 5.18 Energy loss to the environment for azimuth angles -14 and 0 degrees.

Performance of the I-90 solar system were also examined with a lower differential temperature setting of the pump controller. Other than the parasitic power, significant change in performance was not found. Parasitic power for 10°F differential setting is higher than the 16°F, as circulating pump was switched on and off more frequently. Figures showing these comparisons are found in Appendix C.

Summary

Results obtained using TRNSYS simulation program are closely matched with measured data for Lake county solar system. TRNSYS predicts that the three collectors are not sufficient to meet the hot water demand for Lake county rest facility. Also, no significant
difference were noted with 0° azimuth angle and reduced pump on temperature.

5.4 Simulation of Butler county (I-75) rest area solar system.

Similar to I-90 solar system, the I-75 solar system was also modeled for 12 months using TRNSYS. The same program was used but with modifications to Latitude, inlet water temperature profile, circulating pump capacity, the daily flow rate and the azimuth angle.

TRNSYS estimates of solar energy gain, hot water delivered to rest rooms, energy loss to the environment, energy supplied by the heating element, parasitic power draw and the solar energy contribution are compared with field results in Figures 5.19 to 5.25.
Figure 5.19 Experimental and theoretical net solar energy delivered to the tank.

Figure 5.20 Experimental and theoretical hot water energy delivered
Figure 5.21 Energy provided by the heating element.

Figure 5.22 Parasitic power draw at Cincinnati rest area.
Figure 5.23 Theoretical estimate of energy loss to the environment.

Figure 5.24 Experimental and theoretical solar energy contribution.
Figure 5.25 Experimental and theoretical solar energy contribution for I-75 rest area
CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Seventeen highway rest facilities in Ohio are equipped with solar domestic hot water systems. Two solar systems were instrumented and performance and effectiveness were monitored.

Both solar hot water systems and monitoring system operated over a 12 month period from June 1992 to July 1993. The operation of photovoltaic lighting systems was interrupted due to problems with power storage. Nevertheless, photovoltaic data were recorded during this period. Only problem encountered with the solar heating system was the loss of pressure in the collector heat transfer fluid. Both systems had to be recharged once, but data collection or system operation was not affected.

For a typical sunny day, in the summer, the circulating pump at Lake county rest area, operates on demand for nearly 11 hours. But the average pump operating time over the year is only 2.75 hrs/day. For the Butler county solar system, the average pump
operating time is 2.01 hrs/day. In Lake county the pump operates longer duration than at the Butler county site due to the difference in hot water demand intensity of solar energy and ambient conditions such as wind and temperature. Average percent of solar contribution to total energy requirement for the Butler county is higher (72%) than for Lake county (52%).

When the circulating pump operates for 5-7 hours in summer, tank temperature rises as high as 175°F and the water out of hot water tank temperature even after mixing with cold water also rises to 150°F. No electricity was consumed in summer by either hot water system. Storage tank size was sufficient to supply hot water in summer, even when the sunshine was not adequate to activate the circulating pump for 1-2 days. Also, occasional heat losses from the tank to the collector were measured at night from back syphoning.

Average hot water consumptions were 107 and 104 gallons per day for Lake and Butler county rest areas, respectively. There was a 20% less demand for hot water at both rest areas, in summer, when maximum contribution from solar energy is available.

Economic viability of both solar system was investigated with FHWA life cycle cost analysis. Calculations shows that solar domestic hot water systems with electric supplemental heating, is an economical alternative to conventional heating system for both Lake and Butler county rest areas, as summary of the cost analysis is shown in the
Both solar systems would be even more economical if operated at a higher hot water demand. Heat losses of the hot water tank is also a problem and would significantly affect calculations.

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Lake County</th>
<th>Butler County</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conven. system</td>
<td>Solar System</td>
</tr>
<tr>
<td>Equipment</td>
<td>1,750</td>
<td>10,133</td>
</tr>
<tr>
<td>Electric</td>
<td>23,039</td>
<td>11,035</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1,558</td>
<td>3,894</td>
</tr>
<tr>
<td>Total</td>
<td>26,346</td>
<td>25,061</td>
</tr>
</tbody>
</table>

Table 6.1 Summary of the cost analysis for Lake and Butler county rest facilities.

The solar systems were simulated using TRNSYS subroutines based on the actual daily hot water demand for 12 months. Output results closely matched the measured data. Therefore the program was used to evaluate the performance solar systems with modified parameters. Lake county solar system’s performance was examined with three collectors instead of six, using TRNSYS and found that three collectors are not adequate. No significant difference was noted with 0° azimuth angle and 10°F pump on differential temperature setting. TRNSYS could be used to design more efficient and economical solar systems. It can also be used to design systems the different locations around Ohio.

Performance of the photovoltaic lighting system was also investigated. Due to problems with storage, the emergency lightning system was not operational 25% of the time.
Approximately 60% of the available photovoltaic power is wasted. This should be utilized for a different purposes as it vaporize the battery fluid and the system becomes non operational. The emergency lighting system is will liked by operational personal.

6.2 RECOMMENDATIONS

1) In solar domestic hot water systems, collector water pressure should be maintained at recommended level for efficient operation of the system. Nine out of sixteen solar systems inspected in April/May 1993 were found to be at low or zero pressure. To prevent this, a direct connections to water pressure or a regular maintenance schedule is recommended.

2) Heat traps are recommended for the cold liquid pipes of the solar system to prevent back syphoning.

3) Lake county collector panels azimuth angle and Butler county slope of the collector surface could be changed to 0° and 35°, respectively, to harness more solar energy.

4) Simulation was carried out using average weather data. For more accurate results, TRNSYS could be used with actual weather data.
5) As Cleveland has the highest average wind speed in Ohio, collectors with two cover plates may improve the collector efficiency. This could be examined using TRNSYS.

6) Liquid levels should be maintained in the batteries.

7) Excess PV power could be used for other applications or the PV module could be down rated.

8) TRNSYS deck file can be modified to perform economic analysis and PV system performance analysis.
APPENDIX A

DATA ANALYSIS PROGRAM

C***********************************************************************
C**************PROGRAME TO ANALYSE SOLAR ENERGY DATA******
C***********************************************************************

C***********declaration***********

real v2(4000),time(4000),r1(4000),ff(4000)
real twout(4000),twin(4000),tsout(4000),tsin(4000),r2(4000)
real tstr(4000),tcoll(4000),tamb(4000),tmix(4000),pump(4000)
real v3(4000),v4(4000),v5(4000),v6(4000),v7(4000),v8(4000)
integer t3(4000),t4(4000),t5(4000),t6(4000),t7(4000),t8(4000)
real r3(4000),r4(4000),r5(4000),r6(4000),r7(4000),r8(4000)
real pvcells(4000),current(4000),flows(4000),floww(4000),work(4000)
real fs(4000),fw(4000),gs(4000),gw(4000),tots,totw
real e(4000),ee(4000),pt
character line*200
integer k,j,i,popp(4000)
integer t(4000),tl(4000)
real a(8900,16)
C***********************************************************************

C**************openning files***********
open(unit=2, file='data02.27', STATUS='OLD')
open(unit=7, file='cl01.24')
open(unit=8, file='cl01.25')
open(unit=9, file='cl01.26')
open(unit=10, file='cl01.27')
open(unit=11, file='cl01.28')
open(unit=12, file='cl01.29')
open(unit=13, file='cl01.30')
open(unit=14, file='cl01.31')
open(unit=15, file='cl02.01')
open(unit=16, file='cl02.02')
open(unit=17, file='cl02.03')
open(unit=18, file='cl02.04')
open(unit=19, file='cl02.05')
open(unit=20, file='cl02.06')
open(unit=21, file='cl02.07')
open(unit=22, file='cl02.08')
open(unit=23, file='cl02.09')
open(unit=24, file='cl02.10')
open(unit=25, file='cl02.11')
open(unit=26, file='cl02.12')
open(unit=27, file='cl02.13')
open(unit=28, file='cl02.14')
open(unit=29, file='cl02.15')
open(unit=30, file='cl02.16')
open(unit=31, file='cl02.17')
open(unit=32, file='cl02.18')
open(unit=33, file='cl02.19')
open(unit=34, file='cl02.20')
open(unit=35, file='cl02.21')
open(unit=36, file='cl02.22')
open(unit=40, file='clvdat.rev')
open(unit=50, file='dumy.rev')

***** VARIABLES *****

total no of rows

If=3287

initial time

otime = 0.1
c no. of rows in the first file
d1 = 96

rewind 2
do 57 i = 1,lf
read(2,65,end = 180) line
write(40,65) line(18:197)
c read(2,65,end = 180) line
c write(50,65) line(16:180)
65 format(a199)
180 continue
57 continue
rewind 40
do 50 i = 1,lf
read(40,*,end = 181) (a(i,j), j = 1, 14)
50 continue
181 continue
do 500 j = 1, 14
write(*,*) a(1,j)
500 continue

*** removing -10.000 values ***

do 61 i = 1,lf
do 62 j = 1, 11
if (a(i,j).eq.-10.0) then
  if (a((i+1),j).eq.-10.0) then
    a(i,j) = a((i-1),j)
  else
    a(i,j) = (a((i-1),j) + a((i+1),j))/2
  endif
else
  a(i,j) = a((i-1),j)
endif
62 continue
61 continue
do 63 i=1,lf
  do 64 j=12,13
    if (a(i,j).eq.-10.0) then
      a(i,j)=a((i-1),j)
    endif
  64 continue
  63 continue

C***********************************************************************

k=1
  do 51 i=1,lf
    tsin(i)=a(k,3)
    tsout(i)=a(k,4)
    twin(i)=a(k,5)
    twout(i)=a(k,6)
    tmix(i)=a(k,9)
    tcoll(i)=a(k,7)
    tsstr(i)=a(k,8)
    tamb(i)=a(k,10)
    pvcells(i)=a(k,11)
    current(i)=a(k,12)
    pump(i)=a(k,2)
    flows(i)=a(k,13)
    floww(i)=a(k,14)
    e(i)=a(k,1)
  k=k+1
  51 continue
  do 520 i=1,10
    write (*,*)pump(i),floww(i)
  520 continue
  do 1000 i=1,20
    write (*,*) e(i)
  1000 continue

C***********************************************************************

C          calculation of time************

C***********************************************************************

do 12 i=1,lf
  time(1)=time0
time(i) = time(i-1) + 0.25
if(time(i) .gt. 24) then
  time(i) = time(i) - 24.0
endif
continue

C***********************************************************************

C   CALCULATION OF SOLAR AND WATER FLOWS

C***********************************************************************

C   SOLAR LEVELS.

C***********************************************************************

s1 = .6
s2 = .94
s3 = 1.10
s4 = 1.26
s5 = 1.33
s6 = 1.4
s7 = 1.5
s8 = 1.7
s9 = 2.2
s10 = 3
s11 = 4

C***********************************************************************

C   WATER LEVELS.

C***********************************************************************

st1 = .75
st2 = 1.15
st3 = 1.35
st4 = 1.45
st5 = 1.53
st6 = 1.6
st7 = 1.7
st8 = 1.9
st9 = 2.3
st10 = 3
st11 = 4.2
do 600 i = 1, lf
if ((flow(i) .gt. s1) .and. (flow(i) .lt. s2)) then
   fs(i) = 1
else
   if ((flow(i) .gt. s2) .and. (flow(i) .lt. s3)) then
      fs(i) = 2
   else
      if ((flow(i) .gt. s3) .and. (flow(i) .lt. s4)) then
         fs(i) = 3
      else
         if ((flow(i) .gt. s4) .and. (flow(i) .lt. s5)) then
            fs(i) = 4
         else
            if ((flow(i) .gt. s5) .and. (flow(i) .lt. s6)) then
               fs(i) = 5
            else
               if ((flow(i) .gt. s6) .and. (flow(i) .lt. s7)) then
                  fs(i) = 6
               else
                  if ((flow(i) .gt. s7) .and. (flow(i) .lt. s8)) then
                     fs(i) = 7
                  else
                     if ((flow(i) .gt. s8) .and. (flow(i) .lt. s9)) then
                        fs(i) = 8
                     else
                        if ((flow(i) .gt. s9) .and. (flow(i) .lt. s10)) then
                           fs(i) = 9
                        else
                           if ((flow(i) .gt. s10) .and. (flow(i) .lt. s11)) then
                              fs(i) = 10
                           endif
                        endif
                     endif
                  endif
               endif
            endif
         endif
      endif
   endif
endif
endif
endif
endif
endif
endif
600 continue

C***********************************************************************

do 610 i=l,lf
if ((floww(i) .gt. st1) .and. (floww(i) .lt. st2)) then
fw(i) = 1
else
if ((floww(i) .gt. st2) .and. (floww(i) .lt. st3)) then
fw(i) = 2
else
if ((floww(i) .gt. st3) .and. (floww(i) .lt. st4)) then
fw(i) = 3
else
if ((floww(i) .gt. st4) .and. (floww(i) .lt. st5)) then
fw(i) = 4
else
if ((floww(i) .gt. st5) .and. (floww(i) .lt. st6)) then
fw(i) = 5
else
if ((floww(i) .gt. st6) .and. (floww(i) .lt. st7)) then
fw(i) = 6
else
if ((floww(i) .gt. st7) .and. (floww(i) .lt. st8)) then
fw(i) = 7
else
if ((floww(i) .gt. st8) .and. (floww(i) .lt. st9)) then
fw(i) = 8
else
if ((floww(i) .gt. st9) .and. (floww(i) .lt. st10)) then
fw(i) = 9
else
if ((floww(i) .gt. st10) .and. (floww(i) .lt. st11)) then
fw(i)=10
endif
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endi
do 22 i = 1, lf
  v1(i) = twout(i)
  r1(i) = (((v1(i)/5)*3.24)/(1-v1(i)/5))*1000
  v2(i) = twin(i)
  r2(i) = (((v2(i)/4.75)*3.24)/(1-v2(i)/4.75))*1000
22 continue
  call calctemp(lf, t, t1, r1, r2)

*** equations to find tso/tdi ***

do 24 i = 1, lf
  v3(i) = tsout(i)
  r3(i) = (((v3(i)/5)*3.24)/(1-v3(i)/5))*1000
  v4(i) = tsin(i)
  r4(i) = (((v4(i)/5)*3.24)/(1-v4(i)/5))*1000
24 continue
  call calctemp(lf, t3, t4, r3, r4)

*** equations to find tstr/tcoll ***

do 26 i = 1, lf
  v5(i) = tstr(i)
  r5(i) = (((v5(i)/11.2)*9.82)/(1-v5(i)/11.2))*1000
  v6(i) = tcoll(i)
  r6(i) = (((v6(i)/11.2)*8.8)/(1-v6(i)/11.2))*1000
26 continue
  call calctemp(lf, t5, t6, r5, r6)

*** pump status ***

ej = 1
  do 400 i = 1, lf
    if (pump(j).gt.4) then
      popp(j) = 15

```c
else
    popp(j) = 0
endif
    j = j + 1
400 continue
    pt = 0
    do 407 j = 1,lf
        pt = pt + popp(j)
    407 continue
    write (*, *) "tot pump time =", pt

c*****************************************************************************
c*** calculation of find ambient and water mixed temperatures ***
c*****************************************************************************
    vamb = 5.55
    vmix = 5
    do 28 i = 1,lf
        v7(i) = tamb(i)
        r7(i) = (((v7(i)*4.32)/(6-v7(i)))*1000
        v8(i) = tmix(i)
        r8(i) = (((v8(i)*4.32)/(6-v8(i)))*1000
    28 continue
    call calctemp(lf, t7, t8, r7, r8)

c*****************************************************************************
c*** calculating pv power ***
c*****************************************************************************
    do 43 i = 1,lf
        work(i) = current(i)*pvcells(i)
    43 continue

c*****************************************************************************
c*** Element Status ***
c*****************************************************************************
    do 44 i = 1,lf
```

The text in the image contains a code snippet in the C programming language. The code performs calculations to find ambient and water mixed temperatures, calculates PV power, and includes a loop to handle elements status.
if( e(i) .LT. (.5)) then
    ee(i)=0
else
    ee(i)=20
endif

continue

*** writing files ***

do 176 i=1,lf
    ff(i)=0
176 continue

**********+***********Writing day 1************ ************

do 200 i=1,d1
    write(7,122) time(i),t(i),t1(i),t3(i),t4(i),t5(i),t6(i),
    + popp(i),t7(i),t8(i),pvcells(i),current(i),work(i),flows(i)
    + ,floww(i),gs(i),gw(i),ee(i)
122 format(F5.2,9(Ix,i5),8(2x,f8.3))
200 continue

**********writing day 2************ ************

d2=d1+96

do 201 i=d1+1,d2
    write(8,122) time(i),t(i),t1(i),t3(i),t4(i),t5(i),t6(i),
    + popp(i),t7(i),t8(i),pvcells(i),current(i),work(i)
    + ,flows(i),floww(i),gs(i),gw(i),ee(i)
201 continue

**********writing day 3************ ************

d3=d2+96

do 202 i=d2+1,d3
    write(9,122) time(i),t(i),t1(i),t3(i),t4(i),t5(i),t6(i),
    + popp(i),t7(i),t8(i),pvcells(i),current(i),work(i)
    + ,flows(i),floww(i),gs(i),gw(i),ee(i)
202 continue

**********writing day 4************ ************
d4 = d3 + 96
do 203 i = d3 + 1, d4
   write(10, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
   write(l0, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
203 continue

c *********************writing day 5*********************

d5 = d4 + 96
do 204 i = d4 + 1, d5
   write(11, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
   write(11, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
204 continue

c *********************writing day 6*********************

d6 = d5 + 96
do 205 i = d5 + 1, d6
   write(12, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
   write(12, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
205 continue

c *********************writing day 7*********************

d7 = d6 + 96
do 206 i = d6 + 1, d7
   write(13, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
   write(13, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
206 continue

c *********************writing day 8*********************

d8 = d7 + 96
do 207 i = d7 + 1, d8
   write(14, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
   write(14, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
+ , flows(i), floww(i), gs(i), gw(i), ee(i)
207 continue
Writing day 9

```
d9 = d8 + 96
do 208 i = d8 + 1, d9
    write(15, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    flows(i), floww(i), gs(i), gw(i), ee(i)
  208 continue
```

Writing day 10

```
d10 = d9 + 96
do 209 i = d9 + 1, d10
    write(16, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i),
    t6(i), popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    flows(i), floww(i), gs(i), gw(i), ee(i)
  209 continue
```

Writing day 11

```
d11 = d10 + 96
do 210 i = d10 + 1, d11
    write(17, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    flows(i), floww(i), gs(i), gw(i), ee(i)
  210 continue
```

Writing day 12

```
d12 = d11 + 96
do 230 i = d11 + 1, d12
    write(18, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    flows(i), floww(i), gs(i), gw(i), ee(i)
  230 continue
```

Writing day 13

```
d13 = d12 + 96
do 212 i = d12 + 1, d13
    write(19, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    flows(i), floww(i), gs(i), gw(i), ee(i)
```

116
**Writing day 14**

d14 = d13 + 96

do 213 i = d13 + 1, d14

write(20, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    + flows(i), floww(i), gs(i), gw(i), ee(i)

continue

**Writing day 15**

d15 = d14 + 96

do 214 i = d14 + 1, d15

write(21, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i), flows(i)
    + , floww(i), gs(i), gw(i), ee(i)

continue

**Writing day 16**

d16 = d15 + 96

do 215 i = d15 + 1, d16

write(22, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    + , flows(i), floww(i), gs(i), gw(i), ee(i)

continue

**Writing day 17**

d17 = d16 + 96

do 216 i = d16 + 1, d17

write(23, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
    + , flows(i), floww(i), gs(i), gw(i), ee(i)

continue

**Writing day 18**

d18 = d17 + 96

do 217 i = d17 + 1, d18

write(24, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)
**writing day 19**

\[ \text{d19} = \text{d18} + 96 \]
\[ \text{do 218} \quad \text{i} = \text{d18} + 1, \text{d19} \]
\[ \text{write(25, 122)} \quad \text{time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),} \]
\[ + \quad \text{popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)} \]
\[ + \quad \text{flows(i), floww(i), gs(i), gw(i), ee(i)} \]
\[ \text{218 continue} \]

**writing day 20**

\[ \text{d20} = \text{d19} + 96 \]
\[ \text{do 219} \quad \text{i} = \text{d19} + 1, \text{d20} \]
\[ \text{write(26, 122)} \quad \text{time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),} \]
\[ + \quad \text{popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)} \]
\[ + \quad \text{flows(i), floww(i), gs(i), gw(i), ee(i)} \]
\[ \text{219 continue} \]

**writing day 21**

\[ \text{d21} = \text{d20} + 96 \]
\[ \text{do 220} \quad \text{i} = \text{d20} + 1, \text{d21} \]
\[ \text{write(27, 122)} \quad \text{time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),} \]
\[ + \quad \text{popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)} \]
\[ + \quad \text{flows(i), floww(i), gs(i), gw(i), ee(i)} \]
\[ \text{220 continue} \]

**writing day 22**

\[ \text{d22} = \text{d21} + 96 \]
\[ \text{do 221} \quad \text{i} = \text{d21} + 1, \text{d22} \]
\[ \text{write(28, 122)} \quad \text{time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),} \]
\[ + \quad \text{popp(i), t7(i), t8(i), pvcells(i), current(i), work(i)} \]
\[ + \quad \text{flows(i), floww(i), gs(i), gw(i), ee(i)} \]
\[ \text{221 continue} \]

**writing day 23**

\[ \text{d23} = \text{d22} + 96 \]
\begin{verbatim}
do 222 i = d22 + 1, d23
    write(29, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    + flows(i), floww(i), gs(i), gw(i), ee(i)
continue

c ***************writing day 24*******************************

d24 = d23 + 96
do 223 i = d23 + 1, d24
    write(30, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i),
    + t6(i), popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    + flows(i), floww(i), gs(i), gw(i), ee(i)
continue

c ***************writing day 25*******************************

d25 = d24 + 96
do 224 i = d24 + 1, d25
    write(31, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    + flows(i), floww(i), gs(i), gw(i), ee(i)
continue

c ***************writing day 26*******************************

d26 = d25 + 96
do 225 i = d25 + 1, d26
    write(32, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    + flows(i), floww(i), gs(i), gw(i), ee(i)
continue

c ***************writing day 27*******************************

d27 = d26 + 96
do 226 i = d26 + 1, d27
    write(33, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
    + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
    + flows(i), floww(i), gs(i), gw(i), ee(i)
continue
\end{verbatim}
d28 = d27 + 96
do 227 i = d27 + 1, d28
   write(34, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i),
   + t6(i), popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
   + flows(i), floww(i), gs(i), gw(i), ee(i)
   continue

*** writing day 29 ****************************

d29 = d28 + 96
do 228 i = d28 + 1, d29
   write(35, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
   + flows(i), floww(i), gs(i), gw(i), ee(i)
   continue

*** writing day 30 ****************************

d30 = d29 + 96
do 229 i = d29 + 1, d30
   write(36, 122) time(i), t(i), t1(i), t3(i), t4(i), t5(i), t6(i),
   + popp(i), t7(i), t8(i), pvcells(i), current(i), work(i),
   + flows(i), floww(i), gs(i), gw(i), ee(i)
   continue
stop
end

*********** subroutine to calculate temperatures ***********

subroutine calctemp(lf, t, t1, r1, r2)
integer t(1000), t1(1000)
real r1(1000), r2(1000)
integer lf, i
do 300 i = 1, lf
   if (r1(i).gt.19380) then
      t(i) = 98.215433 - 0.0030496570*rl(i) + 0.000000031373620*(rl(i)**2)
   else if ((rl(i).lt.19380).and.(rl(i).gt.4200)) then
      t(i) = 164.03612 - 0.014943636*rl(i) + 0.00000078488143*(rl(i)**2)
   else
      t(i) = 200.0
   end if
300
end
+ 0.000000000016401634*(r1(i)**3)
  else
  t(i)=275.54581-0.11467008*r1(i)+0.000033002452*(r1(i)**2)-
 0.0000000035781569*(r1(i)**3)
  endif
300  continue
    do 301 i=1,lf
    if (r2(i).gt.19380) then
      t1(i)=98.215433-0.0030496570*r2(i)+0.000000031373620*(r2(i)**2)
    else if ((r2(i).lt.19380).and.(r2(i).gt.4200)) then
      t1(i)=164.03612-0.014943636*r2(i)+0.00000078488143*(r2(i)**2)-
 0.000000000016401634*(r2(i)**3)
    else
      t1(i)=275.54581-0.11467008*r2(i)+0.000033002452*(r2(i)**2)-
 0.0000000035781569*(r2(i)**3)
    endif
301  continue
    return 2
end
APPENDIX  B

TRNSYS Deck File

ASSIGN LANKA.LST 6
** Ohio University
** Highway Rest Area Solar Project Analysis
** Annual Calculations
**
** **** Single Tank Internal Heat Exchanger ****
**
** Date: 4/1/92
** Name of system: Internal - Single
** Input prepared by: llcp
**
ASSIGN WDATA.DAT 21
ASSIGN LANKA.OUT 15
ASSIGN LANKA.PLT 14
*
* TRNSED INPUT INFORMATION
* City Input Information
**|<name|filename|Display Field|Value Field|Help No.
* *
* Standard TRNSED Input Form
* *
* | N a m e | T r n s y s | U n i t s | I n p u t u n i t s | U n i t A d d | U n i t M u l t | M i n | M a x & F o r m a t | H e l p N o 
* EQUATIONS 79
* *
* *** Simulation Parameters ****
**
** CITYNO= 4.400000E+01
** |<City | Cities.dat|2|1|23
** LAT= 3.907000E+01
** |<Latitude|Cities.dat|0|3|24
** SC=4871
** SHIFT=0
** START= 1
** STOP= 5.832000E+03
** |<Last Month of Simulation | Stop.dat |1|2|34
** DAY=(START-1.)/24.0+1.
*****Collector SRCC Test Parameters*****

GdotTest = 4.542357E+02
|Collector test flow rate | l/hr|
gal/min|0|0.004403|.1|100.00|6
RhoTest= 1.000000E+03
|Collector test fluid density | Kg/m3|
lb/ft3|0|0.0624|25|99.00 |8

FRTAN = 7.430000E-01
|SRCC Y intercept | 0|0|0|0|0.0000 |3
FRUL = 1.484056E+01
|SRCC First order loss coefficient | kJ/hr-m2-K|
Btu/hr-ft2-F|0|0.04892|0|5.0000|4
FRTWO= 0.000000E+00
|SRCC Second order loss coefficient | kJ/hr-m2-K2|
Btu/hr-ft2-F2|0|0.02718|0|5.0000|35

KA = 1.000000E+00
**Incidence angle modifier constant | 0|0|0|0|0.0000 |41
KB = 8.600000E-01
|1st order incidence angle modifier | 0|0|0|0|0.0000 |42
KC = 0.000000E+00
|2nd order incidence angle modifier | 0|0|0|0|0.0000 |43

*****Collector Parameters*****

AreaPan = 2.166481E+00
|Single panel gross area | m2|
gal/min|0|0.004403|.1|100.00|1
NPANEL = 6.000000E+00
|Total number of panels | 0|0|0|1|100.9
AREA=AREAPAN*NPANEL
NSER = 3.000000E+00
|Number of panels in series | 0|0|0|1|5|10

Gdot = 4.542357E+02
|Collector array flow rate | l/hr|
gal/min|0|0.004403|.1|100.00|11
CPCOLL = 4.186728E+00
|Collector fluid specific heat | kJ/kg-K|
Btu/lb-F|0|0.23885|7|0.1|5.00|7
RhoColl = 1.000000E+03
|Collector fluid density | Kg/m3|
lb/ft3|0|0.0624|25|99.00 |83
Gtest=GdotTest*Rhotest/AreaPan/1000
MFCOLL=GDOT*RHOCOLL/1000
*S
SLOPE= 4.500000E+01
|Collector Slope | Degrees|
Degrees [0, 1, -180, 180] 0.000000E+00
*| Collector Azimuth
Degrees [0, 1, -180, 180] 0.000000E-01
*| Ground Reflectance | 0, 1, 0, 1.00, 27
*| |
QPARl = 6.000000E+01
*| Parasitic Power Draw | W, W, 0, 1.0, 0, 1000.00, 22
*| |
DIPIPE = 1.650919E-02
*| Collector Pipe Outside Diameter | m, in, 0, 39.372, 0.001, 12.00, 68
THINS = 1.269938E-02
*| Thickness of Pipe Insulation | m, in, 0, 39.372, 0.001, 12.00, 68
DI = DIPIPE + 2 * THINS
LI = 7.619628E+00
*| Length of Collector Inlet Pipe
RPIn = 1.467639E-01
*| Collector Pipe Insulation R-value | hr-m2-K/KJ
hr-ft2-F/BTU | 0, 20.441, 0, 99.0, 71
UPin = 2./(RPIn + 7/20.441)
Ain = LI * 3.14159 * DI
* |
UPout = UPin
Aout = Ain
* |
**** Tank Internal Heat Exchanger ****
* |
HXEFF = 4.000000E-01
*| Internal HX effectiveness | 0, 1, 0, 1.000, 47
* |
**** Solar Storage Tank ****
* |
VOLSOL = 4.542014E-01
*| Solar tank volume | m3, gal, 0, 264.2, 0.2, 200.00, 14
HTSOL = 1.828711E+00
*| Solar tank height | m, ft, 0, 3.281, .1, 8.00, 15
HT = -1 * HTSOL
Rsol = 4.892129E-01
*| Solar tank R-value | hr-m2-K/kJ
hr-ft2-F/BTU | 0, 20.441, 0, 99.0, 16
Usol = 2/Rsol
NNODES = 6.000000E+00
*< Stratification Model | Strat.dat | 2, 1, 40
F1 = 0.000000E+00
*< F1 | Strat.dat | 0, 3, 40
F2 = 1.000000E+00
*< F2 | Strat.dat | 0, 4, 40

124
CPTNK = 4.1867
RHO_TNK = 1000.0

* * * ******Auxiliary Heater*****
* * *
TDBTNK= 2.778
**|Auxiliary Heater Dead Band | K| F|0|1.8|0|100.00|85
AUX=16200
*Maximum Auxiliary Heating Rate (KJ/hr)
TIME1= 1.000000E-01
**|Time Aux. Heater First Turned On | | |0|1|0.01|24.00|95
TIME2= 2.397000E+01
**|Time Aux. Heater First Turned Off | | |0|1|0.01|24.00|95
TIME3= 2.398000E+01
**|Time Aux. Heater Turned Back On | | |0|1|0.01|24.00|95
TIME4= 2.399000E+01
**|Time Aux. Heater Turned Back Off | | |0|1|0.01|24.00|95
* * * ******Controller*****
* * *
UDB = 8.888889E+00
**|Turn-on dead band | K| F|0|1.8|0|100.00|17
LDB = 2.777778E+00
**|Turn-off dead band | K| F|0|1.8|0|100.00|18
QCONT = 1.000000E+01
**|Controller Parasitic Power | W| W|0|1.0|0|100.00|89
TMAX = 8.222223E+01
**|High Limit Cutout Temperature | K| F|17.7777|1.8|0|400.00|88
* * *
* ** ******Load Parameters*****
* * *
DAILY = 3.406897E+02
**|Daily flow rate to load | l/day|Gallons/Day|0|0.26417|1|300.00|86
DRAW = DAILY*RHO_TNK/1000
*

* NODE CALCULATIONS - KLEINBACH'S PAPER
T=(DRAW)/(VOLSOL*RHO_TNK)
N=23.1*(T)**(-0.966)
N1=INT(N)+1.
N2=MIN(10,N1)
M1=NNODES*F1
NREC=N2*F2
NODES=MAX(NREC,M1)
* TIMESTEP CALCULATION
STEP=1./12
*
*-----------------------------------
*Variables for the Developer to set
*-----------------------------------

125
* FIXED SIMULATION PARAMETERS
TI = 48
*
* TANK ENVIRONMENT TEMPERATURE
TENV = [54,4]+(22.22-[54,4])/3.
*
*SET POINT TEMP.
TSET = 48
*
LHEAT1=INT(NODES/3+0.5)
LHEAT=MAX(1,LHEAT1)
*Location of Auxiliary Heater-Assumed Top
LSTAT1=INT(NODES/3+0.5)
LSTAT=MAX(1,LSTAT1)
*Location of Auxiliary Heater Thermostat-Assumed Top
*
* PIPE LOSS CALCS
TPOUT=[5,1]+0.5*QPAR1*[2,1]*3.6/(MFCOLL*CPCOLL)
THXHIN=TENV+([1,1]-TENV)*EXP(-UPIN*AIN/(MFCOLL*CPCOLL))
TCIN=TENV+(TPOUT-TENV)*EXP(-UPOUT*AOUT/(MFCOLL*CPCOLL))
*
MFCOLD=[3,2]*CPCOLL/CPTNK
*
SIMULATION start stop STEP
LIMITS 80 30
TOLERANCES 0.001 0.001
*
UNIT 19 TYPE 14 WATER MAINS TEMP. PROFILE
PARAMETERS 48
0,9.22 744,9.22 744,9.22 1416,9.22 1416,9.44 2160,9.44 2160,9.77
2880,9.77 2880,10.06 3624,10.06 3624,10.33 4344,10.33 4344,10.44
5088,10.44 5088,10.38 5832,10.38 5832,10.22 6552,10.22 6552,9.94
7296,9.94
7296,9.61 8016,9.61 8016,9.28 8760,9.28
*
UNIT 18 TYPE 14 AUXILIARY HEATER TIMER FUNCTION
PARAMETERS 20
* 1 IMPLIES ON, 0 IMPLIES OFF
0,0 TIME1,0 TIME1,1 TIME2,1 TIME2,0 TIME3,0 TIME3,1 TIME4,1 TIME4,0
24,0
*
UNIT 14 TYPE 14 RAND LOAD PROFILE
PARAMETERS 78
0,1.5 1,1.5 1,0 6,0 6,1 7,1 7,3.5 8,3.5 8,5 9,5 9,6 10,6
10,4.5 11,4.5 11,3 12,3 12,2.5 13,2.5 13,3.5 14,3.5 14,1.5
16,1.5 16,1 17,1 17,2.5 18,2.5 18,4.5 19,4.5 19,8 20,8 20,6.5
21,6.5
21,4.5 22,4.5 22,3.5 23,3.5 23,3 24,3 24,1.5
*
EQUATIONS 4
MLOAD=[14,1]*DRAW/67
TOUT=MIN([4,3],TSET)
GAMMA1=MIN(1,((TSET-[19,1])/(MAX(0.1,([4,3]-[19,1])))
MOUT=MLOAD*GAMMA1

UNIT 54 TYPE 54 WEATHER GENERATOR
PARAMETERS 7
*UNITS OUNITS LU CITY# MODEL HRC SRC
1 1 21 CITYNO 1 2 1

UNIT 16 TYPE 16 RADIATION PROCESSOR
PARAMETERS 7
* RADMODE TRACKMODE TILTMODE DAY LAT SC SHFT
1 1 1 DAY LAT SC SHIFT
INPUTS 6
* I TD1 TD2 RHOG BETAI GAMMAI
54,7 54,19 54,20 RHOG SLOPE GAMMAI
0.0 0.0 0.0 RHOG SLOPE GAMMAI

UNIT 1 TYPE 1 SOLAR COLLECTOR
PARAMETERS 14
* MODE NS A CPC EFFMODE GTEN A B C EFF CPF OMODE KA KB KC
1 NSER AREA CPCOLL 1 GTEN FRTAN FRUL FRTWO -1 CPCOLL 1 KB KC
INPUTS 10
* TI MC MF TA IT I ID RHOG THETA SLOPE
TCIN 3,2 3,2 54,4 16,6 16,4 16,5 RHOG 16,9 SLOPE
22.0 MFCOLL MFCOLL 22.0 0.0 0.0 0.0 RHOG 0.0 SLOPE

UNIT 3 TYPE 3 PUMP
PARAMETERS 1
MFCOLL
INPUTS 3
5,1 MFCOLL 2,1
22.0 MFCOLL 0.0

UNIT 2 TYPE 72 PUMP CONTROLLER
PARAMETERS 4
3 UDB LDB TMAX
INPUTS 4
1,1 4,1 2,1 4,3
22.0 22.0 0.0 100.0

UNIT 5 TYPE 5 HEAT EXCHANGER
PARAMETERS 4
4 HXEFF CPCOLL CPTNK
INPUTS 4
THXHIN 1,2 4,1 MFCOLD
22.0 MFCOLL 20.0 0.0

UNIT 4 TYPE 4 MAIN STORAGE TANK
PARAMETERS 13
2 VOLSOL CPTNK RHOTNK USOL HT AUX LHEAT LSTAT TSET TDBTNK 0 TSET
INPUTS 6

127
5,3 5,4 19,1 MOUT TENV 18,1
22.0 0.0 22.0 0.0 22.0 0.0
DERIVATIVES NODES
TI TI TI TI TI TI TI TI TI TI TI TI

EQUATIONS 10
QDEL=MLOAD*CPTNK*(TOUT-[19,1])
QPAR=QPAR1*[2,1]+QCONT
QU=[1,3]
QSOTN=[4,9]
QLSOTN=[4,5]
QLAUTN=0.0
QAUX=[4,8]
QPHAUX=0
IATILT=[16,6]*AREA
TTNMX=85.

* UNIT 24 TYPE 24 INTEGRATOR
PARAMETERS 1
-1
INPUTS 7
QU QSOTN QLSOTN QAUX QLATNM QDEL QPAR
0.0 0.0 0.0 0.0 0.0 0.0 0.0

* UNIT 25 TYPE 25 PRINTER
PARAMETERS 4
-1 START STOP 14
INPUTS 7
24,1 24,2 24,3 24,4 24,5 24,6 24,7
QU QSOTN QLSOTN QAUX QLATNM QDEL QPAR

* UNIT 26 TYPE 25 PRINTER
PARAMETERS 4
-1 START STOP 15
INPUTS 6
24,1 24,2 24,3 24,4 24,6 24,7
QU QSOTN QLSOTN QAUX QDEL QPAR

END
APPENDIX C

TRNSYS OUTPUT FOR 10°F AND 16°F PUMP ON
TEMPERATURE SETTINGS

(Butler County)
Figure C.1 Theoretical parasitic power draw

Figure C.2 Hot water delivered
Figure C.3 Energy supplied by the heating element

Figure C.4 Solar energy gain
Figure C.5  Solar energy delivered to the storage tank

Figure C.6  Energy loss to the environment
APPENDIX D

Economic analysis for Cincinnati(I75) solar system.

This analysis has been carried out similar to the Cleveland (I90) economic analysis in Chapter 4. Other than the electricity cost all other costs such as equipments and maintenance are obtained from the Cleveland solar system calculations.

Electricity Cost

Electrical cost of both solar hot water system were estimated using solar and hot water BTU meter reading.

\[
\begin{align*}
\text{Total Hot Water Demand per Anum} & = 18.88 \text{ MBTU} \\
\text{Total Solar contribution per Anum} & = 14.88 \text{ MBTU} \\
\text{Heat Supplied by the heating element} & = 4.00 \text{ MBTU} \\
\text{Cost of electricity per Anum (@ 0.10/kWh)} & = $117.20
\end{align*}
\]
<table>
<thead>
<tr>
<th>YEAR</th>
<th>FUTURE WORTH</th>
<th>PRESENT WORTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>117.20</td>
<td>177.20</td>
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<td>1993</td>
<td>135.37</td>
<td>123.06</td>
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<td>1994</td>
<td>156.35</td>
<td>129.21</td>
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<td>1995</td>
<td>180.58</td>
<td>135.67</td>
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<td>1996</td>
<td>208.57</td>
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<td>1999</td>
<td>321.37</td>
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<td>881.20</td>
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<td>2011</td>
<td>1811.28</td>
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</table>

Total present worth of electricity cost = $3935.33

Table 1 Electricity cost for solar system with electric backup for a period of 20 years.
Maintenance Cost

Maintenance cost estimated by ODOT of 250$ per year has been used and the present value is shown in the table 2.

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<tr>
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<td>2007</td>
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<td>2009</td>
<td>789.70</td>
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<td>844.98</td>
<td>151.98</td>
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<td>2011</td>
<td>904.13</td>
<td>147.83</td>
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</table>

Total present worth of maintenance cost = 3893.96

Table 2 Present worth of maintenance cost for solar system with backup heating element
Cost of Conventional Heating System

Electricity cost

Total hot water demand = 18.88 MBTU
= 5531.70 kWh

Cost (@ 10cts. per kWh) = $ 553.17

Table 3 shows the total present worth of electricity cost for a period of 20 years.

<table>
<thead>
<tr>
<th>YEAR</th>
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<th>PRESENT WORTH</th>
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Total present worth of electricity cost = $ 18291.09

Table 3 Present worth of electricity cost for the conventional heating system.
### Maintenance Cost

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<tr>
<td>2003</td>
<td>210.49</td>
<td>73.77</td>
</tr>
<tr>
<td>2004</td>
<td>225.22</td>
<td>71.76</td>
</tr>
<tr>
<td>2005</td>
<td>240.98</td>
<td>69.80</td>
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<tr>
<td>2006</td>
<td>257.85</td>
<td>67.90</td>
</tr>
<tr>
<td>2007</td>
<td>275.90</td>
<td>66.05</td>
</tr>
<tr>
<td>2008</td>
<td>295.22</td>
<td>64.25</td>
</tr>
<tr>
<td>2009</td>
<td>315.88</td>
<td>62.50</td>
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<tr>
<td>2010</td>
<td>337.99</td>
<td>60.79</td>
</tr>
<tr>
<td>2011</td>
<td>361.65</td>
<td>59.13</td>
</tr>
</tbody>
</table>

Total present worth of electricity cost = $1557.59

Table 4 Present worth of maintenance cost for the conventional system.
Summary

<table>
<thead>
<tr>
<th></th>
<th>Conventional system</th>
<th>Solar system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment cost ($)</td>
<td>1,750.00</td>
<td>10,133.00</td>
</tr>
<tr>
<td>Electricity cost ($)</td>
<td>18,219.09</td>
<td>3,935.33</td>
</tr>
<tr>
<td>Maintenance cost ($)</td>
<td>1,557.59</td>
<td>3,893.96</td>
</tr>
<tr>
<td>Total cost ($)</td>
<td>21,598.68</td>
<td>17,962.29</td>
</tr>
</tbody>
</table>

Table 5  Summary of the cost analysis of Cincinnati (I-75) solar system.
REFERENCES


(8) Associate Editor, "Photovoltaic Systems Today", Mechanical Engineer Vol 29, No. 9, 1992


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