

# **40th ASES National Solar Conference 2011**

**(SOLAR 2011)**

**Raleigh, North Carolina, USA  
17-20 May 2011**

ISBN: 978-1-61839-427-9

**Printed from e-media with permission by:**

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Red Hook, NY 12571



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**Paper Number and Title:** Effect on System Efficiency from Combining Solar Thermal and Photovoltaic Energy Systems in non-Grid Applications: Phase 1

**To be Published in:** SOLAR 2011 Conference Proceedings

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# EFFECT ON SYSTEM EFFICIENCY FROM COMBINING SOLAR THERMAL AND PHOTOVOLTAIC ENERGY SYSTEMS IN NON-GRID APPLICATIONS: PHASE 1

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## ABSTRACT

This project will study the amount of energy that can be collected through the use and combining of photovoltaic (PV) and solar thermal (ST) systems in the Midwest. The results will be used specifically to inform the energy design for a modular home made from a recycled shipping container and more broadly what appears to be a gap in scholarly articles about combined or hybrid solar energy systems. A LabView™ simulation, based on National Oceanic and Atmospheric Administration (NOAA) solar insolation tables for our latitude, was used in phase 1 to determine the amount of energy that can be collected from solar photovoltaic modules for electricity and evacuated tubes with heat pipes for thermal energy. In phase 2, the physical systems will be tested separately and then combined for further testing.

This project will determine if an efficiency increase can be achieved by integrating two different solar power systems, using the excess energy from the PV system to supplement the thermal energy captured by the ST collectors.

Efficiency increase will be measured as the useful application of heat that would have been rejected to the atmosphere if the two systems were separate. The method for measuring efficiency will follow ASHRAE 93 and IEC 61724 guidelines. The authors hypothesize that by using PV generated energy that would otherwise have been wasted, because it was not immediately needed to charge batteries or energize loads, to augment the ST system to heat and store hot water, waste can be avoided and the overall system efficiency can be increased. Additionally, it

is anticipated that the combined system will supply ample energy and may require a separate dump load during peak hours to prevent overheating of the thermal system but may still improve overall efficiency.

## 1. INTRODUCTION

The aim of the whole *Eco-Ready Shelter* research project is to study the suitability of a shipping container for the development and creation of a sustainable (green), self sufficient, energy efficient and zero emission dorm room for two students on the IUPUI campus. Although several options are available to power this kind of building, the most attractive is the use of solar energy. This paper is a sub-study of the *Eco-Ready Shelter* project and is meant to study a combined system of thermal and photovoltaic (PV) solar systems. These systems will supply all of the required energy that is to be used in self-sufficient housing. The purpose of the study is to determine the feasibility of connecting solar photovoltaic and solar thermal systems for use as an energy provider to housing markets, mainly to determine the amount of energy that can be collected and stored, and the system efficiencies.

Energy systems built around photovoltaic cells will have fluctuations in the output based on surrounding conditions. When an energy deficit is incurred, additional energy can be

supplied from another source such as a battery or the grid. When too much power is generated by the system, energy can be initially dumped into a battery for latter use when needed. However, once the battery is fully charged, the power must be removed or routed elsewhere lest the battery be damaged. This research seeks to harness the excess energy and use it to supply hot water to the *Eco-Ready Shelter* or other eco-friendly housing.

## 2. PATENT AND LITERATURE SEARCH

An online patent search with the Patent Storm<sup>1</sup> did not yield any results of previous patents using a load dump resistor from a PV system in conjunction with a thermal collector system as a means of heating water. Several sources were found that did propose similar ideas, but did not possess any mention of patents or previous research<sup>2,3</sup>. Similarly, there were no articles found in academic journals or conference proceedings.

## 3. SYSTEM SPECIFICATION

The combined system that is the subject of this research consists of a solar photovoltaic system that works together with a solar thermal system. The picture shown below in Fig.1 shows the basic design of such a system (battery system not shown). This is the system that could be implemented for housing purposes.

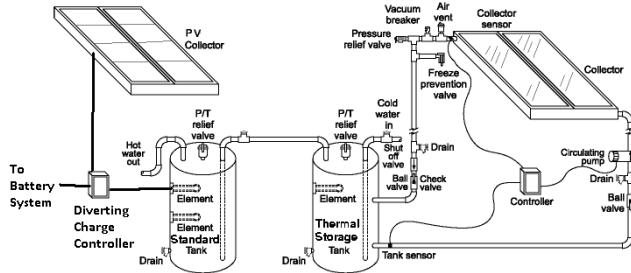


Fig. 1: Design of Combined Solar Thermal System

The thermal side of the system is comprised of a set of thirty evacuated tube-type solar collectors, meanwhile, the PV side is comprised of fourteen 62.24”x 31.85” x 1.57” photovoltaic modules. A solar collector is a device that absorbs thermal energy from the sun and converts it into usable heat. The solar collectors are of the active system, where a transfer fluid (50% Water-50% Glycol) is used to transfer heat form the collectors to the water system. The

thermal collectors will only be used for the water heating system, meanwhile, the photovoltaic system will be providing mainly all the power required for the dorm room, storing some in the battery system and “dump” excess energy to the water heating system, supplementing the solar collectors.

## 4. METHODOLOGY

### 4.1 Solar Photovoltaic System

For the photovoltaic system, it was too costly to actually purchase the fourteen 62.24”x 31.85” x 1.57” photovoltaic modules. To overcome this hurdle, a simulation was done. The simulation was done on a computer program which runs simulation called MATLAB. In order to run the simulation, it is necessary to know the amount of electrical energy that would be needed from the system and more importantly, the amount of energy that could be supplied. The circuit model of a theoretical photovoltaic cell is shown below in Fig 2.

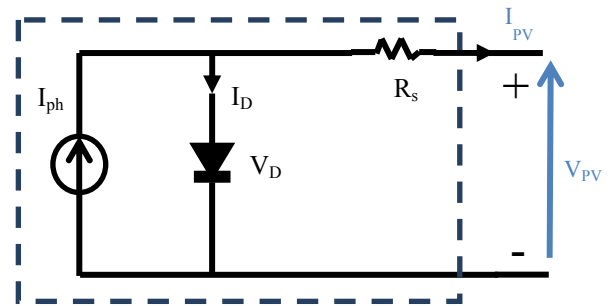


Fig. 2: PV cell

The theoretical equations that characterize a PV cell are shown below in equations (1) – (5).

$$I = I_{ph} - I_D \quad (1)$$

$$I_{PV} = I_{ph} - I_0 \cdot \left( \frac{q(V_{PV} + I_{PV} R_s \frac{N_S}{N_P})}{e^{N_S A k (T_C + 273.15)}} - 1 \right) \quad (2)$$

$$I_{ph} = \left( \frac{G}{G_{ref}} \right) \cdot N_P \cdot \left[ I_{sc} + K_i \left( (T_C + 273,15) - (T_{cref} + 273,15) \right) \right] \quad (3)$$

$$I_0 = \frac{I_{sc}}{e^{\left( \frac{q V_{oc}}{N_S k A (T_C + 273,15)} \right) - 1}} \cdot \left( \frac{T_C + 273,15}{T_{cref} + 273,15} \right)^3 \quad (4)$$



$$e^{\left(\frac{q \cdot E_g}{N_s \cdot k \cdot A} \left( \frac{1}{(T_{cref} + 273,15)} - \frac{1}{(T_c + 273,15)} \right) \right)} \cdot N_p$$

$$V_{PV} = \frac{N_s \cdot A \cdot k \cdot (T_c + 273,15)}{q} \cdot \ln \left( \frac{I_{ph} - I_{PV}}{I_0} + 1 \right) - I_{PV} \cdot R_s \cdot \frac{N_s}{N_p} \quad (5)$$

The definitions of the notation and variables used in the above equations are given as:

- $I_D$  is the diode current;
- $I_{ph}$  is the photoelectric current related to a given condition of radiation and of temperature;
- $V_{PV}$  is the output voltage [V];
- $I_{PV}$  is the output current [A]
- $I_0$  is the saturation diode current [A]
- $A$  is the form which represents an index of the cell failing;
- $R_s$  is the series resistance of the cell [ $\Omega$ ];
- $q$  is the electron charge ( $1.602 \times 10^{-19} C$ );
- $k$  is the Boltzmann constant ( $1.38 \times 10^{-23} J/K$ );
- $T_c$  is the module temperature [ $^{\circ}C$ ];
- $T_{cref}$  is the module temperature under standard conditions [ $^{\circ}C$ ];
- $E_g$  is the energy gap of the material with whom the cell is made (for the silicon it's 1.12 eV);
- $G$  is the radiation [ $W/m^2$ ];
- $G_{ref}$  is the radiation under standard conditions [ $W/m^2$ ];
- $K_i$  is the temperature coefficient of the short-circuit current [A/K];
- $N_s$  the number of series modules;
- $N_p$  is the number of parallel modules.

For modeling the photovoltaic panels, we use the block diagrams on the software MATLAB SIMULINK™. After that, we enter the data that you can see in Table 1 of the PV Module GSA221 from the manufacturer's website<sup>5</sup>. The program used in the simulation can be seen in Fig 3, 4, 5.

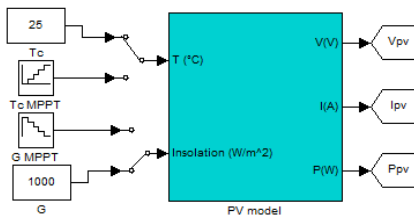


Fig. 3: Matlab™ PV model

TABLE 1: TECHNICAL DATA USED AS INPUT FOR THE PV MODULE GSA211.<sup>4</sup>

Nominal peak power (W)	210
Nominal voltage (V) Vmpp	38.8
Nominal current (A) Impp	5.42
Open-circuit voltage (V) Voc	46.6
Short-circuit current (A) Isc	5.78
Nominal Operating Cell Temp ( $^{\circ}C$ )	46
Temperature Coefficient of Isc (A/ $^{\circ}C$ )	0.0023
Cell Type	Monocrystalline

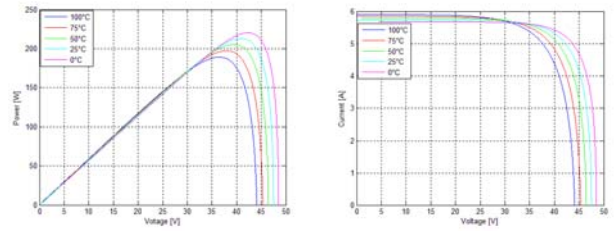


Fig. 4: Curve with  $G=1000 W/m^2$

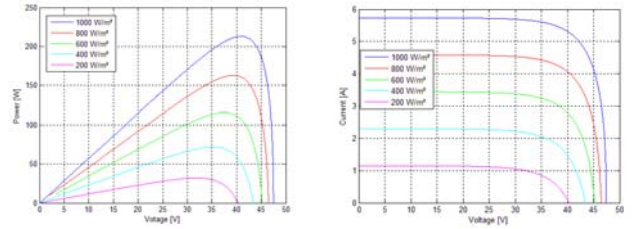


Fig. 5: Curve with  $T=25^{\circ}C$

After determining the amount energy that could be supplied by this photovoltaic system, as mentioned earlier, it had to be determined whether the amount energy supplied by the photovoltaic system is adequate for the amount of energy needed by the unit. When initial planning was conducted, energy demands were the first consideration since these parameters determine the rest of the specifications of the entire project. After much brainstorming, the following appliances in Table 2 were confirmed to be certain items that will be used. Meanwhile, Table 3 shows the final actual energy needed after correction.

TABLE 2: THE DAILY USAGE OF APPLIANCES IN THE UNIT

Load Description	Q	T	Y	Load Current (A)	Load Voltage (V)	DC Load Power (W)	AC Load Power (W)	Daily Duty Cycle (Hrs/Day)	Weekly Duty Cycle	Power Conversion Efficiency	Nominal System Voltage	Amp-Hour Load (AH/Day)
Lights (DC)	4	X		6.667	X 12	= 80	N/A	X 7	7/7	÷ .9	÷ 48	= 13
Fan (DC)	2	X		3.333	X 12	= 40	N/A	X 15	7/7	÷ .9	÷ 48	= 14
Cell Phone (DC)	1	X		0.417	X 12	= 5	N/A	X 2	4/7	÷ .9	÷ 48	= 0.14
19" LCD TV(AC)	1	X		0.417	X 120	N/A	= 50	X 5	7/7	÷ .85	÷ 48	= 6.2
Laptop (AC)	1	X		0.417	X 120	N/A	= 50	X 8	7/7	÷ .85	÷ 48	= 10
Mini fridge (AC)	1	X		0.333	X 120	N/A	= 40	X 24	7/7	÷ .85	÷ 48	= 24
Microwave (AC)	1	X		6.250	X 120	N/A	= 750	X 0.75	7/7	÷ .85	÷ 48	= 14
Toaster (AC)	1	X		6.667	X 120	N/A	= 800	X 0.25	7/7	÷ .85	÷ 48	= 5
Hair-Dryer (AC)	1	X		10.00	X 120	N/A	= 1200	X 0.5	7/7	÷ .85	÷ 48	= 15
				Total Power		125W <sub>DC</sub>	2890W <sub>AC</sub>			Total AH/Day Load		74.12

TABLE 3: THE FINAL ENERGY REQUIRED

Total DC Load Power (W)	Total AC Load Power (W)	Nominal System Voltage (V)	Peak Current Draw (A)	Total AH/Day Load (AH/Day)	Wire Efficiency Factor (decimal)	Battery Efficiency Factor (decimal)	Corrected AH Load (AH/Day)
125	+ 2890	÷ 48	= 62.82	74.12	÷ 0.85	÷ 0.85	= 102

4.2 Solar Thermal System

Similar to the photovoltaic system, a simulation using LABVIEW was done in order to proceed without conducting a physical test. Actual operating data was used from past experiments with thermal collectors by one of the authors. The data consisted of the flow rate of the glycol/water mixture and the inlet and outlet temperatures of the mixture. From this data, the rate of energy gathered could be calculated using the equation (1) below.

$$P = \dot{m}c (T_{out} - T_{in}) \quad (1)$$

In this equation, P is power and c is specific heat of the glycol/water mixture. T<sub>out</sub> stands for the temperature of the mixture at the outlet while T<sub>in</sub> stands for the temperature of the glycol at the inlet to the solar thermal collector. From the power, the daily energy can be easily calculated by finding the area under the power curve.

4.3 The Combined System

A simulation of the combined system was run on LabView software. The LabView program was used to combine the collected inputs of the two systems and control how the power was used. The power was managed such that when the average power demand of the shelter exceeds what is collected, power is drawn from the battery to make up the remainder. When power taken in exceeds what is needed, the energy is first fed into the battery. When the battery is fully charged, the power is dumped into the thermal system. The block diagram of the program is shown in Fig 10 in the Appendix. The front panel of the same program is shown in Fig 11 in the Appendix. The calculations made by the program are discussed in the Results section. An actual solar thermal collection system comprised of one set of thirty evacuated tube solar collectors is being assembled for

further testing in phase 2, along with an array of sixteen photovoltaic panels.

### 5. RESULTS

The solar simulation used one day of valid data, per ASHRAE 93 standard, to produce a power curve as well as values for every half hour between 11:00am and 3:00pm. The resulting values from the simulation are shown in Table 4. A graph of the power per PV module is shown in Fig 6.

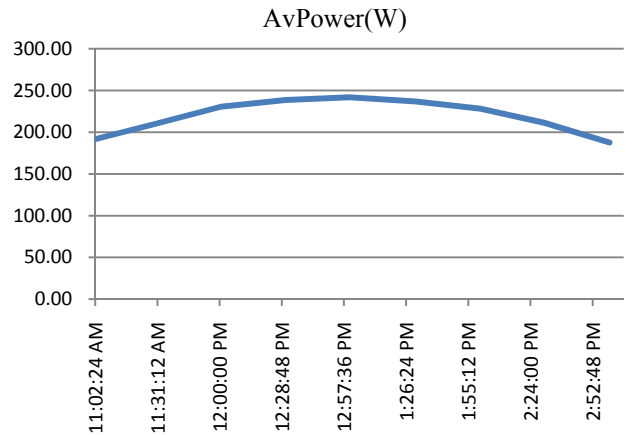


Fig. 6 - Power Curve from MATLAB SIMULINK solar simulation program

TABLE 4: RESULTS FROM THE PV MODEL

Time	AvgOAT (°F)	AvgOAT (°C)	AvgInt (W/m <sup>2</sup> )	AvgPower (W)	AvgCurrent (A)	AvgVoltage (V)
2/26 11:00:36 AM	27.996	-2.22	895.062	190.51	4.8	40.17
2/26 11:30:36 AM	28.814	-1.77	977.618	210.19	4.9	43.01
2/26 12:00:36 PM	28.847	-1.75	1041.187	230.49	5.3	43.50
2/26 12:30:38 PM	29.507	-1.39	1070.603	238.64	5.5	43.40
2/26 1:00:08 PM	30.345	-0.92	1080.054	241.77	5.6	43.17
2/26 1:30:38 PM	30.389	-0.90	1062.595	236.96	5.6	42.31
2/26 2:00:38 PM	30.612	-0.77	1034.902	228.19	5.5	41.51
2/26 2:30:35 PM	30.791	-0.67	981.898	211.26	5.2	40.71
2/26 3:00:35 PM	30.883	-0.62	900.501	187.55	4.9	38.32

The results from the LABVIEW™ simulation show the interaction between the PV and solar thermal systems. The operation of these systems was set to be from 11am to 3pm. Each time point represents a 30 minute interval. The results show the system operation characteristics, such as: the power graph, Fig 7, gives the instantaneous power available to the system. The thick solid blue line shows that the PV panels collect a maximum of 2.89kW at solar noon and stores the energy in the battery (dotted green line) from 11am to 2pm and then diverts the power into the solar thermal tank element (thin solid purple line). After 2pm the battery is fully charged and all the PV power is diverted and the total thermal power collected (dash-dot-dot-dash brown line) rises rapidly.

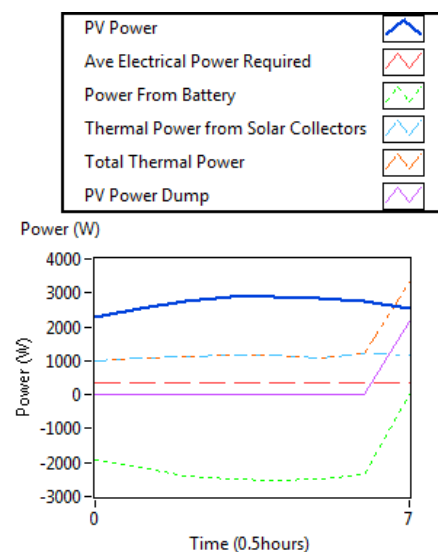


Fig. 7: The Power Graph

The energy graph, Fig. 8, shows the total amount of energy collected at a given time. The power graph shows that the combined system will be able to operate in the expected manner; the battery can be refilled completely before being needed again; the deficit will not build. Excess energy from the photovoltaic system will raise the temperature of the water for the hot water system. The energy graph shows that the total amount of energy will exceed what is needed for normal operation.

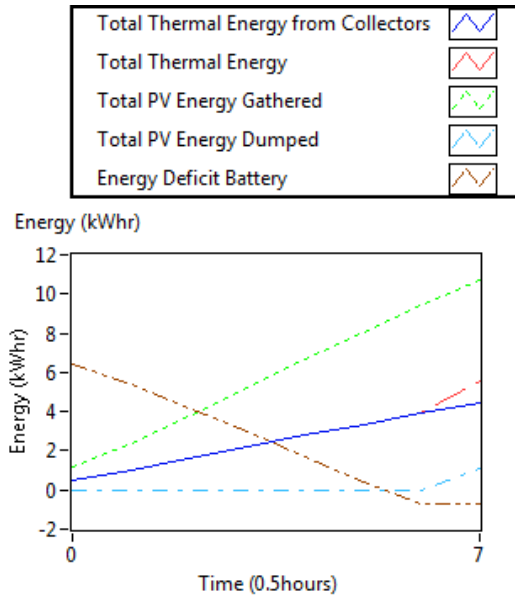


Fig. 8: The Energy Graph

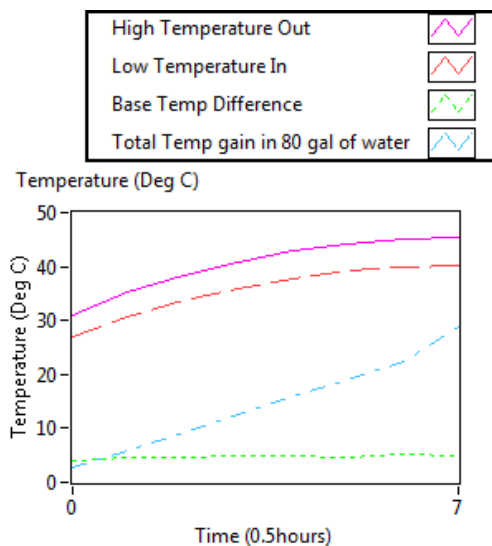


Fig. 9: The Temperature Graph

The temperature graph, Fig. 9, illustrates actual fluid temperatures in a physical collector and the simulated temperature in a storage tank.

TABLE 5: RESULTING NUMBERS

Total PV Energy Collected (kWhr)	10.73
Total PV Energy Needed (kWhr)	8.9
Total PV Energy Dumped (kWhr)	1.83
Total Energy from Thermal Collectors (BTU)	15295
Total Thermal Energy Collected (BTU)	21539
Percent Increase in Thermal Energy (%)	28.99

## 6. CONCLUSIONS

The data reveals that the thermal system is undersized during the harshest time of year and that the PV system is properly sized for the worst month. Diverting causes a 29% increase in thermal energy collected. This method requires the addition of a DC heating element and an additional diverting charge controller, however using a moderate 10¢/kWhr, the system has a simple payback of four years. In fact, the PV system may require a separate dump load or shunting during peak season to prevent overheating of the thermal system. Further testing is planned for the PV and thermal collectors on the Eco Ready Shelter from April-July, 2011 to verify the simulation and prove the savings.

## 7. REFERENCES

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## 8. APPENDIX

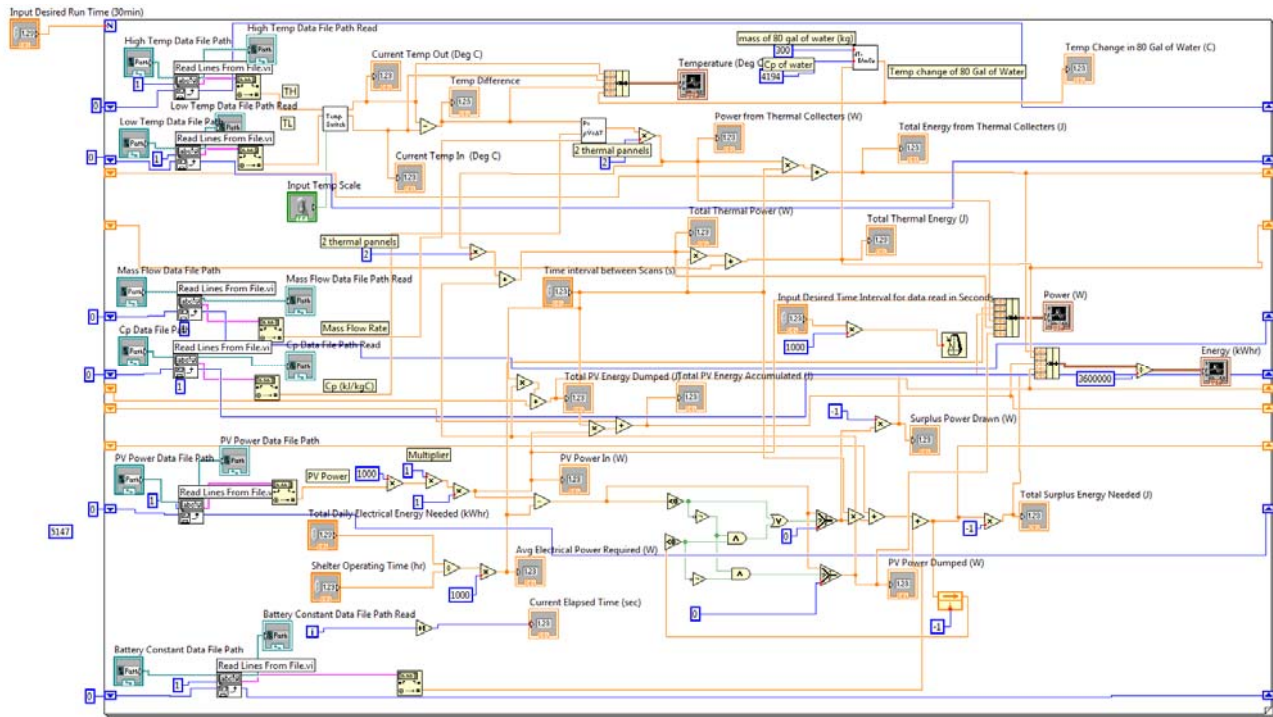


Fig. 10: Block Diagram of LabView™ Program for Combined System

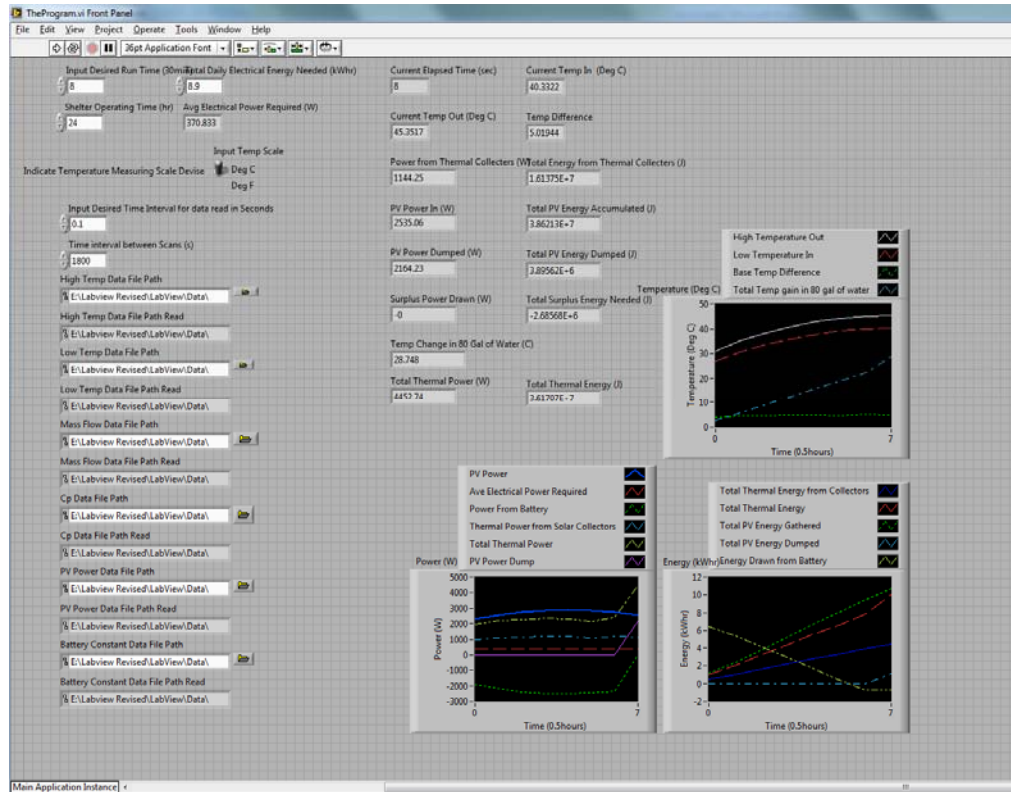


Fig. 11: Front Panel of LabView™ Program for Combined System