LITERATURE REVIEW OF UNCERTAINTY OF ANALYSIS METHODS
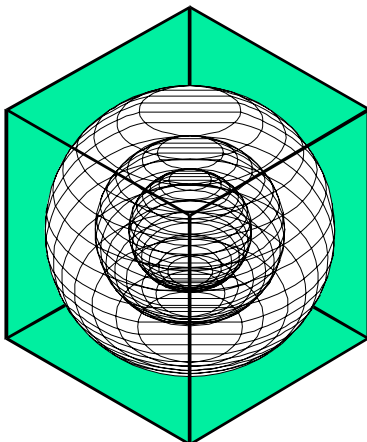
(PV F-Chart Program)

Report to the
Texas Commission on Environmental Quality

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1 Executive Summary

This report reviews the reported uncertainty of the PV F-Chart analysis method by reviewing the published related accuracy of PV F-Chart analysis versus measured data, PV F-Chart predictions versus other methods, and PV F-Chart predictions versus TRNSYS simulations. This report begins with a review of the history of the PV F-Chart method, and includes an example PV F-Chart calculation. In summary, from the literature it was found that hourly PV F-Chart analysis versus measured data were shown to be within 4% of on-site measurement, PV F-Chart predictions versus TRNSYS simulations and another graphical method were also within 4% of annual values.

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2   Introduction

This literature review covers the PV F-Chart program, which is one of the legacy programs in the ESL's Emissions Calculator (eCALC), a web-based emissions reductions calculator developed for the State of Texas. The eCALC program is a tool for those who want to see how their energy savings has reduced NOx emissions, a by-product made during the burning of fossil fuels. This report includes a brief history of the PV F-Chart method, its applications, accuracies, basic equations, and an example calculation.

3   History of the PV F-Chart Method

The PV F-Chart method is an analysis that is useful for the design of photovoltaic systems and for the estimation of the long term average performance of utility interface systems, battery storage systems, and systems without interface or battery storage. The PV F-Chart method consists of a combination of correlations and fundamental expressions for the hourly calculations of solar radiation at a given location. It uses long-term monthly average solar radiation and ambient temperature to predict the annual performance of a photovoltaic array. It was developed by Klein and Beckman (1983; 1985) as shown in Figure 1, and is based on the previous work by Siegel et al. (1981), Evans (1978; 1981), and Clark et al. (1983 and 1984). The PV F-Chart analysis draws on the earlier work by Siegel et al. (1981) who developed a method for estimating the monthly-average conventional energy displaced by a photovoltaic system, and Evans (1978; 1981) who developed a hybrid photovoltaic/thermal models and a simplified procedure for predicting long-term monthly average output from a photovoltaic array. The work of Siegel and Evans was extended by Clark et al. (1983 & 1984), who developed a computationally simplified algorithm for evaluating the hourly utilizability function, and a method for predicting the long-term performance using the utilizability function. The utilizability function can be traced back to the work by Klein et al. (1978), Liu and Jordan (1963), Hottel and Whillier (1955), and Whillier (1953a; 1953b).

There are three primary procedures used in the PV F-Chart method, including:
1) estimating the monthly average hourly solar radiation on inclined surfaces from average-daily, monthly solar radiation; 2) calculating the monthly-average, hourly solar radiation utilizability; and 3) use of the monthly average hourly ambient temperatures in the PV array performance prediction. Additional details about the method can be found in the PV F-Chart manual (Klein and Beckman, 1985). The φ concept, or utilizability, is also central to the development of the PV F-Chart method. Whillier (1953a; 1953b) was the first to develop the concept of utilizability. Hottel and Whillier (1955) later developed location-dependent monthly average hourly utilizability and Liu and Jordan (1963) generalized the Whillier's φ concept to location-independent, monthly average hourly utilizability.

The Windows version of PV F-Chart, version 3.01W, was developed by Klein and Beckman (1993), and is available on the Internet web site www.fchart.com. A PV F-Chart version running in the MAC system is also available. Version 3.3 of the PV F-Chart method running in the DOS mode is the version used in the ESL's emissions calculator.
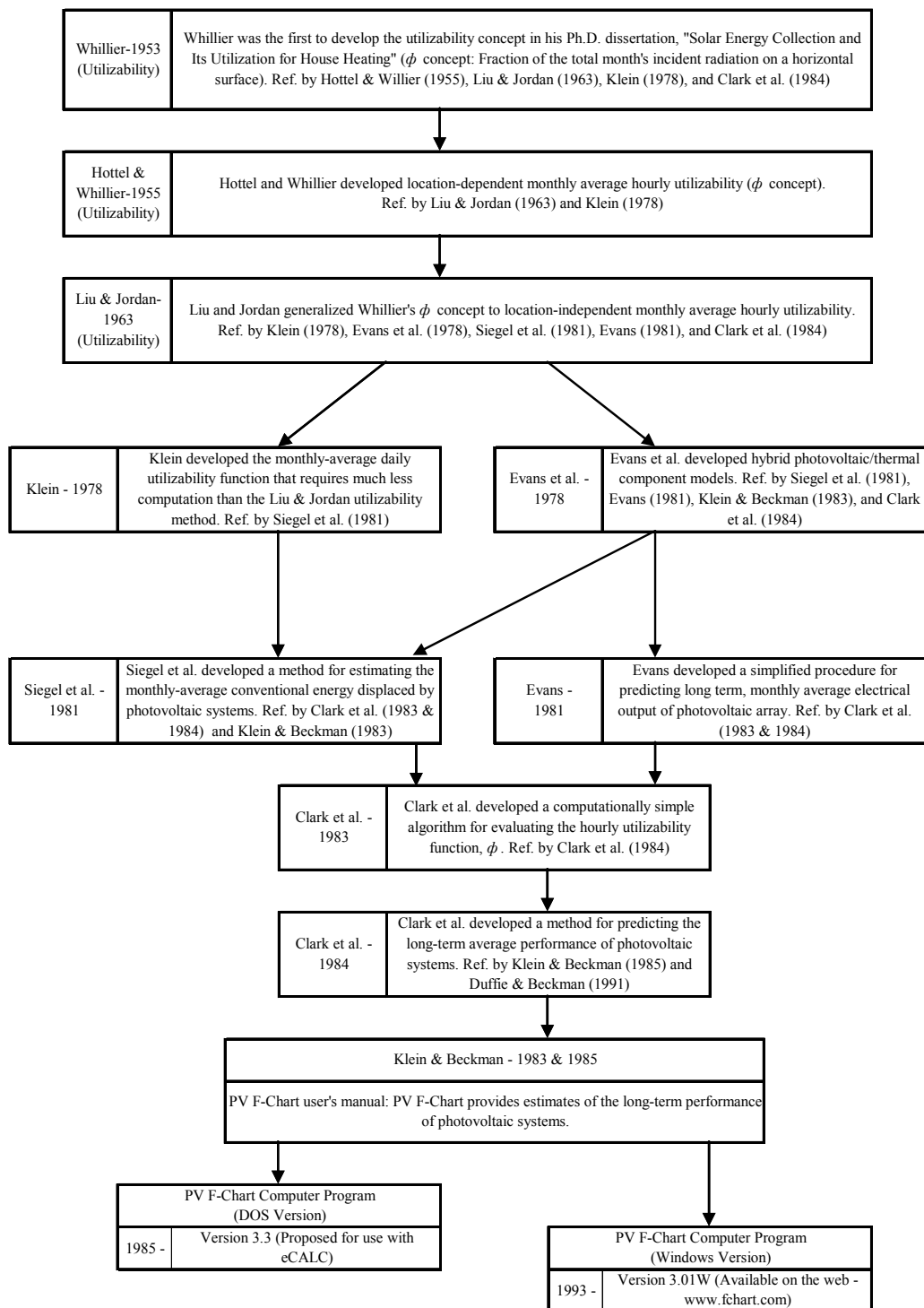
History of the PV F-Chart Method

Whillier-1953 (Utilizability)	Whillier was the first to develop the utilizability concept in his Ph.D. dissertation, "Solar Energy Collection and Its Utilization for House Heating" (ϕ concept: Fraction of the total month's incident radiation on a horizontal surface). Ref. by Hottel & Willier (1955), Liu & Jordan (1963), Klein (1978), and Clark et al. (1984)

Hottel & Whillier-1955 (Utilizability)	Hottel and Whillier developed location-dependent monthly average hourly utilizability (ϕ concept). Ref. by Liu & Jordan (1963) and Klein (1978)

Liu & Jordan-1963 (Utilizability)	Liu and Jordan generalized Whillier's ϕ concept to location-independent monthly average hourly utilizability. Ref. by Klein (1978), Evans et al. (1978), Siegel et al. (1981), Evans (1981), and Clark et al. (1984)

Klein - 1978	Klein developed the monthly-average daily utilizability function that requires much less computation than the Liu & Jordan utilizability method. Ref. by Siegel et al. (1981)

Evans et al. - 1978	Evans et al. developed hybrid photovoltaic/thermal component models. Ref. by Siegel et al. (1981), Evans (1981), Klein & Beckman (1983), and Clark et al. (1984)

Siegel et al. - 1981	Siegel et al. developed a method for estimating the monthly-average conventional energy displaced by photovoltaic systems. Ref. by Clark et al. (1983 & 1984) and Klein & Beckman (1983)

Evans - 1981	Evans developed a simplified procedure for predicting long term, monthly average electrical output of photovoltaic array. Ref. by Clark et al. (1983 & 1984)

Clark et al. - 1983	Clark et al. developed a computationally simple algorithm for evaluating the hourly utilizability function, ϕ. Ref. by Clark et al. (1984)

Clark et al. - 1984	Clark et al. developed a method for predicting the long-term average performance of photovoltaic systems. Ref. by Klein & Beckman (1985) and Duffie & Beckman (1991)

Klein & Beckman - 1983 & 1985
PV F-Chart user's manual: PV F-Chart provides estimates of the long-term performance of photovoltaic systems.

PV F-Chart Computer Program (DOS Version)	
1985 -	Version 3.3 (Proposed for use with eCALC)

PV F-Chart Computer Program (Windows Version)	
1993 -	Version 3.01W (Available on the web - www.fchart.com)

Figure 1. History Diagram of the PV F-Chart Method.

4 Applications of the PV F-Chart Method

PV F-Chart estimates the long-term, average performance of the photovoltaic systems listed below:

- ❑ Utility feedback system
- ❑ Battery storage system
- ❑ No feedback or storage system

PV F-Chart can also evaluate the performance of photovoltaic systems with the following different type of collector and collector tracking schemes:

- ❑ Stationary Flat-Plate Collectors
- ❑ Compound Parabolic Concentrating Collectors
- ❑ 1 and 2-Axis Tracking Collectors

PV F-Chart provides energy performance and economic evaluations for each scenario analyzed.

5 Accuracy of the PV F-Chart Method

Several studies were identified that cited the accuracy of the PV F-Chart method, including Menicucci and Fernandez (1984), Hoover (1980), and Clark et al. (1984). Menicucci and Fernandez (1984) quantified the accuracy of the PV F-Chart and SOLCEL-II performance models (Hoover, 1980) based on field data. In this study two sites were analyzed, the Northeast Residential Experiment Station (NERES) in Boston, Massachusetts, and the Southwest Residential Experiment Station (SWRES) in Las Cruces, New Mexico, using two system configurations, integral and stand-alone. The study reports that the difference of the results between measurement and PV F-Chart calculations was 4% on an annual basis when the radiation was measured on the plane of the collector array.

Clark et al. (1984) presented the accuracy of their method (PV F-Chart) for the calculation of the monthly solar load fraction from comparing the results of their method with those of other two methods, TRNSYS simulations (Klein 1973; 1981) and the graphical method of Evans et al. (1981). Clark et al.'s reported that their method agreed well with the TRNSYS hourly simulations, citing an annual difference between the two methods of 4%.

6   Basic Equations of the PV F-Chart Method (PV F-Chart User's Manual, Klein & Beckman, 1993, Chapter 5 Algorithms, Duffie and Beckman 1991).

The monthly-average hourly array electricity output $\overline{E}_i$ for the hour i can be found using the following expression:

$$\textbf{Equation 1:}\quad \overline{E}_i = A_c \overline{I}_T \overline{\eta}_i$$

where
A_c = photovoltaic cell array area (m²),
$\overline{I}_T$ = monthly-average hourly solar radiation on tilted surface (MJ/m²), and
$\overline{\eta}_i$ = monthly-average array efficiency for the hour i.

The monthly-average hourly solar radiation on tilted surface $\overline{I}_T$ can then be found from the following equation:

$$\textbf{Equation 2:}\quad \overline{I}_T = \overline{K}_T \overline{H}_o \left[\left(r_t - \frac{\overline{H}_d}{\overline{H}} r_d\right)R_b + \frac{\overline{H}_d}{\overline{H}} r_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g r_t \left(\frac{1-\cos\beta}{2}\right)\right]$$

where

$\overline{K}_T$ = monthly-average daily clearness index,
$\overline{H}_o$ = monthly-average daily extraterrestrial solar radiation (MJ/m²),
r_t = ratio of total radiation in an hour to total in a day,
$\overline{H}_d$ = monthly-average daily diffuse solar radiation (MJ/m²),
$\overline{H}$ = monthly-average daily solar radiation (MJ/m²),
r_d = ratio of diffuse radiation in an hour to diffuse in a day (%),
R_b = ratio of beam radiation on a tilted surface to that on a horizontal surface (%),
β = tilt of the array from horizontal (degrees), and
ρ_g = Ground reflectance (%).

The monthly average array efficiency $\overline{\eta}_i$ for the hour i is then found from:

$$\textbf{Equation 3:}\ \overline{\eta}_i = \eta_{mp,ref}\eta_e \left[1 + \frac{\mu_{mp}}{\eta_{mp,ref}}(\overline{T}_{a,i} - T_{ref}) + \frac{\mu_{mp}\overline{I}_T}{\eta_{mp,ref}}\frac{\tau\alpha}{U_L}(1-\eta_{mp,ref})Z_i\right]$$

where

$\eta_{mp,ref}$ = maximum power point efficiency from measurement at reference

condition,

η_e = efficiency of any power conditioning equipment,

μ_{mp} = temperature coefficient at the maximum power point efficiency measurement,

$\overline{T}_{a,i}$ = average ambient temperature for the hour i (°F),

T_{ref} = temperature from measurement at reference condition (°F),

τ = transmittance,

α = absorptance,

U_L = collector overall heat loss coefficient, and

Z_i = $\dfrac{1}{N\overline{I}_T^2}\displaystyle\sum_{n=1}^{N} I_{T,n}^2$ (where N = number of days), which can be expressed empirically as,

$$Z_i = \left(\frac{\overline{I}_o}{\overline{I}_T}\right)^2 (a_1 b_1 + a_2 b_2 + a_3 b_3)$$

where

$$a_1 = R_b^2 + \rho(1-\cos\beta)R_b + \rho^2(1-\cos\beta)^2/4$$
$$a_2 = R_b(1+\cos\beta-2R_b) + \rho(1+\cos\beta-2R_b)(1-\cos\beta)/2$$
$$a_3 = [(1-\cos\beta)/2 - R_b]^2$$
$$b_1 = -0.1551 + 0.9226\overline{k}_T$$
$$b_2 = 0.1456 + 0.0544\ln\overline{k}_T$$
$$b_3 = \overline{k}_T(0.2769 - 0.3184\overline{k}_T)$$

The utilizability function, ϕ, is defined using the following expression:

Equation 4: $\phi = \begin{cases} 0 & if \quad X_c \geq X_m \\ (1-X_c/X_m)^2 & if \quad X_m = 2 \\ \left| \|g\| - [g^2 + (1+2g)(1-X_c/X_m)^2]^{1/2} \right| & otherwise \end{cases}$

Where

X_c = monthly-average critical radiation ratio (L_i/E_i, where L_i is the load for the hour i and E_i is the electrical energy output of the array),

$$X_m = 1.85 + 0.169\overline{R}_h / \overline{k}_T^2 - 0.0696 \cos\beta / \overline{k}_T^2 - 0.981\overline{k}_T / \cos^2\delta$$

where

$\overline{R}_h$ = ratio of monthly-average hourly radiation on the tilted surface to that on a horizontal surface, ($\overline{I}_T / \overline{I}$, where $\overline{I}$ is monthly-average hourly radiation),

$\overline{k}_T$ = monthly-average hourly clearness index ($\overline{I} / \overline{I}_o$),

β = slope of the array,

δ = declination of the earth, and

g = $(X_m - 1)/(2 - X_m)$.

6.1 Example 1: Calculation of Monthly Electrical Output and Solar Fraction for a PV Power System Array (From: Duffie & Beckman (1991), Example 23.7.1, pp. 790-792).

Determine the monthly electrical output and solar fraction for a PV power system array with four modules, having the following system characteristics: Nominal Operating Cell Temperature (NOCT) is 46 ºC, reference temperature is 25 ºC, maximum power efficiency is 10.4%, single module area is 0.427 m², temperature coefficient of maximum power point efficiency is -0.00050, efficiency of maximum power point electronics is 0.9, array slope is 35º, array azimuth is 0º, usable battery capacity is 1200 Wh, battery efficiency is 0.8, location of the system is at a latitude of 40º, the month is March. The monthly-average daily horizontal radiation is 13.2 MJ/m², the ground reflectance is 0.2, and the load is constant at 100 W between 9 AM and 3 PM and zero at other times. The monthly-average hourly temperatures, beginning at 6:00 a.m. are 4, 5, 5, 6, 8, 10, 11, 12, 12, 11, 10, and 9 ºC. $\overline{K}_T$ is 0.481, $\overline{H}_o$ is 27.4 MJ/m², r_t is 0.129, r_d is 0.123, R_b is 1.347, δ is -2.4º, Z_i is 1.525, and $\overline{H}_d / \overline{H}$ is 0.448.

Solution for the hour 10 to 11:

From Equation 2, the monthly-average hourly solar radiation on tilted surface is

$$\overline{I}_T = \overline{K}_T \overline{H}_o \left[\left(r_t - \frac{\overline{H}_d}{\overline{H}} r_d \right) R_b + \frac{\overline{H}_d}{\overline{H}} r_d \left(\frac{1+\cos\beta}{2} \right) + \rho_g r_t \left(\frac{1-\cos\beta}{2} \right) \right]$$

$$= 0.481 * 27.4 \left[(0.129 - 0.448 * 0.123)1.347 + 0.448 * 0.123 \left(\frac{1+\cos35}{2} \right) + 0.2 * 0.129 \left(\frac{1-\cos35}{2} \right) \right]$$

$$= 2.0 \text{ MJ/m}^2.$$

From Equation 3, the monthly average array efficiency is

$$\overline{\eta}_i = \eta_{mp,ref}\,\eta_e\left[1 + \frac{\mu_{mp}}{\eta_{mp,ref}}(\overline{T}_{a,i} - T_{ref}) + \frac{\mu_{mp}}{\eta_{mp,ref}}\frac{\overline{I}_T}{U_L}\frac{\tau\alpha}{U_L}(1 - \eta_{mp,ref})Z_i\right]$$

$$= 0.104*0.9\left[1 - \frac{0.0005}{0.104}(8 - 25) - \frac{0.0005*2*10^6}{0.104*30.7*3600}(1 - 0.104)1.525\right]$$

$$= 0.090.$$

From Equation 1, the monthly-average hourly array electrical energy output is

$$\overline{E}_i = A_c\,\overline{I}_T\,\overline{\eta}_i$$

$$= 4 * 0.427 * 2\ 10^6 * 0.090/3600$$

$$= 85.4\ \text{W}.$$

From Equation 4, the utilizability function is

$$\phi = \begin{cases} 0 & if \quad X_{c,i} \geq X_m \\ (1 - X_{c,i}/X_m)^2 & if \quad X_m = 2 \\ \left|\,|g| - \left[g^2 + (1 + 2g)(1 - X_{c,i}/X_m)^2\right]^{1/2}\right| & otherwise \end{cases}$$

where $X_{c,i}$, R_h, $\overline{k}_T$, X_m, and g are calculated as

$$X_{c,i} = \overline{L}_i / \overline{E}_i = 100/85.4 = 1.166,$$

$$R_h = \overline{I}_T / \overline{I} = \overline{I}_T /(\overline{H}_T r_T) = 2.00/(13.2*0.129) = 1.17,$$

$$\overline{k}_T = \overline{I}/\overline{I}_o = \frac{r_t}{r_d}\overline{K}_T = \frac{0.129}{0.123}0.481 = 0.5045,$$

$$X_m = 1.85 + 0.169\overline{R}_h / \overline{k}_T^2 - 0.0696\cos\beta / \overline{k}_T^2 - 0.981\overline{k}_T / \cos^2\delta$$

$$= 1.85 + 0.169*1.17/0.505^2 - 0.0696*\cos 35/0.505^2 - 0.981*0.505/\cos^2(-2.4)$$

$$= 1.907,\ \text{and}$$

$$g = (X_m - 1)/(2 - X_m) = (1.907 - 1)/(2 - 1.907) = 9.76.$$

Since neither $X_{c,i} \geq X_m$ nor $X_m = 2$ from the calculation results above

$$\phi = \left\| g \right| - \left[g^2 + (1 + 2g)(1 - X_c / X_m)^2 \right]^{1/2} \right|$$

$$= \left\| 9.76 \right| - [9.76^2 + (1 + 2*9.76)(1 - 1.166/1.907)^2]^{1/2} \right|$$

$$= 0.159.$$

Therefore, the monthly-average fraction of the load for the hour 10-11 AM carried by the PV system without batteries, $f_{o,i(10:00\text{-}11:00\ AM)}$, is

$$f_{o,i(i=10\text{-}11\ AM)} = \frac{\overline{E}_{L,i}}{\overline{L}_i} = \frac{\overline{E}_i(1-\phi_i)}{\overline{L}_i} = \frac{85.4(1-0.159)}{100}$$

$$= 0.718\ (71.8\%).$$

Table 1 shows the results for all of the hours.

Hour	T_a °C	$\overline{I}_T$ MJ	Z_i	$\overline{\eta}_i$	$\overline{E}_i$ Wh	$\overline{L}_i$ Wh	$\overline{X}_{c,i}$	ϕ_i	$\overline{E}_{ex,i}$ Wh	$\overline{E}_{L,i}$ Wh
6-7	4	0.15	2.228	0.102	7	0	0.000	1.000	7	0
7-8	5	0.60	1.906	0.099	28	0	0.000	1.000	28	0
8-9	5	1.11	1.728	0.096	50	0	0.000	1.000	50	0
9-10	6	1.61	1.604	0.093	71	100	1.412	0.087	6	65
10-11	8	2.00	1.525	0.090	86	100	1.166	0.159	14	72
11-12	10	2.22	1.486	0.088	93	100	1.072	0.193	18	75
12-1	11	2.22	1.486	0.088	93	100	1.077	0.191	18	75
1-2	12	2.00	1.525	0.088	84	100	1.189	0.149	13	71
2-3	12	1.61	1.604	0.090	69	100	1.454	0.075	5	64
3-4	11	1.11	1.728	0.093	49	0	0.000	1.000	49	0
4-5	10	0.60	1.906	0.096	27	0	0.000	1.000	27	0
5-6	9	0.15	2.228	0.100	7	0	0.000	1.000	7	0
Totals					664	600			242	422

Table 1.   Values and Calculation Results for the Calculation of Monthly-Average Fraction of the Load Carried by the PV System without Batteries.

The monthly-average electrical output $\overline{E}$ is 664 Wh, the monthly-average load $\overline{L}$ is 600 Wh, and the monthly-average to the load $\overline{E}_L$ is 422 Wh. So the monthly-average fraction of the load carried by the PV system without batteries, f_o, is

$$f_o = \frac{\overline{E}_L}{\overline{L}} = \frac{422}{600}$$

$$= 0.703 \ (70.3\%)$$

6.2 Example 2: Calculations of Monthly Electrical Output and Solar Fraction for a PV Power System Array Using the PV F-Chart Program of DOS Version 3.1.

This second example shows the selections of system, collector type and other parameters that are needed for the PV F-Chart program to calculate the hourly, monthly, and annual electrical output and solar fraction for a PV power system array.

Figures 2 and 3 show the selection of system type and collector type. In this example, system type 3, a stand-alone system, is selected and collector type 1, flat-plate, is selected.
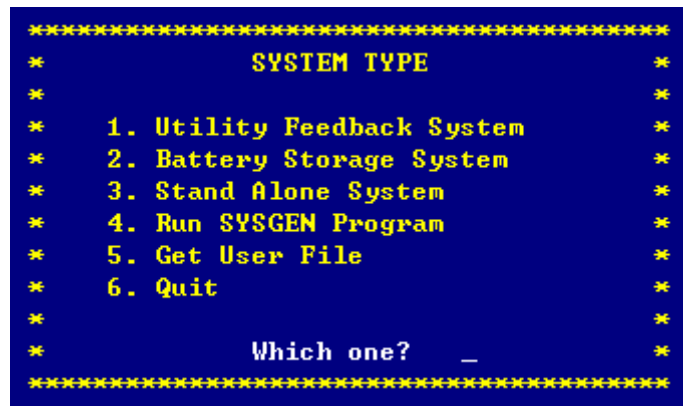
```
***********************************************
*              SYSTEM TYPE                    *
*                                             *
*     1. Utility Feedback System              *
*     2. Battery Storage System               *
*     3. Stand Alone System                   *
*     4. Run SYSGEN Program                   *
*     5. Get User File                        *
*     6. Quit                                 *
*                                             *
*              Which one?    _                *
***********************************************
```

Figure 2. Selection of System Type in the PV F-Chart Program.

```
***********************************************
*             COLLECTOR TYPE                  *
*                                             *
*       1. Flat-Plate                         *
*       2. Compound Parabolic                 *
*       3. One-Axis Tracking                  *
*       4. Two-Axis Tracking                  *
*      Esc Return to Main Menu                *
*                                             *
*              Which one?    _                *
***********************************************
```
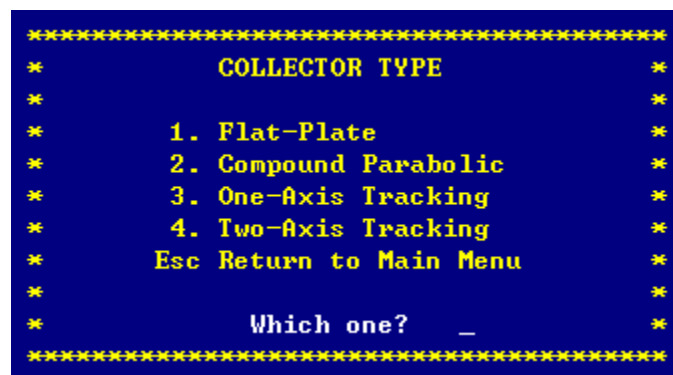
Figure 3. Selection of Collector Type in the PV F-Chart Program.

Figure 4 shows the parameters and values used for running PV F-Chart example for the Houston, Texas, climate.

```
1   City number for HOUSTON        TX................   102
2   Output: 1 for summary, 2 for detailed (Neg: graph)  1
3   Cell temperature at NOCT conditions..............   44        C
4   Array reference efficiency.......................   .104
5   Array reference temperature......................   28        C
6   Max. power eff. temperature coeff. (times 1000)...  4.3       1/C
7   Eff. of maximum power point tracking electronics..  .9
8   Efficiency of power conditioning electronics......  .88
9   Percent standard deviation of the load...........   0         %
10  Array area.......................................   6         m^2
11  Array slope......................................   50        deg
12  Array azimuth (south=0)..........................   0         deg
```

**Figure 4. Detail Input Parameters Used in the PV F-Chart Program
for the Example Problem 2.**

Using the above inputs, PV F-Chart calculates electricity produced by the system as
shown in Figure 5 and Figure 6. Figure 5 shows the hourly values predicted for the
January performance, including the total solar radiation incident on the collector, the
array efficiency, the total electric demand on the system, the percent of the load supplied
directly by the array (F), and the total electrical energy (XS). The monthly total values
are shown in the bottom of the figure, where the solar radiation is 648.90 kWh for the
month of January, and the percent of load (F) supplied directly by the array is 30.3%.

			Jan		
Time	Solar	Eff	Load	F	XS
	kWh	%	kWh	%	kWh
7- 8	22.04	8.8	3.10	44.1	0.34
8- 9	45.74	9.1	3.29	68.7	1.43
9-10	69.34	9.1	3.50	79.8	2.75
10-11	88.36	9.0	3.75	84.6	3.80
11-12	98.97	8.9	4.00	86.2	4.30
12-13	98.97	8.9	4.25	85.3	4.10
13-14	88.36	8.9	4.46	81.8	3.27
14-15	69.34	9.0	4.65	74.1	2.03
15-16	45.74	9.0	4.77	59.3	0.79
16-17	22.04	8.6	4.84	33.2	0.07
Month	648.90	8.9	93.00	30.3	22.87

**Figure 5. Calculation Results of Monthly-Average Fraction
of the Load Carried by the PV System for January.**

Figure 6 shows the calculation results of annual fraction of the load carried by the PV
system and monthly fraction for the 12 months. The fifth column with 'Buy' is the total
electrical energy that should be purchased from the utility to satisfy the load in kWh. The
result in Figure 6 shows us that the annual fraction of the load supplied by the array is
35.5%; therefore, 706.6 kWh of electricity must be purchased from the utility to meet the
total load of the system in the Houston, Texas, climate.

Figure 6. Calculation Results of Yearly-Average Fraction of the Load Carried by the PV System.

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