Centrum för solenergiforskning
Solar Energy Research Center

A computer study of the improvement of PV panel monthly outputs when the panel azimuth is changed thrice daily

Eva Lindberg and Lars Broman

SERC

Avdelningen för energi.
miljö och byggande
Högskolan Dalarna
781 88 Borlänge

Tel: +46 23 778700
Tel: +46 23 778701

Besöksadress/Street adress:
Forskargatan 8
Borlänge

HÖGSKOLAN
Dalarna

ISSN 1103-1816
ISRN HFB-SERC--50--SE
June 1994

A computer study of the improvement of PV panel monthly outputs when the panel azimuth is changed thrice daily.

Eva Lindberg and Lars Broman

Solar Energy Research Center
University College of Falun Borlänge
P. O. Box 10044, S-781 10 Borlänge, Sweden
Phone +46 243 73757 Fax +46 243 73750
e-mail eli@hfb.se (EL) and lbr@hfb.se (LB)

ABSTRACT

The purpose of the calculations was to estimate the most suitable slopes and azimuths for three different positions per day of a solar panel in order to obtain the most possible energy from the PV panel compared with a stationary PV panel. The calculations were made in the computer program PV F-CHART.

KEYWORDS

Photovoltaics, PV F-CHART, calculations, tracking.

INTRODUCTION

Broman and Datta (1991) have compared stationary solar collectors tilted towards the south with one-axis tracking solar collectors with help of the computer program F-CHART. It was shown that the amount of heat energy obtained could be increased by about 40-45 % if tracking collectors were used. Datta, Broman and Garg (1992) then compared Sweden and India, and it was shown that the improvment in energy obtained was only 15-20 % in India. In Sweden solar tracking is obviously an advantage during the summer.

The reason for this is illustrated in the Figures 1 and 2, which show the solar positions in the hemisphere in Borlänge and New Delhi. At the time of the summer solstice the solar azimuth varies from -143° to +143° in Borlänge but only from -117° to +117° in New Delhi.

According to Duffie-Beckman the following equations are valid:

- for the sunset hour angle ω_s $\quad \cos\omega_s = -\tan\phi\tan\delta$
- for the solar azimuth angle γ_s $\quad \sin\gamma_s = \sin\omega_s\cos\delta$

where ϕ is the latitude and δ is the declination.

These equations give, for Borlänge (ϕ=60°) and New Delhi (ϕ=29°) and δ=23°

Borlänge	$\omega_s = 139°$	$\gamma_s = 143°$
New Delhi	$\omega_s = 104°$	$\gamma_s = 117°$

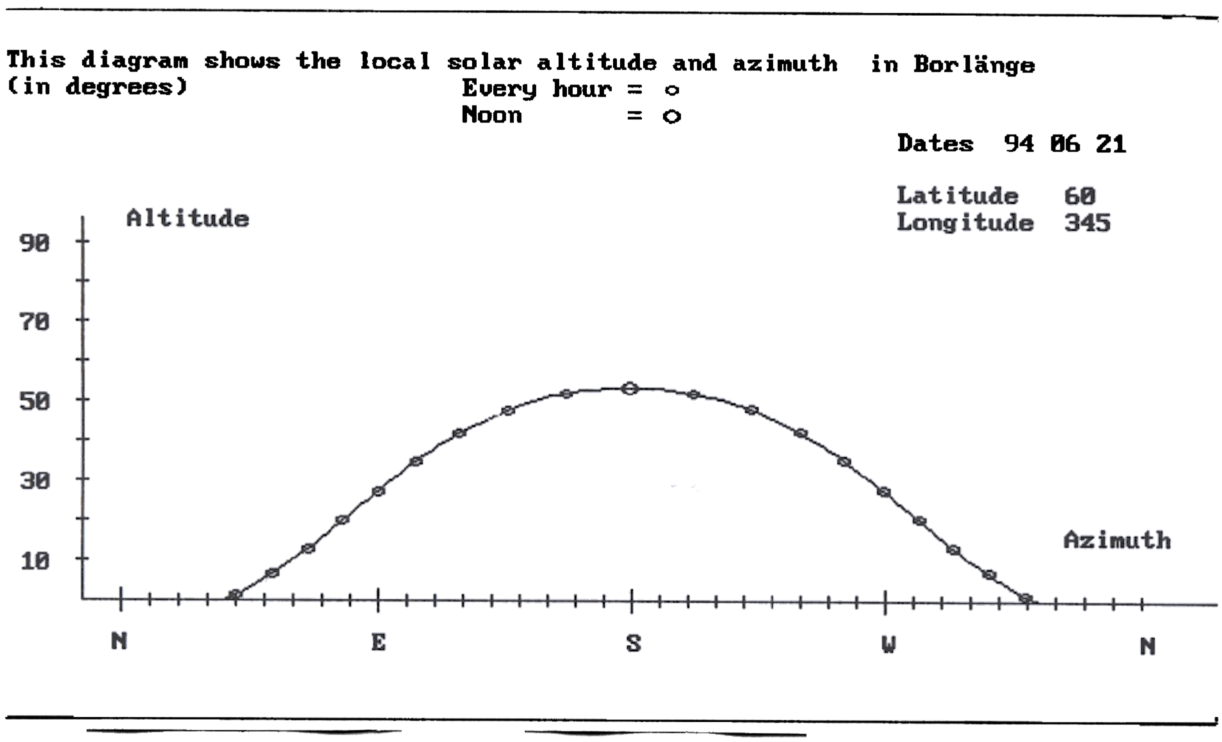

Figure 1. The solar positions at summer solstice in Borlänge.

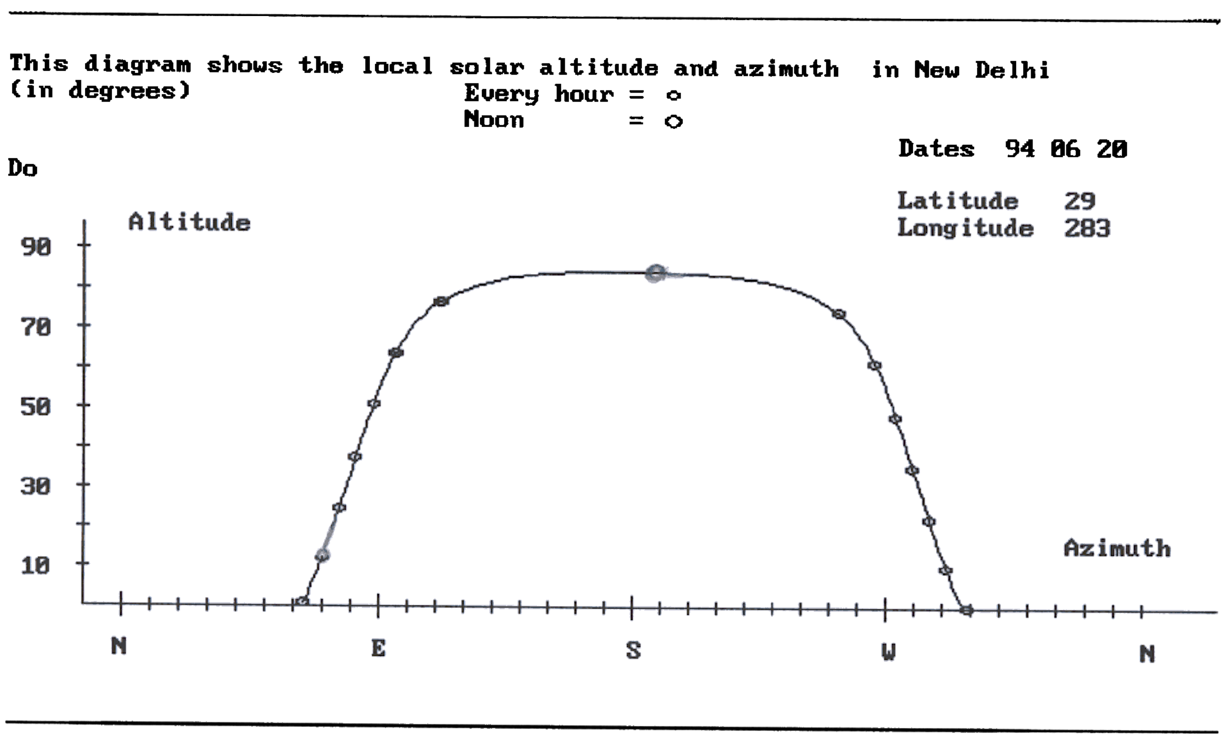

Figure 2. The solar positions at summer solstice in New Delhi.

Measurements on PV cells with different tilts have been performed by Jantsch et. al (1991). The results indicate that the tilt angle yielding maximum annual energy depends on latitude and diffuse fraction of insolation. According to Jantsch et. al. maximum power point tracking, if it requires additional hardware, does not pay off in energy terms compared with an optimally fixed voltage.

There are commercial tracking equipments for sale. The economic advantage of tracking panels is doubtful, especially when the array consists of only one or two panels for a summer cottage. Would it be more profitable with solar panels attached to a vertical axis which is turned manually twice during the day and once in the late evening?

METHOD

The computer program PV F-CHART (Klein and Beckman 1993) has been used for the calculations. PV F-CHART provides long-term average performance estimates for stand-alone PV systems and for systems having utility feedback capability or battery storage. Power conditioning equipment maintains the array output at its maximum power point. The monthly average hourly load on the system is supplied by the user. The program includes monthly horizontal solar radiation data and average ambient temperature for 350 locations in USA, Canada and Europe, but the user may add data for more locations. Collector types are flat plate, compound parabolic, one-axis tracking or two-axis tracking. PV F-CHART is controlled by a set of commands, and system outputs are insolation energy, total electrical demand, array efficiency, percent of the load supplied by the system and energy loss.

CALCULATIONS

The stand-alone PV system, which is used in the calculations, consists of a flat plate solar panel area of 10 m^2. No consideration is taken to energy losses due to increase of cell temperature, to varying efficiency depending on solar incident angle, nor to power conditioning electronics. PV F-CHART has been used to calculate the total and the monthly average hourly insolation on the surface with different tilts and azimuths. Monthly values of solar radiation on a horizontal surface $\overline{H}$ were obtained from the the Swedish Meteorogical and Hydrological Institute. Table 1 shows $\overline{H}$ for the three investigated locations.

Table 1. Monthly global insolation on a horizontal surface $\overline{H}$

	Lund, lat. 55.4°		Borlänge, lat. 60.4°		Luleå, lat. 65.5°	
	kWh/m^2	MJ/m^2	kWh/m^2	MJ/m^2	kWh/m^2	MJ/m^2
May	172	619	164	590	153	551
June	186	670	173	623	172	619
July	170	610	152	547	161	580
August	125	448	111	400	111	400

Three locations at different latitudes; the south, the middle and the north of Sweden have been investigated. The tilt has been varied from 40° to 65° in 5° stages, and the azimuth has been varied from -75/0/+75 degrees to -105/0/+105 degrees. Table 2 is an extract of the full Table showing the monthly insolation on the tilted panel in kWh/m^2 in Borlänge when the tilt and then the azimuth are varied. For each month the best choice of azimuth at a given tilt for the solar panel is underlined. A sensitivity analysis has been made too, showing the loss of energy if the solar panel is turned one hour earlier in the morning or one hour later in the afternoon; see Table 3. Table 4 shows energy obtained with different tilts with the solar panel facing south. Table 5 is a comparision with a horizontal one-axis tracking solar panel and finally a comparision with a two-axis tracking solar panel.

The column Sum gives the sum of the collected energy for the four months when the solar panel is kept at a fixed slope and the azimuth is varied three times per day. For example; at late evening the panel is turned to -95 degrees (east), at 9.00 am next morning the panel is turned to the south, and at 3.00 pm turned to 95 degrees (west). Figure 3 shows a diagram of the total hourly insolation. As can be seen in the diagram, from 9.00 to 10.00 am the collected energy is about the same for the first two alternatives of turning.

For each location, a Figure illustrates the total hourly insolation for the best choice of tilt and azimuth according to the column Sum and in the same Figure a dashed curve shows the total hourly insolation when the solar panel is kept at the most appropriate fixed tilt facing south. The Figures show the month of June.

<u>Borlänge, latitude 60.4.</u>

Turning hours: 9.30 am and 2.30 pm at azimuths ±75° and ±80°
9.00 am and 3.00 pm for the other azimuths.

Table 2. Total monthly insolation [kWh/m^2] at panels with different tilts and azimuths in Borlänge.

Tilt	Az	May	June	July	August	Sum
50°	0 fixed	167.6	165.1	148.5	121.3	602.4
	-75/0/+75	231.4	234.7	204.7	157.3	828.0
	-80/0/+80	<u>232.4</u>	236.8	206.3	<u>157.6</u>	833.1
	-85/0/+85	231.6	236.8	206.2	156.9	831.6
	-90/0/+90	232.0	238.1	207.2	156.8	834.1
	-95/0/+95	231.8	238.9	<u>207.6</u>	156.4	<u>834.7</u>
	-100/0/+100	231.1	<u>239.1</u>	<u>207.6</u>	155.7	833.5
	-105/0/+105	229.9	238.7	207.1	154.6	830.4
55°	0 fixed	163.3	159.9	144.2	118.9	586.3
	-75/0/+75	230.8	233.3	203.7	157.3	825.0
	-80/0/+80	<u>231.9</u>	235.6	205.4	<u>157.6</u>	830.5
	-85/0/+85	231.0	235.7	205.3	156.9	828.9
	-90/0/+90	231.5	237.1	206.3	156.8	831.6
	-95/0/+95	231.3	237.9	<u>206.8</u>	156.3	<u>832.3</u>
	-100/0/+100	230.5	<u>238.1</u>	<u>206.8</u>	155.6	831.0
	-105/0/+105	229.2	237.7	206.3	154.4	827.6

If the solar panel is turned one hour earlier or one hour later the decreased amount of solar insolation would be:

Table 3. Insolation loss [kWh/m²] if panel turning is one hour off.

Az	May	June	July	August	Sum
-85/0/+85	4.3	4.2	3.5	2.5	14.6
-95/0/+95	3.7	3.8	3.1	2.1	12.6
-105/0/+105	2.9	3.1	2.5	1.5	10.0
-85/0/+85	4.6	4.5	3.7	2.7	15.5
-95/0/+95	4.0	4.0	3.3	2.2	13.5
-105/0/+105	3.1	3.3	2.6	1.6	10.64

Investigation of the most suitable tilt when the solar panel is turned south:

Table 4. Total insolation [kWh/m²] for different tilts on a panel facing south in Borlänge

	Az	May	June	July	August	Sum
20°	0	176.4	<u>180.2</u>	<u>160.0</u>	122.4	630.0
25°	0	<u>177.2</u>	179.9	<u>160.0</u>	123.7	<u>640.8</u>
30°	0	176.9	178.6	159.2	124.3	639.0
35°	0	175.7	176.4	157.5	<u>124.5</u>	634.1

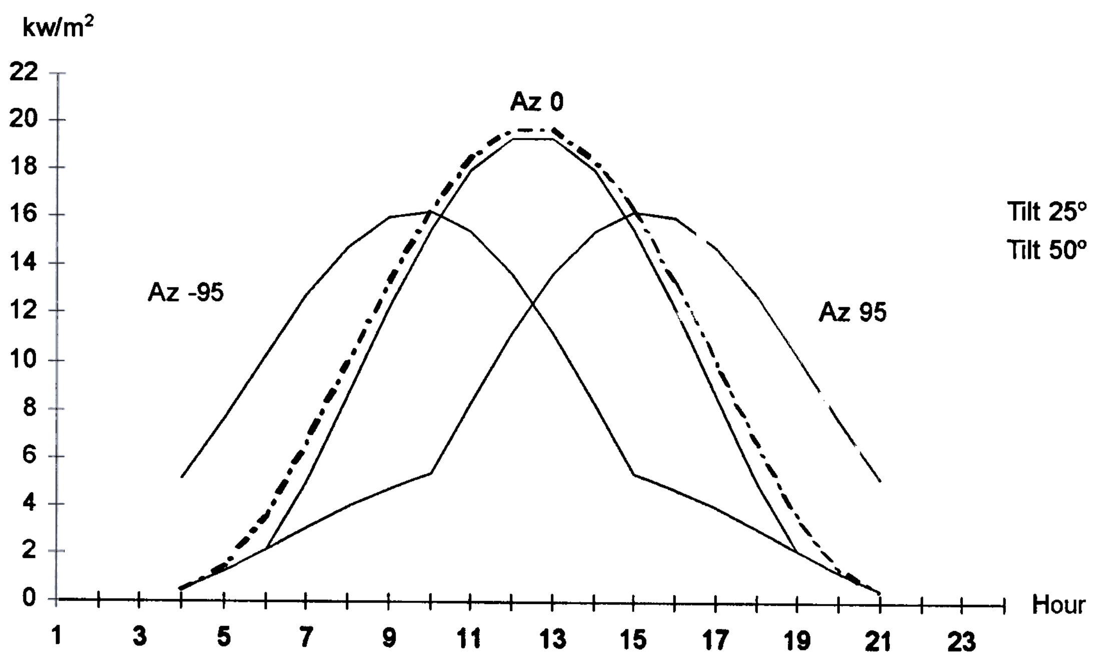

Figure 3. Total hourly insolation for Borlänge in June, using PV F-CHART, on the PV panel with the best choice of slope, 50°, and three different azimuths. The dashed line shows the total hourly insolation for the panel facing south and best choice of slope, 25°.

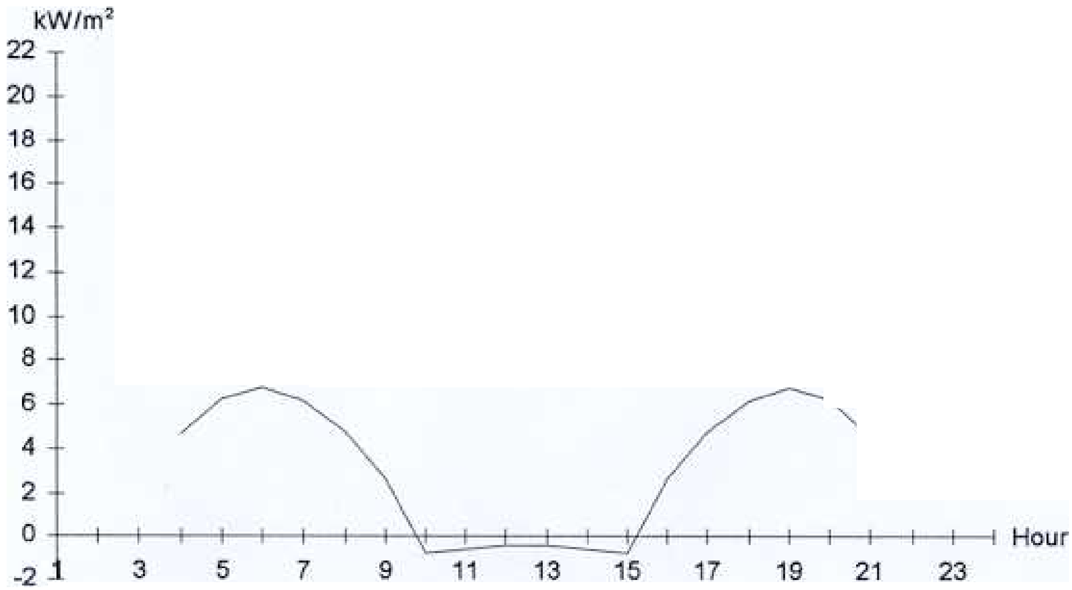

Figure 4. Hourly increase in insolation if the PV panel is changed thrice daily as compared with insolation if the PV panel is fixed and at the best slope.

The following Table shows the insolation on a vertical axis tracking solar panel and on a two-axis tracking panel to be compared with the results in tables 1 and 3.

Table 5. Monthly insolation [kWh/m^2] with vertical axis and two-axis tracking in Borlänge.

	Az	May	June	July	August	Sum
25°	0	244.3	251.0	218.6	165.3	879.2
30°	0	245.0	251.2	218.8	166.3	881.4
35°	0	245.1	251.0	218.5	166.8	881.1
40°	0	244.4	249.5	217.6	166.9	878.4
45°	0	243.0	247.8	216.2	166.4	873.3
Two-axis tracking:						
		249.6	260.3	225.2	168.0	903.0

Lund, latitude 55.4

Turning hours: 9.30 and 14.30 at azimuths ∓80° and ∓85°
9.00 and 15.00 for the other azimuths

Table 6. Total monthly insolation [kWh/m^2] for different tilts and azimuths in Lund.

	Az	May	June	July	August	Sum
...	....					
45°	0 fixed	173.7	177.5	165.6	133.8	650.6
	-85/0/+80	235.0	240.5	222.4	166.3	864.1
	-85/0/+85	235.6	252.2	223.2	166.1	877.1
	-90/0/+90	234.3	251.6	222.0	164.9	872.8
	-95/0/+95	234.3	252.5	222.1	164.4	873.3
	-100/0/+100	233.8	252.9	221.8	163.5	872.0
	-105/0/+105	232.9	252.7	221.1	162.4	869.1

Az	May	June	July	August	Sum
0 fixed	169.4	177.5	165.6	131.5	534.1
-80/0/+80	235.0	240.5	222.4	166.5	874.1
-85/0/+85	235.6	252.2	223.2	166.2	876.2
-90/0/+90	234.3	251.6	222.0	165.0	872.6
-95/0/+95	234.3	252.5	222.1	164.4	873.1
-100/0/+100	233.8	252.9	221.8	163.5	871.8
-105/0/+105	232.9	252.7	221.1	162.3	868.5

Investigation of the most suitable tilt when the solar panel is turned south.

Table 7. Total insolation [kWh/m^2] for different tilts on a panel facing south in Lund.

Tilt	Az	May	June	July	August	Sum
15°	0	181.4	192.0	176.5	133.6	683.5
20°	0	182.4	192.0	176.8	135.3	686.5
25°	0	182.4	191.0	176.3	136.2	685.9
30°	0	181.5	188.9	174.7	136.7	681.7

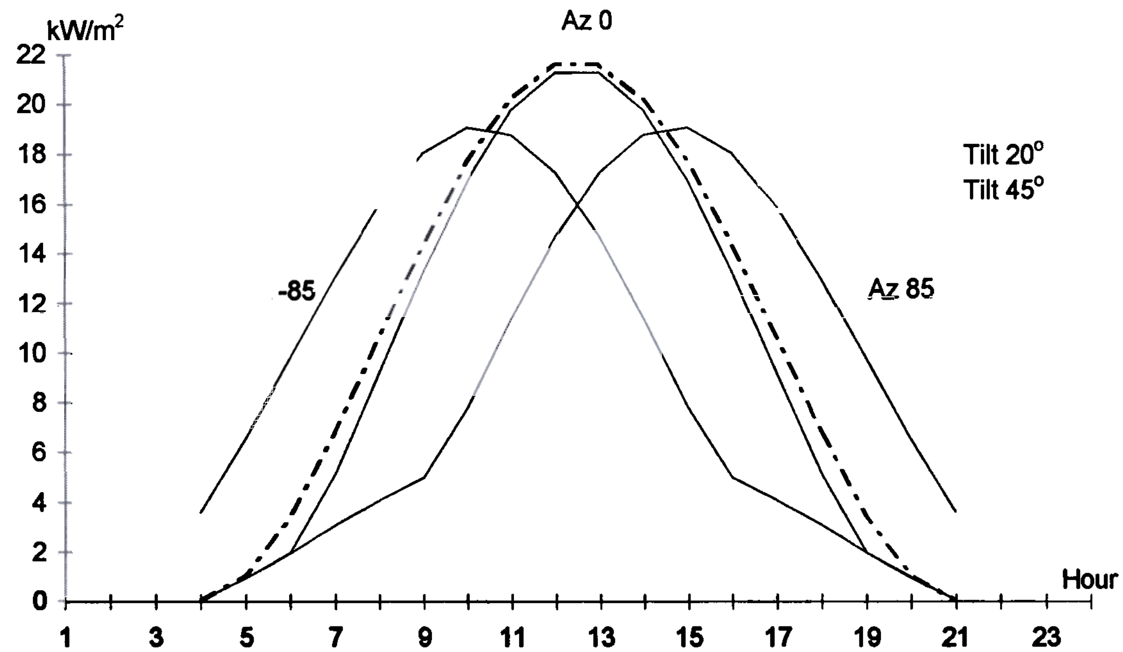

Figure 5. Total hourly insolation [kWh/m^2] for Lund in June, using PV F-CHART, on the PV panel with the best choice of tilt, 45°, and three different azimuths. The dashed line shows the total hourly insolation on the panel when facing south and best choice of slope, 20°.

Table 8. Monthly insolation [kWh/m^2] with vertical axis and two-axis tracking in Lund.

Tilt	Az	May	June	July	August	Sum
20°	0	249.1	269.4	234.8	172.9	926.1
25°	0	250.0	269.8	235.1	174.1	929.0
30°	0	250.1	269.4	234.8	174.8	929.2
35°	0	249.6	268.4	233.8	174.9	926.6
40°	0	248.3	266.7	232.1	174.4	921.4
45°	0	246.2	264.2	229.7	173.4	915.6
Two-axis tracking:						
			279.0	239.6	175.6	948.5

Luleå, latitude 65.5

Turning hours: 9.00 am and 3.00 pm.

Table 9 Total monthly insolation [kWh/m^2] for different tilts and azimuths in Luleå

Tilt	Az	May	June	July	August	Sum
...						
50°	0 fixed	161.8	167.2	163.1	129.6	621.7
	-85/0/+85	231.3	246.0	237.4	172.5	887.3
	-90/0/+90	232.6	248.6	239.1	172.3	892.2
	-95/0/+95	232.4	250.6	240.2	171.8	895.0
	-100/0/+100	232.1	252.0	240.5	170.8	895.4
	-105/0/+105	231.3	252.7	240.6	169.4	894.0
55°	0 fixed	158.4	162.8	159.2	127.9	608.2
	-85/0/+85	231.8	245.8	237.6	173.4	888.6
	-90/0/+90	232.8	248.6	239.4	173.2	894.0
	-95/0/+95	233.0	250.7	240.6	172.6	897.0
	-100/0/+100	232.7	252.1	241.1	171.6	897.5
	-105/0/+105	231.7	252.9	241.0	170.1	895.9

Investigation of the most suitable tilt when the solar panel is turned south:

Table 10. Total insolation [kWh/m^2] for different tilts on a panel facing south in Luleå.

Tilt	Az	May	June	July	August	Sum
25°	0	167.9	178.6	172.0	128.6	647.1
30°	0	168.3	178.2	171.9	130.1	648.5
35°	0	167.9	176.7	171.0	130.8	646.4
40°	0	166.6	174.4	169.1	131.1	641.2
45°	0	164.4	171.1	166.3	130.7	632.5

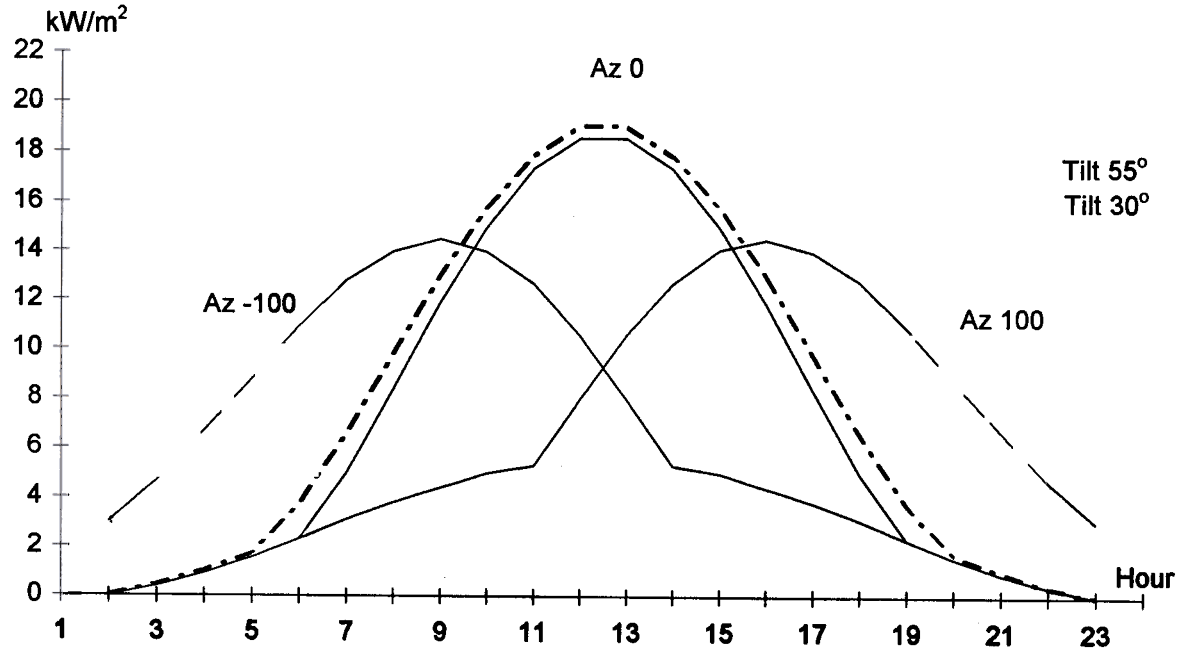

Figure 6. Total hourly insolation for Luleå in June, using PV F-CHART, on the PV panel with the slope 55°, and three different azimuths. The dashed line shows the total hourly insolation on the panel when facing south and best choice of slope, 30°.

Table 11. Comparision with vertical axis and two-axis tracking in Luleå.

Slope Az	May	June	July	August	Sum
30°	244.7	264.5	253.0	181.9	944.1
35°	245.6	265.7	253.9	183.1	948.3
40°	<u>245.8</u>	<u>266.4</u>	<u>254.2</u>	183.8	950.2
45°	245.4	<u>266.4</u>	253.9	<u>184.0</u>	949.6
50°	244.4	265.8	253.0	183.6	946.6
Two-axis tracking:					
		283.8	265.7	185.5	987.9

Table 12 shows the energy gain in % when the PV panel is turned thrice daily compared to when the PV panel is fix in the best choice of tilt facing south.

Table 12. Insolation gain (%) for turned panel over fixed.

	May	June	July	August	Sum
Luleå	38	42	40	32	38
Borlänge	31	33	30	26	30
Lund	29	31	26	23	28

DISCUSSION

In the previous chapter, the monthly insolation on a PV panel has been calculated in kWh/m^2. Assuming that the PV system efficiency is unsensitive to variables like insolation, ambient temperature, etc., the energy delivered by the system is proportional to the insolation.

Results are summerized in Table 12. As can be seen from the Tables, the improvement obtained by turning the PV panel three times a day as compared with a fixed panel is 30 % for Borlänge, 28 % for Lund and 38 % for Luleå. Measurements are planned for the summer of 1994 in order to validate the PV F-CHART calculations. Two similar 50 W crystalline silicon panels will be used in the measurements. One fixed and one adjustable PV panel are connected to a diode bridge and a data logger. Voltage and current from the two PV panels are measured every 6th minute simultaneously with a pyranometer measurement of the global insolation.

For a PV panel with two modules and a total cost of SEK 6000 (approx. USD 750), an adjustable mount that does cost less than SEK 1700-2300 (USD 210-280) more than a fixed mount will be economically profitable.

REFERENCES

L. Broman and G. Datta (1991). Solar Collector Geometries at High Latitudes. Proc. ISES Solar World Congress, pp 1227-1232.

G. Datta, L. Broman and H. P. Garg (1992). Optimization of Collector Tilts Using F-CHART Method. Proc. Second World Renewable Energy Congress, pp 1051-1055.

J. A. Duffie and W. A. Beckman (1991). Solar Engineering of Thermal Processes, Wiley Sons, Inc.

M. Jantsch, M Stoll, W. Roth, H. Schmidt, J. Schmid. (1991) The effekt of Tilt Angle and Voltage Conditions on PV System Performance. An Experimental Investigation. Proc. 10th European Photovoltaic Solar Energy Conference, pp 431-434.

S. Klein and W. A. Beckman (1993). PV F-CHART Users Manual.