

Optimum Tilt of Solar Panels

<http://www.macslab.com/optisolar.html>

To get the most from solar panels, you need to point them in the direction that captures the most sun. But there are a number of variables in figuring out the best direction. This page is designed to help you find the best placement for your solar panels in your situation.

This advice applies to any type of panel that gets energy from the sun; photovoltaic, solar hot water, etc. We assume that the panel is fixed, or has a tilt that can be adjusted seasonally. (Panels that track the movement of the sun throughout the day can receive 10% (in winter) to 40% (in summer) more energy than fixed panels. This page doesn't discuss tracking panels.)

Solar panels should always face true south if you are in the northern hemisphere, or true north if you are in the southern hemisphere. True north is not the same as magnetic north. If you are using a compass to orient your panels, you need to correct for the difference, which varies from place to place. Search the web for "magnetic declination" to find the correction for your location.

The next question is, at what angle from horizontal should the panels be tilted? Books and articles on solar energy often give the advice that the tilt should be equal to your latitude, plus 15 degrees in winter, or minus 15 degrees in summer. It turns out that you can do better than this - about 4% better.

Fixed or Adjustable?

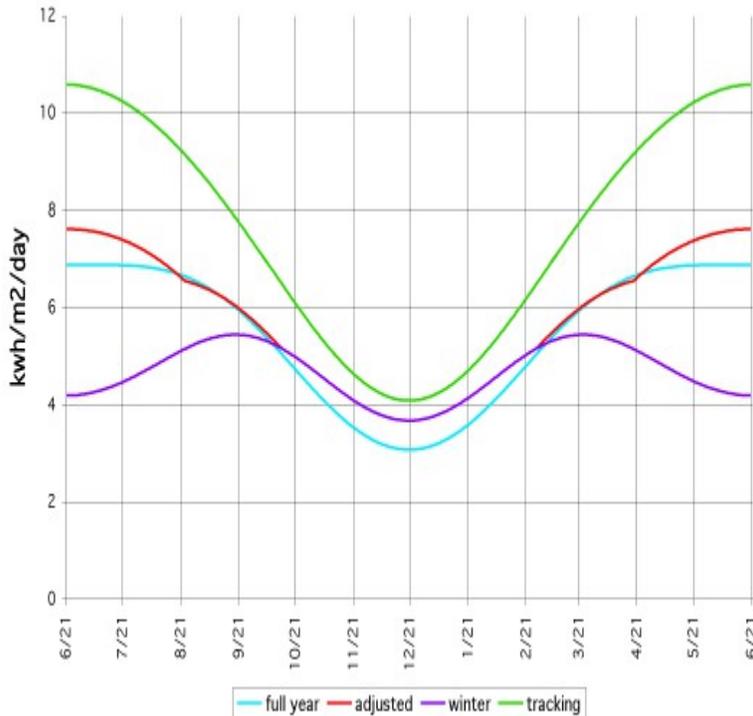
It is simplest to mount your solar panels at a fixed tilt and just leave them there. But because the sun is higher in the summer and lower in the winter, you can capture more energy during the whole year by adjusting the tilt of the panels according to the season. The following table shows the effect of adjusting the angle, using a system at 40° latitude as an example. (The comparison would be a little different for different latitudes.) Each option is compared with the energy received by the best possible tracker that always keeps the panel pointed directly at the sun.

	Fixed	Adj. 2 seasons	Adj. 4 seasons	2-axis tracker
% of optimum	71.1%	75.2%	75.7%	100%

In short, adjusting the tilt twice a year gives you a meaningful boost in energy. Adjusting four times a year produces only a little more, but could be important if you need to optimize production in spring and fall. You can jump to the section on the best fixed tilt angle, or skip to the sections on two-season or four-season adjusting.

The graph below shows the effect of adjusting the tilt. The turquoise line shows the amount of solar energy you would get each day if the panel is fixed at the full year angle. The red line shows how much you would get by adjusting the tilt four times a year as described below. For comparison, the green line shows the energy you would get from two-axis tracking, which always points the panel directly at the sun. (The violet line is the solar energy per day if the panel is fixed

at the winter angle, discussed below.) These figures are calculated for 40° latitude.



Fixed Tilt

If your solar panels will have a fixed tilt angle, and you want to get the most energy over the whole year, then this section is for you. A fixed angle is convenient, but note that there are some disadvantages. As mentioned above, you'll get less power than if you adjusted the angle. Also, if you live where there is snow, adjusting the panels to a steeper angle in winter makes it more likely that they will shed snow. A panel covered in snow produces little or no power.

Use one of these formulas to find the best angle from the horizontal at which the panel should be tilted:

- If your latitude is below 25°, use the latitude times 0.87.
- If your latitude is between 25° and 50°, use the latitude, times 0.76, plus 3.1 degrees.
- If your latitude is above 50°, see Other Situations below.

This table gives some examples for different latitudes. It also shows the average insolation on the panel over the year (in kWh/m² per day), and the energy received compared to the best possible tracker.

Latitude	Full year angle	Avg. insolation on panel	% of optimum
0° (Quito)	0.0	6.5	72%
5° (Bogotá)	4.4	6.5	72%
10° (Caracas)	8.7	6.5	72%
15° (Dakar)	13.1	6.4	72%
20° (Mérida)	17.4	6.3	72%
25° (Key West, Taipei)	22.1	6.2	72%
30° (Houston, Cairo)	25.9	6.1	71%
35° (Albuquerque, Tokyo)	29.7	6.0	71%
40° (Denver, Madrid)	33.5	5.7	71%
45° (Minneapolis, Milano)	37.3	5.4	71%
50° (Winnipeg, Prague)	41.1	5.1	70%

Adjusting the tilt twice a year

If you are going to adjust the tilt of your solar panels twice a year, and you want to get the most energy over the whole year, then this section is for you.

The following table gives the best dates on which to adjust:

	Northern hemisphere	Southern hemisphere
Adjust to summer angle on	March 30	September 29
Adjust to winter angle on	September 12	March 14

If your latitude is between 25° and 50°, then the best tilt angle for summer is the latitude, times 0.93, minus 21 degrees. The best tilt angle for winter is the latitude, times 0.875, plus 19.2 degrees. If your latitude is outside this range, see Other Situations below. This table gives some examples:

Latitude	Summer angle	Winter angle	Avg. insolation on panel	% of optimum
25°	2.3	41.1	6.6	76%
30°	6.9	45.5	6.4	76%
35°	11.6	49.8	6.2	76%
40°	16.2	54.2	6.0	75%
45°	20.9	58.6	5.7	75%
50°	25.5	63.0	5.3	74%

Adjusting the tilt four times a year

If you are going to adjust the tilt of your solar panels four times a year, and you want to get the most energy over the whole year, then this section is for you. This would be your situation if you are connected to the grid and can use or sell all the power you produce.

The following table gives the best dates on which to adjust:

	Northern hemisphere	Southern hemisphere
Adjust to summer angle on	April 18	October 18
Adjust to autumn angle on	August 24	February 23
Adjust to winter angle on	October 7	April 8
Adjust to spring angle on	March 5	September 4

If your latitude is between 25° and 50°, then the best tilt angles are:

- For summer, take the latitude, multiply by 0.92, and subtract 24.3 degrees.
- For spring and autumn, take the latitude, multiply by 0.98, and subtract 2.3 degrees.
- For winter, take the latitude, multiply by 0.89, and add 24 degrees.

If your latitude is outside this range, see Other Situations below.

If you want to adjust the tilt of your panels four times a year, you can use these figures to keep capturing the most energy year-round. This table gives some examples:

Latitude	Summer angle	Spring/autumn angle	Winter angle
25°	-1.3	22.2	46.3
30°	3.3	27.1	50.7
35°	7.9	32.0	55.2
40°	12.5	36.9	59.6
45°	17.1	41.8	64.1
50°	21.7	46.7	68.5

In winter, a panel fixed at the winter angle will be relatively efficient, capturing 81 to 88 percent of the energy compared to optimum tracking. In the spring, summer, and autumn, the efficiency is lower (74-75% in spring/autumn, and 68-74% in summer), because in these seasons the sun travels a larger area of the sky, and a fixed panel can't capture as much of it. These are the seasons in which tracking systems give the most benefit.

Note that the winter angle is about 5° steeper than what has been commonly recommended. The reason is that in the winter, most of the solar energy comes at midday, so the panel should be pointed almost directly at the sun at noon. The angle is fine-tuned to gather the most total energy throughout the day.

The summer angles are about 12 degrees flatter than is usually recommended. In fact, at 25° latitude in summer, the panel should actually be tilted slightly away from the equator.

Tilt Fixed at Winter Angle

If your need for energy is highest in the winter, or the same throughout the year, you may want to just leave the tilt at the winter setting. This could be the case if, for instance, you are using passive solar to heat a greenhouse. Although you could get more energy during other seasons by adjusting the tilt, you will get enough energy without making any adjustment. The following tables assume that the tilt is set at the winter optimum all year long. They show the amount of insolation (in kWh/m²) on the panel each day, averaged over the season.

Latitude 30° Tilt 50.7°		
Season	Insolation on panel	% of winter insolation
Winter	5.6	100%
Spring, Autumn	6.0	107%
Summer	5.1	91%

Latitude 40° Tilt 59.6°		
Season	Insolation on panel	% of winter insolation
Winter	4.7	100%
Spring, Autumn	5.8	123%
Summer	5.1	109%

Latitude 50° Tilt 68.5°		
Season	Insolation on panel	% of winter insolation
Winter	3.4	100%
Spring, Autumn	5.4	158%
Summer	5.1	150%

Confused about tilt angles?

A zero tilt angle means that the face of the panel is aimed directly overhead. A positive tilt angle means that the panel faces more towards the equator. In the northern hemisphere that would mean tilting so it faces towards the South. Rarely, the tilt angle can be negative; this means the panel faces away from the equator.

Time-of-Use Rates

In some grid-connected systems, energy is more valuable during peak periods. To see the effect of this on panel orientation, look at my time-of-use page.

Other Situations

Perhaps your panels are on a roof that is not oriented exactly to the south. Or you are at a latitude outside the range for which these formulas work. These situations are more complex than can be handled by a simple formula.

I can do calculations for your custom situation for a consulting fee. See my rates.

Assumptions

These calculations are based on an idealized situation. They assume that you have an unobstructed view of the sky, with no trees, hills, clouds, dust, or haze ever blocking the sun.

You may need to make adjustments for your situation. For example, if you have trees to the east but not the west, it may be better for you to aim your solar panels slightly to the west. Or if you often have clouds in the afternoon but not the morning, you might aim your panels slightly to the east.

The calculations also assume that you are near sea level. At very high altitude, the optimum angle could be a little different.

Don't obsess about the exact angles just because I've calculated them to the tenth of a degree. A difference of a few degrees will make very little difference in the energy you gather.

Why does this work?

The recommended angles can seem counterintuitive. For example, consider summer at 40° latitude. At noon on the solstice, the sun is 40° - 23.5° which is 16.5° from directly overhead. To capture the most sun at that time you would tilt the panel 16.5° to point it directly at the sun. On other days of the summer it is a bit lower in the sky, so you would want to tilt the panel a bit more. Yet we say to tilt it only 12.5°. The sun is never that high. How can that be right?

The answer is that we are considering the whole day, not just noon. In the morning and evening, the sun moves lower in the sky and also further north (if you are in the northern hemisphere). It is necessary to tilt less to the south (or more to the north) to collect that sunlight.

How these numbers were calculated

For each configuration of latitude and season, over 12,000 data points were calculated for various times throughout the day and the year. For each data point, the equations of celestial mechanics were used to determine the height and azimuth of the sun. The intensity of the sun was corrected to account for the increased absorption by the atmosphere when the sun is lower in the sky, using the formula:

$$\text{intensity in kw/m}^2 = 1.35 * (1.00/1.35)^{\sec(\text{angle of sun from zenith})}$$

This formula assumes that the earth is flat, so a factor was applied to account for the curvature of the earth (and therefore the earth's atmosphere). These factors, and the angle of the sun with respect to the panel, then determine the insolation on the panel. An iterative method then determined the angles that give the maximum total insolation during each season. Given those angles, the beginning and ending dates of the season were then adjusted to the optimum, then the angles recalculated, until the process converged. After the optimum dates and angles were calculated, it was determined that a linear formula closely approximates the optimum. The formulas are only accurate within the specified range.

Other published articles on tilt angles have used less accurate calculations. For example, Richard Perez and Sam Coleman, in "PV Module Angles", Home Power n.34 p.14-16, 1993, recommend an angle that puts the panel perpendicular to the sun's rays at noon. That is indeed the best angle at noon on that day, but it does not take into account the best angle for capturing solar energy at other times of the day. That article also leaves it to the reader to estimate the best angle over the period until the next time the tilt is adjusted. Percentages may not be exact due to rounding.

Links

You may find these links useful.

http://www.nrel.gov/rredc/solar_resource.html

The National Renewable Energy Laboratory has copious data on solar energy available at different locations in the United States, a performance calculator for PV systems, and more.

<http://www.gaisma.com>

This site has sunrise, sunset, and insolation data for worldwide locations.

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