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Experiments on solar radiation

with the solar radiation measurement module SUSE 5.23

Learning Station C11

9 Pages

This manual is also suitable for the measurement model SUSE 4.24 to a limited extent.

A Physical basics on irradiance and solar energy
B Experiments

If we analyse the solar radiation through precise measurements in experiments, it is necessary to know it's emergence from the sun and it's structures on earth.

A1 The emergence of solar radiation through nuclear fusion in the sun
A2 The expansion of radiation from the sun through the atmosphere to the ground
A3 The intensity distribution of the radiation
A4 Global radiation, direct and diffuse radiation
A5 From irradiance to solar energy: hourly and daily progression of the radiation and determination of the irradiated energy

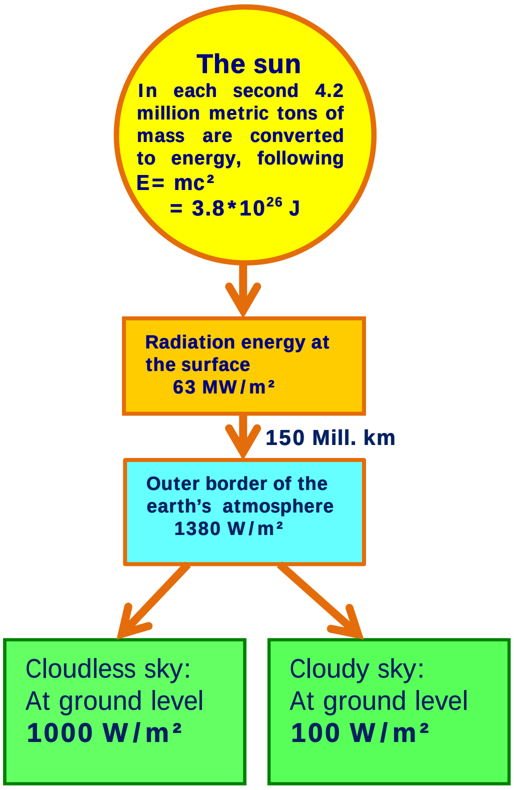


Fig.1: Emergence and progression of the solar radiation

A1 Nuclear fusion inside the sun:

The sun is a giant nuclear fusion reactor, which emits it's energy in the form of radiation energy into space. In the sun's core the proton-proton reaction runs at 100 million °C, in the process deuterium nuclei fuse to helium nuclei. Greatly simplified this proton-proton reaction can be described as the amalgamation of four protons to one helium nucleus, in the intermediate reactions positrons, neutrinos and gamma radiation are also created. The mass of one helium nucleus is smaller than the mass of the original protons, the missing mass was converted to energy following Einstein's equation **$E = mc^2$.**

Inside the sun in every second 567 million metric tons of hydrogen merge into 562,8 million metric tons of helium. Therefore our sun gets 4,2 million metric tons lighter each second. According to Einstein this results in an emission of radiation equivalent to $3.8 \cdot 10^{26}$ J each second, which adds up to **63 MW** (megawatts) per 1 m². 10 m² of the sun's surface emit as much energy as a coal-burning power plant with 630 MW.

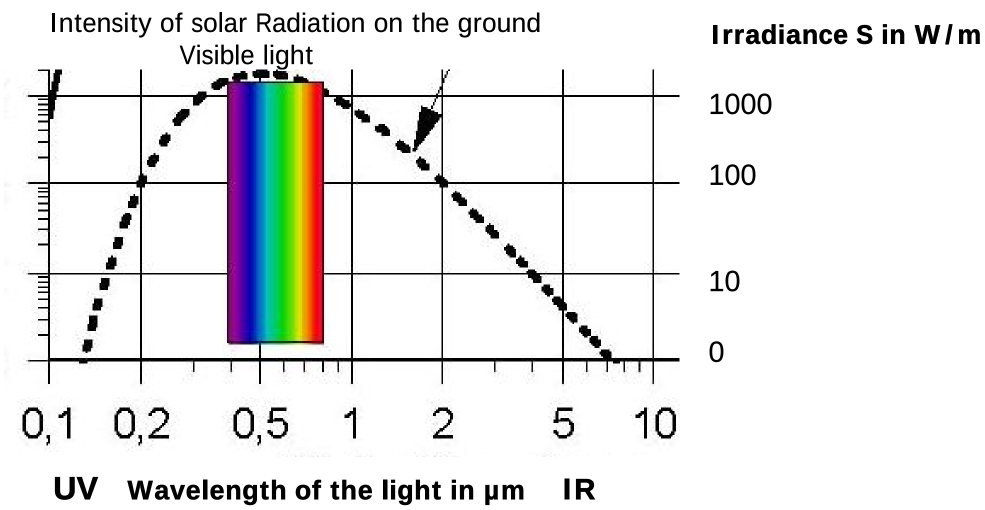
Because the earth is much smaller than the sun and 150 km away, only a very small portion of the emitted energy hits the earth at the outer border of the atmosphere:

Only **1380 W/m²**, that's the **solar constant**.

A2 The expansion of radiation from the sun through the atmosphere to the ground

At the ground level an irradiance of **S = 1000 W/m²** reaches the earth through a cloudless sky, the rest of the energy of 380 W/m² is needed for chemical and physical reactions in the atmosphere (e.g. in the ozone layer). This value of 1000 W/m² can be measured precisely in the summer with bright sunshine.
Under a cloudy sky the clouds absorb a large portion of the radiation energy, with heavy clouding for example only 100 W/m² reach the ground. Also in winter the irradiance doesn't reach the value of 1000 W/m² even in bright sunshine, because the longer way of the light in winter absorbs energy travelling through the atmosphere, the value only reaches up to 600 W/m². All the corresponding measurements will be conducted with **SUSE 5.23**.

A3 The intensity distribution of the radiation



The wavelength range of sunlight runs from 0.15 µm in UV light over visible light (rainbow spectrum, 400 – 800 nm) up to long wave infrared light (IR) at about 7µm.
The maximum of the radiation is green light with about 550 nm (0.55 µm). For silicon solar cells especially the light in the range of 500 – 1100 nm is very important. The highest sensibility of Si solar cells is reached in the red and infrared light up to 1100 nm.

A4 Global radiation, direct and diffuse radiation

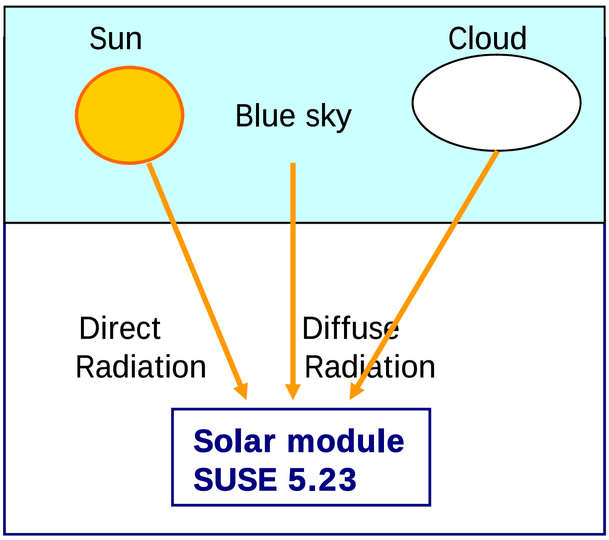


Fig.3: Global radiation = sum of direct and diffuse radiation

A4 Global radiation, direct and diffuse radiation

If we hold the solar module **SUSE 5.23** towards the sky, towards the sun, in bright sunshine, we measure the **direct radiation** of the sun on the one hand, but we also measure the radiation of the bright blue sky or single white clouds, the **diffuse radiation**. Both kinds of radiation together account for the **global radiation**, that we measure with **SUSE 5.23**. Under a dull, cloudy sky we only have diffuse radiation, that stems from the whole sky, with a small stronger component in the direction of the sun.

A5 From irradiance to solar energy: hourly and daily progression of the radiation and determination of the irradiated energy

With our solar module **SUSE 5.23** we measure the momentary radiated power (irradiance) in W/m², to measure the irradiated energy in a time frame t we have to multiply a constant irradiance with the time t and we then get the irradiated energy W for this time frame per m².

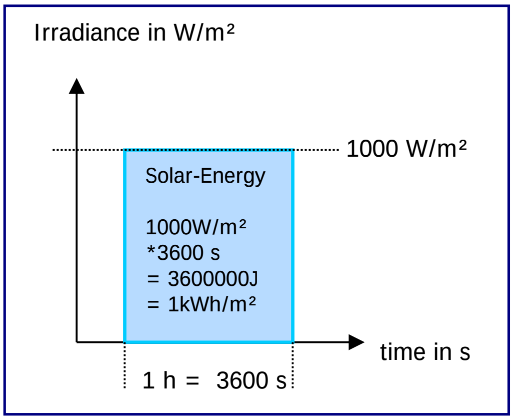


Fig.4: Irradiated solar energy with an irradiance of 1000 W/m² and a time span of 1 h = 3600 s

Because the sun migrates – seen from earth – from east to west and reaches it's highest point at noon (12 o'clock), we would have to rotate our solar module in steps of about 5 minutes constantly in horizontal and vertical direction, so that the solar radiation always hits the solar cell vertically. We will conduct this in the experiments. If we assume that on such a sunny sommer day the irradiance stays at 1000 W/m² for exactly one hour (3600 s), then **per 1 m²** we get exactly an irradiated energy of 3 600 000 J = **1 kWh**, the adjacent figure shows this energetic situation.

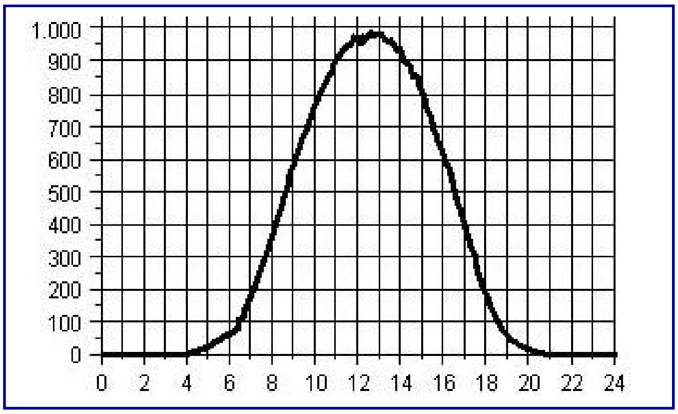


Fig.5: Intraday progress of an irradiance in W/m² (y-axis) from 0 to 24 o'clock (x-axis) on a cloudless summer day (source: NILS- ISFH). The measurement module **SUSE 5.23** is mounted on a southerly roof with 35° inclination.

In practice the situation is more complex, because in bright sunshine with a firmly mounted device **SUSE 5.23** (on a southerly roof with 35° inclination) in the morning after sunrise the solar radiation strikes coming from the east in a flat angle, at noon at 12:00 it strikes the solar cell nearly vertical and in the evening in a very flat angle to the west. The adjacent figure shows such a real situation.
The irradiance starts at 4 in the morning, increases with the altitude of the sun in the form of a bell curve, reaches it's maximum of 1000 W/m² at noon and decays in the afternoon until it goes back to 0 at 21 in the evening.

The **irradiated energy** is the area = the integral under the curve of the irradiance. Each rectangle of the graph is equivalent to an energy of 100 Wh = 0,1 kWh, the whole area is about 7,5 kWh, that much energy was irradiated across the day on a roof area of 1 m². In units of electricity rates of 20 ct/kWh this energy is equivalent to a value of 3.75 Euros per m². The energy can be calculated by counting the boxes, if the mathematical function is known the area can be determined by mathematical integration.

On clouded days with a rapid change of clouds and sunshine the situation is even more complex, the daily energy would only be 3-4 kWh per m², on a very dull winter's day under 1 kWh per m². We can conduct all the measurements with our measurement module **SUSE 5.23**.

B 7 experiments with the solar module SUSE 5.23

1. **Measuring the irradiance S in W/m² in natural sunlight**
2. **Measuring the irradiance S in W/m² of light sources**
3. **Measuring the sun's position**
4. **Measuring the direct radiation and the diffuse radiation and problems of shadowing**
5. **Measuring the global radiation on roof areas**
6. **Measuring the hourly or daily progress with PC interface, determination of the irradiated solar energy in kWh or J**
7. **Absorption measurements with glass, plexiglass, transparent envelopes**

Additional optional devices and components:

1 Halogen spot light 500 W on desk support
1 optical bench PV 5.0 with halogen spot light 5.16 and transformer 12V/60 W
1 compass, common school stands (tripod, rods, muffs), 1 folding rule
PC- Interface (e.g. Cassylab) and Notebook + 2 Lab wires

B1 Measuring the irradiance S in W/m² in natural sunlight

Our eye is a very bad measurement tool for solar and light radiation, through the iris aperture we perceive very bright light as less intensive and dim light (e.g. at dawn) as much more bright than is really is.

Therefore we want to estimate the expected light intensity before conducting the measurements and compare them to the precise values after the measurements and calculate the discrepancy in %!
The direction towards the sun can be found by finding the maximum value on the display, even under a clouded sky!

Chose convenient measurement situations from the table!

Radiation situation	**Estimate in W/m²**	**Measurement in W/m²**	**Difference in %**
Bright sunshine in the summer, no clouds **SUSE 5.23** directed towards the sun In the morning: ....o'clock			
Bright sunshine in the summer, no clouds **SUSE 5.23** directed towards the sun At noon: 12 o'clock			
Bright sunshine in the summer, no clouds **SUSE 5.23** directed towards the sun In the evening: ....o'clock			
Bright sunshine in the winter, no clouds **SUSE 5.23** directed towards the sun In the morning: ....o'clock			
Bright sunshine in the winter, no clouds **SUSE 5.23** directed towards the sun At noon: 12 o'clock			
Bright sunshine in the winter, no clouds **SUSE 5.23** directed towards the sun In the evening: ....o'clock			
Slightly clouded sky **SUSE 5.23** directed towards the sun			

Time:.......................o'clock in the summer half-year			
Slightly clouded sky **SUSE 5.23** directed towards the sun Time:.......................o'clock in the winter half-year			
Strongly clouded sky **SUSE 5.23** directed towards the sun Time:.......................o'clock in the summer half-year			
Strongly clouded sky **SUSE 5.23** directed towards the sun Time:.......................o'clock in the winter half-year			
Very clouded sky, extremely dull weather **SUSE 5.23** directed towards the sun Time:.......................o'clock in the winter half-year			

Assess your measurements here:

B2 Measuring the irradiance S in W / m² of light sources

Radiation situation	Estimate in W / m²	Measurement in W / m²	Difference in %
20 cm in front of halogen spot lamp 500 W			
40 cm in front of halogen spot lamp 500 W			
80 cm in front of halogen spot lamp 500 W			
On optical bench **SUSE 5.0** with halogen spot lamp 35 W Distance to lamp 15 cm			

On optical bench **SUSE 5.0** with halogen spot lamp 35 W Distance to lamp 30 cm			
South window, module held vertically in front of the pane (outside!)			
South window, module held vertically behind the pane (inside!)			
Module illuminated with flashlight Indoors Module directed towards window			
Indoors Module directed towards ceiling lighting			
In front of car front light in upper beam mode, measurement directly at the glass			
Overhead projector Module **SUSE 5.23** in the middle of the glass pane, directed downwards, towards the light source			
Overhead projector Module **SUSE 5.23** in a corner at the edge of the glass pane directed downwards, towards the light source			

Assess your measurements here:

B3 Measuring the sun's position

With astronomical tables or calculations the position of the sun can be determined in every place on earth and every time of the day in the azimuth (angle in the horizontal plane) and elevation (angle in the vertical plane). With PV 5.23 this measurement can also be conducted as follows:
Align the solar module PV 5.23 – in bright sunshine – with the help of a compass exactly horizontally towards north. Now mount a set square with a stand setting parallel to one edge of the casing. Now rotate the module horizontally until the maximum irradiance value is displayed, then you found the horizontal direction. Measure the rotational angle with the set square.
Now tilt the device backwards until the absolute maximum of the irradiance value is reached. Now you also have the vertical angle (elevation) set. Now measure the vertical angle with a small plumb line and the set square.

B4 Measuring the direct radiation and the diffuse radiation and problems of shadowing

If we align the module **SUSE 5.23** with the sun in bright sunshine, about 90% of the light come directly from the sun (**direct radiation**), about 10% from the bright blue sky (**diffuse radiation**), both of them together adds up to the global radiation, which we measure with the solar cell of the device. To only measure the diffuse radiation, we align the module exactly with the sun with the help of a stand setting. Now we take a 10x10 cm square of black cardboard on a 50 cm long piece of wire and take that some dm in front of the solar cell, so that the shadow of the cardboard exactly covers the solar cell. Now we measure only the diffuse radiation, because the direct light of the sun doesn't reach the solar cell anymore.

A big problem for solar panels on roofs is caused by unwanted shadowing through neighbouring buildings, trees, chimneys, antenna masts...., that shadow the solar cell for a certain time frame. Simulate this by shadowing the solar cell by hand for 1/3 or with only one finger. Measure this situation:

Radiation situation	Irradiance in W/m^2	Reduction in % compared to the not shadowed solar cell
Solar cell directed towards the sun, no shadowing		
Shadowing of 1/3 of the solar cell with the hand in about 10 cm distance		
Shadowing of the solar cell with one finger in about 10 cm distance		

Assess your measurements here:

B5 Measuring the global radiation on roof areas

If an accessible and safe to enter roof area is designated for a solar panel, the irradiance – and over a time frame – also the solar energy can be measured. The module is mounted exactly parallel to the roof area on the roof and the irradiance S is measured. The solar energy is obtained, if the irradiance is documented over a certain period of time (1-6 hours or more) manually or with a PC interface in a minute cycle, the values have to be noted in a table and the graph S(t) has to be plotted.

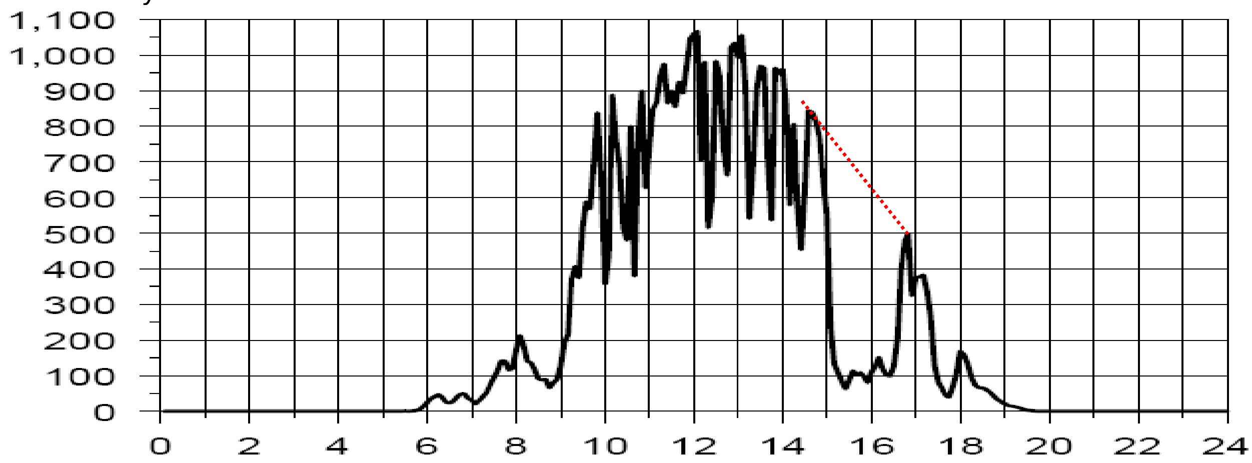
If the t-axis is parted into seconds (e.g. 5mm for 1 min = 60 seconds), the area under the curve is the illuminated solar energy in Watt-seconds = Joule.

If the display of the device **SUSE 5.23** is covered, because it was mounted parallel to the roof area, a voltmeter in the measurement range 200 mV can be connected to the test jacks, it shows the identical value to the display. These wires to the voltmeter can be pretty long, 10....20 m, because only a voltage is measured.

B6 Measuring the hourly or daily progress with PC interface, determination of the irradiated solar energy in kWh or J

The measurement of an irradiance profile over several hours or a whole day to determine the irradiated energy cannot be conducted manually anymore with **SUSE 5.23**, here a PC interface for automated measurements is needed. The module is directed towards the south and tilted to 35°, this would be the ideal roof position for the installation of a solar panel in Germany. Now a PC interface is connected to the test jacks, which measures the irradiance S in cycles of 1 or 5 minutes. In an example measurement the following day progress was produced on a rainy april day:

y- axis: Irradiance in W/m²



x-axis: Time in hours Source: NILS- ISFH

Recording of a day profile of the irradiance and determination of the irradiated energy
The cavings of the irradiance caused by clouding are clearly recognizable, this happened several times on this spring day in April. Through counting of the energy boxes (100 Wh each) the irradiated solar energy of the day per m² can be determined.

On a day with bright sunshine 7 kWh would be irradiated, on this cloudy day it was only 5 kWh.
Especially between 15:00 and 17:00 the clouding was very heavy, the trend of the graph with bright sunshine is marked with a red dashed line! So the irradiated solar energy is reduced significantly through clouding.

B7 Absorption measurements with glass, plexiglass or foil

Glass or plexiglass or foils (e.g. sheet protector) don't let the light pass 100% (transmission), but instead absorb part of the irradiated light, so that with 100% irradiation less than 100% of the

7.1 Experiment setting:

7.1.1 Required components
Measurement module SUSE 5.23, optical bench SUSE 5.0 or similar, halogen spot light SUSE 5.16 with transformer 12 V/60 W, transparent materials (glass/plexiglass/foil)

7.1.2 Setting + procedure
On the optical bench the halogen spot light is mounted in a distance of about 20 cm to the measurement module SUSE 5.23 and directly aligned to the measurement module. The transparent materials are hold <u>directly in front of the solar cell</u>, so that the solar cell is covered completely. The value for the irradiance S in W/m² is measured once without any material and 1x for each material.

7.2 The measurements
Note the values in the table and calculate the transmission in % and as a factor:

Material	Measurement of the irradiance S without any material in W/m²	Measurement of the irradiance S with material in W/m²	Transmission in % (Difference of the values divided by S without material * 100) Transmission factor
Thin glass plate Thickness = mm			
Plexiglass plate Thickness = mm			
Thick glass plate Thickness = mm			
1 sheet protector			
2 sheet protectors on top of each other			
5 sheet protectors on top of each other			

Explain your results here:

If you need more information, please send a mail to: info@sundidactics.de