Photovoltaics as a sustainable energy supply

- components of modern systems for photovoltaic utilisation
- physical characteristics of solar cells and photovoltaic modules under different conditions

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Photovoltaics as a sustainable energy supply

In recent years, successful development of technology and economic incentives have led to a significant growth in installed photovoltaic capacity. Generated solar electricity is fed directly into an energy provider's grid or consumed on site. The applications range from ground-mounted systems with several 100 MW to building-integrated modules and the supply of self-sufficient micro-consumers.

The advantages of converting light directly into electricity are well known: solar electricity contributes to protecting the environment, reduces the cost of electricity transmission and provides an independent and affordable energy supply.

Solar cooling means a process in which the cooling process is powered directly by solar energy. Solar energy thus serves as a regenerative source of drive heat.

The advantage of solar plants for cooling is that the availability of solar energy increases as the demand for cooling increases. Solar cooling concepts gaining popularity both for small decentralised applications and on a large scale.

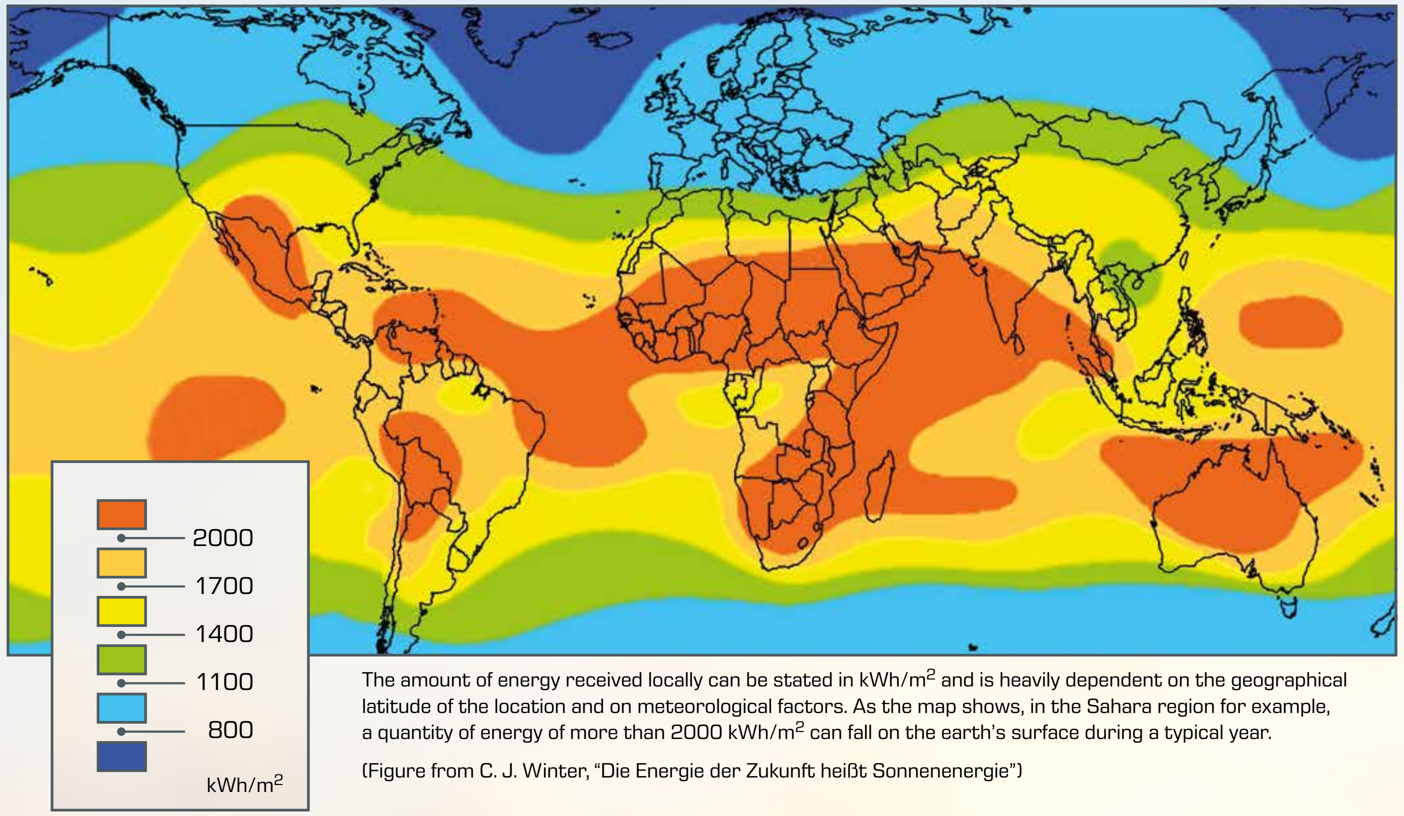
In order to tap the full potential of solar energy as a sustainable energy supply worldwide, it is essential that we understand and develop sometimes very different concepts of use.

Photovoltaics

Basic knowledge
Solar energy

Energy galore

The amount of solar energy that falls on the Earth's land areas in a year is almost 2,000 times greater than the entire world's energy demand. Given the global climate problem, using this potential in the best possible way seems self-evident.

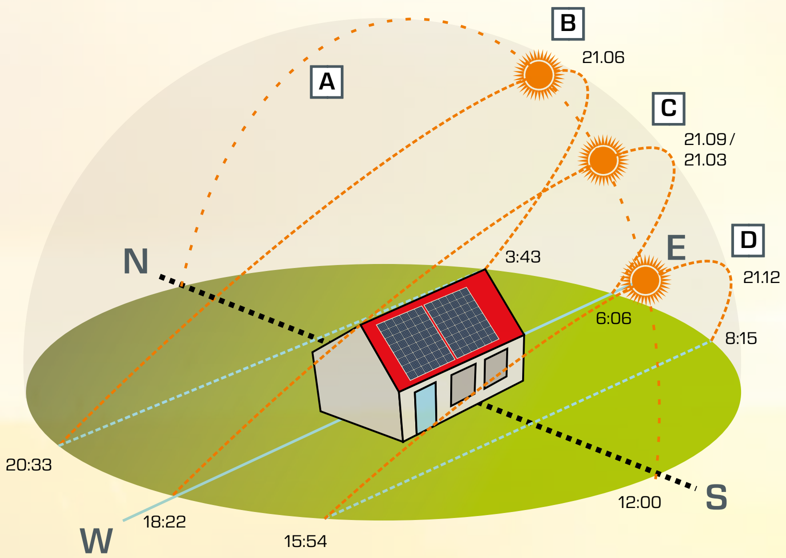


The amount of energy received locally can be stated in kWh/m^2 and is heavily dependent on the geographical latitude of the location and on meteorological factors. As the map shows, in the Sahara region for example, a quantity of energy of more than 2000 kWh/m^2 can fall on the earth's surface during a typical year.

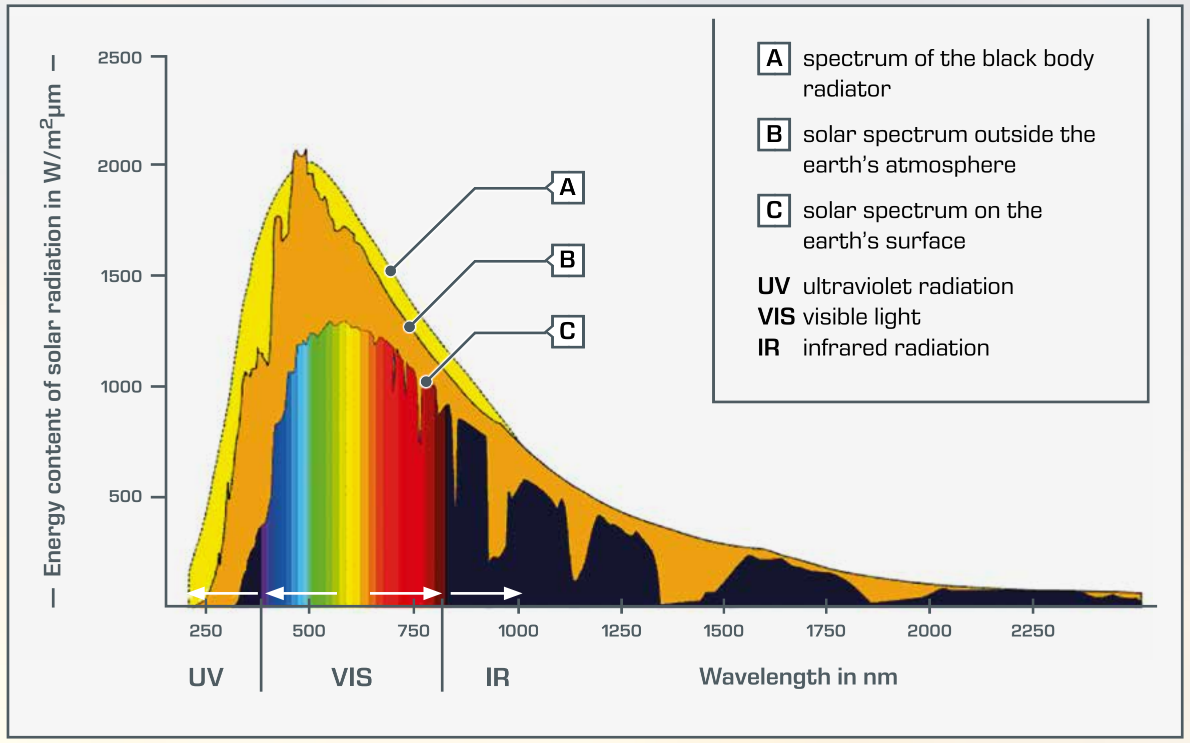
(Figure from C. J. Winter, "Die Energie der Zukunft heißt Sonnenenergie")

The orientation of the module surfaces to the cardinal point and their inclination play a significant role in optimising the yield of a solar installation. The illustration shows the path of the sun visible on the Earth at different seasons of the year. The times given for sunrise and sunset are for Berlin:

- A zenith
- B summer solstice
- C beginning of spring/autumn
- D winter solstice



In order to optimise the use of solar radiation, it is necessary to understand its properties. The spectral composition of sunlight is of interest in this regard. Through spectroscopic studies, it is possible to determine the energy content of sunlight at different wavelengths. If one is then able to better adapt the spectral properties of the receiver or absorber to the solar spectrum, then a key condition for improving the energy balance is met.



The spectrum of sunlight

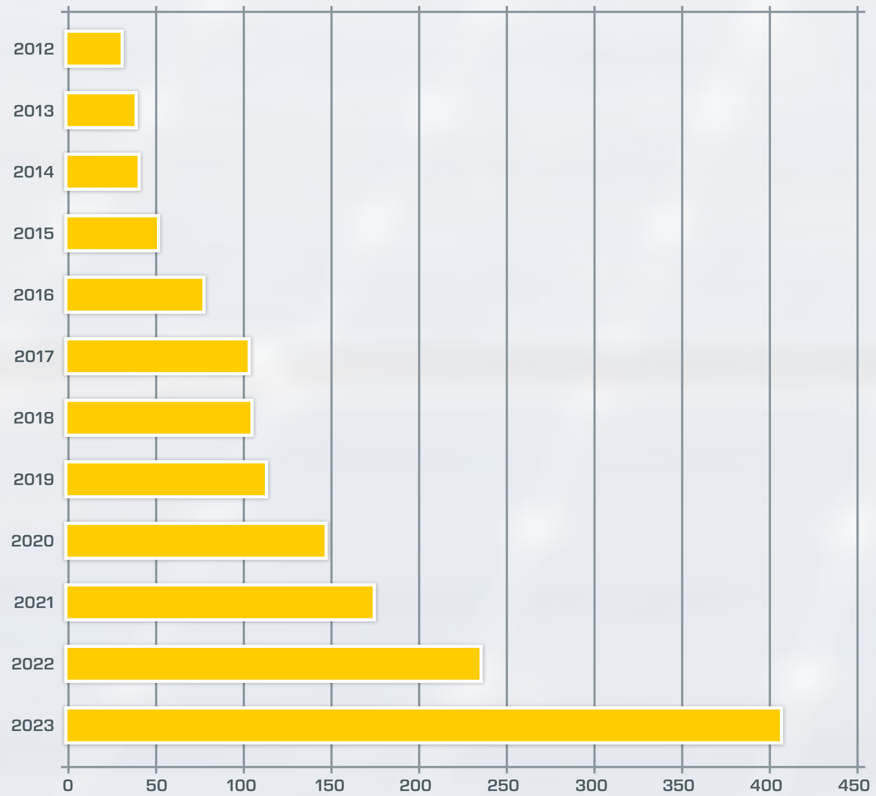
Inside the sun fusion processes lead to temperatures of up to 15 · 10^6 K. However, the spectrum of emitted sunlight is based on processes in the outer layers of the sun. The spectral composition can be described theoretically by a so-called black body with a surface temperature of 5777K.

On its way to the earth's surface, the solar radiation is weakened in the atmosphere by scattering and absorption.

Basic knowledge
Photovoltaics

The energy payback period is the time it takes for a photovoltaic system to generate as much energy as was consumed for its production, installation and maintenance. According to the IEA (International Energy Agency), this period was around 1 to 1,3 years in Europe in 2023.

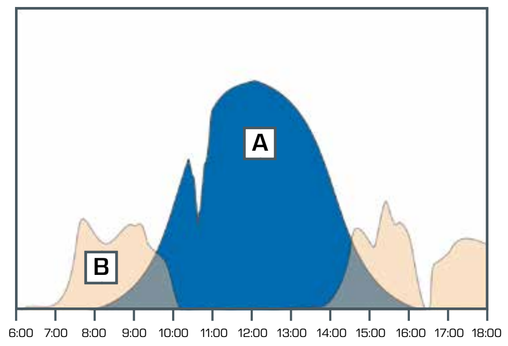
By the end of 2023, systems with a total electrical output of more than 1580 GW had been installed worldwide. As can be seen in the diagram below, the capacity of newly installed systems increased from 236 GWp to more than 400 GWp in 2022 and 2023.



Annual photovoltaic capacity installed worldwide in GWp (source: IEA-PVPS)

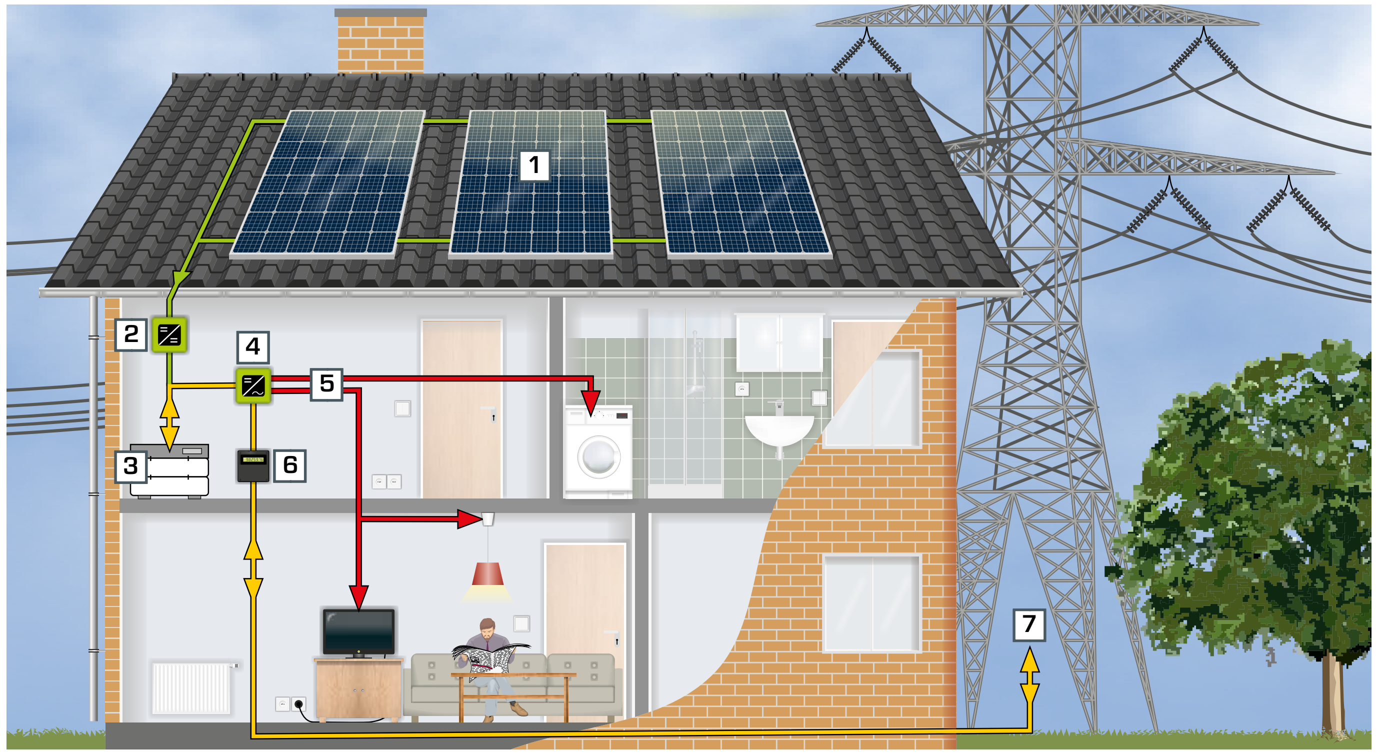
Solar electricity and electricity demand in a residential building

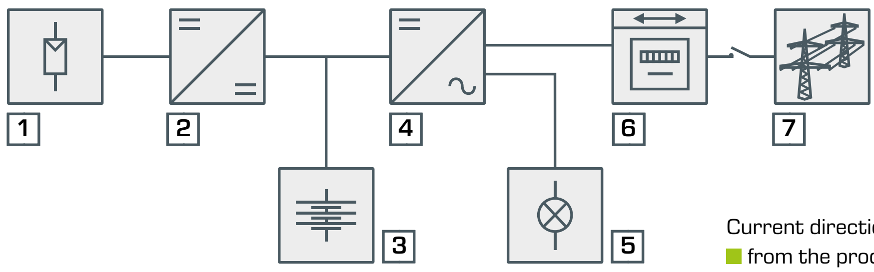
Typical measurement data for the generated solar electricity and the electricity demand of a residential building throughout a day show the need for stored electricity. Only the storage of electricity make it possible to cover the demand in the morning and evening hours.



A electricity generation by photovoltaic modules
B coverage of electricity demand by storages

System components for solar electricity utilisation

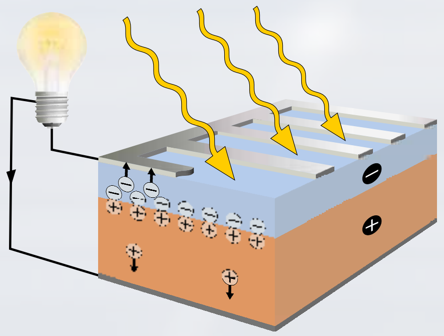




1 photovoltaic modules
2 charge controller
3 electricity storage
4 hybrid inverter
5 consumer
6 bidirectional electricity meter
7 grid connection

Current direction
from the producer · to the consumer · depending on operation

How semiconductor solar cells work



A semiconductor solar cell converts the radiation energy of light into electrical energy. This requires that the absorbed photons have sufficient energy and/or wavelength. An electron can only be released from the bond of the atomic crystal lattice if the absorbed energy in the semiconductor is sufficient. The mobile electron leaves a free space behind in the crystal lattice. This space, known as a hole, has a positive electrical charge and can also move freely in the semiconductor.

In order to be able to use this mobile electrical charge carrier, an electric field is established in the semiconductor by doping it with suitable impurity atoms.

Under the influence of this internal electric field, generated positive and negative charge carriers can be separated in the solar cell. This means it is possible to use the solar cell as a source in an electrical circuit.

Using solar electricity efficiently

In order to collect the photovoltaic solar electricity, 36 (for example) individual solar cells are combined into one single module. The subsequent use of the solar electricity can be divided into different concepts:

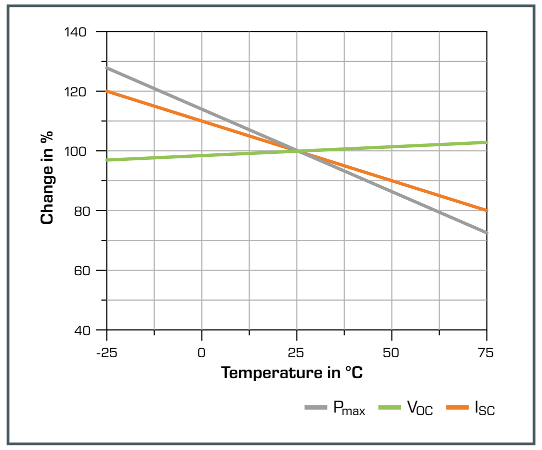
- stand-alone operation
- grid-connected operation
- grid-connected operation with storage

Stand-alone operation is suitable for applications in remote locations with no connection to a public power grid. In this case, some kind of storage is crucial for an uninterrupted electricity supply, in order to also be able to use the electrical energy at night, for example.

Grid-connected photovoltaic installations feed the solar electricity directly into the public grid. This type of setup requires an inverter to convert the direct current of the photovoltaic modules into an alternating current with the appropriate frequency and voltage.

An excess supply of feed-in electricity can cause the public power grid to become unstable. To avoid this effect, there are financial incentives to encourage the private consumption of solar electricity in Germany. Storage systems are added to the necessary grid-connected photovoltaic installations. By skilfully managing consumption and storage load, the proportion of solar electricity that is consumed at the point of generation can be increased considerably.

ET 252
Solar cell measurements



ET 252 is used to analyse the effects of temperature on the solar cell.

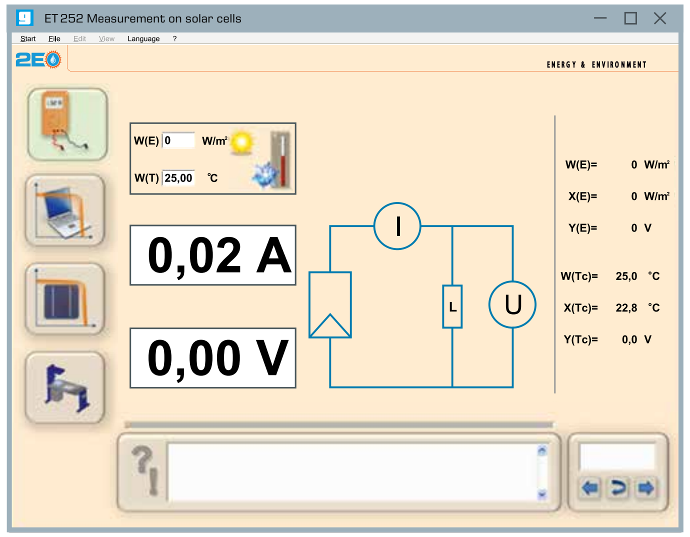
About the product:

ET 252 enables the fundamental relationships of photovoltaics in carefully thought out experiments.

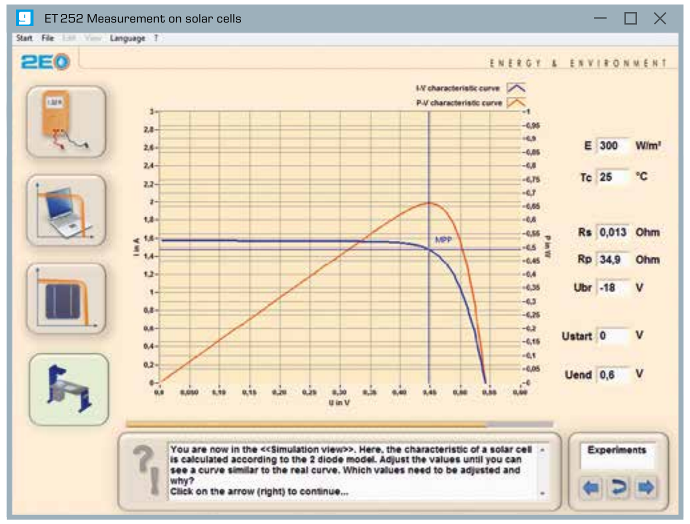
Four solar cells are the main components of the experimental unit. These cells are irradiated with an adjustable lighting unit. A regulated Peltier cooling element selectively controls the temperature of the solar cells. This allows comparative measurements on the influence of temperature on the characteristic variables of the cells.

Software with tutorial function

The extensive GUNT software operates all device functions from an external PC or notebook, via a USB interface. Besides controlling the brightness and temperature, it is also possible to configure the automated measurement of the characteristic curve via the controllable current sink.



The GUNT software includes an integrated tutorial function that aids the introduction to the fundamentals of photovoltaics in didactically balanced steps and that illustrates the device's various measurement capabilities.



In simulation mode, it is possible to study the effects of specific cell parameters on the current/voltage characteristic.

Learning objectives

- physical behaviour of solar cells under varying illuminance and temperature
- plotting of current-voltage characteristics
- calculation of current strength and achievable output based on the single diode model
- how illuminance and temperature affect the characteristics
- interconnection of solar cells in parallel and serial connection
- effect of bypass diodes
- power degradation due to shading

ET 255
Modular solar electricity system with accessories

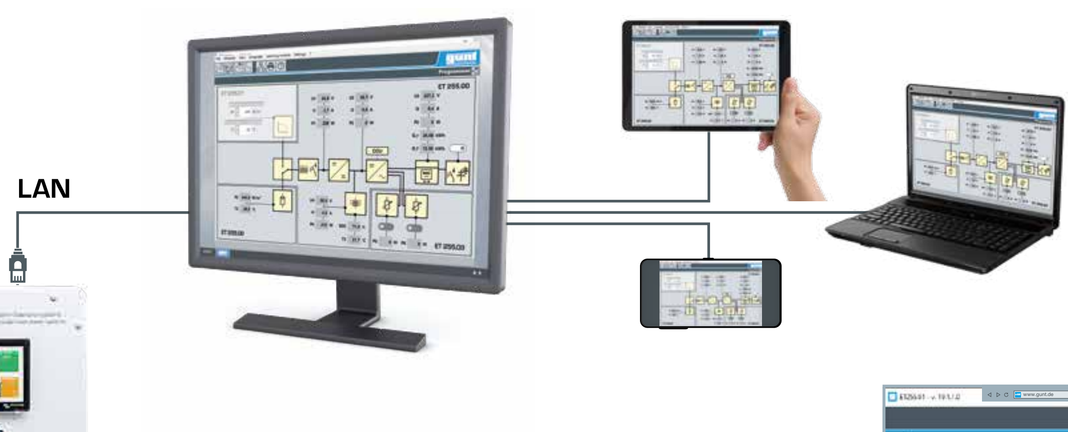
Solar electricity from photovoltaic systems can be used for feeding into a public power grid (grid-connected operation) or for local consumption (stand-alone operation). In modern solar electricity systems, demand and availability-controlled utilisation includes a combination of both operating options. Storage systems and so-called energy management systems are used to control the energy flows.

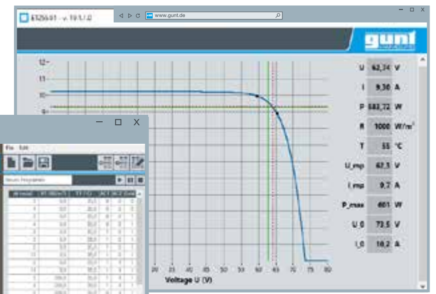
To enable advanced experiments with current components from photovoltaic practice, GUNT offers a system consisting of coordinated experimental components. Together with the accessories, the behaviour of a solar electricity system can be investigated under varying operating conditions.

About the product:

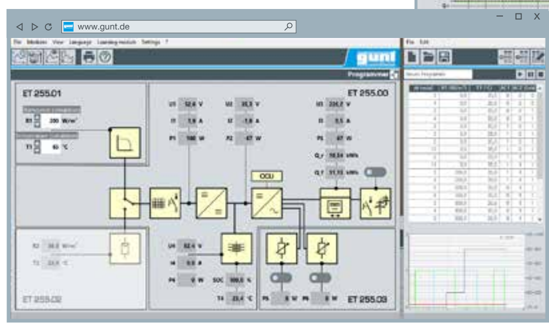
The GUNT software on an external PC is used for operation of the solar electricity system and for recording and displaying the measured values. It is also possible to control experiment sequences with defined generation and consumption profiles.

The network-capable GUNT software makes it possible to follow and analyse the experiments at any number of workstations via a LAN/WLAN connection to the local network.





Simulated characteristic curve



System diagram with programme generator

Learning objectives

- investigate components of modern systems for use of photovoltaics
- performance optimisation through maximum power point tracking
- function of inverters and charge controllers
- operating behaviour with varying illuminance and temperature
- efficiency and dynamic behaviour of system components
- energy management systems for optimising self-consumption in grid-connected operation
- battery management systems for the optimised use of storage systems
- use cases with changing grid availability
- experiments with specified generation and consumption profiles

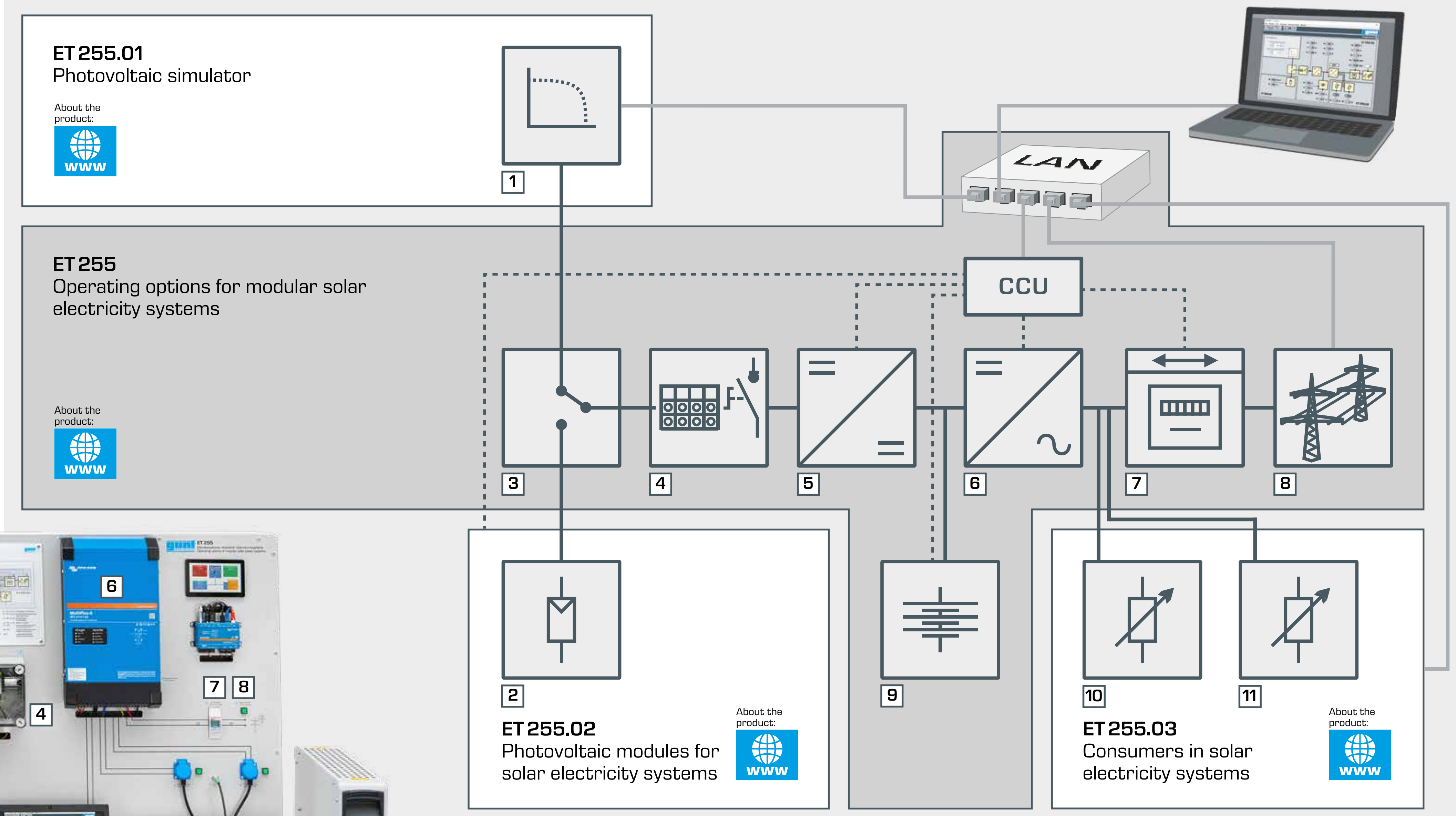
Connected components of a modern solar electricity system with ET 255

Configuration of the complete ET 255 system with accessories

The ET 255 trainer contains networked components of a solar electricity system such as a lithium iron phosphate accumulator as storage, an MPP charge controller, a grid inverter and a bidirectional electricity meter as well as an energy management system (EMS). The energy management system records the energy flows and controls the individual components of the system.

Either the ET 255.01 photovoltaic simulator or the photovoltaic modules ET 255.02, serve as the solar electricity source. To ensure sufficient illuminance, the trainer should be operated with sunlight or the optionally available HL 313.01 artificial light source.

ET 255.03 contains two controllable electrical consumers that are prioritised differently when supplied by ET 255.



1 photovoltaic simulator ET 255.01
2 photovoltaic modules ET 255.02
3 toggle switch
4 circuit breaker and overvoltage protection
5 MPP charge controller
6 grid inverter
7 bidirectional electricity meter
8 grid connection
9 storage
10 adjustable AC-consumer 1 ET 255.03
11 adjustable AC-consumer 2 ET 255.03

The trainer is controlled via the GUNT software on an external PC (not included), which is connected via a network interface. Data from the grid inverter, the bidirectional electricity meter, the battery management system of the storage system, the MPP charge controller and the photovoltaic modules are recorded in the central communication and control unit (CCU).

ET 250
Photovoltaic modules measurements

With this trainer, all key aspects in the operation of photovoltaic modules can be practically demonstrated. ET 250 has two photovoltaic modules. The modules can be connected either in series or in parallel. The tilt angle of the modules can be adjusted individually. A measuring unit is provided for the experiments, which clearly displays all relevant measured values. Current-voltage curves can be created from the measured values. These characteristic curves are an important criterion for assessing the capacity of a photovoltaic system.

About the product:

For laboratory experiments under uniform light conditions, we recommend our **artificial light source HL 313.01**.

About the product:

This light source can be used to create reproducible experimental conditions indoors. The light source contains eight halogen spotlights, arranged in two rows. The inclination angle of each halogen spotlight can be adjusted to conduct the respective experiment with incident light that is as perpendicular as possible.

Learning objectives

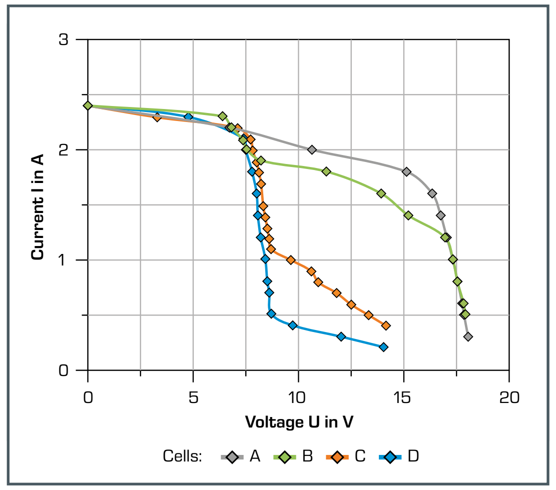
- physical behaviour of photovoltaic modules under varying illuminance, temperature and shading
- familiarisation with key characteristic variables such as short-circuit current, open-circuit voltage and maximum output
- plotting current-voltage curves in parallel and series connection
- influence of the inclination of the photovoltaic modules
- determining the efficiency

Components and accessories

1 slide resistor as a variable load
2 measuring amplifier
3 inclinometer
4 temperature sensor
5 illuminance sensor
6 pivotable photovoltaic modules

Experiments in shading

In many places, shading is a major cause of yield losses. ET 250 is also designed for specific experiments on this effect. The results can be compared with documented reference experiments.



Current-voltage curves for shading of individual cells

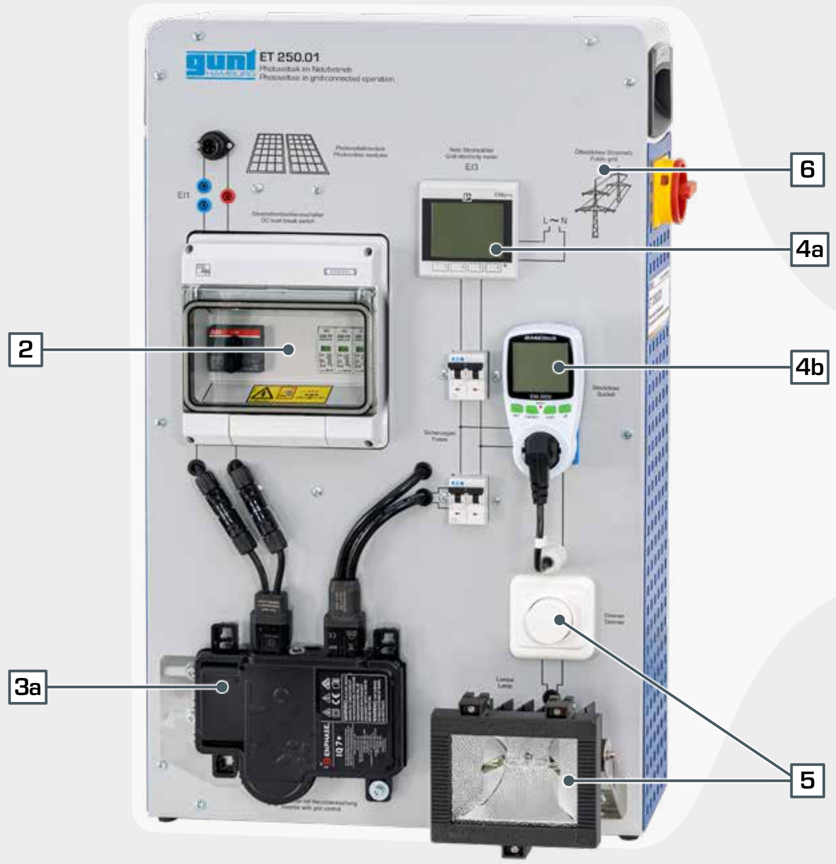
Shading due to clouds

ET 250.01
Photovoltaic in grid-connected operation

ET 250.01 is designed as an extension module for ET 250 and allows to meaningfully supplement the learning content of ET 250. This experimental unit contains practical components from the field of photovoltaics which are needed to use the solar electricity when connected to a public grid. The inverter with maximum power point tracking works in line-commutated mode and varies current and voltage for maximum output of the photovoltaic modules. The quantities of electricity withdrawn or fed in are recorded via a modern bidirectional electricity meter.

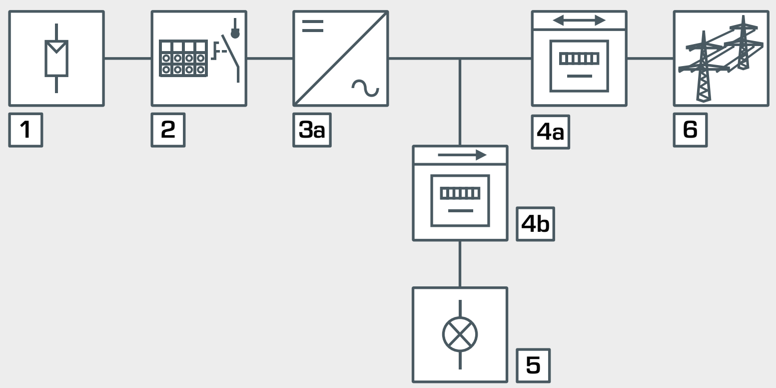
About the product:

WWW



ET 250.01 Photovoltaic in grid-connected operation

ET 250 Photovoltaic modules measurements

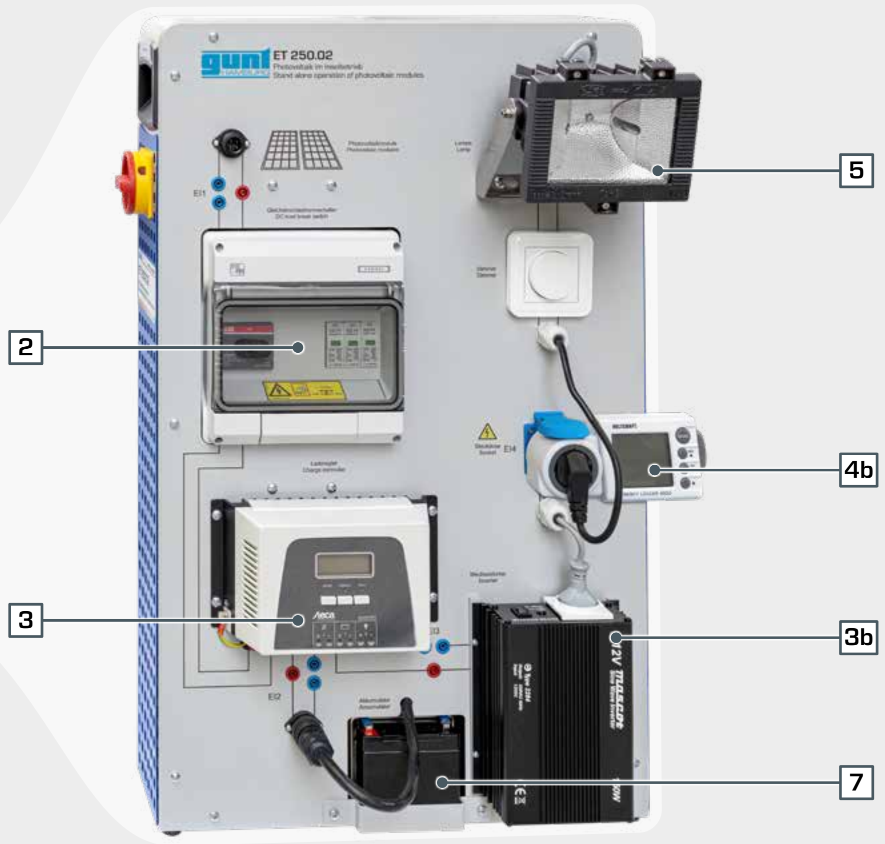


ET 250.02
Stand-alone operation of photovoltaic modules

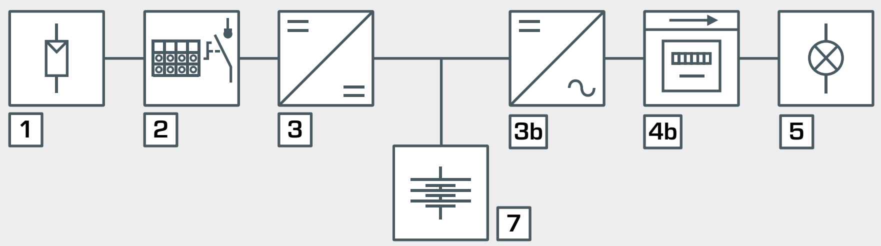
ET 250.02 is another extension module for ET 250. The unit allows to teach key aspects of solar electricity use in stand-alone systems. ET 250.02 contains all the necessary components: The charge controller with maximum power point tracking monitors the voltage of the accumulator and optimises the operating point of the photovoltaic modules. Simpler inverters can be used in stand-alone operation, since monitoring of the mains voltage is not necessary.

About the product:

WWW



ET 250.02 Stand-alone operation of photovoltaic modules



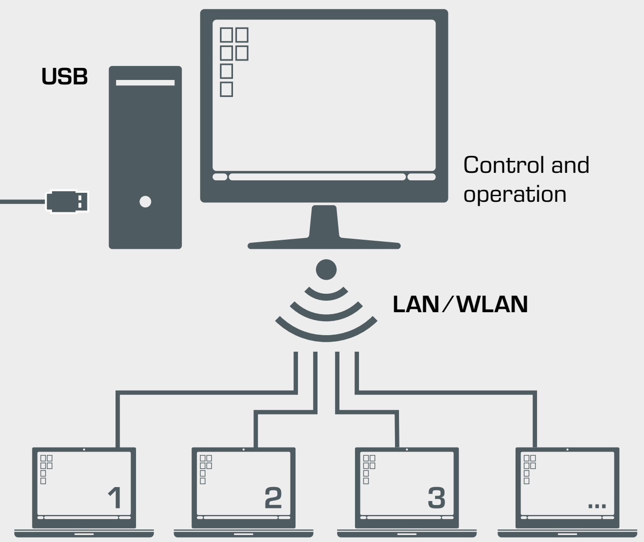
1 photovoltaic modules from ET 250
2 circuit breaker and overvoltage protection
3 charge controller with maximum power point tracking
3a line-commutated inverter with maximum power point tracking
3b simple inverter
4a bidirectional electricity meter grid feed
4b electricity meter own consumption
5 halogen lamp with dimmer
6 grid feed
7 accumulator as storage

Learning objectives

- components from the field of solar electricity usage
- function of direct current switch disconnector and voltage surge protection
- function of charge controllers and inverters
- effect of load on the efficiency of the components
- effect of fluctuations in solar energy supply and electricity consumption on system efficiency
- function of modern electricity meters
- energy balance in stand-alone and grid-connected operation

ET 256
Cooling with solar electricity

- compression refrigeration system for operation with photovoltaic modules from ET 250, ET 255.02 or with ET 256.01 Laboratory power supply
- control unit starts the compressor as soon as sufficient electrical power is available from the photovoltaic modules
- long cooling time due to cold accumulators and insulation
- network capable GUNT software for controlling and balancing energy flows



GUNT software for controlling the device and for measurement data acquisition via PC

Learning objectives

- supply a compression refrigeration system with current from photovoltaic modules
- components of a photovoltaic refrigerating plant
- operation of the compressor with changing power supply and cooling demand
- charge and discharge of cold accumulators
- coefficient of performance of the refrigerating plant dependent on operating conditions
- refrigeration cycle in the log p-h diagram
- energy flow balance

The ET 256 experimental unit contains a refrigeration chamber that is cooled by a typical compression refrigeration circuit. As a special feature, via a control unit it is possible to supply the reciprocating compressor directly with electricity from the photovoltaic modules of ET 250 or ET 255.02. Alternatively, the unit can be supplied with power via the ET 256.01 Laboratory power supply unit.

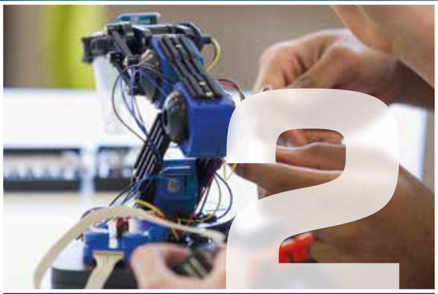
About the product:

WWW

The complete GUNT programme

Engineering mechanics and engineering design

- statics
- strength of materials
- dynamics
- machine dynamics
- engineering design
- materials testing



Mechatronics

- engineering drawing
- cutaway models
- dimensional metrology
- fasteners and machine parts
- manufacturing engineering
- assembly projects
- maintenance
- machinery diagnosis
- automation and process control engineering

Thermal engineering

- fundamentals of thermodynamics
- heat exchangers
- thermal fluid energy machines
- internal combustion engines
- refrigeration
- HVAC

Fluid mechanics

- steady flow
- transient flow
- flow around bodies
- components in piping systems and plant design
- turbomachines
- positive displacement machines
- hydraulic engineering

Process engineering

- mechanical process engineering
- thermal process engineering
- chemical process engineering
- biological process engineering
- water treatment

2E Energy & Environment

Energy

- solar energy
- hydropower and ocean energy
- wind power
- biomass
- geothermal energy
- energy systems
- energy efficiency in buildings

Environment

- water
- air
- soil
- waste

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