

Thermodynamic Aspects of Increasing Energy Efficiency in Solar Energy

Khabibillo Pakhirdinov

Andijan State Technical Institute

Assistant of the Department of Civil Engineering and Architecture
3rd year building and structure construction direction Group K-60-23
student Islamova Madinabonu Toshtemir kizi

Abstract. In this article, the importance of the laws of thermodynamics in the use of solar energy is analyzed. The process of converting solar radiation into thermal energy is explained on the basis of the law of conservation of energy and the concept of entropy. The operating principles of solar collectors and photovoltaic panels are considered from a thermodynamic point of view. Attention will also be paid to methods of increasing energy efficiency, reducing heat losses, and the rational use of renewable energy sources. The research results show that thermodynamics is an important scientific basis for the development of solar energy.

Keywords: Solar energy, Thermodynamics, Alternative energy, Energy efficiency, Thermal energy, Electrical energy, Entropy, Energy cycle.

Introduction

Currently, the demand for energy resources on a global scale is sharply increasing. Population growth, the expansion of industrial production, and technological progress contribute to increased energy consumption. At the same time, the depletion of traditional fuel sources and environmental problems are forcing humanity to search for alternative energy sources.[1]

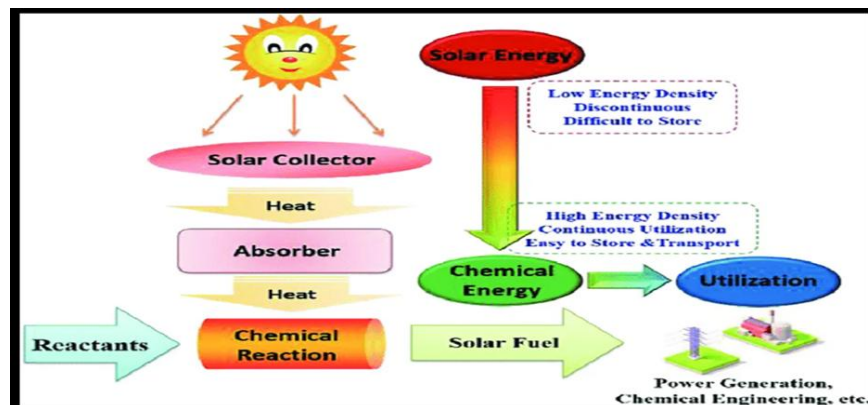
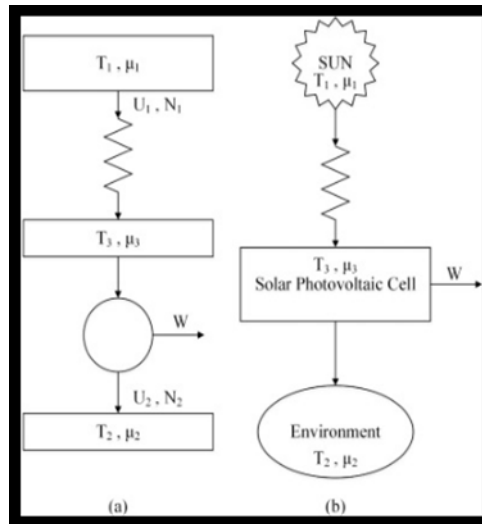


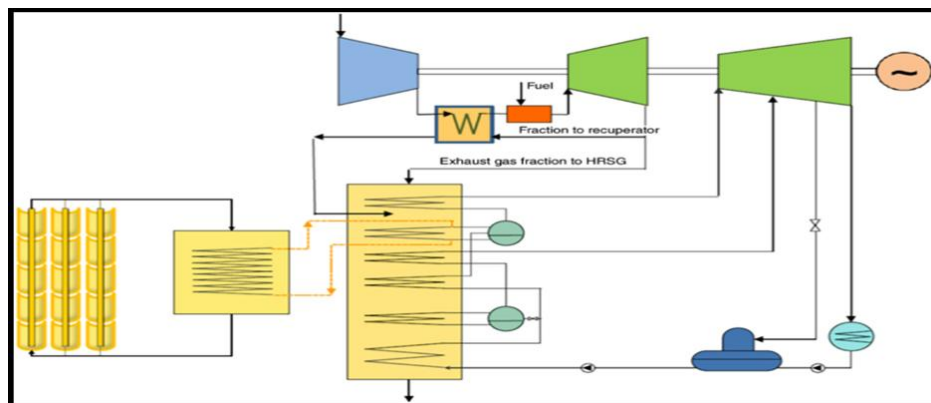
Figure 1. Technological scheme for converting solar energy into chemical energy.

Among renewable energy sources, solar energy is considered the most promising and environmentally friendly. A huge amount of energy reaches the Earth's surface from the Sun every year. The efficient use of this energy is one of the important directions of modern energy.[2]



Picture 2. Thermodynamic diagram of the operation of a heat engine (a) and a solar photovoltaic cell (b).

- T_1, μ_1 – Sun (high-temperature source);
- T_3, μ_3 – Solar photovoltaic cell (absorbing layer);
- T_2, μ_2 – Environment (low-temperature heat receiver);
- W (Work) – useful work or generated electricity;
- T, μ – Temperature and chemical potential at the corresponding stages.



Picture 3. Diagram of the combined (hybrid) thermodynamic cycle of a solar and gas turbine.

On the left (Sun part):

Solar collectors (parabolic trays): Solar energy storage devices.

Heat exchanger (Yellow square): A unit that transfers heat from the sun to the main cycle.

Above (Gas turbine section):

Compressor (Blue cone): A device for compressing air.

Combustion chamber (part labeled Fuel): A place where fuel burns and heat is released.

Gas turbine (Green cone): A component that converts thermal energy into mechanical work.

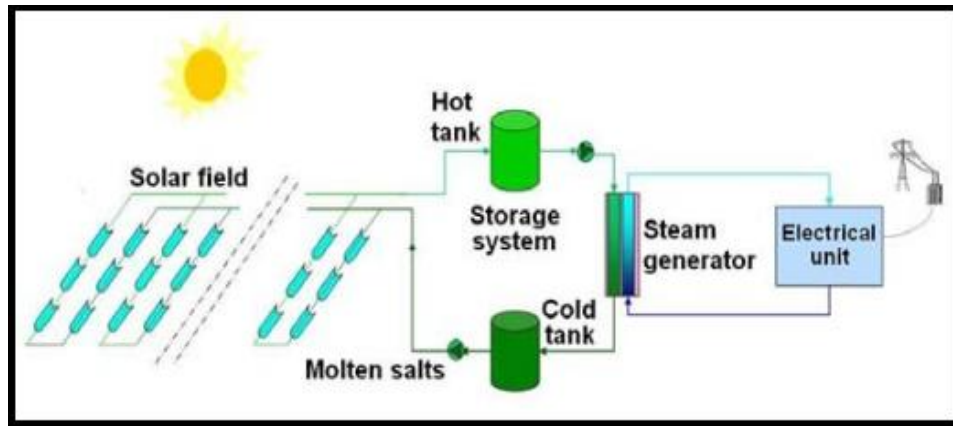
Generator (Right edge circle): A device that generates electricity.

Center and bottom (Heat recovery):

HRSG (Heat Utilization Boiler): A vertical unit that generates steam using the hot gases exiting the turbine.

Recuperator (symbol W): A device for the recirculation of heat.

Pump and Condenser (Bottom Parts): Water circulation and cooling system.



Picture 4. Technological scheme of a solar thermal power plant with a heat storage system.

Solar field — Solar field (collector field).

Molten salts — Dissolved salts (heat-carrying fluid).

Storage system — storage (accumulator) system.

Hot tank — A hot reservoir (for salt).

Cold tank — A cold reservoir (for salt).

Steam generator.

Electrical unit — Electrical unit (turbine and generator).

In explaining the scientific basis of solar energy, the science of thermodynamics is of great importance, and the laws of thermodynamics are the main scientific basis for the use of solar energy. Scientists around the world explain this process mainly through the 1st law (justification of energy) and the 2nd law (entropy and efficiency threshold).[3]

John A. Duffie - a famous American scientist in the field of solar energy, in his book "Solar Engineering of Thermal Processes," emphasizes that the calculation of the energy balance in solar energy systems is carried out on the basis of the first law.

Sunlight → heat → mechanical energy → electrical energy.

Frank Kreith is a renowned American engineer-scientist who has made significant contributions to the fields of thermal engineering, thermodynamics, and renewable energy.[4]

It was shown that energy balance equations are used in calculating the efficiency of solar collectors.

Each solar installation is analyzed through incoming and outgoing energy flows.

Methodology

According to research by the International Energy Agency: The law of conservation of energy flows is the main computational model for assessing the performance of solar energy systems.[5]

The First Law of Thermodynamics and Solar Energy

The first law of thermodynamics is called the law of conservation of energy, that is, energy does not disappear, but only passes from one form to another. According to this law:

$$Q = \Delta U + A$$

here

Q - heat energy supplied to the system;

ΔU - change in internal energy;

A - completed work.

In solar energy systems, this law explains the process of converting solar radiation into thermal energy.[6]

The Second Law of Thermodynamics and Energy Losses

The second law of thermodynamics shows the existence of losses in energy conversion processes.

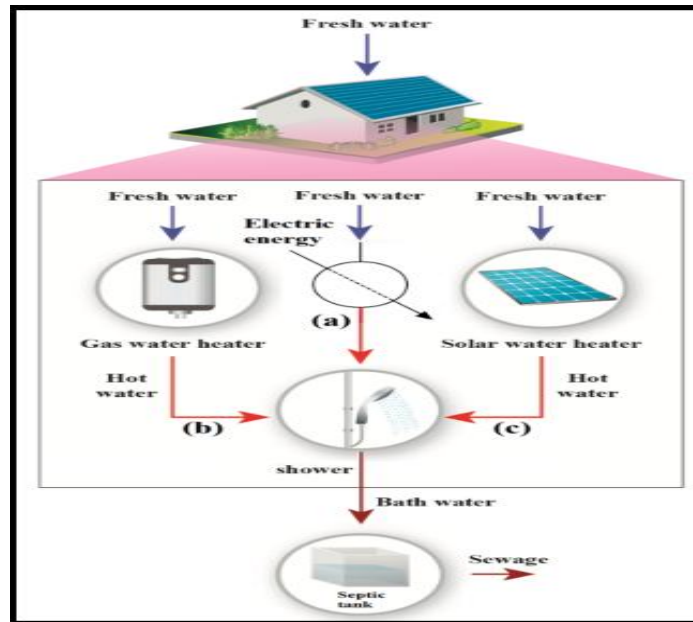
This law is expressed by the following equation:

$$\Delta S \geq 0$$

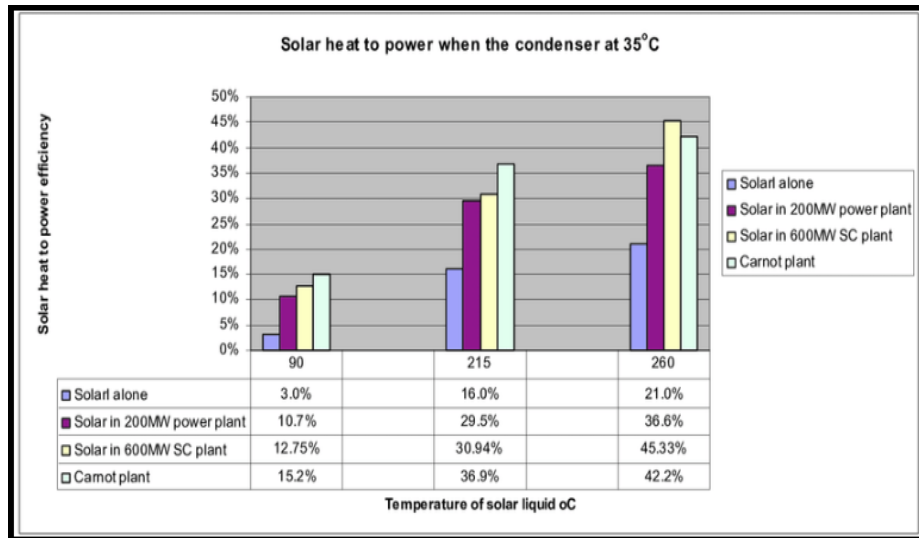
where S is entropy.

In solar energy systems: processes such as heat losses, efficiency of electricity conversion, and heating of devices are explained by this law.

The Picture 5. second law of thermodynamics shows that energy cannot be fully converted into useful work. This limits the maximum efficiency of solar energy installations.[7]



Picture 5. Hot water supply scheme for a residential building based on solar and traditional energy sources.



Picture 6. The change in system efficiency depending on the temperature of the solar coolant at a capacitor temperature of 35°C.

Solar heat to power efficiency — The efficiency of converting solar heat into electricity.

Temperature of solar liquid °C — The temperature of the solar thermal fluid, °C.

Solar alone — Only the solar installation itself.

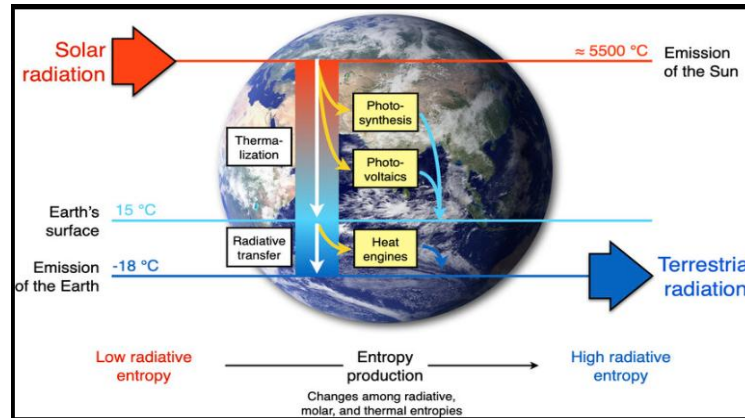
Solar in 200MW power plant — a solar system integrated into a 200 MW power plant.

Solar in 600MW SC plant is a solar system integrated into a 600 MW ultra-critical (SC) station.

Carnot plant — Carnot cycle (theoretical maximum efficiency).

Thermodynamic analysis:

Efficiency increases with increasing temperature. This proves that, according to the Picture 7. second law of thermodynamics (Carnot's theorem), the higher the temperature of the working fluid, the higher the maximum efficiency of the system.



Picture 7. Diagram of solar energy transformation and entropy increase in the Earth's atmosphere.

Top and right:

Solar radiation – Solar radiation.

Emission of the Sun (~5500 °C) – the temperature of the Sun's radiation.

At the Center (Energy Processes):

Photo-synthesis – Photosynthesis (accumulation of biological energy).

Photo-voltaics – Photovoltaics (production of electrical energy).

Heat engines – Heat engines (mechanical work).

Thermalization – Thermal equilibrium.

Radiative transfer – Energy transfer through radiation.

Temperature lines:

Earth's surface (15 °C) – The average temperature of the Earth's surface.

Emission of the Earth (-18 °C) – The effective radiation temperature of the Earth.

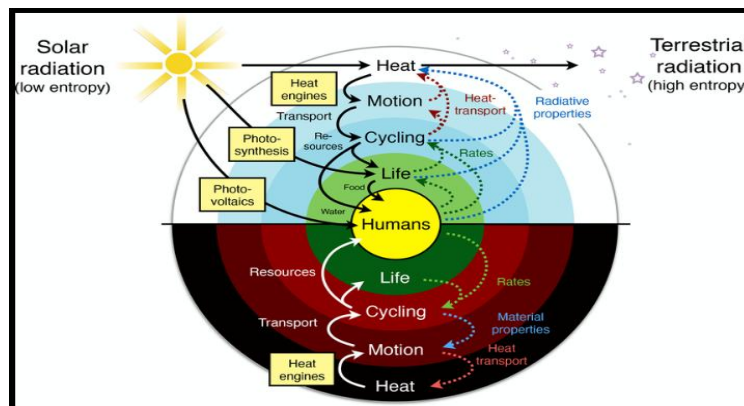
Terrestrial radiation – Earth's thermal radiation (flow returning to space).

Below (Thermodynamic concepts):

Low radiative entropy – Low radiation entropy (ordered energy).

Entropy production – The formation of entropy (an increase in disorder).

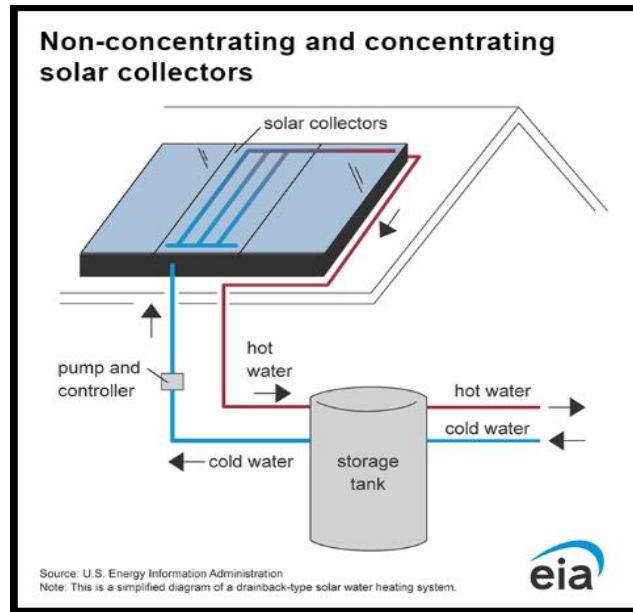
High radiative entropy (s).



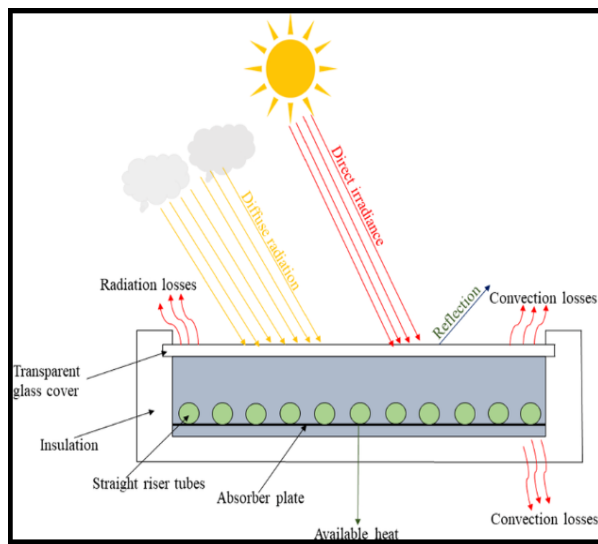
Picture 8. A diagram of the relationship between energy flows, the cycle of matter, and human activity in the Earth's system.

Results and Discussion

The Picture 9. second law of thermodynamics shows that energy cannot be fully converted into useful work. This limits the maximum efficiency of solar energy installations.[8]

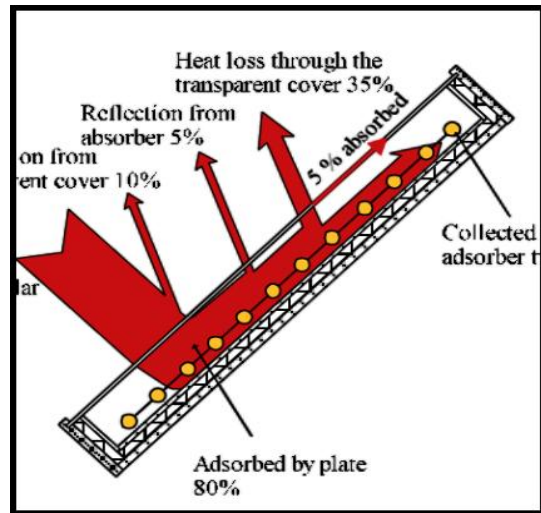


Picture 9. Scheme for converting solar energy into thermal energy and transmitting it.



Picture 10. Diagram of heat balance and energy losses in a flat solar collector.

The Picture 10. illustrates the first law of thermodynamics (the law of conservation of energy): radiation from the sun (Direct/Diffuse radiation) is converted into useful heat (Available heat), and some of it is released into the environment through radiation losses (Radiation losses), convection losses (Convection losses), and reflection (Reflection).



Picture 11. Balance of energy distribution and losses in the solar collector (in percent).

This scheme expresses the law of conservation of energy in terms of numbers.

Total incoming solar energy is distributed as follows:

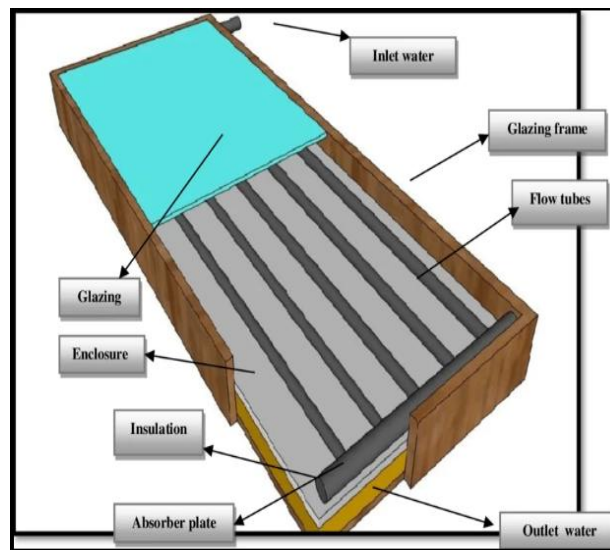
80% is the energy absorbed by the plate (the useful part).

10% - Radiation reflected from a transparent coating.

5% - radiation reflected from the absorber (absorber).

35% - Total heat loss through the transparent coating.

Note: In the Picture, the sum of the percentages can exceed 100, which means that different physical processes (radiation and convection) are calculated separately.



Picture 12. Structural design and main elements of a flat solar collector.

This Picture shows the parts required to control thermal conductivity and convection.

Physical process: The transparent coating allows radiation to penetrate, creating a "greenhouse effect," while the insulation prevents heat from escaping through the conduction (processes related to the 2nd law of thermodynamics).

Principle of operation of solar collectors.

The main function of solar collectors is the conversion of solar radiation into thermal energy. This process is based on the laws of heat transfer and energy exchange.

Process steps

Energy exchange in a solar collector occurs in the following sequential processes:

1. Sunlight falls on the absorber plate.
2. The absorber plate heats up.
3. The resulting heat is transferred to the heat carrier liquid.

4. The heated liquid becomes an energy carrier and moves through the system (for example, to a hot water supply or heating system).

These processes are mathematically expressed through the laws of heat transfer.

The Table 1. main function of solar collectors is the conversion of solar radiation into thermal energy.

The process consists of the following steps:

1. Sunlight falls on the absorber plate.
2. The plate heats up.
3. Heat is transferred to the liquid.
4. The heated liquid becomes an energy carrier.

This process is described by heat transfer equations.[9]

$$Q = kA(T_1 - T_2)$$

This is the heat transfer equation, where the symbols mean:

The Table 1. main function of solar collectors is the conversion of solar radiation into thermal energy.

Sign	Meaning	Unit of measurement
Q	Amount of heat supplied	W(vatt) or J/S
k	Heat transfer coefficient (property of material or system)	W/(m ² · K)
A	Area of the heat exchange surface	m ²
T ₁	Temperature on the hot side	°C or K
T ₂	Temperature on the cold side	°C or K
(T ₁ - T ₂)	Temperature difference	°C or K

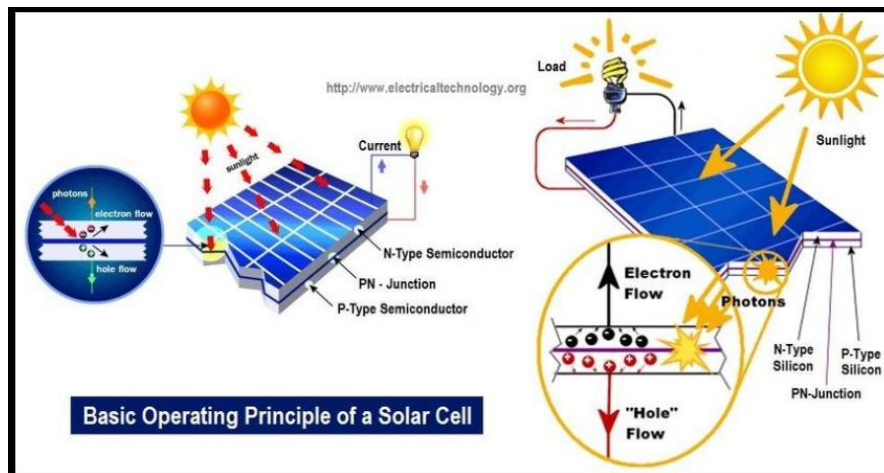
Physical content

This equation shows the following: When the Picture 13. temperature difference is large, heat transfer is greater, when the heat exchange surface area is large, more heat is transferred, when the heat transfer coefficient of the material is large, heat is transferred faster. Therefore, in modern solar collectors, the absorber plate is made of materials with high thermal conductivity, and the collector surface is designed to absorb maximum solar radiation.

Example. If: k=5, W/(m² · K), A=2 m², T₁=80°, T₂=30°C :

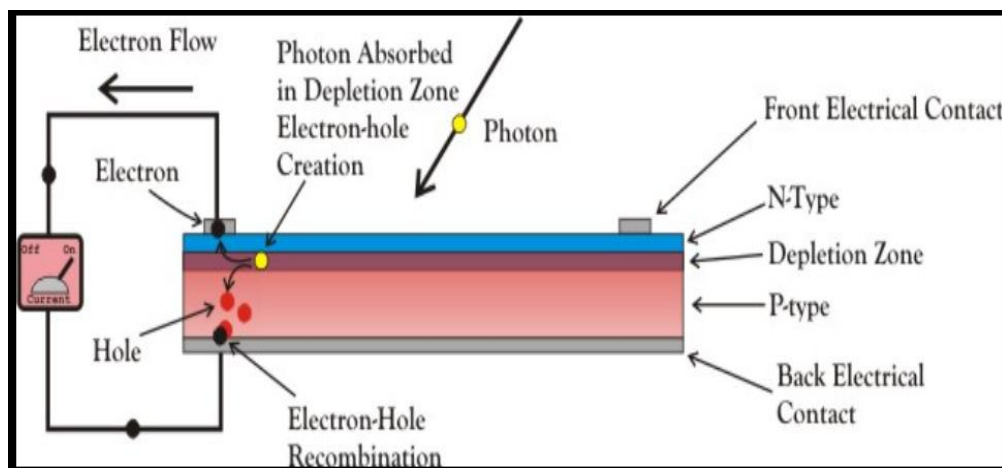
Q = 5 × 2 × (80 - 30) = 500 W. Therefore, 500 watts of heat are transferred.

1. Principle of operation of photovoltaic panels



Picture 13. The operating principle of a solar cell and the process of photoelectric conversion.

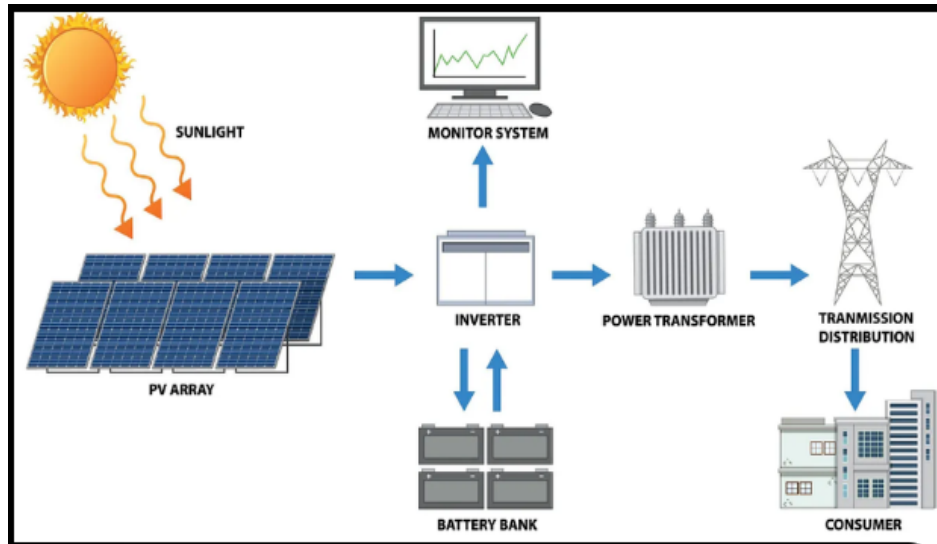
The Picture 14. shows the conversion of radiation energy (photons) into electrical energy. From a thermodynamic perspective, this process is associated with the Shockley-Quisser boundary (theoretical efficiency limit) and is crucial for explaining entropy changes and irreversible energy losses within the system.



Picture 14. Diagram of quantum processes in the p-n junction region of a solar cell.

Description from a thermodynamic perspective:

This Picture 15. image is very useful for explaining electron-hole recombination, an irreversible process related to the second law of thermodynamics. As a result of recombination, energy is released as heat rather than being converted into useful electricity, which reduces the overall efficiency (KPI) of the system.



Picture 15. General operation and energy distribution scheme of a photovoltaic plant.

Relation to thermodynamics:

This Picture shows the systematic application of the laws of thermodynamics. In the article, this image can be commented on as follows:

In the process of converting energy from one type to another (solar -> electric -> chemical (battery) -> electric), thermodynamic losses occur at each stage (inverter, transformer, power lines). The total efficiency of the system depends on the efficiency of all its components.

Photoelectric panels (solar panels) are devices that convert sunlight directly into electrical energy. This process is carried out on the basis of the photoelectric effect. The photoelectric effect was theoretically explained by Albert Einstein in 1905, and for this scientific work he received the Nobel Prize in 1921.

Solar panels consist mainly of photocells made of semiconductor materials (often silicon).[10]

Stages of the photoelectric process

The process of energy generation in solar panels consists of the following stages:

1. Sunlight falls on the panel surface
Light from the Sun consists of a stream of photons, which collide with the surface of the photocell.
2. The energy of a photon excites electrons.

The energy of a photon excites electrons in the atoms of a semiconductor, and they are released from the atom.

3. Electrons and holes are formed.

After the release of an electron, an electron-hole pair is formed in the semiconductor structure.

4. the p-n junction creates an electric field.

The solar cell contains p-type and n-type semiconductor layers, at the boundary of which an internal electric field arises.

5. Electric current is generated.

An internal electric field Table 2. moves electrons along an external circuit, resulting in a direct current (DC).

Table 2. Photoelectric effect equation[11]

$$E = h \cdot \nu$$

Here:

Sign	Meaning	Unit of measurement
E	photon energy	Joule (J)
h	Planck's constant	$6,626 \cdot 10^{-34} J \cdot s$
ν	frequency of light	Hz(1/s)

ν (ν) is a Greek letter that often resembles the letter v , but actually denotes frequency.

So, the formula gives $E = h \times \nu$.

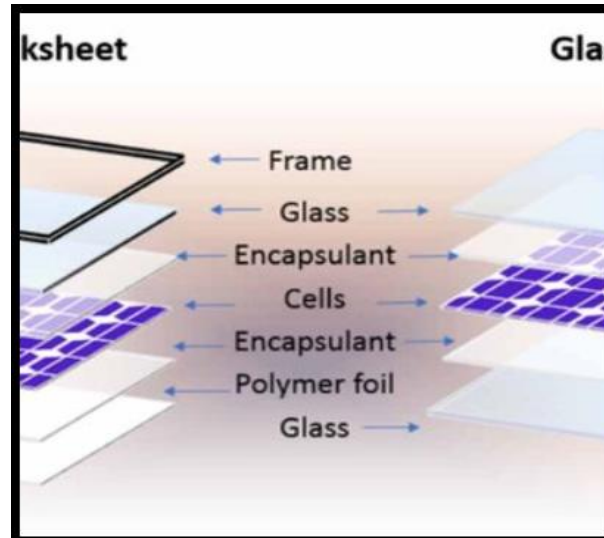
This equation shows that the energy of a photon must be sufficient to knock an electron out of the atom.

Frequency is often expressed in terms of wavelength. In this case, the Picture 16. formula is written as follows:

$$E = \frac{hc}{\lambda}$$

Here: s - speed of light, λ - wavelength.

Main parts of the solar panel



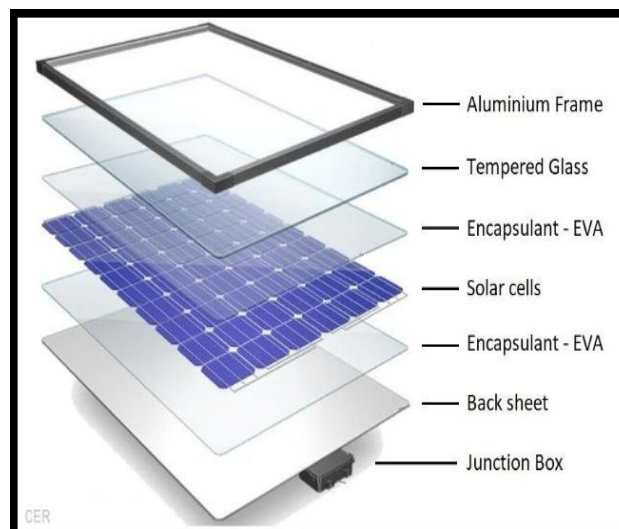
Picture. 16. Multilayer structure and components of a solar panel.

Relation to thermodynamics:

From a thermodynamic perspective, this Picture is very important because:

1. Heat exchange: Layers (glass, EVA, polymer) must effectively remove heat from the solar cell, as the panel's efficiency decreases as the temperature increases.

2. Entropy protection: Insulation and sealing (Encapsulant) protects against negative environmental influences (moisture, oxidation) and slows down system degradation (increased clutter).



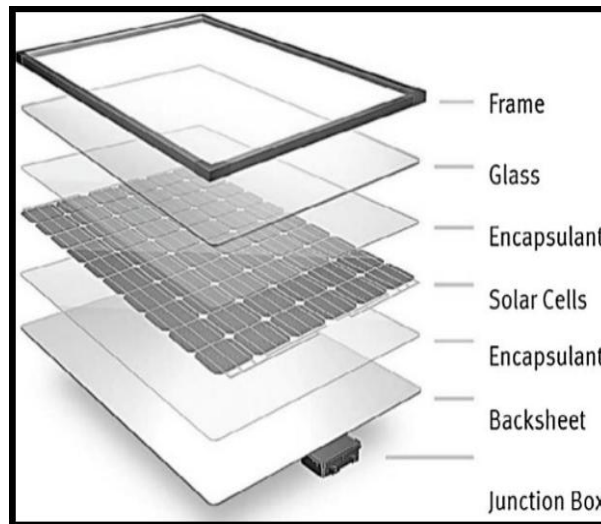
Picture. 17. Layered structure and structural elements of the photovoltaic module.

Relationship between thermodynamics and design:

In the article, you can comment on this image as follows:

The layered structure of the panel serves not only for protection but also for thermal management. For example, an aluminum frame serves as a heat spreader (radiator), which prevents overheating of elements

in thermodynamic processes and helps maintain efficiency

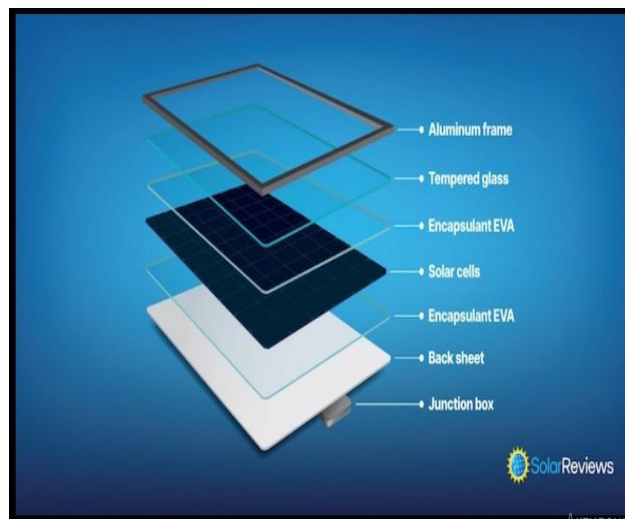


Picture. 18. Layered structure and structural elements of the photovoltaic module.

Relationship between thermodynamics and design:

In the article, you can comment on this image as follows:

The layered structure of the panel serves not only for protection but also for thermal management. For example, an aluminum frame serves as a heat spreader (radiator), which prevents overheating of elements in thermodynamic processes and helps maintain efficiency.



Picture. 19. Modern design and components of a solar panel.

Commentary on the topic of thermodynamics:

Each layer shown in this image (especially Encapsulant EVA and Back sheet) plays an important role in managing the heat inside the panel. According to the laws of thermodynamics, the lower the operating temperature of the panel, the higher its energy efficiency. These structural elements serve to ensure the efficient dissipation of heat into the environment.

Solar panels (photovoltaic modules) are complex multilayer devices that convert solar radiation into electrical energy. They consist of several important structural elements, each of which ensures the efficiency, strength, and longevity of the panel.[12]

Main parts of the solar panel.

Solar panels consist of several basic elements:

1. Protective glass - transmits sunlight and protects elements.
2. Photocells (solar cells) - convert energy into electricity.
3. Electrical contacts - transmit current to the external circuit.
4. Backsheet - performs the function of mechanical protection.
5. Frame (aluminum) - firmly holds the panel.

Solar panel performance

The Table 3. effectiveness of solar panels depends on the following factors: type of semiconductor material, solar radiation intensity, panel temperature, angle of incidence of light, type of technology.[13]

Table 3. Performance typically

Panel Type	Efficiency
Monocrystalline silicon	18–25 %
Polycrystalline silicon	15–20 %
Thin-layer panels	10–15 %

In recent scientific research, the following high-performance panels are being developed: perovskite solar cells, tandem solar cells, multi-junction cells.

Photoelectric panels are one of the most efficient technologies that directly convert solar energy into electricity. Their operation is based on the photoelectric effect, semiconductor physics, and electric fields. Modern scientific research is aimed at increasing panel efficiency and reducing energy losses.

In solar panels, electrical energy is generated by the photoelectric effect.

Progress:

1. Light with a photon falls on a semiconductor.
2. The electron is released.
3. Electric current is generated, resulting in panel efficiency typically around 15-25%.

Solar thermal power plants

Solar radiation is concentrated in solar thermal power plants.

Process: sunlight → high temperature → steam → turbine → generator → electricity

This process works on the basis of the Carnot cycle.

Methods of increasing energy efficiency

The following technologies are used to increase the efficiency of solar energy systems:

- selective absorber coatings
- vacuum collectors
- cooling systems
- energy storage systems
- intelligent control systems[14]

Modern solar technologies

Currently, the following new technologies are used in solar energy:

- Perovskite solar cells
- Bifacial solar panels
- Floating solar plants
- AI-based energy management

These technologies dramatically increase energy efficiency.

Energy-saving technologies

Storage of solar energy is carried out through the following systems:

- Heat accumulators
- dissolved salt systems
- lithium-ion batteries[15]

Conclusion

The laws of thermodynamics are an important scientific basis for the efficient use of solar energy. By deeply analyzing the processes of energy conversion, it is possible to increase the efficiency of solar installations. The application of modern materials and technologies allows for the creation of energy-saving systems. In the future, solar energy will play an important role in solving global energy problems.

References

- [1] Law of the Republic of Uzbekistan, "On the use of renewable energy sources," Tashkent, 2019.
- [2] "Uzbekistan – 2030 Strategy," Tashkent, 2023.
- [3] Academy of Sciences of Uzbekistan, Collection of scientific research on energy problems. Tashkent:

Academy of Sciences Publishing House, 2021.

[4] Tashkent State Technical University, Collection of scientific articles on renewable energy sources. Tashkent: TDTU Publishing House, 2022.

[5] Andijan State Technical Institute, Scientific research on energy efficiency and renewable energy sources. Andijan: ADTI Publishing House, 2023.

[6] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes. Wiley, 2013.

[7] F. Kreith and J. F. Kreider, Principles of Solar Engineering. Taylor & Francis.

[8] Y. A. Çengel and M. A. Boles, Thermodynamics: An Engineering Approach. McGraw-Hill Education.

[9] A. Bejan, Advanced Engineering Thermodynamics. Wiley, 2016.

[10] M. A. Green, Solar Cells: Operating Principles, Technology and System Applications. Prentice Hall.

[11] A. Luque and S. Hegedus, Handbook of Photovoltaic Science and Engineering. Wiley.

[12] G. N. Tiwari and S. Dubey, Fundamentals of Photovoltaic Modules and Their Applications. Royal Society of Chemistry.

[13] A. Einstein, "On an heuristic viewpoint concerning the production and transformation of light," Annalen der Physik, 1905.

[14] S. Carnot, Reflections on the Motive Power of Fire. Paris, 1824.

[15] International Energy Agency, World Energy Outlook 2023, 2023.