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Teaching unit:
The Photovoltaic Journey: Capturing the Sun

DiFC - University of Palermo

BIOS4YOU AR 2.0

BIO-INSPIRED STEM TOPICS FOR ENGAGING YOUNG GENERATIONS THANKS TO THE USE OF AUGMENTED REALITY

Project Number: KA220-BW-23-30-126516

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Contents

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General topic of the learning path	The Photovoltaic Journey: Capturing the Sun
Specific name of the learning unit	Energy conversion in solar cells; from photons to electrons; physics of photovoltaic systems
Age of the target users	17–19 years old
Requirements for the learner	Basic knowledge of physics (electromagnetic waves, energy, electric current and voltage), chemistry (atomic structure, electrons, chemical bonds), and introductory concepts of electricity and energy conversion.
Description of the learning unit	The unit guides students and teachers through an interdisciplinary pathway integrating physics, chemistry, and technology to understand how solar energy is captured and converted into electrical energy through photovoltaic cells. Students will explore the journey of photons from sunlight to the generation of electric current, analyzing the layered structure of solar cells (P-N junction, semiconductors), the photovoltaic effect, and electron flow mechanisms.The use of digital and AR tools is intended to make otherwise invisible processes visible (photon absorption, electron-hole pair generation, electric field in the junction, current flow), clearly and progressively linking physical principles with technological applications for sustainable energy generation.
Subject: Parties involved	Physics (Optics, Electromagnetism), Chemistry (Semiconductor materials), Technology

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	(Photovoltaic engineering), Sustainability (Renewable energy)
Keywords	Solar energy; Photovoltaic cell; Photons; Electrons; P-N junction; Semiconductors; Energy conversion; Electric current; Renewable energy; AR; Scene-based learning
Key qualifications, skills and knowledge that can be acquired	● Reasoning & problem solving on energy conversion processes ● Design thinking applied to sequential visualization of physical phenomena ● Practical knowledge: photovoltaic effect, semiconductor physics, solar cell structure, electrical circuits ● Digital/AR skills: 3D visualization of atomic-scale processes, interactive diagrams, scene navigation
Resources and didactic aids used	AR platforms (e.g., Delightex Studio – Spaces, Marker), reliable web resources and educational videos on solar energy and photovoltaics, scientific articles and databases; diagrams and 3D models (solar cell layers, P-N junction, electron flow, photovoltaic systems) and textual overlays for key data.
Assessment criteria and evaluation	Evaluation of knowledge (photon-to-electron-to-current sequence), skills (cause-effect relationships between photon absorption and electrical power generation), and competences (conscious use of AR tools, interdisciplinary integration between physics and sustainable energy technology).

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1. The Photovoltaic Journey: Capturing the Sun

Energy conversion in solar cells; from photons to electrons; physics of photovoltaic systems

Solar energy conversion arises from the intersection of quantum physics and materials engineering. Sunlight, composed of photons carrying discrete packets of energy, strikes the surface of a photovoltaic cell and interacts with semiconductor materials.

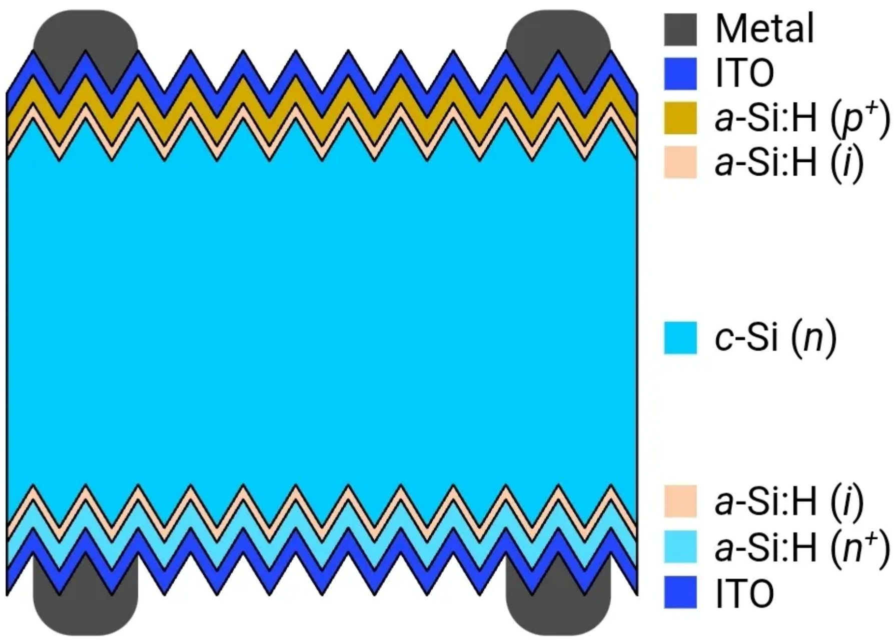

Figure 1. Cross-sectional structure of a silicon heterojunction solar cell showing layered architecture. The n-type crystalline silicon (c-Si) forms the main absorber layer, with thin amorphous silicon (a-Si:H) passivation layers and transparent ITO contacts. (Source: Wikimedia Commons, CC BY-SA 4.0)

Here, photons are absorbed, generating electron-hole pairs that, under the influence of an internal electric field, separate and flow through an external circuit. Harnessing solar energy does not mean passively collecting heat, but actively converting light into usable electrical current through precisely engineered atomic-scale structures.

The efficiency of energy conversion depends on the material properties and the architecture of the solar cell. Silicon, the most commonly used semiconductor, is "doped" with impurities to create two distinct regions: an N-type layer (electron-rich) and a P-type layer (hole-rich). At the interface between these layers-the P-N junction-an electric field forms naturally. This field is essential: it provides the driving force that separates photo-generated electrons and holes, preventing them from recombining and ensuring that charge carriers flow in a specific direction to produce current.

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The photovoltaic effect begins when a photon with sufficient energy strikes the semiconductor material. If the photon's energy exceeds the bandgap-the minimum energy required to free an electron from its atomic bond-the electron is promoted from the valence band to the conduction band, leaving behind a positively charged "hole." This electron-hole pair represents the fundamental unit of solar energy conversion: light energy transformed into charge separation at the atomic level.
The P-N junction acts as a one-way gate for charge carriers. The built-in electric field sweeps electrons toward the N-type region and holes toward the P-type region. When metallic contacts are attached to both sides and connected through an external circuit, electrons flow from the N-side through the circuit to the P-side, generating electric current. The voltage produced by a single silicon cell is approximately 0.5–0.6 volts; multiple cells are connected in series to achieve higher voltages suitable for practical applications.
Energy output and efficiency are influenced by several factors: the intensity and spectrum of incoming light, the quality of semiconductor materials, the temperature of the cell, and the design of anti-reflective coatings that maximize photon absorption. Modern silicon solar cells achieve efficiencies of 15–22%, meaning that only a fraction of incident solar energy is converted into electricity. Advanced materials such as perovskites and multi-junction cells push efficiencies higher, but trade-offs in cost, stability, and manufacturing complexity remain active areas of research.
From an educational perspective, it is crucial to clarify the sequential chain of events: (1) photons arrive and penetrate the cell surface; (2) photons with adequate energy generate electron-hole pairs in the semiconductor; (3) the electric field at the P-N junction separates these charge carriers; (4) electrons flow through an external circuit, producing electrical current; (5) energy is delivered to a load (lamp, battery, grid). Presenting these steps in an ordered manner helps students connect quantum-scale phenomena with macroscopic energy generation.
The targeted use of digital and augmented reality tools makes it possible to visualize otherwise invisible processes, such as photon absorption at the atomic level, the formation of the depletion region in the P-N junction, and the directional flow of electrons through the circuit. Scene-by-scene visualization facilitates the understanding of relationships between microscopic physics and large-scale renewable energy systems.

Let’s reflect together.
Why can't we extract electrical energy from sunlight without semiconductors? How does the P-N junction transform random photon absorption into directed electron flow? What role does the bandgap energy play in determining which wavelengths of light can be converted into electricity? These questions help link observable solar energy phenomena to the underlying quantum and electrical mechanisms.

2. Explore Module

Engagement phase

Guiding question. *Can we extract electricity from sunlight without moving parts?*

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The lesson opens with a brief demonstration: a small solar panel connected to an LED or a calculator. When exposed to light, the device works; when covered, it stops. The purpose is not simply to show that "solar panels work," but to introduce the idea that light energy can be directly converted into electrical energy through solid-state physics-no turbines, no combustion, no mechanical motion required.

Initial stimuli (videos and short resources)

How do solar panels work? TED-Ed: a clear animated overview of photovoltaic cells, the P-N junction, and electron flow.
https://www.youtube.com/watch?v=xKxrkht7CpY

Solar Energy Basics – U.S. Department of Energy: an accessible introduction to photovoltaic technology and renewable energy systems.
https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics

Photoelectric Effect: photoelectric Effect: interactive exploration of how photons interact with metal surfaces to eject electrons, demonstrating quantum properties of light.
https://phet.colorado.edu/en/simulations/photoelectric

Kick-off activity (5–10 min).
A quick demonstration or video clip showing a solar cell powering a small motor or charging a battery invites students to ask, "*How does light become electricity without wires moving or chemicals reacting?*" The goal is to highlight that **energy conversion is a quantum process** occurring at the atomic level within semiconductor materials, not a macroscopic mechanical or thermal transformation.

Suggested video: *How Solar Panels Work* (SciShow)
https://www.youtube.com/watch?v=L_q6LRgKpTw

Brainstorming activities in the classroom

Leading question. Without light, there is no photovoltaic current: what happens to photons as they enter the solar cell, and how do they generate an electrical signal that can power devices?

Prompting questions

What determines whether a photon can generate electricity in a solar cell?
The photon's energy must exceed the semiconductor's bandgap; silicon's bandgap (~1.1 eV) means only photons with wavelengths shorter than ~1100 nm (visible and near-infrared light) can free electrons and generate current.

Why can't we use all the sunlight that hits a solar panel?
Because photons with energy below the bandgap pass through without generating charge carriers, while

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photons with much higher energy waste excess energy as heat. This is why single-junction silicon cells have a theoretical maximum efficiency of ~33% (Shockley-Queisser limit).

Does the solar cell "store" electricity like a battery?
No; the solar cell generates current only when illuminated. The photovoltaic effect produces charge separation and flow in real-time; to store energy, an external battery or capacitor is needed.

Why do some solar panels work better in direct sunlight than in shade?
Because light intensity (photon flux) directly affects the number of electron-hole pairs generated. Lower intensity means fewer photons, fewer charge carriers, and reduced current output. Voltage remains relatively stable, but current drops significantly.

Micro-task.
Label the layers of a solar cell (anti-reflective coating, N-type silicon, P-N junction, P-type silicon, back contact) using a worksheet or an interactive diagram.
Suggested resource: **Solar Cell Structure Diagram** - Encyclopædia Britannica
https://www.britannica.com/technology/solar-cell

Basic Level

Physics of Solar Energy Conversion

Light, absorption, and photon energy
Solar energy conversion begins when photons from sunlight strike the surface of a photovoltaic cell. Sunlight is a mixture of electromagnetic waves spanning ultraviolet, visible, and infrared wavelengths. Each photon carries a discrete packet of energy determined by its wavelength: shorter wavelengths (blue light) carry more energy than longer wavelengths (red light).

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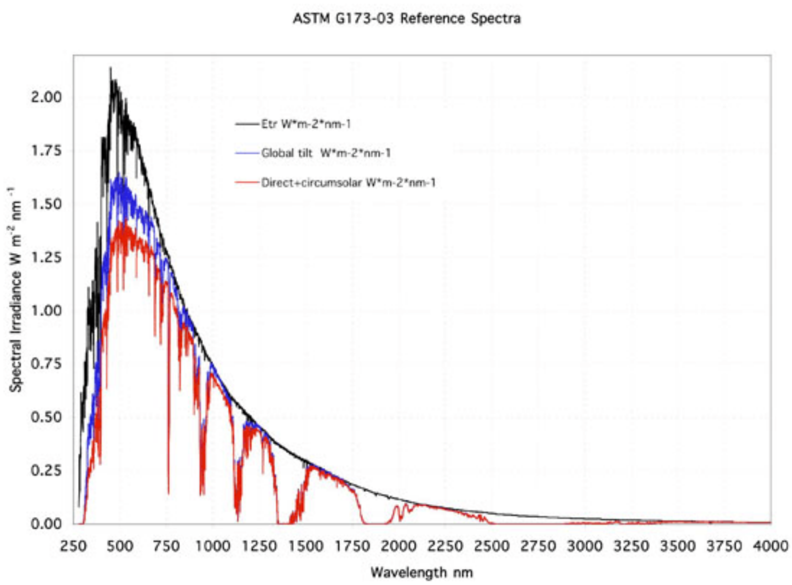

Figure 2. Solar spectral irradiance (ASTM G173-03 reference spectra) showing the distribution of photon energy across wavelengths. Silicon solar cells with a bandgap of ~1.1 eV (corresponding to ~1100 nm wavelength) can only convert visible and near-infrared photons. (Source: NREL)

When a photon enters a semiconductor material like silicon, it may be absorbed, reflected, or transmitted.

Absorption is key: if the photon's energy equals or exceeds the material's bandgap energy (the minimum energy required to free an electron from its atomic bond), the electron is promoted from the valence band to the conduction band.

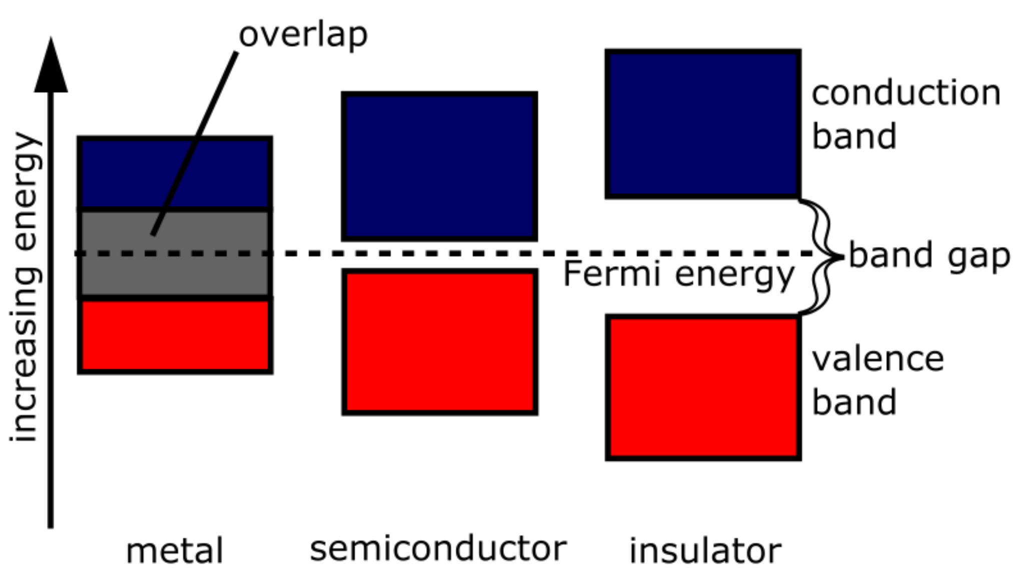

Figure 3. Comparison of energy band structures in metals, semiconductors, and insulators. In semiconductors like silicon, the band gap (Eg ≈ 1.1 eV) is small enough that photons can excite electrons from the valence band (red) to

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the conduction band (blue), enabling photovoltaic energy conversion. (Source: Wikimedia Commons, Public Domain)

This creates an **electron-hole pair**-a mobile negative charge (electron) and a corresponding positive vacancy (hole).

What determines whether a photon is absorbed or passes through?
The relationship between photon energy and the semiconductor's bandgap. Silicon's bandgap is ~1.1 eV, corresponding to infrared light at ~1100 nm. Photons with less energy pass through; photons with much more energy generate heat after freeing electrons.

From photons to electrons: the P-N junction

The absorbed photon creates an electron-hole pair, but without an internal electric field, these charges would quickly recombine, releasing energy as heat rather than electricity. This is where the **P-N junction** becomes essential.

Silicon is "doped" with impurities to create two distinct regions:

- **N-type silicon**: doped with phosphorus (extra electrons → negative charge carriers)
- **P-type silicon**: doped with boron (deficit of electrons → positive "holes")

At the boundary between N-type and P-type regions, **a depletion zone forms naturally**. Electrons from the N-side diffuse across to fill holes on the P-side, leaving behind positively charged atoms on the N-side and negatively charged atoms on the P-side. This charge separation creates a **built-in electric field** pointing from N to P.

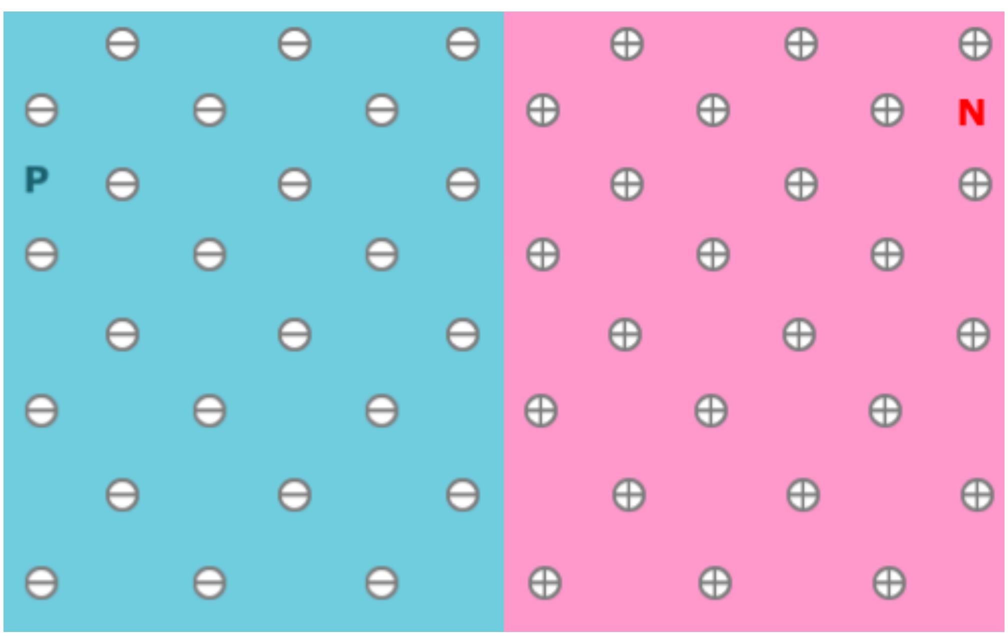

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Figure 4. Schematic representation of a P-N junction before equilibrium. The P-type region (left, cyan) contains excess holes (positive charge carriers), while the N-type region (right, pink) contains excess electrons (negative charge carriers). When the two regions are brought into contact, charge carriers diffuse across the junction. (Source: PVEducation.org, educational use)

When a photon generates an electron-hole pair near the junction, the electric field sweeps the electron toward the N-side and the hole toward the P-side. **This separation prevents recombination** and drives charge carriers in opposite directions, creating a voltage difference between the two sides of the cell.

Why do electron-hole pairs separate instead of recombining immediately?
Because the electric field at the P-N junction provides a driving force stronger than random thermal motion, directing electrons and holes away from each other before they can recombine.

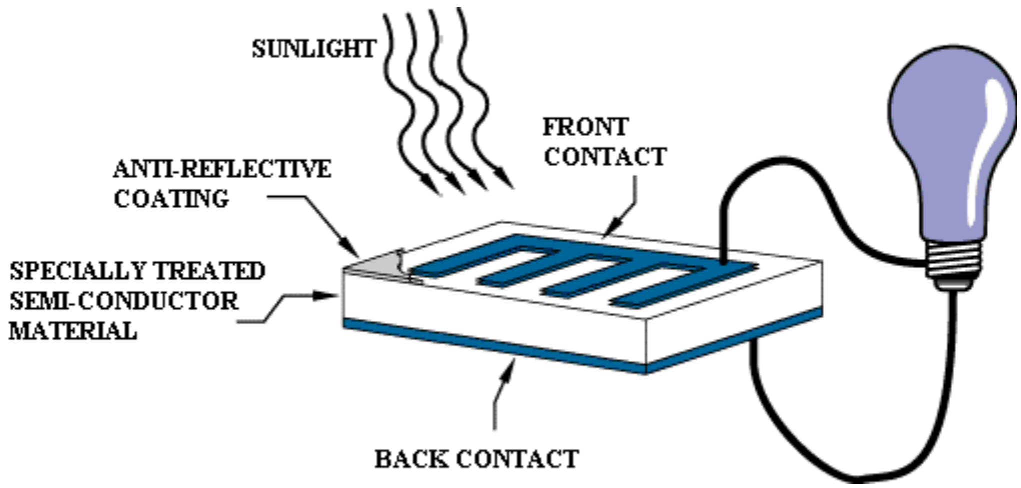

Figure 5. Complete solar cell operation showing the conversion of sunlight into electrical current. Photons strike the semiconductor material through the anti-reflective coating, generating electron-hole pairs that are separated by the internal electric field. The electrons flow through the external circuit (represented by the light bulb) before returning to recombine, creating usable electrical power. (Source: Wikimedia Commons, Public Domain)

Layered structure and charge collection

A typical silicon solar cell has multiple layers optimized for light absorption and charge collection:

Anti-reflective coating (top): reduces reflection, maximizing photon entry
N-type silicon (thin layer): electron-rich region where electrons are collected
P-N junction (interface): where the electric field separates charge carriers
P-type silicon (thicker base): where holes are collected
Metal contacts (top and bottom): conduct electrons out to an external circuit

The front contact is designed as a grid pattern to minimize shading while collecting current. The back contact covers the entire rear surface for maximum conductivity.

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Why is the N-layer thinner than the P-layer?
Because most photons are absorbed near the surface; a thin N-layer ensures photo-generated carriers are close to the junction's electric field for efficient separation, while the thicker P-layer absorbs longer-wavelength photons deeper in the material.

From the junction to the circuit: current and voltage

When sunlight illuminates the cell, continuous photon absorption generates a steady supply of electron-hole pairs. The junction's electric field continuously separates these charges, driving electrons toward the N-side and holes toward the P-side.

When metal contacts are attached and connected through an external circuit, **electrons flow from the N-side, through the circuit (powering a load), and return to the P-side** to recombine with holes. This flow constitutes **photovoltaic current**.

The voltage produced by a single silicon cell is approximately **0.5–0.6 volts**, determined by the bandgap energy and junction characteristics. Current depends on light intensity and cell area: more photons → more electron-hole pairs → higher current.

If a single cell produces only ~0.5V, how do solar panels generate useful voltages?
Multiple cells are connected in **series** (positive terminal of one to negative terminal of the next) to add voltages. A typical panel contains 60–72 cells in series, producing 30–40 volts under standard conditions.

From theory to everyday objects

The same principles operating in solar cells are found in:

- **Solar calculators**: small cells providing milliwatts of power for low-energy devices
- **Rooftop solar panels**: arrays of series-connected cells generating kilowatts for homes
- **Solar farms**: large-scale installations producing megawatts for the electrical grid
- **Space satellites**: high-efficiency multi-junction cells powering spacecraft where reliability is critical

Bringing quantum physics out of the abstract helps students understand not only *how* photovoltaics work, but *why* design choices (bandgap selection, anti-reflective coatings, cell thickness) directly impact real-world energy performance.

Let’s reflect together.
Converting sunlight into electricity requires precise control at the atomic level. If the P-N junction is essential for charge separation, why can't we use any semiconductor? What role does doping play in creating the internal electric field? How do temperature, shading, and material quality affect the efficiency of energy conversion?

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Web-based resources

How do solar panels work? – TED-Ed
https://www.youtube.com/watch?v=xKxrkht7CpY
Animated explanation of photovoltaic cells and electron flow.

Solar Photovoltaic Technology Basics – U.S. Department of Energy
https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics
Overview of PV technology and solar energy conversion.

PhET – Photoelectric Effect
https://phet.colorado.edu/en/simulations/photoelectric
Interactive exploration of photon energy and electron ejection.

Advanced Level

Quantum mechanics of photovoltaic conversion

The photovoltaic effect is fundamentally a quantum phenomenon. When a photon is absorbed by a silicon atom, its energy must overcome the **bandgap energy** ($E_g \approx 1.1$ eV for crystalline silicon) to promote an electron from the valence band to the conduction band. This process creates an **electron-hole pair** with a probability determined by the material's absorption coefficient and photon energy.

Energy losses occur at multiple stages:

- **Photons with $E < E_g$** pass through without generating charge carriers (transmission losses)
- **Photons with $E >> E_g$** generate "hot" carriers that quickly lose excess energy as heat through **thermalization**
- **Surface reflection** (without anti-reflective coating, ~30% of incident light is lost)
- **Recombination** (electron-hole pairs recombine before reaching contacts, releasing energy as heat or light)

The **Shockley-Queisser limit** establishes the theoretical maximum efficiency for a single-junction solar cell at ~33% under standard solar spectrum (AM1.5G). Real-world silicon cells achieve 15–22% due to additional losses from resistance, imperfect materials, and non-ideal junction properties.

Efficiency, spectral response, and material optimization

Solar cell efficiency depends critically on how well the semiconductor's bandgap matches the solar spectrum. Silicon's 1.1 eV bandgap is a compromise: it captures visible and near-infrared light effectively but cannot utilize lower-energy infrared photons or fully exploit high-energy ultraviolet photons.

Advanced strategies to overcome the Shockley-Queisser limit:

- **Multi-junction (tandem) cells**: Stack semiconductors with different bandgaps (e.g., GaInP/GaAs/Ge) so each layer absorbs a specific portion of the spectrum. Lab efficiencies exceed 47% under concentrated sunlight.

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- **Perovskite cells**: Hybrid organic-inorganic materials with tunable bandgaps, rapid charge transport, and solution-processable fabrication. Current efficiencies approach 26%, but stability and scalability remain challenges.
- **Hot carrier cells** (experimental): Harvest energy from hot carriers before thermalization, potentially exceeding 66% efficiency. Requires ultrafast charge extraction mechanisms not yet commercially viable.

Why do high-energy photons reduce overall efficiency?
Because excess energy above the bandgap is rapidly lost as heat through phonon emission (thermalization) within picoseconds. A 3 eV photon (UV) generates the same single electron-hole pair as a 1.2 eV photon (red), wasting 1.9 eV as heat.

Why can't we simply use a very small bandgap to capture all photons?
Because smaller bandgaps produce lower voltage ($V \propto Eg$), and thermal generation of carriers increases, raising "dark current" that reduces net efficiency. There's an optimal bandgap (~1.1–1.4 eV) balancing photon absorption and voltage output.

Charge transport, recombination, and device physics
After generation at the junction, charge carriers must travel to the contacts without recombining. **Recombination mechanisms** limit efficiency:

- **Radiative recombination**: electron-hole pairs recombine, emitting photons (significant in direct-bandgap materials like GaAs, minimal in silicon)
- **Auger recombination**: three-particle interaction where energy is transferred to a third carrier instead of emitted as light (increases at high carrier densities)
- **Shockley-Read-Hall (SRH) recombination**: defects and impurities in the crystal lattice trap carriers, facilitating recombination (dominates in lower-quality silicon)

High-quality **crystalline silicon** minimizes SRH recombination through controlled manufacturing. **Passivation layers** (e.g., silicon nitride, aluminum oxide) on surfaces reduce interface recombination. **Doping profiles** are optimized so the electric field extends across the active region, ensuring rapid carrier separation.

Why does temperature reduce solar cell efficiency?
Because higher temperature increases lattice vibrations (phonons), which scatter charge carriers, reduce mobility, and increase recombination rates. Additionally, the bandgap decreases slightly with temperature (~–0.3 meV/K for silicon), reducing voltage output. Typical efficiency loss: ~0.4% per °C above 25°C.

System integration and real-world performance
A photovoltaic system includes not just solar cells, but:

- **Inverters**: convert DC output to AC for grid compatibility

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- **Maximum Power Point Tracking (MPPT)**: continuously adjusts load to extract maximum power as light conditions change
- **Energy storage** (optional): batteries store excess generation for nighttime or cloudy periods
- **Grid connection**: feed surplus energy to the electrical grid, often with net metering policies

Capacity factor (actual energy output / theoretical maximum) for solar installations is typically 15–25%, constrained by:

- Day/night cycles
- Weather variability
- Seasonal changes in sun angle
- System losses (wiring resistance, inverter inefficiency, shading)

Why do solar panels degrade over time?
UV exposure, moisture ingress, thermal cycling, and potential-induced degradation (PID) gradually reduce efficiency. High-quality modules lose ~0.5% efficiency per year; warranties typically guarantee 80% output after 25 years.

Let's reflect together

Why do modern solar cells still operate far below the Shockley-Queisser limit?
Because real-world materials have defects, surfaces introduce recombination, and charge extraction isn't perfectly efficient. Bridging the gap between theoretical and practical performance drives ongoing research in material science and device engineering.

Why can't we achieve 100% efficiency even with perfect materials?
Because fundamental thermodynamic and quantum mechanical constraints apply: not all photons can be absorbed (spectral mismatch), thermalization wastes high-energy photons, and maintaining voltage output requires some energy dissipation. The second law of thermodynamics ultimately limits conversion efficiency.

Flipped Learning:

Objective. Prepare for classroom discussion by understanding the sequence *photon → absorption → charge separation → current flow* and the physics/engineering connections in photovoltaic systems.

Tasks (to be submitted as a 1–2-page report or 6–8 slides):

1. **Short reading** on the structure of a silicon solar cell and the path of photons. Highlight: anti-reflective coating, N-type layer, P-N junction, P-type layer, metal contacts.
2. **Worksheet "N-type vs. P-type Silicon"**: complete a table with:
    - Doping element (phosphorus/boron)
    - Majority charge carrier (electrons/holes)

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- Role in charge separation
- Position in cell structure (top/bottom)

3. **PhET Semiconductors simulation**: create two screenshots -
   a. **Intrinsic (undoped) silicon**: observe energy bands and lack of free carriers
   b. **Doped silicon (N+P junction)**: observe band bending, built-in electric field, and charge separation under illumination
4. **Short synthesis (max 120 words)**: explain in your own words how the solar cell does not "collect" sunlight like a thermal panel but **converts photon energy into separated electrical charges** through quantum absorption and junction physics.
5. **Three debriefing questions**:
   - One on **quantum physics**: Why must photon energy exceed the bandgap?
   - One on **materials science**: How does doping create an electric field?
   - One on **systems engineering**: Why do solar panels produce DC but homes use AC?

Submission. Upload the PDF or slides to the class channel before the lesson.

3. Operation Module

Basic Level

Understanding the photovoltaic conversion process can be deepened through a series of practical activities that allow students to observe both quantum and electrical phenomena involved in solar energy capture. The aim of this section is to apply, in a guided way, the concepts of photon absorption, charge separation, and current generation studied in the theoretical part, connecting the **physics of semiconductors** with **real-world energy systems**.
When light strikes a semiconductor material, photons with sufficient energy excite electrons from bound states into mobile charge carriers-a quantum phenomenon invisible to direct observation but measurable through electrical instruments. Students can observe this behavior using a simple experiment: connect a small solar cell to a multimeter and expose it to different light sources (sunlight, LED lamp, flashlight). As light intensity increases, current rises proportionally, while voltage remains relatively stable. This direct measurement illustrates how photon flux translates into electrical output.

Through the simulation, students can observe energy band diagrams, apply doping to create N-type and P-type regions, and visualize how the P-N junction generates a built-in electric field. When light is introduced, students see electron-hole pairs generated and separated by the junction field, producing current flow. This activity helps students understand how **doping and junction physics enable directional charge transport**-the foundation of photovoltaic operation.

From these observations arise essential questions: What is the relationship between photon energy and electron excitation? Why does doping create an internal electric field without external voltage?

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Comparing the simulated semiconductor with real solar cell structure clarifies how material engineering at the atomic scale determines macroscopic electrical performance.

The focus then shifts to the **layered architecture of solar cells**. Students analyze the arrangement of functional layers-anti-reflective coating, N-type emitter, P-N junction, P-type base, metal contacts-and their complementary roles:

- The **anti-reflective coating** maximizes photon entry by reducing surface reflection
- The **thin N-layer** captures electrons generated near the surface
- The **P-N junction** creates the electric field that separates charge carriers
- The **thick P-layer** absorbs longer-wavelength photons deeper in the material
- **Metal contacts** collect and conduct current to external circuits

The class discussion continues by analyzing cell behavior under varying light conditions. Why does current output change dramatically with shading while voltage remains relatively stable? The answer lies in the **direct proportionality between photon flux and charge carrier generation**. This collective reflection helps students understand how solar system design must account for partial shading, orientation, and time-of-day variations.

Students are then invited to compare solar cells with everyday energy devices:

- **Solar calculators**: low-power applications where small cells provide sufficient energy
- **Rooftop panels**: series-connected cells generating household-scale power
- **Grid-scale solar farms**: megawatt installations with inverters, transformers, and storage systems
- **Space satellites**: high-efficiency multi-junction cells where reliability and weight are critical

Through this analogy, photovoltaics is reinterpreted as a **quantum-to-grid energy conversion chain** connecting atomic physics, materials engineering, and electrical systems.

Let's reflect together. Solar energy conversion is a complex process combining quantum mechanics, solid-state physics, and electrical engineering. How does semiconductor bandgap limit the wavelengths that can be converted to electricity? What engineering strategies maximize photon absorption and minimize charge recombination? How do real-world constraints-cost, durability, scalability-influence solar cell design choices?

Advanced Level

The advanced level deepens the connection between photon absorption and the flow of electrical current through external circuits. Students observe how light energy is converted into separated charges within the P-N junction and how these charge carriers propagate through the semiconductor and metallic contacts to deliver power.

To understand the sequence of events, the concept of **band bending** at the P-N junction is introduced: when N-type and P-type regions contact, electrons diffuse from N to P and holes diffuse from P to N until an equilibrium is reached. This creates a **depletion region** depleted of mobile carriers, with fixed positive

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charges on the N-side and fixed negative charges on the P-side. The resulting electric field (~10^5 V/cm) is strong enough to separate photo-generated electron-hole pairs before they recombine.

The propagation of charge carriers and the generation of electrical current is illustrated through an **Augmented Reality simulation** developed with **Delightex Studio – Spaces (Marker)**: https://edu.delightex.com/Studio/Spaces

Using mobile devices, students explore a three-dimensional model of a solar cell:

1. Observe photons striking the surface and penetrating the semiconductor
2. Visualize electron-hole pair generation when photon energy exceeds the bandgap
3. Follow electrons swept toward the N-layer and holes toward the P-layer by the junction field
4. See electrons flowing through the external circuit (wire, load, return path)
5. Track the complete current loop from generation to load and back

During the activity, guiding questions are proposed:
– At what point in the cell does light become separated electrical charges?
At the P-N junction, where the built-in electric field separates photo-generated electrons and holes before they recombine.

– Why does current flow through the external circuit when the cell is illuminated?
Because the junction continuously generates a voltage difference (photovoltage) between the N-side and P-side, driving electrons through the circuit to minimize the potential difference.

– How does the solar cell produce power without consuming fuel or moving parts?
By directly converting photon energy into charge separation through quantum absorption, then extracting those separated charges as current through metallic contacts-a solid-state energy conversion with no mechanical or chemical transformations.

Answers emerge through group discussion and comparison between quantum-scale carrier generation and macroscopic electrical measurements.

The lesson ends with a reflection on the **evolution of photovoltaic technology**. Students compare first-generation crystalline silicon cells with emerging technologies:

Technology	Efficiency	Advantages	Challenges
Crystalline Silicon	15–22%	Mature, stable, scalable	Resource-intensive, rigid
Thin-Film (CdTe, CIGS)	10–15%	Flexible, lightweight	Lower efficiency, toxic materials
Perovskite	20–26% (lab)	High efficiency, low-cost processing	Stability, degradation, lead content

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Technology	Efficiency	Advantages	Challenges
Multi-junction (GaAs)	30–47%	Ultra-high efficiency	Expensive, used in space/concentrators

Let's reflect together. Do modern solar technologies truly approach fundamental physical limits, or is there room for breakthroughs in materials science and device architecture? Can we engineer cells that convert all solar wavelengths efficiently, or will spectral mismatch always constrain single-junction systems? How do economic and environmental factors (manufacturing energy, rare materials, recycling) influence which technologies scale globally?

Activities:

The concluding activities aim to consolidate learning and encourage peer collaboration.

Activity 1: Concept Map

Students create a **concept map** representing the complete sequence of photovoltaic conversion, from photon to electrical power, indicating for each phase:

- The **physical phenomenon** (absorption, excitation, separation, flow)
- The **material/structure involved** (semiconductor, P-N junction, contacts, circuit)
- The **type of energy** (photon → kinetic → potential → electrical)

Activity 2: Augmented Reality Experience

Students experience a complete Augmented Reality journey through the photovoltaic conversion process using Delightex Studio – Spaces (Marker). The AR exercise guides students through 5 sequential scenes that visualize each phase of solar energy conversion:

Scene 1: Introduction with animated sun and START button
Scene 2: Photon arrival and energy requirements (bandgap threshold)
Scene 3: P-N junction structure and charge separation
Scene 4: Current flow through external circuit and energy delivery to load
Scene 5: Final assessment with sequential conceptual quizzes

Each scene includes visual elements (diagrams, animated particles, color-coded spheres for electrons/holes), explanatory text overlays, and interactive quizzes with immediate feedback. Students navigate sequentially by tapping buttons, observing visual consequences (color desaturation for wrong answers, firework effects for success), and answering questions about photon energy thresholds, P-N junction function, and circuit behavior. The complete journey takes approximately 5-7 minutes and can be experienced individually or in small groups for collaborative discussion.

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Optional extension: In small groups, students can design follow-up scenes focusing on advanced topics such as anti-reflective coatings, multi-junction cells, or real-world solar panel installations, adding their own explanatory texts and visual indicators.

Activity 3: Interactive Quiz

To verify understanding at each stage, the AR experience includes **integrated quizzes with immediate visual feedback**. Students answer multiple-choice questions embedded within the sequential scenes:

Scene 2 Quiz:

- What determines if a photon can generate electricity?
  (Correct: Photon energy vs bandgap)

Scene 3 Quiz:

- What creates the electric field that separates charge carriers?
  (Correct: P-N junction doping)

Scene 4 Quiz:

- Why does current stop when we cover the solar panel?
  (Correct: No photons = no electron-hole pairs generated)

Scene 5 Final Assessment (3 sequential quizzes):

1. How do we increase voltage output?
   (Correct: Connect cells in series)
2. Why can't infrared photons generate current in silicon?
   (Correct: Energy < bandgap at 1.1 eV)
3. What prevents electron-hole recombination?
   (Correct: P-N junction electric field)

Each quiz provides **visual feedback**: correct answers maintain vibrant colors and enable progression to the next scene, while incorrect answers trigger visual consequences (desaturation, animation stops) and allow unlimited retries, encouraging reasoning without penalties

Optional discussion questions for advanced exploration:

- Why does shading reduce current but not voltage in series-connected cells?
- What limits the maximum efficiency of single-junction solar cells?
- How do multi-junction cells overcome the Shockley-Queisser limit?

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Activity 4: Plenary Discussion

The module closes with a **plenary discussion** in which students:

- Critically analyze the results obtained from simulations and AR experiences
- Compare photovoltaic conversion with other energy technologies (fossil fuels, wind, hydro)
- Reflect on the role of solar energy in global decarbonization and sustainability
- Discuss trade-offs between efficiency, cost, environmental impact, and scalability

Expected output
At the end of the Operation Module, students should be able to:
- Describe in scientific language the full sequence of photovoltaic conversion, from photon absorption to electrical current generation
- Link quantum physics (bandgap, photon energy, charge carriers) with macroscopic electrical behavior (voltage, current, power)
- Use digital and AR tools to represent complex atomic-scale phenomena and visualize energy flow through photovoltaic systems
- Develop a critical approach toward solar energy technologies, understanding their physical limits, engineering trade-offs, and societal implications for renewable energy transition

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