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New Delhi

SUSTAINABLE SOLAR ENERGY TECHNOLOGIES

Department of Chemistry, School of Applied sciences

OPEN ELECTIVE

SUSTAINABLE SOLAR ENERGY TECHNOLOGIES

COURSE CODE: B24ASO603 **CREDIT : 3**

SYLLABUS

Introduction: Solar spectrum, light -matter interaction, energy availability, merits of solar energy, commercial realization and challenges, solar conversion technologies, Solar industries, solar initiatives, solar energy market.

Case studies: Solar energy comparison with Renewable energy tech and their integration.

COURSE OUTCOMES

	Course Outcomes	POs	PSOs
CO1	Evaluate the intricate problems in solar energy conversion and solution through clean energy systems.	1,2,12	1,2,3
CO2	Value the advances in different solar energy conversion processes.	1,2,	1,2,3
CO3	Perceive the need of solar energy conversion materials in semiconductor devices technologies.	1,2	1,2,3
C04	Judge and implement different semiconductor in photoelectrosynthesis.	1,2,12	1,2,3
C05	Critically analyze the cost and implementation of solar technologies – solar to electric, solar to chemical, solar to thermal, solar to light.	1,2	1,2,3
C06	Analyze the importance of miniaturization of devices and nanotechnology.	1,2,12	1,2,3

Light-Matter Interactions

1. Absorption

- When light is absorbed by a material, its energy is transferred to the atoms, molecules, or electrons in the material.
- Absorption depends on the wavelength of light and the electronic structure of the material.
- Example: **Solar cells (Photovoltaics)** absorb sunlight to generate electricity.

2. Reflection

- Light bounces off the surface of a material without being absorbed.
- The degree of reflection depends on the material's refractive index and surface smoothness.
- Example: **Mirrors reflect light efficiently due to their polished metal surfaces.**

3. Transmission

- Light passes through a material with little to no absorption.
- Transparent materials allow transmission, while opaque materials block it.
- Example: **Glass windows allow sunlight to pass through.**

Light-Matter Interactions

4. Refraction

- Light bends when it enters a medium with a different refractive index.
- This phenomenon is described by **Snell's Law**.
- Example: **A straw appearing bent in water due to light refraction.**

5. Scattering

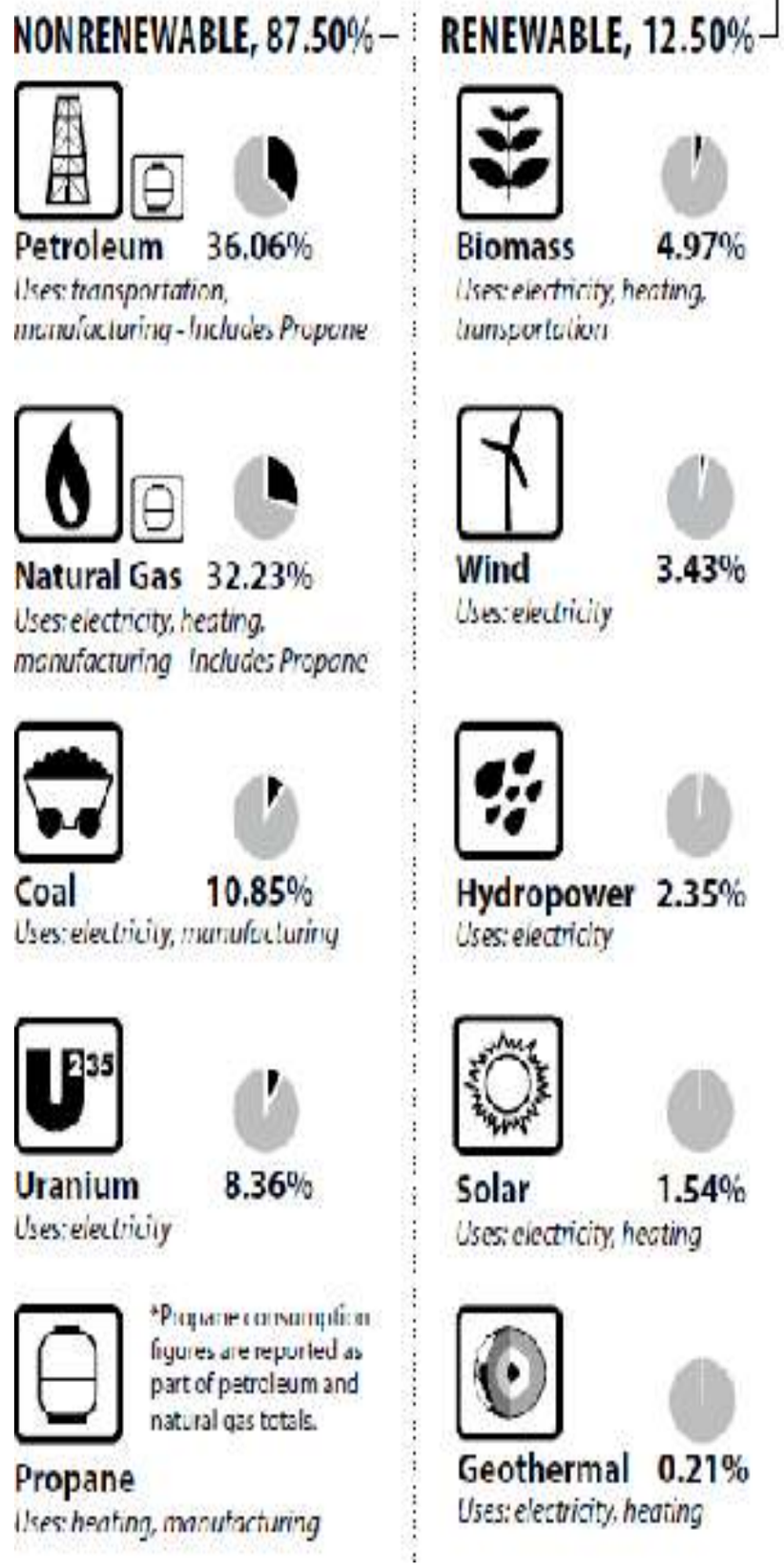
- Light changes direction due to interaction with particles or imperfections in a medium.
- Can be **Rayleigh scattering** (small particles, blue sky effect) or **Mie scattering** (larger particles, white clouds).
- Example: **Sky appears blue due to Rayleigh scattering of sunlight.**

6. Emission (Luminescence and Fluorescence)

- Some materials absorb light and then re-emit it at a different wavelength.
- Fluorescence occurs when the re-emission is nearly instantaneous.
- Example: **Fluorescent lights and glow-in-the-dark materials.**
- **Photoelectric Effect**
- Light ejects electrons from a material when it has enough energy.
- Explained by Einstein, it supports the quantum nature of light.
- Example: **Solar panels work based on the photoelectric effect.**

Energy source and consumption

- Major energy consumption – non-renewable.
- Clean energy - Zero emission is < 8 %.
- Need to increase Renewable usage.
- Need of solar energy conversion technologies.
- Eliminate atmospheric carbon.
- Carbon capture technologies.

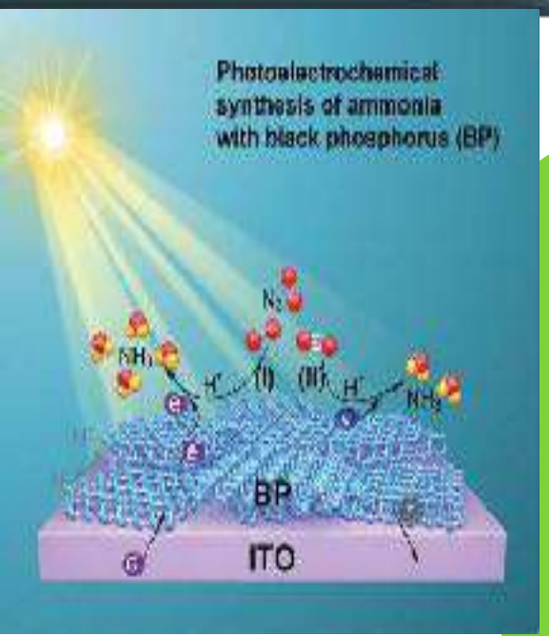


INTRODUCTION TO SOLAR ENERGY - ADVANCES

- Solar energy, due to its widespread availability and inexhaustible nature, is considered one of the most promising clean renewable energy sources for achieving carbon neutrality and energy security.
- Advances in solar photovoltaic technology have led to improvements in efficiency, cost, and energy storage, making it a more viable option for renewable energy generation. However, **solar energy's intermittent nature remains a limitation,** often addressed through energy storage systems tailored to the specific generation technology.
- Researchers are working to enhance solar cell efficiency by developing new materials for more effective sunlight collection and conversion.

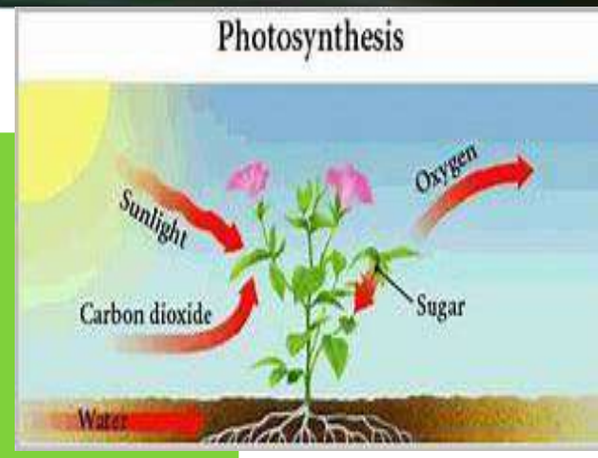
- The total annual energy used by the world in 1 year is 4.6 × 1020 J, and the sun provides this energy in 1 h.
- Solar energy can be used in various applications, including solar thermal systems for heat, and electricity generation through concentrated solar power, solar photovoltaic (SPV) systems, photo-assisted fuel cells, and CO_2 reduction to produce hydrocarbons and fuels like hydrogen. Each technology harvests sunlight rays and converts them into different end forms.
- For example, solar energy can be naturally converted into solar fuel through the process of photosynthesis. Also, through photosynthesis, plants store energy from the sun, where protons and electrons are produced, which can be further metabolized to produce H_2 and CH_4.

Energy conversion and storage

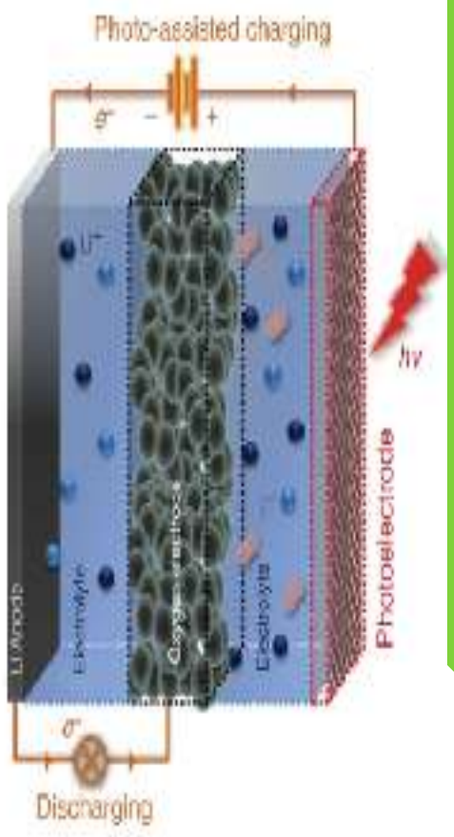


Solar Energy

- Solar – material aspects
- Renewable Tech
- Light harvesting - photosynthesis
- Conversion efficiency - cost
- Energy conversion methods
- Mimic bio processes



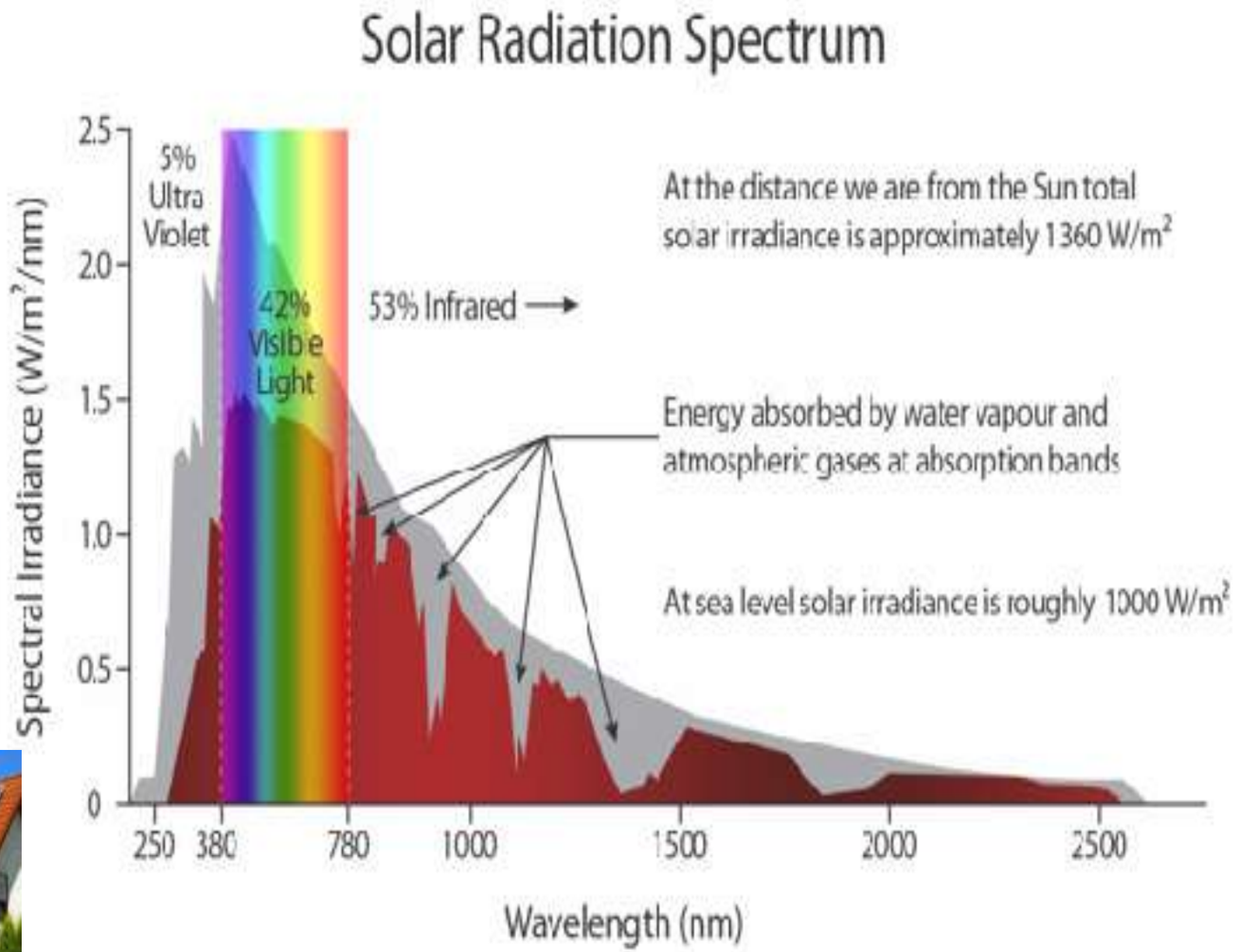

DTE solar array in Southfield, MI



Solar spectrum- Energy conversion

- Solar spectrum to electrical – visible spectrum – 42 % useful
- Visible active materials – Band structures
- Only 42 % useful
- Conversion efficiency – 18 %
- Cost
- Durability
- Solar conversion Tech
- Roof top PV
- Floating PV
- Solar to fuel
- Solar EV charging
- Solar to Steam

At Earth's average distance from the Sun-150 million kilometers, the average intensity of solar energy reaching the top of the atmosphere - **1,360 watts per square meter.**



Solar conversion technologies

1. **Photovoltaic (PV) Cells:** Made of semiconductor materials (usually silicon), PV cells generate electricity when exposed to sunlight due to the photovoltaic effect.

2. **Concentrated Solar Power (CSP):** CSP systems use mirrors or lenses to concentrate sunlight onto a receiver, which then heats a fluid to produce steam. This steam drives a turbine to generate electricity. These systems are typically used in large-scale power plants.

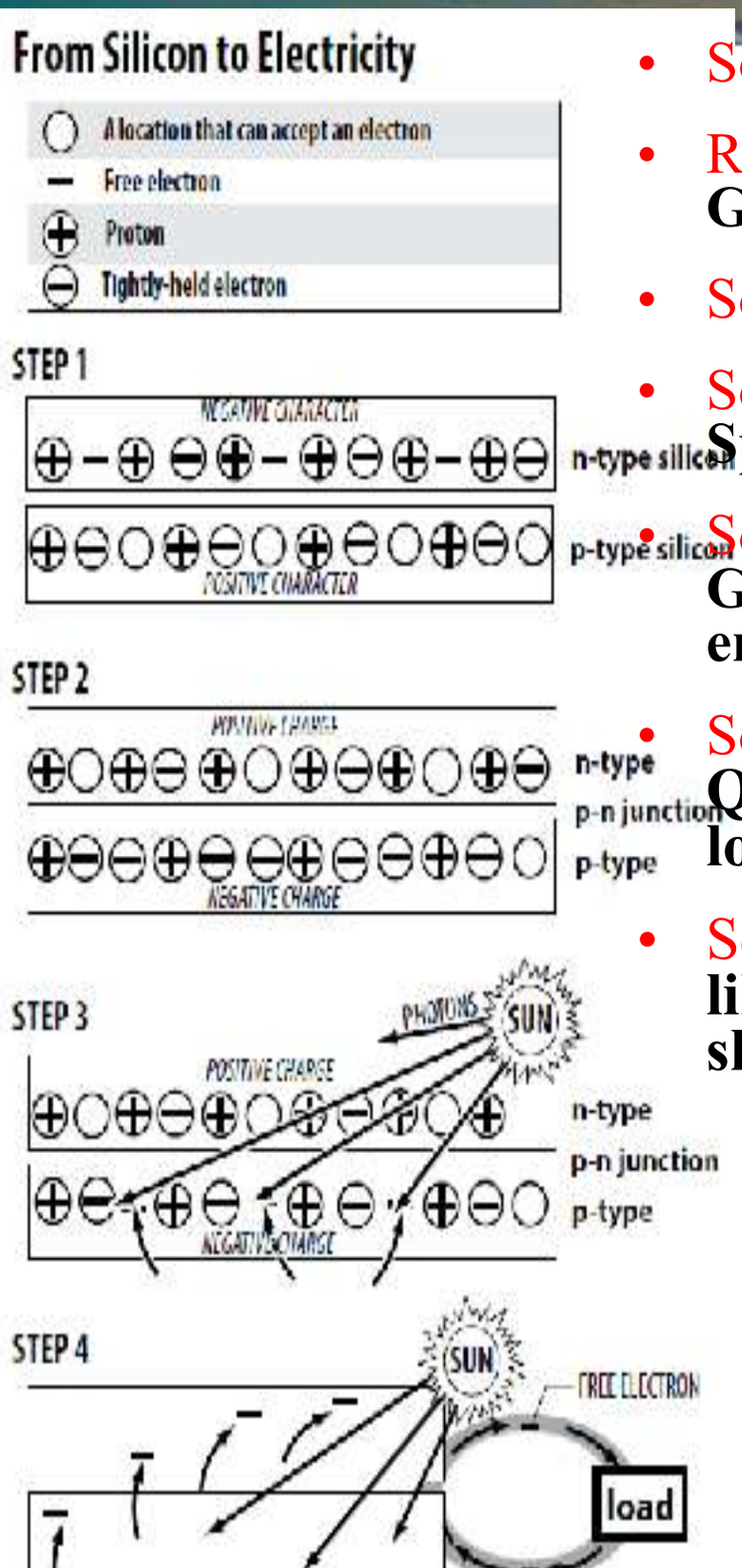
3. **Solar Water Heating Systems:** Solar energy heats water directly, which is then stored in a tank for use in homes or industrial applications.

4. **Solar Thermal Energy:** used in industrial heating processes, solar cooling, and even for space heating in buildings.

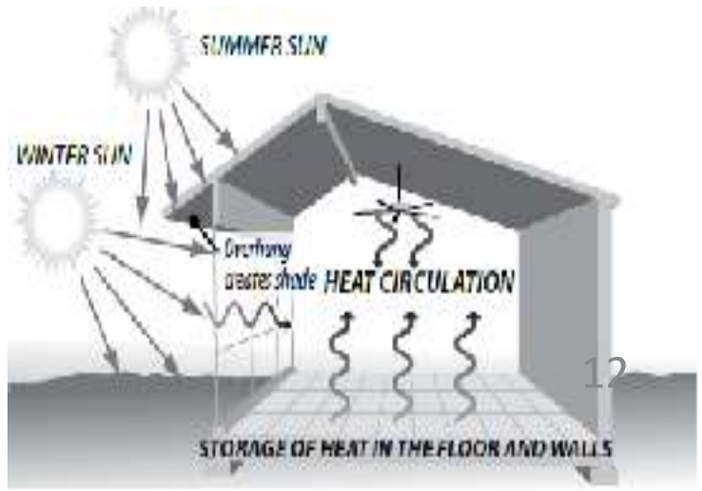
5. **Solar Fuel Generation:** Uses sunlight to split water molecules into hydrogen and oxygen or to convert carbon dioxide into synthetic fuels.

6. **Building-Integrated Photovoltaics:** These materials replace conventional building elements while also generating electricity.

Clean energy conversion Solar cells



- Solar cell tech- **Monocrystalline/polycrystalline/thin film/Perovskite cells.**
- Roof top SC- **Solar Panels, Inverters/Battery Storage/Grid-Tied vs. Off-Grid.**
- Solar – electric **- Generate electricity directly from sunlight.**
- Solar – thermal **- Solar Water Heaters/Concentrated Solar Power/Solar Space Heating and Cooling.**
- Solar – lighting (PLED)-**Used in solar lighting systems-Street Lights, Garden and Pathway Lights, PLED Technology (durable, flexible, and energy-efficient).**
- Solar – windows **- Transparent solar panels-Photovoltaic Coatings, Quantum Dots or Organic PV (Still a developing technology, with lower efficiency compared to traditional solar panels).**
- Solar – fuels-**Hydrogen and Synthetic Fuels: synthetic hydrocarbons, like methane or methanol, which can be used as liquid fuels for cars, ships, and planes.**

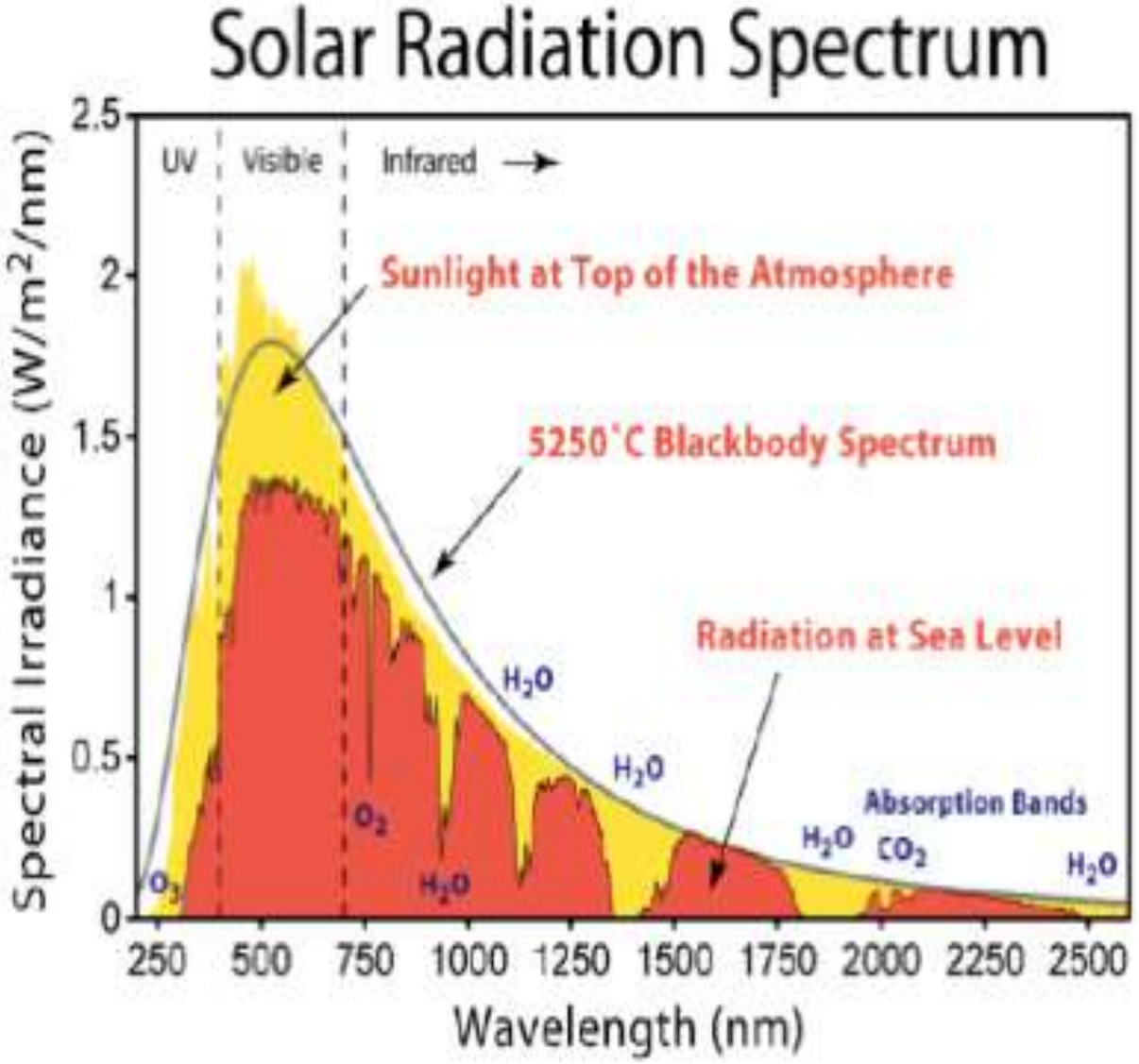


Solar radiation spectrum

- Visible radiation is 45-47 %
- UV - 3 %
- IR – 50- 52 %
- UV and Vis will excite the

•Valence band electron to the conduction band based on the band gap.

•IR can only do bond vibration.



•**Ultraviolet (UV) Light** (10–400 nm) – High-energy radiation, mostly absorbed by the ozone layer.

•**Visible Light** (400–700 nm) – The portion detectable by the human eye, playing a crucial role in photosynthesis and solar energy applications.

•**Infrared (IR) Light** (700 nm–1 mm) – Radiant heat energy, crucial for thermal solar applications.

PHOTOVOLTAIC MATERIALS

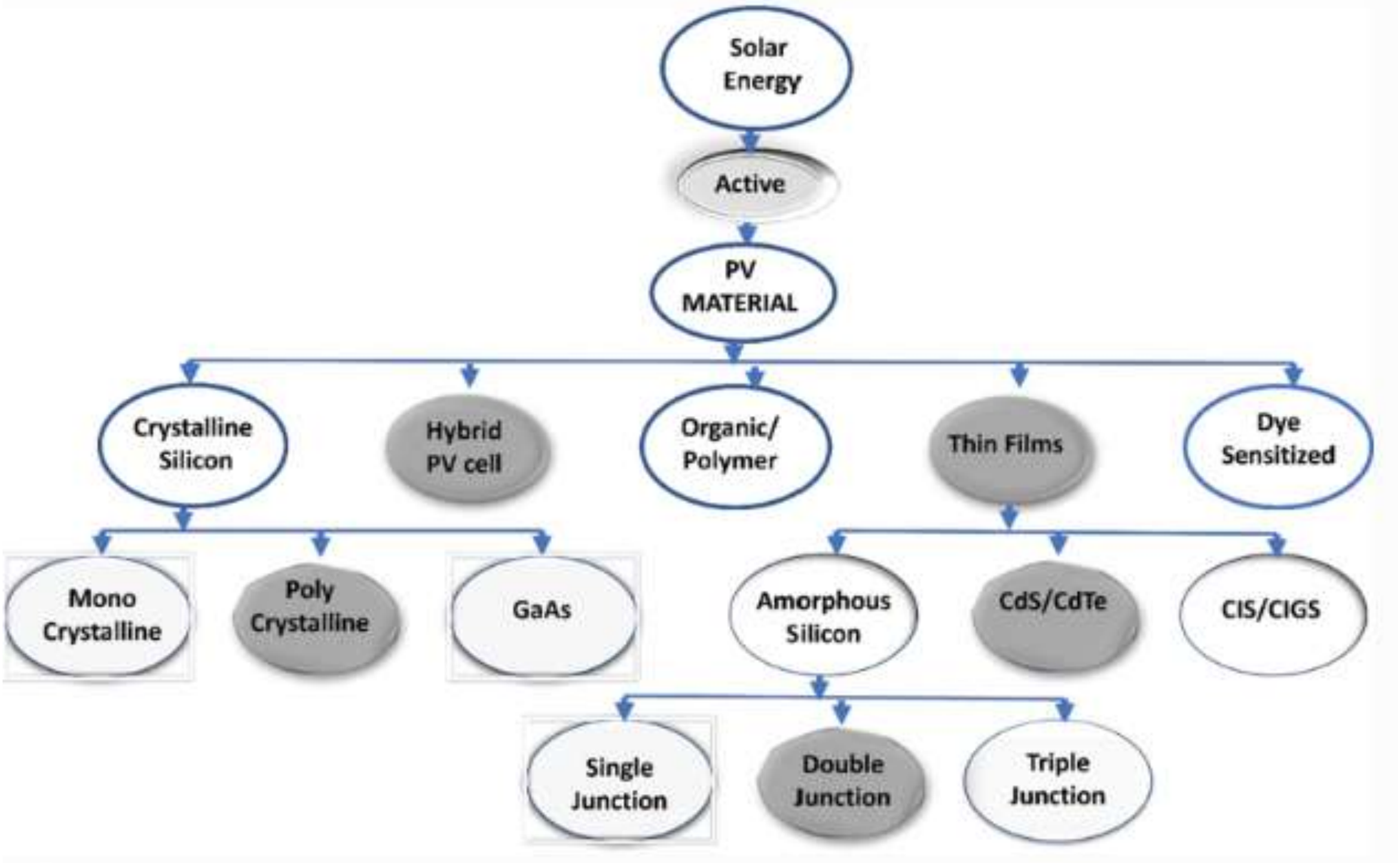
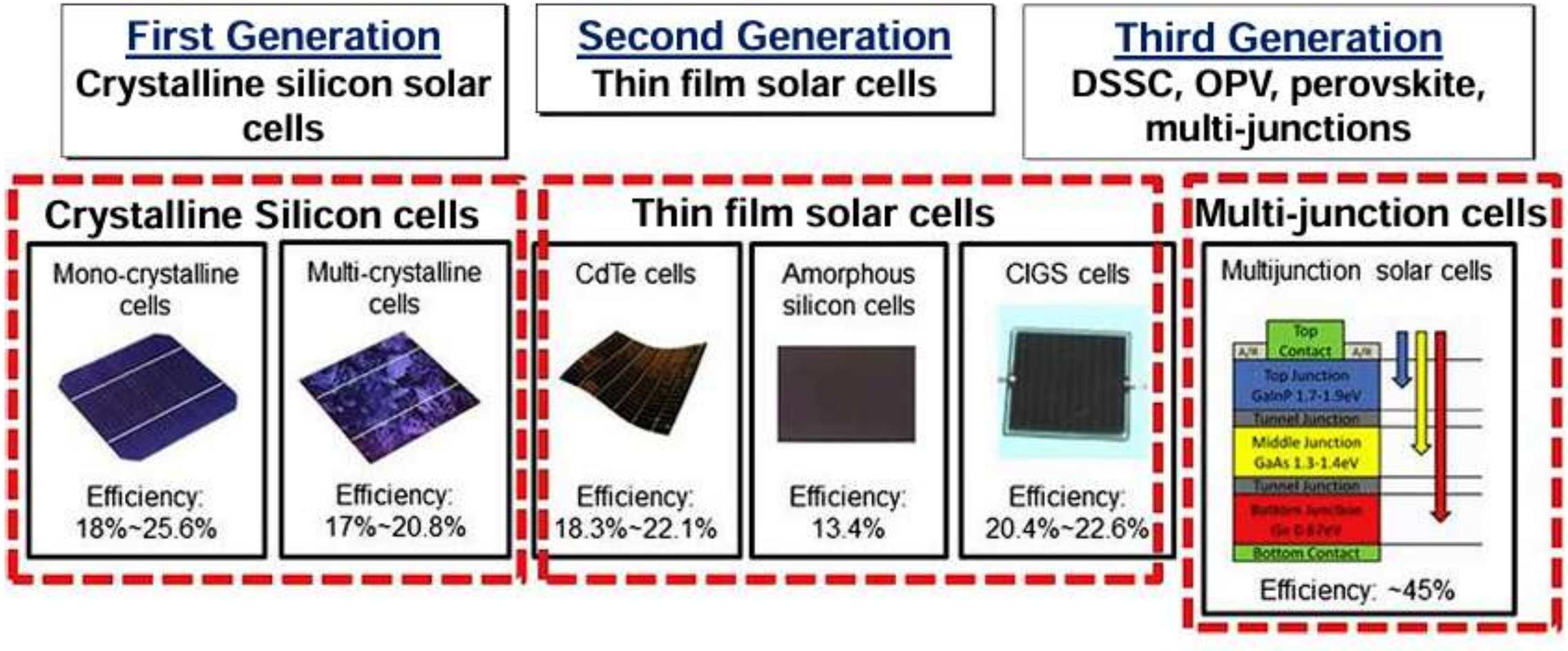


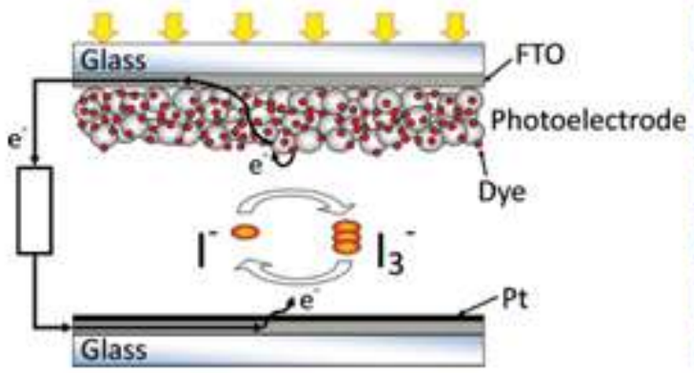
Table 1: Properties of different generations of solar cells

FIRST	SECOND	THIRD	FOURTH
Monocrystalline silicon solar cells	Amorphous silicon solar cells	Dye-sensitized solar cells (DSSC)	Graphene and graphene-derivative solar cells
Polycrystalline silicon solar cells	Copper indium gallium selenide (CIGS)	Quantum Dot solar cells	Carbon nanotubes
	Cadmium telluride	Perovskite solar cells	Metal nanoparticles and metal oxides
	Copper zinc tin sulfide	Organic solar cells	
	Gallium arsenide	Multi-junction solar cells	
	Gallium indium phosphorous		



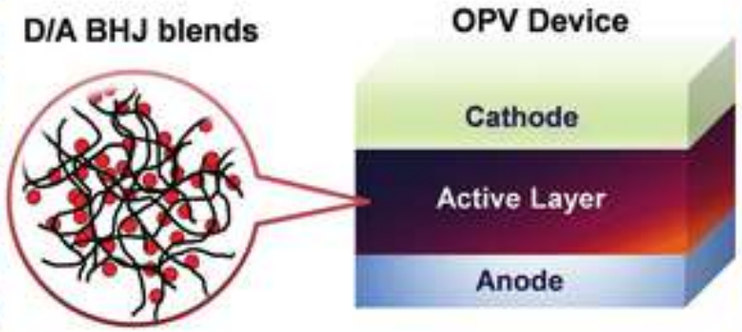
Photovoltaic technologies – 3rd generation

DYE-SENSITISED SOLAR CELLS (DSSC)



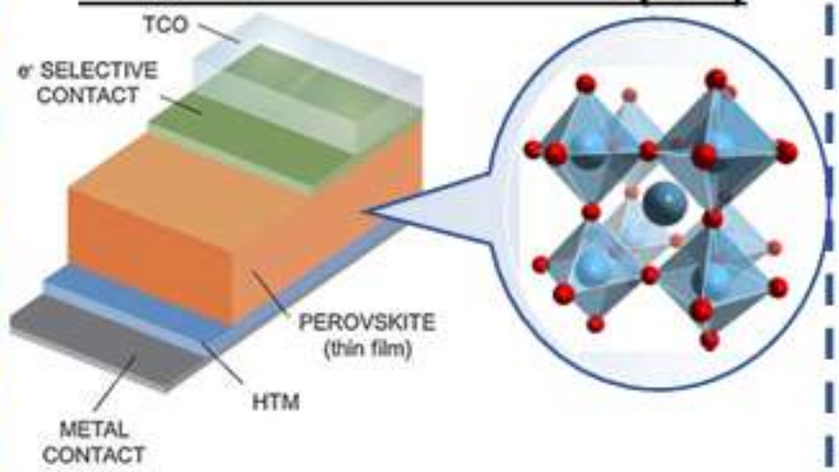
- Photosensitive **organic dye**
- Efficiency: 12.3%

ORGANIC PHOTOVOLTAICS (OPV)



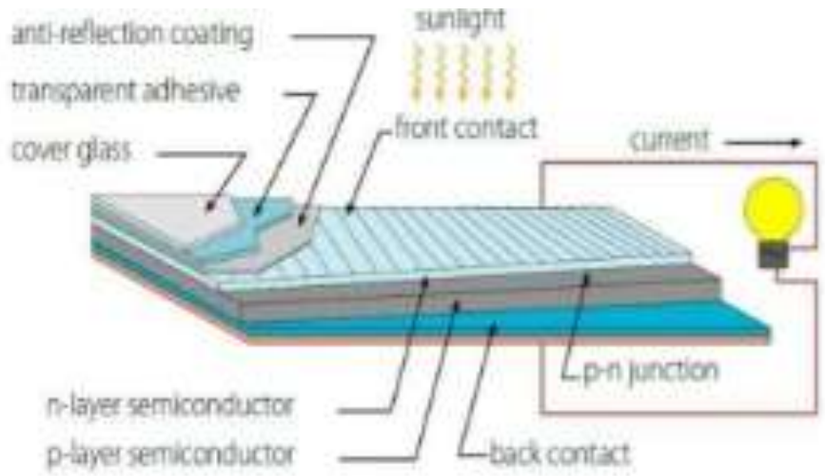
- Donor/acceptor system of **polymers and small molecules**
- Efficiency: 17.4%

PEROVSKITE SOLAR CELLS (PSC)

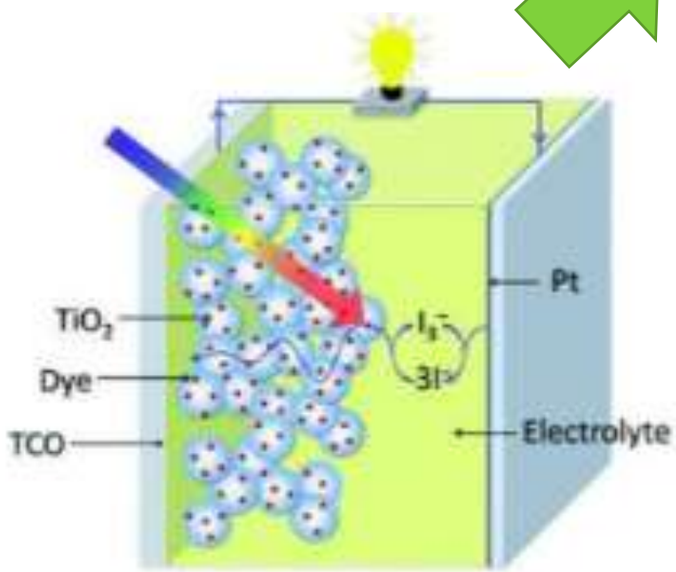


- Hybrid organic inorganic **perovskite crystalline** absorber
- Efficiency: 25.2%

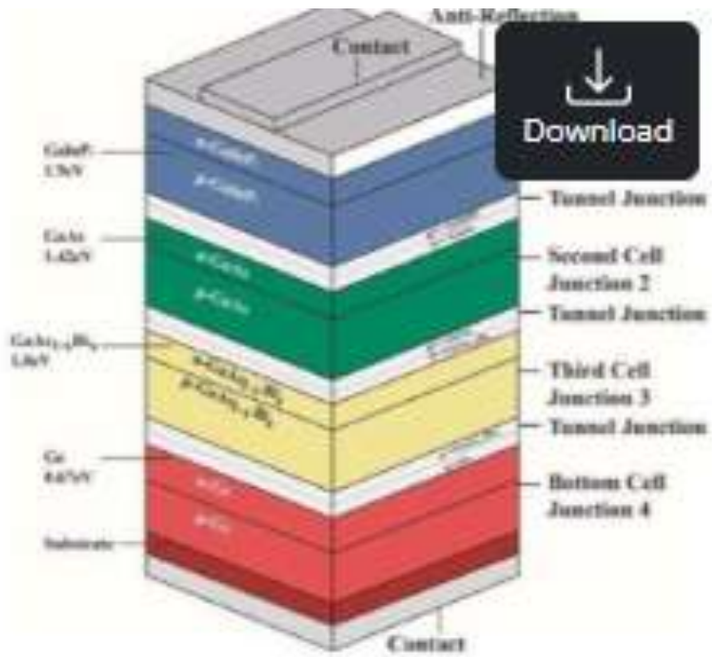
DIFFERENT SOLAR CELL SYSTEMS



Semiconductor type photovoltaic cell



Dye sensitized solar cell



Multi junction solar cell

Quantum dot solar cell

Thin film solar cell

Silicon-based solar cell (traditional)

DEVICE LIMITATIONS

1. **Efficiency**: Most solar cells are only 15–22% efficient. Advanced cells can go higher but usually cost more and may be less stable.
2. **Dependence on Sunlight**: Solar devices need sunlight, so power generation drops during cloudy weather, at night, and in low-sunlight regions.
3. **Need for Storage**: Because sunlight is inconsistent, batteries or storage systems are needed for steady power, which adds to the cost.
4. **High Setup Cost**: Although prices are dropping, the initial cost for equipment and installation can still be high.
5. **Space Requirements**: Solar farms need a lot of space, which may not be available in crowded areas. Rooftop panels are limited by roof space.
6. **Material Limitations**: Some solar cells use rare or toxic materials, raising environmental and supply concerns.
7. **Durability**: Some cells, like organic and perovskites types, have shorter lifespan and degrade faster than traditional silicon cells.
8. **Environmental Impact**: Manufacturing solar panels can be energy-intensive and involves hazardous chemicals like **CdTe.**
9. **Heat Sensitivity**: High temperatures can reduce the efficiency of solar panels, especially silicon-based ones.

MERITS OF SOLAR ENERGY

1. **Renewable & Abundant:** Unlimited energy source.
2. **Environmentally Friendly:** No greenhouse gas emissions.
3. **Decentralized Energy Production:** Suitable for remote locations.
4. **Low Operating Costs:** Once installed, maintenance costs are minimal.
5. **Versatile Applications:** Used for electricity (solar PV), heating (solar thermal), and industrial processes.

POTENTIAL APPLICATIONS

- **Hydrogen Production**: Green hydrogen created through artificial photosynthesis could serve as a clean fuel in energy-intensive industries and transportation.
- **Synthetic Fuels**: Artificial photosynthesis could produce synthetic hydrocarbons that can be directly used in existing fossil-fuel infrastructure, like aviation fuel.
- **Carbon Recycling**: Industries could use artificial photosynthesis to capture CO_2 emissions and convert them into valuable products, such as chemicals or fuels.
- Electricity Generation
- Water Desalination
- Industrial Processes
- Enhanced Oil Recovery
- Solar Cooking
- **Application includes carbon capture and utilization (CCU)** technologies, which aim to capture CO_2 emissions from industrial processes and convert it into valuable products like fuels, plastics, or chemicals.

COMMERCIAL REALIZATION & CHALLENGES

Commercial Realization

1. **Solar Photovoltaic (PV) Systems** – Converts sunlight into electricity.
2. **Concentrated Solar Power (CSP)** – Uses mirrors to focus sunlight for heat generation.
3. **Solar Water Heaters & Cookers** – Efficient household applications.
4. **Solar Farms & Rooftop Systems** – Large-scale and decentralized energy generation.

Challenges

1. **Manufacturing Complexities:** Producing high-efficiency solar panels on a large scale involves advanced materials and fabrication techniques, leading to increased manufacturing costs.
2. **Intermittency & Energy Storage:** Solar energy availability depends on weather and time of day; storage solutions like batteries are needed.
3. **High Initial Costs:** Though decreasing, installation costs are still significant.
4. **Land & Space Requirements:** Large-scale solar farms need vast areas.
5. **Material & Manufacturing Constraints:** Dependence on rare earth elements and high-purity silicon.
6. **Grid Integration Issues:** Infrastructure challenges for handling variable solar power.

SOLAR INDUSTRIES

The **solar industry** is a rapidly growing sector that focuses on harnessing energy from the sun for various applications. It consists of multiple segments, each playing a crucial role in the production, distribution, and utilization of solar energy.

1. Solar Panel Manufacturing: These companies manufacture photovoltaic (PV) panels, which convert sunlight into electricity. They produce different types of solar panels, including:

a. **Monocrystalline Panels** (High efficiency, long lifespan)

b. **Polycrystalline Panels** (Lower cost, slightly lower efficiency)

c. **Thin-Film Solar Panels** (Flexible, lightweight, used for large-scale installations)

Leading Companies

- **First Solar** (USA) – Specializes in thin-film solar technology
- **Jinko Solar** (China) – Largest global PV module manufacturer
- **Trina Solar** (China) – One of the most efficient panel manufacturers
- **Canadian Solar** (Canada) – Provides solar panels and energy storage solutions
- **Adani Solar** (India) – One of India's top solar panel manufacturers

SOLAR INDUSTRIES

2. **Solar Inverter Manufacturing:** Solar inverters convert the direct current (DC) from solar panels into alternating current (AC) for household or industrial use.

Types of Solar Inverters:

a. **String Inverters** (Common for residential solar systems)

b. **Micro inverters** (Higher efficiency, installed on each panel)

c. **Hybrid Inverters** (Work with battery storage for backup power)

Leading Companies

- **Solar Edge Technologies** (Israel) – Offers high-efficiency inverters with smart monitoring.
- **Enphase Energy** (USA) – Specializes in micro inverters
- **SMA Solar Technology** (Germany) – Provides a range of inverters for residential and commercial use.
- **Schneider Electric** (France) – Develops hybrid inverters for solar energy

SOLAR INDUSTRIES

3. **Solar Energy Production :** These companies own and operate large-scale solar power plants that generate electricity for grids, governments, and industries.

Leading Companies

- **NextEra Energy** (USA) – One of the world's largest solar power producers
- **Adani Green Energy** (India) – Largest solar power producer in India
- **Tata Power Solar** (India) – Major player in large-scale solar projects
- **ReNew Power** (India) – Specializes in solar and wind energy projects

4. **Residential & Commercial Solar Installation:** Businesses that install solar panels on homes and commercial buildings. Example: **Sun run, Tesla Solar, Vivint Solar.**

Leading Companies

- **Sunrun** (USA) – Offers solar leasing and installation
- **Tesla Solar** (USA) – Known for its solar roof tiles and Power wall battery
- **Vivint Solar** (USA) – Residential solar solutions provider
- **Waaree Energies** (India) – Provides turnkey solar installation services

5. **Solar Battery & Energy Storage Solutions:** Companies producing batteries to store solar energy for later use.

Types of Solar Batteries:

1. **Lithium-Ion Batteries** (High efficiency, long lifespan)
2. **Lead-Acid Batteries** (Low cost but shorter lifespan)
3. **Flow Batteries** (Best for large-scale energy storage)

Leading Companies

- **Tesla Power wall** (USA) – Home battery for solar energy storage
- **LG Chem** (South Korea) – Produces high-performance lithium-ion batteries
- **BYD** (China) – Large-scale battery manufacturer
- **Sonnen** (Germany) – Offers intelligent home battery storage solutions

SOLAR INDUSTRIES

6. **Solar Thermal Energy Companies:** Firms focusing on concentrated solar power (CSP) using mirrors to generate heat.

Leading Companies

- **BrightSource Energy** (USA) – Develops large-scale CSP projects
- **Abengoa Solar** (Spain) – Specializes in solar thermal plants
- **ACWA Power** (Saudi Arabia) – Focuses on large CSP projects in the Middle East

7. **Solar Component & Raw Material Suppliers:** Companies producing essential materials like silicon wafers, glass, and frames for solar panel production.

Leading Companies

- **Wacker Chemie** (Germany) – Produces polysilicon for solar cells
- **REC Silicon** (Norway) – One of the largest silicon suppliers
- **DOW Corning** (USA) – Provides specialty materials for solar panels

SOLAR INDUSTRIES

8. **Solar Software & Monitoring Solutions:** With advancements in technology, companies offering software for solar system monitoring, efficiency analysis, and grid management.

Leading Companies

- **Aurora Solar** (USA) – AI-driven solar design and simulation software
- **Sense** (USA) – Real-time energy monitoring for solar users
- **Solar Analytics** (Australia) – Smart solar energy monitoring solutions

SOLAR INITIATIVES- GLOBAL INVESTMENTS AND INITIATIVES

The global solar energy market is experiencing significant growth, driven by technological advancements, substantial investments, and supportive government policies.

1. **China:** Leading the world in solar power generation, China has invested **nearly $940 billion in clean energy in 2024,** focusing on solar, batteries, and EV infrastructure.

2. In **February 2024,** the Indian government launched the **Pradhan Mantri Surya Ghar Muft Bijli Yojana,** aiming to install rooftop solar panels for 10 million households, providing them with 300 units of free electricity monthly. The scheme offers direct subsidies and concessional loans to beneficiaries, promoting energy self-reliance and reducing electricity bills.

SOLAR INITIATIVES

3. **United States**: Added **48.2 GW of renewable energy in 2024**, driven by the **Inflation Reduction Act** that provides incentives for solar adoption.

4. **Japan**: Investing **$1.5 billion** in **ultra-thin perovskite solar panels** to reduce dependency on Chinese solar technology.

Corporate & Private Sector Solar Initiatives

- **Google**: Aims for 100% renewable energy-powered data centers by 2030
- **Tesla Solar Roof**: Expanding residential solar-integrated roofing
- **Lightsource bp**: Secured 1.3 GW solar projects with major corporations
- **Amazon**: Investing in large-scale solar farms for carbon neutrality

SOLAR INITIATIVES

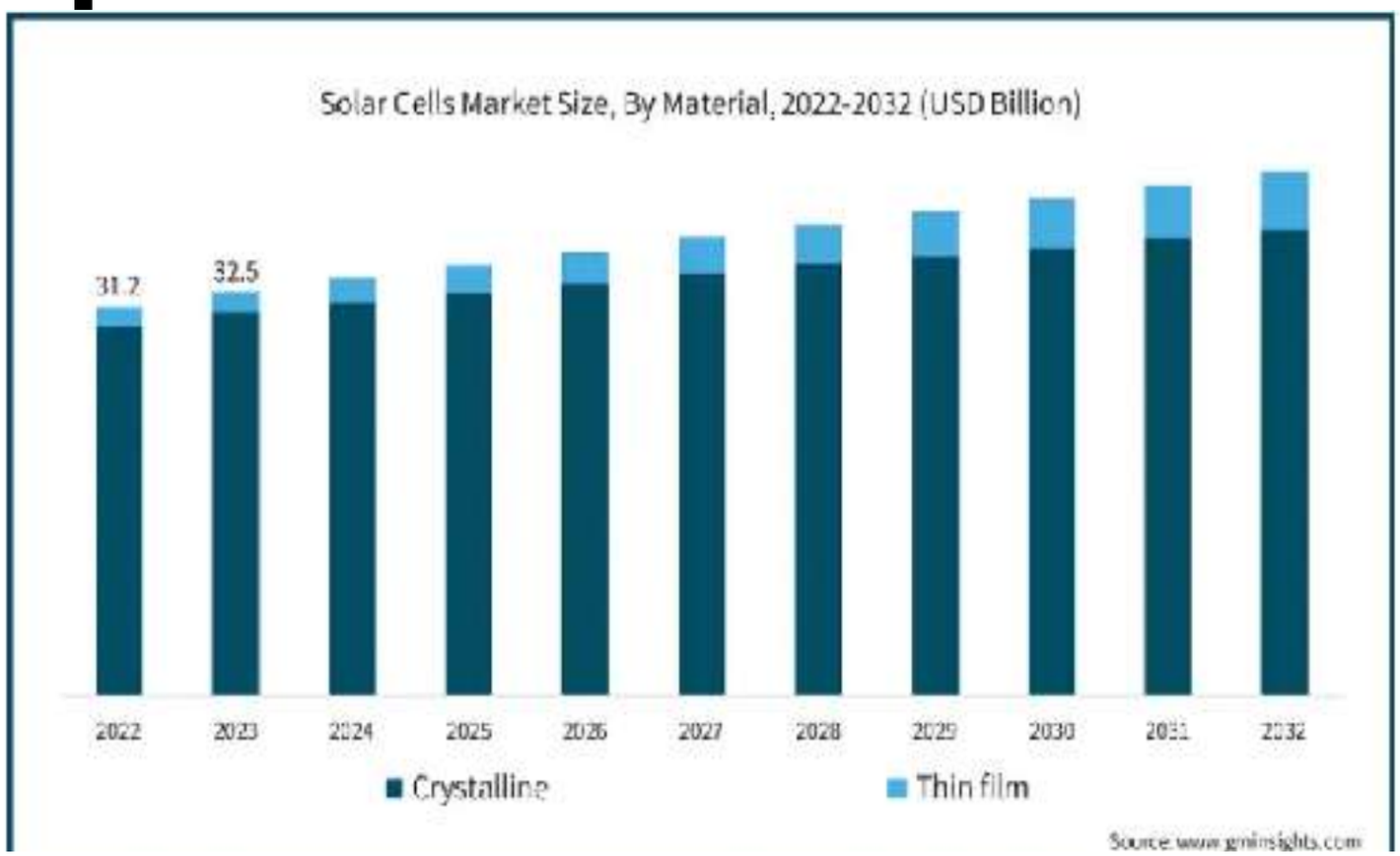
Key Trends & Challenges

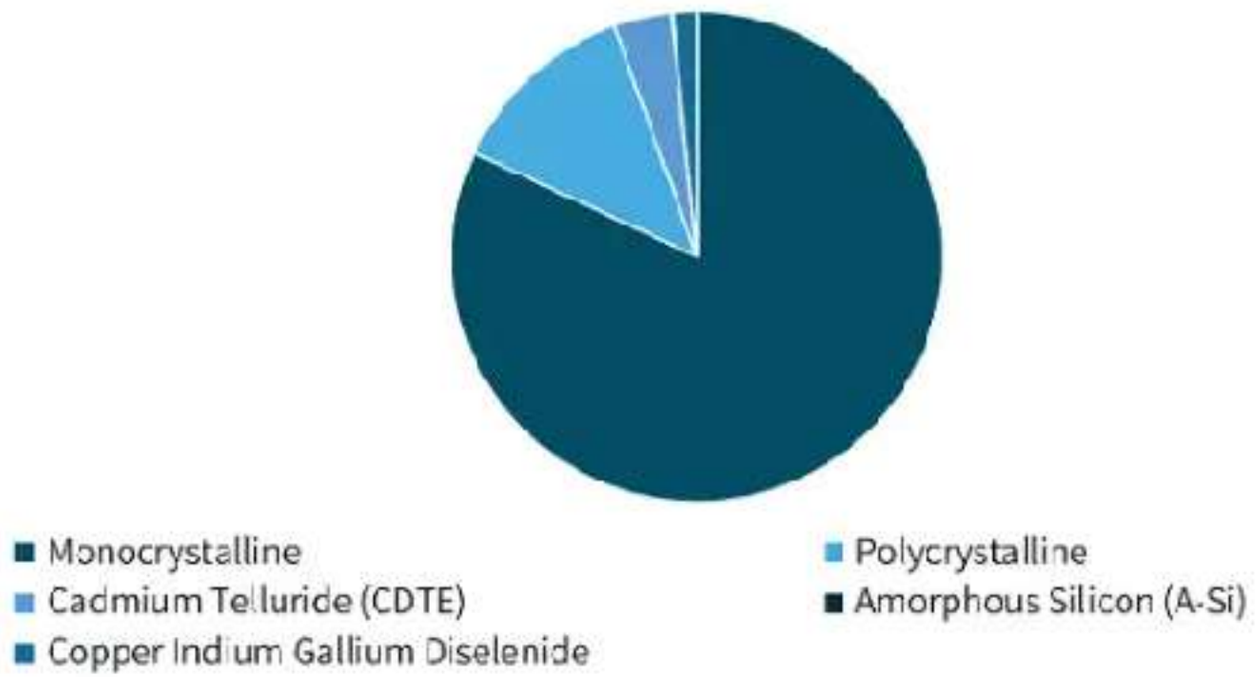
- **Growth in Solar Storage**: Rising adoption of **battery storage solutions**
- **High Interest Rates**: Impacting investment in solar projects
- **Policy Uncertainty**: Political shifts may affect solar incentives

- Technological innovations have significantly reduced costs, with solar panel prices dropping by 66% over the past two years and battery system prices by 58% in the last year. These reductions enhance the competitiveness of renewable energy projects and open new opportunities for grid stabilization.

- As of January 31, 2025, India’s installed solar capacity reached 100.33 GW, making it the world's third-largest solar power producer. The country surpassed its National Solar Mission target of 100 GW by 2022 and aims for 500 GW of renewable energy by 2030.
- The Indian solar energy market, valued at USD 38 billion in 2021, is projected to reach USD 238 billion by 2030, growing at a CAGR of 40%. This growth is driven by government policies, technological advancements, and rising demand for clean energy.

SOLAR CELL MARKET SIZE





Based on material, the **crystalline solar cells industry** is anticipated to cross over USD 37 billion by 2032, on account of high efficiency and low costs.

The global solar cell market has been experiencing significant growth, driven by the increasing adoption of renewable energy sources and supportive government policies.

In 2024, the market was valued at approximately USD 149.45 billion and is projected to reach around USD 730.74 billion by 2034, reflecting a compound annual growth rate (CAGR) of 17.2% during this period.