EV20001: ENVIRONMENTAL SCIENCE

Lecture #5

Renewable Energy – I

Dr. Shamik Chowdhury

School of Environmental Science and Engineering

E-mail: shamikc@iitkgp.ac.in

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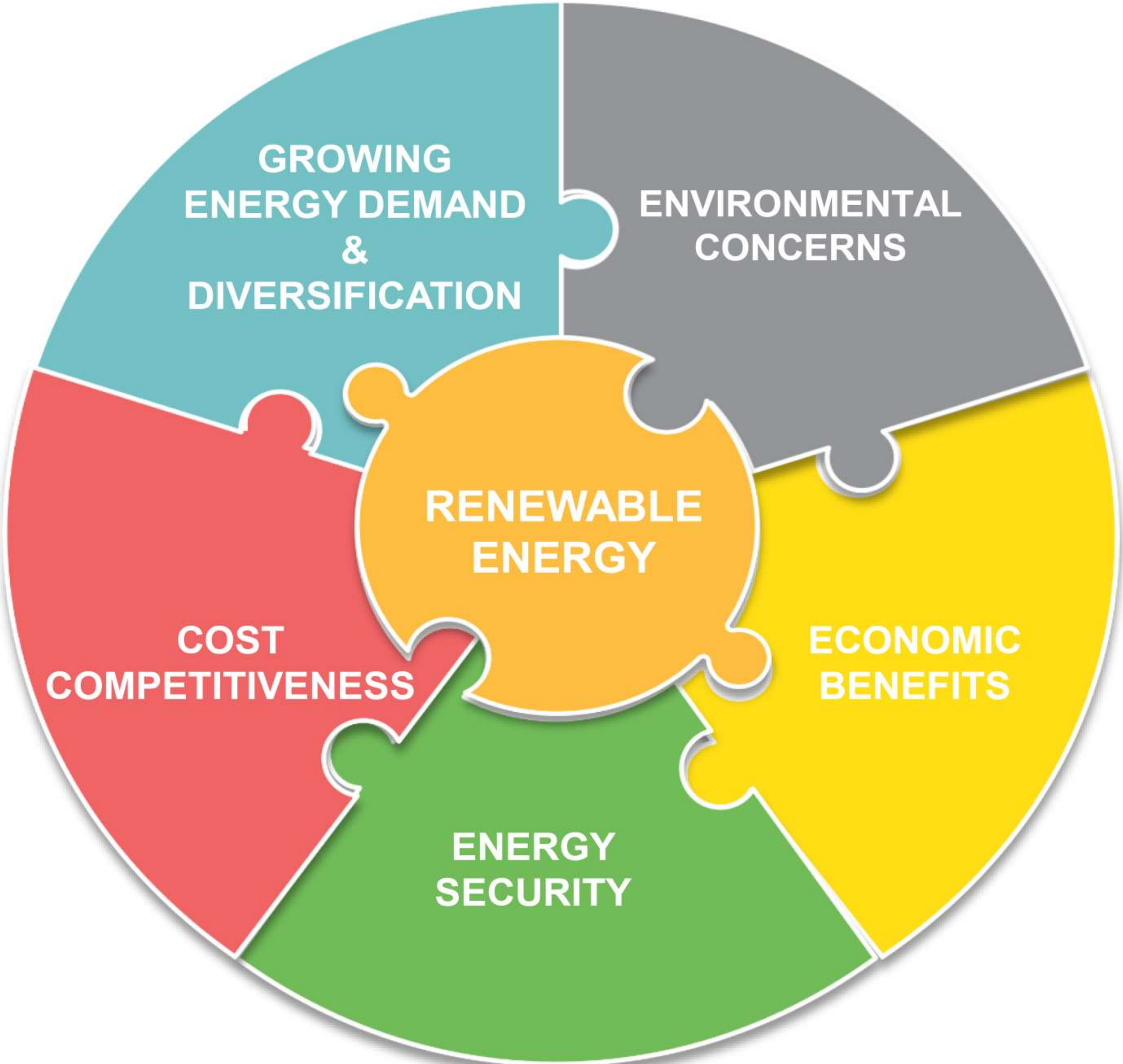
Renewable energy

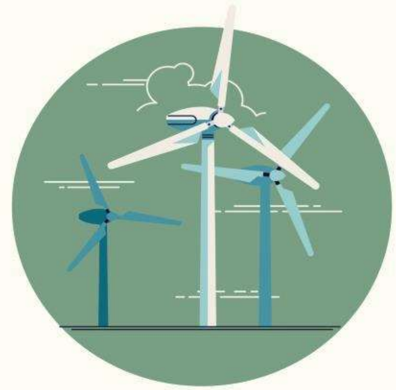
- Renewable energy (RE) is any form of energy that is **replenished by natural processes** at a rate that equals or exceeds its rate of use.
- RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar radiation, geothermal heat, hydropower, tides and waves, and wind.
- Unlike fossil fuels, RE sources do not directly emit CO_2 when producing electricity. In order to cut global CO_2 emissions by at least 80% by 2050 and slow the projected climate change, the world will need to transition to RE.
- Most RE technologies produce lower conventional air and water pollutants than fossil fuels, thereby greatly reducing the pollution of air, land and water.
- RE can also result in a more decentralized and efficient energy economy that would be less vulnerable to supply cutoffs from terrorist attacks and natural disasters, improve economic and national security for many countries by reducing their dependence on imported crude oil and natural gas, create large numbers of jobs and save consumers money.

Key drivers of renewable energy



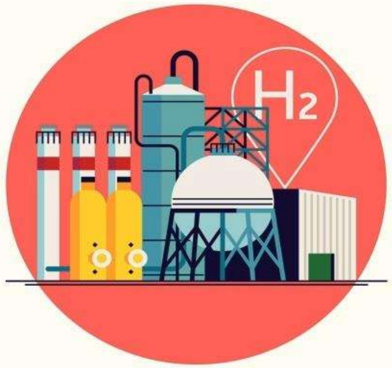
Types of renewable energy resources

Solar Energy



Wind Energy

Geothermal Energy

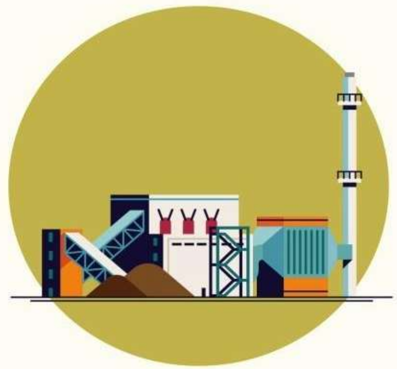


Hydrogen Energy

Tidal Energy

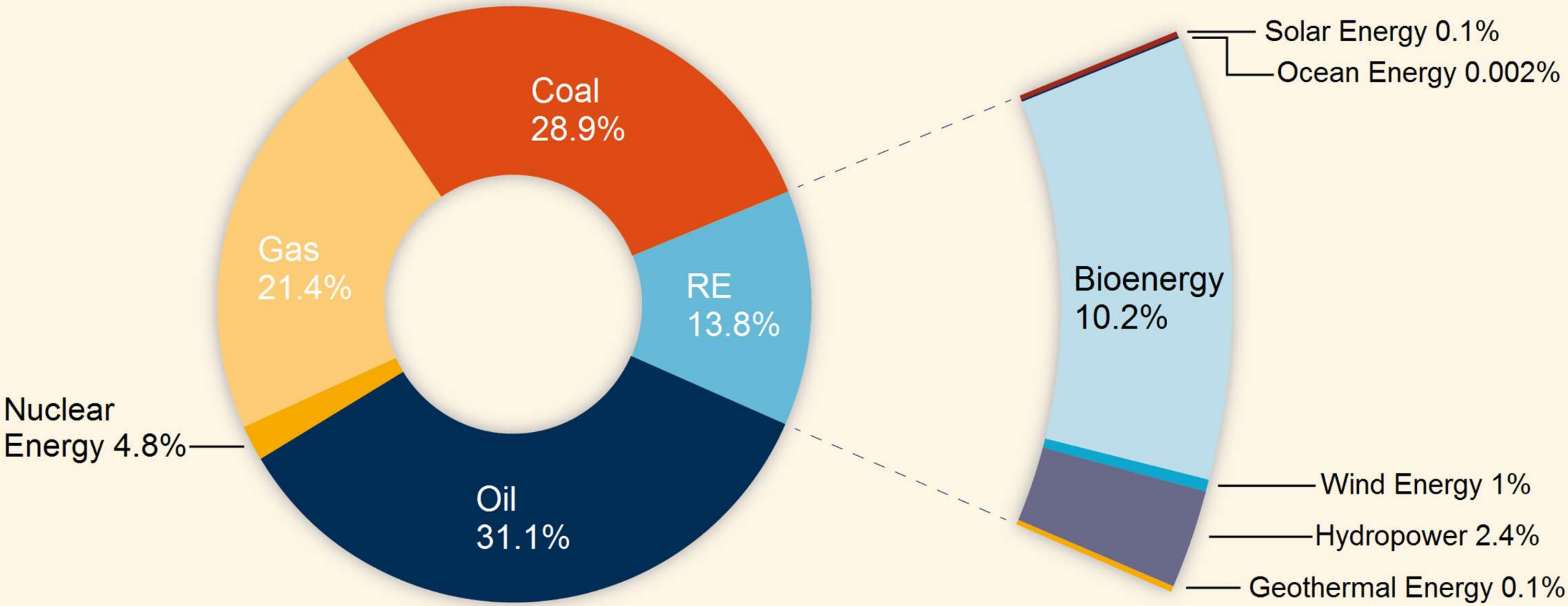
Wave Energy

Hydroelectricity



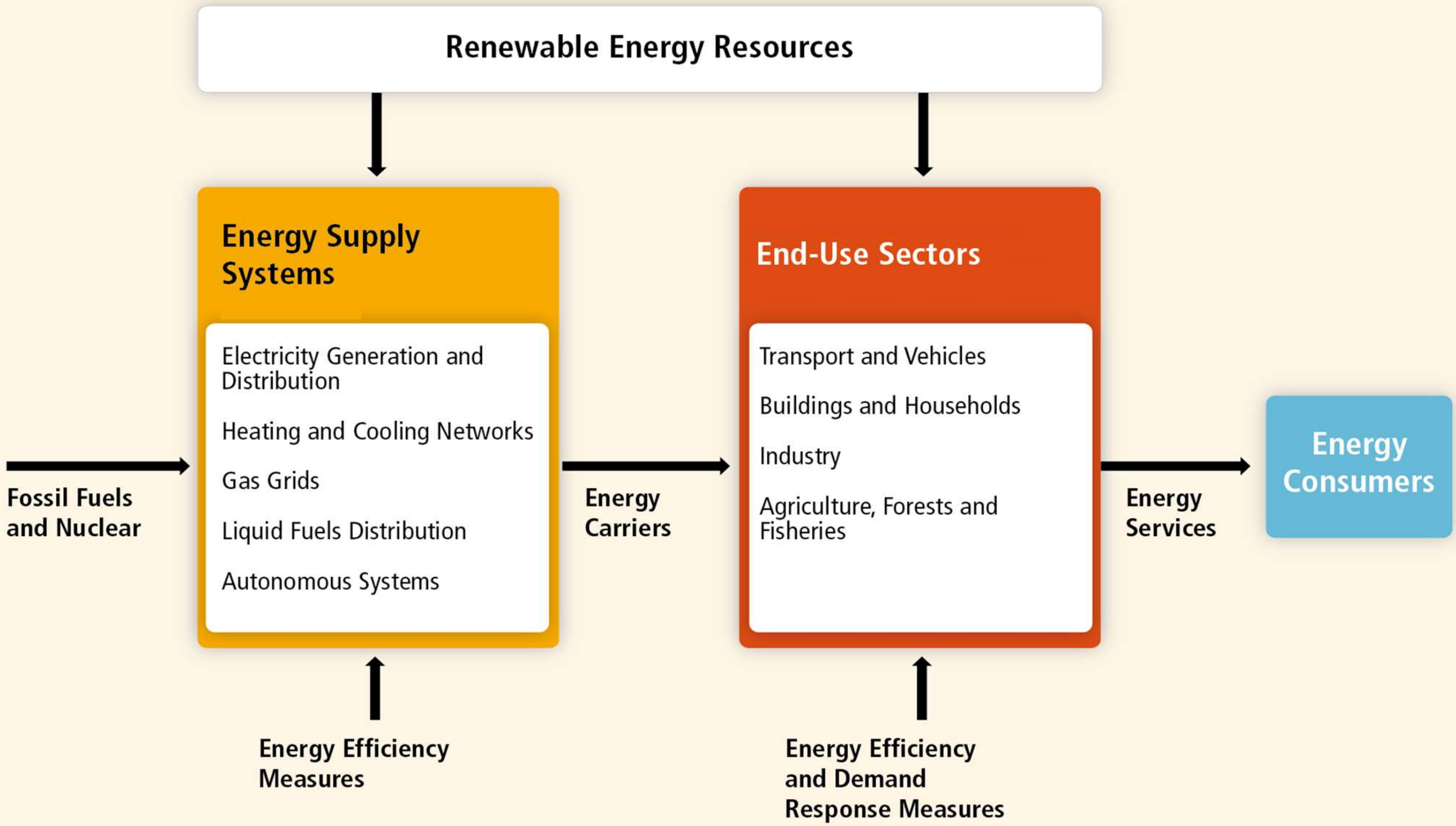
Biomass Energy

- Deployment of RE has been increasing rapidly in recent years. On a global basis, it is estimated that RE accounted for 13.8% of the total primary energy supply in 2013. The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) of the biomass fuel used in traditional cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well. Hydropower represented 2.4%, whereas other RE sources accounted for 1.2%.



Shares of energy sources in total global total primary energy supply in 2013

- Various RE resources are already being successfully integrated into energy supply systems and into end-use sectors.

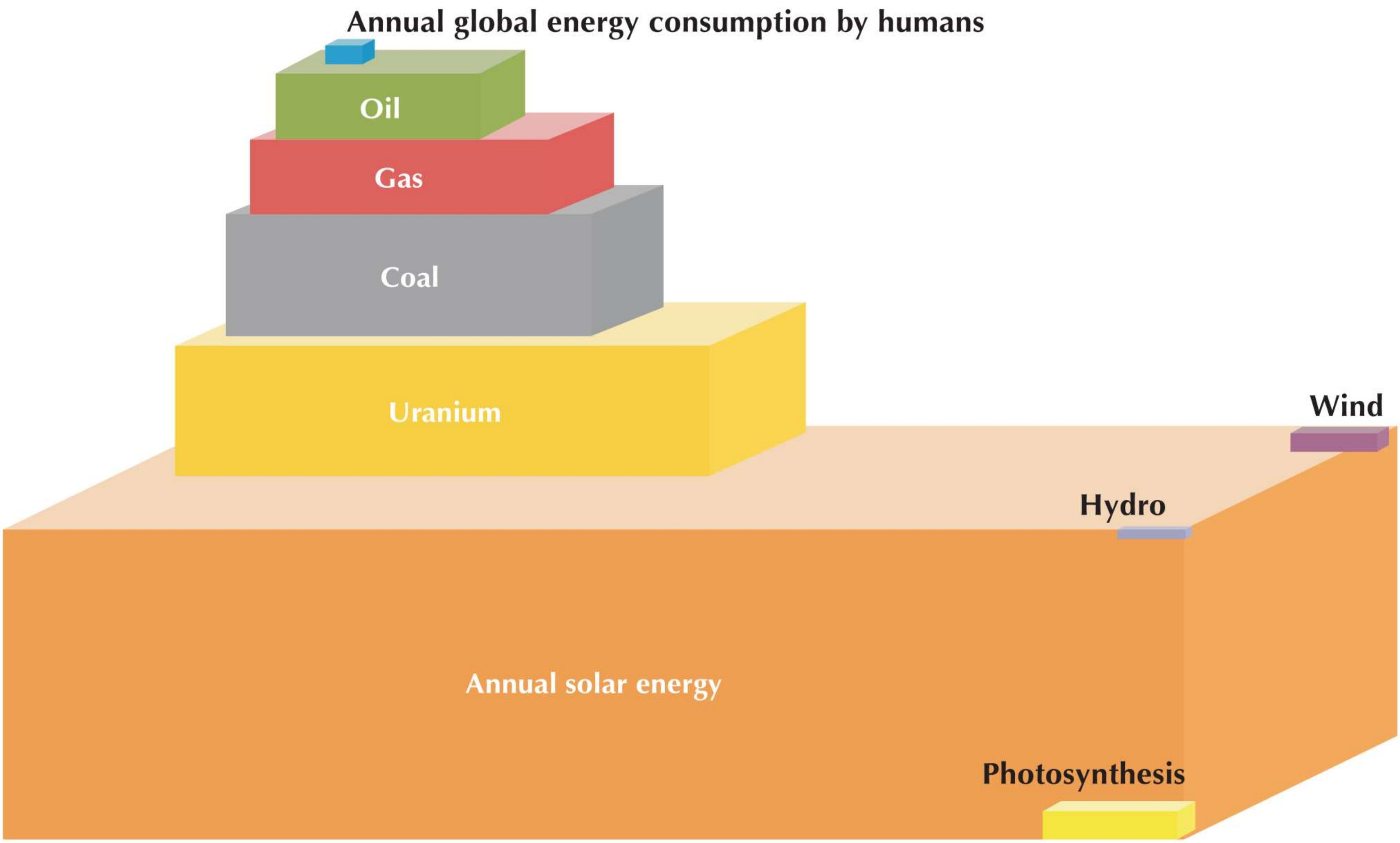


Pathways for RE integration to provide energy services, either into energy supply systems or on-site for use by the end-use sectors.

Solar Energy

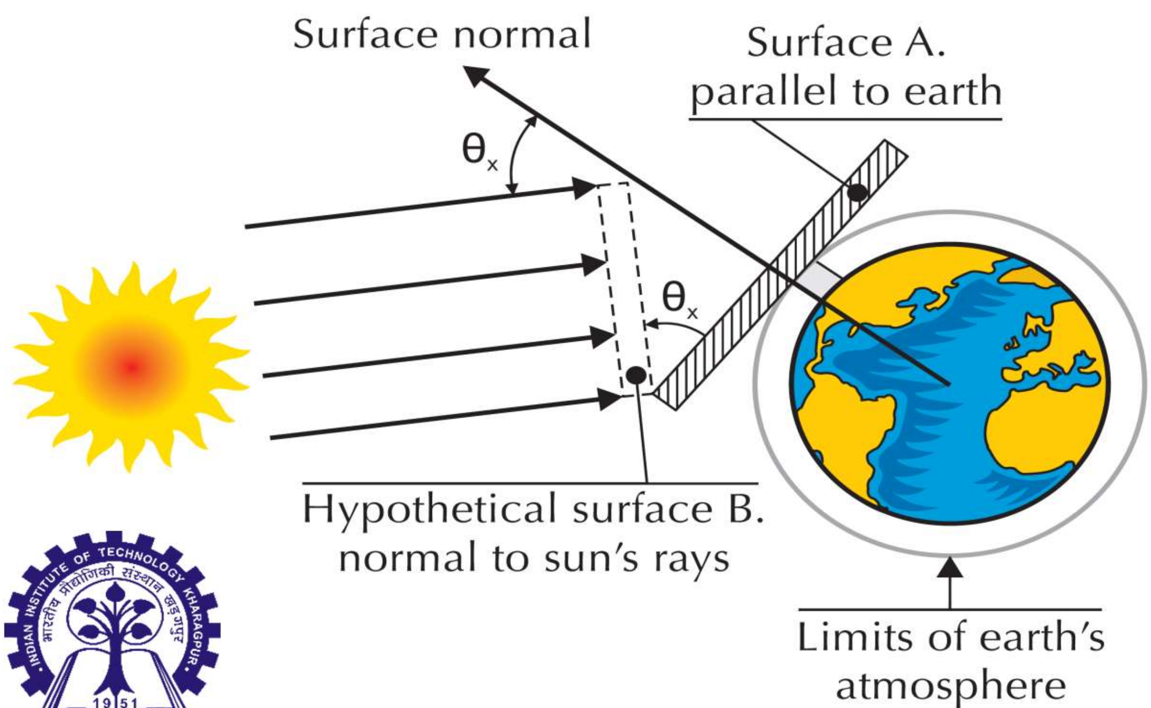
Direct solar energy

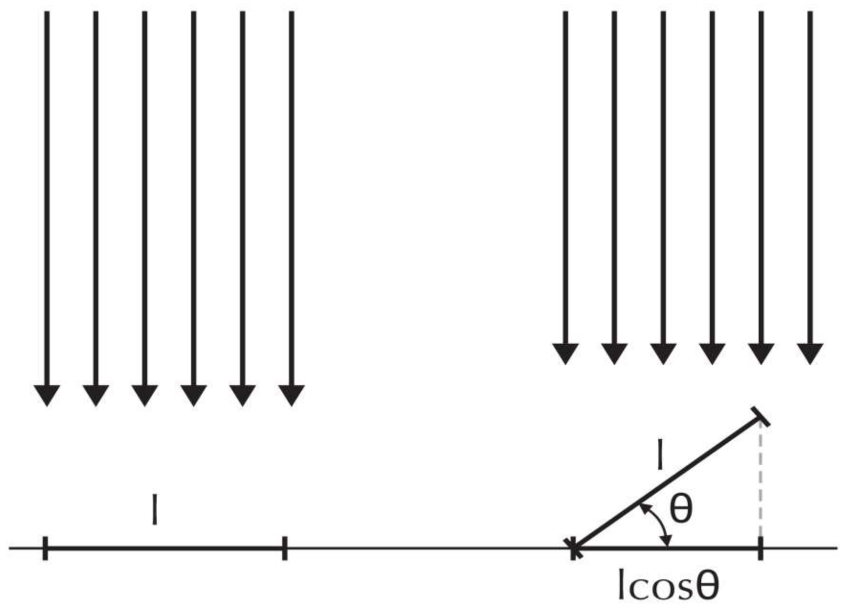
- Solar energy is the largest energy resource on Earth – and is inexhaustible.



- Solar irradiance is maximal when the sun is directly overhead. When the sun is lower in the sky, its energy is spread over a larger area, and is therefore weaker per surface area. This is called the **cosine effect**.
- More specifically, supposing no atmosphere, in any place on a horizontal surface the direction of the sun at its zenith forms an angle with the vertical. The irradiance received on that surface is equal to the irradiance on a surface perpendicular to the direction of the sun, multiplied by the cosine of this angle.

The cosine effect





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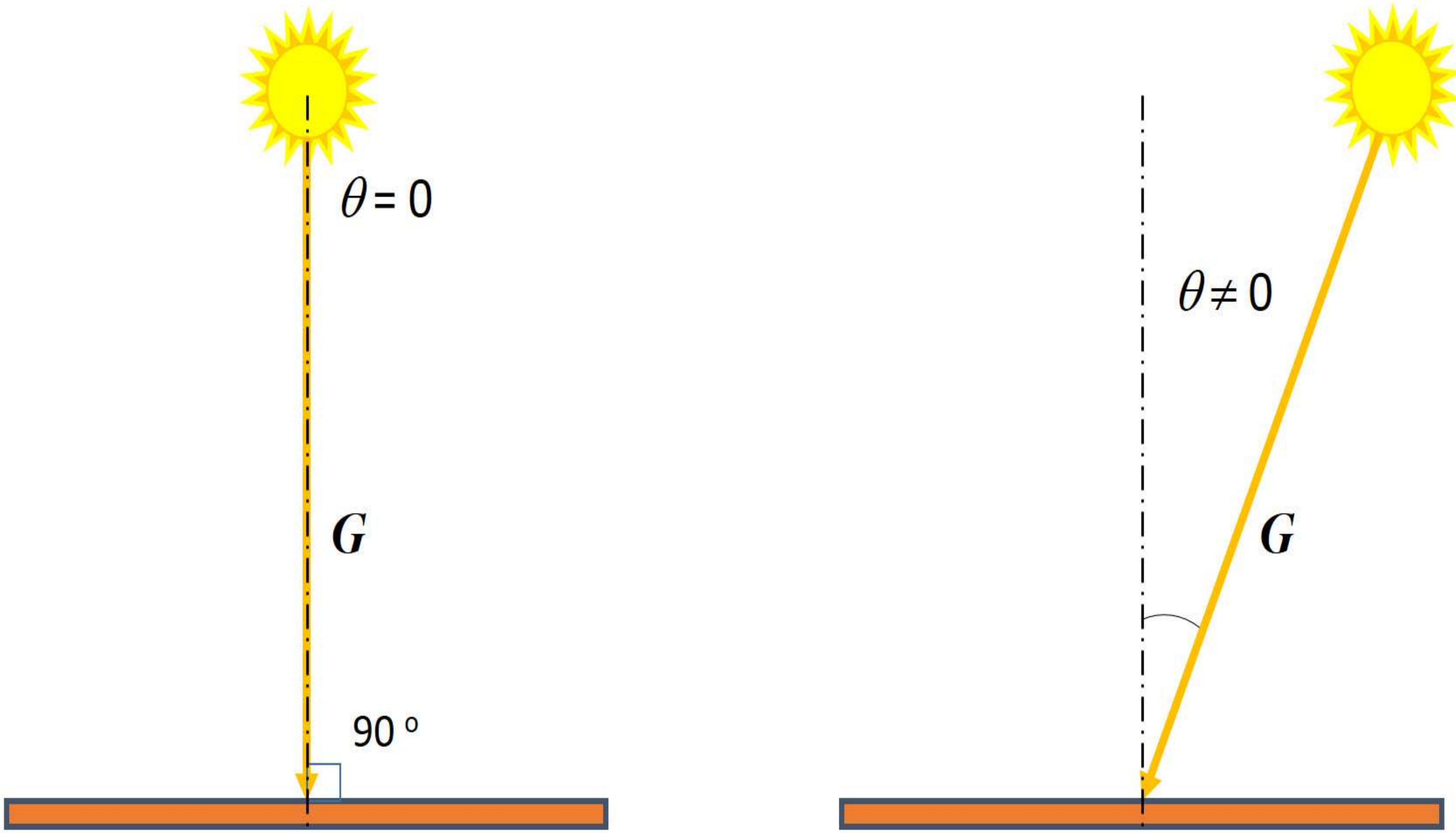

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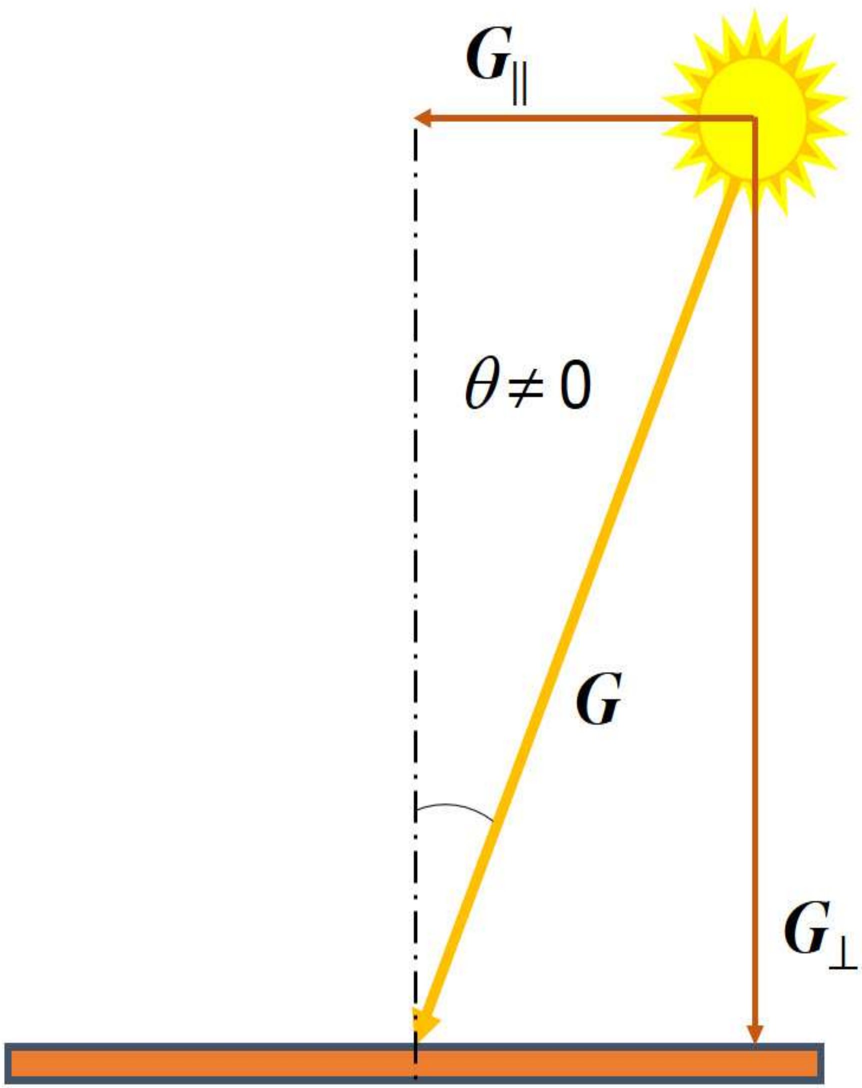

$$G_{\perp} = G\cos(\theta)$$

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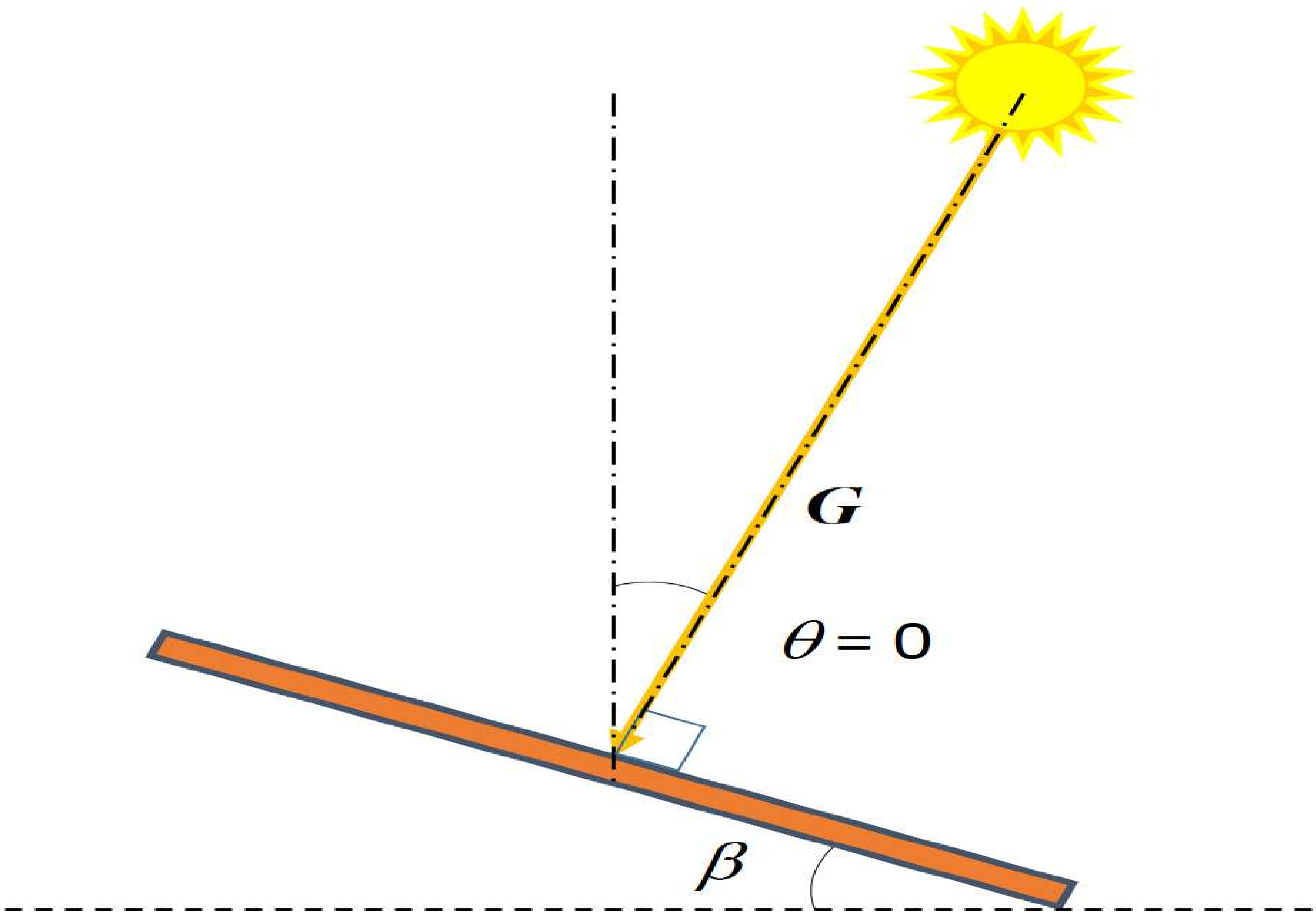
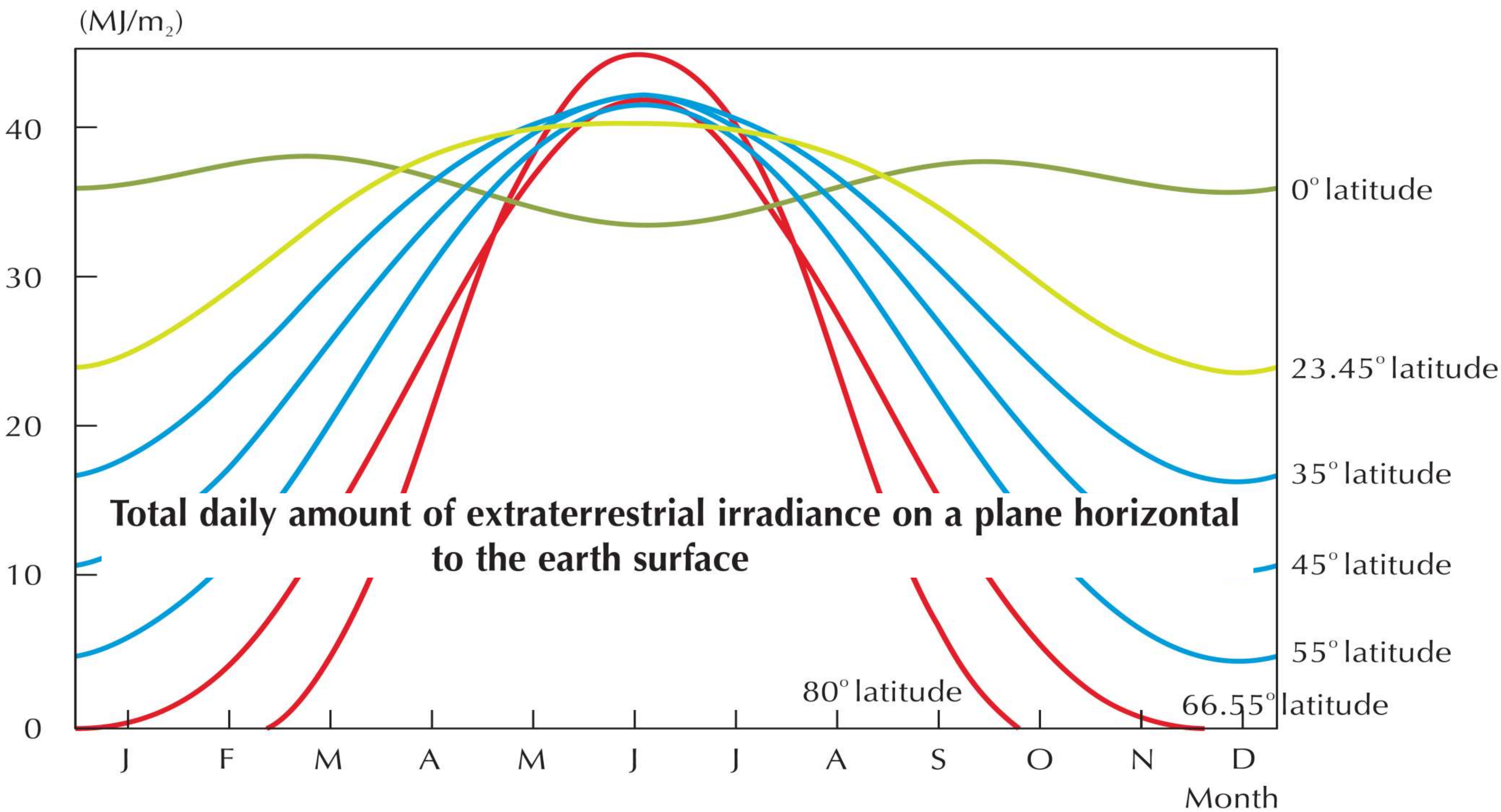
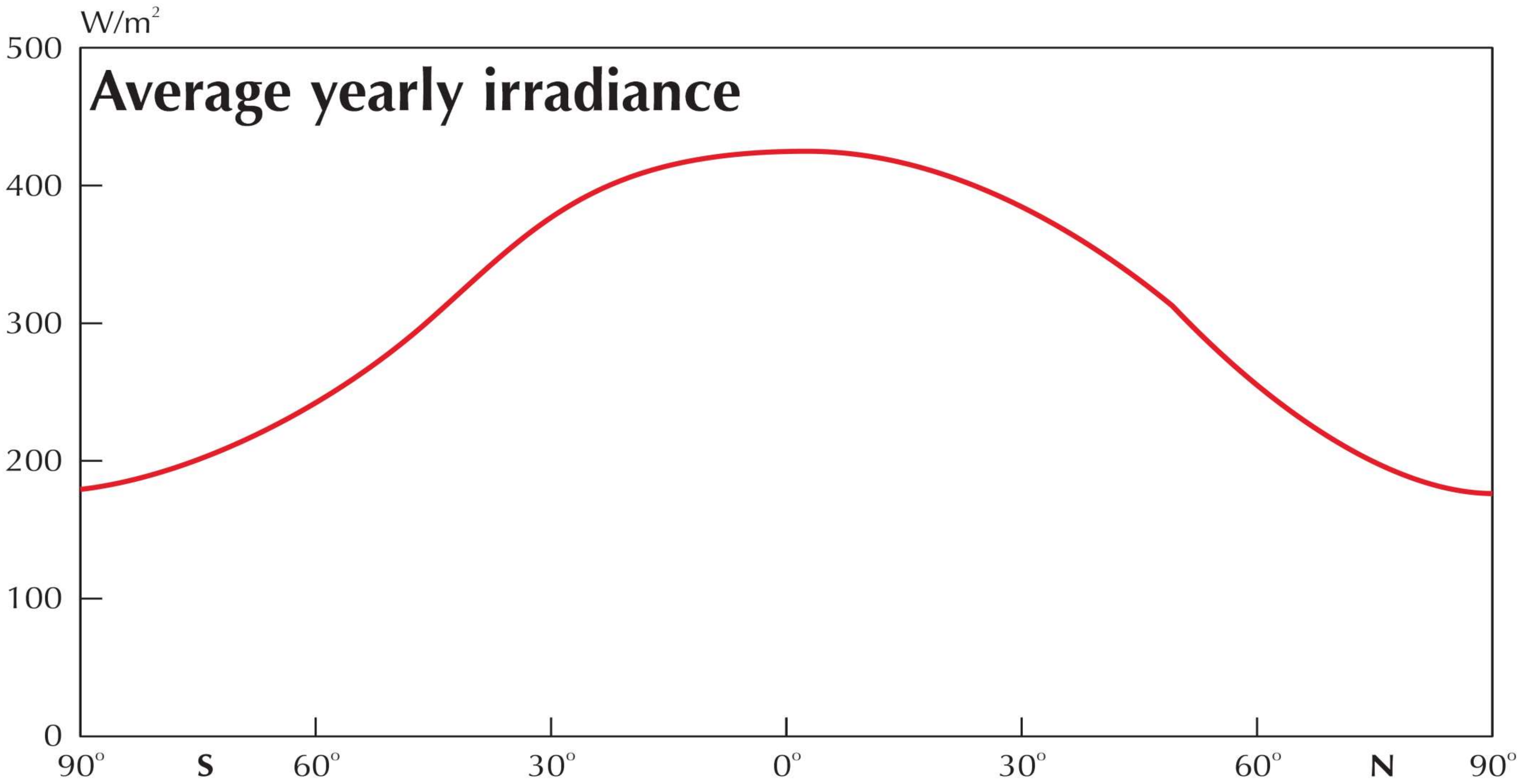


- Solar irradiance varies over the year at diverse latitudes – very much at high latitudes, especially beyond the polar circles, and very little in the tropics.



- Solar irradiance is of fundamental importance for harvesting high quality solar energy and is deemed good to excellent between 10° and 40°, South or North.

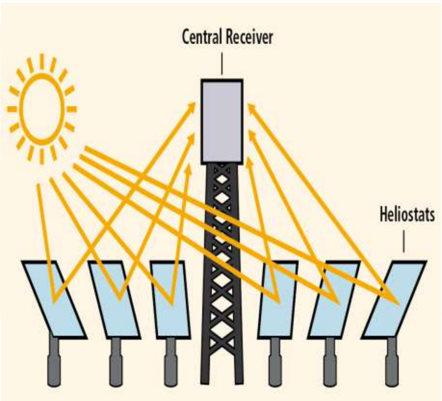


Capturing solar energy

- There are two main methods of capturing energy from the sun:
  - **Heat:** irradiative solar energy is easily transformed into heat through absorption by gases, liquids or solid materials
  - **Photoreaction:** solar radiation can be viewed as a flux of elementary particles that can promote photoreactions and generate a flow of electrons.

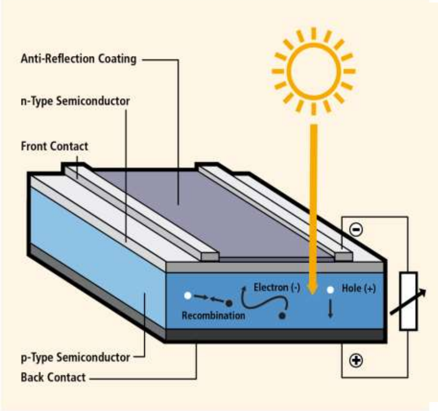
- Depending on the capturing mechanism, there are four major direct solar energy technologies.

Concentrating Solar Power (CSP)



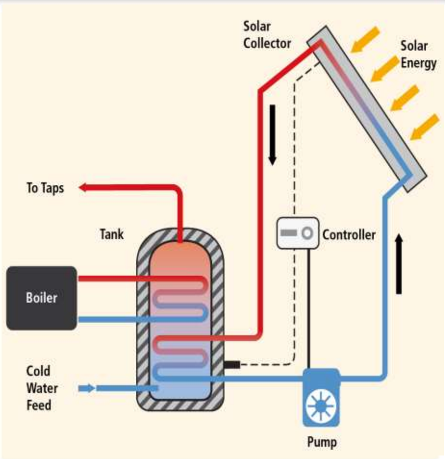
Electricity is generated by the **optical concentration** of solar energy, producing high-temperature fluids or materials to drive heat engines and electrical generators.

Solar Photovoltaic (PV)



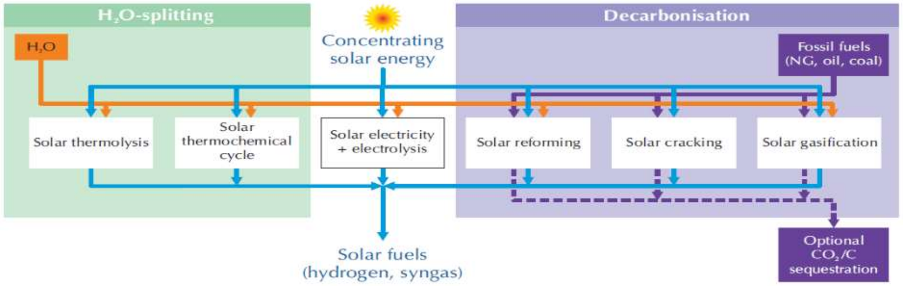
Electricity generation via direct conversion of sunlight to electricity by **photovoltaic cells** (conduction of electrons in semiconductors).

Solar Thermal



Solar panels made up of evacuated tubes or flat-plate collectors **heat up water stored in a tank**. The energy is used for hot-water supply and, occasionally, space heating.

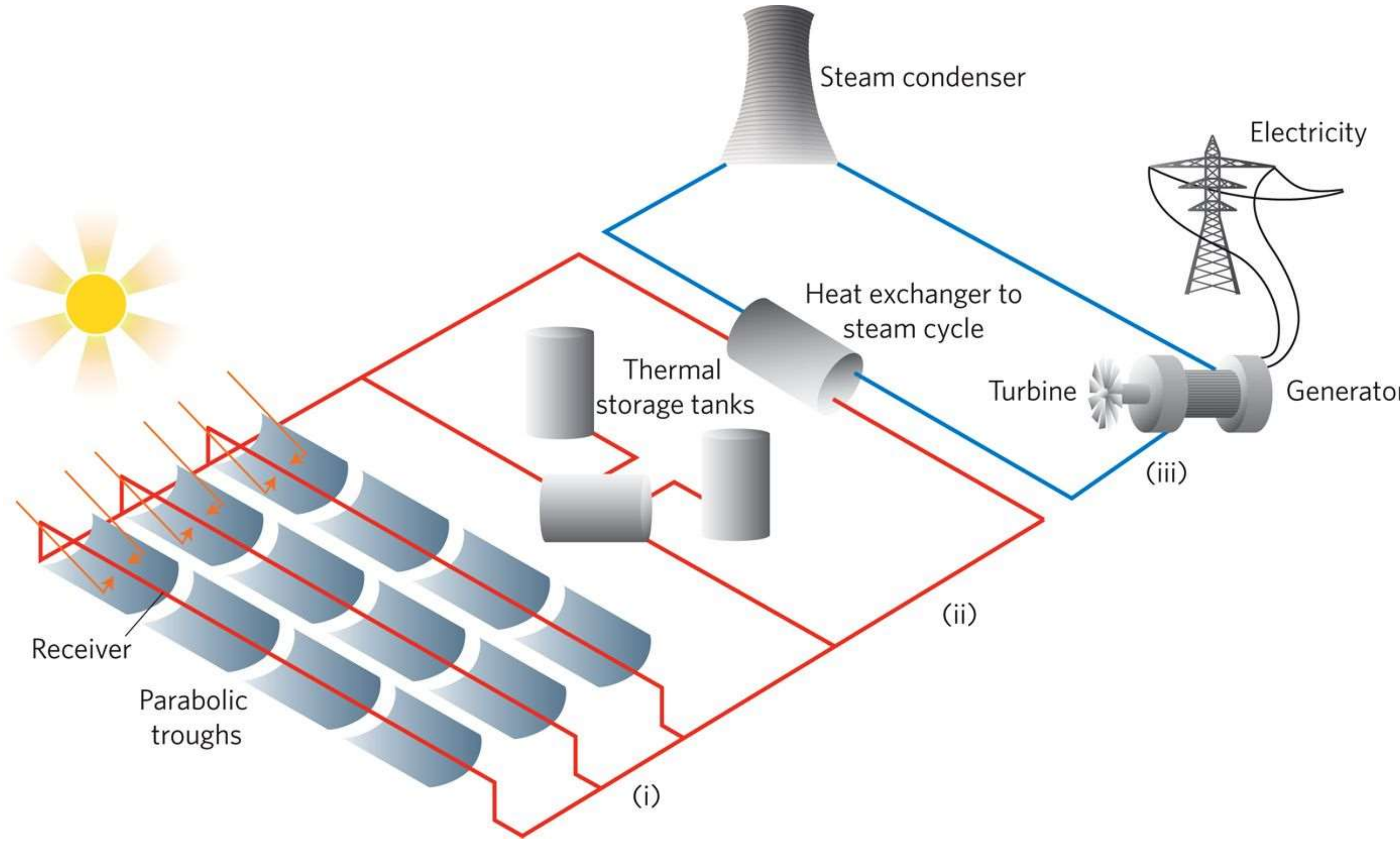
Solar fuels



Solar Fuels processes are being designed to transform the radiative energy of the sun into chemical energy carriers such as hydrogen or synthetic hydrocarbons fuels (*e.g.* electrolysis, thermolysis, photolysis).

Concentrating solar power

- Concentrating solar power (CSP) technologies use different mirror configurations to concentrate solar energy onto a receiver and convert it into heat. The heat can then be used to create steam to drive a turbine to produce electrical power or used as industrial process heat.



CSP plants consist of (i) a solar collector field, (ii) a heat transfer circuit that may include thermal storage and (iii) a conventional power block that converts the high temperature heat to electricity.

- Four main categories of CSP technologies coexist, distinguished by the way they focus the sun’s rays and the technology used to receive the sun’s energy.

THE 4 CSP TECHNOLOGIES

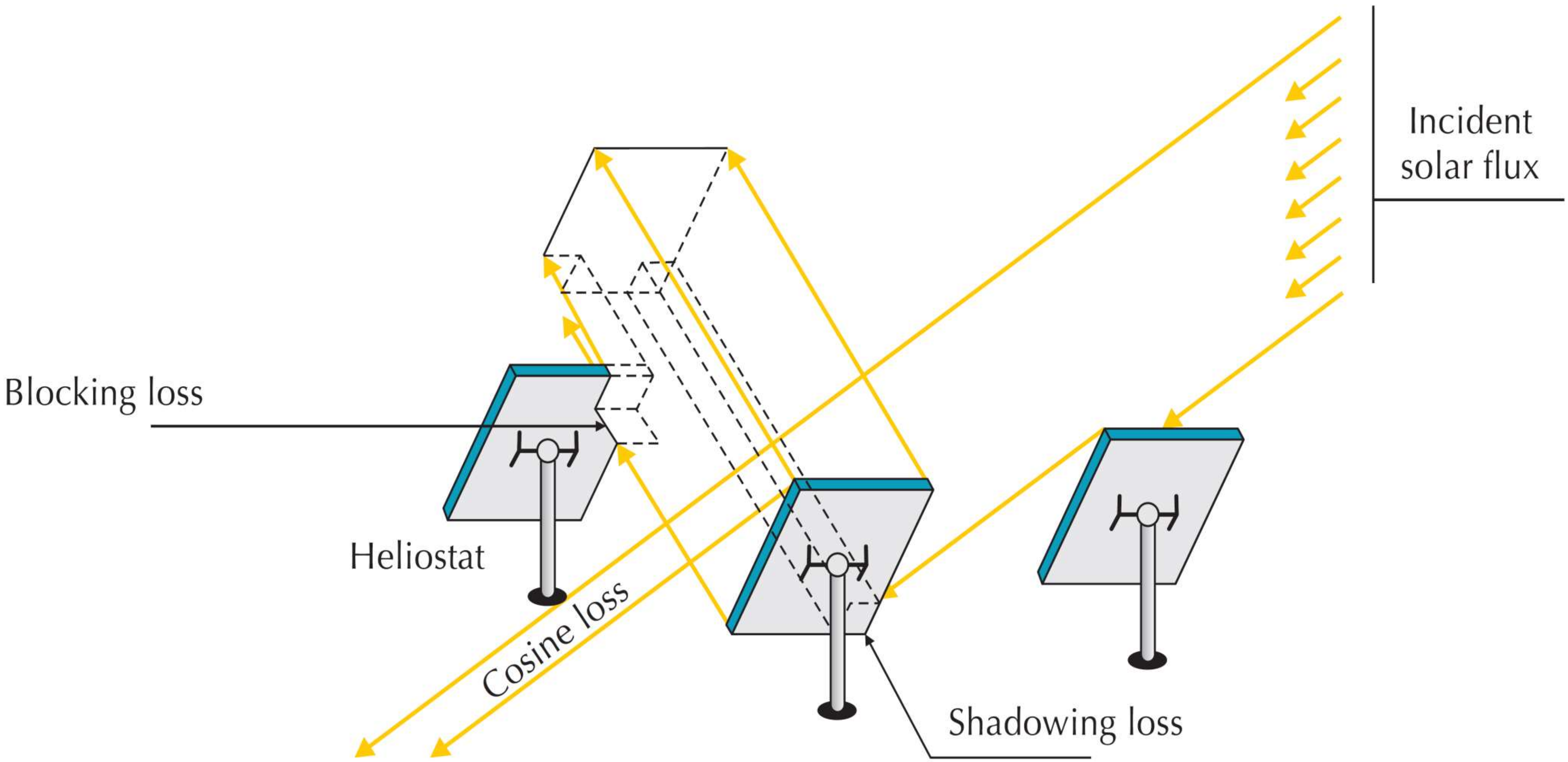
Receiver mobility	Line focus	Point focus
Fixed Receiver remains stationary and mechanically independent of the concentrating system, which is common for all the mirrors.	Linear Fresnel 	Solar Tower 
Tracking/aligned Receiver and concentrating system move together. Mobile receivers enable an optimal arrangement between concentrator and receiver, regardless of the position of the sun.	Parabolic Trough 	Parabolic Dish 

Increasing optical efficiency

Increasing optical efficiency

- The 392 MW *Ivanpah Solar Power Facility*, located in California's Mojave Desert, is the world's largest CSP project currently in operation. It deploys 173,500 heliostats, each with two mirrors, focusing solar energy on boilers located on three centralized solar power towers.

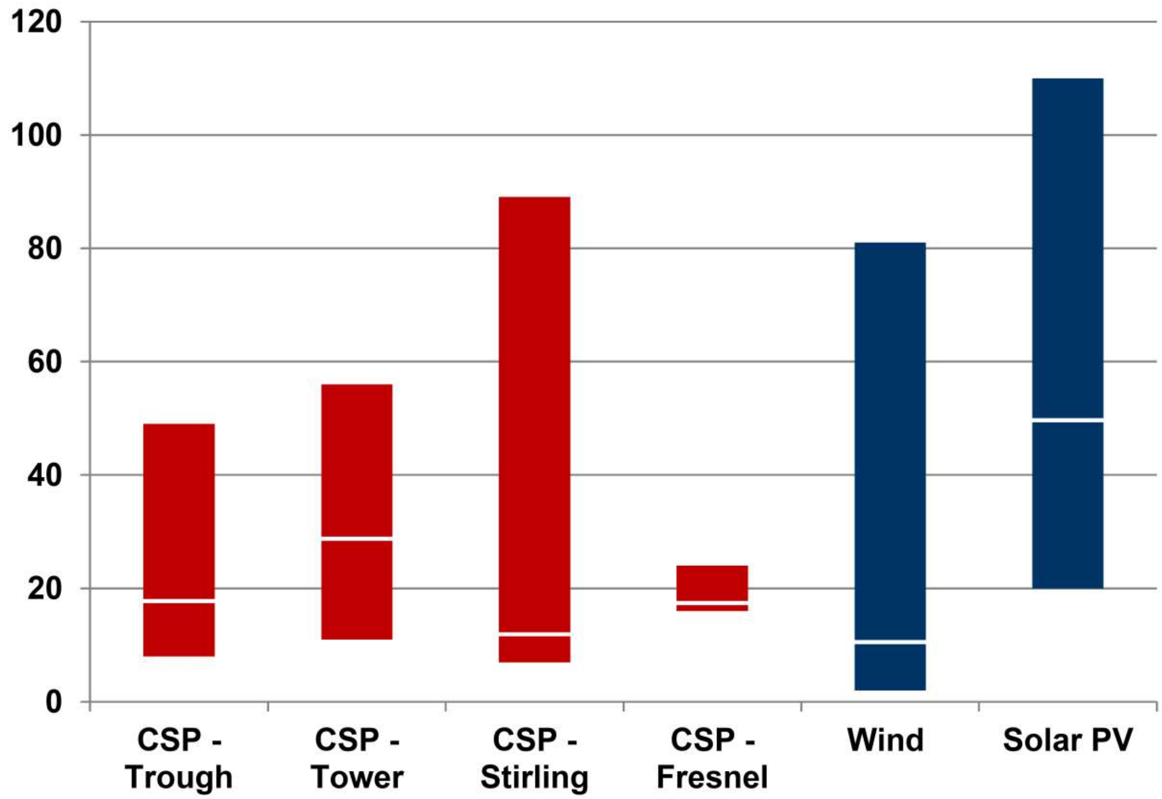
- Heliostats must be distanced from each other to minimize blocking and shading.



Environmental and social impacts

- Greenhouse gas emissions from CSP are low and, when thermal storage is included, are not exacerbated by emissions from back-up plants.

LIFECYCLE GREENHOUSE GAS (GHG) EMISSIONS
g CO_2 eq / kWh



Median g CO_2 eq / kWh	CSP - Trough	CSP - Tower	CSP - Stirling	CSP - Fresnel	Wind	Solar PV
	19	28	13	18	12	48

- CSP does not directly emit GHGs or other pollutants when producing electricity.
- CSP emits fewer GHGs over its lifecycle than Solar Photovoltaic (PV) and Wind. If thermal storage is included, CSP also has the advantage of not incurring emissions from the back-up plants that would otherwise be needed to balance intermittency.
- The manufacturing and disposal processes associated with CSP generate pollutants. CSP makes much more intense use of materials than other technologies. However, the main materials used are commonplace commodities such as steel, glass and concrete, for which recycling rates are high.
- Few toxic substances are used in CSP plants. The synthetic organic heat transfer fluids used in parabolic troughs present the greatest risks. They can catch fire and contaminate soils. One goal of research is to replace toxic heat transfer fluids with water or molten salts.
- Finally, CSP's land requirement averages 50 MW per km², which is intermediate between solar PV and Wind. Visual impact should be limited if CSP plants are to be built in arid, uninhabited areas.

The good and bad of CSP

Trade-Offs

Solar Energy for High-Temperature Heat and Electricity

Advantages

Moderate environmental impact

No CO_2 emissions

Fast construction (1–2 years)

Costs reduced with natural gas turbine backup

Disadvantages

Low efficiency

Low net energy

High costs

Environmental costs not included in market price

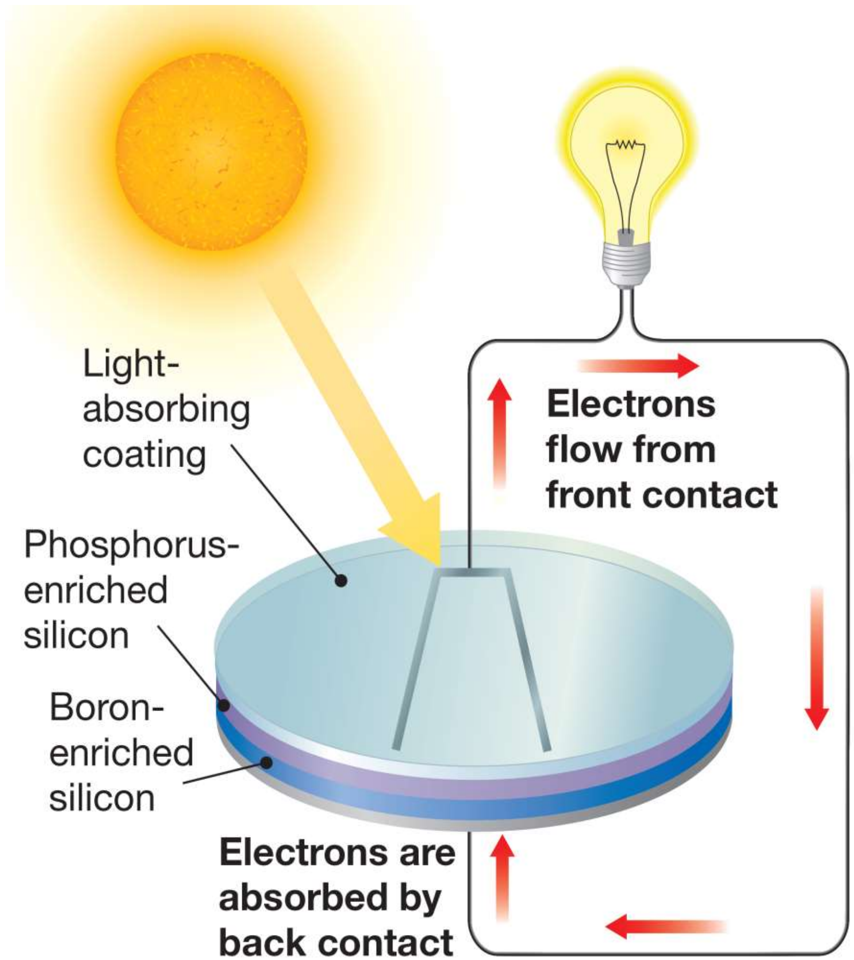
Needs backup or storage system

Needs access to sun most of the time

May disturb desert areas

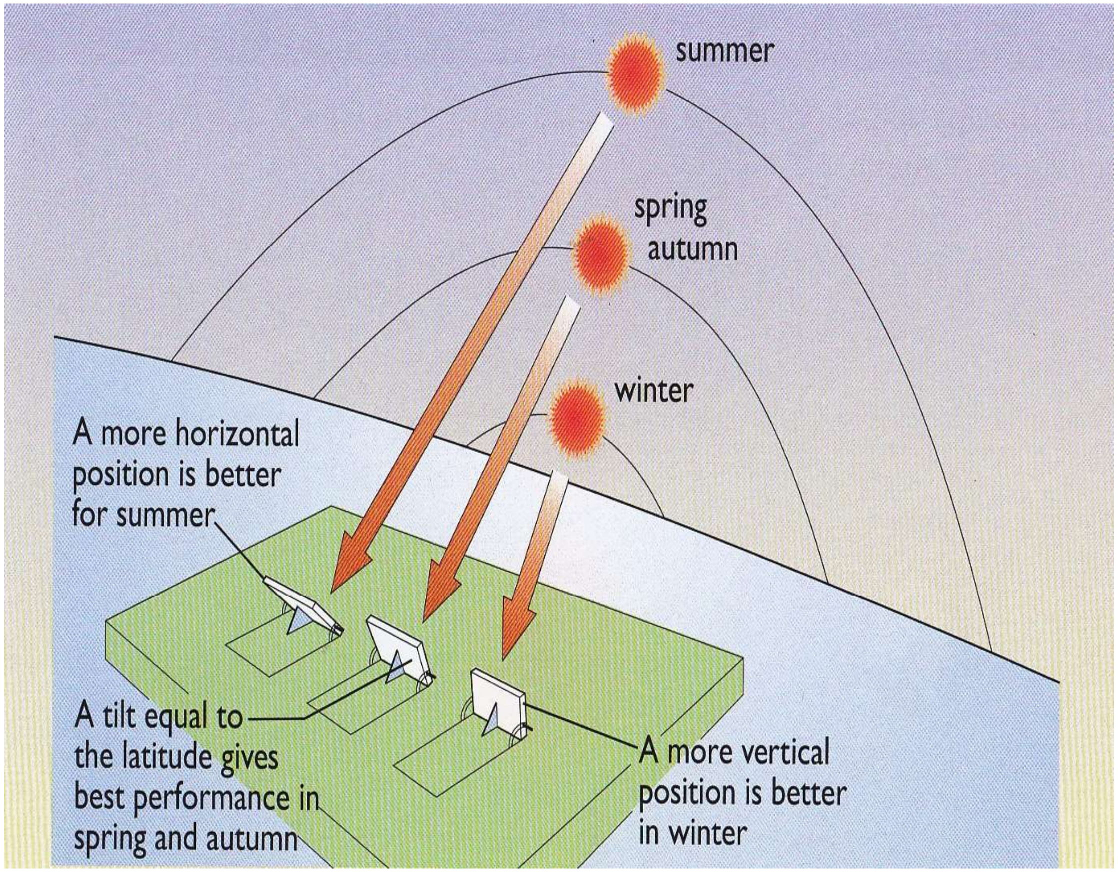
Solar photovoltaic

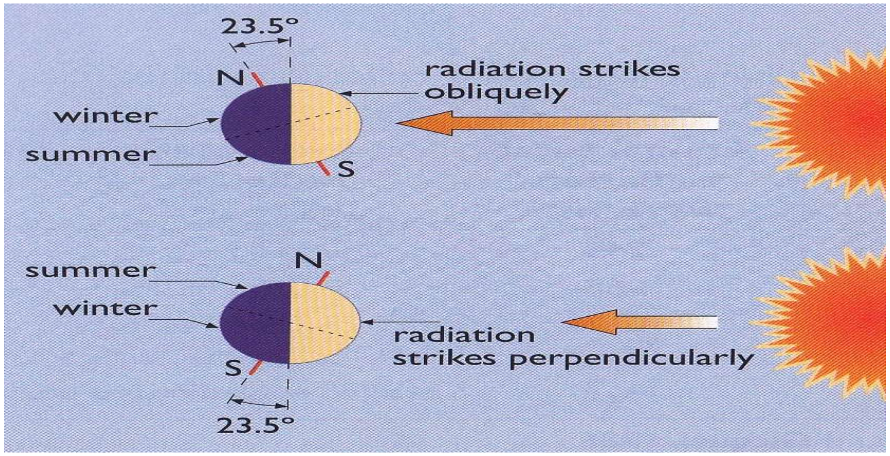
- Photovoltaic (PV) cells, also called solar cells, generate electricity by exploiting the photovoltaic effect.

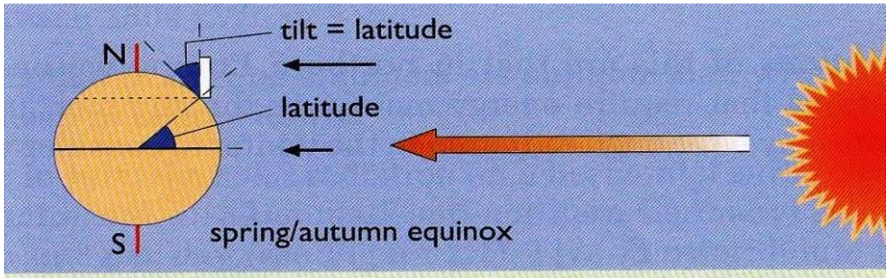


In a **solar cell**, sunlight falls on a semiconductor, causing it to release electrons. The electrons flow through a circuit that is completed when another semiconductor in the solar cell absorbs electrons and passes them on to the first semiconductor.

- To collect as much radiation as possible, a PV module should face the equator and must be tilted toward the sun. During summer (when the amount and intensity of solar radiation is more), the tilt angle should be less than the latitude to maximize solar collection. For maximum solar collection in winter (when more solar radiation may be needed), the tilt angle should be greater than the latitude angle.







A surface tilted at the latitude angle will be perpendicular to the Sun's rays at mid-day on the spring or autumn equinox

Solar PV applications

- PV has four end-use sectors with varying costs and performance requirements.

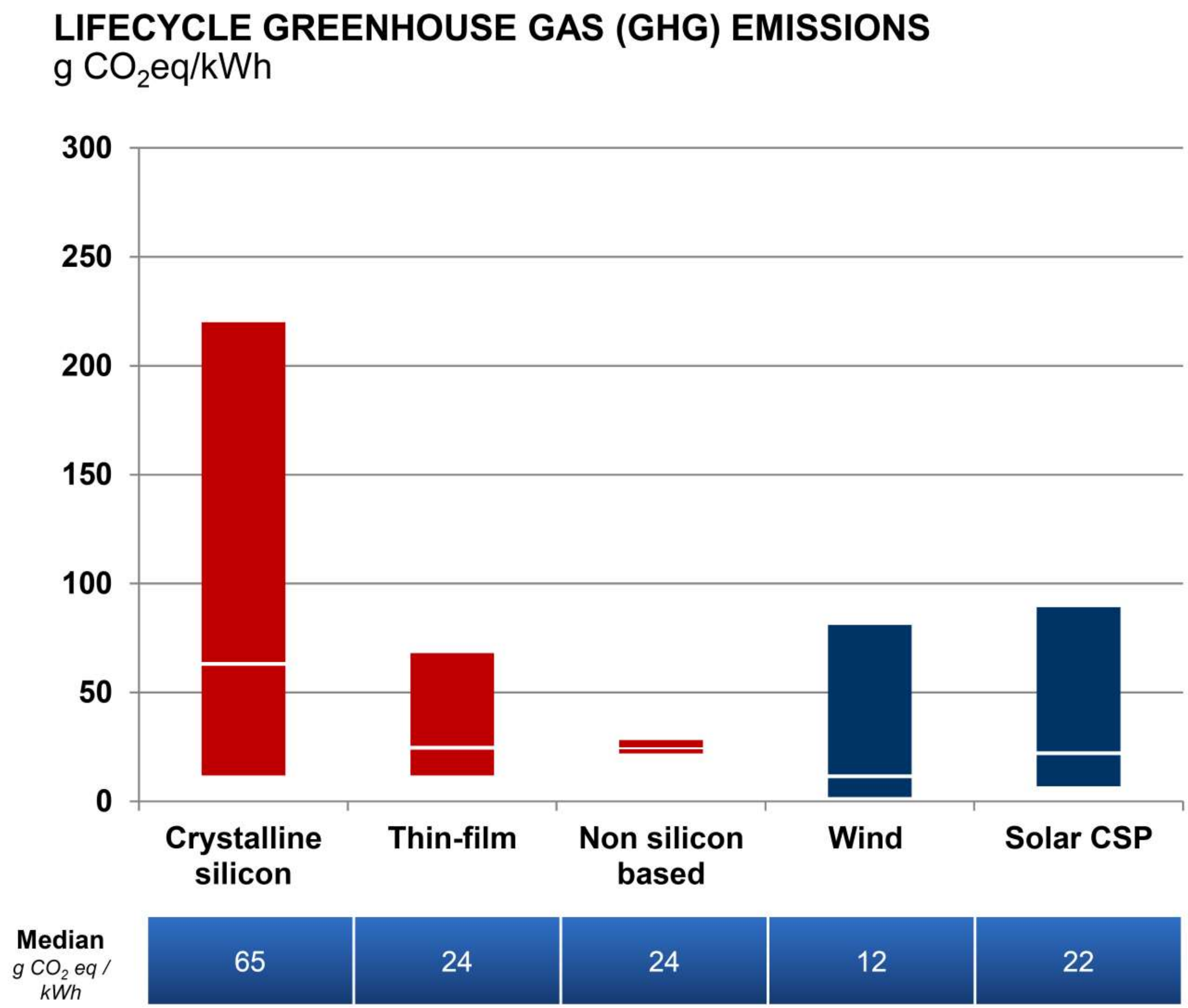
GRID CONNECTED

Residential	Commercial / industrial	Utility	Off-grid
Up to 20 kW	Up to 1 MW	1 MW upwards	Varying sizes
			
▪ Individual buildings / houses	▪ Commercial office buildings, schools, hospitals and retail	▪ Starting at 1 MW ▪ Mounted on buildings or directly on the ground	▪ Telecommunication units, remote communities and rural electricity supply

- The *Topaz Solar Farm* in San Luis Obispo County, California is the world's largest photovoltaic (PV) power plant. This facility has the capacity to generate 550 MW of solar electricity, which is enough to power 160,000 homes and displace 377,000 tons of CO_2 every year.

Environmental and social impacts

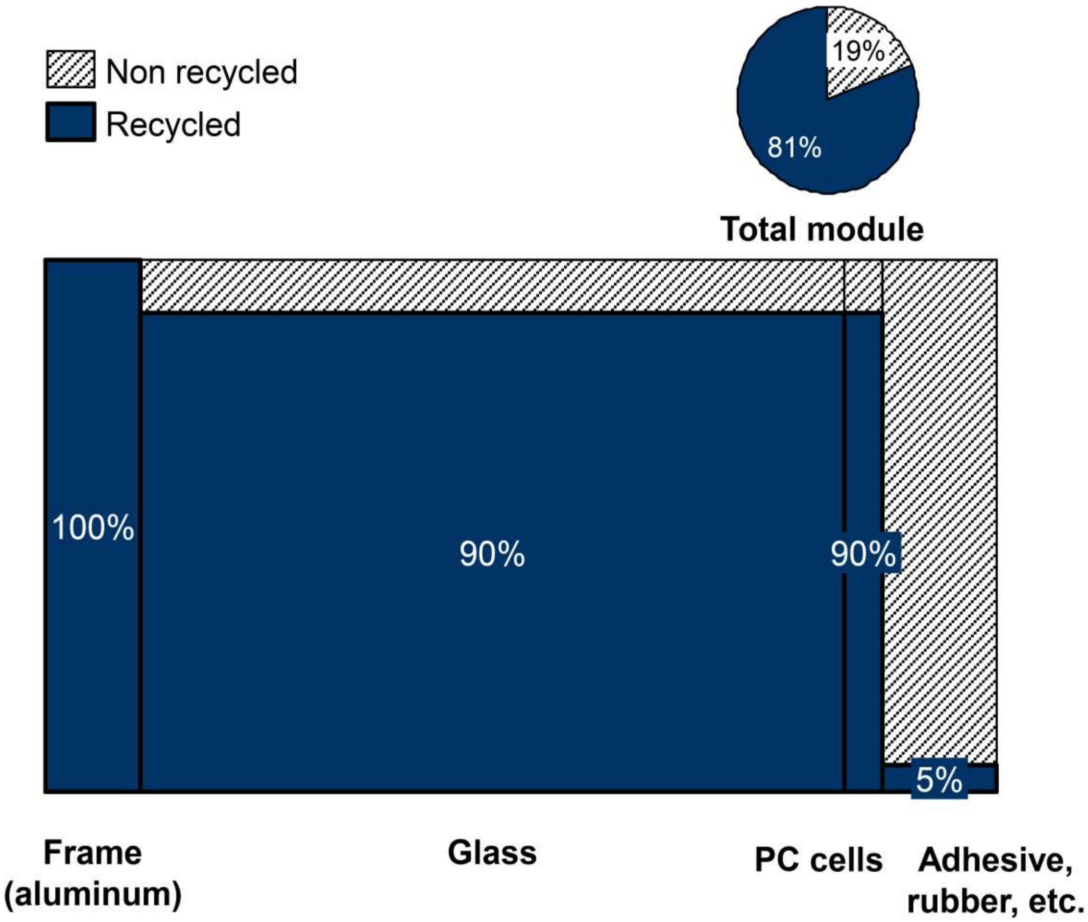
- Greenhouse gas (GHG) emissions from solar PV are low, but the technology's overall environmental impact depends on power-system integration.



- Solar photovoltaic (PV) does not directly emit GHGs or other pollutants. However, median solar PV emissions range between 24 and 65 g CO_2 equivalent per kWh over the entire lifecycle, depending upon the material used for the cells. This range is close to concentrating solar power and wind, and significantly lower than natural gas and coal-fired power plants that range from 500 to 1,000 gCO_2eq/kWh, respectively, for conventional combustion turbines in the US.
- Lifecycle emissions depend on control and recycling measures during the manufacturing process, as well as installation, Operation & Maintenance, and disposal procedures.
- Crystalline silicon production is electricity intensive, so lifecycle emissions depend on the carbon content of the electricity used.
- Replacing fossil-fuel power capacity with solar PV may result in an increase in the use of flexible back-up plants. This could lead to a rise in GHG emissions, although the impact would be highly system specific. In general, however, greater use of solar PV should reduce significantly pollutants and GHG emissions.

- Recycling is crucial in ensuring the PV industry is sustainable.

RECYCLABILITY OF A TYPICAL CRYSTALLINE PV MODULE
% of total mass



- Production of crystalline silicon modules generates a large amount of electronic waste, as in the semi-conductor industry.
- Recycling and disposal processes are therefore essential and will be even more crucial for thin films because of the use of rare metals.
- Recycling is already a core part of the PV industry as:
  - It is economically viable for large-scale applications. It is predicted that 80%-96% of glass, ethylene vinyl acetate and metals will be recycled;
  - Modules are being designed to aid recycling;
  - Solar PV manufacturers are increasingly being held responsible for the lifecycle impact of their products.

The good and bad of solar PV

Trade-Offs

Solar Cells

Advantages

- Fairly high net energy yield
- Work on cloudy days
- Quick installation
- Easily expanded or moved
- No CO_2 emissions
- Low environmental impact
- Last 20–40 years
- Low land use (if on roof or built into walls or windows)
- Reduces dependence on fossil fuels

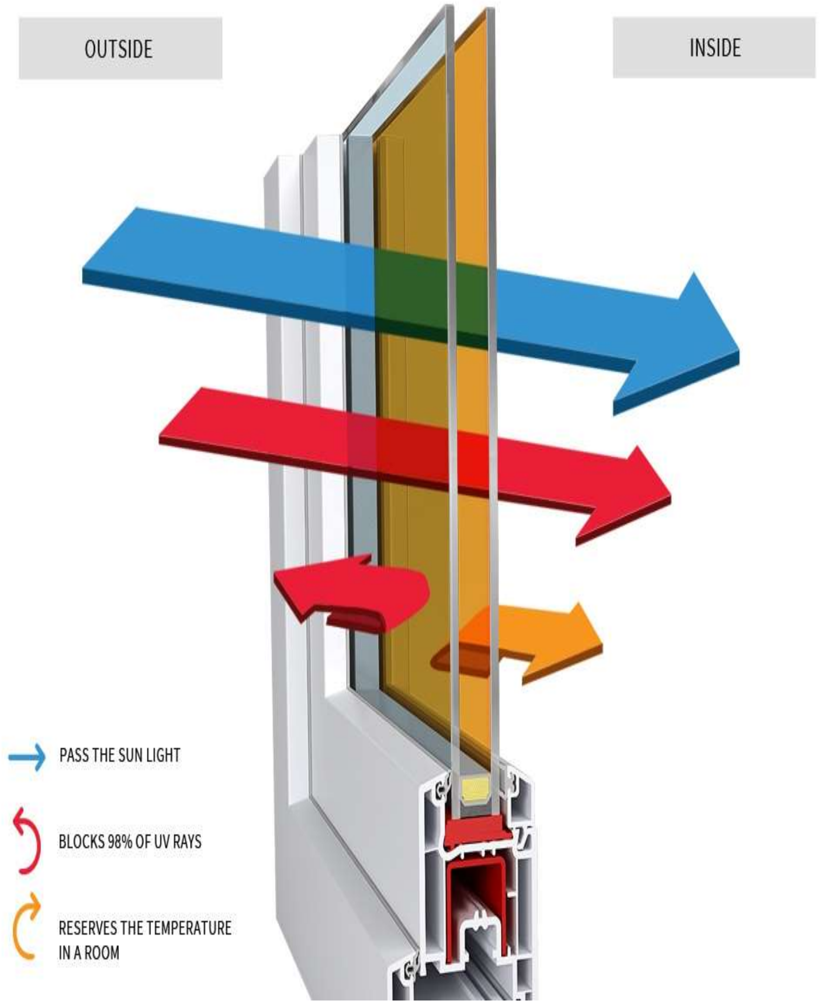
Disadvantages

- Need access to sun
- Low efficiency
- Need electricity storage system or backup
- Environmental costs not included in market price
- High costs (but should be competitive in 5–15 years)
- High land use (solar-cell power plants) could disrupt desert areas
- DC current must be converted to AC

Solar thermal energy

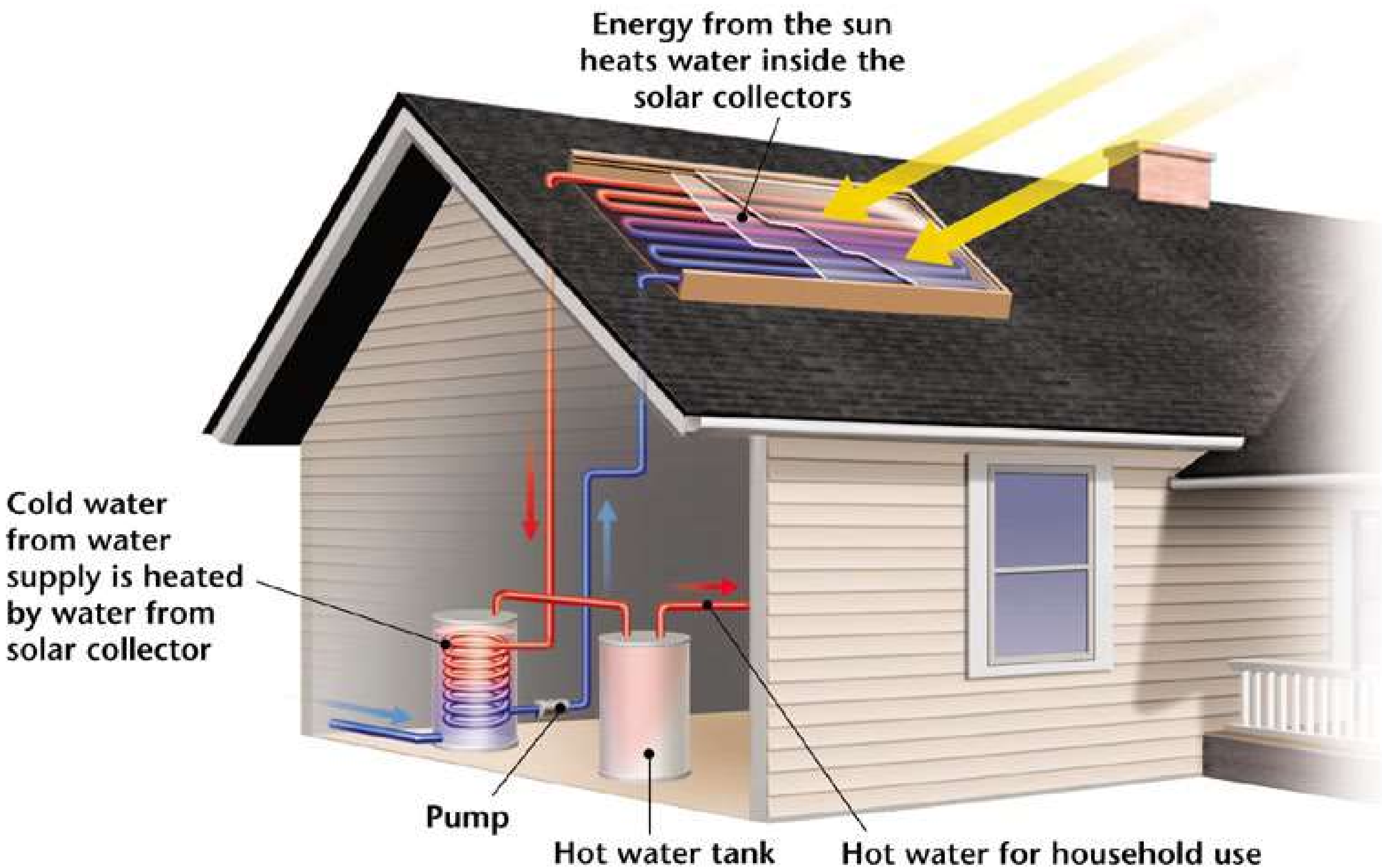
- Solar thermal energy is a form of energy and a technology for harnessing solar energy to generate thermal energy or electrical energy for use in the residential and commercial sectors.

- Solar thermal collection methods are many and varied, but depend mostly on the principle of glazing, in particular its ability to transmit visible light but block infrared radiation. These include:
  - Active solar heating/cooling
  - Passive solar heating/cooling
  - Solar daylighting



Active solar heating

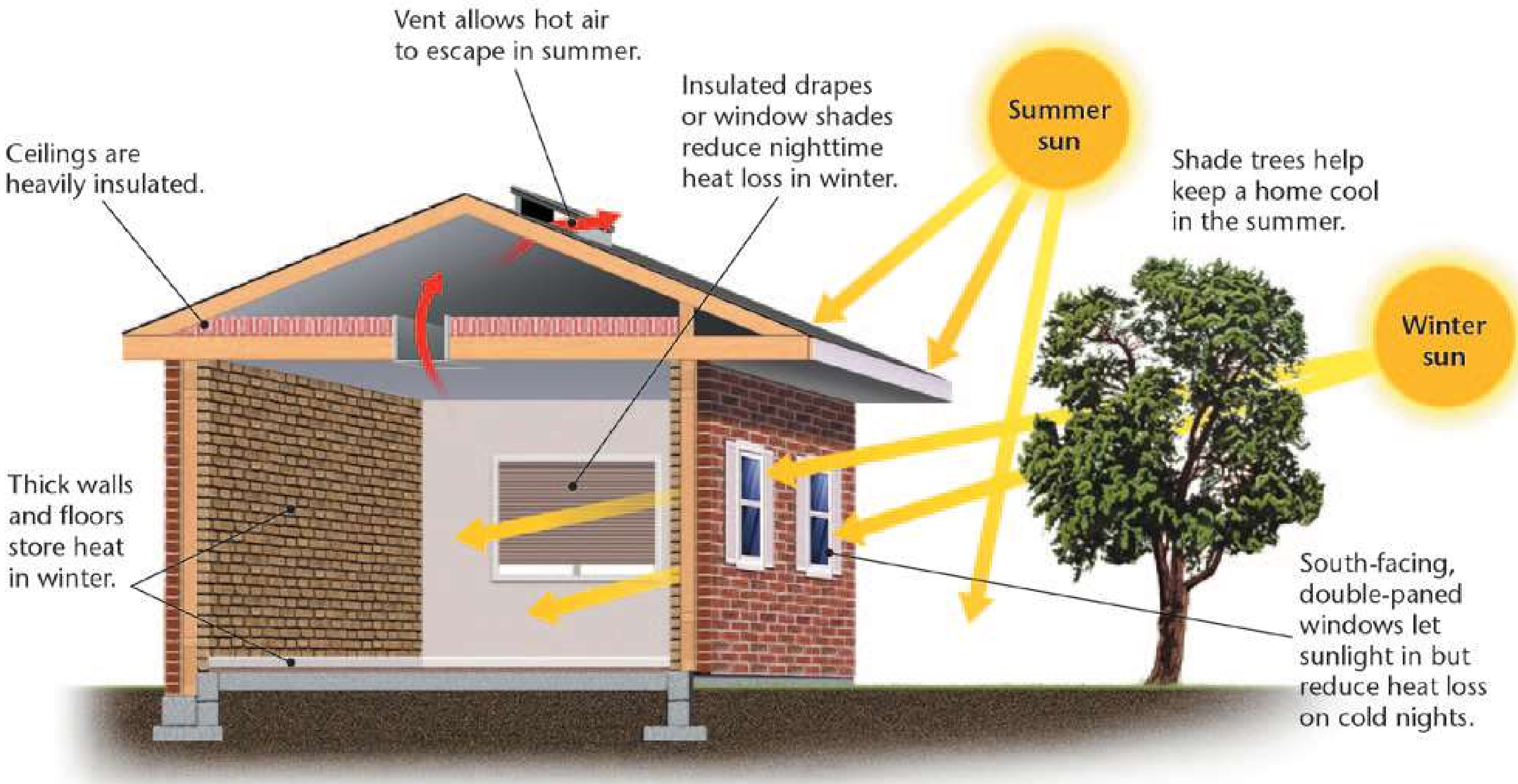
- In active solar heating systems, energy from the sun is gathered by collectors and used to heat water or to heat a building.



In an **active solar water heating system**, a liquid is pumped through solar collectors. The heated liquid flows through a heat exchanger that transfers the energy to water, which is used in a household.

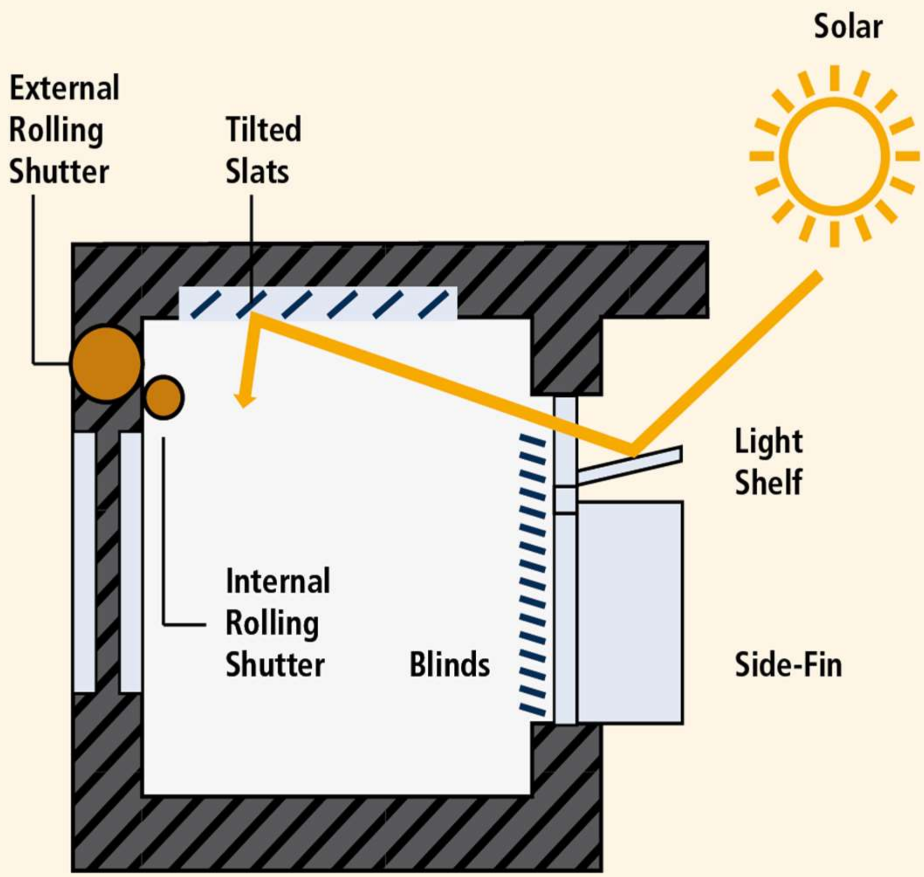
Passive solar heating

- Passive solar energy technologies absorb solar energy, store and distribute it in a natural manner (e.g., natural ventilation), without using mechanical devices (such as fans, blowers, or pumps).



A **passive solar house** is designed to reduce heating and cooling expenses and is oriented according to the yearly movement of the sun. In summer, the sun's path is high in the sky and the overhang of the roof shades the building and keeps it cool. In winter, the sun's path is lower in the sky, so sunlight shines into the house and warms it.

Solar daylighting



Schematic of several daylighting concepts designed to redistribute daylight into the office interior space.

- **Daylighting** is a combination of energy conservation and passive solar design.
- It aims to make the most of the natural daylight that is available.
- Traditional techniques include: shallow-plan design, allowing daylight to penetrate all rooms and corridors; light wells in the centre of buildings; roof lights; tall windows, which allow light to penetrate deep inside rooms; task lighting directly over the workplace, rather than lighting the whole building interior; and deep windows that reveal and light room surfaces to cut the risk of glare.

- In the solar settlement at Freiburg, Germany, the future of solar building and living in harmony with nature is already a reality. All roofs are covered with standard large area PV modules which are smartly integrated in a plane above the south facing roofs of the different buildings. It is the first housing community in the world in which all the homes produce a positive energy balance due to their passive solar design integrated with active solar heating and cooling.

The good and bad of solar thermal energy

Trade-Offs

Passive or Active Solar Heating

Advantages	Disadvantages
Energy is free	Need access to sun 60% of time
Net energy is moderate (active) to high (passive)	Sun can be blocked by trees and other structures
Quick installation	Environmental costs not included in market price
No CO_2 emissions	Need heat storage system
Very low air and water pollution	High cost (active)
Very low land disturbance (built into roof or windows)	Active system needs maintenance and repair
Moderate cost (passive)	Active collectors unattractive

Solar fuels

- Solar fuel technologies convert solar energy into chemical fuels, which can be a desirable method of storing and transporting solar energy.

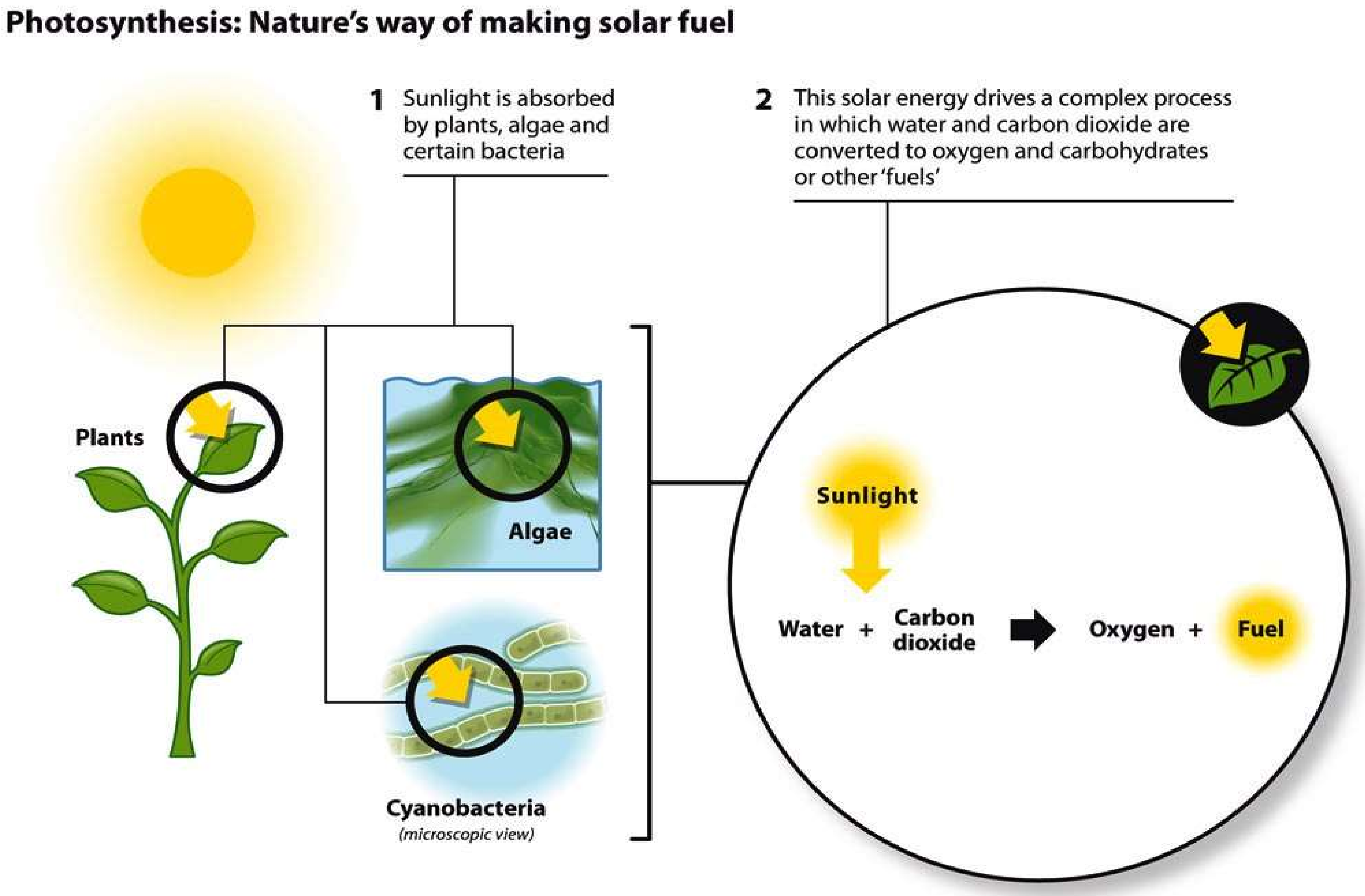
- They can be used in a much wider variety of higher-efficiency applications than just electricity generation cycles.

- Solar fuels can be processed into liquid transportation fuels or used directly to generate electricity in fuel cells; they can be employed as fuels for high-efficiency gas-turbine cycles or internal combustion engines; and they can serve for upgrading fossil fuels, or for producing industrial or domestic heat.

- There are three basic routes, alone or in combination, for producing storable and transportable fuels from solar energy: (i) photochemical/photobiological; (ii) artificial photosynthesis; and (iii) thermochemical approaches.

Photochemical/Photobiological method

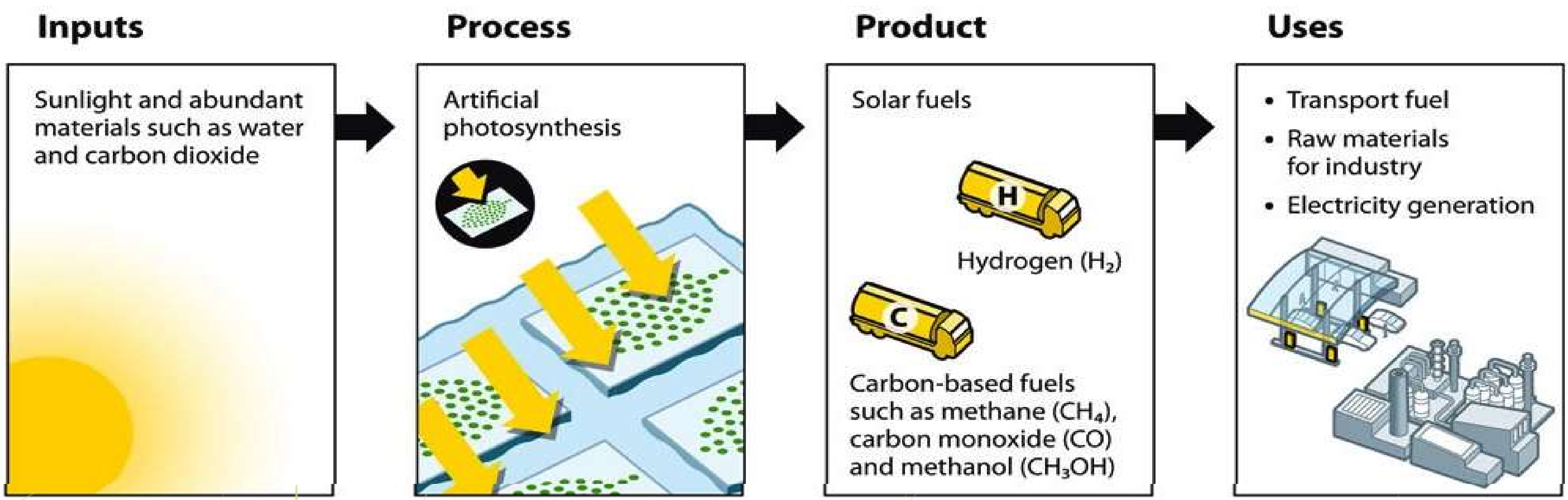
- Photochemical/photobiological routes make direct use of solar photon energy for converting CO_2 into synthetic liquid fuel (natural photosynthesis).



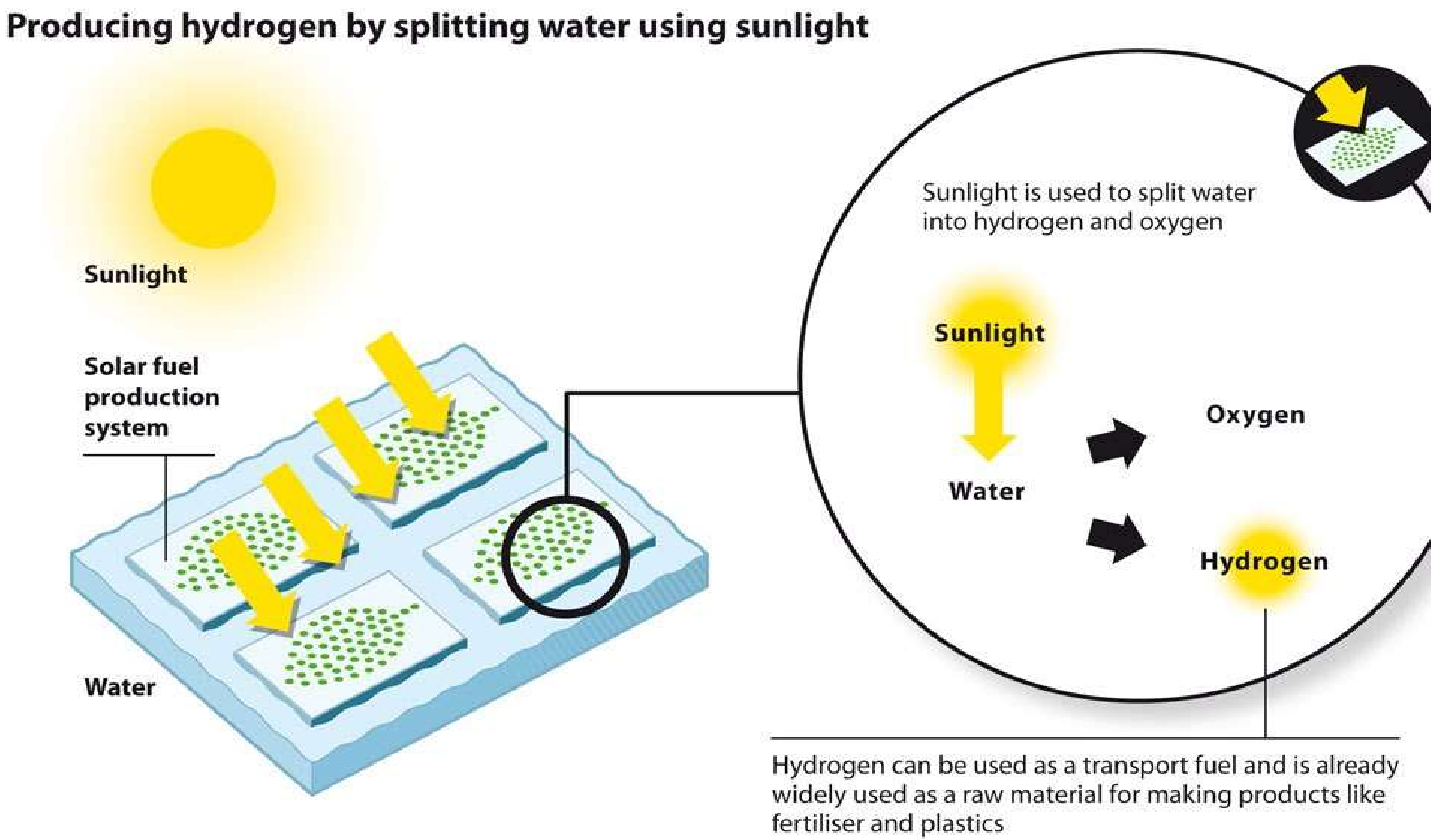
Artificial photosynthesis

- Artificial photosynthesis (also called artificial leaves) mimics the natural process of photosynthesis to convert raw materials like water and CO_2 into clean fuels and value-added chemicals (e.g., H_2, CO and hydrocarbons).

Artificial photosynthesis pathway from sunlight to fuels



- Photocatalytic water splitting converts water into hydrogen ions and oxygen, and is an active research area in artificial photosynthesis.



Applications of solar fuels

- Solar fuels can not only be used for transport and electricity generation but also as feedstock in (the chemical) industry.