Mohamed Boudiaf University (M'sila)
Department of Electrical Engineering
Option : Renewable Energy and Environment

Year 2025/2026
Year of study: 3rd year Bachelor's degree

Chapter 3: Thermal conversion: medium and high temperatures application

III.1 Introduction:

Solar energy is one of the main renewable energy sources available on Earth. It is inexhaustible on a human scale and represents each year more than 10,000 times the world's total energy consumption. The direct use of this resource can take several forms: **photovoltaic**, **thermal**, and **photochemical**.

Thermal conversion of solar energy involves transforming the incident solar radiation into useful heat, which can then be used for **heating**, **cooling**, **steam generation**, or further converted into **mechanical** or **electrical energy** through thermodynamic cycles.

Depending on the temperature reached by the heat-transfer fluid within the system, three main categories of applications can be distinguished:

- **Low temperature (T < 100 °C):** domestic hot water production, space heating, solar drying, etc.
- **Medium temperature (100–400 °C):** industrial processes, solar furnaces, absorption cooling systems.
- **High temperature (T > 400 °C):** thermoelectric conversion, power cycles (Rankine, Brayton, Stirling), and **concentrated solar power plants**.

This section of the course focuses specifically on **solar energy conversion at medium and high temperatures**, where the available energy density becomes sufficient to drive thermal machines or demanding industrial processes.

III.2 Principles of thermal conversion of solar energy

The solar radiation incident on a surface is mainly composed of two components:

- **Direct radiation**, coming directly from the solar disk,

- **Diffuse radiation**, resulting from atmospheric scattering.

The **surface power density** received on a plane perpendicular to the solar rays is called the **Direct Normal Irradiance (DNI)**.

The basic energy relationship is given by:

$$Q_{sol} = IDNI \times A \times \eta_{optical} \quad (3.1)$$

where:

- Qsol: useful thermal power received (W),
- IDNI: direct normal irradiance (W/m²),
- A: collector aperture area (m²),
- ηoptical: optical efficiency of the concentrator (dimensionless).

To achieve high temperatures, it is necessary to **concentrate the solar flux** onto a smaller surface — this is the **principle of solar concentration**.

III.3 Temperature ranges

3.1. Low Temperature (≤ 100 °C)

Applications: solar water heaters, agricultural drying, space heating. The collectors used are generally **flat-plate collectors**, glazed or unglazed, operating with a **heat transfer fluid** (water or air).

3.2. Medium Temperature (100–400 °C)

Applications: industrial drying processes, steam generation, solar furnaces, chemical reactors. **Linear concentration systems** (such as **parabolic troughs** and **Fresnel reflectors**) are the most suitable for this temperature range.

3.3. High Temperature (> 400 °C)

Applications: electricity generation through **thermodynamic cycles** (Rankine, Brayton, Stirling). The dominant technologies are **solar power towers** (with heliostats) and **point-focus parabolic concentrators** (**dish systems**).

III.4 Solar Concentrators

III.4.1 General Principle

A **solar concentrator** is an optical device designed to **increase the density of the solar flux** received on a target surface, called the **receiver**. The principle is based on the **reflection** or **refraction** of the incident solar radiation using **mirrors** or **lenses**.

In this way, the solar energy intercepted by a **large aperture area** Aap is redirected and concentrated onto a **smaller receiver area** Arec, where the temperature can rise significantly.

The **concentration ratio** is defined as:

$$C = \frac{A_{ap}}{A_{rec}} \quad (3.2)$$

where:

- C: concentration factor,
- Aap: aperture area of the concentrator (m^2),
- Arec: receiver area (m^2).

This factor represents the **power density gain** on the receiver surface. For example, a factor of C=100 means that the solar energy is **100 times more concentrated** than under direct (unconcentrated) irradiation.

III.4.2 Types of Solar Concentrators

III.4.2.1 Parabolic Trough Concentrator

The **parabolic trough concentrator** consists of a mirror with a **parabolic shape** along a straight generatrix, which focuses the solar radiation onto a **receiver tube** located along the **focal line**, as illustrated in **Figure 1**. The **heat transfer fluid** (such as thermal oil, molten salts, or pressurized water) flows through the tube and is heated up to **300–400 °C**.

Main characteristics:

- **Single-axis solar tracking** (generally East–West).
- **Concentration ratio:** C≈30–100C \approx 30–100C≈30–100.
- **Typical optical efficiency:** 0.7 to 0.8.
- **Applications:** SEGS power plants, industrial thermal systems.

III.4.2.2 Paraboloid Dish Concentrator (Dish System)

This system consists of a **three-dimensional parabolic dish** that focuses solar radiation onto a **single focal point**, as illustrated in **Figure 2**.The **receiver** is located at the focus and typically supplies heat to a **Stirling engine**.

Characteristics:

- **Dual-axis solar tracking**, ensuring maximum concentration.
- **Operating temperatures:** 700–1000 °C.
- **Concentration ratio:** C≈500–2000.

- **Very high overall efficiency**, reaching up to **30 %**.

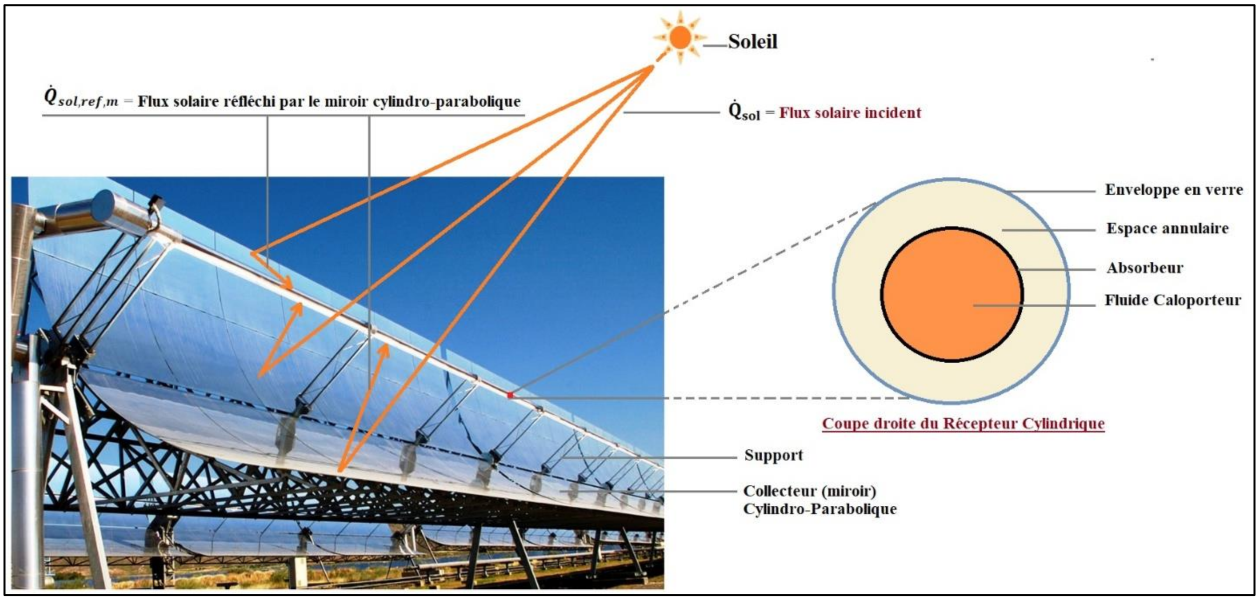


Figure 1 : Concentrateur cylindro-parabolique [Web 1].

III.4.2.3 Solar Power Tower with Heliostats

The **solar power tower** system uses a **field of flat, orientable mirrors** called **heliostats**, which reflect solar radiation toward a **receiver** located at the top of a **central tower**. The **heat transfer fluid** (air, molten salts, or solid particles) reaches temperatures of **500–1000 °C**, sufficient to drive **power cycles** such as **Rankine** or **Brayton** cycles.

Characteristics:

- **Very high concentration ratio:** C>1000.
- **Overall efficiency:** 15–20 %.
- **Technology used in:** *Solar Two*, *PS10*, *Crescent Dunes* power plants.

III.4.2.4 Linear Fresnel Concentrator

The **Linear Fresnel Concentrator (LFC)** is a **cost-effective alternative** to the **parabolic trough system**. It consists of **rows of flat mirror strips**, each slightly tilted to concentrate solar radiation onto a **fixed receiver tube** positioned above the mirrors.

Advantages:

- Simple and low-cost structure,
- Single-axis solar tracking,
- Good compromise between efficiency and cost.

Drawback:

- Slightly lower efficiency compared to the parabolic trough concentrator (**C ≈ 20–60**).

Figure 2 : Concentrateur paraboloïde de révolution (Dish System).

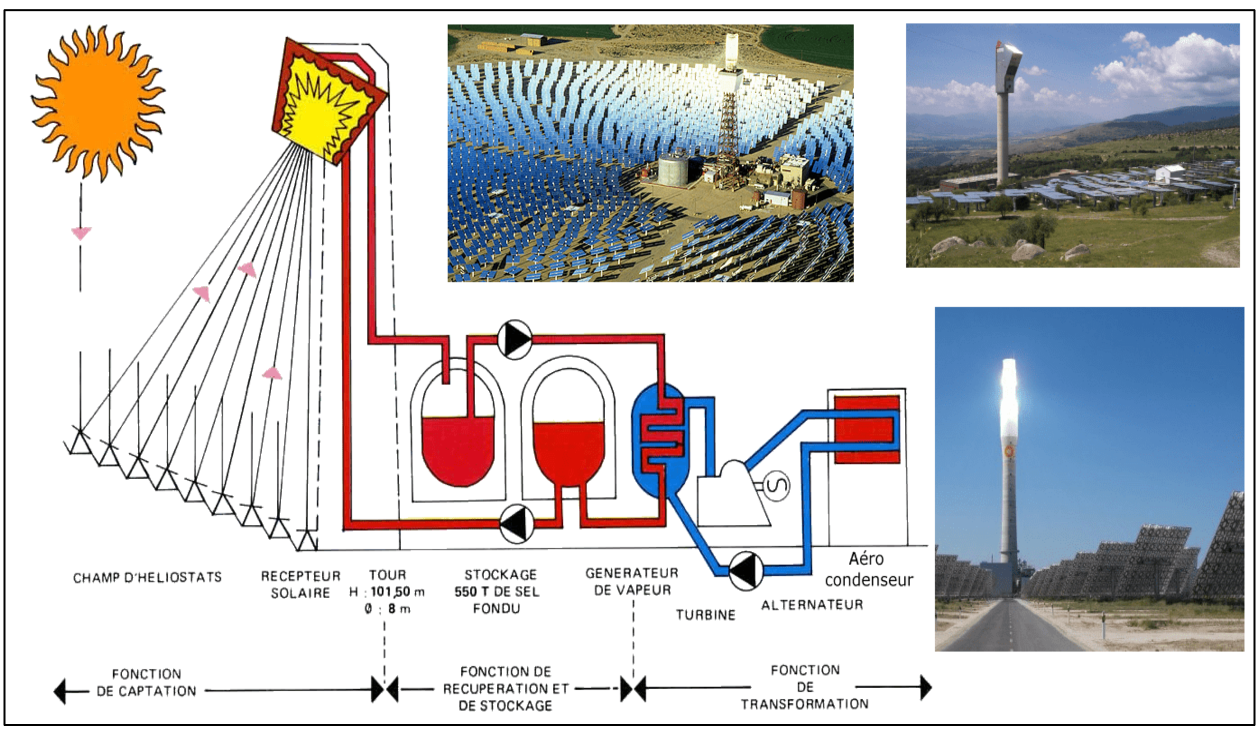


Figure 3 : Solar Power Tower with Heliostats.

Figure 4 : Linear Fresnel Concentrator.

The synthetic comparison of these concentrator types is summarized in **Table 1**.

Table 1. Comparison of Solar Concentrators

Type of Concentrator	Solar Tracking	Temperature (°C)	Concentration Ratio	Overall Efficiency	Example of Application
Parabolic trough	1 axis	300–400	30–100	70–80 %	SEGS power plants
Paraboloid (dish)	2 axes	700–1000	500–2000	80–90 %	Stirling engine systems
Solar tower (heliostats)	2 axes (heliostats)	500–1000	1000–3000	70–80 %	Rankine/Brayton power cycles
Linear Fresnel	1 axis	250–400	20–60	60–75 %	Industrial process heat, steam generation

III.5 Thermodynamic Cycles Applied to Solar Energy

Medium- and high-temperature solar systems allow the conversion of **thermal energy into mechanical energy** and then into **electricity** using **thermodynamic cycles**. The three main cycles used are:

- **Rankine cycle**,

- **Brayton cycle**,
- **Stirling cycle**.

III.5.1 Rankine Cycle

The **Rankine cycle** is the most widely used thermodynamic cycle for electricity generation from a heat source. It is based on the **vaporization and condensation** of a working fluid (usually water, but also organic fluids in **ORC cycles**).

As shown in **Figure 5**, the cycle has four main stages:

1. **Liquid compression (pump):** Isentropic transformation:

$1 \rightarrow 2: W_{pump} = v(P_2 - P_1)$

2. **Heating and vaporization (solar boiler):** Isobaric transformation:

$2 \rightarrow 3: Q_{in} = h_3 - h_2$

Expansion in the turbine: Isentropic transformation (ideal):

$3 \rightarrow 4: W_{turb} = h_3 - h_4$

4. **Condensation:** Isobaric transformation:

$4 \rightarrow 1: Q_{out} = h_4 - h_1$

Thermal efficiency:

$\eta_{th} = W_{turb} - W_{pump} / Q_{in} = (h_3 - h_4) - (h_2 - h_1) / (h_3 - h_2)$

In the case of a **solar power plant** using the Rankine cycle, an example is shown in **Figure 6**, which consists of:

- A **field of solar concentrators** (providing solar heat),
- A **solar heat exchanger/boiler**,
- A **steam turbine**,
- A **condenser**,
- A **feedwater pump**.

Operation: Liquid water is pumped to the solar boiler, vaporized by concentrated solar energy, expanded in the turbine, then condensed and recycled.

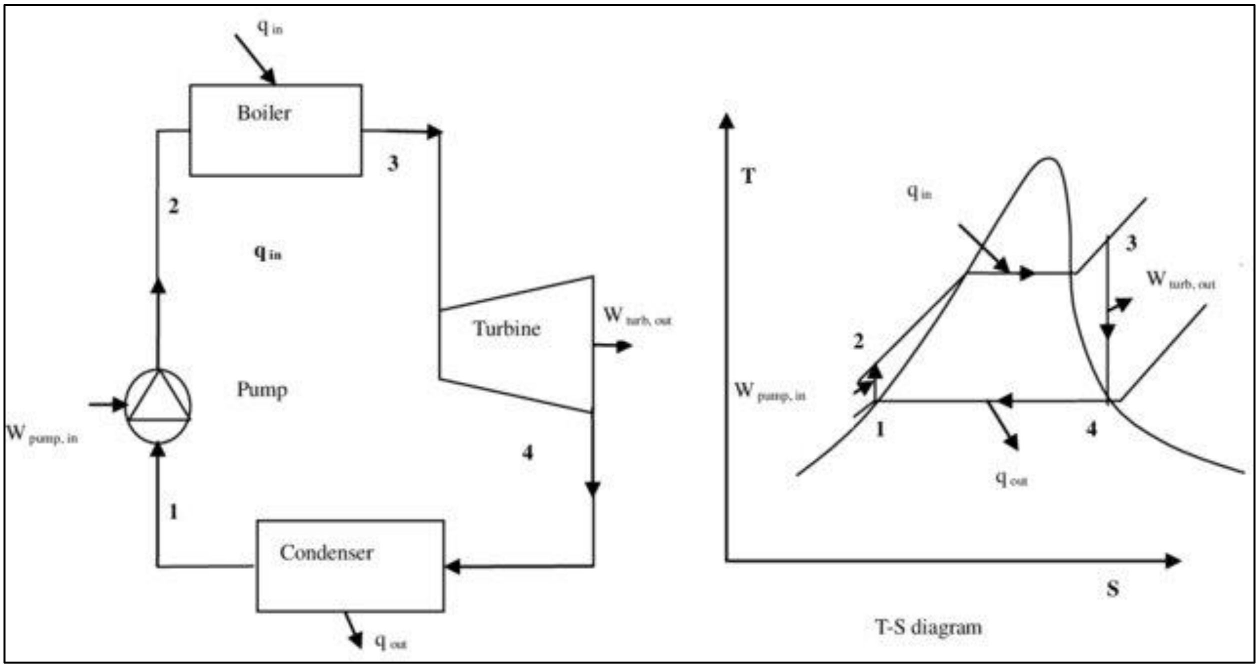


Figure 5 : RankineCycle.

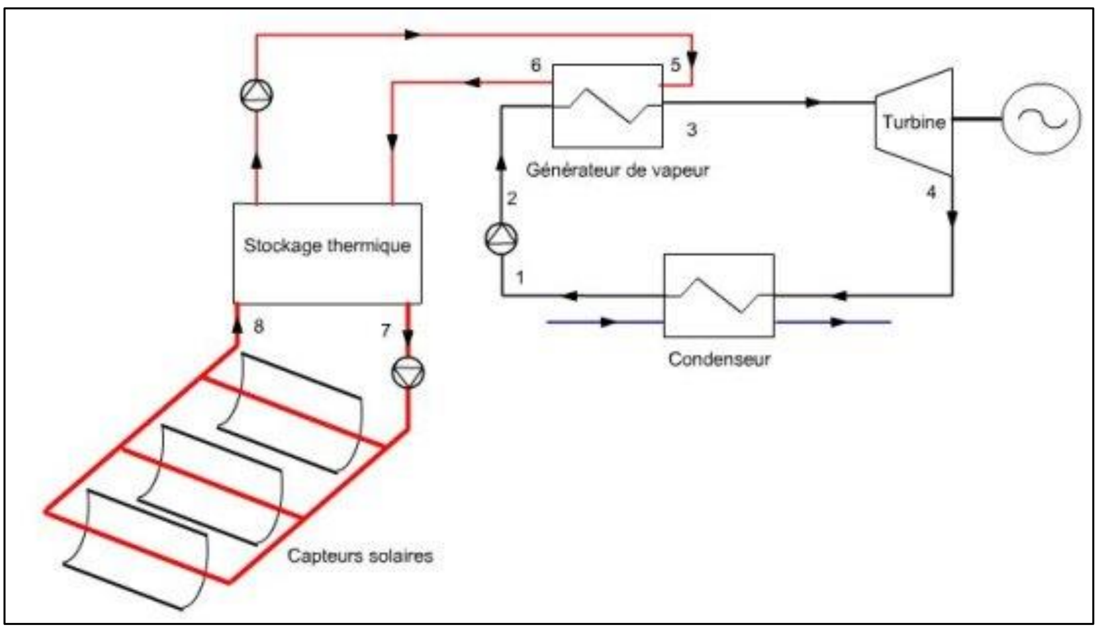
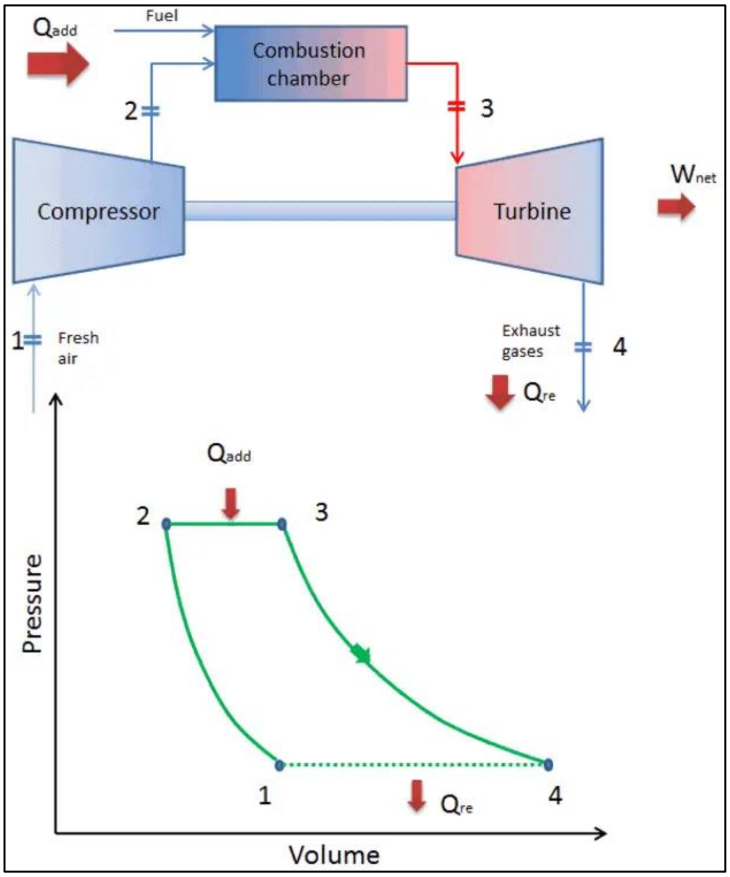


Figure 6 : Rankine Cycle in a Parabolic Trough Concentrator

Variants of the Rankine cycle can be implemented as follows:

- **Organic Rankine Cycle (ORC):** uses organic working fluids with low boiling points (e.g., pentane, toluene, R245fa) for **medium-temperature ranges (100–300 °C)**.
- **Molten Salt Rankine Cycle:** used in **solar tower systems** operating at **500–600 °C**.

- **Supercritical Rankine Cycle:** operates at **pressures above 22 MPa**, achieving **efficiencies greater than 40%**.



- Figure 7 : Brayton Cycle.

III.5.2 Brayton Cycle

The **Brayton cycle** (or **gas cycle**) is used in **gas turbines** and in some **solar systems** employing **air or helium** as the working fluid. It is based on the **compression, heating, and expansion** of a gas **without phase change**.The cycle consists of **four main stages** (see Figure 7):

1. **Adiabatic compression:**

$1 \rightarrow 2: W_{comp} = c_p(T_2 - T_1)$

2. **Constant-pressure heating (solar receiver):**

$2 \rightarrow 3: Q_{in} = c_p(T_3 - T_2)$

3. **Adiabatic expansion in the turbine:**

$3 \rightarrow 4: W_{turb} = c_p(T_3 - T_4)$

Constant-pressure cooling:

$4 \rightarrow 1: Q_{out} = c_p(T_4 - T_1)$

For an **ideal gas** undergoing **isentropic transformations**, the **thermal efficiency** of the Brayton cycle is expressed as:

$$\eta_{th} = 1 - 1/(r_p^{(\gamma-1)/\gamma})$$

where:

- $r_p = P_2/P_1$ is the **pressure ratio**,
- $\gamma = c_p/c_v$ is the **specific heat ratio**.

Possible improvements to the Brayton cycle include:

- **Regeneration:** recovering heat from the exhaust gases to preheat the compressed air, thereby increasing efficiency.
- **Intercooling and reheating:** used in **multi-stage systems** to enhance performance.

In **solar applications**, the Brayton cycle is well suited to **solar tower systems** with **air receivers**, where the air is directly heated to **800–1000 °C**.

Efficiencies can reach **35–40%**, with **unit power outputs** ranging from **100 kW to several megawatts**.

III.5.3. The Stirling Cycle

The Stirling engine is a piston engine operating in a closed cycle with a permanent gas (helium, hydrogen, or air). It converts heat into mechanical work through alternating expansion and compression of the gas between two sources at different temperatures.

1. **Isothermal heating at high temperature (TH):** the gas expands and produces work.
2. **Isochoric heat transfer through the regenerator:** heat is temporarily stored.
3. **Isothermal cooling at low temperature (TL):** the gas is compressed.
4. **Reverse isochoric transfer:** the regenerator releases the stored heat.

The **theoretical efficiency** of the Stirling cycle is equal to that of the Carnot cycle:

$\eta_{th} = 1 - T_L/T_H$

However, **mechanical, conduction, and regeneration losses** reduce the **actual efficiency** to about **30–35%**.

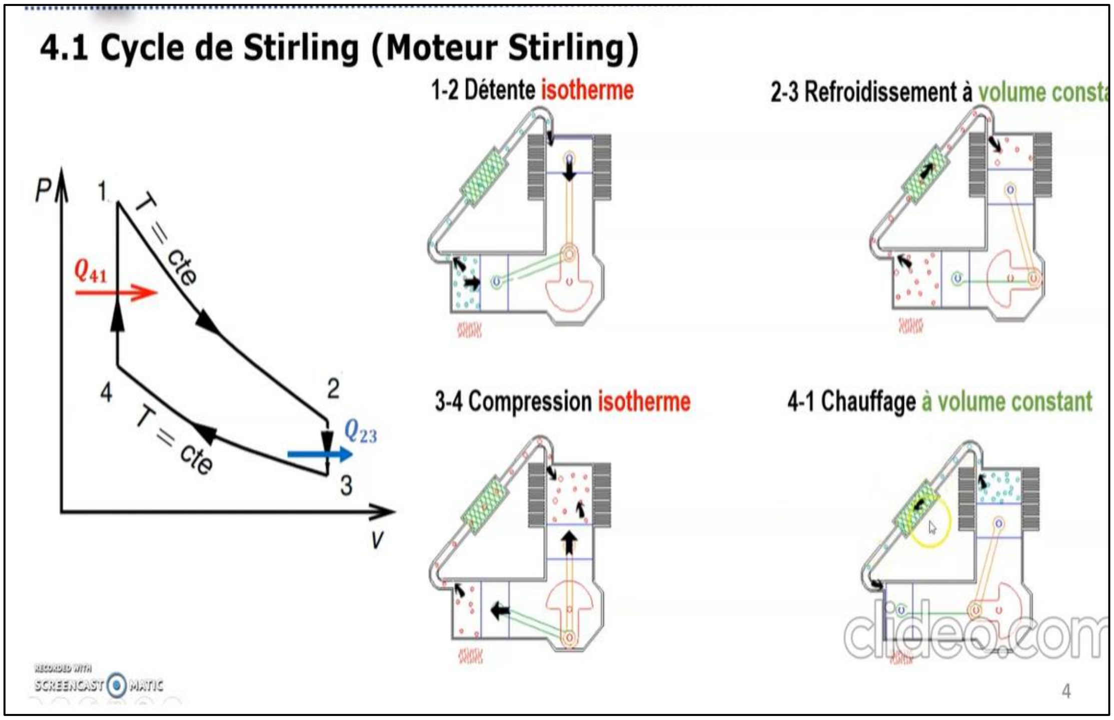


Figure 8 : Striling cycle.

In Solar Applications:

- The Stirling engine is often coupled with a **parabolic dish concentrator**.
- The focal point reaches temperatures of **800 to 1000 °C**.
- The **electrical power output** ranges from **1 to 50 kW**.

Advantages:

- High efficiency for small-scale systems.
- Quiet and reliable operation.

Disadvantages:

- High cost of the receiver and regenerator.
- Sealing issues with light gases.

Comparison of the Main Thermodynamic Cycles

Cycle	Working Fluid	Temperature Range (°C)	Typical Efficiency	Solar Application
Rankine	Water / Organic fluid	150–600	25–40 %	Solar towers, Parabolic troughs
Brayton	Air / Helium	400–1000	30–40 %	Solar towers
Stirling	Closed gas (He, H_2)	600–1000	30–35 %	Parabolic dishes

III.6. Example of Solar Coupling — Rankine Cycle with Parabolic Trough Collectors

A typical functional diagram includes:

1. A **field of parabolic trough collectors (PTC)**.
2. A **heat transfer fluid** (oil or molten salts).
3. A **heat exchanger** producing **steam**.
4. A **steam turbine** driving an **electric generator**.
5. A **condenser** and **recirculation pump**.

The overall efficiency is given by:

$\eta_{global} = \eta_{opt} \times \eta_{th} \times \eta_{cycle}$

With:

- $\eta_{opt} \approx 0.75$ (optical efficiency of the concentrator),
- $\eta_{th} \approx 0.85$ (thermal transfer efficiency),
- $\eta_{cycle} \approx 0.35$ (Rankine cycle efficiency).

Thus:

$\eta_{global} \approx 0.22$ or 22%

This efficiency corresponds to **typical values for commercial solar thermal power plants**.