



**Department of Information Engineering and
Mathematical Sciences**

Technologies for Environmental Resource Management

PROJECT REPORT: ENERGY CONVERSION FROM SOLAR SOURCES

Project Report

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Abstract

Solar energy stands at the forefront of the global transition toward sustainable energy systems, offering an abundant, clean, and versatile source of power to meet rising energy demands while mitigating climate change. This report presents a comprehensive analysis of solar energy conversion technologies, systematically examining both established and emerging solutions. Beginning with the scientific fundamentals of solar radiation and energy conversion mechanisms, the study explores how photonic and thermal pathways are harnessed through photovoltaic (PV) and solar thermal systems. A detailed evaluation of conventional PV technologies—such as monocrystalline silicon, polycrystalline silicon, and thin-film modules (CdTe, CIGS)—is provided, including their efficiency metrics, temperature sensitivities, and market penetration rates. In parallel, advanced technologies like perovskite tandem cells, organic photovoltaics, and quantum dot solar cells are assessed, highlighting their potential for efficiency breakthroughs alongside challenges related to material stability and lifecycle sustainability.

Solar thermal technologies are critically analyzed, covering flat plate collectors, evacuated tube collectors, solar air heaters, and desalination units, emphasizing their roles in residential, commercial, and industrial applications. Concentrated Solar Power (CSP) systems—featuring parabolic troughs, solar towers, and linear Fresnel reflectors—are explored for their ability to integrate thermal energy storage, enhancing dispatchability and grid reliability. The report also investigates hybrid energy systems, including PV + battery storage, PV + hydrogen electrolysis, PVT modules, and smart hybrid configurations with energy management systems (EMS), offering solutions to the intermittency and variability of solar resources.

In addition to technical systems, the study examines passive solar design strategies, including Trombe walls, thermal mass utilization, daylighting optimization, and solar chimneys, which contribute significantly to building energy efficiency and occupant comfort. Special emphasis is placed on the sustainability aspects of solar technologies across their full lifecycle, from raw material extraction to end-of-life recycling. Circular economy approaches, critical material management, and lifecycle assessment indicators such as energy payback time (EPBT) and global warming potential (GWP) are discussed in detail.

Italy's leadership in solar deployment, policy initiatives such as REPowerEU and the National Energy and Climate Plan (PNIEC), and innovative practices like agrivoltaics and floating PV systems are highlighted as case studies. Through comparative analysis, strategic recommendations, and identification of future research priorities, this report underscores the pivotal role of interdisciplinary innovation, smart hybridization, and lifecycle-oriented design in maximizing the contribution of solar energy to a resilient and decarbonized energy future.

Table of Contents

PROJECT REPORT: ENERGY CONVERSION FROM SOLAR SOURCES.....	1
Abstract.....	2
Table of Contents	3
List of Figures and Tables.....	7
Chapter 1 – Introduction	9
1.1 Context and Background of Solar Energy Utilization.....	9
1.2 Objectives of the Report	10
1.3 Scope and Methodology	11
1.4 Structure of the Report.....	12
Chapter 2 – Fundamentals of Solar Energy Conversion	12
2.1 Solar Radiation and the Solar Spectrum	12
2.2 Energy Conversion Pathways	13
2.2.1 Photovoltaic (PV) Conversion.....	13
• Monocrystalline: 22–24%.....	14
• Polycrystalline: 18–20%.....	14
• Thin-Film (CdTe, CIGS): 10–18%.....	14
2.2.2 Thermal Conversion	14
2.2.3 Concentrated Solar Power (CSP)	14
2.3 Efficiency and Performance Indicators	15
2.3.1 Standard Test Conditions (STC)	15
2.3.2 Performance Ratio (PR)	16
2.4 Environmental and Climatic Influences	16
Chapter 3 – Photovoltaic Technologies	17
3.1 Introduction to Photovoltaic Systems	17
3.2 Crystalline Silicon Technologies.....	18
3.2.1 Monocrystalline Silicon (Mono-Si).....	18
3.2.2 Polycrystalline Silicon (Poly-Si)	19
3.3 Thin-Film Technologies	19
3.3.1 Amorphous Silicon (a-Si)	19

3.3.2 Cadmium Telluride (CdTe).....	19
3.3.3 Copper Indium Gallium Selenide (CIGS).....	19
3.4 Emerging and Experimental PV Technologies	20
3.4.1 Perovskite Solar Cells (PSC)	20
3.4.2 Organic and Dye-Sensitized Solar Cells	20
3.4.3 Quantum Dot (QD) Solar Cells	20
3.5 Novel Applications and Integration	20
3.5.1 Bifacial Modules.....	20
3.5.2 Building-Integrated PV (BIPV).....	20
3.5.3 Floating PV.....	20
3.6 Comparative Assessment and Outlook.....	21
Chapter 4 – Solar Thermal Technologies	21
4.1 Overview of Solar Thermal Energy	21
4.2 Flat Plate Collectors (FPCs).....	22
4.3 Evacuated Tube Collectors (ETCs).....	22
4.4 Solar Water Heating Systems (SWHs).....	23
4.5 Solar Air Heaters	24
4.6 Solar Cookers	24
4.7 Solar Desalination Units	24
4.8 Solar Dryers	25
4.9 Solar Absorption Cooling and Chillers.....	25
4.10 Solar Greenhouses	26
Chapter 5 – Concentrated Solar Power (CSP) Systems	26
5.1 Introduction to Concentrated Solar Power	26
5.2 Parabolic Trough Systems	27
5.3 Solar Power Tower Systems	27
5.4 Linear Fresnel Reflector Systems.....	28
5.5 Dish-Stirling Engines.....	28
5.6 Thermal Energy Storage (TES) in CSP	29
5.7 Hybrid and Multi-Generation CSP Applications	30

5.8 Comparative Analysis of CSP Technologies	30
5.9 CSP Deployment in Italy and the EU	30
Chapter 6 – Hybrid Solar Energy Systems.....	31
6.1 Introduction.....	31
6.2 Photovoltaic + Thermal (PVT) Systems	31
6.3 PV + Battery Systems	32
6.4 PV + Wind or Diesel Hybrid Systems.....	32
6.5 PV + Hydrogen Electrolysis.....	33
6.6 CSP + Hybrid Systems.....	33
6.7 Smart Hybrid Systems with IoT and EMS	33
6.8 Comparative Analysis.....	34
Chapter 7 – Passive Solar Systems	34
7.1 Introduction.....	34
7.2 Passive Solar Heating Strategies.....	35
7.2.1 Direct Gain	35
7.2.2 Indirect Gain – Trombe Wall.....	36
7.3 Passive Solar Cooling Strategies	37
7.3.1 Shading Devices and Overhangs	37
7.3.2 Cross Ventilation	38
7.4 Daylighting and Visual Comfort	38
7.5 Thermal Mass for Heat Storage and Lag	39
7.6 Stack and Buoyancy Ventilation	39
7.7 Climate-Specific Passive Strategies.....	40
Chapter 8 – Emerging and Future Solar Energy Conversion Technologies.....	40
8.1 Introduction.....	40
8.2 Tandem and Multijunction Solar Cells	41
8.2.1 Theoretical Background	41
8.2.2 Current Status.....	41
8.3 Perovskite Solar Cells (PSC).....	42
8.3.1 Advantages of Perovskite Materials	42

8.3.2 Critical Barriers	42
8.4 Quantum Dot and Organic Photovoltaics	42
8.4.1 Quantum Dot Solar Cells (QDSC)	42
8.4.2 Organic Photovoltaics (OPV).....	42
8.5 Artificial Photosynthesis and Photoelectrochemical Systems	42
8.5.1 Working Principle.....	42
8.5.2 Challenges.....	43
8.6 Solar Thermochemical Hydrogen Production	43
8.6.1 Process Overview.....	43
8.6.2 Current Status.....	43
8.7 Adaptive Solar Technologies	44
8.7.1 Dynamic Solar Facades.....	44
8.7.2 Wearable Solar	44
8.8 Floating CSP and CPVT Technologies	44
8.8.1 Floating CSP	44
8.8.2 CPVT Systems.....	44
Chapter 9 – Conclusions and Recommendations.....	44
9.1 Comprehensive Review and Integration.....	44
9.2 Summary of Key Technical Findings	45
9.2.1 Photovoltaic and Hybrid Systems	45
9.2.2 Solar Thermal and CSP	45
9.2.3 Passive Solar Systems.....	45
9.3 Comparative Evaluation.....	46
9.4 Cross-Cutting Challenges.....	46
9.5 Policy and Deployment Recommendations	47
9.5.1 For Policymakers	47
9.5.2 For Industry.....	47
9.5.3 For Researchers	47
9.6 Future Research Directions	47
9.7 Final Remarks	47

Chapter 10 – Sustainability, Circular Economy, and Lifecycle Assessment in Solar Energy Systems	48
10.1 Introduction.....	48
10.2 Lifecycle Stages of Solar Energy Technologies	48
10.3 Lifecycle Metrics of Key Solar Technologies.....	49
10.4 Critical Materials and Environmental Hotspots.....	49
10.4.1 Use of Critical Raw Materials (CRM)	49
10.5 Energy and Water Usage in Solar Manufacturing	49
10.6 Circular Economy Approaches for Solar Technologies	50
10.7 Global End-of-Life (EOL) Policies and Best Practices.....	50
10.7.1 Europe	50
10.7.2 Asia	50
10.7.3 North America	50
10.8 Lifecycle and Sustainability Challenges for Emerging Solar Technologies	51
10.8.1 Perovskite Solar Cells	51
10.8.2 Tandem PV and Quantum Dot Solar Cells.....	51
10.9 Lifecycle KPIs Across Solar Technologies.....	51
10.10 Recommendations for Achieving Sustainable Solar Deployment	51
10.11 Final Reflections.....	52
REFERENCES	52

List of Figures and Tables

Figure 1 – Global Solar Irradiance Potential (kWh/m ² /year)	10
Figure 2 – Solar Spectrum and Wavelength Utilization by Technology Type	13
Figure 3 – Impact of Temperature on PV Output (Normalized).....	15
Figure 4 – Lifecycle Greenhouse Gas Emissions by Technology Type	17
Figure 5 – Working Principle of a Crystalline Silicon PV Cell 9312654022	18
Figure 6 – Cross-Section of a Flat Plate Solar Collector.....	22
Figure 7 – Cross-Section of a Heat Pipe Evacuated Tube Collector	23
Figure 8 – Single-Basin Solar Still with Reflective Cover.....	25
Figure 9 – General CSP Process Flow Diagram.....	26

Figure 10 – Solar Power Tower with Two-Tank Thermal Storage.....	28
Figure 11 – Dish-Stirling Prototype Used in Solar Thermal Cogeneration.....	29
Figure 12 – Classification of Hybrid Solar Systems.....	31
Figure 13 – Smart Hybrid System with EMS Integration	34
Figure 14 – Energy Flows in Passive Solar Design	35
Figure 15 – Passive Solar Heating System Types: Direct Gain, Trombe Wall, and Sunspace	37
Figure 16 – Solar Path with Overhang Sizing	38
Figure 17 – Solar Chimney and Buoyancy Ventilation Diagram.....	40
Figure 18 – Tandem Solar Cell Architecture	41
Figure 19 – Schematic of a PEC Water Splitting System.....	43
Table 1 - Classification of Solar Energy Conversion Technologies	11
Table 2 – Solar Energy Conversion Technologies: Operating Ranges and Applications.....	14
Table 3 – Comparison of Mono-Si vs. Poly-Si Modules	19
Table 4 – Comparative Summary of PV Technologies (2023).....	21
Table 5 – Technical Parameters of Flat Plate Collectors	22
Table 6 – Passive vs. Active SWH System Comparison.....	23
Table 7 – Solar Cooling System Comparison.....	26
Table 8 – SEGS VI Plant Parameters (California)	27
Table 9 – Technical Comparison of CSP System Types.....	30
Table 10 – Efficiency and Use Cases of PVT Variants	31
Table 11 – Summary of Hybrid Solar System Types	34
Table 12 – Recommended Glazing Ratios by Climate Zone	36
Table 13 – Daylighting Strategies by Orientation.....	38
Table 14 – Thermal Mass Properties.....	39
Table 15 – Passive Strategies by Climate; Each climate benefits from different passive techniques:.....	40
Table 16 – Thermochemical Hydrogen Candidates	44
Table 17 – Comparative Assessment of Solar Energy Technologies	46
Table 18 – Priority Research Areas for Solar Innovation (2025–2030)	47
Table 19 – Lifecycle Assessment Metrics of Major Solar Technologies	49
Table 20 – Recovery Routes for PV Module Components.....	50
Table 21 – Sustainability KPIs for Leading Solar Technologies.....	51

Chapter 1 – Introduction

1.1 Context and Background of Solar Energy Utilization

The global energy sector is undergoing a structural transformation driven by the urgent need to mitigate climate change, reduce dependence on fossil fuels, and enhance energy security. According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to below 1.5°C requires a reduction of CO₂ emissions by at least 45% from 2010 levels by 2030 [1]. Despite this, fossil fuels still accounted for approximately 77% of the global primary energy supply as of 2022 [2].

Solar energy, among all renewable sources, is the most abundant and widely distributed. The Earth continuously receives around 173,000 terawatts (TW) of solar radiation - more than 10,000 times the world's total energy demand [3]. Harnessing even a fraction of this potential could enable a carbon-neutral energy future.

Solar energy can be converted into usable forms through three major technology types: photovoltaic (PV) systems that convert sunlight directly into electricity using semiconductor materials; solar thermal systems that use solar radiation to heat water or air for domestic and industrial use; and concentrated solar power (CSP) systems, which focus sunlight using mirrors or lenses to produce high-temperature heat that drives turbines for electricity generation [4].

Recent advancements have also introduced hybrid systems such as PV combined with battery storage or thermal collectors (PVT), and emerging technologies like perovskite tandem cells, photoelectrochemical (PEC) hydrogen production, and artificial photosynthesis [5].

In the European Union, solar energy is central to achieving decarbonization targets. The REPowerEU Plan proposes over 600 GW of installed PV capacity by 2030, more than double current levels [6].

Italy is one of Europe's solar leaders. As of 2023, the country had more than 25 GW of installed solar PV capacity [7], supported by incentives such as Conto Energia (2005–2013), Superbonus 110%, and regional feed-in tariffs. The country's Mediterranean climate provides high solar irradiance, especially in southern regions like Sicily, Apulia, and Calabria, where global horizontal irradiance (GHI) exceeds 1,600 kWh/m²/year [8]. These regions are ideal for both rooftop PV and utility-scale solar plants.

Italy also leads in innovative deployments such as building-integrated photovoltaics (BIPV), floating PV installations, and agrivoltaic systems that combine solar energy production with agriculture [9].

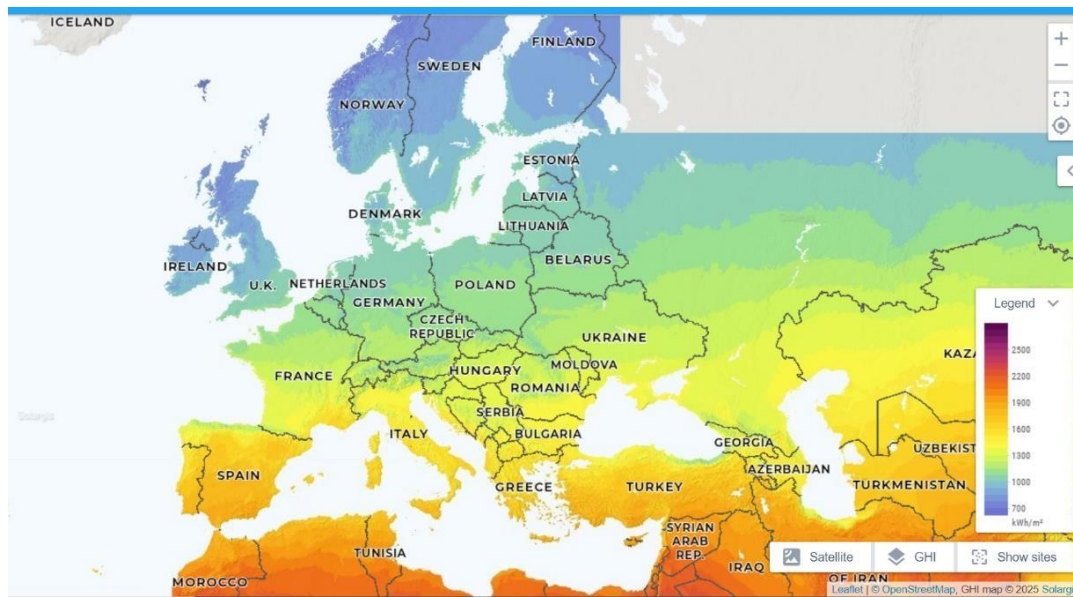


Figure 1 – Global Solar Irradiance Potential ($\text{kWh/m}^2/\text{year}$)

Map highlighting Global Horizontal Irradiance (GHI) across Europe and the Mediterranean region. Southern Italy - particularly Sicily, Apulia, and Calabria - demonstrates high solar potential, exceeding $1,600 \text{ kWh/m}^2/\text{year}$, making it ideal for PV deployment. (Adapted from World Bank Global Solar Atlas, 2023 [10]).

1.2 Objectives of the Report

This report aims to deliver a comprehensive, technically detailed analysis of solar energy conversion systems, both conventional and emerging. The objectives are as follows:

1. To classify solar energy systems by type (PV, thermal, CSP, hybrid, passive, advanced) and operational principle.
2. To evaluate key performance parameters including conversion efficiency, energy yield, degradation rate, and energy payback time.
3. To compare technologies based on economic indicators such as installation cost (€/kWp), levelized cost of electricity (LCOE), and return on investment (ROI).
4. To present recent innovations such as tandem perovskite cells, solar textiles, and PEC hydrogen generation.
5. To examine Italy's solar energy implementation in the context of EU policy and climate targets.

Table 1 - Classification of Solar Energy Conversion Technologies

Technology Type	Conversion Mechanism	Energy Output	Maturity Level
Crystalline & Thin-Film PV	Photoelectric effect	Electricity	Commercial
Solar Thermal Collectors	Thermal conduction	Hot water / heat	Commercial
Concentrated Solar Power (CSP)	Optical-thermal-electric	Electricity	Utility-scale
Hybrid (PVT, PV+Storage)	Combined electrical/thermal	Electricity + heat	Emerging
Passive Solar Design	Architectural heat capture	Heating/lighting	Traditional
Advanced (Perovskite, PEC, CPVT)	Quantum, catalytic processes	Electricity / fuels	Experimental

The classification presented in the table is based on widely accepted technology definitions found in international energy reports [2][5] institutional publications by GSE and ENEA [7][8], simulation data from platforms such as the Global Solar Atlas and PVGIS [10][11], and established engineering references including Duffie and Beckman's solar energy handbook [12].

1.3 Scope and Methodology

- This report comprises six core technical chapters (Chapters 3-8), each focused on a class of solar energy technologies. Each chapter includes:
- Scientific and engineering principles such as photovoltaic material behavior, heat transfer, and optical concentration
- Efficiency ranges based on standard test conditions (STC), temperature coefficients, and degradation rates
- Typical applications in Italy and globally (e.g., rooftop residential systems, agrivoltaic farms, industrial process heat)
- Advantages and limitations with respect to cost, climate sensitivity, and land use
- Visual elements including system diagrams, process flows, and performance graphs
- Data sources include:
- Peer-reviewed journals (Applied Energy, Renewable Energy, Solar Energy)
- Reports from IEA, IRENA, Fraunhofer ISE [2][5]

- Italian government institutions (ENEA, GSE, MiTE) [7][8]
- Solar simulation tools and open-access databases (PVGIS, Global Solar Atlas) [10][11]
- Engineering reference texts including Duffie & Beckman (2013) [12]

1.4 Structure of the Report

The report is organized into the following chapters:

- Chapter 2: Scientific foundations of solar radiation and energy conversion
- Chapter 3: Photovoltaic systems including monocrystalline, thin-film, tandem, and flexible solar cells
- Chapter 4: Solar thermal systems and collector configurations for water, space, and process heating
- Chapter 5: Concentrated solar power (CSP) technologies and thermal energy storage
- Chapter 6: Hybrid solar energy systems (PV + storage, PVT, smart grid)
- Chapter 7: Passive solar energy systems and bioclimatic architecture
- Chapter 8: Emerging technologies including solar fuels, PEC hydrogen, and adaptive facades
- Chapter 9: Environmental and financial comparison of solar systems
- Chapter 10: Strategic conclusions and recommendations

Chapter 2 – Fundamentals of Solar Energy Conversion

2.1 Solar Radiation and the Solar Spectrum

Solar energy originates from electromagnetic radiation emitted by the Sun, which behaves nearly as a blackbody with a surface temperature of $\sim 5,778$ K. According to Planck's law, this results in a solar spectrum peaking around 500 nm in the visible range and extending from ultraviolet (UV) to infrared (IR) wavelengths [13].

At the top of the Earth's atmosphere, the solar constant is approximately $1,366 \text{ W/m}^2$ [14]. However, due to scattering and absorption by atmospheric gases and aerosols, the average Global Horizontal Irradiance (GHI) at ground level under clear sky conditions typically ranges from 900 to $1,000 \text{ W/m}^2$ [15].

Italy benefits significantly from solar availability. The southern regions, such as Sicily and Apulia, receive annual GHI levels exceeding $1,600 \text{ kWh/m}^2/\text{year}$ [16].

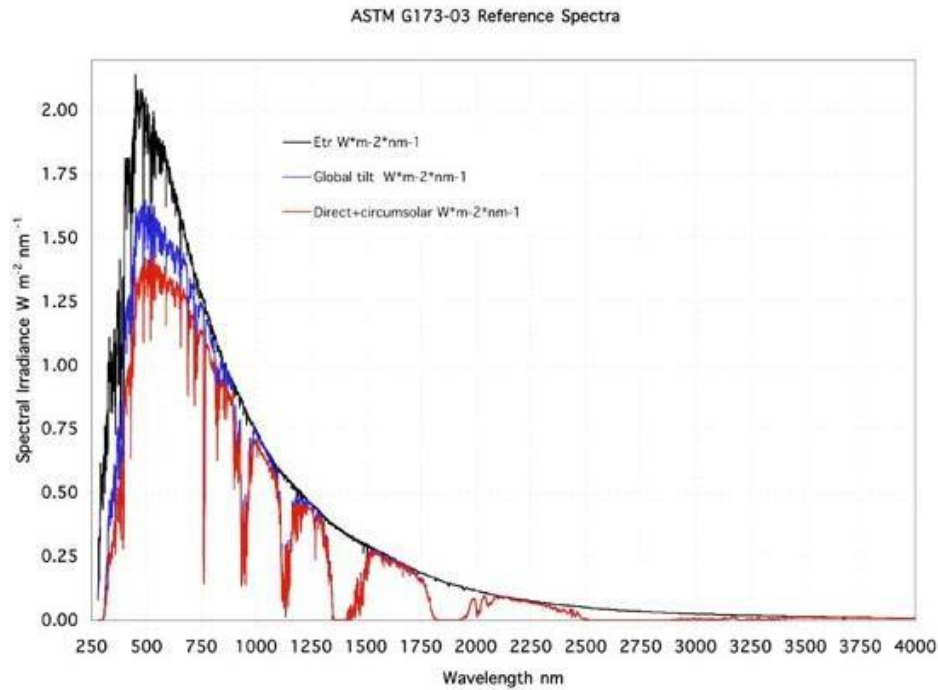


Figure 2 – Solar Spectrum and Wavelength Utilization by Technology Type

The graph illustrates the spectral distribution of solar radiation under AM1.5 atmospheric conditions as standardized by ASTM G-173-03. The global tilt and direct + circumsolar irradiance curves are shown across the 250–4000 nm range. PV systems typically operate within 300–1,100 nm, while thermal collectors benefit from a broader range including infrared wavelengths [13][17][21].

2.2 Energy Conversion Pathways

Solar energy is converted through two main mechanisms:

- **Photonic conversion:** Converts solar photons into electricity via the photoelectric effect (e.g., PV, CPV)
- **Thermal conversion:** Converts solar radiation into heat using collectors (e.g., CSP, solar water heaters)

2.2.1 Photovoltaic (PV) Conversion

PV conversion utilizes the photoelectric effect, where photons excite electrons across the bandgap of a semiconductor material, generating current across a p-n junction [18]. Crystalline silicon is dominant due to its efficiency, stability, and falling production costs [19].

$$\eta_{PV} = \frac{P_{out}}{E \cdot A}$$

Where:

- P_{out} = electric power output (W)
- E = incident irradiance (W/m^2)
- A = panel area (m^2)

Commercial PV module efficiencies [19][20]:

Where:

- Monocrystalline: 22–24%
- Polycrystalline: 18–20%
- Thin-Film (CdTe, CIGS): 10–18%

2.2.2 Thermal Conversion

Solar thermal collectors use selective surfaces to absorb radiation and transfer it to a fluid medium via conduction and convection. The heated fluid is then used for domestic water, space heating, or industrial processes.

Table 2 – Solar Energy Conversion Technologies: Operating Ranges and Applications

System Type	Energy Output	Efficiency Range	Scale of Use
Crystalline PV	Electricity	18–24%	Residential–Utility
Thin-Film PV	Electricity	10–18%	Portable/Urban
Flat Plate Collectors	Heat (Water)	40–60%	Domestic/Commercial
Evacuated Tube (ETC)	Heat (Hot Water)	60–75%	Cold/Cloudy Zones
CSP (Tower + Storage)	Electricity (via Heat)	25–40%	Utility-Scale

Table illustrates energy output types, efficiency ranges, and deployment scales for leading solar energy technologies. (Adapted from: Kalogirou [17], IRENA [21], Fraunhofer ISE [19])

2.2.3 Concentrated Solar Power (CSP)

CSP uses mirrors to concentrate sunlight onto a receiver, heating a fluid to produce steam and generate electricity. Storage integration allows for night-time generation. Main CSP types include:

- Parabolic Troughs
- Solar Power Towers (central receivers)
- Linear Fresnel Reflectors

- Dish-Stirling Engines

Thermal-to-electric efficiencies of modern CSP systems can exceed 40%, especially when coupled with molten salt storage [21] .

2.3 Efficiency and Performance Indicators

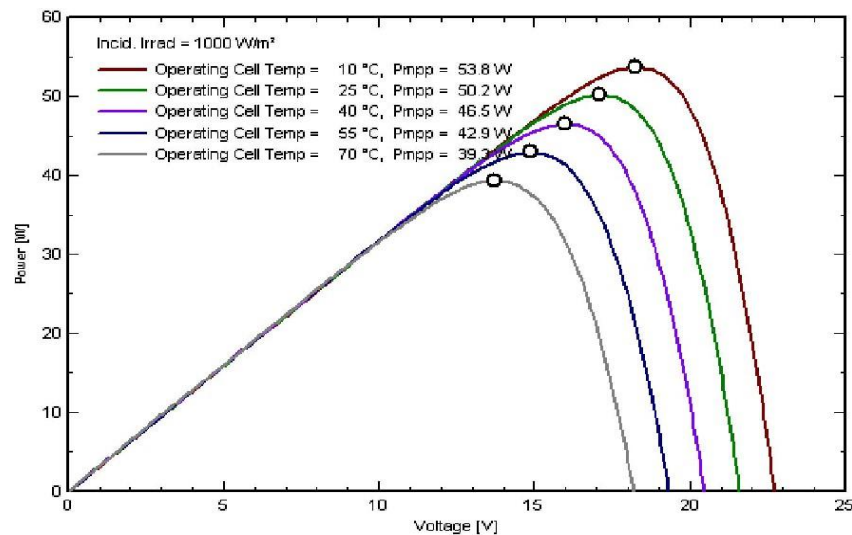


Figure 3 – Impact of Temperature on PV Output (Normalized)

The graph shows the P–V characteristics of a crystalline silicon PV module at varying operating cell temperatures (10°C to 70°C). As the temperature increases, the maximum power point (P_{mp}) decreases significantly - from 53.8 W at 10°C to 39.3 W at 70°C - illustrating the typical 0.4–0.5%/°C performance degradation found in silicon-based PV modules. (Adapted from: Fesharaki et al. [25])

2.3.1 Standard Test Conditions (STC)

All module ratings are based on STC:

- Irradiance = 1,000 W/m²
- Cell temperature = 25°C
- Air Mass = 1.5 (AM1.5)

Real-world performance is impacted by:

- Temperature coefficient (–0.4 to –0.5%/°C for silicon modules)
- Inverter and cable losses
- Dust and soiling

2.3.2 Performance Ratio (PR)

$$PR = \frac{\text{Actual Energy Output}}{\text{Theoretical Output at STC}}$$

Typical PR values:

- **PV systems:** 0.75–0.90
- **CSP systems:** vary depending on DNI and storage integration

2.4 Environmental and Climatic Influences

Performance is strongly linked to:

- **Irradiance and solar geometry**
Italy's optimal tilt angle ranges between 20°–35°, facing due south, maximizing annual output [16].
- **Ambient temperature**
High temperatures decrease PV voltage and reduce efficiency. Thermal systems, however, may benefit up to ~80°C [17].
- **Dust and air pollution**
Can reduce output by 5–25%, especially in arid and semi-arid zones [24].
- **Lifecycle emissions**
PV systems emit 20–50 g CO₂-eq/kWh vs. 900+ g CO₂-eq/kWh for coal [23].

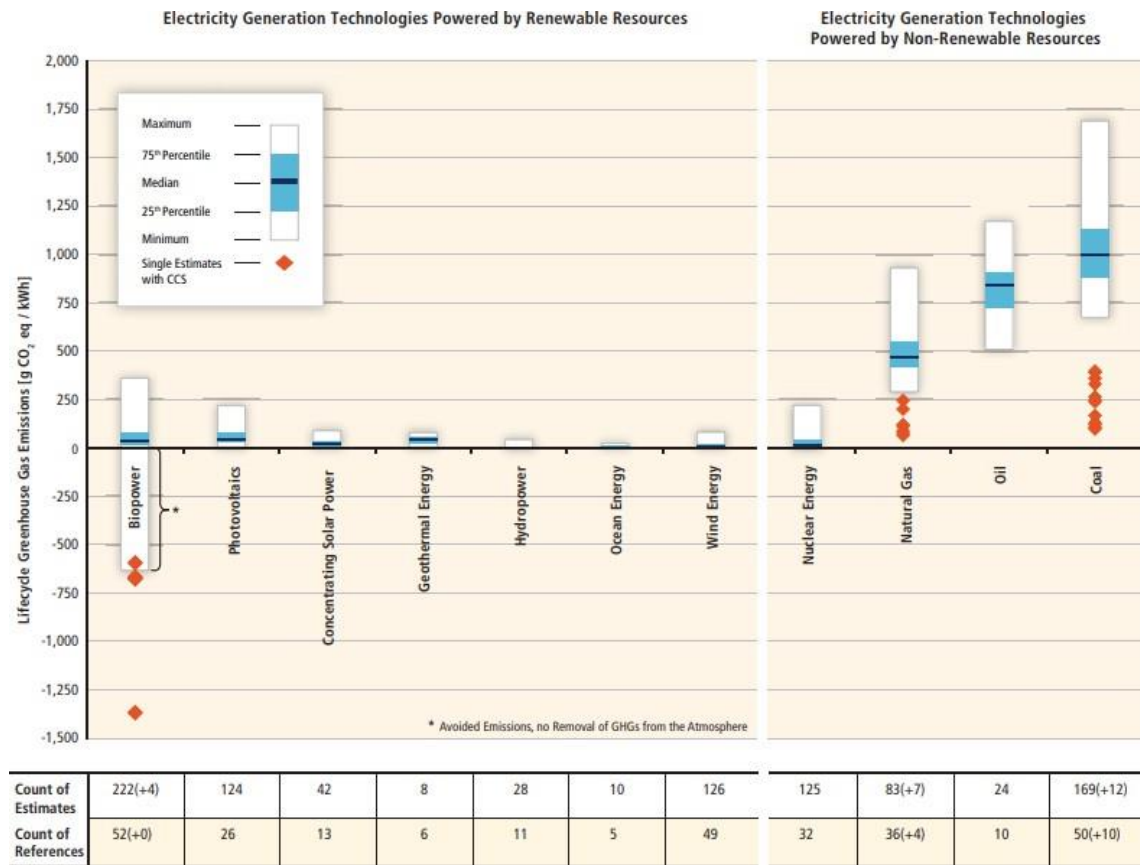


Figure 4 – Lifecycle Greenhouse Gas Emissions by Technology Type

This chart shows the estimated lifecycle greenhouse gas emissions of major electricity generation technologies in g CO₂-eq per kWh. Coal and oil have the highest emissions, while wind, nuclear, and solar PV exhibit substantially lower lifecycle values. (Adapted from: IPCC SRREN, 2011 – Figure SPM.8 [26])

Chapter 3 – Photovoltaic Technologies

3.1 Introduction to Photovoltaic Systems

Photovoltaic (PV) technologies convert sunlight directly into electricity using the photoelectric effect. When photons strike a semiconductor material - typically silicon - they excite electrons across the bandgap, creating an electric field at a p-n junction that drives current flow [27]. The generated direct current (DC) is converted to alternating current (AC) via inverters for grid compatibility.

Since the first silicon solar cell by Bell Labs in 1954, PV technologies have evolved into three generations: First Generation: Crystalline silicon (c-Si), Second Generation: Thin-film (e.g., CdTe, CIGS), Third Generation: Emerging technologies (e.g., perovskite, organic, quantum dot) [28]. As of 2023, global PV capacity surpassed 1.2 TW, with crystalline silicon representing over 90% of the market [29]. Italy's share exceeds 25 GW, largely deployed under regional and national incentives [30].

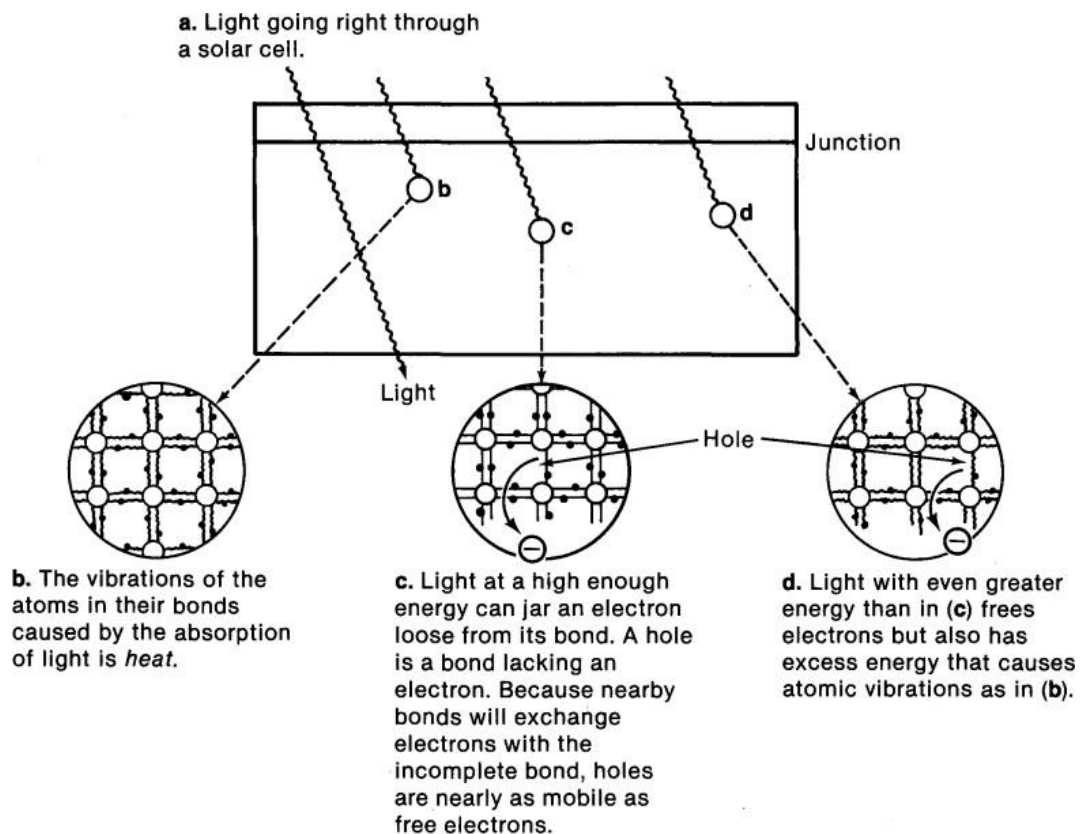


Figure 5 – Working Principle of a Crystalline Silicon PV Cell 9312654022

Illustration of light absorption, electron-hole pair generation, current flow, and recombination in a p-n junction. Incident photons either pass through, generate heat, or excite charge carriers that create usable electrical energy. (Adapted from: [NREL, 1991] [27])

3.2 Crystalline Silicon Technologies

3.2.1 Monocrystalline Silicon (Mono-Si)

Mono-Si cells are fabricated using the Czochralski (CZ) method, resulting in uniform crystal structure, high carrier mobility, and module efficiencies of 22-24% under STC [28],[31]. Key advantages include:

- High fill factor (>80%),

- Lower temperature coefficient ($\sim -0.4\%/^{\circ}\text{C}$),
- Long lifetime ($\sim 25\text{-}30$ years).

Downsides include higher cost and material loss during wafer slicing [27].

3.2.2 Polycrystalline Silicon (Poly-Si)

Poly-Si is produced via directional solidification, forming multiple crystalline grains. Although less efficient (18-20%), it is cheaper and requires less energy to manufacture [31].

Table 3 – Comparison of Mono-Si vs. Poly-Si Modules

Feature	Mono-Si	Poly-Si
Efficiency (STC)	22–24%	18–20%
Temperature Coefficient	$-0.40\%/^{\circ}\text{C}$	$-0.45\%/^{\circ}\text{C}$
Cost per Watt	Higher	Lower
Market Share (2023)	$\sim 55\%$	$\sim 35\%$

Monocrystalline systems are preferred in space-limited or high-efficiency applications. Polycrystalline is still common in cost-sensitive installations. (Sources: Fraunhofer ISE [31], IEA PVPS [29])

3.3 Thin-Film Technologies

Thin-film solar cells use micrometer-scale absorber layers deposited onto glass, plastic, or metal substrates.

3.3.1 Amorphous Silicon (a-Si)

Efficiency: 6-9%

Used in BIPV, calculators, and shading systems. Performance degrades under sunlight exposure (Staebler-Wronski effect) but recovers when stored in the dark [27].

3.3.2 Cadmium Telluride (CdTe)

Efficiency: 16-19%

CdTe's high absorption coefficient allows use of very thin layers. Widely deployed in utility-scale solar farms in the U.S. [32]. Environmental concerns due to cadmium are mitigated by stable encapsulation and dedicated recycling schemes [33] .

3.3.3 Copper Indium Gallium Selenide (CIGS)

Efficiency: 17–21% (lab)

Best-performing thin-film under flexible conditions. Commercial use is limited due to complex manufacturing and scarcity of indium and gallium [28].

3.4 Emerging and Experimental PV Technologies

3.4.1 Perovskite Solar Cells (PSC)

PSC devices based on $\text{CH}_3\text{NH}_3\text{PbI}_3$ have achieved lab efficiencies $>26\%$ [28]. They are lightweight, printable, and ideal for tandem integration with silicon, reaching combined efficiencies over 30% [35]. Key challenges include humidity instability and lead toxicity.

3.4.2 Organic and Dye-Sensitized Solar Cells

Efficiencies:

- OPV: $10\text{--}13\%$,
- DSSC: $7\text{--}11\%$ [36].
Advantages: semi-transparency, flexible substrates, aesthetic options. Still under research-scale deployment [36].

3.4.3 Quantum Dot (QD) Solar Cells

Use quantum confinement to tune bandgaps. Promising for multi-exciton generation, but limited by toxicity (Pb, Cd) and scalability [37].

3.5 Novel Applications and Integration

3.5.1 Bifacial Modules

Generate power from both faces, improving output by $5\text{--}25\%$ depending on ground reflectivity (albedo) [29].

3.5.2 Building-Integrated PV (BIPV)

Used as construction elements in windows, façades, roofs. Supported in Italy through Conto Energia and urban planning codes [30].

3.5.3 Floating PV

Deployed on lakes, reservoirs, and canals, floating systems improve panel cooling and water conservation [38].

3.6 Comparative Assessment and Outlook

Table 4 – Comparative Summary of PV Technologies (2023)

Technology	Efficiency	Cost (\$/W)	Lifespan	Features	Stage
Mono-Si	22–24%	0.25–0.35	25–30 y	Compact, efficient	Commercial
Poly-Si	18–20%	0.20–0.30	25 y	Low cost	Commercial
CdTe	16–19%	0.30–0.40	25 y	High scale, toxic materials	Commercial
CIGS	17–21%	0.35–0.50	20–25 y	Flexible, high lab efficiency	Niche commercial
Perovskite	20–26%	TBD	<10 y	Tandem-ready, unstable	R&D
Organic (OPV)	8–13%	TBD	5–10 y	Transparent, colored	Experimental
Quantum Dot	7–12%	TBD	Unknown	Tunable bandgap, theoretical >30%	Lab scale

PV technologies continue to evolve toward higher efficiency, material circularity, and multifunctional deployment. Tandem and bifacial modules are expected to dominate next-generation commercial markets. (Green et al. [28], NREL [34], IRENA [32], Jeong et al. [35])

Chapter 4 – Solar Thermal Technologies

4.1 Overview of Solar Thermal Energy

Solar thermal systems convert sunlight into thermal energy using basic heat transfer principles—primarily conduction, convection, and radiation. These systems are widely used for water and space heating, industrial process heat, desalination, drying, and even cooling. Unlike PV systems that generate electricity, solar thermal systems utilize absorber surfaces to heat a fluid directly [38].

As of 2022, global installed solar thermal capacity exceeded 500 GWth, with top deployments in China, Germany, and Italy [39][40]. Italy benefits from its Mediterranean climate, which supports year-round operation in most regions [43].

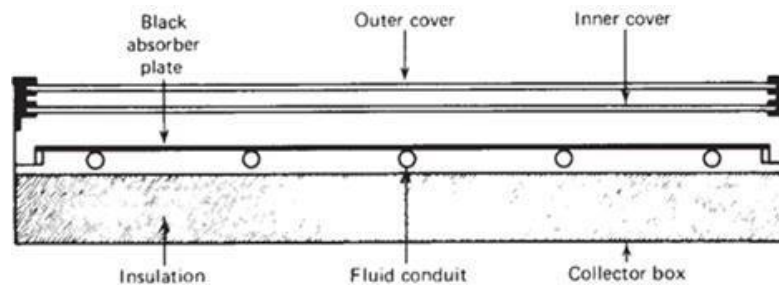


Figure 6 – Cross-Section of a Flat Plate Solar Collector

Illustrates the major components of a typical flat plate solar collector system, including the black absorber plate for heat capture, inner and outer glass covers for reducing thermal losses, fluid conduits for heat transport, insulation for minimizing back losses, and the structural collector box. (Adapted from Duffie & Beckman [41])

4.2 Flat Plate Collectors (FPCs)

Flat Plate Collectors (FPCs) are the most common solar thermal systems for domestic use. Their structure includes:

- A selective-coated absorber,
- Copper or aluminum tubing bonded to the absorber,
- Insulated housing and transparent glass or polymer glazing.

Typical operating temperatures range from 30–80°C, and thermal efficiencies reach 50–70% under standard conditions [38][41].

Table 5 – Technical Parameters of Flat Plate Collectors

Parameter	Typical Value
Optical Efficiency (η_o)	0.70–0.75
Heat Loss Coefficient (U_L)	4–6 W/m ² ·K
Surface Area	1.5–2.5 m ² /module
Operating Temp. Range	30–80°C

FPCs are ideal for Italy's mild climates where freeze protection is less critical [43].

4.3 Evacuated Tube Collectors (ETCs)

ETCs use vacuum-sealed double glass tubes to minimize convective and conductive losses. Each tube typically contains: A selective absorber, A vacuum layer between glass shells, Optional heat pipe or U-tube.

These systems operate efficiently in cold climates and reach temperatures above 100°C [42].

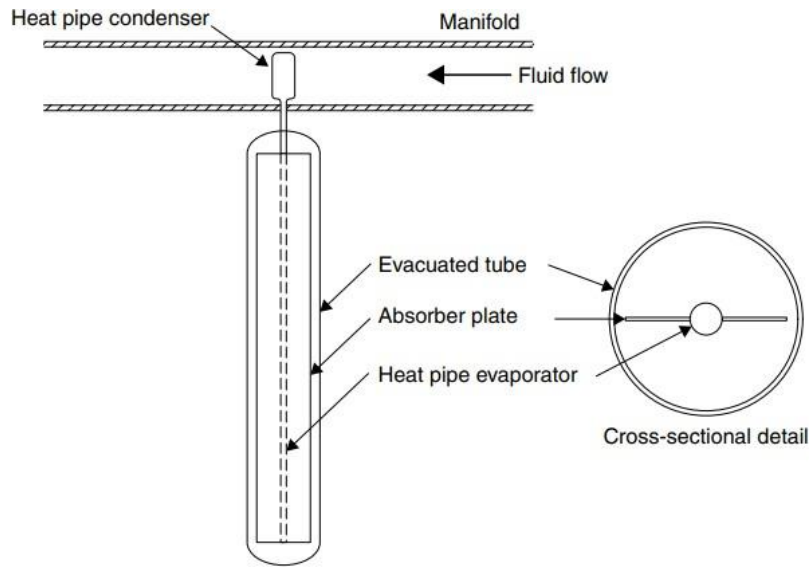


Figure 7 – Cross-Section of a Heat Pipe Evacuated Tube Collector

This figure illustrates a modern evacuated tube collector, consisting of a heat pipe evaporator inside a vacuum-sealed glass tube. Solar radiation is absorbed by the absorber plate, heating the evaporator fluid inside the heat pipe. The heated vapor rises to the heat pipe condenser located in the manifold, where it releases heat to the circulating fluid (e.g., water or glycol mixture). The cooled fluid then returns by gravity to repeat the cycle. A cross-sectional detail shows the evacuated tube structure with the absorber plate and internal heat pipe. (Adapted from: Kalogirou [38], *Solar Energy Engineering: Processes and Systems*)

4.4 Solar Water Heating Systems (SWHs)

SWH systems are categorized into:

- Passive systems: thermosiphon flow, low cost, no pump,
- Active systems: pumped circulation, higher capacity and control.

Italy's Superbonus 110% and ClimaBonus programs provide tax credits for installing SWHs in homes and businesses [44].

Table 6 – Passive vs. Active SWH System Comparison

Feature	Passive	Active
Pump Required	No	Yes
Installation Cost	Low	Moderate–High
Freeze Protection	Limited	Full (with glycol)
Typical Use	Residential	Residential/Commercial

SWH systems are increasingly adopted in Italy under incentive programs [44].

4.5 Solar Air Heaters

Solar air heaters are simple devices for preheating ventilation air or drying crops. They consist of:

- A dark absorber plate,
- Transparent cover (glass/plastic),
- Insulated backing,
- Airflow channels.

Efficiencies vary from 40 - 60%, depending on air speed and temperature difference [45]. They're ideal for low-tech applications in rural and agricultural settings.

4.6 Solar Cookers

Solar cookers convert direct sunlight into thermal energy for cooking and sterilizing. Types include:

- Box-type: insulated enclosure, 50 - 100°C,
- Parabolic: focused dish, 150 - 300°C,
- Panel cookers: reflective foils and central pot, ~120°C.

These devices are portable, emission-free, and useful in remote areas. However, they're affected by weather, timing, and cooking consistency [46].

4.7 Solar Desalination Units

Solar desalination uses heat to purify seawater. Methods include:

- Solar stills: evaporation-condensation,
- Membrane distillation,
- Multi-effect distillation (MED) with thermal collectors.

Efficiency is modest in simple stills (30–40%), but CPC-enhanced systems perform better in island or coastal communities [47].

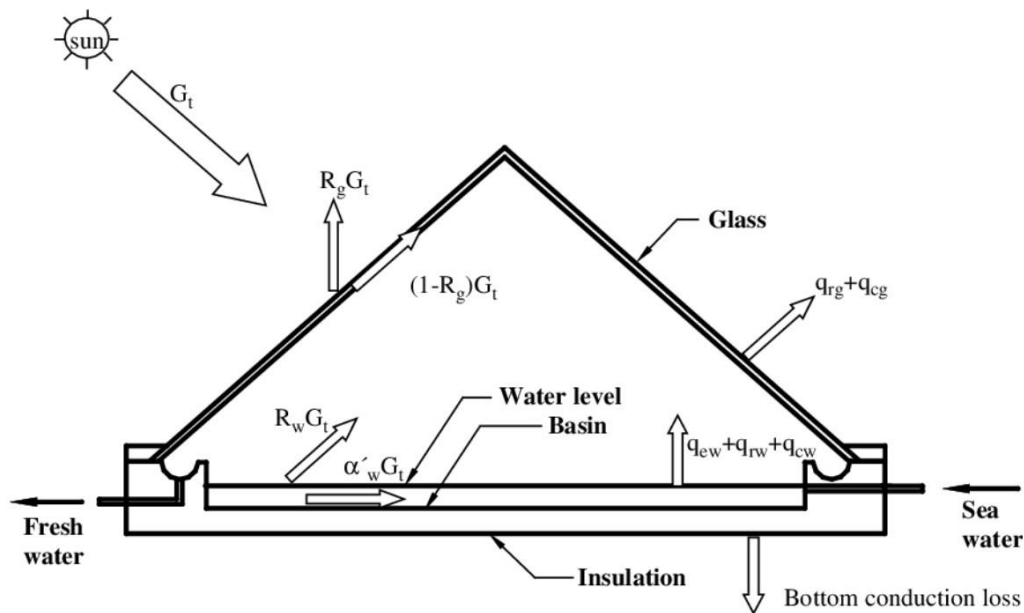


Figure 8 – Single-Basin Solar Still with Reflective Cover

This figure shows the operational principle of a single-basin solar still. Solar radiation (G_t) enters through a sloped glass cover. Part of it is reflected ($R_g G_t$), and part penetrates to heat the seawater inside the basin. The absorbed energy causes evaporation, and the resulting vapor condenses on the cooler glass underside, producing fresh water. Heat losses include reflection, conduction at the basin bottom, and radiative and convective losses through the glass. The insulation minimizes conduction loss, while the system layout maximizes fresh water yield. (Source: Adapted from Kalogirou [47])

4.8 Solar Dryers

Solar dryers reduce moisture in food, herbs, and biomass, minimizing spoilage. Types include:

- **Direct dryers:** transparent covers expose product to sunlight,
- **Indirect dryers:** heated air is channeled over the product.

Drying temperatures of 40–70°C and time reductions up to 60% make them efficient alternatives to open-air drying [48].

4.9 Solar Absorption Cooling and Chillers

Solar thermal energy can drive absorption refrigeration systems, ideal for cooling during sunny periods. Main working fluids:

- LiBr–Water (for chilled water),
- $\text{NH}_3\text{--H}_2\text{O}$ (for freezing).

COP ranges from 0.6–0.8, depending on temperature source and configuration [49].

Table 7 – Solar Cooling System Comparison

System Type	COP	Collector Type	Temp. Needed	Use Case
Absorption (LiBr)	0.7	ETC/FPC	70–95°C	Commercial
Adsorption	0.6	FPC	60–80°C	Limited
Desiccant Cooling	0.5	FPC/Air	~60°C	Ventilation

Solar cooling is growing in smart buildings and zero-energy designs in Italy [50].

4.10 Solar Greenhouses

Solar greenhouses use passive and active solar methods for temperature control and crop productivity. Design features:

- South-facing glazing,
- Thermal mass storage (e.g., barrels, concrete),
- Optional solar air heaters.

These systems support year-round agriculture in Mediterranean regions like Apulia and Sicily [51].

Chapter 5 – Concentrated Solar Power (CSP) Systems

5.1 Introduction to Concentrated Solar Power

Concentrated Solar Power (CSP) systems utilize direct normal irradiance (DNI) to generate high-temperature thermal energy, which is converted into electricity through thermodynamic cycles, typically Rankine steam cycles [52]. Unlike photovoltaic systems, CSP leverages optical mirrors/lenses and thermal conversion, allowing for thermal energy storage (TES) and dispatchable electricity production [22].

CSP requires high solar resource regions ($\text{DNI} > 1,800\text{--}2,000 \text{ kWh/m}^2/\text{year}$) and is best suited to locations such as Southern Europe, the Middle East, and North Africa [53]. Its ability to store thermal energy makes it a key technology for grid stability and renewable integration [54].

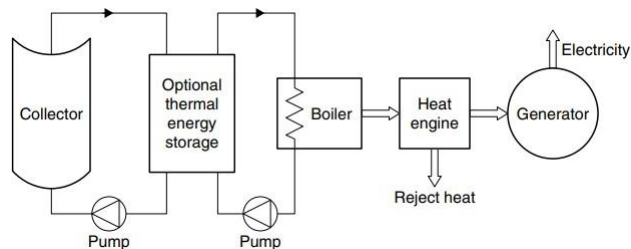


Figure 9 – General CSP Process Flow Diagram

Schematic flow of a typical Concentrated Solar Power (CSP) system illustrating the energy conversion process: solar radiation is collected → heat transfer fluid circulates through a boiler → drives a heat engine → produces electricity via a generator, with optional thermal energy storage integration and heat rejection systems. (Adapted from Kalogirou [59])

5.2 Parabolic Trough Systems

Parabolic trough collectors (PTCs) are the most commercially deployed CSP technology, accounting for around 60% of installed capacity [55]. They focus sunlight onto a receiver tube using parabolic-shaped mirrors.

- **Heat transfer fluid (HTF):** Synthetic oil (e.g., Dowtherm A) heated to ~390°C.
- **Output:** Superheated steam drives a turbine.

Table 8 – SEGS VI Plant Parameters (California)

Parameter	Value
Collector Aperture	5.76 m
Receiver Temperature	~390°C
Solar Field Size	~200,000 m ²
Net Output	30–50 MW

PTCs achieve 55–65% thermal efficiency and 15–20% solar-electric efficiency [56]. Italy’s Archimede Plant in Sicily integrates molten salt storage with trough collectors, enabling nighttime operation [57].

5.3 Solar Power Tower Systems

Solar towers use a central receiver atop a tower, with thousands of heliostats (dual-axis mirrors) reflecting sunlight to it. The system heats molten salts directly to ~565°C.

Advantages:

- Higher thermal-to-electric conversion efficiency,
- Better storage compatibility,
- Smaller receiver surface = less radiative loss [58].

Examples:

- **PS10/PS20 (Spain)** – early commercial systems.
- **Gemasolar (Spain)** – 19.9 MW capacity, 15-hour thermal storage.

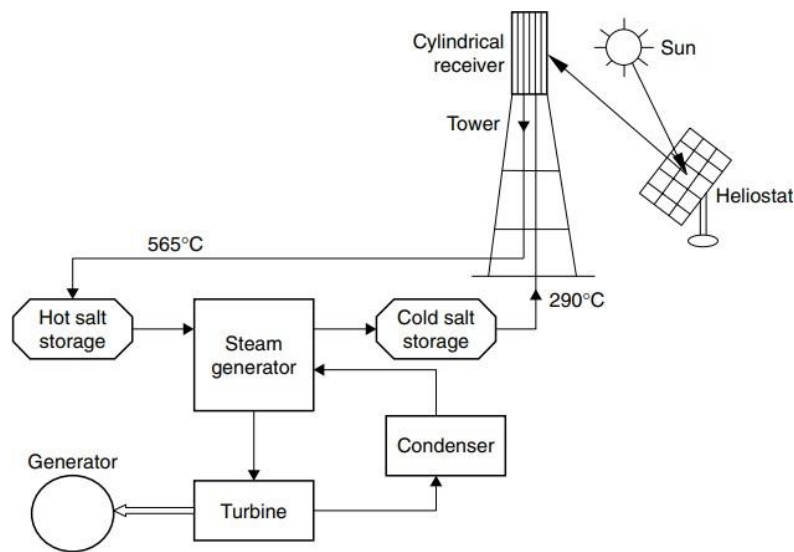


Figure 10 – Solar Power Tower with Two-Tank Thermal Storage

Shows: heliostat field reflecting sunlight to a receiver atop a tower, heating molten salts for storage and steam generation. System includes hot/cold salt tanks, steam generator, turbine, condenser, and electricity generation cycle. (Adapted from García-Barberena et al., 2015) [58],

5.4 Linear Fresnel Reflector Systems

Linear Fresnel Reflectors (LFRs) use flat or slightly curved mirrors that focus sunlight on a fixed linear receiver. Though less efficient than troughs, they are:

- Cheaper to construct,
- Require less land and maintenance,
- Produce heat at 250–300°C [60].

Used in industrial heat supply and medium-scale steam generation.

5.5 Dish-Stirling Engines

Dish systems are modular, high-efficiency CSP technologies that use a parabolic dish to focus sunlight onto a receiver powering a Stirling engine.

- **Temperatures:** 650–800°C,
- **Efficiency:** 30–35% (highest among CSP systems),
- **Output:** 3–25 kW per module [61].

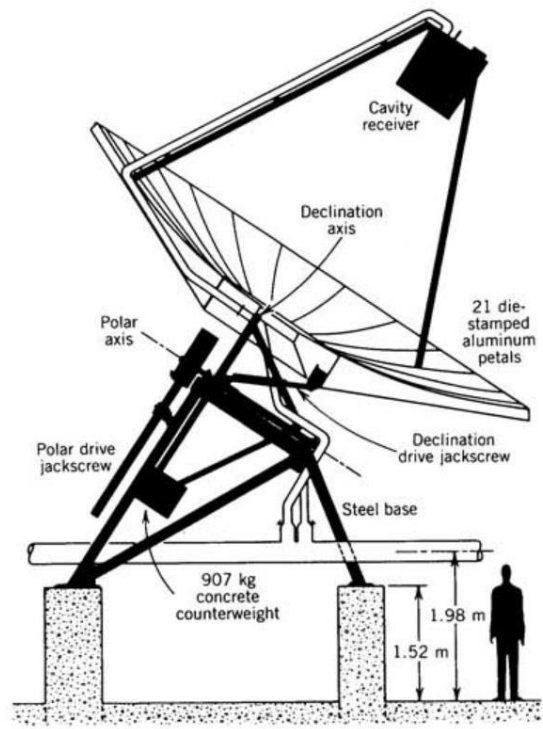


Figure 11 – Dish-Stirling Prototype Used in Solar Thermal Cogeneration

Illustration of a parabolic dish reflector featuring a cavity receiver mounted on the focal point, supported by polar and declination axis drive systems. The dish is composed of 21 die-stamped aluminum petals with a 907 kg concrete counterweight for structural stability. This prototype, deployed in Shenandoah, Georgia, was designed for solar thermal cogeneration applications using a Stirling engine configuration. (Adapted from Figure 9.19, Stine & Geyer [61])

5.6 Thermal Energy Storage (TES) in CSP

TES enhances CSP by storing heat, allowing generation even when the sun is not shining.

Storage methods:

- **Sensible heat storage** using molten salts (290–565°C),
- **Latent heat storage** using phase change materials (PCMs),
- **Thermochemical storage** using reversible chemical reactions (e.g., CaO/CaCO_3) [57].

Round-trip efficiency: 90–95%,

Storage duration: up to 15 hours,

Cost: ~\$30–50/kWhth [57].

5.7 Hybrid and Multi-Generation CSP Applications

CSP can be hybridized to support multiple outputs or stabilize grids:

- **ISCC Plants:** Combines CSP with gas turbines (e.g., Ain Beni Mathar, Morocco).
- **CSP + Desalination:** Uses heat to power MED or MSF desalination plants [59].
- **CSP + Hydrogen:** High-temp towers enable thermochemical hydrogen production (e.g., S-I cycles) [54].

5.8 Comparative Analysis of CSP Technologies

Table 9 – Technical Comparison of CSP System Types

Feature	Trough	Tower	LFR	Dish-Stirling
Temp Range (°C)	290–390	500–600	250–300	600–800
Storage Integration	High	Very High	Medium	Low
Net Efficiency	15–20%	18–23%	12–16%	25–30%
Modularity	Medium	Low	Medium	High
Commercial Status	Mature	Scaling	Emerging	Pilot

Comparison based on temperature, scalability, and energy performance [52][53][55][62].

5.9 CSP Deployment in Italy and the EU

Italy's CSP potential is concentrated in Sicily, Sardinia, Apulia, and Calabria, where DNI exceeds 1,800 kWh/m²/year [57].

Key project:

- Archimede Plant (Sicily): Europe's first molten salt + parabolic trough plant (5 MW, 8-hour storage).

CSP is included in Italy's updated 2024 National Energy and Climate Plan (PNIEC), supporting dispatchable renewables for balancing PV and wind [63].

EU programs supporting CSP development:

- Horizon Europe,
- Mission Innovation,
- Green Deal Calls (LC-SC3-RES-3-2020).

Chapter 6 – Hybrid Solar Energy Systems

6.1 Introduction

Hybrid solar energy systems combine multiple energy generation or storage technologies to enhance efficiency, reliability, and flexibility. These configurations allow systems to:

- Address PV intermittency,
- Increase total solar energy conversion,
- Enable energy storage or fuel production (e.g., hydrogen),
- Improve energy access in remote or variable-demand zones [64][65].

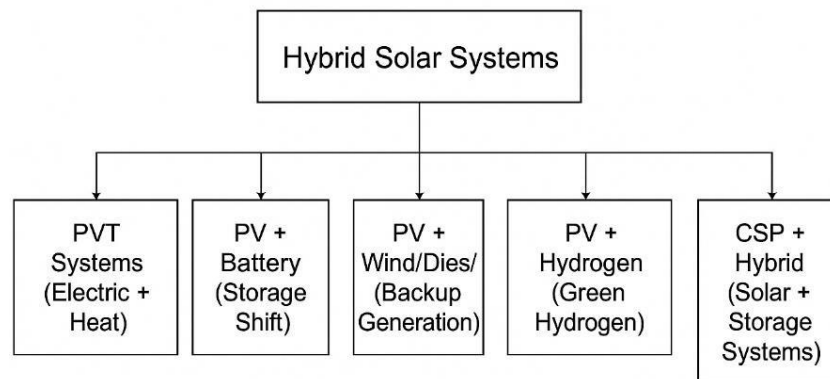


Figure 12 – Classification of Hybrid Solar Systems

This diagram demonstrates how hybrid solar configurations integrate multiple technologies to improve energy efficiency, storage, and dispatchability.
(Adapted from Kalogirou [64] and IEA [65])

6.2 Photovoltaic + Thermal (PVT) Systems

PVT systems recover waste heat from PV panels, combining electrical and thermal energy generation in a single module.

Typical performance includes:

- **Electrical efficiency:** 15–20%,
- **Thermal efficiency:** 40–60%,
- **Total system efficiency:** 55–80% [66][67].

Table 10 – Efficiency and Use Cases of PVT Variants

Variant	Heat Transfer Fluid	Efficiency Gain	Common Application
Flat-Plate	Water/Glycol	+35–50%	Domestic Hot Water (DHW)
Air-Based	Air	+30–40%	Greenhouses, Ventilation
Concentrated	Oil/Air	+50–60%	Industrial Process Heat

This table summarizes the main types of Photovoltaic-Thermal (PVT) systems, indicating their working fluid, typical efficiency improvements compared to standard PV modules, and common areas of application. Flat-plate PVTs are common in residential settings, air-based systems suit agricultural and ventilation needs, while concentrated systems are deployed in industrial heating processes [64][66]

6.3 PV + Battery Systems

Battery Energy Storage Systems (BESS) enable load-shifting, self-consumption, and off-grid operation.

Modern systems utilize:

- Lithium-ion (LFP/NMC) chemistries,
- Round-trip efficiencies of 85–95%,
- Cycle life up to 10,000 for LFP [68].

Use cases include:

- Residential self-consumption,
- Rural electrification and telecom towers,
- EV charging stations and load balancing.

6.4 PV + Wind or Diesel Hybrid Systems

Hybridizing PV with wind or diesel generators increases energy availability:

- Wind often complements PV (e.g., night or winter),
- Diesel serves as firm backup for critical systems.

Performance indicators:

- LCOE reduced by 30–50% compared to diesel-only,
- Renewable share: 50–90% depending on wind potential and battery capacity [69].

Applications:

- Military and emergency power systems,
- Islanded microgrids,
- Off-grid industrial zones.

6.5 PV + Hydrogen Electrolysis

Surplus solar PV electricity can be used to split water via electrolysis to produce green hydrogen:

- **Electrolyzer efficiency:** 60–70%,
- **Energy content of H₂:** 33.3 kWh/kg,
- **Hydrogen applications:** mobility, fuel cells, ammonia production, seasonal storage [65].

Challenges include:

- High CAPEX (~700–1,200 USD/kW),
- Need for compression, purification, and storage,
- Sensitivity of electrolyzers to intermittent solar input.

6.6 CSP + Hybrid Systems

CSP's high-temperature thermal output enables versatile hybridization:

- **ISCC (Integrated Solar Combined Cycle):** Combines CSP with gas turbines for 50–60% net efficiency,
- **Biomass co-firing:** Supports 24/7 operation in agro-industrial zones,
- **Desalination:** MED or RO units powered by waste heat,
- **Thermochemical hydrogen production:** High-temp towers enable H₂ cycles like Zn/ZnO or S-I [70].

Example: Ain Beni Mathar (Morocco) – 20 MWe solar + 450 MWe gas.

6.7 Smart Hybrid Systems with IoT and EMS

Modern hybrid solar systems integrate smart control and forecasting for optimal performance:

- **IoT Sensors:** irradiance, SoC, temperature, fault detection,
- **Energy Management Systems (EMS):** manage charging, dispatch, grid feed-in,
- **Forecasting tools:** weather and load prediction.

Applications:

- Smart buildings (PVT + battery + HVAC),
- Agrivoltaics with sensor-based irrigation,
- Islanded microgrids with demand prediction.

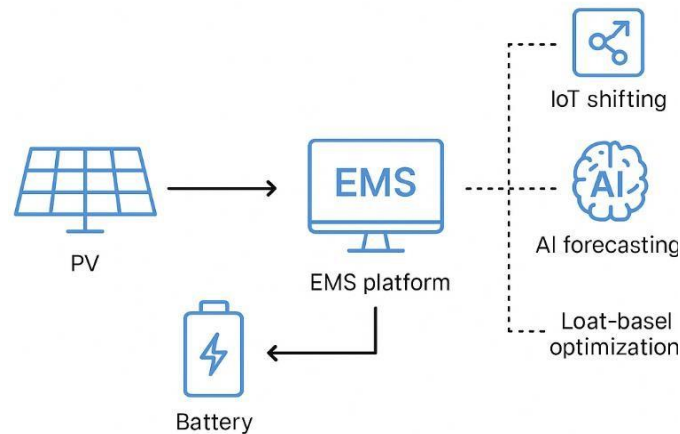


Figure 13 – Smart Hybrid System with EMS Integration

Illustrates a smart hybrid system combining photovoltaic (PV) panels, battery storage, and an Energy Management System (EMS) for dynamic load shifting, IoT-based optimization, and AI-driven forecasting. This integration enables real-time monitoring, predictive maintenance, and efficient energy distribution, especially for smart grids and zero-energy buildings. (Source adapted from Kalogirou [71])

6.8 Comparative Analysis

Table 11 – Summary of Hybrid Solar System Types

System Type	Output Type	Efficiency	Dispatchability	CAPEX Trend
PVT	Electricity + Heat	55–80%	Medium	Moderate
PV + Battery	Electricity	85–95% (RTE)	High	Decreasing
PV + Wind/Diesel	Electricity	50–70%	Very High	Moderate
PV + Hydrogen	Fuel (H ₂)	10–20%	High (storable)	High
CSP + Hybrid	Electricity + Heat/Fuel	25–50%	Very High	High

This table compares various hybrid solar system configurations based on their primary output (electricity, heat, or fuel), efficiency range, dispatchability (ability to deliver energy on demand), and capital expenditure (CAPEX) trends. Hybrid systems such as PV + Battery and CSP + Hybrid demonstrate high dispatchability, critical for energy security in fluctuating solar conditions. (Data adapted from Kalogirou [64] and IEA [65])

Chapter 7 – Passive Solar Systems

7.1 Introduction

Passive solar systems aim to reduce building energy needs by naturally utilizing solar radiation, heat flow, and air movement without mechanical equipment. They rely on architectural design, orientation, and material properties to achieve heating, cooling, and lighting [72][73].

Advantages include:

- Reduced energy bills,
- Lower maintenance,
- Enhanced sustainability,
- Increased comfort.

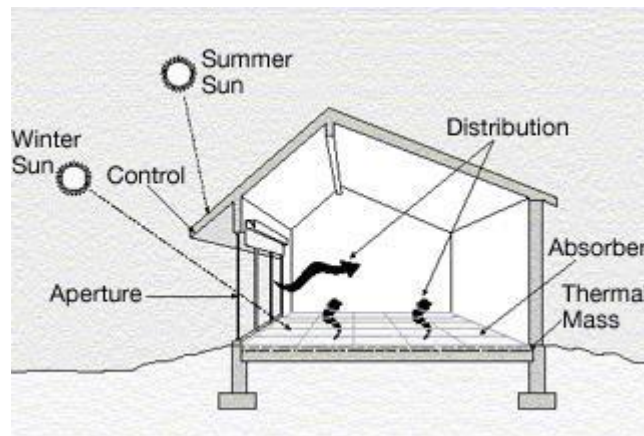


Figure 14 – Energy Flows in Passive Solar Design

Illustration of passive solar design elements including aperture positioning, solar gain control, thermal mass storage, and heat distribution within a building. The diagram distinguishes winter and summer sun angles to optimize heating and cooling through architectural design. (Source: Adapted from "Passive Solar Building Design," Wikipedia, retrieved from [72][73].

7.2 Passive Solar Heating Strategies

7.2.1 Direct Gain

Direct gain is the simplest passive heating method:

Solar radiation enters south-facing windows, is absorbed by internal mass (concrete, tiles, water barrels), and is re-radiated when needed.

Design guidelines:

- $SHGC > 0.55$,
- $U\text{-value} \leq 1.6 \text{ W/m}^2\cdot\text{K}$,
- Thermal mass/glazing area ratio $\approx 6:1$ [74].

Table 12 – Recommended Glazing Ratios by Climate Zone

Climate Zone	Glazing % of Floor Area	Thermal Mass Needed
Zone 3	7–9%	Low–Moderate
Zone 4–5	10–12%	Moderate–High
Zone 6+	12–15%	High

This table presents optimized south-facing glazing percentages relative to floor area for passive solar heating designs across different climate zones. As climate severity increases (moving from Zone 3 to Zone 6+), a higher proportion of glazing and greater thermal mass are recommended to maximize solar gain while maintaining indoor comfort. The balance between glazing area and thermal mass is critical to prevent overheating during the day and heat loss at night. (Data sourced and adapted from Mazria [72], and Szokolay [73]).

7.2.2 Indirect Gain – Trombe Wall

A Trombe wall is a massive wall placed behind south-facing glazing that stores daytime heat and releases it at night.

Design features:

- Wall thickness: 20–40 cm,
- Air gap: 2–5 cm,
- Dark coating to improve absorption.

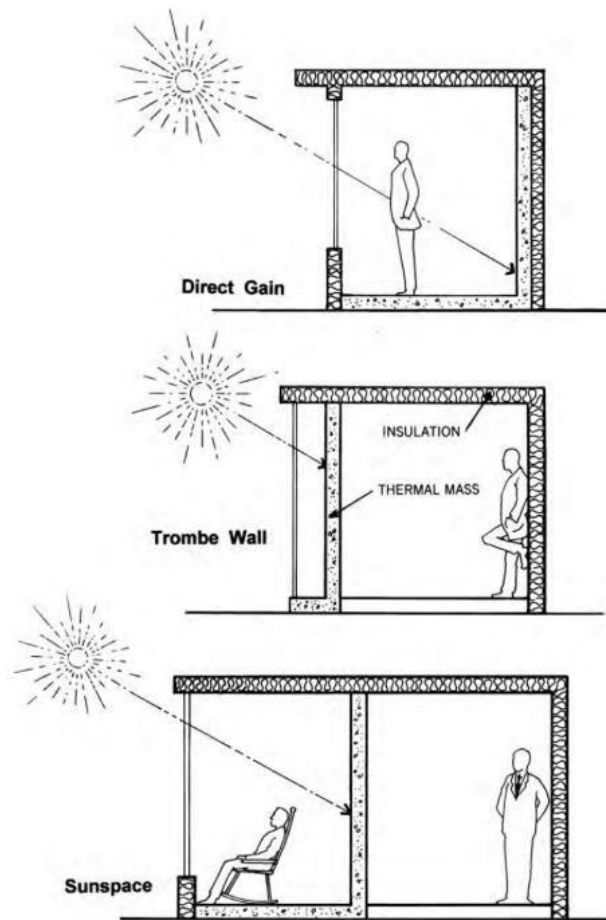


Figure 15 – Passive Solar Heating System Types: Direct Gain, Trombe Wall, and Sunspace
Illustration showing the three primary passive solar heating strategies: direct solar gain into living spaces, indirect gain using a Trombe wall for thermal storage, and isolated gain through a sunspace structure. (Adapted from Unit 2 – Solar and Renewable Energy Technologies, Yinmuga, [75])

7.3 Passive Solar Cooling Strategies

7.3.1 Shading Devices and Overhangs

Overhangs block high-angle summer sun but allow low-angle winter sunlight.

Overhang length:

$$L = H \times \tan(\theta_{\text{summer}})$$

- East/west façades prefer vertical fins or trees [74].

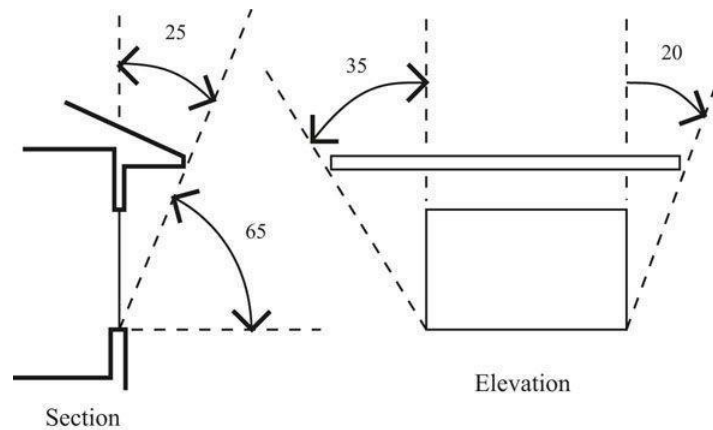


Figure 16 – Solar Path with Overhang Sizing

Illustrates optimal shading configuration based on solar altitude angles during summer and winter. The overhang blocks high-angle summer sun while allowing low-angle winter sun to enter the space. (Adapted from Civil Engineer Key: Solar Control and Shading [74]).

7.3.2 Cross Ventilation

Natural air movement across the building cools the space:

- Openable area $\geq 10\text{--}15\%$ of floor area,
- Wind speeds $\geq 1\text{ m/s}$ recommended for comfort.

7.4 Daylighting and Visual Comfort

Daylighting reduces lighting loads and enhances indoor comfort.

Strategies:

- North-facing glazing for diffuse light,
- Light shelves for deeper penetration,
- Clerestory windows for upper daylighting [76].

Target Daylight Factor (DF): 2–5%.

Table 13 – Daylighting Strategies by Orientation

Orientation	Strategy	Benefit
North	Uniform glazing	Low glare, high color rendering
South	Controlled shading	Balanced light + winter gain
East/West	Vertical shading fins	Glare protection

This table summarizes optimal daylighting techniques based on building orientation. North-facing façades benefit from uniform glazing to deliver soft, diffused light with minimal glare. South-facing façades require dynamic shading (e.g., overhangs) to balance natural daylighting while allowing beneficial winter solar gains. East and West façades are prone to low-angle sunlight and glare; thus, vertical fins or louvers are recommended for effective solar control and visual comfort. (Data adapted from Chiras [76].

7.5 Thermal Mass for Heat Storage and Lag

Thermal mass materials store daytime heat and release it slowly at night.

Performance depends on:

- Material density (ρ),
- Specific heat (c_p),
- Thickness (d),
- Thermal conductivity (k) [73].

Table 14 – Thermal Mass Properties

Material	Time Lag (hrs, 20 cm)	Heat Capacity (kJ/m ² ·K)
Concrete	6–8	400–500
Brick	4–6	300–400
Water Wall	8–10	1,200–1,300

This table summarizes optimal daylighting techniques based on building orientation. North-facing façades benefit from uniform glazing to deliver soft, diffused light with minimal glare. South-facing façades require dynamic shading (e.g., overhangs) to balance natural daylighting while allowing beneficial winter solar gains. East and West façades are prone to low-angle sunlight and glare; thus, vertical fins or louvers are recommended for effective solar control and visual comfort [73].

7.6 Stack and Buoyancy Ventilation

Thermal chimneys exploit buoyancy: hot air rises and exits through a vertical shaft, pulling cooler air inside.

Key parameters:

- Shaft height (H) > 3 m,
- Temperature difference (ΔT) > 5°C [77].

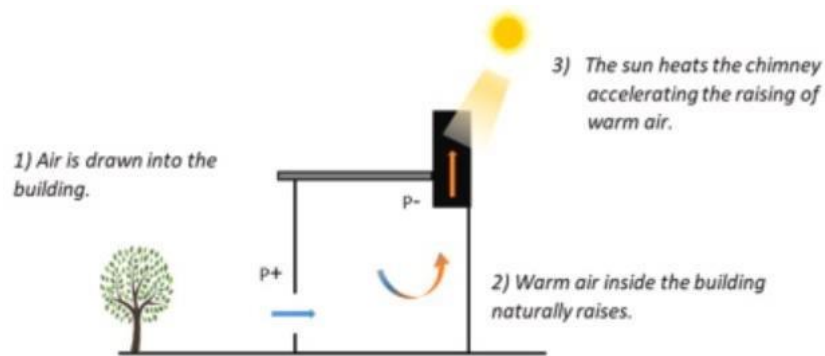


Figure 17 – Solar Chimney and Buoyancy Ventilation Diagram

This schematic illustrates the working principle of a solar chimney. Solar radiation heats the chimney structure, causing the warm indoor air to rise through buoyancy. As the warm air exits, it creates a negative pressure zone, drawing fresh outdoor air into the building and promoting continuous natural ventilation without mechanical assistance. This system enhances energy efficiency, thermal comfort, and indoor air quality. (Source: Adapted from ScienceDirect Topics [77].)

7.7 Climate-Specific Passive Strategies

Table 15 – Passive Strategies by Climate; Each climate benefits from different passive techniques:

Climate	Winter Strategy	Summer Strategy
Cold	Direct gain + Trombe wall	Night cooling ventilation
Temperate	Thermal mass + daylighting	Overhang shading
Hot–Dry	Thick mass + shading	Cross and stack ventilation
Hot–Humid	Shading + ventilation	Operable windows, daylighting

This table summarizes effective passive design strategies tailored for different climatic conditions. In cold climates, maximizing solar gains during winter and enhancing nighttime ventilation in summer are key. Temperate zones benefit from a balance of thermal mass and shading strategies. Hot–dry climates prioritize heavy thermal mass and ventilation techniques, while hot–humid climates focus on maximizing ventilation and minimizing direct solar gains through shading. (Data adapted from Mazria [72] Szokolay [73]).

Chapter 8 – Emerging and Future Solar Energy Conversion Technologies

8.1 Introduction

The evolution of solar energy technologies continues to push boundaries beyond conventional photovoltaic (PV) and solar thermal systems. Emerging technologies aim to enhance efficiency, reduce costs, and expand applications. This chapter delves into advanced concepts such as tandem and multijunction solar cells, perovskite solar cells, quantum dot and organic

photovoltaics, artificial photosynthesis, solar thermochemical hydrogen production, adaptive solar technologies, and floating concentrated solar power systems.

8.2 Tandem and Multijunction Solar Cells

8.2.1 Theoretical Background

Single-junction solar cells are limited by the Shockley - Queisser limit (~33.7% efficiency) due to thermalization and transmission losses. Tandem and multijunction solar cells overcome this by stacking multiple layers with varying bandgaps, allowing for better utilization of the solar spectrum.

8.2.2 Current Status

- **Perovskite/Silicon Tandems:** Achieved certified efficiencies over 32.5% [78].
- **GaInP/GaAs/Ge Triple Junctions:** Exceed 47% efficiency under concentrated sunlight [78].

Challenges include:

- Thermal management
- Interface recombination
- Scalability for mass production

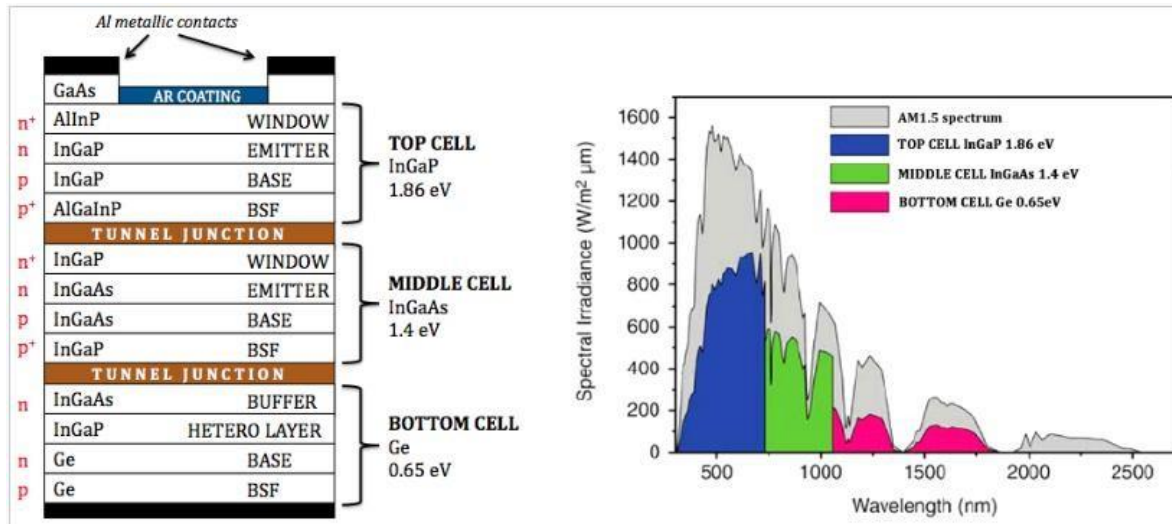


Figure 18 – Tandem Solar Cell Architecture

(a) Structure of a multi-junction solar cell showing key layers: p-n junctions, BSF layers, window layers, tunnel junctions, AR coating, and contacts.

(b) Spectral irradiance (AM1.5) and absorption ranges for top (InGaP), middle (InGaAs), and bottom (Ge) cells. (Adapted from Wikipedia "Multi-junction solar cell," Figure C (a) and (b) [78]).

8.3 Perovskite Solar Cells (PSC)

8.3.1 Advantages of Perovskite Materials

Perovskite materials, such as methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$), offer high absorption coefficients, long carrier diffusion lengths, and tunable bandgaps. These properties enable high efficiencies with low-cost, low-temperature fabrication processes [78].

8.3.2 Critical Barriers

- Ionic migration causing hysteresis
- Thermal instability above 85°C
- Lead toxicity concerns
- Degradation under UV exposure

Research Directions:

- Development of lead-free perovskites
- Improved encapsulation techniques
- 2D/3D hybrid structures for enhanced stability

8.4 Quantum Dot and Organic Photovoltaics

8.4.1 Quantum Dot Solar Cells (QDSC)

Quantum dots (QDs) offer size-tunable bandgaps and potential for multiple exciton generation. Materials like PbS and CdSe have demonstrated lab efficiencies around 14%, with ongoing research to improve stability and scalability [81].

8.4.2 Organic Photovoltaics (OPV)

OPVs utilize organic molecules for light absorption and charge transport. Advantages include flexibility, lightweight, and potential for low-cost production. Current certified efficiencies are around 17–19%, with applications in building-integrated photovoltaics and portable devices [82].

8.5 Artificial Photosynthesis and Photoelectrochemical Systems

8.5.1 Working Principle

Artificial photosynthesis aims to mimic natural processes to convert solar energy into chemical fuels. Photoelectrochemical (PEC) systems split water into hydrogen and oxygen using semiconductor electrodes and sunlight [83].

8.5.2 Challenges

- Low solar-to-hydrogen efficiencies
- Material degradation
 - High overpotentials required for reactions

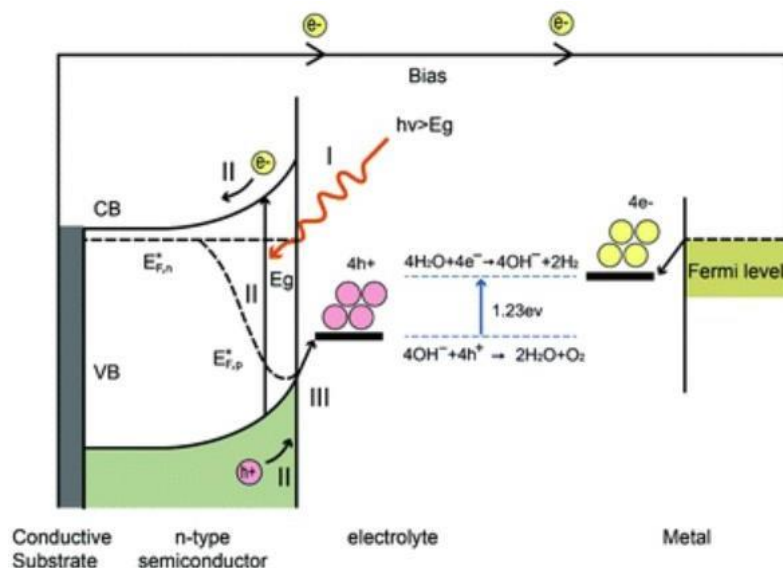


Figure 19 – Schematic of a PEC Water Splitting System

Diagram showing the n-type semiconductor under solar illumination, generating electron-hole pairs for water splitting. Photoexcited electrons flow through an external circuit to a metal cathode, reducing protons to hydrogen, while holes oxidize water at the semiconductor surface.

(Source: Adapted from Wang & Domen [83])

8.6 Solar Thermochemical Hydrogen Production

8.6.1 Process Overview

Solar thermochemical hydrogen production involves high-temperature redox cycles using metal oxides to split water. The process typically includes a reduction step at high temperatures and an oxidation step at lower temperatures to produce hydrogen [84].

8.6.2 Current Status

- **Cerium Oxide (CeO_2)**: Stable and recyclable, but with slow kinetics.
- **Zinc Oxide (ZnO)**: High conversion rates but requires very high temperatures.
- **Ferrites (Fe_3O_4)**: Abundant and scalable, with moderate efficiency.

Table 16 – Thermochemical Hydrogen Candidates

Material	Reduction Temp (°C)	Notes
CeO ₂	~1400	Stable, slow kinetics
ZnO	~1600	High conversion, high temp
Fe ₃ O ₄	1200–1300	Scalable, moderate efficiency

Table illustrates key materials used in solar thermochemical hydrogen production, their reduction temperatures, and notable characteristics.

(Adapted from Alonso et al. [84])

8.7 Adaptive Solar Technologies

8.7.1 Dynamic Solar Facades

Integration of PV systems with dynamic building facades allows for real-time optimization of solar energy capture. Technologies include electrochromic glass and AI-controlled shading systems, enhancing energy efficiency in buildings [85].

8.7.2 Wearable Solar

Advancements in flexible PV materials have led to the development of wearable solar devices. These can power small electronics and sensors, with ongoing research focusing on improving durability and energy density [86].

8.8 Floating CSP and CPVT Technologies

8.8.1 Floating CSP

Floating Concentrated Solar Power (CSP) systems are deployed on water bodies, reducing land use and benefiting from natural cooling effects, which can enhance efficiency.

8.8.2 CPVT Systems

Concentrated Photovoltaic Thermal (CPVT) systems combine high-efficiency PV cells with thermal collectors, achieving overall system efficiencies up to 80–85% by utilizing both electrical and thermal outputs [79].

Chapter 9 – Conclusions and Recommendations

9.1 Comprehensive Review and Integration

This report has systematically reviewed solar energy technologies including traditional photovoltaic (PV) systems, hybrid PV technologies, solar thermal collectors, Concentrated Solar Power (CSP), passive solar designs, and next-generation technologies such as tandem solar cells, photoelectrochemical water splitting, and adaptive solar facades.

Evaluation criteria included:

- Energy conversion efficiency,
- Storage integration capabilities,
- Grid compatibility,
- Technological maturity,
- Scalability potential,
- Environmental and lifecycle impacts.

9.2 Summary of Key Technical Findings

9.2.1 Photovoltaic and Hybrid Systems

Crystalline silicon photovoltaic technologies maintain global dominance due to mature supply chains, cost reductions, and high efficiencies (>20%) [87].

Hybrid solar systems (e.g., PV+Battery, PV+Thermal) enhance system flexibility but require significant advancements in storage technology economics to reach mass adoption.

Tandem solar cells—particularly perovskite/silicon combinations—have achieved laboratory efficiencies exceeding 32%, indicating strong potential despite challenges like stability and manufacturing scalability [87].

9.2.2 Solar Thermal and CSP

Solar thermal collectors such as flat-plate and evacuated tube systems offer 50–70% thermal efficiency, primarily for domestic hot water and industrial heating [89].

CSP systems, especially those with molten salt storage, deliver high dispatchability. However, CSP adoption remains geographically limited due to high DNI (Direct Normal Irradiance) requirements and elevated capital costs [90][93].

9.2.3 Passive Solar Systems

Passive solar techniques like Trombe walls, thermal mass, natural ventilation, and daylight optimization can reduce HVAC energy demands by 40–50% [91][92].

Site-specific climatic design, proper material selection, and architectural integration are essential for maximum performance.

9.3 Comparative Evaluation

Table 17 – Comparative Assessment of Solar Energy Technologies

Technology	Efficiency (%)	Storage Integration	Grid Readiness	Maturity Level	Cost Trend	Flexibility
Crystalline Silicon PV	20–23	Requires battery	High	Commercial	Decreasing	High
Perovskite-Silicon Tandem	30–33	Requires storage	Moderate	Pilot/Research	Decreasing (lab)	Moderate
CSP with Molten Salt Storage	18–25	Thermal-ready	Large-scale only	Commercial	Expensive	Medium
PVT Hybrid Systems	55–75 (thermal + electrical)	Partial (thermal)	Easy	Emerging	Moderate	Medium
Passive Solar Design	N/A	N/A	N/A	Traditional	Low	Climate-specific
PEC / Solar Fuels	<15	Fuel-form storage	Developing	Research	High (experimental)	High (future)

(Adapted from Green et al. [87], IEA [88], Kalogirou [89], Dünya Bankası [90], Mazria [91], Szokolay [92], SolarPACES [93])

9.4 Cross-Cutting Challenges

Common challenges across solar technologies include:

- **Storage and Dispatchability:** Addressing intermittency through chemical (hydrogen) and thermal storage systems.
- **Material Sustainability:** Reducing the environmental footprint of materials such as lead (in perovskites) and cadmium (in thin films)[87] [88].
- **System Durability:** Achieving 25+ year operational life, particularly critical for utility-scale solar [87].
- **Standardization Gaps:** Creating unified international testing and certification standards to facilitate market entry for emerging technologies [87][88].

9.5 Policy and Deployment Recommendations

9.5.1 For Policymakers

- Incentivize higher performance through feed-in tariffs linked to efficiency metrics,
- Integrate mandatory solar readiness (BIPV compatibility) in new building codes,
- Fund pilot projects for tandem PV, solar fuels, and seasonal storage systems.

9.5.2 For Industry

- Develop modular hybrid systems (PV + thermal + storage),
- Create standardized interoperable platforms for PV, hydrogen, and thermal coupling,
- Promote durable encapsulation solutions for flexible and tandem photovoltaics.

9.5.3 For Researchers

- Focus on lead-free perovskite materials (e.g., tin halides),
- Advance catalyst efficiencies for PEC and solar fuel systems,
- Implement AI-based predictive maintenance in solar hybrid installations.

9.6 Future Research Directions

Table 18 – Priority Research Areas for Solar Innovation (2025–2030)

Research Area	Objective	Example Output
Perovskite Stability	Achieve operational lifetimes >10 years	Stable tandem modules for BIPV
Solar Hydrogen Production	Hydrogen under <\$2/kg	Integrated PV-electrolyzer systems
Adaptive Solar Facades	Dynamic performance optimization	AI-driven BIPV shading and tracking
Passive-Active Hybrid Systems	Combine passive solar gain + active HVAC	PCM-embedded walls + solar chimneys

(Adapted from Green et al. , IEA [88], Kalogirou [89], Dünya Bankası [90], Mazria [91], Szokolay [92], SolarPACES [93])

9.7 Final Remarks

Solar energy will be the centerpiece of global decarbonization efforts over the next decades.

Highlights include:

- Crystalline silicon PV's continued dominance,
- CSP's role in providing firm renewable capacity,

- Passive solar's critical contribution to energy-efficient building designs,
- Emerging technologies (perovskite tandems, solar fuels, PEC hydrogen) poised to revolutionize solar economics and applications.

An integrated multidisciplinary approach - linking materials science, engineering, architecture, and digital technologies - will be vital to unlock the full potential of solar energy as the future's primary clean power source.

Chapter 10 – Sustainability, Circular Economy, and Lifecycle Assessment in Solar Energy Systems

10.1 Introduction

The transition to renewable energy is central to mitigating climate change. However, sustainability in solar energy extends beyond merely operating with low emissions - it demands minimizing environmental impacts across the entire lifecycle of solar technologies. This includes responsible sourcing of materials, energy-efficient manufacturing, sustainable usage, and effective end-of-life (EOL) strategies like recycling and circular economy integration [94][95][96][97].

By 2050, it is projected that solar photovoltaic (PV) systems alone could account for over 60 million metric tons of cumulative waste globally if not properly managed [94]. Ensuring circularity and sustainability of solar systems is therefore not optional but essential for a truly clean energy future.

10.2 Lifecycle Stages of Solar Energy Technologies

The sustainability of solar technologies is typically assessed by evaluating each stage of their lifecycle:

- **Raw Material Extraction and Processing:** Mining of quartz (for silicon), silver, cadmium, indium, tellurium, etc.
- **Manufacturing and Assembly:** Energy- and resource-intensive fabrication processes.
- **Transportation and Installation:** Carbon footprint associated with module logistics.
- **Use Phase:** Minimal emissions; degradation rates impact system longevity.
- **End-of-Life (EOL):** Potential landfill waste versus recycling or repurposing opportunities.

10.3 Lifecycle Metrics of Key Solar Technologies

Key metrics used in lifecycle assessments include:

- **Energy Payback Time (EPBT):** Time needed to generate the energy spent in production.
- **Global Warming Potential (GWP):** Greenhouse gas emissions in grams CO₂-equivalent per kWh over lifetime.
- **Recyclability Rate (%):** Portion of the system that can be effectively recovered.

Table 19 – Lifecycle Assessment Metrics of Major Solar Technologies

Technology	EPBT (Years)	GWP (g CO ₂ -eq/kWh)	Recyclability (%)	TRL (Technology Readiness Level)
Monocrystalline Silicon	1.5–2.5	25–50	85–95	9
CdTe Thin-Film PV	0.5–1.2	10–30	>90 (with smelting)	9
Perovskite Tandem PV	<0.5 (lab)	~20 (estimated)	<50 (uncertain)	4–5
CSP with Molten Salt Storage	2.0–3.5	25–45	High (steel/glass)	8
PVT Hybrid Panels	1.5–2.0	~35–45	Moderate	7

Data sourced from [94] Fthenakis & Kim (2011), [95] IEA-PVPS (2022), [96] IRENA (2016), and [97] Green et al. (2023).

10.4 Critical Materials and Environmental Hotspots

10.4.1 Use of Critical Raw Materials (CRM)

Several solar technologies depend heavily on rare, geopolitically sensitive, or toxic elements:

- **Silver (Ag):** Key conductor in PV cells; intense global demand pressure.
- **Indium (In) and Gallium (Ga):** Core to CIGS and III–V multijunction technologies.
- **Tellurium (Te):** Essential for CdTe thin-film PVs; scarce and geographically limited.
- **Lead (Pb):** Used in high-performance perovskite cells.

10.5 Energy and Water Usage in Solar Manufacturing

- **Crystalline Silicon PV:** Highly energy-intensive (~4,000–5,000 kWh/kg for purified silicon) [96].
- **CdTe and Perovskite Thin-Films:** Require significantly lower energy due to thin-layer deposition at low temperatures.

Water Consumption:

- CSP plants with wet cooling consume 3.5–4.5 m³/MWh, which is considerably higher than PV [97].
- Dry-cooled CSP reduces water use but can lower efficiency by 5–8%.

10.6 Circular Economy Approaches for Solar Technologies

Circular economy in solar energy promotes:

- **Design for Disassembly (DfD):** Enabling easier repair and recycling.
- **Extended Producer Responsibility (EPR):** Making manufacturers accountable for EOL management.
- **Material Recovery:** Especially for metals like silver, aluminum, glass, and silicon.

Table 20 – Recovery Routes for PV Module Components

Component	Recovery Method	Yield (%)	Environmental Risk
Aluminum Frame	Mechanical separation	>95%	Low
Glass	Crushing and screening	~90%	Medium (coating loss)
EVA Encapsulant	Pyrolysis/Incineration	20–40%	Medium (gas emissions)
Silicon Wafers	Chemical treatment	~85%	Moderate
Silver	Leaching/extraction	<10%	High (hazardous waste)

Data adapted from [95]] IEA-PVPS (2022) and [96]IRENA (2016).

10.7 Global End-of-Life (EOL) Policies and Best Practices

10.7.1 Europe

- **EU WEEE Directive 2012/19/EU:** Mandates PV collection and recycling.
- **Goals:** 85% collection, 80% material recovery.
- **Leading recycling companies:** Veolia (France), Reiling PV (Germany) [95].

10.7.2 Asia

- Japan: Leading semi-automated recycling R&D.
- India: Draft regulation requires PV take-back programs (2023).

10.7.3 North America

- California SB 489: PV modules classified as “universal waste”.
- No comprehensive federal recycling mandate (as of 2024).

10.8 Lifecycle and Sustainability Challenges for Emerging Solar Technologies

10.8.1 Perovskite Solar Cells

- Ultra-low manufacturing energy.
- Major concerns over Pb leaching and limited operational durability.
- Encapsulation and protective barrier technologies under intensive development [97].

10.8.2 Tandem PV and Quantum Dot Solar Cells

- Difficult end-of-life recovery due to multilayer architectures.
- QD devices often use Cd or Pb, raising toxicity concerns.

10.9 Lifecycle KPIs Across Solar Technologies

Table 21 – Sustainability KPIs for Leading Solar Technologies

KPI	Monocrystalline PV	CdTe Thin-Film	Perovskite PV	CSP (Tower/Storage)
EPBT (years)	1.5–2.5	0.5–1	<0.5 (lab)	2–4
GWP (g CO ₂ -eq/kWh)	25–50	10–30	~20 est.	25–45
Toxic Material Risk	Moderate	High	High	Low
Recyclability (%)	High	High	Low	High
EPR Regulation Compliance	✓	✓	✗	✓

Lifecycle and sustainability performance compiled based on [94]

10.10 Recommendations for Achieving Sustainable Solar Deployment

- **Policy Recommendations:**
 - Mandate recyclability and sustainability scores in public tenders.
 - Support EPR mechanisms and circular business models.
- **Research Priorities:**
 - Develop Pb-free perovskites (e.g., CsSnI₃).
 - Innovate high-recovery recycling for tandem and flexible devices.
- **Industry Actions:**
 - Integrate QR-code and blockchain tracking systems for traceability.
 - Invest in industrial-scale PV recycling infrastructure.

10.11 Final Reflections

Achieving a truly sustainable solar economy requires aligning technical innovation with environmental stewardship. It is no longer sufficient to focus on operational emissions; the entire lifecycle must be optimized for circularity, minimal carbon footprint, material security, and social equity.

Future solar energy systems must be modular, repairable, recyclable, and ethically sourced, contributing not only to energy decarbonization but also to holistic planetary sustainability.

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