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Solar Based Poly-Generation Systems for a Carbon Neutral Future with Focus on Hydrogen Production: A Comprehensive Review

G. S. Girishkumar[1]†, M. R. Kamesh[1], N. Shreekala[2], D. Yogaraj[3], M. Mohammed Nadeem[4], B. R. Hemanth[5] and K. S. Nagaprasad[6]

[1]Department of Mechanical Engineering, Dayananda Sagar College of Engineering, Bengaluru-560078, Karnataka, India

[2]Department of Mechanical Engineering, Global Academy of Technology, Bengaluru-560098, Karnataka, India

[3]Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai-600062, Tamil Nadu, India

[4]Department of Mechanical Engineering, University of Greater Manchester, RAK Academic Centre, UAE

[5]Department of Mechanical Engineering, ATME College of Engineering, Mysuru-570 028, Karnataka, India

[6]Department of Mechanical Engineering, K.S. Institute of Technology, Bengaluru-560 109, Karnataka, India
†Corresponding author: G. S. Girishkumar; girishsachin010@gmail.com

[1]ORCID: 0000-0001-5479-0309, [2]ORCID: 0000-0003-3917-9370, [3]ORCID: 0000-0003-2205-8388, [4]ORCID: 0000-0002-1604-6340, [5]ORCID: 0000-0002-8928-7145, [6]ORCID: 0000-0002-4685-2933, and [7]ORCID: 0009-0000-6137-4485

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ABSTRACT

The solar driven energy systems show a significant contribution in accomplishing global sustainability goals and reducing greenhouse gas emissions and pollutant levels. Increase in development of multi-generation systems is predominantly significant, since these systems are efficiently address the growing and diverse demands of energy needs. Simultaneously, hydrogen has emerged as a promising alternative fuel, garnering considerable attention for its potential to replace conventional energy sources. In addition to hydrogen, other distinctive outputs like power, heating, cooling, domestic hot water, and freshwater demands can be met using this technology. As the energy from the sun is being used extensively for electricity and heat generation, photovoltaic-thermal (PVT) systems are emerging as highly reliable and capable approach for sustainable energy solutions. This study emphasizes on the inclusion of hydrogen production methods into poly-generation systems. And recent progresses in concentrated photovoltaic-thermal and photovoltaic-thermal technologies, focusing on improvements in system performance. This study clinches that different system configurations, and incorporation with new technologies have significantly optimized PVT designs. Looking ahead, PVT systems offer a promising route for clean energy production. The integration of PVT and CCHP technologies marks a transformative step toward achieving net-zero energy buildings and decarbonized energy systems, making them a crucial element in the global transition to clean and efficient energy production. Further progress in cost-competitiveness could drive broader adoption. Additionally, it presents the growing demand to explore the potential of green hydrogen as an energy source and as an energy carrier. The study concludes that Concentrated Photovoltaic Thermal (CPVT) systems demonstrate outstanding performance in solar-based multi-generation applications, achieving energy efficiency as high as 78.93% and exergy efficiency up to 65%. These high values underscore the capability of CPVT technology to effectively harness both electrical and thermal energy, making it highly suitable for integrated systems targeting hydrogen production, heating and cooling.

INTRODUCTION

The energy needs of a country are complex and serve as the foundation for economic growth, the development of social infrastructure, and the improvement of human living standards. Meeting these needs requires a dependable and sustainable energy supply system that offers extensive social, economic, and environmental advantages. Recently, there has been considerable research interest in poly-generation systems integrated setups that can produce various energy outputs (such as electricity, heating, cooling, hydrogen, etc.) from a single or combined input source. While the idea of poly-generation has been around for many years, modern applications focus on achieving greater efficiency, reducing emissions, and optimizing resource use. A major driving force behind the adoption of poly-generation technologies is their capacity to utilize a range of energy resources, including both renewable sources (like solar, wind, biomass, and geothermal) and traditional fossil fuels (such as natural gas and coal) in hybrid setups. This combination enhances operational flexibility and boosts the sustainability of the overall energy system. The growing global population has significantly increased the demand for energy services. At the same time, the limited availability of fossil fuel reserves, along with rising concerns about climate change and environmental harm, has hastened the global transition to low-carbon and renewable energy technologies. In this shift, poly-generation systems play a crucial role by enabling the simultaneous production of multiple energy vectors, thereby reducing energy waste and maximizing the use of primary energy sources. Henceforth, it is very essential to establish an energy efficient system integrating with renewable energy sources to meet local energy demands and to achieve sustainability. PVT systems combine photovoltaic (PV) cells with thermal collectors in a single unit, enabling the concurrent production of electricity and thermal energy from solar radiation. This dual capability not only boosts the overall energy conversion efficiency of solar systems but also minimizes the land and material needs compared to using separate PV and solar thermal units. In the realm of CCHP systems, PVT technologies are crucial. The electricity produced by the PV component can power building systems and appliances, while the thermal energy collected can be used in absorption chillers or heat exchangers for space cooling, heating, or domestic hot water production. This integrated method allows for year-round energy use, significantly enhancing the system's exergy efficiency and supporting the concept of tri-generation, which involves cooling, heating, and power from a single energy source. Furthermore, PVT-based CCHP systems are especially beneficial for residential, commercial, and institutional buildings, particularly in areas with high solar insolation. They decrease reliance on fossil fuels, reduce greenhouse gas emissions, and contribute to decentralized, sustainable energy infrastructures. When combined with energy storage and smart control systems, PVT-CCHP configurations can offer stable, dispatchable energy services tailored to changing demand patterns. Solar irradiation is regarded as high readiness and its ability to be converted into useful thermal energy or into a usable power source. A poly-generation system is an integrated energy system which yields several energy outputs to fulfill local load demands. The allocation of total primary energy ingesting is around 31% worldwide, which is approximated to increase by an average value of 1.5% annually. In a world facing ever-increasing energy demands, poly-generation systems integrated with renewable energy sources represent a sustainable solution. To fully harness the potential benefits of poly-generation systems integrated with renewable energy, a holistic approach is essential.

The review highlights several significant knowledge gaps in the area of poly-generation systems, focusing on system integration, efficiency benchmarking, and techno-economic challenges.

System Integration Challenges;

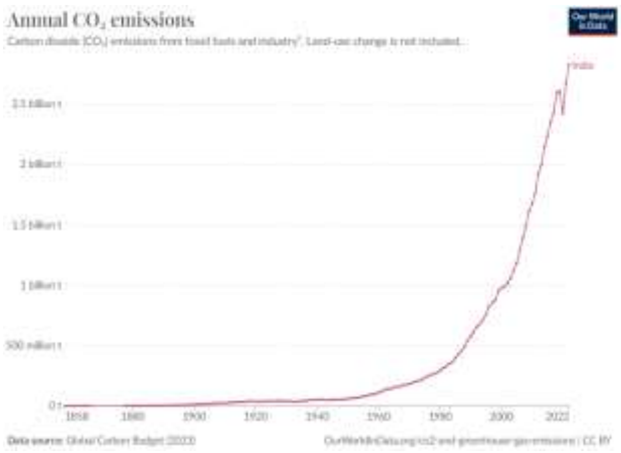
- There is a scarcity of comprehensive analyses regarding the optimal integration of Photovoltaic-Thermal (PVT) systems within Cooling, Heating, and Power (CCHP) frameworks.
- There is an absence of standardized frameworks or methodologies for combining renewable and conventional energy sources within poly-generation systems to address varying local energy needs.
- There is a lack of studies on smart control strategies and energy management systems that dynamically optimize the real-time operation of PVT-CCHP systems.

Efficiency Benchmarking Deficiencies;

- Few comparative studies examine the exergy and energy efficiencies of PVT-based poly-generation systems compared to conventional or mono-generation setups.·
- The absence of universally accepted performance metrics and benchmarks for multi-output energy systems complicates cross-technology comparisons.
- There is a lack of real-world performance validation and long-term efficiency tracking under diverse climatic and load conditions.

Techno-Economic Barriers;

- There is an inadequate assessment of capital and operational costs, payback periods, and Levelized Cost of Energy (LCOE) specific to integrated PVT-CCHP systems.
- Limited data exist on the economic feasibility and scalability of such systems, especially in residential and institutional applications.
- Few policy analyses explore the financial incentives, subsidies, and regulatory frameworks necessary to encourage widespread adoption.



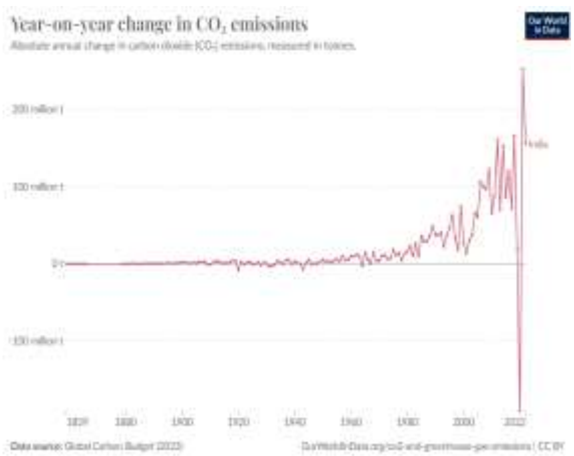


Fig. 1a: Carbon dioxide emission annually. Fig. 1b: Carbon dioxide emission Year-on-year in India.

From the figures 1a and 1b shown above, before the Industrial Revolution took place in 1850, the levels of emissions were minimal. However, it wasn't until the mid-20th century that the emissions would go up. As of 1950, 6 billion tons of CO_2 was emitted per year globally, but this has now risen to more than 20 billion tons by 1990 **[**https://ourworldindata.org/grapher**].**

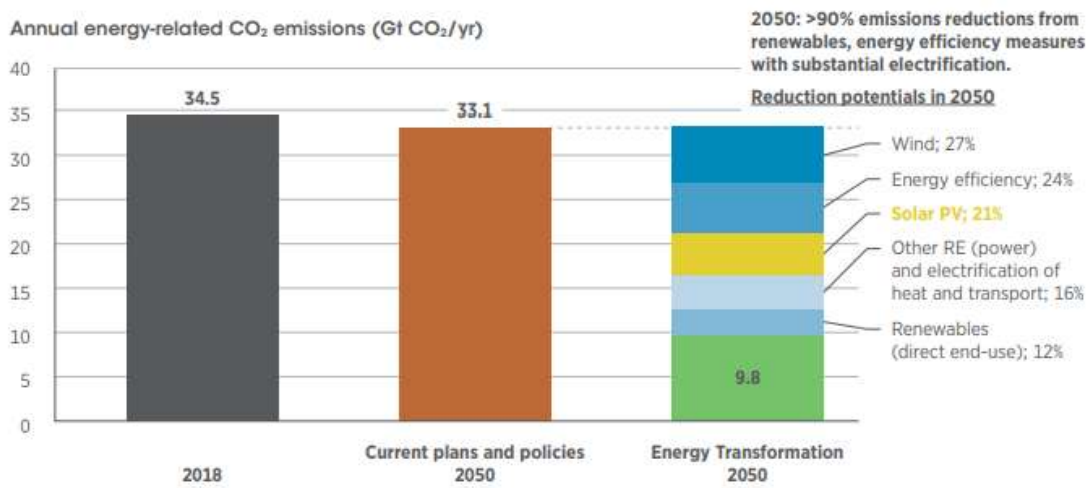


Fig. 1c: Overall energy-sector emissions reductions needed to meet Paris climate goals (https://mnre.gov.in/2022-23)

India has planned to accomplish approximately half of its power consumption from renewable energy sources by 2023 according to the latest National Determined Contribution (NDC) updates. A sum of 167.75 GW worth of Renewable Energy capacity had been established as of 31st December 2022 within India. Another 78.75 GW worth projects were being executed while another 32.60 GW were at different stages of bidding process. According to the REN21 Renewables 2022 Global Status Report, India ranks 4th in terms of Renewable Energy Installed Capacity, 4th in Wind Power capacity & 4th in Solar Power capacity. The renewable energy installation has increased from 76.37 GW in 2014 to 167.75 GW in 2022 which is an increase by about 2.20 times. Power generation from solar energy has also increased from 2.63 GW in 2014 to reach 63.30 GW in 2022 (https://mnre.gov.in/2022-23).

Table 1: Total electric power installations Sector wise from clean energy sources (https://mnre.gov.in/2022-23)

Sector	Installed capacity (GW)	Under Implementation (GW)	Tendered (GW)	Total Installed/ Pipeline (GW)
Solar Power	63.30	51.13	20.34	134.77
Wind Power	41.93	12.93	1.20	56.06
Bio Energy	10.73	---	---	10.73
Small Hydro	4.94	0.54	0.00	5.48
Hybrid/ Round the Clock (RTC)/ Peaking Power/ Thermal + RE Bundling	---	---	11.06	11.06
Sub-Total	**120.90**	**64.6**	**32.6**	**218.10**
Large Hydro	46.85	14.15	---	61.00
Total	**167.75**	**78.75**	**32.60**	**279.10**

India receives a significant amount of Direct Normal Irradiance (DNI), ranging from 4 to 7 kWh/m² per day, highlighting the significant potential for decentralized solar energy applications, particularly through Concentrating Solar Power (CSP) technologies. The major ways to harness solar power include providing heat for end-users and transforming it into electricity with PV cells, steam turbine, or any other technology after the sunlight is absorbed by various collectors. Thus, the main two strategies involve solar PV and thermal electricity generation. Different solar technologies including concentrating solar power (CSP) and Photovoltaic (PV) had been widely described in many research studies. The abundance of solar energy with zero pollution makes it one of the most promising renewable sources; it has no cost attached to it. However, the popularization of large-scale solar power generation has been hindered by the fact that solar energy is not always available leading to difficulties in its commercialization thereby place limitation on its technological use (Gang wang et al. 2024)

1.1 The Role of Renewable Energy in Poly-generation systems

A fast-tracked transition of our global energy infrastructure is critical if we want to align ourselves with Paris Agreement's aim of limiting global warming to below 1.5 degrees Celsius within this century, as against levels that existed before large-scale industrialization took place. In addition, changing the world's energy system will also enhance energy security as well as improve the availability of affordable and widespread energy access. This is important for countries that rely largely on imported fossil fuels **(**Milad Soltani et al. 2023**)**

- Environmental Benefits of Poly-generation Systems

The integration of poly-generation systems in urban areas is seen as one of the promising routes for addressing CO_2 mitigation problems. Poly-generation systems integrated with renewable energy sources offer a range of environmental benefits that are crucial for addressing the challenges of climate change and enhancing energy security.

- Carbon Neutrality: Mitigating Climate Change

Renewable energy sources are inherently carbon neutral, meaning they emit no net carbon dioxide when producing energy. This characteristic aligns perfectly with the sustainability goals of poly-generation systems and contributes significantly to reducing the overall carbon footprint of energy production.

- Energy Reliability: Diverse Resource Mix

Poly-generation systems can attain betterment from the diversity of renewable energy sources. The energy system with the combination of renewable energy sources, these systems become more resilient to fluctuations in resource availability. This reliability is especially crucial in regions with variable weather patterns.

- Localized Energy Production: Decentralization

Renewable energy sources often enable decentralized energy production. This decentralization can reduce the need for extensive transmission and distribution networks, improving energy security and grid resilience. Furthermore, it empowers local communities to take charge of their energy production.

2. Materials and Methods

This review adopts a systematic and thematic methodology to examine the present state and future potential of solar-based poly-generation systems, with a particular emphasis on hydrogen production for carbon-neutral purposes. An extensive literature review was conducted, spanning from 2012 to 2024, utilizing academic databases such as Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar. The search employed keywords like solar poly-generation, PVT systems, CCHP, solar hydrogen production, photo-electrochemical hydrogen, thermochemical cycles, exergy analysis, and techno-economic evaluation. Studies were chosen based on their relevance to integrated systems that produce multiple energy outputs, especially those involving solar PV/PVT technologies, while works focused solely on mono-generation or lacking practical validation were omitted. The selected literature was categorized into thematic areas: solar resource characterization, poly-generation configurations, hydrogen production methods, system integration and controls, efficiency and exergy performance, techno-economic and environmental assessments, and policy and deployment strategies.

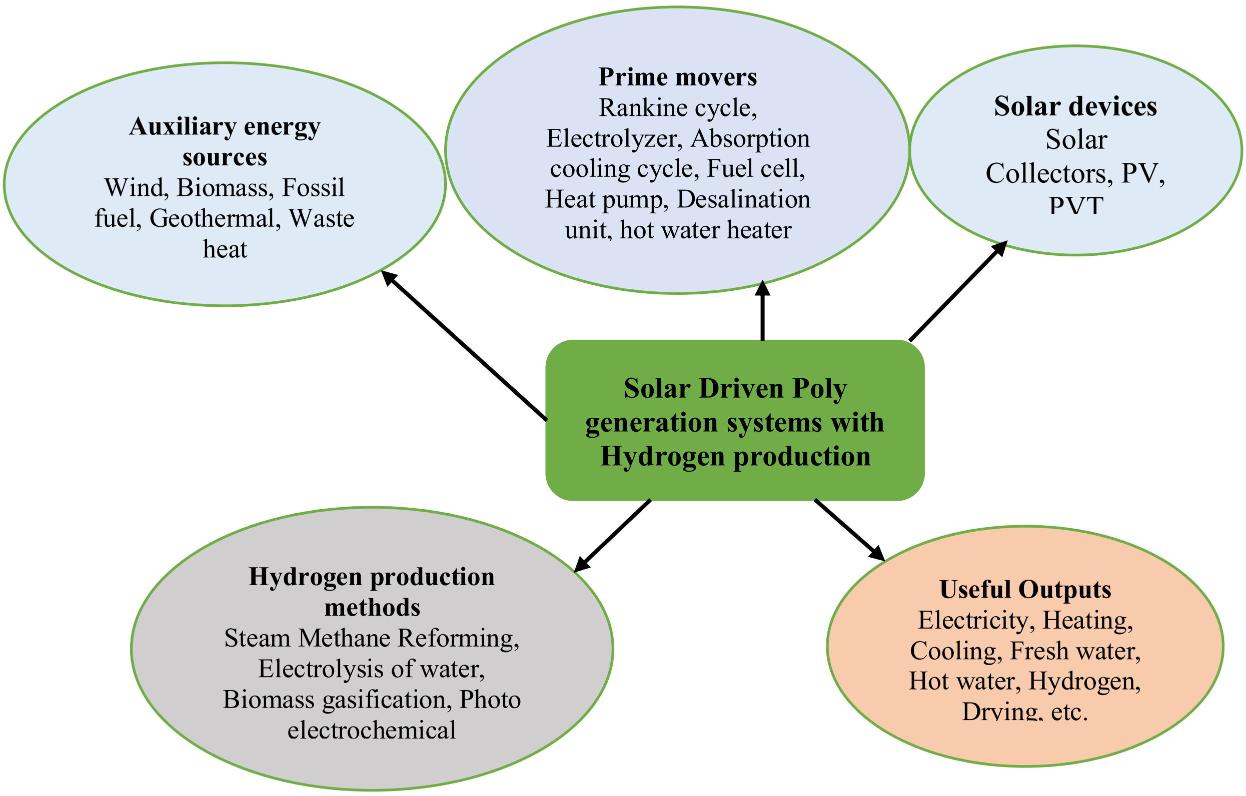


Fig. 2: Major components and useful outputs of typical solar driven poly-generation systems

2.1 Scope of Non-conventional sources-based hybrid power generation in India

The need to offer a clean and environmentally friendly alternative has never been greater than it is now because of the growing consumption of energy and the problems associated with the shortage of fossil resources. Numerous renewable energy sources have been used over the recent past, but they have always been faced with constraints relating to economics, technological development and many other things. This is because a significant portion of these types of fuels are applied in contemporary electricity production systems that are not as efficient as they should be. India has a large agricultural and allied sector which accounts a significant contribution in the country's economy accounting for about 20% of the GDP and the largest source of employment with over 50 percent of population engaged in it. It offers a vast renewable biomass resource base to the country. For India, biomass has been a significant energy source ever since. It's renewable, carbon-neutral and it could generate serious livelihood opportunities. However, to exploit its full potential, the availability of biomass in the country should be first assessed and quantified in diverse states. Highlighting the essence of this, the Ministry of New and Renewable Energy (MNRE), recently provided a study on an assessment on country's biomass potential to the Administrative Staff College of India (ASCI), Hyderabad. The study reckons the estimated surplus biomass availability of about 230 million metric tonnes per annum (2017-18) from agricultural residues and a biomass power potential of about 28 GW for the country. As per the report from ASCI for MNRE, the Biomass and Energy Management Division under Sardar Swaran Singh National Institute of Bioenergy (SSS-NIBE) has developed National Biomass Atlas to enable easier understanding of the bio mass availability in the country.

Solar-biomass hybridization is a seasonal supplementation with two sources of energy. This is in addition to the fact that it is from renewable sources of energy. Comparatively, the biomass input energy consumption and feed stock are reduced by hybridization as compared to the biomass only. The hybrid solar–biomass power plant might be most useful to enterprises connected with sugar cane, textile, chemicals petrochemicals and commercial power attraction (Moslem Sharifishourabi et al. 2024)

2.2 Typical poly-generation system

Fig. 2 displays a block diagram of a typical poly-generation system. The energy requirements of heating, cooling, power, and other beneficial outputs like hydrogen can be satisfied by this system. Since the construction sector accounts for almost 40% of worldwide energy consumption, power, heating, and cooling are the most prevalent energy demands (Milad Soltani et al. 2023). A poly-generation unit is essentially made up of at least one primary mover. This device is typically used to generate electricity and is powered by fuel or heat input.

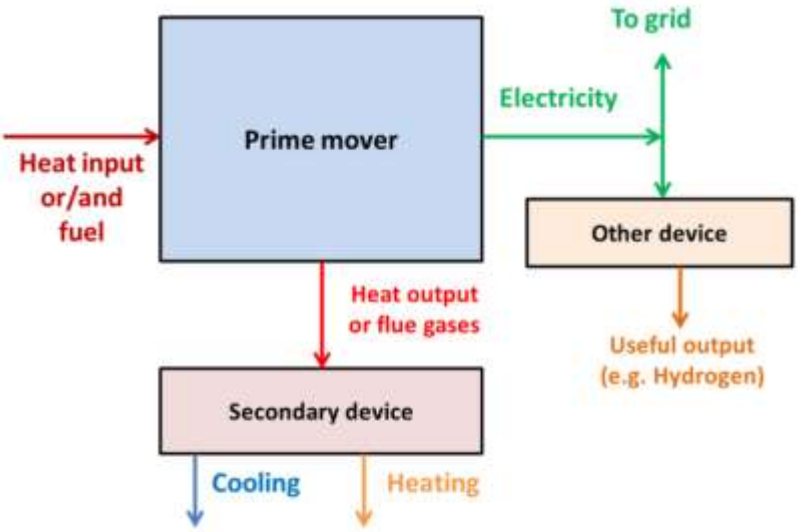


Fig. 3: Typical Poly-generation system (Alibakhsh Kasaeiana et al. 2020)

2.2.1 Efficiency definitions in poly-generation systems

Poly-generation systems are evaluated based on energy and exergy efficiency standards.

The efficiency of energy (η_{en}) is defined as the energy yield ($E_{n, out}$) in relation to energy intake (En, in):

$$\eta_{en} = \frac{\Sigma\, En,out}{\Sigma\, En,in} \text{ ---------- (i)}$$

Similarly, the exergy efficiency (η_{ex}) is defined as the exergy yield ($E_{x,out}$) versus energy intake ($E_{x,in}$).

$$\eta_{ex} = \frac{\Sigma\, Ex,out}{\Sigma\, Ex,in} \text{ ---------- (ii)}$$

A typical solar driven (Qs) and an additional heat input (Q_{aux}) tri-generation system meant to produce electricity (P_{el}), heat (Q_{heat}) at T_{heat}, and cools (Q_{cool}) at T_{cool}.

The energy efficiency of the above considered system can be determined by using;

$$\eta_{en} = \frac{Qheat+Qcool+Qel}{Qs+Qaux} \text{ --------- (iii)}$$

The exergy efficiency of the above considered system can be determined by using;

$$\eta ex = \frac{Qheat\left(1-\frac{To}{Theat}\right)+Qcool\left(\frac{To}{Tcool}-1\right)+Pel}{Eex,s+Eex,aux} \text{ ------- (iv)}$$

The ambient temperature (T_0) is often set to 298.15 K, whereas the temperature levels (T_{heat}) and (T_{cool}) in Kelvin units.

The Petela model [8] can be used to determine the exergy flow from solar irradiation (Ex,s).

$$Eex,\ s = Q_S\left[1-\frac{4}{3}\frac{To}{Tsun}+\frac{1}{3}\left(\frac{To}{Tsun}\right)^4\right] \text{--------- (v)}$$

Where, T_{sun}= 5770 K be the temperature of the Sun and it is the mean temperature of outer layer.

2.3 Pathways for poly-generation energy systems

Integration of renewable energy sources to produce and meet the energy demands is the key feature of poly-generation systems. Depending on power ranges, application, and cost considerations, the most suitable prime mover and mechanism for converting energy are chosen. Currently, certain research studies include: (i) using renewable energy units as fully as possible in homes, offices and factories, (ii) using various sources of power to run fuel cells, optimal design of a poly-generation network, and (iii) several options for such systems in terms of their application within residential areas, commercial buildings and factories.

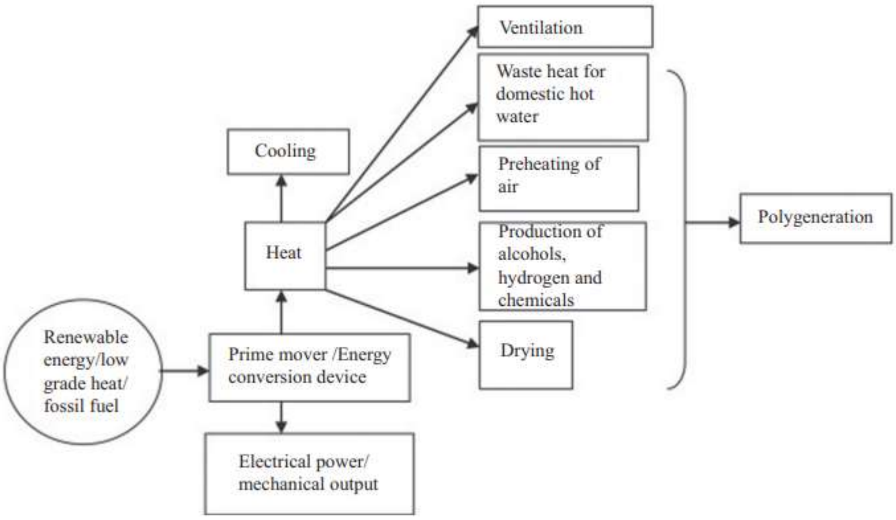


Fig. 4: Possible pathways of poly-generation systems (Moraba Caroline Lebepe et al. 2025).

Poly-generation systems can utilize prime movers like Sterling engines, reciprocating engines, steam engines and organic Rankine cycles as well as gas turbines and micro-gas turbines so that they may generate power and heat with it.

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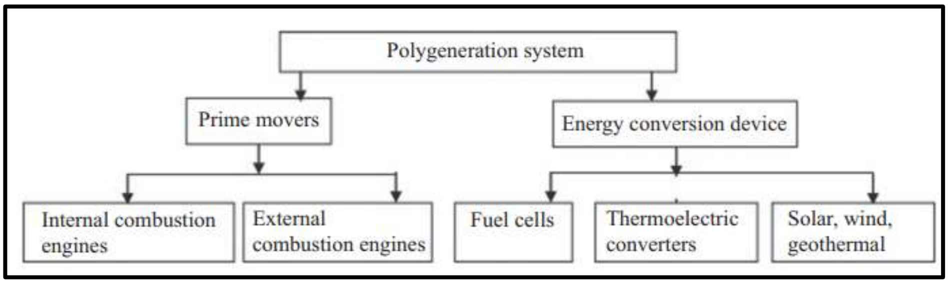

Fig. 5: Various prime movers and energy conversion devices in poly-generation systems (Moraba Caroline Lebepe et al. 2025).

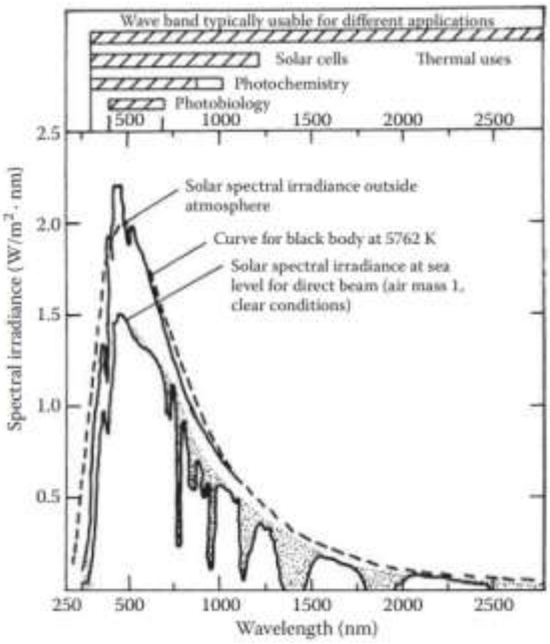

Fig. 6: Spectral irradiance curves for direct sunlight are extraterrestrial and at sea level with the sun directly overhead.

Shaded areas indicate absorption owing to atmospheric constituents, mainly H_2O, CO_2, and O_3. Wavelengths potentially utilized in different solar energy applications are indicated at the top.

India is experiencing a swift shift in its renewable energy sector, driven by the pressing need to reduce carbon emissions, bolster energy security, and satisfy increasing energy demands. Situated in a solar-rich tropical zone, India benefits from an average solar insolation of 4–7 kWh/m²/day over 280–300 clear-sky days each year, equating to more than 5,000 trillion kWh of solar potential annually. This plentiful resource underpins solar-based poly-generation systems, which provide electricity, heat, cooling, and hydrogen from a single, integrated platform. Figure 6 depicts the solar spectral irradiance, emphasizing the 400–2500 nm range where the majority of solar energy is concentrated. This range is crucial for key solar technologies, such as photovoltaic, photo-thermal, and photochemical hydrogen processes. PVT (Photovoltaic-Thermal) systems are particularly efficient in this range, capturing both electrical and thermal energy, thus enhancing system-level energy and exergy efficiency while reducing land usage. India's goals—500 GW of non-fossil capacity by 2030 and 5 MTPA of green hydrogen under the National Green Hydrogen Mission—underscore the strategic importance of harnessing this solar potential. Combining solar energy with hydrogen production through PEC, thermochemical, or PV/PVT-powered electrolysis provides a scalable approach to decarbonize the transport, industry, and power sectors.

This review emphasizes the alignment between solar-based poly-generation systems and India's long-term carbon neutrality objectives.

2.4 Overview of Solar Energy Technologies

2.4.1 Solar Collectors

Solar collectors are devices which receives solar radiation and converts into thermal energy (thermal collectors) or with some collectors providing both outputs (photovoltaic-thermal – PVT). Focusing and non-focusing (or flat) collectors are the two types of solar collectors. Concentrating technologies have a concentrating surface that expands the effective aperture and directs sunlight onto the receiver, a little area. Concentrating collectors are frequently used in conjunction with other thermal devices because they typically function at higher temperatures than flat collectors.

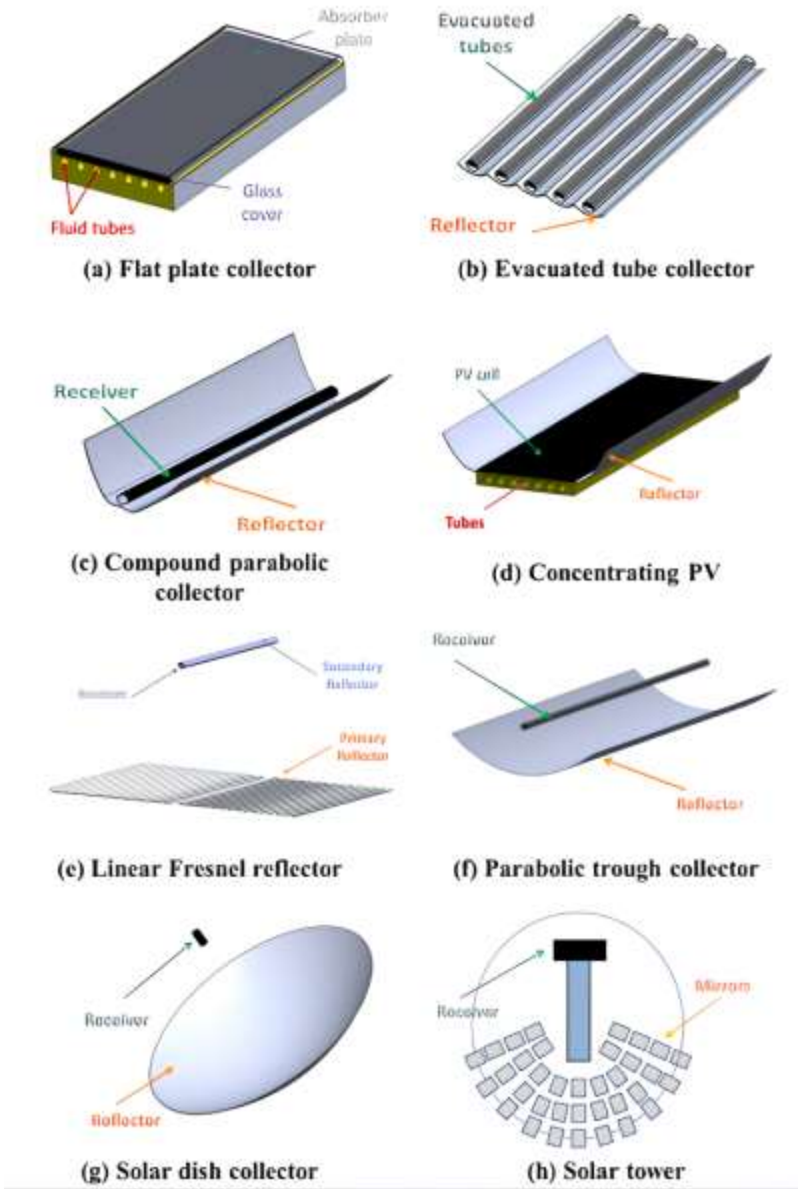

Fig. 7: The most usual types of solar collectors (Alibakhsh Kasaeiana et al. 2020).

Solar energy technologies capture the plentiful and renewable power from the sun, transforming it into usable forms like electricity, heat, or chemical fuels. These technologies are generally divided into photovoltaic (PV) systems, concentrated solar power (CSP) systems, and photovoltaic-thermal (PVT) hybrid systems, each with unique operating principles, applications, and efficiency traits.

1. Photovoltaic (PV) Systems

PV systems directly convert solar radiation into electricity through the photovoltaic effect in semiconductor materials.

Common PV technologies include Crystalline Silicon (c-Si) PV: This dominates the market (~90%) due to its maturity, reliability, and relatively high efficiency (15–22%). Thin-Film PV: This category includes amorphous silicon (a-Si), cadmium telluride (CdTe), and CIGS (Cu (In,Ga)Se_2). These are lighter and cheaper to manufacture but generally have lower efficiency. Emerging PV Technologies: These include perovskite solar cells, quantum dot PVs, and organic PVs, which are promising for their tunability and low-cost processing, though they are still in development. PV systems are modular and scalable, making them suitable for both grid-connected and standalone (off-grid) applications.

2. Concentrated Solar Power (CSP) Systems

CSP technologies use mirrors or lenses to focus direct sunlight onto a receiver to generate high temperatures, which are then used to produce steam and drive a turbine for electricity generation. CSP systems include Parabolic Trough Collectors (PTC), Linear Fresnel Reflectors (LFR), Solar Power Towers (central receivers), and Parabolic Dishes. CSP systems are ideal for utility-scale applications in regions with high DNI (Direct Normal Irradiance) and can incorporate thermal energy storage (TES), such as molten salts, to provide dispatchable power.

3. Photovoltaic-Thermal (PVT) Hybrid Systems

PVT systems combine PV modules with solar thermal collectors to simultaneously produce electricity and useful heat. The thermal collector removes excess heat from the PV cells, thereby enhancing electrical efficiency and extending module lifespan.

Types of PVT systems include Air-based PVT, Water-based PVT and Concentrated PVT (CPVT) systems. PVT systems are particularly effective in applications that require both thermal and electrical outputs, such as in poly-generation, building-integrated systems, and solar-assisted heating/cooling.

4. Solar-to-Fuel Technologies (Advanced)

Emerging technologies aim to convert solar energy into chemical fuels like hydrogen through processes such as: Photo-electrochemical (PEC) water splitting solar thermochemical cycles Solar-powered electrolysis These technologies are crucial to long-term strategies for solar-based fuel generation and storage, aligning with de-carbonization and hydrogen economy goals.

2.5 Solar-driven multi-generation units

To address varied requirements of contemporary society, systems that may provide several beneficial outputs have been developed in recent decades to improve the efficient use of natural resources and lower carbon emissions. In addition to producing electricity, tri-generation systems that incorporate cooling (also known as combined cooling, heat, and power, or CCHP) units, and combined heat and power (CHP) or cogeneration units have established themselves as technologies. Furthermore, systems known as multi-generation (MG) or poly-generation have been introduced to generate more than three outputs, including chemicals, hydrogen, and freshwater, in addition to electricity, heat, and cooling. Renewable energy sources or traditional fossil fuels can power these systems. Because of their efficiency and sustainability, solar-powered MG setups have attracted a lot of attention from academics, researchers, and industry.

2.5.1 Hydrogen as an output

Hydrogen is becoming an essential element in the worldwide shift towards carbon-neutral energy systems, offering a clean, adaptable, and high-energy-density option across multiple sectors. When generated through electrolysis powered by renewable energy known as green hydrogen it facilitates the de-carbonization of energy consumption without producing direct greenhouse gas emissions. As an energy carrier rather than a primary energy source, hydrogen enables the storage and transportation of excess renewable energy, thus addressing the variability of solar and wind power. Its importance is particularly notable in sectors that are difficult to electrify, such as heavy industry, long-distance transportation, and high-temperature industrial processes, where direct electrification is often impractical. In solar-based poly-generation systems, hydrogen production improves system integration and efficiency by using surplus electricity or thermal energy to drive water-splitting processes. Additionally, hydrogen can be stored and later utilized in fuel cells or gas turbines for electricity generation, allowing for long-term energy storage and grid stabilization. The environmental advantages are significant, as green hydrogen eliminates carbon emissions at the point of use, supports the circular carbon economy, and aids in meeting international climate goals. With decreasing costs of solar power and electrolysis technologies, along with growing policy support, hydrogen is set to play a transformative role in fostering a resilient, multi-sectoral, and low-carbon energy future. The methods available for hydrogen production are mentioned in figure 8.

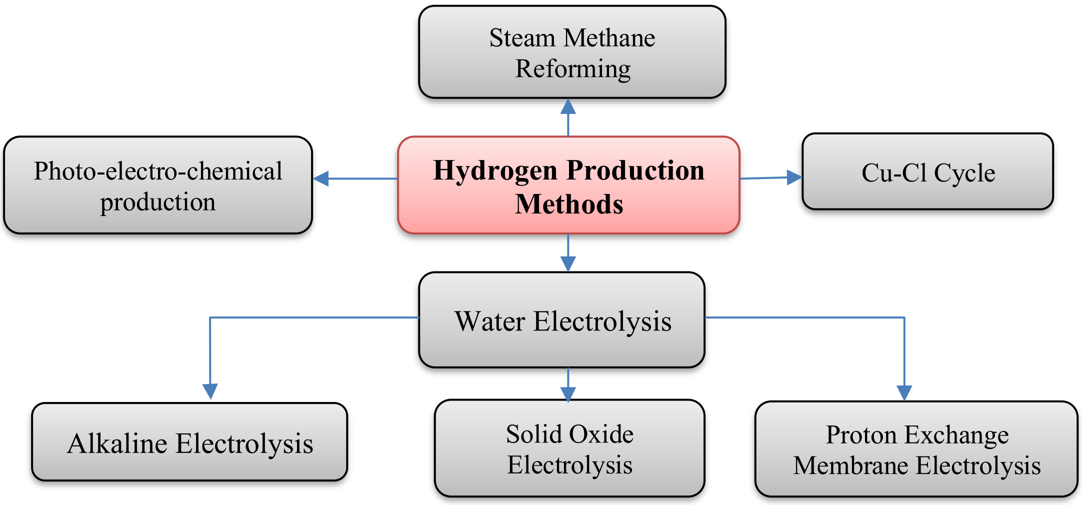

Fig. 8: Hydrogen Production methods.

Steam methane reforming: Methane (CH_4) reacts with steam to produce hydrogen.

$$CH4 + H2O \leftrightarrow 3H2 + CO \quad \Delta H = 206\ kJ/mol\ CH4 \text{-------- (i)}$$

The reaction is endothermic nature, this process needs a lot of steam and a high operating temperature (700–900°C). Because of its cost and temperature and chemical characteristics, the SMR process generally take place in a reformer with several tubes filled with a catalyst, typically nickel, supported by alumina (AlO_3) particles. The water-gas shift (WGS) reaction which converts synthesis gas particularly carbon monoxide to carbon dioxide as shown in the reaction below.

$$CO + H20 \leftrightarrow H2 + CO2 \ \ \Delta H = -41.2kJ/mol\ CO \text{------ (ii)}$$

This two-stage, somewhat exothermic process lowers carbon monoxide (CO) molecules and generates more hydrogen. Nickel catalyzes the first stage, which needs higher temperatures (300–450°C), while copper catalyzes the second stage, which runs at lower temperatures (200–250°C). The following equation provides the overall reaction.

$$CH4 + 2H2O \leftrightarrow 4H2 + CO2 \quad \Delta H = 164.8\ kJ/mol\ CH4 \text{----- (iii)}$$

Pressure-swing adsorption (PSA) is used to segregate the resulting gas mixture and produce 99.999% pure hydrogen. SMR is the most economical, extensively used, and energy-efficient way to produce hydrogen. The main process for creating hydrogen now is steam reforming natural gas.

2.5.2 Green Hydrogen by Water electrolysis.

Green hydrogen is becoming as one of the main carriers of the global shift since there is growing commitment to combat climate change and to avoid the dependence of fossil fuels. One of the most promising methods for utilizing green hydrogen and lowering carbon dioxide emissions is solar hydrogen synthesis via electrolysis (Moraba Caroline Lebepe et al. 2025).

Green hydrogen refers to hydrogen generated by electrolysis or photo-catalysis of water with renewable energy source as input. In this technique, the carbon footprint can be very low whereas but using fossil fuels can significantly increase. If Carbon Capture and Storage is done, the hydrogen is then referred as blue hydrogen and the cost associated with this on a higher side than gray hydrogen. But cost incurred for green hydrogen production is huge because of the electrolysis cells and power from renewable energy sources. Which currently avoid green hydrogen from being produced on a big scale. Both technology advancements and regulatory assistance are encouragingly making low-carbon approaches more cost-effective in the pursuit of carbon neutrality (Teng Hu et al. 2025). The hydrogen production ways have been depicted in figure 9.

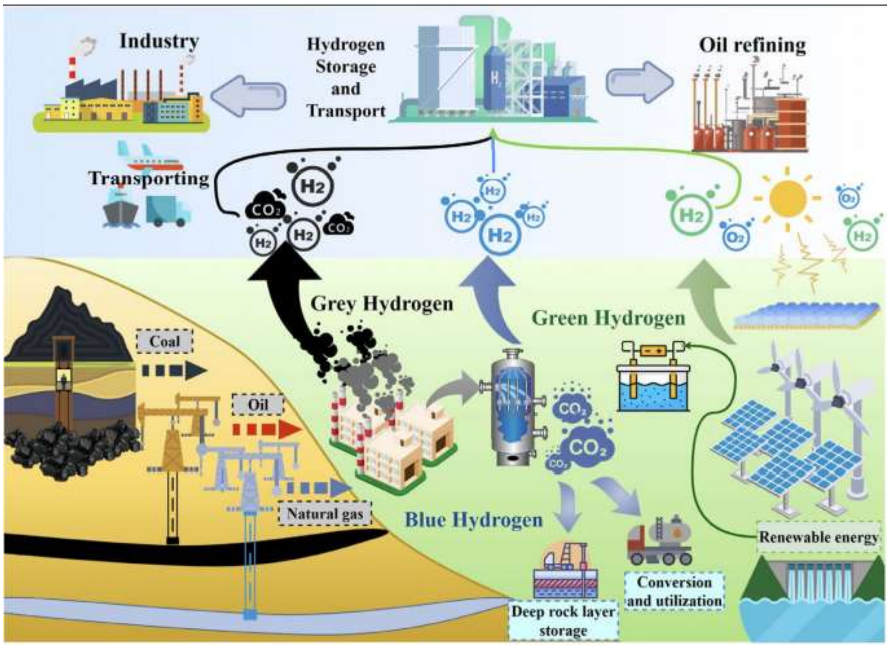

Fig. 9: Overview of hydrogen production pathways; grey (from fossil fuels), blue (with carbon capture and storage), and green (from renewable energy) along with storage, transport, and industrial applications enabling a low-carbon energy transition [Teng Hu et al. 2025].

Working principle through schematic representation of Alkaline, Proton exchange membrane and Solid oxide electrolyzers are shown in figure 10.

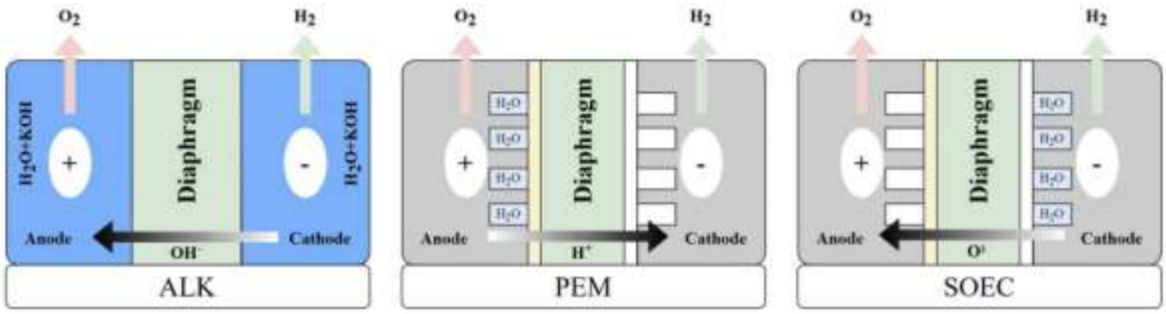

Fig. 10: Figure: Schematic comparison of three main water electrolysis technologies—Alkaline (ALK), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis Cell (SOEC)—illustrating ion transport mechanisms, electrode reactions, and gas outputs for hydrogen production [Teng Hu et al. 2025].

This process, which includes splitting water molecules, produces hydrogen in a clean, carbon-free manner. Energy, usually in the form of heat or electricity, is needed for this highly endothermic process and can be produced from renewable resources. Alkaline electrolysis, solid oxide electrolysis, and proton exchange membrane (PEM) electrolysis are the electrolysis techniques that are currently being developed and marketed.

Table 2: Types of Electrolyzers.

Sl. No.	Electrolyzers	Operating Temperature	Advantages	Applications
1	Proton Exchange Membrane (PEM)	50–80°C	High hydrogen purity (99.999%) Compact and efficient Fast response to power fluctuations	Renewable energy integration Transportation Small to medium-scale industrial use
2	Alkaline Electrolyzers	60–80°C	Lower capital cost compared to PEM. Proven, mature technology. Long operational lifespan	Large-scale industrial hydrogen production Chemical processes (ammonia, methanol production) Steelmaking
3	Solid Oxide Electrolyzers (SOE or SOEC)	700–1,000°C	Highest efficiency (up to 90%) Can utilize waste heat from industrial processes. Compatible with CO_2 electrolysis for synthetic fuels	Industrial heat and hydrogen integration Power-to-gas and synthetic fuel production Energy storage
4	Anion Exchange Membrane (AEM) Electrolyzers	50–70°C	Combines benefits of PEM and alkaline technologies Lower cost due to non-precious metal catalysts Safer operation (no liquid electrolytes)	Distributed hydrogen generation Decentralized energy applications

Proton Exchange Membrane (PEM) electrolysis uses a solid polymer electrolyte, such as Nafion TM, whereas alkaline electrolyzer uses a liquid alkaline electrolyte, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH). While Solid Oxide Electrolyzer Cell (SOEC) systems requires thermal energy at higher temperature, both require electrical input. PEM electrolysis is usually employed in small-scale plants, whereas alkaline electrolysis works well for medium- and large-scale facilities. PEM cells can adjust to the varying electricity from renewable sources, occupies less space, and superior dynamic performance. These cells deliver an improved efficiency and purity of hydrogen, but quiet expensive.

For PEM electrolysis; Anode; $2H_2O \longrightarrow O_2 + 4H^+ + 4e^-$

Cathode; $2H^+ + 2e^- \longrightarrow H_2$

For alkaline and solid oxide electrolysis;

Anode; $4OH^- \longrightarrow O_2 + 2H_2O^+ + 4e^-$

Cathode; $2H_2O^+ + 2e^- \longrightarrow 2OH^- + H_2$

Technologies for manufacturing hydrogen have advanced significantly, especially in the area of green hydrogen production from renewable resources. In the meantime, solar radiation provides a clean, renewable energy source that has enormous potential to satisfy the many demands of contemporary society. This energy can be used to create heat using solar thermal collectors or electricity using photovoltaic cells. Since solar collectors can produce heat at different temperatures, they are a promising and adaptable technology that is perfect for incorporation into poly-generation systems.

Nowadays fuel cell powered vehicles where hydrogen being the fuel input of such devices are most likely to replace existing EVs which needs charging the battery using power supplying from traditional grid. Since the severe concern of the battery used in EVs like lithium-ion batteries (LIB) are taking longer duration to charge and chances of explosion due to overheating or short-circuit, limited battery cycle life. The adoption of fuel cell powered vehicles is essential **[**Manjegowda, N. B. et al. 2024**].**

3. Methodology of Hydrogen production in Multi-generation Systems

3.1 PTC based MG systems with Hydrogen production

Parabolic trough collectors (PTC) may function at temperatures as high as 400–500 °C, they have been the subject of numerous research in the literature on poly-generation systems. As a result, this kind of collector may accommodate a variety of setups. PTCs are typically used along with biomass boilers for providing uninterrupted heat along the day, particularly when solar energy is scarce. To generate heating or cooling, absorption heat pumps are frequently incorporated into the system. Internal combustion engines, gas turbines, and Rankine cycles utilizing water/steam or organic fluids are the main movers utilized in these systems. A synopsis of the research on PTC in poly-generation is given in Table 4.

An oxy-hydrogen combustor powered by a sustainable poly-generation system for distant areas that uses solar and wind energy was the subject of a thermodynamic analysis. Electricity, fresh water, hydrogen (H_2), oxygen (O2), cooling, water heating, and hot air were all continuously produced by the system. Overall, there was a 50% energy efficiency and a 34% energy efficiency (Muhammad Luqman, et al. 2020). A new hybrid system based on solar and geothermal energy for a building was proposed and assessed. The simulation results showed that the electrolyzer produced 2.7 kg/h of hydrogen. It was found that the maximum exergy destruction rate occurred in the parabolic trough collector (Farrukh Khalid et al. 2017). An innovative solar-powered multi-generation system was suggested and examined. The suggested system generated electricity, fresh water, hydrogen, cooling, and household hot water. The findings demonstrated that both energy and exergy efficiency values increased as the turbine input pressure increased (Rami S. El-Emam et al. 2018). A poly generation system was proposed and analyzed through energy and exergy assessments. The outputs included hot water, electricity, heating, cooling, dry air, and hydrogen production. The overall energetic and exergetic efficiencies of the system were found to be 70% and 53%, respectively (Moslem Sharifishourabi, et al. 2017).

Table 3: PTC based MG Systems

Study	Components	Results
M. Almahdi et al. 2016	Biomass belt dryer, TES, PEMWE, ORC, ACC and HP	Energy Efficiency= 20.7% Exergy Efficiency =21.7% Mass of hydrogen =0.001693 kg/s
Mahmood et al. 2021	ORC, PEMWE, TES, hydrogen-oxy combustor, ACC, desalination unit	Energy Efficiency = 41 % Exergy Efficiency =28.4% Mass of hydrogen=0.01 kg/s
Nejat Tukenmez et al. 2020	ORC, PEMWE, TES, hydrogen compression system, desalination unit, KC, ejector cooling cycle, dryer, DHW heater.	Energy Efficiency = 59.34% Exergy Efficiency =56.51% Hydrogen=0.0043 kg/s
Sinan Ozlu et al. 2016	PEMWE, TES, Rankine Cycle, desalination unit, water heater	Energy Efficiency = 36% Exergy Efficiency =44% Hydrogen=0.63 kg/s
Bamisile et al. 2020	Rankine Cycle, ACC, PEMWE, DHW heater	Energy Efficiency = 71.6% Exergy Efficiency =24.5% Hydrogen=0.9785 kg/s
Bozgeyik et al. 2022	ORC, PEMWE, DHW heater, desalination unit	Energy Efficiency = 78 % Exergy Efficiency =25.50% Amount of hydrogen =20.39 kg/day
Mohammad Javad Shabani, et al. 2024	ORC, Brayton cycle, MED, PEMWE, Kalina cycle, and ejector cooling.	Energy Efficiency= 38.45 % Exergy Efficiency =35.64%
Xia Qing et al. 2024	TES, Dual-Pressure Organic Rankine Cycle (DORC), a Compression Refrigeration System (CRC), PEMWE, and a Claude Hydrogen Liquefaction unit (CHL).	Power= 13.45 MW Cooling= 3.41 MW Hydrogen=27.3 kg/h SPP= 5.77 years.
Mehmet Gursoy et al. 2024	Power cycles (steam and organic Rankine cycles), MED, PEMWE, hydrogen storage and refueling	Energy Efficiency= 15.83 % Exergy Efficiency =16.61%
Mert Temiz et al. 2024	TES, RC and ORC	Energy Efficiency = 31.29% Exergy Efficiency =19.71%

Murat Koc et al. 2024	Desalination unit, Gas turbine, PEMWE	Energy Efficiency = 55.91% Exergy Efficiency =49.19%
Muhammad Luqman et al. 2020	RC, MSF, Wind turbine, desalination unit, PEMWE, a refrigeration unit, drying unit for food, a combustor, Water heater, units for storage.	Energy Efficiency = 50% Exergy Efficiency =34% Fresh water 828 m^3/day Hot air= 36 kg/s Hot water= 31 kg/s

The rate of hydrogen production from solar-based poly-generation systems worldwide has shown a steady increase from 2012 to 2024. This growth is largely attributed to advancements in electrolysis technology, enhanced energy management techniques, and rising policy support for green hydrogen. In the initial years (2012–2015), production rates were relatively low, generally under 0.5 Nm^3/h per MW of solar capacity, due to high system costs and inefficient electrolyzers [IRENA, 2022].

From 2016 to 2020, the introduction of PEM (Proton Exchange Membrane) and AEM (Anion Exchange Membrane) electrolyzers improved compatibility with fluctuating solar inputs, raising production rates to over 1 Nm^3/h per MW. The adoption of hybrid systems combining solar with wind, biomass, or geothermal sources further increased reliability and operational hours [Buttler, A. et al. 2018].

After 2020, there was a notable rise in pilot and commercial-scale projects worldwide, especially in Europe, the Middle East, and the Asia-Pacific region [IEA, 2023]. By 2024, cutting-edge solar-integrated hydrogen systems have reached production rates surpassing 4 Nm^3/h per MW, particularly when enhanced with AI-based controls and thermal coupling technologies like CPVT-electrolyzer integration. This upward trend is anticipated to persist, driven by the commercialization of next-generation electrolyzers and further decreases in the Levelized Cost of Hydrogen (LCOH).

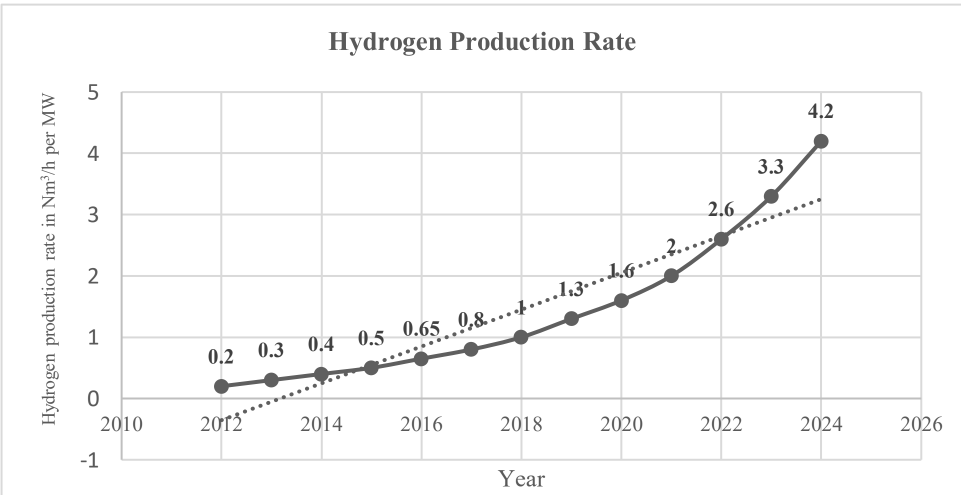

Fig. 11: Hydrogen production rate from solar based poly-generation systems (2012-2024).

The graph (Fig. 11) shows a consistent rise in hydrogen production rate from 0.2 to 4.2 Nm^3/h per MW between 2012 and 2024, highlighting rapid advancements in solar-based hydrogen technologies.

Designed and analyzed energy and exergy performance a solar thermal-based poly-generation system that produced electricity, cooling effect, heating effect and hydrogen. The non-continuous nature of renewable energy source was addressed by incorporating with hot and cold energy storage to operate an organic Rankine cycle and provide cooling at night. The overall energy and energy efficiencies which were equal to 20.7% and 13.7%, respectively (M. Almahdi, et al. 2016)

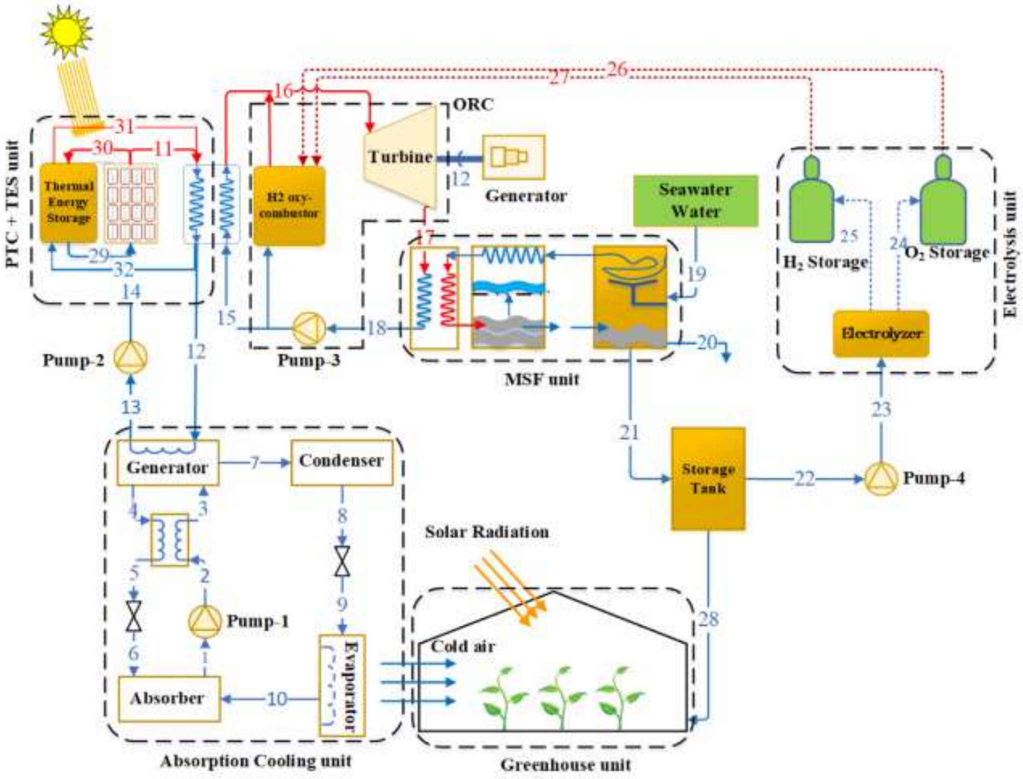

Fig. 12: Solar based MG plant covering the various demands [Farhat Mahmood et al. 2021].

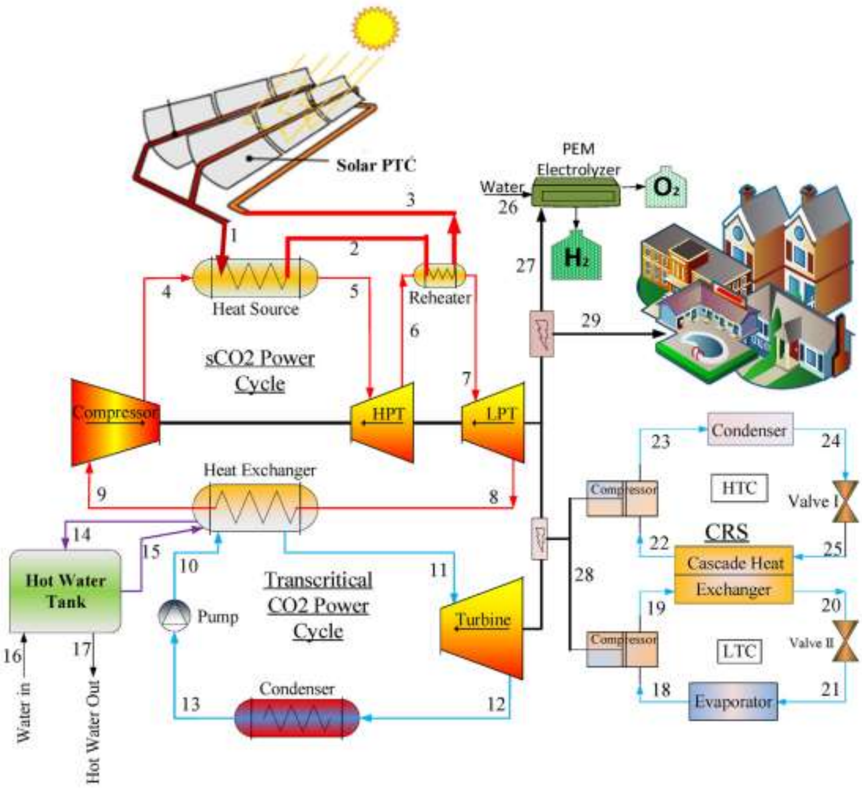

Fig. 13: CO_2 based comprehensive energy system [Olusola Bamisile et al. 2021].

Investigated portable solar power system in form of novel poly-generation system experimentally. This system included photovoltaic panels, evacuated solar collector, vapour compression refrigeration and desalination unit. The results yielded that majority of the power around 471 W supplied by photovoltaic panels and most of the power consumed by compressor. Also, the system could be able to supply 16.5 L distillated water per hour (Milad Soltani et al. 2023).

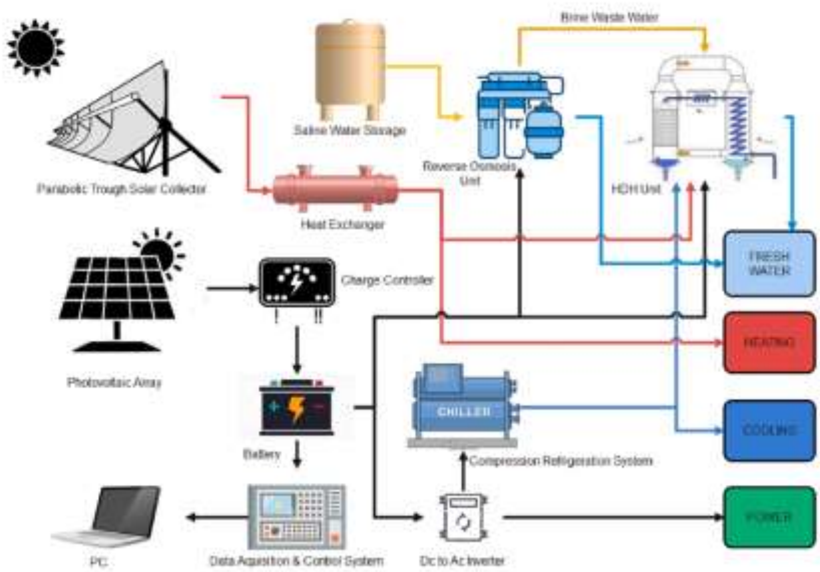

Fig. 14: Proposed poly-generation system [Olusola Bamisile et al. 2021].

Performed thermodynamic assessment for a self-sustaining multi generation system that provides production of drinking water, electricity, and hydrogen. The plant always produced electricity and potable water simultaneously with a supply of 500 kW-h per day while producing a significant amount of freshwater as well (Nicolas Cobos Ullvius et al. 2023). The author outlines a novel energy system used in generating different substances like electricity, heating and cooling. It comes with an overall power capacity of 12839.500 kW for electricity generation, 791.8 kW for heating systems and 937 kW meant for cooling ones. The system further can produce 32.92 kg/h of hydrogen. The system achieves overall energy and exergy efficiencies of 37.68 % and 71.25 % (Moslem Sharifishourabi et al.2024).

3.2 Solar tower-based MG systems with Hydrogen production

Examined an integrated energy system based on renewable resources. When solar energy was unavailable, biomass fuel was utilized as a backup energy source. The system was intended to generate hydrogen, cooling, and power. It had energy efficiency of 39.99% and exergy efficiency of 27.47% (Rami S. El-Emam et al. 2017). Analysed to evaluate the performance of a self-sustaining poly-generation system that was combined with the production of freshwater, power, and hydrogen. This system's ability to constantly supply 500 kW and produce a significant amount of freshwater (6500 L per day) was evaluated (Masoud Rokni 2019). Studied the effectiveness of a self-sustaining poly-generation system that combined the production of freshwater, electricity, and hydrogen. This system's capacity to generate a significant 6500 L of freshwater per day and deliver 500 kW around-the-clock was evaluated (Nicolás Cobos Ullvius et al. 2019). Iinvestigated an innovative solar-powered intergenerational energy system. Through electrolysis, the system produces fresh water, heating, cooling, and hydrogen. Along with producing 90 kg/s of fresh water and 1.25 kg/h of hydrogen, it was also built to meet the demand for 4 MW of electricity (Rami S. El-Emam et al. 2017).

3.3 PV based MG Systems with Hydrogen production.

Poly-generation Microgrids (PMG) was designed to provide various outputs, including electricity, heat, cold, hydrogen fuel, and clean water (S. Srinivasa Murthy et al. 2020).

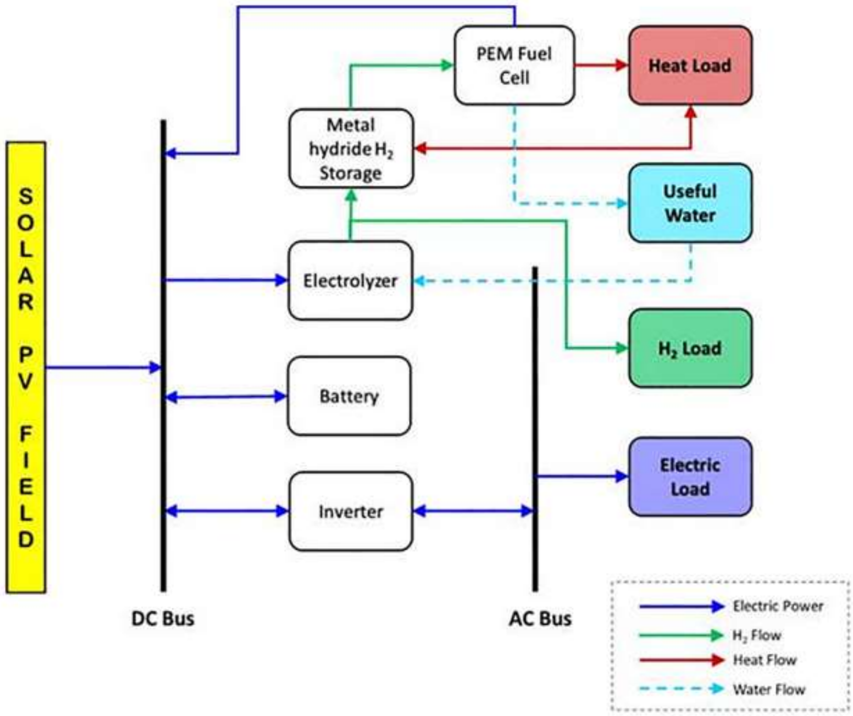

Fig. 15: Schematic of H_2 Storage Integrated System for stand-alone poly-generation micro-grid (Srinivasa Murthy et al. 2020).

Studied optimization of poly-generation unit which provides electricity through a PV array and a digester that is fueled by animal and agriculture wastes**.** The surplus gas ejected from the digester used to heat and light the kitchen, while the remaining waste heat has been supplied for water filtration using a membrane distillation unit. The outcome was met through which it was found that the daily demand of electricity would be met without any difficulties from cooking fuel measuring 0.4 m^3 and drinking water amounting to 2-3 liters at the same time. Economic point of view also this system was shown as better than any other renewable sources (Ershad Ullah Khan et al. 2015). An analysis of unique poly-generation arrangements for a community building to address the basic energy demands. In all cases, it was assumed that 100% of these five requirements would be met using only renewable energies namely, PV and PVT panels as well as biomass backup boilers (BB) solar cells (Javier Uche, et al. 2022). In this study, they had focused on numerically assessing the energy as well as economic viability of a novel hybrid poly-generation system that is fueled by biomass, wind and solar power and meant for micro district residential application. The results demonstrated that it is possible to create a power generation system that meets user demand for electric power while also fulfilling the needs for cooling, heating, hot domestic water, and freshwater production. Based on the many scenarios examined, economic analysis indicates that the payback period could range from 5.67 years to 12.20 years. This signifies that the project is profitable

(Rafal Figaj et al. 2022).

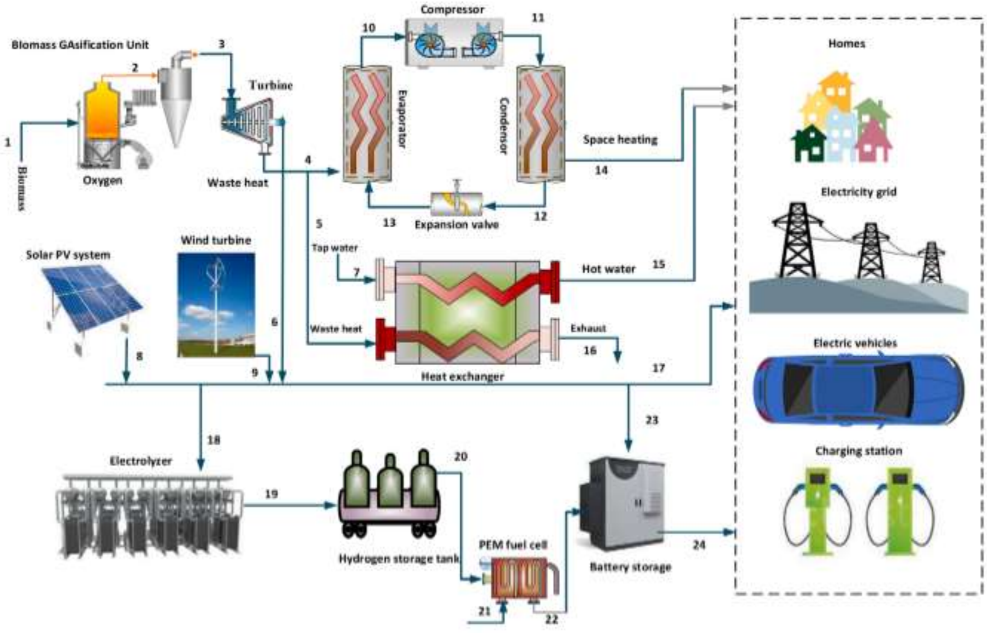

Fig. 16: Schematic of the proposed hybrid poly-generation system (Rafal Figaj et al. 2022).

Analyzed solar based poly-generation system thermodynamically. The system delivered exergy efficiency as 44%. The authors showed that system energy efficiency was being improved by 16% with the integration of the cooling system (Shahid Islam et al. 2017). Investigated solar based a CCHP system integrated with reversible solid oxide fuel cell (R-SOFC). The system used high-temperature metal hydrides (MH) method which is chemical based storage of hydrogen. The system's round-trip energy efficiency was 36% more than that of a single R-SOFC (Mykhaylo Lototskyy et al. 2018). As a clean burning gas, hydrogen does not emit carbon dioxide when it is burned; therefore, one way is to make it available without burning other fuels. Afterwards follow other studies being done on hydrogen generation using renewable sources of energy as we all know them today. Study of this nature has shown that it’s possible to come up with a number of workable strategies for integrating electrolyzer unit into PV panels systems so that hydrogen is produced in environmentally friendly manner leading also to higher performance of poly-generation facilities (Farbod Esmaeilion et al. 2022). The authors focused on solar, biomass, and wind energy sources to suit the community's different needs. A part of power produced by PV cells is utilized for hydrogen production to run an electrolyzer. The stored hydrogen is then fed to a proton exchange membrane (PEM) fuel cell, which produces additional electricity to EV charging. Whereas the biomass supplied to a gasification unit to get hot water and to fulfil space heating requirement as shown in figure 16 (Muhammad Ishaq et al. 2024).

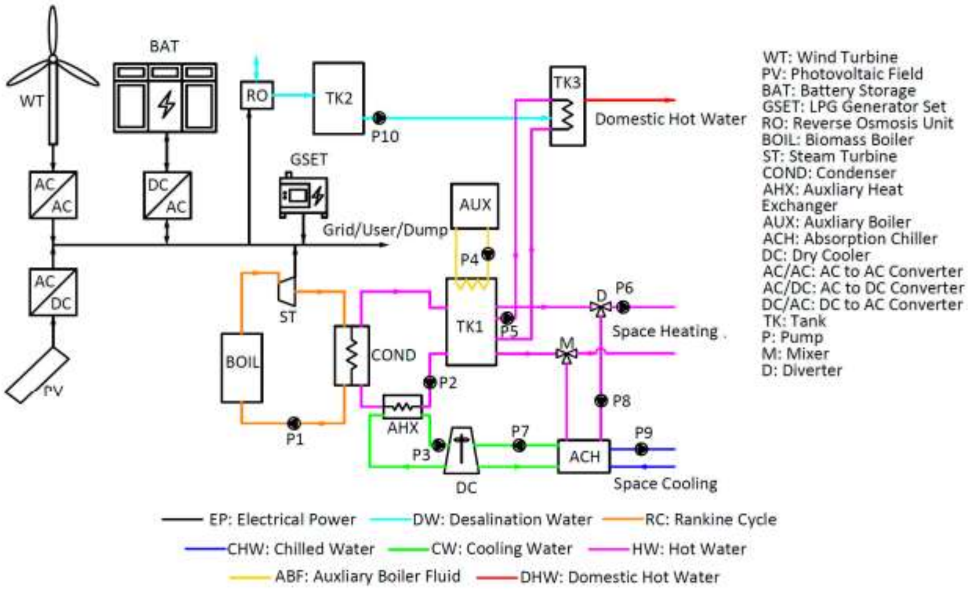

Fig. 17: A schematic layout of the proposed tri-renewable energy coupled with battery and hydrogen storage (Muhammad Ishaq et al. 2024).

Examined solar based green hydrogen production system with different configurations of eletrolyzer and PV panel. Among the four configurations proposed, the results obtained with the mono-crystalline solar PV panel and alkaline electrolyser provided the lowest Levelized Cost of Hydrogen (LCOH) (Moraba Caroline Lebepe et al. 2025).

3.4 PVT/CPVT based MG Systems with Hydrogen production.

Poly-generation systems with photovoltaic thermal units

The essential goal of photovoltaic collectors and photovoltaic/thermal collectors is to enhance electrical and thermal efficiency. To overcome the aforesaid issue, these collectors integrated with other power generation equipment to increase the plant's overall efficiency. Concentrating thermal photovoltaics (CPVT) are hybrid solar collectors that generate heat and electricity. These systems typically have a surface covered in photovoltaic (PV) cells and fluid-filled tubes beneath them to cool the cells, improving their electrical production and providing usable heat. Because of the utilization of concentrators, CPVT may operate at 100°C or higher, making it an efficient cogeneration system. With the addition of a few components, CPVT systems can be converted into tri generation or poly generation systems that produce heat, power, and other useful outputs. They either harness or scatter solar radiation, depending on their shape.

As a result, this part investigates and evaluates poly generation facilities outfitted with a photovoltaic or photovoltaic/thermal collector.

Proposed an off-grid system which successfully combined a floor heating system with a vapor compression desalination unit to meet electricity, heating, and freshwater requirements. This integration highlights the system's sustainability and independence from the grid (Jing Zhu a et al. 2024).

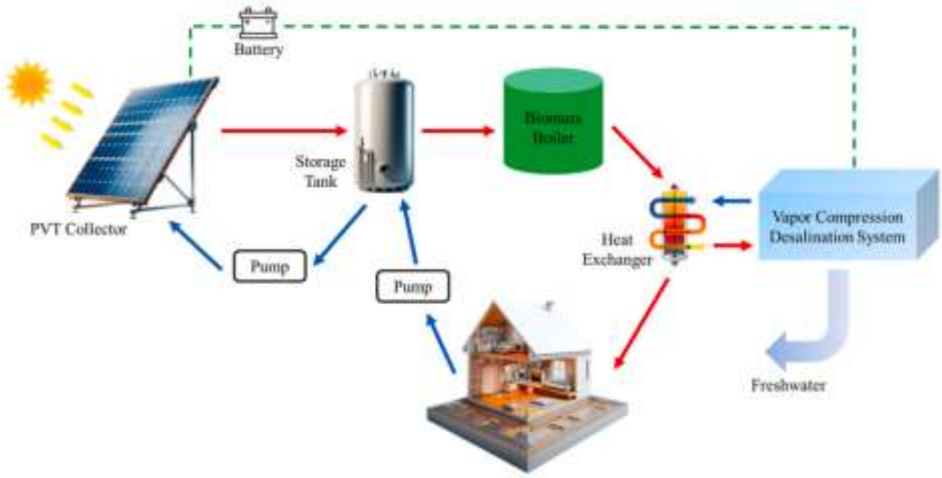

Fig. 18: The schematic of the proposed system (Jing Zhu a et al. 2024).

Proposed novel solar- geothermal hybrid system sources for hydrogen production, power generation, cooling, and heating for practical applications. It was suggested to have geothermal water temperature exceeds 210°C, the system's overall energy and exergy efficiency will also be increased (Yusuf Bicer et al. 2016).

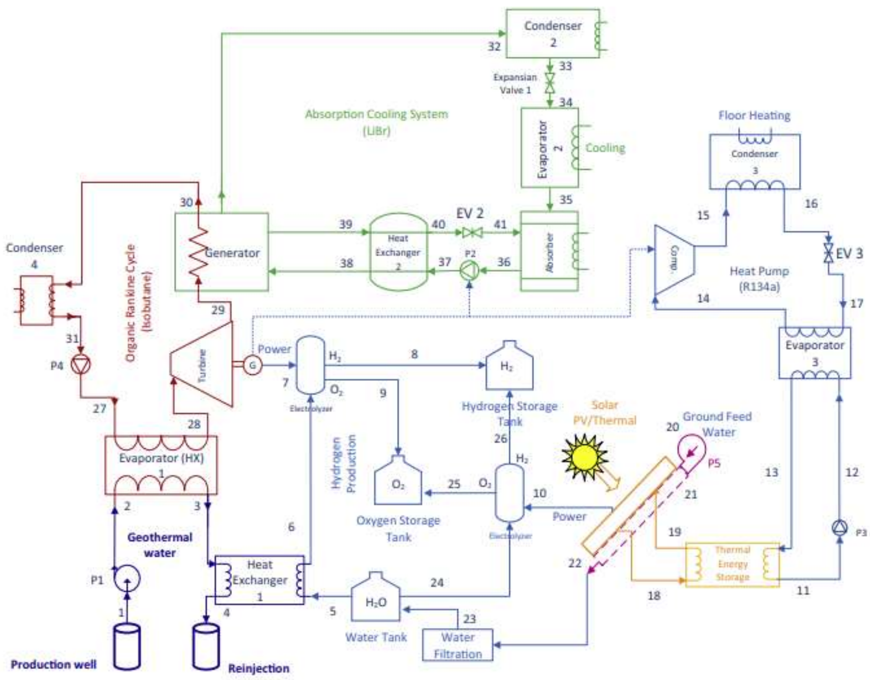
Fig. 19: Schematic diagram of designed multi-generation system (Yusuf Bicer et al. 2016).

[49] This study looked into the integration of the Kalina cycle with a concentrated photovoltaic thermal system for multi-generation and hydrogen production. Photovoltaic cells, a Kalina cycle, a hot water tank, a proton exchange membrane electrolyzer, a single-effect absorption system, and a hot air tank were used in the simulations to generate hot water, hydrogen, hot air, power, and cooling. The results revealed that adding the Kalina cycle raised the multi-generation system's overall energy efficiency from 68.73% to 70.08%. Additionally, the integration of the Kalina system produced an extra 417 kW of electricity, highlighting the significance of this configuration as shown in figures 20a & 20b (Olusola Bamisile et al. 2020).

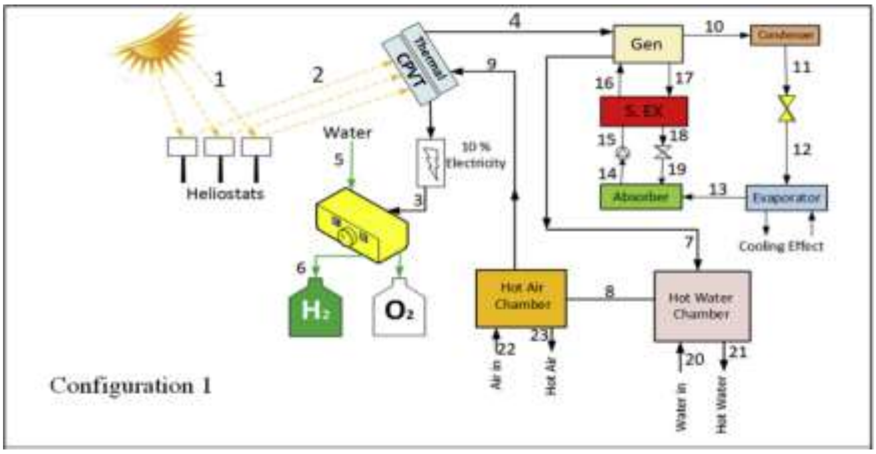

Fig. 20a: CPVT powered multi-generation system and CPVT integrated with Kalina cycle multi-generation system schematic diagram (Olusola Bamisile et al. 2020).

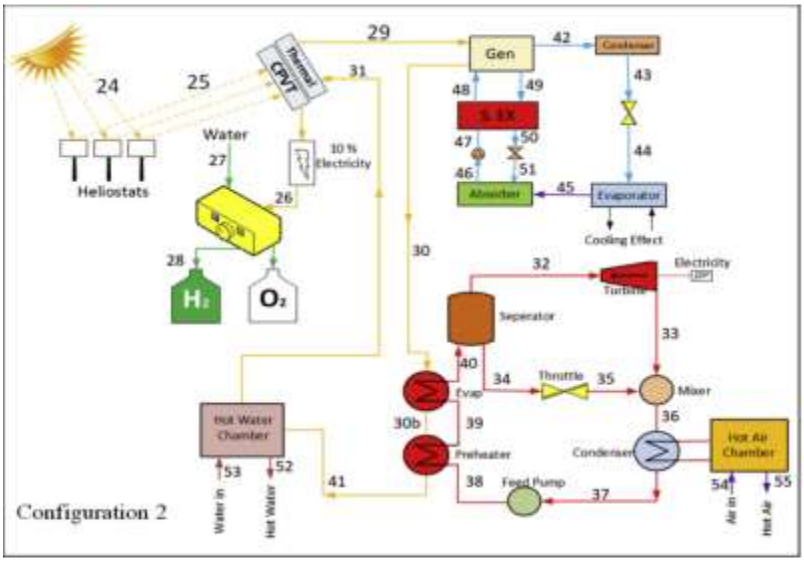

Fig. 20b: CPVT powered multi-generation system and CPVT integrated with Kalina cycle multi-generation system schematic Diagram (Olusola Bamisile et al. 2020).

Presented and investigated a novel multi-generation system, combining an ocean thermal energy conversion (OTEC) system with flat plate and PV/T solar collectors. The system also included a reverse osmosis desalination plant for producing freshwater, a single-effect absorption chiller, and a PEM electrolyzer. To assess the system's performance, thermodynamic evaluation was used. The results revealed an exergy efficiency of 60%, with the system's total cost rate at the time being 154 $/h (Pouria Ahmadi, et., al. 2014). Examined a multi-generation system to meet a building's heating, power, and water needs in St. Petersburg (Russia). The dynamic analysis results indicated that the proposed system could meet up to 70% of the electricity demand and 57.9% of the heat need without the utilization of an auxiliary system (Mahdi Deymi-Dashtebayaz et al. 2022). In this study, two wind-solar-based polygeneration systems, Comprehensive Energy System (CES-1) and CES-2, were assessed to produce hydrogen, hot water, electricity, and cooling. The two systems had poly-generation thermal and exergy efficiencies of 48.08% and 31.67% for CES-1, and 59.7% and 43.91% for CES-2, respectively (Dongsheng Cai, et al. 2020). Proposed and thermodynamically analyzed a novel solar-based system consisting of photovoltaic panels, a photo-electrochemical water splitting reactor, and a fuel cell system for providing electricity and heat to a small community with the option of operating off-grid and producing fresh water. For the conditions in question, the system achieved overall energy and exergy efficiencies of up to 19% and 12%, respectively (Nicola Franzese, et al. 2020).

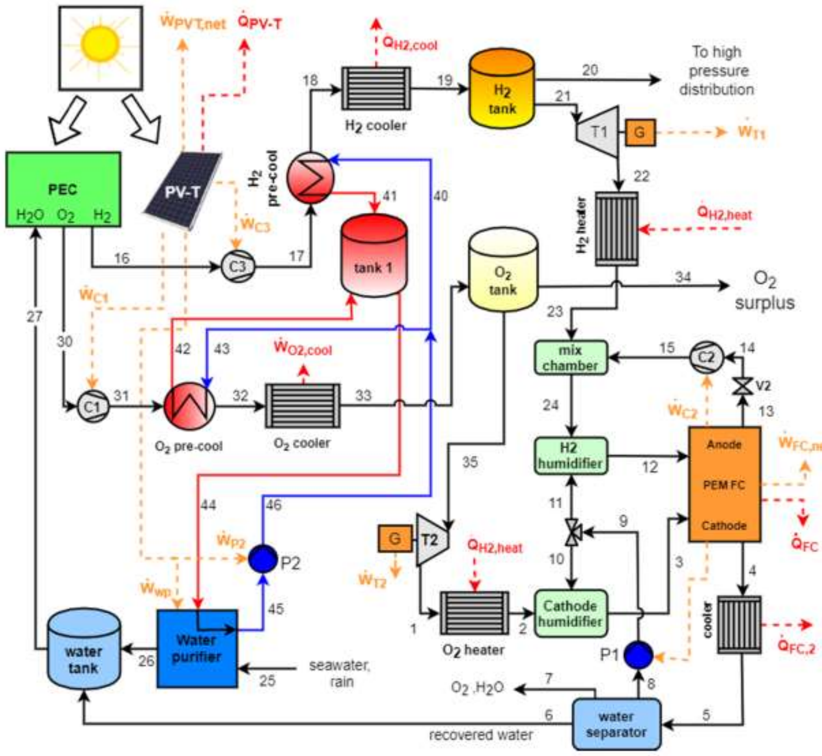

Fig. 21: Schematic diagram of the proposed multigenerational system for hydrogen, power, and district heating (Nicola Franzese, et al. 2020).

Investigated a PV/T powered poly-generation energy system for CCHP & CPHH mode. The results showed that Optimization results highlight the system's strong performance, achieving total energy efficiencies of up to 85.90% and 86.97% for CPHH in spring and winter, and 88.26% for CPCH in summer, with product unit costs as low as $22.21 per GJ. Also, this research offers valuable insights into developing efficient, renewable energy-integrated multi-generation systems (Penglai Wang et al. 2024). This study investigated green hydrogen poly generation system by electrolysers. The authors suggested that SOEC avoids the inevitable energy loss in AE and PEME. But SOECs are most suitable high temperature plication. For general flexibility and integration with renewable energy, PEM electrolyzers are often considered the best option despite their higher cost. Investigated a PVT investigations with emphasis on studies which include environmental issues about PVT technology (Shuhao Zhang et al. 2023). This work underlined effect of heat transfer fluid in a PVT system. The study showed that PVT water system gives better environmental performance than PVT air system because of its better heat absorption capacity. Also suggested that CPVT systems would be better replacement of PV cell with a concentrator material which contributes cost reduction and less environmental impact (Chr. Lamnatou et al. 2017). A biomass and solar integrated system for the multi-generation of useful outputs, combining two renewable energy sources to produce multiple outputs (e.g., power, cooling, hot water, heated air), was developed and presented. The overall energy and exergy efficiencies of the system were determined to be 66.5% and 39.7%, respectively (Farrukh Khalid et. al 2015). A solar cogeneration system was investigated, exergy analysis showed that the CPVT is the principal source of exergy destruction. Exergo-economic analysis highlighted the CPVT's economic importance, with a capital investment cost of $0.08946/h and an exergo-economic efficiency of 28.82% (Ehsan Akrami et al. 2017). María economic assessment of optimized solar combined heating and power system based on a novel PVT collector was investigated. The study that among the system components, the PVT collector cost had the greatest influence on system economics, accounting for approximately 38% of the total investment. Government incentives, if properly implemented, were shown to improve system economics in the short term. However, in low-latitude locations, these incentives might not be necessary, as high irradiance levels and energy prices contributed to favorable PBTs (Herrandoa et al. 2018). Presented a dynamic simulation and showed that the system was capable of producing power, heating, cooling, and DHW over the entire year. It was found that from the dynamic simulation results, significant amount energy saving can be achieved with PVT which coupled to an absorption chiller to meet cooling demand (Francesco Calise et al. 2012). Investigated a solar tri-generation system. The poly-generation system analyzed to produce electricity, and desalted water. The study provided key suggestions to reduce the SPBs: i) It was found from the study that the optimal ration of solar field area and ACH capacity (at constant MED capacity) around 5.9 m^2/kW; ii) prefer a storage tank with smaller volumes (around 15 L/m^2); iii) finally, exit temperatures from the solar field during summer and winter would be around 85°C and 55°C respectively (Francesco Calise, et., al 2014). Presented novel solar tri-generation system. The plant was proposed to meet basic energy demands for a small residential building. The results showed that thermal and electrical efficiencies were above 40% and 10%, respectively. The Simple Payback period was found to be 5.36 years; this period decreased to 2.33 years when a capital investment incentive of 30% was available (Francesco Calise et al. 2016).

Parametric analysis has been carried out on a proposed solar tower based multi-generation plant for sustainable hydrogen generation using solar energy. The overall energy and exergy efficiencies of the proposed system had 38.66% and 34.14% respectively. The net power from the system was 8041 kW. And, among the components of the cycle, solar tower had maximum exergy destruction rate (Fatih Yilmaz et al. 2025). This study demonstrates that the portable hybrid system's green hydrogen, with its significant calorific value, serves as an eco-friendly fuel alternative. It has the potential to replace traditional fuels like LPG, commonly used for cooking in rural areas. The system harnesses energy from a micro-hydraulic setup, which can be installed in water bodies with limited volume capacity (Villanueva E.A et al. 2025).

Table 4: Comparison table of PVT and CPVT along with hydrogen production systems

3.5 Poly-generation systems with Hydrogen production by combined solar technologies.

Poly-generation systems that integrate hydrogen production with combined solar technologies are

System	Energy Efficiency (%)	Exergy Efficiency (%)	Hydrogen Production Rate	Economic Viability	Limitations
PTC + SOE + CCHP	60–68%	35–45%	~0.044–0.107 kg/h	Moderate – high capital cost, better with scale	Large land area, thermal losses, needs thermal storage
Solar Tower + SOE + CCHP	65–75%	40–50%	~0.0899–0.161 kg/h	High – feasible at utility scale	High capital cost, complex heliostat field control
PV + PEM + CCHP	50–60%	20–30%	~0.0267–0.0623 kg/h	Moderate – depends on PV cost and O&M	Low thermal recovery, less efficient hydrogen generation
PVT + PEM + CCHP	70–75%	35–50%	~0.0719–0.134 kg/h	Improving – dual output adds value	Integration complexity, cost of thermal management
CPVT + PEM + CCHP	**75–80%**	**60–65%**	**~0.1078–0.17** kg/h	Promising – high energy yield per area	Thermal management challenges, expensive materials
PTC + SOE + CCHP	60–68%	35–45%	~0.044–0.1078 kg/h	Moderate – high capital cost, better with scale	Large land area, thermal losses, needs thermal storage

designed to produce multiple energy forms—such as electricity, heat, and hydrogen—simultaneously. These systems often combine solar technologies like photovoltaic (PV), concentrated solar power (CSP), and solar thermal collectors with a hydrogen production unit, typically utilizing electrolysis powered by solar electricity. In this process, electricity is used to split water into hydrogen and oxygen, with the hydrogen being stored for future use as a clean energy source. A poly-generation system is proposed, utilizing thermal energy from ocean. The system's performance is evaluated thermodynamically, focusing on minimizing total cost and maximizing cycle exergy efficiency using an evolutionary algorithm (Pouria Ahmadi et al. 2014).

3.6 PCM based MG Systems

In recent times, there has been upward attention in multi-generation systems. The integration of PDC-based multi-generation systems with PCMs has primarily been conducted theoretically, with limited experimental study in this field. Furthermore, most of the research focuses on specific outputs like as power, fresh water, and hydrogen. Other frequent outputs and combinations of multi-generation systems with PCM integration have received less research attention (Esfanjani P et al. 2024).

Poly-generation system is treated as one of the most attractive approaches to enhance energy efficiency to control environmental pollution. The articles reviewed for poly-generation systems are solar based as in all the systems the output of one component becomes the input for subsequent component. Also, several utility outputs are obtained. This way, the amount of useful energy in the given amount of input is harnessed to a maximum extent, thus maintaining a very high energy efficiency (M R Kamesh et al. 2020). As far as freshwater scarcity is concerned, solar desalination would be the better approach using solar stills or using low grade heat from any of the components in multi-generation system to produce fresh water (G S Girishkumar G S et al. 2024).

Techno-Economic Considerations of Solar-Driven Poly-generation Systems with Hydrogen Production

Solar-driven poly-generation systems that produce hydrogen present a comprehensive approach to achieving carbon-neutral energy by generating various outputs such as electricity, heat, cooling, water, and hydrogen from solar power. However, their widespread implementation hinges on their techno-economic viability.

Technical Considerations: These systems boost overall efficiency (up to 70–80%) by harnessing both thermal and electrical solar outputs. The integration with Proton Exchange Membrane (PEM) or Solid Oxide Electrolyzers (SOE) facilitates hydrogen production from variable solar energy. Configurations like CPVT-PEM or solar thermal-SOE enhance performance but necessitate sophisticated control systems. AI-based energy management is increasingly employed for real-time optimization.

Economic Considerations: The capital costs remain substantial, ranging from $1,000–$2,500 per kW, due to the requirement for multiple subsystems. Operational expenses, including maintenance and water purification, add 5–10% of CAPEX annually. The Levelized Cost of Hydrogen (LCOH) has decreased from over $10/kg in 2012 to $4–6/kg in 2024, with expectations of reaching $2–3/kg by 2030, supported by technological advancements and policy incentives.

Value Enhancement: The co-production of thermal energy, cooling, and water enhances return on investment and shortens payback periods to 7–10 years, particularly in off-grid or industrial areas.

Policy Support and Opportunities: Incentives for green hydrogen, carbon pricing, and public-private partnerships promote adoption. Despite obstacles like high initial investment and infrastructure gaps, opportunities exist in local manufacturing, modular system designs, and digital optimization tools.

4. CONCLUSIONS

Solar-powered multi-generation (MG) systems display great potential as energy solutions that can resourcefully meet a wide range of energy needs, while also being environmentally sustainable. These systems offer a clean alternative to traditional energy sources, aligning with the growing global focus on reducing carbon footprints. One of the primary provision of solar-powered MG installations is the integration of system to produce hydrogen. This review study focuses on hydrogen generation integrated into solar-based poly-generation systems, filling a significant gap in existing research. By investigating this growing mix, the study hopes to broaden understanding and provide significant insights for improving the usage of renewable energy technology.

The following conclusions are drawn from the present study are.

i. Concentrating thermal collectors and hybrid solar technologies such as PVT or CPVT are the principal devices for the majority of MG systems. Also, in some other systems PV panels and FPCs could be used.

ii. Proton Exchange Membrane (PEM) electrolysis is considered a more feasible and commonly used approach for hydrogen production compared to Solid Oxide Electrolysis (SOE) in solar-based poly-generation systems. This preference is attributed to its greater operational flexibility, quicker response time, and ability to work well with the variable nature of solar energy, making it more apt for integration into renewable energy systems aimed at achieving carbon neutrality. PEM electrolysis generates hydrogen at a lower cost than alkaline electrolysis, although systems powered by natural gas are more expensive.

iii. Due to the inherent variability of solar energy, solar-based poly-generation systems frequently include additional renewable sources like biomass, geothermal, and wind to maintain stable operations and continuous hydrogen production, particularly in off-grid or fluctuating demand situations.

iv. PTCs offer superior energy and exergy efficiency, while CPVT systems can achieve even higher efficiency. The highest recorded energy efficiency was 78.93%, with a peak exergy efficiency of 65% for a CPVT-based multi-generation system. Additionally, hybrid systems that combine PVs and wind turbines are more economically feasible.

v. Apart from production of hydrogen, the most common useful outputs like drying, ammonia, hot water, freshwater, heating, cooling, and power.

vi. Overall, solar-powered MG systems with integrated hydrogen production show promise as clean energy solutions aligned with sustainability goals, but further research and development is needed in some areas.

Future Research Directions and Technical Barriers

To accelerate the adoption of solar-powered poly-generation systems for carbon neutrality, future research should focus on these key areas:

Thermal Management in CPVT Systems: Excess heat can degrade photovoltaic efficiency in CPVT systems. Advanced cooling techniques, such as heat pipes, liquid cooling, and phase change materials, are needed to maintain thermal stability and optimize energy capture.

Integration of Intelligent Control Systems: Upcoming studies should emphasize the use of AI and machine learning-based control strategies to dynamically manage energy distribution, optimize the balance between thermal and electrical loads, and enhance hydrogen production efficiency under varying solar input conditions. Advanced Thermal Management Strategies: Efficient heat management in concentrated photovoltaic/thermal (CPVT) systems remains a major challenge. Research should explore innovative heat sink materials, hybrid Nano fluids, and phase change materials (PCMs) to improve thermal regulation and reduce performance degradation.

Cost and Durability of Hydrogen Subsystems: Proton exchange membrane (PEM) electrolyzers face issues due to high initial costs and limited durability under fluctuating solar-powered conditions. Future research should focus on: Developing cost-effective, non-precious metal catalysts. Improving membrane stability and water management during intermittent operation. Integrating modular, scalable PEM units designed for poly-generation systems.

System-Level Optimization and Modeling: Comprehensive system models that incorporate energy, exergy, economic, and environmental (4E) assessments are essential. Coupled optimization of subsystems (e.g., solar field, storage, electrolyzer) using multi-objective algorithms can guide optimal configurations for different climatic zones and user needs. Hybrid Energy Storage Integration: Effectively incorporating hybrid storage systems (thermal, electrical, and chemical) is crucial to mitigate the intermittency of solar resources. The focus should be on developing intelligent energy dispatch algorithms for real-time management of storage–load–production synergy.

Techno-Economic Feasibility and Policy Support: More detailed techno-economic analyses are needed to assess long-term viability. Policies should promote modular, off-grid poly-generation units in rural or industrial areas, with localized hydrogen production for mobility or fuel cell applications.

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