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Renewable Energy Technologies: A Physics-Based Review

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Abstract

Renewable energy technologies are central to achieving a sustainable and low-carbon energy future. This review examines the physics-based principles underlying major renewable energy technologies, including solar, wind, hydropower, ocean energy, and energy storage systems. Fundamental concepts such as thermodynamics, electromagnetism, semiconductor physics, and electrochemical processes are explored to explain energy conversion mechanisms and performance limitations. The study discusses photovoltaic and solar thermal technologies, wind turbine aerodynamics, hydropower generation, tidal and wave energy systems, battery storage, hydrogen energy, and fuel cells. Additionally, challenges related to grid integration, system stability, energy storage, and sustainability assessment are analyzed. The review highlights recent technological advancements, policy considerations, and emerging research directions that support the transition toward reliable, efficient, and environmentally sustainable energy systems. Understanding the physical foundations of renewable energy technologies is essential for improving efficiency, reducing costs, and accelerating global adoption.

Keywords: *Renewable Energy, Energy Conversion, Photovoltaics, Solar Energy, Wind Energy, Hydropower, Energy Storage, Hydrogen Fuel Cells, Grid Integration, Sustainability.*

Introduction

Energy is an essential resource for all forms of human activity, from running a light bulb in a home to powering an entire nation. It powers our homes, industries, transportation, communication, etc. Economic growth and energy use are closely linked; therefore, the development of sustainable energy has been increasingly prioritized in recent years. Although the main Southeast Asian countries have sufficient fossil fuel reserves, they continue to leverage solar and wind energy, leading to extensive research and development on their potential. Photovoltaic technology, since 1954, has stimulated substantial interest and deployment through its seamless integration into the existing energy and electricity system. Photovoltaic technology allows electricity to be generated directly from sunlight using materials or devices called semiconductors. Due to high fossil fuel prices, renewable energy has become a critical issue. Even as the world struggles to curb greenhouse gas emissions, the energy landscape continues to change dramatically. Energy resources once considered potentially unlimited are now viewed as finite, and the developing world is seeking solutions to prevent future resource depletion while meeting the growing need for energy and electricity (Jahankhani et al., 2011), (SARKAR and Odyuo, 2019), (Hardwick et al., 2018).

Fundamental Principles of Energy Conversion

The term energy conversion broadly refers to the transformation from one form of energy to another and encompasses the physically measurable capacity of a system to perform work on another system. Fundamental scientific principles underlie many of its aspects, and such principles vary depending on the particular form of energy being converted. Energy conversion principles are naturally coupled to physical principles and materials science in numerous realms, including thermodynamic transformations, electromagnetic induction, semiconductor junctions, and electrochemical reactions (A. Alam and Ryyan Khan, 2012). Thermodynamic cycles and Joule heating govern power generation; Maxwell's equations delineate the behavior of electric generators, motors, and transformers; quantum effects, such as band-gap formation, carrier transport, and defect states, influence photovoltaics (PV) and batteries; and electrochemical reactions determine the working of fuel cells and electrolyzers. Every energy conversion process depends on boundary conditions and assumptions that delimit its applicability and relevance to particular applications. Metrics such as the economy of the technology and the social-environmental consequences of its deployment strongly influence the evaluation of energy-conversion devices but are intimately affected by the physics of operation.

Performance indicators and efficiency are, therefore, chosen as focal interest. Table 1 lists the principal energy-conversion devices alongside the corresponding bounds on efficiency and performance indicators that are targeted. Energy conversion refers to the transfer of energy from one form to another. It considers the key physics principles across technologies including thermodynamics, electromagnetism, quantum mechanics and materials science. The scope is defined broadly to encompass technologies that serve to generate, transport, store, transform, utilise or convert energy in any form, including fossil fuels, solar energy, wind energy, hydropower, mechanical energy, hydrogen and electricity. Energy conversion systems are of fundamental importance in the transition to an affordable, secure, equitable and sustainable energy system. Decarbonization of the world energy system is critical to mitigating climate change and enabling global development. Policy incentives, economic mechanisms, and engineering designs therefore encourage continued focus and advancement of energy conversion.

1. Thermodynamics of Power Generation

The conversion of energy into useful forms is governed by fundamental physical principles, such as conservation laws and equations of state, which constrain the operation of energy conversion systems. Although energy conversion encompasses a wide range of processes, detailed consideration shows that it can be broadly divided into two major classes: conversion from high-temperature sources, such as fossil and biomass fuels, concentrated solar radiation, and low-grade waste heat, into work or high-temperature fuels; and conversion from high-grade sources, such as fossil fuels, wind, sunlight, and ocean waves, into low-temperature heat. Energy conversion from a lower-grade source into work is ultimately limited by fundamental thermodynamic principles, regardless of the source characteristics; such systems are governed by the Carnot cycle, which defines the highest achievable efficiency and the operational performance of the engine, providing detailed design guidance. The same thermodynamic principles govern heat engines and heat pumps, allowing development of a uniform treatment.

Power generation encompasses the conversion of various primary energy sources, including fossil fuels, biomass, geothermal, wind, solar, river flow, tidal movement, ocean waves, and ocean temperature gradients, into electrical energy. To better understand commonalities across energy sources, the analysis adopts a broad perspective and encompasses any process that ultimately generates fluids supplied to a turbine. Despite the diversity of energy sources and conversion technologies, there is a clear hierarchy. Gas- and steam-turbine cycles closely match direct fuel use, whereas other systems such as organic Rankine cycles are often installed as separate plants for further energy extraction. Concentration technologies, such as solar thermal systems, aim to increase the thermal energy of an intermediate heat transfer fluid, providing a consistent route to turbine fluid generation (Ramos Cabal et al., 2018).

2. Electromagnetism in Energy Conversion

Electromagnetism plays a key role in energy conversion processes in wave energy converters and electric drives. Electromagnetic energy can be obtained by direct, lossless conversion from gravitational and kinetic energies using an electromechanical system with a superconducting coil. Detailed research on wave energy converters and design techniques includes crest level optimization and direct-drive systems. Specific focus areas comprise permanent magnet generators for renewable energy, wind turbine systems, and wave energy systems, emphasizing control and electrical configuration.

Electromagnetic induction is described by Faraday's law, which specifies the induced electromotive force (EMF) in a closed circuit as the negative time rate of change of the magnetic flux through that circuit. The motivation for the arrangement of charge carriers is a change of magnetic flux threading the circuit loop. Through conductive coils, the induced EMF generates electric currents and drives electric loads in power generation systems (Penalba et al., 2017). The magneto-mechanical systems involved consist of either a non-rotating conductor within a rotating magnetic field, or a rotating conductor immersed in a stationary magnetic field. The mechanics of electric generators explain the working principles of electric motors under Faraday's law.

3. Quantum and Material Considerations

Energy conversion in solid-state and nano-electronic devices is driven by the transport of charge, spin, heat, or other degrees of freedom equivalent to these quantities. The underlying physics governing these devices—quantum, crystal structure, etc.—determines permissible motions of charge carrier types and ultimately affects operating principles, limits, degradation, and reliability concerns. Although classical electrodynamics and thermodynamics sufficient for describing classical electrical and thermal machines are not entirely adequate, significant insight into physics and limits is still gained because basic mechanisms are fundamentally unchanged.

Carrier transport, including generation, recombination, and defect densities, is a significant focus of physics-based efforts aimed at improving photovoltaic-side and storage-side technology. In six-interaction models of carrier diffusion in a semiconductor under illumination, fundamental drift, thermalization, and recombination limits equate to transparent conducting oxides' (TCO) transparency, cathode–anode separation distance, and other basic losses (A. Alam and Ryyan Khan, 2012). Similarly, electrode materials for batteries directly associated with charge/discharge capacity, duration, and other performance metrics are explored from a physics perspective. Performance limits foundational in laser technology also carry over when minimizing device duration rather than maximizing total energy. Time and scale feasibility is assessed for carrier transport, defect criticality, and materials choice, reinforcing the contention that excessive focus on materials rather than theory leads to long research cycles or even permanent stagnation. The desire to eliminate metal would also indicate a need to minimize dimensions for nano- devices, yet efforts to grow TCO nanowires with 100% transparency and conductivity consumed 4–5 years. Performance limits of simplistic models attainable with basic transport consideration constitute another important grounds for prioritizing classical-device advancement, addressing fundamental performance gaps, and enabling more aggressive circuit-type downsizing.

Solar Energy Technologies

Semiconductor physics provides a theoretical foundation and a description of loss mechanisms for photovoltaic devices. Hypothetical approaches based on radiative rates as limited by Shockley-Queisser would retain thermodynamic consistency with irreversible processes. However, large bandgaps fundamentally limit efficiency maximization, with materials beyond the visible spectrum lacking mature photonic technology. Scaling optical surfaces offers more viable paths to reduced cost and higher absorption. Optical systems increase time of interaction, enabling search for low-cost materials that absorb over many decades. Selective surfaces or cavity-enhanced approaches enable photon energy down-conversion or up-conversion energy recovery from thermal losses. Luminescent materials with appropriate phonon structure could yield significant enthalpy recovery from pigment absorbance. Designs without costly concentrators remain in demand and further capacity for cost-critical improvement exists. Continual downward cost-curve projections expected near-term targets to remain valid.

Geometric rather than temporal multiple reflections in expertly shaped geometries or prisms enable postponement of light trapping at physics-limited fdark●fabsorpt penalties. Distributed micro-concentration combined with widely employed glass panels and thin high-symmetrical mirrors exhibits compatibility with standard sheets and additional absorption pathways. Non-linear materials in optical harmonics could recover efficiency lost in tandem non-absorption gaps and offer long-established technology development. Low-temperature materials compatible with back-surface photonic and optical-generation enhancement schemes might permit geological-scale enthalpy-release recovery from non-thermal-photon illumination.

Tropospheric chemistry or photolysis could utilize Gt2 content already established on stranded gaseous proceeds and gas-cycle enhancement options accompany abundant H2O content. Geo-sequestration containing super-critical conditions reaches economic breakeven at the well-head, H2O-capturing options under consideration. Current, electrochemical, hydrothermal, biochemical, catalytic, vehicle, dispatch-maintaining approaches already validated on stranded or dilute organics hold further promise. Contributions proven viable retain applicability under anticipated operating-selectivity shifts. Gathered-state polymer blends responsive only to single-sided exposure offer payload-distribution independence and periodic regeneration-extension maintenance potential. Multi-length-scale pedal-limb-self-pinching-strain models structured at partial flow and independently exploited low-dissipation-integration provide direct-link and broad-support configuration-cultural-continuity access.

Moore-law-like behaviour extends production, incorporation, and exchange-filling-processes; vehicle regional-hydra, train-road alignment expedition, universal plastic, or disperse-format-process scheme benefit. Prototypes in variable-function preferred/rejection/disobligatory-acquisition-discharge-exchange-requests, proximity-and-orientation-based-function-sequencing shared via subtitles assimilated at item-to-entity or entity-to-enterprise-range aggregation. Edwards-physics-reduction, Air-transport-field-principles, surface-tension reduction, labour-saving, blending-characteristics experimental-model formulations also deployed. (Eisa Elbasheer Abbas, 2019)

1. **Photovoltaics: Semiconductor Physics and Device Operation**

Semiconductor physics governs the operation of photovoltaic (PV) devices. The most widely adopted PV technology today is crystalline silicon (Si), which provides a stable and ready-to-use supply of energy for a moderate capital cost (Guerra et al., 2018). Also, it is important to recognize that light interacts with materials at the atomic level. Thus, a fundamental understanding of solid-state physics, as specific as possible considering the system in question, is paramount to investigate light absorbers of any kind or, more broadly, any sensor intended to detect electromagnetic radiation.

Most commonly used PV devices consist of a p-n junction where photons of energy exceeding the semiconductor's band-gap energy generate electron-hole pairs that subsequently lead to a photocurrent once separated by an external electric field. However, light absorption, charge carrier generation, and transport comprise competing mechanisms that take place during the physical operation of solar cells. These mechanisms produce both energy losses and carrier collection that together determine the final, usable power of the device.

Ever since the first solar cells appeared in the 1950s, the efficiency of silicon photovoltaic devices has been steadily and constantly increasing. More than fifty years of intense research and development efforts have paid off, resulting in a figure of merit representing their energy-conversion efficiency that has now reached nearly 27% in certified laboratory demonstration systems worldwide. Unfortunately, modes of loss remain; therefore, efficiency has not yet attained its thermodynamic limit. The improvement of bulk Si technology through surface passivation, material quality enhancement, and optimised epitaxy is still being pursued to reach the single-junction maximum efficiency of 29% in the foreseeable future.

Third-generation photovoltaic solar cells attempt to recover some of the lost energy through the addition of new physical effects. These cells generally target composite efficiencies higher than 40% by means of multi-junction schemes. Tolerance to strict cracks resulting from thermal expansion mismatches allows many thin-film, polycrystalline, and non-absorption-limited materials to enclose open-circuit voltage losses. Exploration has turned toward organics, hybrids, plasmonic structures, and nanostructuring. Capturing new options at the above stages counts with UV, IR, and direct-colour coupling devices, organic-based and colour-converting systems. An alternative PV concept includes photoelectrochemical routes and related devices.

Regarding light-colour nondiscriminating inner modes, carrier transfer from low to high-conduction bands, e.g., along with their reversal from high- to low-permittivity dielectric materials, along with p-n, p-i-n, and light-emitting or light-receiving surface effects, short-distance hops ultimately from electronic resistive loss down have also been investigated.

2. **Solar Thermal Systems: Collectors, Absorbers, and Heat Transfer**

Solar thermal collectors for industrial process heat applications are still in development, with few available in the market. Medium temperature collectors suitable for SHIP applications operate in the range of 80–250 °C. Compound parabolic concentrator (CPC) collectors use non-imaging optics to concentrate sunlight on an absorber, allowing for greater light intake and less precise tracking than parabolic trough collectors. Concentrating collectors are used for high-temperature applications like steam production for thermal power generation. Concentrating solar power systems use solar radiation to produce electricity through thermal processes, including central receiver systems with heliostats focusing sunlight on a tower-mounted receiver that absorbs radiation to generate superheated steam, and parabolic dish collectors that focus sunlight onto a receiver at the focal point (Selvakumar et al., 2010).

Reflecting surfaces can concentrate solar irradiation onto a collector, enabling higher temperatures than non-concentrating systems, useful for applications requiring heat between 80 °C and 250 °C. Improving collector performance and efficiency is a focus of recent research. Direct absorption solar collectors transfer incident solar energy directly into the working fluid, which flows in open-loop or closed-loop configurations. Common working fluids include water, ethylene glycol, and oils, but they have poor thermal conductivity compared to metals like copper and iron. Recent studies aim to enhance thermal properties by adding nanometer-scale particles to the fluids, creating nanofluids with improved heat transfer characteristics (Chamsa-ard et al., 2017).

3. **Concentrated Solar Power: Thermal Cycles and Efficiency**

Concentrated Solar Power (CSP) systems convert solar energy to thermal energy using mirrors and related mechanisms that focus sunlight onto a small area (Rovira et al., 2018). Thermal energy conversion encompasses three main cycles: Rankine, and more recently, Brayton and combined Brayton-Rankine. The viability of CSP systems hinges on the availability of thermal energy storage, which enables operation when sunlight is scarce. The overall efficiency of CSP systems correlates strongly with the solar collector employed and its integration with the power cycle. CSP techniques that focus on direct absorption of solar energy in the working fluid permit the use of heat transfer fluids with higher boiling points, broadening the choice of thermal cycles and materials. The associated two-phase energy conversion cycle and the corresponding collection efficiency influence the total efficiency significantly (Song et al., 2019). Various supercritical carbon dioxide configurations compatible with direct absorption of solar heat are under investigation.

Wind Energy Systems

Wind energy systems generate electricity from atmospheric winds. They typically feature a horizontal-axis turbine mounted on a tower. The turbine rotor converts wind energy into mechanical shaft energy. This is transferred through a drivetrain to an electric generator, which converts the mechanical energy into electrical energy for the grid. The overall efficiency of the system depends on the aerodynamic characteristics of the rotor, mechanical and electrical losses in the drivetrain and generator, and power electronics that integrate the system into the electrical grid. With the advent of large, multi-megawatt wind turbines, system efficiency has grown to become a distinct and important subject for investigations in renewable energy technology (Mehedi Hasan, 2017).

A horizontal-axis wind turbine exposes a rotating blade to the wind, generating lift that drives the rotor. The power extracted is a function of the wind speed, rotor diameter, and performance coefficients. The wind speed distribution at a site determines the annual energy produced by the turbine. Three aerodynamic phenomena influence performance coefficients: wind shear, which causes the speed and direction of the wind to vary with height above the ground; tip loss due to reduced local angle of attack at the blade tip; and the unsteady behavior of the separated vortex generated at moderate Reynolds numbers. Enhancing rotor performance coefficients affects energy capture and turbine economics (Basem Tawfiq Albassioni et al., 2019).

1. **Aerodynamics and Turbine Performance**

In the aerodynamics of a wind turbine, the rotor interacts with the flow field to extract energy from the wind. Consider a wind turbine rotor located in the open atmosphere. It extracts power from the wind, which involves a change in the wind velocity as the flow passes through. Wind velocity is normally considered to decrease in the vicinity of a wind turbine rotor. Wind velocity and the area swept by the wind turbine determine the theoretical maximum power that can be extracted from the wind.

Let U_0 be the free-stream wind velocity, A be the swept area of a wind turbine and P be the power extracted from the wind. According to the continuity and fluid mechanics of an incompressible flow, the power P that can be extracted from the wind can be conceptualized following

P = 0.5ρU_0^3 A C_{p}. (Liam Poland, 2018)

Where ρ is the density of the wind, C_{p} is the power coefficient a measure of the turbine efficiency defined by

C_{p} = P/\left(0.5ρU_0^3 A\right).

C_{p} can be maximized, studied, and analyzed by researchers. The maximum attainable power coefficient for a horizontal-axis wind turbine is fundamentally limited to the well-known Betz limit of 0.593. The power coefficient is influenced by other geometric and flow conditions. The velocity profile of a wind turbine is of great importance since it impacts the power coefficient (Liam Poland, 2018).

2. **Mechanical and Electrical Transmission**

Mechanical and electrical transmission connects the turbine and generator, transmitting mechanical power to an electrical generator. Various arrangements exist, with direct-drive systems gaining prominence. Mechanical transmission requires a gearbox to ensure the generator speed matches the turbine. Multiple single or double-stage gearboxes are commonly used. Multi-megawatt wind turbines rely on large planetary or bevel gear systems to mitigate weight and size restrictions in the drivetrain. Mechanical drive trains are challenging to seal, leading to a requirement for lubrication. Sealed oil lubrication systems can operate globally, however they can limit reliability and increase maintenance-frequency, often leading to line-condition monitoring. Drive-train lubrication and condition monitoring remain vital areas of research, given the significant downtime and associated costs arising from repair and maintenance.

3. **Control Strategies and Grid Integration**

Although wind is a variable resource, control techniques can provide greater power quality and grid stability. Yaw and pitch regulation improve output and enable grid-connected operation under variable conditions. Grid-following control maintains frequency and voltage at the inverter output, while grid-forming control enables operation in islanded mode. Power quality deterioration due to harmonics, inter-harmonics, flicker, and voltage sags can occur at high integration levels (SARKAR and Odyuo, 2019). Wind turbines connected to power systems often use maximum power point tracking to adjust reference mechanical power. When turbines operate at constant power, additional control strategies mitigate voltage and frequency fluctuations and enable participation in automatic generation control.

Well-designed controls enable wind energy systems to meet performance requirements for grid-connected operation. Yaw control achieves coordinated turbine orientation while mitigating fatigue from wind direction variability. Pitch control dampens oscillations due to transient wind gusts while counteracting occurring aerodynamic stall (Ravi et al., 2023). In distributed generation and microgrids, renewable integration can lower system inertia and damping, impairing stability. Feedback control strategies adjust reference generator speed to damp trends in rotor speed and electrical-power fluctuations. Distributed control schemes enable interconnection among multiple turbines and coordination of system-level operability, enhancing performance in loosely coupled networks (Ngancha et al., 2017).

Hydropower and Ocean Energy

Hydropower maintains a significant role in the global renewable energy portfolio. Employed for millennia in traditional water mills, its potential is now harnessed to generate electricity using large-scale hydroelectric plants which rely upon a mature, predictable, and environmentally well-characterized resource. Ocean energy (for example, tidal and wave energy) represents a less-established sector. It has yet to enjoy extensive commercialization. Focused activities include tidal-range energy systems, marine-current energy converters, and offshore/inshore wave-energy systems (Dolores Esteban Pérez et al., 2019). Ocean energy is considered alongside wind energy or marine energy. Offshore marine energy systems benefit from proximity to—and synergy with—offshore wind installations (Pérez-Vigueras et al., 2023). Substantial installed capacity is forecast to support the deployment of ocean-energy systems (Ramadass, 2010).

1. **Conventional Hydropower: Efficiency and Environmental Considerations**

Conventional hydropower systems convert the gravitational potential energy of stored water into electrical energy through the operation of turbines or turbines-generators. The overall efficiency of these plants can vary significantly (40% to 90%), depending both on the design of the turbine and the operational conditions at which they are run. The design of these systems and the control of the water flow from the water reservoir to the turbine-generator units will ultimately depend on the available energy conversion system used on the particular hydro-power electricity generation system. The widespread and extensive monitoring of the available water-energy resources to develop new or existing hydropower sites (Al Tamimi, 2018) has resulted in the heightening of stringent environmental obligations to comply with regulation from functions such as the water-releasing levels after plant-felling)that. The environmental mandates that accompany hydropower system-development concern the compliance of water-amount disposal after dam build–up, energy exposure from artificial dissolvable gas during reservoir evacuation, increased muddiness of the water disposal from desserts-water exposition, and tribulation from the submerged sub aquatic-seed seedlings (J Panarella, 2018). Various studies have highlighted the necessity of optimizing the turbine types as well as granting the environmentally friendly modification design to preserve the ecological sustainability.

2. **Tidal and Wave Energy: Fundamentals and Feasibility**

Tidal energy relies on the periodic rise and fall of ocean water levels due to lunar and solar gravitational forces. Water movements associated with these periodic variations can be harnessed using tidal stream generators or gated tidal barrage systems. Tidal energy has an advantage over other renewable sources in that its high predictability helps match supply with demand more closely. In contrast, wave energy systems extract energy from orbital motions of water particles in surface gravity waves. The nature of surface waves—periodic, irregular, and relatively short time scale—imposes challenges on energy extraction systems. The feasibility of wave energy systems remains uncertain on a large scale and they can have adverse environmental impacts (Song Ngu, 2013).

Energy Storage and Conversion Technologies

Energy storage and conversion technologies are critical for optimal utilization of renewable sources like solar, wind, ocean, and hydropower (Yunus et al., 2012). Storage and conversion technologies are crucial for ensuring stable energy supplies from these sources. They provide firm capacity, enable long-distance transmission, decouple production from consumption, and enhance energy security. They are essential for the transition to cleaner, more sustainable energy systems. Among energy storage options, batteries are widely used. Electrochemical storage systems extract energy from electricity-generating processes through redox reactions, storing energy in chemical form. Various materials and configurations influence battery performance, giving rise to different chemistries. Other energy storage technologies include thermal and mechanical systems, while hydrogen technologies enable energy conversion and storage via electrolysis, chemical processes, combustion, or fuel cells. Electrochemical principles underpin these conversion and storage technologies.

1. **Battery Physics and Degradation Mechanisms**

A battery is a type of electrochemical cell designed to convert chemical energy into electrical energy through oxidation-reduction (redox) reactions. Batteries can be classified into primary (non-rechargeable) and secondary (rechargeable) types, based on whether the original redox reactions can be reversed. In principle, degradation of primary batteries is not an issue because the chemical reactions cannot be reversed; however, the deterioration of chemistry and performance in such batteries over time is still a crucial concern (Brosa Planella and Dhammika Widanage, 2022). Given that the focus of degradation research is on secondary batteries, an understanding of battery physics, battery electrochemistry, and related aging mechanisms and indicators is a prerequisite for analyzing energy storage technologies such as batteries. The working principle of a lithium-ion battery, one of the most widely used secondary batteries, is described in detail to provide insight into its electrochemical mechanism and how capacity fade occurs. This section also covers some aging mechanisms typically considered in the research literature and some commercially used methods for estimating battery state of health (Zhao et al., 2022).

2. **Thermal and Mechanical Storage Methods**

For thermally stored energy, a range of storage methods have been developed for both high and low-temperature. High-temperature thermal storage materials that have been investigated at various research institutes include concrete, bricks, and ceramics (Bravo Hidalgo, 2018). These materials can be stored and used directly without additional heat transfer elements. The idea is the utilization of sensible heat by heating or cooling a material over different temperatures. For a low-temperature thermal storage technology, air is commonly used as the heat transfer fluid, and a packed bed built up with rocks, sand, or other containers has been widely studied (Davenne et al., 2017). Concrete, bricks and other materials with high thermal conductivity could greatly enhance the efficiency while lengthy modeling and simulation were required to analysis the detailed heat transfer processes.

3. **Hydrogen and Fuel Cells: Electrochemical Principles**

The generation and use of hydrogen as an energy carrier offer an alternative to traditional non-renewable carriers such as fossil fuels. Hydrogen is a versatile energy carrier produced primarily from fossil fuels today. When the feedstock is renewable and the conversion processes are clean, hydrogen offers a sustainable energy vector. The energy conversion from hydrogen to electricity can be achieved in fuel cells, which are electrochemical devices that convert the chemical energy of hydrogen directly to electrical energy. At the system level, hydrogen technologies span the following four steps: (i) production from renewable electricity (input: electricity / output: hydrogen), (ii) conversion to electricity in fuel cells (input: hydrogen / output: electricity), (iii) storage (input: hydrogen / output: hydrogen), and (iv) compression (input: hydrogen / output: hydrogen). Hydrogen can be produced from water electrolysis, biomass gasification, photolysis, thermal dissociation, or produced by reforming hydrocarbons, which is the most widely used method today (Kim, 2019). Other methods also include photocatalysis, thermochemical cycles, thermolysis, biophotolysis, subterraneous banking, and photoelectrochemical splits (Michal et al., 2014). The worldwide hydrogen production amount is 70 million tons, used in ammonia synthesis (45% of total), petroleum upgrading (30% of total), treating metals, and other chemicals. The production technologies are well established and reliable, in particular the steam reforming of naphtha and the water-gas shift processes. Hydrogen is stored in tanks up to 700 bar, or in chemical bonds (such as ammonia, methanol, or hydrocarbons fluoride). Many hydrogen production pathways are coupled with direct hydrogen fuel cells or adapted for the electrodes configuration. Direct hydrogen fuel cells are used in transport. Most applications scenario involves on-board hydrogen generation.

Grid Integration and Systems Modeling

Amid rising levels of renewable energy generation, questions have arisen concerning the stability and reliability of power systems with high fractions of renewable sources in the generation mix. Power electronics interfaces convert the generated electricity into forms compatible with the grid and that enable either grid-following or grid-forming control methods, each featuring distinct behaviours during grid disturbances and allowing a greater or smaller share of intermittent resources such as wind and solar generation (Albernaz Lacerda et al., 2021). Further, modelling studies facilitate the assessment of power system strategies fostering the addition of renewable generation while retaining stability, resilience, and dispatchable capacity.

The increasing penetration of renewable energy sources (RES) into the electrical power system presents fundamental challenges at the system level, with technologic possibilities spanning the entire transmission, distribution, and end-use sectors. Among the RES in widespread use—wind, solar, geothermal, hydro, ocean, and biomass—only a few adequately supply nationwide generation while simultaneously addressing capacity, energy, and investment, as well as material and environmental limitations. Consequently, viable paths towards a sustainable, reliable, and renewable future employ two or more of these existing resources alongside energy storage, co-generation, conversion, and transmission technologies (Pagola et al., 2019). Most pioneering RES technologies were developed independently, and the modelling available thus focuses on generation options relating only to individual components.

1. **Power Electronics and Grid Interfaces**

Emerging technologies for managing energy and reducing consumption are continuously changing the way electrical energy is generated, transmitted, and used. Hence, novel materials, devices, and systems are needed to foster a renewable future. In generation, the reliance on fossil fuels is now backed by the adoption of wind and solar sources. In transmission, the implementation of power electronics allows for AC and DC power grid interconnections. A unified and thorough treatment of underlining physics for energy materials, devices, and systems can help shaping the future electric energy landscape.

Understanding the fundamental principles of energy conversion enables the synthesis of scattered knowledge about diverse renewable technologies and their physical processes from energy source to end user. Energy principles govern new technologies that deliver alternative energy. Energy conversion is a topic that encompasses all science and engineering disciplines. Electrochemical capacitors, electrochemical cells, batteries, fuel cells, supercapacitors, and thermoelectric materials and then continued by Non photovoltaic solar devices, solar materials, solar concentrators, solar receivers. Even thermodynamics, solid mechanics, electromagnetic waves, fluid mechanics, wave mechanics, molecular dynamics molecular motion are important for the future of electric energy science and technology. (Almasoudi, 2018) (SARKAR and Odyuo, 2019)

2. **Stability, Resilience, and Dispatchable Capacity**

Stability, resilience, and dispatchable capacity are central to operating electricity networks, especially with high penetrations of variable renewables like solar and wind (Paul Rouse et al., 2018). Stability relates to the ability of a system to return to equilibrium after a disturbance, while resilience denotes the capacity to maintain essential functions through and recover from disruption. As the energy mix evolves in response to climate change, preserving both stability and resilience will require rethinking the sources of ancillary and operating reserve services and the manner in which they are sustained. Dispatchable capacity refers to the ability to supply energy on demand, a characteristic traditionally associated with fossil generators and hydro systems. While storage technologies including batteries, pumped hydro, and flywheels provide significant quantities of dispatchable capacity that can be called upon when needed, short-duration options will be increasingly supplemented by other strategies. These include coordinated control of distributed energy resources such as rooftop solar, flexible loads like electric vehicles or water heaters that can be cycled and delayed within certain limits, fossil-fuel generators equipped with carbon capture and pilot hydrogen systems, renewable supply-curtailment strategies that favor low-cost or low-carbon industrial processes, and strategic grid-interconnect planning (Fernando Alves et al., 2022).

3. **Life-Cycle Assessment and Sustainability Metrics**

The global expansion of the renewable energy sector makes reliable life-cycle assessment (LCA) necessary to quantify overall environmental reductions. Materials extraction and component manufacture create the largest single LCA impacts for most renewable technologies, with substantial variation based on system specifications and design choices (Ozoemena et al., 2017). To avoid mis-attributing overall sustainability based on the one-time aquatic use of freshwater, relevant metrics must capture the detrimental effects of freshwater consumption, evaporation, and discharge. In building-focused LCA, guidance and software often fail to evaluate the impact of on-site renewable generation and the subsequent export of renewable electricity to the grid—an oversight that can mask significant benefits (Galpin and Moncaster, 2017). Relying on national electricity grids with limited or no realistic carbon intensity estimates creates false certainty about carbon-neutral on-site generation.

Policy, Economics, and Future Directions

The rapid growth of renewable energy technologies over the last two decades has necessitated governmental policies and financial incentives to enable commercialization. Even with the considerable recent cost declines in photovoltaic (PV) and wind systems, which have enhanced market competitiveness, continued policy support remains essential at this stage of technology maturation. Cost studies of various renewable energy technologies identify statistically significant learning curves, which demonstrate the decline in levelized cost of energy (LCOE) with cumulative installed capacity. These studies suggest a continued downward trajectory over the next decade until LCOE levels out, driven by ongoing research, development, and demonstration (RD&D) activities and the search for broader market applications. At this juncture, government policy plays a crucial role in stimulating deployment, accelerating technology advancement, and opening new avenues for commercialization (L. Davies, 2018).

Important policy questions center on the most suitable instruments, complementary market mechanisms, and regulatory practices to promote wide-scale adoption of renewable generation technologies. The nature, duration, and degree of government assistance required ultimately depends on the market structure, electrical-grid features, and risk perception associated with each energy generation technology. Beyond these considerations, specific research needs remain pivotal to advancing the eligible technologies and stimulating widespread commercial deployment.

1. **Cost Reduction and Technology Maturation**

Technological advances and project development experience have driven rapid cost reductions across renewable energy technologies. Publicly available projections reflect expectations of continued declines in capital and operating costs. Modelling indicates that further reductions are essential for investment in renewables to meet emission targets at reasonable levels (E.T. Bistline et al., 2022). Most studies report capacity expansion and energy storage costs across a wide range of scenarios; historical variations often exhibit a capacity-specific learning curve. A simplified learning-curve framework averages costs across subsequently deployed technologies and captures the initial rapid reduction frequently encountered in new energy technologies.

Progress continues at variable rates across the sector. Modelling focused on liberalised markets quantified reductions in capital and other expenditure components for 2018–2030 in reference cases with gradual declines; use of mid-points to represent the centre of the distribution shows projected capacity, operation and maintenance (O&M), and financing costs converge towards reduced averages as the pace of decline slows. Financing costs, particularly for renewables, are now widespread, but true availability of generalised estimates remains limited (Glenk et al., 2021).

2. **Policy Instruments and Market Design**

Renewable energy technologies have made remarkable progress in recent decades, leading to substantial reductions in cost (Di Foggia and Beccarello, 2024). As renewable energy sources have advanced, the importance of appropriately designed policy instruments and market mechanisms has grown commensurately. The power generation landscape is rapidly moving toward a world dominated by distributed intermittent renewable energies—primarily due to climate change mitigation targets to limit global warming to 1.5°C—and therefore it is crucial to understand how to properly implement policy instruments for their deployment. Both technology-related policies and economic policies can accelerate the deployment of distributed renewable energy, yet other instruments support systems integration and network reinforcement. Despite advances in the state of knowledge and technology, regulatory barriers still limit renewable-energy radiation.

3. **Research Gaps and Emerging Frontiers**

Various resources highlight critical issues in current renewable energy systems and suggest potential directions for future work. Emphasis on grid issues indicates the importance of electricity systems in effectively utilizing renewable energy. Future developments are expected to emphasize distributed generation, increased demand-side flexibility, augmented use of conventional generators as virtual running reserves, and the development of energy carriers and storage technologies for vehicle electrification. To navigate, monitor, or secure energy flows in both supply and demand, the establishment of a framework of power system resilience has been proposed as a growing research area. Correspondingly, fuel cells, which can operate with either green hydrogen or commercial fuels for which demand reduction is needed, have been identified as an important class of devices needing additional study (SARKAR and Odyuo, 2019).

Additional concerns include cost trajectories, urban vibes of individual and communal generation, and storage. Long-term projections of sustainable electricity generation costs would benefit from supplementary scrutiny. Among grid-level solar technologies, solar forecasting methods, along with the associated effects of photovoltaic fluctuation, voltage variation, and existing on-vehicle distribution levels, remain critical considerations for renewable integration. Similarly, the feasibility of large-scale photovoltaic penetration in the highly populated Kyushu region of Japan, including the effectiveness of solar panels under overcast weather conditions, constitutes another relevant gap. At the supply-demand interface, optimization models for distributed generation planning continue to seek wider attention. Identification of institutional issues and grid infrastructure, matched with the desire for renewable-energy-driven electric transportation, has also been singled out as a pressing challenge for further investigation.

Conclusion

Various renewable energy technologies have been examined in terms of their physics-based foundations and theoretical performance limits. Energy conversion principles have been established, and boundaries have been defined to assess the current state of various technologies and the most promising avenues for continued progress.

Progress toward a sustainable energy system will ultimately require transformative advances in fossil-free technologies that work compatibly with existing systems. Energy supply and demand remain coupled at the system level, and measures used to suppress one cannot necessarily be used to achieve the same with the other. Continued efforts will be necessary long after there is widespread use of fossil-free technologies.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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