



Review Article about Utilizing Renewable Energy in Medical Equipment

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Annotation: Renewable energy sources such as wind, solar, hydropower, geothermal, and biomass are increasingly used to power medical equipment. The health sector can benefit from renewable energy on economic, health, and environmental grounds. For example, solar energy can ensure reliable, economical, and waste-free hospital power. However, the health sector often fails to take full advantage of renewable energy, highlighting a pressing opportunity to leverage these sources. Demand-side management can optimize hospital energy use, ensuring that critical loads such as surgical theatre lighting, vaccine cold chains, and essential medical equipment receive priority power allocation. Access to electricity is essential for improving economic and social welfare in rural areas. Globally, electrification reached 89% in 2017, up from 83% in 2010, yet almost 840 million people remain without access. The absence of proper medical facilities in rural settings contributes to high maternal mortality, which could be reduced by 70% with improved electrical access. Diesel generators are commonly used as backup power sources, but they are

expensive and generate environmental pollution. Hybrid renewable energy systems incorporating solar, wind, and other resources represent a viable alternative for remote locations. These systems, modelled via comprehensive techno-economic and environmental analyses—often employing HOMER software—highlight the significance of operational costs, renewable fraction, and system optimization. Nonetheless, the power management of hospital loads has attracted limited attention. A grid-independent hybrid renewable energy system combined with demand-side management can satisfy both electrical and thermal hospital loads, offering an optimized configuration that meets healthcare energy requirements effectively.

Keywords: renewable energy, hydropower, geothermal, biomass

1. Introduction to Renewable Energy in Healthcare

Renewable energy is primarily derived from various natural resources that can be continuously replenished, including sunlight, wind, flowing water, geothermal heat, and biomass. The increasing adoption of renewable energy sources in healthcare facilities plays a crucial role in addressing significant concerns about excess heat generation and carbon emissions that are typically associated with the use of fossil fuels. It is essential to recognize that many components of medical equipment require regulated heating temperatures to function optimally. As current energy sources heavily rely on fossil fuels, this raises critical concerns about climate change, air pollution, and economic sustainability on a global scale. Renewable energy sources, which are recognized as the fastest-growing segment of energy production, have the potential to satisfy a substantial portion of future global energy demand. Thus, utilizing renewable energy for powering medical equipment and other healthcare necessities becomes an increasingly important subject for ongoing research and development within the field. [1][2]

2. Types of Renewable Energy Sources

Energy is undeniably one of the most crucial factors for survival, progress, and overall development in modern society. However, the ongoing and increasing reliance on fossil fuels is projected to accelerate the rate of global warming in the future, leading to dire environmental consequences. The steep growth in global energy demand over recent years has revived significant interest in alternative energy technologies and solutions. Recently, the manufacturing and utilization of renewable energy sources have emerged as paramount to effectively power a country and achieve sustainability. Renewable energy encompasses energy that is generated using abundant natural sources, such as sunlight, wind, and water, without causing any harmful disturbances to the existing natural resources. This form of energy can be consistently obtained without any significant financial constraints because it fundamentally depends on the environment and the earth's natural cycles. These renewable energy resources are not only inexhaustible but also less polluting, making them an environmentally friendly option, and they

tend to be more economically viable compared to conventional sources. This renewable and affordable energy resource is gaining increasing public support, particularly solar energy, which is recognized as the most persistent and reliable source of energy available on Earth. [3][4]

2.1. Solar Energy

Solar energy is fundamentally defined as the radiant light and heat emitted by the sun, which can be harnessed and applied in a variety of diverse applications. Among these applications, electricity generation, water heating, and heating and cooling for buildings stand out as particularly noteworthy. The reason for its domestic pre-eminence among all renewable energy sources largely stems from its technological maturity, alongside its incredibly high availability. Solar energy is not only utilized for these practical applications; it also readily powers essential medical equipment, including devices like X-ray machines and ultraviolet sterilizers, which are crucial in healthcare settings. However, the expansive land footprint required for solar farming might pose significant challenges that could curtail future electricity production, and this potential limitation may ultimately constrain the availability of solar energy. To address these challenges effectively, large-scale photovoltaic projects, including groundbreaking initiatives such as the Desertec initiative and the innovative Solar Updraft Tower concept, demonstrate practical and promising ways to mitigate these issues and enhance the sustainability of solar energy harvesting. [1]

2.2. Wind Energy

Wind energy, or wind power, derives from the wind—air in motion relative to the surface of the Earth. The motion of air implies stored energy, called kinetic energy. When the wind moves over a propeller blade, this kinetic energy is converted to rotary mechanical energy of the shaft. The shaft is connected to a generator; the generator converts the mechanical energy to electrical energy. The strength of the wind and the area we use determine the power generated in a turbine. The kinetic energy of the wind is calculated as $E = \frac{1}{2} m v^2$; m = mass of air, v = velocity; the power is calculated as $P = E/t = \frac{1}{2} \rho A v^3$, where P = power (watts), ρ = air density (kg/m^3), A = the area swept by wind turbine (m^2), v = wind speed (m/s).

The advantages of wind energy are that it is cheaper than conventional power, requires no processing of waste, is cost-effective, has no polluting and emission effect, and can be set up at any location where energy is needed for hospital operation in remote areas.

2.3. Hydropower

Hydropower energy is generated by the flow of water. It represents one of the earliest sources that humanity has exploited to create mechanical and electrical energy. One of the most ancient methods of energy conversion and usage involved harnessing water mills to drive mechanical machinery such as grinding mills, presses, and saws.

Hydropower harnesses the natural energy of rivers and water reservoirs, enabling hydropower plants to effectively generate electricity. This electricity is crucial as it powers essential medical equipment as well as provides illumination in rural and isolated medical centers, ensuring that healthcare services remain operational. Due to the consistent flow of water, medical clinics and local villagers alike can rely on a dependable and renewable energy source. This energy not only supports vital medical needs but also does so in a manner that produces absolutely no pollution, contributing positively to the environment and enhancing the quality of life in these communities. [5]

2.4. Geothermal Energy

According to recent studies, deep geothermal systems comprise a variety of methods that include techniques such as fluid extraction and reinjection in formations that possess high permeability. Furthermore, these systems create or take advantage of fluid and rock permeability through stimulation processes, as well as thermally enhanced formations that do not require any fluid

flow whatsoever to function effectively. However, it has been found that stand-alone systems designed for downhole power generation in boreholes that extend below 10,000 feet are quite limited. On the other hand, the use of electric submersible pump motors for artificial lift remains the most prevalent application for downhole power in the industry today. In the oil sector, shallow geothermal systems located far below the 5,000-foot mark are frequently recognized as the primary source of energy. In addition, thermoelectric technology presents an innovative approach for extracting electricity from geothermal resources; potential improvements to this technology could arise from the development of high-performance thermoelectric materials specifically designed to utilize nanofluids as the cold side fluid. One innovative approach proposes a sustainable single-well solution that is based on the concept of thermally-enhanced Bottom Hole Elements (BHEs). This aims to effectively overcome the limitations associated with lower entropy, shallower geothermal resources, while simultaneously mitigating risks that are related to reservoir stimulation processes. Moreover, it is noted that the final cost associated with thermoelectric generation is influenced by both the materials used and the thermoelements involved in the process. Additionally, several patents have been documented that enhance the BHE principle by increasing the surface contact area and incorporating various materials that improve heat transfer efficiency. Nevertheless, it is important to note that these proposed solutions still lack comprehensive investigations into their thermal sustainability over extended periods of use. [6][7]

2.5. Biomass Energy

Biomass energy harnesses the chemical energy stored in biological materials, such as plants, trees, and animal waste, which renews over relatively short timescales. Unlike fossil fuels, biomass resources can be replenished within a human lifespan and, therefore, constitute a renewable source of energy. Biomass energy can be converted into various useful forms, including heat, electricity, and transport fuels. In the medical sector, biomass energy offers the potential to power equipment for hygiene, sterilization, heat, cold, and electricity supply [8] [2].

3. Importance of Renewable Energy in Medical Equipment

Good health is one of the most important goals of human beings because it has great influence on people's performance throughout life. If the health condition of an individual is well, he/she can accomplish all tasks, work, or anything. Medical equipment machines that are used in hospitals or clinics require energy to operate. Medical equipment with renewable energy can make better health and improve the economic situation. Renewable energy deserves more attention because it offers numerous environmental benefits, such as reducing pollution and greenhouse gas emissions, as well as health benefits related to pollution reductions achieved by increasing the use of renewable energy. Therefore, it is important to use renewable energy in medical equipment [1].

4. Case Studies of Renewable Energy in Medical Settings

Numerous instances demonstrate successful renewable energy implementations within medical settings. Solar-powered medical devices are increasingly employed in developing regions where reliable grid electricity is unavailable, ensuring uninterrupted operation of equipment crucial for patient care [1]. Hospitals have also adopted wind energy to supplement conventional power sources, providing a sustainable and cost-effective solution to meet their extensive electricity demands [2]. Hydropower constitutes a significant energy source for rural clinics, particularly in isolated areas disconnected from national grids, supporting essential healthcare operations with minimal environmental impact [9].

4.1. Solar-Powered Medical Devices

Solar-powered medical devices can supply hospitals and communities with medical power and equipment when grid-connected power is costly, unavailable, or unreliable. Inadequate power uses fossil fuel generators, increasing operation and maintenance costs; when solar powered

there is sunshine on fuel that can be used freely. Yet solar solutions are seldom adopted by the health sector because the energy needs of healthcare facilities are still poorly understood, which often results in the installation of ill-adapted systems.

The primary priority of a healthcare facility in terms of electricity usage should be critical loads, which include lighting in surgical theatres, cold chains for vaccines and medications, and essential medical equipment such as oxygen concentrators and ventilators. Solar energy is capable of supplying reliable, economical and waste-free power to isolate rural locations without electricity or to support grid-connected hospitals that suffer frequent outages [1].

In India, UNICEF's 'Solar for Healthcare' project installed solar electricity systems at 295 Primary Health Centers, over 350 Sub-Centers, and 120 Community Health Centers, and designed a Solar Power Based Cold Chain Solution at 10 Primary Health Centres, thereby strengthening the health infrastructure and improving overall healthcare delivery. During the COVID-19 pandemic lockdown, a rural tertiary hospital in India managed to maintain its health services uninterrupted by relying on a 10 kWp solar photovoltaic system. In Liberia, electricity access to health facilities increased from 54% in 2011 to 62% in 2012 due to an influx of solar power systems and improvements of grid connections. Solar PV systems for primary health care typically range from 1.5 kW to 20 kW, with larger systems deployed in grid-connected healthcare facilities.

4.2. Wind Energy for Hospital Operations

Wind energy—utilizing the movement of air to generate power—is harnessed through turbines that convert kinetic energy into mechanical energy, which drives electrical generators. Wind turbines are adaptable in size and design, enabling varied energy outputs from small-scale installations to large wind farms. This form of renewable energy is well-suited to hospitals, where it can efficiently supply electricity to medical devices, supporting continuous healthcare operations and reducing reliance on non-renewable sources [10].

4.3. Hydropower in Rural Clinics

Hydropower is the kinetic energy of moving water, which can be converted into mechanical energy or electrical energy for human use. Water flow through a hydraulic turbine drives a generator and produces electricity. It has been used to power thermal devices in the northern mountainous areas of Vietnam [11]. Local portable solar generator sets are available to provide lighting and heat for rural clinics; with low water levels, wind turbines can supplement an off-grid solar–hydropower system. Hydropower is significant for rural and mountainous areas with limited access to public electric grids; hydropower and solar energy combined are inexpensive, reliable, and environmentally friendly.

5. Challenges in Implementing Renewable Energy Solutions

Renewable energy sources represent a highly sustainable and inexhaustible alternative to traditional fossil fuels that have dominated the energy landscape for decades. Over the course of recent years, the widespread adoption of renewable power has transformed into a critical societal goal and objective, one that is vital for environmentally conscious development. However, the full integration of electricity generated from renewable sources into various applications—including essential medical equipment—has not yet been completely realized to its full potential. Several primary challenges hinder this process, including the additional costs that often arise when renewable energy serves to supplement or replace existing grid power. Furthermore, the complexities in maintenance that come with renewable energy systems can at times exceed the capabilities of many organizations, making implementation more daunting. Additionally, there are regulatory barriers that comprise strict laws and guidelines governing both electrical and medical devices, which complicate the path toward widespread acceptance and use. To effectively address these pressing issues, various proposed designs for renewable-energy equipment emphasize on-site, dedicated power generation systems. Such solutions eliminate

initial investment concerns by ensuring that the energy produced is used directly on-site, reducing waste and maximizing efficiency. This approach directs all generated power toward the specific device in question, which ultimately facilitates a scenario of near-zero net energy consumption. By doing so, it aims to overcome several obstacles that have previously been linked to applications of renewable energy and their broader integration into various sectors. [2]

5.1. Initial Cost and Investment

The implementation of renewable energy systems encounters significant economic hurdles that affect their widespread adoption in medical contexts.

For developing small-scale applications, the heavy initial investment in equipment emerges as the principal barrier [12]. Procurement costs alone represent a large share of the necessary expenditure. To recoup these upfront expenses, ample operational time is required, extending the payback period and exacerbating the financial challenge. Beyond acquisition, establishing robust maintenance capabilities consumes additional resources, yet is equally essential for system sustainability. Contemporary solutions that encourage comprehensive spending evaluations during tender processes can readily solve these procurement difficulties through clear upfront cost identification.

However, running expenses further intensify the problematic financial landscape. Capturing these outlays in a consistent and exhaustive manner remains a nontrivial task, preventing straightforward comparisons between alternative renewable energy options and even hindering informed budget planning. Employing self-learning predictive models that consider historical expenditure trends presents a viable approach to achieving accurate and dynamic cost forecasting.

Thus, whether in developing or developed regions, initial capital requirements and ongoing operational costs stand as major impediments to renewable energy projects. Large investments are requisite not only for system acquisition but also for training personnel dedicated to routine maintenance and upkeep. Overcoming such substantial economic commitments is necessary to expand sustainable energy use in healthcare environments.

5.2. Maintenance and Technical Expertise

Medical equipment is often placed in difficult-to-access locations, and spare parts and components can be challenging to replace when repairs are needed. Effective management, maintenance, and conservation programs, combined with cost-effective procurement strategies, are essential for sustainability but leave opportunities for improvement. Lack of appropriate maintenance techniques and associated costs frequently leads to premature equipment failures. The shortage of qualified technical personnel further hampers maintenance efforts. Several projects have proposed design guidelines and remedies to increase the longevity and reliability of medical equipment in under-resourced environments. Research into power generation architectures has demonstrated the benefits of renewable energy. For example, the implementation of a 3-phase grid-connected solar power system at Mulanje Mission Hospital demonstrated that solar investments can ensure reliable electricity, extend equipment lifespan, and reduce costs, yielding a good return on investment [9]. A stand-alone hybrid renewable energy system was found to provide the most efficient, reliable, and clean power supply for rural healthcare facilities without grid access in Bangladesh, thereby supporting uninterrupted power for medical equipment [2]. Sustainable support of renewable energy-powered medical systems requires access to local maintenance expertise and a steady supply of parts, as shortages in these areas cause well-functioning equipment to become incapacitated [13].

5.3. Regulatory and Compliance Issues

Regulatory and compliance issues form a significant barrier in the transition from traditional to renewable energy for powering medical equipment. The assured quality of medical devices

depends on platform quality; once established, design approaches can evolve independently across regions and time frames. International standards reduce many technology regulatory issues. Despite leaps in device miniaturization, integrating on-chip power generation represents a new set of challenges for technology transfer and regulatory authorities. Wind, solar, and other renewables pose significant, although not insurmountable, obstacles as shown by existing standards and guidelines [14].

6. Innovative Technologies in Renewable Energy for Healthcare

Renewable energy technologies have made significant progress over the last decade and many new ideas have emerged for the replacement of conventional energy. Energy requirements, environmental concerns and financial factors have motivated the efforts to install renewable energies as alternatives to conventional fossil fuels and also as potential options for sustainable growth in developing countries. The world's population is growing rapidly, with its corresponding increase in demand for main resources such as food, water, energy and health. The area of health receives a lot of attention from all nations. Modern medical and scientific equipment in the health sector requires a constant and very reliable source of energy to function efficiently and continuously. Many remote and rural areas especially in developing countries remote and rural areas do not have access to the grid and the overall expansion of the centralized grid structure is difficult, and the cost tends to be uneconomic in these locations. Solar, wind and biogas are examples of renewable energy which can be used for medical equipment in hospitals and health bases.

6.1. Energy Storage Solutions

Ensuring reliable and uninterrupted power supply remains a critical requirement in medical services. Energy-storage devices play an elementary role in guaranteeing that medical equipment, such as oxygen machines, ventilators, and masks, never face power outages. Noteworthy technologies accommodate this need by storing surplus renewable power and converting it to usable electricity during demand surges or grid outages. Storage solutions encompass lithium-ion and nickel-cadmium batteries, pumped-storage hydroelectricity, thermal storage, compressed air energy storage, flywheel compounds, and double-layer capacitors [15]. Batteries serve as the primary storage option charged by electrical grids or an array of renewable sources. For example, a hybrid inverter system incorporates solar photovoltaic panels, batteries, and a control mechanism to facilitate energy production, storage, and management [16]. Lately, battery-electric vehicles have emerged as valuable mobile storage systems, further expanding the spectrum of accessible solutions. Ancillary technologies include smart grids and energy-monitoring systems capable of tightening energy security and constantly monitoring power flow across systems. Implementing smart-networked grids may optimize energy use, minimize healthcare facilities' foot-print, and encourage prolonged green-life service. An alternative solution entails the deployment of portable medical-device systems that are compact, lightweight, and unobtrusive for off-grid applications.

6.2. Smart Grids and Energy Management

While renewable energy is environmentally beneficial, it has operational drawbacks that must be addressed for widespread adoption in healthcare. Concentrated solar power and photovoltaic devices are weather-dependent and can be unreliable in certain locations. Geothermal systems require significant structural modifications. Large biomass systems produce emissions, though small plants are cleaner. These challenges can be mitigated through innovative technologies. Energy storage solutions enable continuous power supply, even without active generation. Smart grids integrate renewable sources, manage consumption, and improve overall grid resilience. Portable renewable energy devices provide flexible power options for medical equipment in diverse settings [17] [18].

6.3. Portable Renewable Energy Devices

Portable renewable energy devices play a pivotal role in powering medicine and healthcare, particularly in out-of-hospital settings and remote or undeveloped areas [2]. Examples include portable solar ovens that sterilize environments, sterilize medical equipment, heat substances, and pasteurize beverages or food. Solar immature glass and thermally insulated solar boxes are also designed to sterilize medical equipment. Empowered by improved portable medical units and reliable home medical equipment, the use of portable devices for meeting the demands of modern emergency medical services is increasing [19].

7. Environmental Impact of Renewable Energy in Healthcare

Hospitals account for approximately 4.4% of the global carbon footprint, with scientists warning that the healthcare industry risks becoming a major contributor to climate change. To counter these environmental impacts, new strategies aim to reduce the carbon footprint of hospital construction and operation. Some innovative approaches include energy-efficient operating rooms, reuse of single-use devices, prevention of overdiagnosis, and better waste management. For example, energy-efficient practices in operating rooms can save US\$25,000 annually per room, and optimizing waste streams and recycling efforts can yield substantial cost reductions [20]. In 2020, the National Health Service (NHS) estimated that decarbonization investments would eventually save £650 million annually, with individual facilities reducing costs by hundreds of thousands of pounds through the adoption of LED lighting and solar power. Similarly, a Spanish study revealed potential energy savings ranging from €25 to €55 per square meter in healthcare buildings. Employing thermal energy storage in combination with heat pumps can lower primary energy consumption by up to 71%, while managing occupant-driven lighting usage deviations offers potential savings of nearly 50%. However, the development of green hospitals faces barriers including system redundancy, regulatory compliance, extended operational hours, infection control requirements, ventilation standards, and accreditation criteria.

7.1. Reduction of Carbon Footprint

Renewable energy plays a crucial role in significantly reducing carbon emissions and minimizing environmental footprints within the healthcare sector. By adopting these sustainable energy sources, hospitals and medical facilities can effectively limit hazardous waste generation and greatly diminish both air and water pollution, fostering a healthier environment for both patients and communities. In addition, carbon offsets can effectively counterbalance any remaining emissions, leading to a notable decrease in the overall carbon footprint associated with medical supply chains. Furthermore, the implementation of sub-metering in healthcare settings is essential, as it influences energy efficiency investments and enhances the overall efficacy of energy systems implemented in these facilities. The presence of large medical equipment often leads to increased energy consumption, a necessary trade-off made to adequately meet clinical needs and provide essential care. It is also important to acknowledge that medical supplies contribute significantly to hazardous healthcare waste, primarily arising from packaging materials and the disposal processes employed. By focusing on green medical waste strategies, healthcare providers can efficiently reduce environmental pollution, thereby avoiding a range of adverse health effects that could impact both staff and patients. [21][22][23]

7.2. Sustainable Resource Management

Sustainable resource management is a significant aspect of environmental sustainability, as it involves controlling the use of resources to ensure their availability for future generations. Insufficient supply of resources can lead to conflicts, poverty, and severe damage to the biosphere. Water resource management is critical due to increasing water demands and decreasing supply. Solutions for sustainable resource management include increased water productivity, water demand management, improved water supply infrastructure, full-cost pricing

of water, decentralized decision-making, designing for development, reducing exports of water-intensive products, damming smaller rivers, and enhanced recycling.

Identified barriers to resource management in Australia comprise economic and social priorities, lack of integration, enforcement problems, economic constraints, ineffective participation, political factors, limited resources and capacity, lacking knowledge and awareness, and establishment problems. Implementing integrated water resource management (IWRM) can help overcome these challenges, although effective implementation remains difficult. The global wine industry also faces a sustainability dilemma due to limited natural resources and niche requirements. Sustainable viticulture emphasizes efficient resource use, elimination of pollution, and enhancement of biodiversity. [2] [13] [22]

8. Future Trends in Renewable Energy for Medical Equipment

The ongoing proliferation of renewable energy sources ushers in a constellation of promising prospects for the future of medical equipment and the attendant healthcare ecosystem. The established reliance on conventional and decidedly finite energy depots inevitably gives way before inexorable trends advancing ever-decreasing costs of photovoltaic (PV) panels accompanied by increasingly efficient energy conversion and storage [1]. Augmented by the advent of novel materials such as perovskite–silicon crystalline silicon tandem solar cells, substantial impetus is thus imparted to a broadening adoption curve for solar-powered medical devices.

Concomitant declines in energy demand, achieved through the application of power electronics and energy management techniques, ensure a further alleviation of energy consumption levels and serve to decrease nominal sizes of requisite PV modules. Such reductions translate unequivocally into more manageable dimensions for devices of clinical pertinence, thereby widening the circle of possible employment scenarios. The ongoing transition from fossil- to plant-based feedstocks further mitigates the environmental footprint of future biomedical apparatus, supporting concomitant adherence to sustainability objectives on the part of manufacturers. Considerations of economic consequence equally underscore the growing utility of renewable energy system (RES) operation, as variability in the price of electricity and volatile oil markets generate an increasingly wide gap in cost between conventional systems and their renewable counterparts.

Cognizance of the evolving landscape dictates recognition of a concomitant focus on additional facets of medical equipment performance outside of its mere power source. The gradual transition from stationary to mobile healthcare thus motivates the exploitation of remotely managed and autonomous technologies, augmented by telemedicine and immersive applications—a true synergy again established by the presence of reliable green power. Even within health-sector configurations residing well within the reach of the power grid, active facility demands nevertheless highlight the importance of continued innovation and the adoption of renewable paradigms as principal instruments for broadening the scope of currently achievable objectives.

8.1. Advancements in Energy Efficiency

Medical equipment plays a critical role in modern healthcare systems, and it is of utmost importance to power these systems using renewable energy [1]. Subsequently, many efforts are underway to increase the energy efficiency of such systems [24]. These advancements may have a significant impact on healthcare provision in remote locations where power is often unavailable or unstable. Major progress is expected in the near future within the framework of the in-development Standards and Metrology Institute for Islamic Countries (SMIIC) Energy Efficiency Framework [22].

8.2. Integration with Telemedicine

Remote healthcare has benefited from rapid advancements in network infrastructure and sensing technologies, facilitating telemedicine applications such as remote consultation, monitoring, diagnosis, and surgical guidance. Telemedicine systems often incorporate wearable sensors and embedded devices to collect patient information and generate relevant messages, enabling efficient healthcare delivery in remote or underserved areas [1].

Effective remote monitoring, wireless data transmission, and Internet-of-Things (IoT) communication require diverse diagnostics, rapid data processing, and continuous energy supply. Renewables have become an integral part of telemedicine infrastructure, supplying energy for remote healthcare applications, where they provide reliable power, regulate data sensing, monitoring, and processing, and check critical parameters.

Advances in energy conversion, storage, and supply, combined with smart grids and distributed energy systems, help to power telemedicine infrastructure, thereby reducing the cost of energy and minimizing greenhouse-gas emissions [2] [11].

8.3. Global Adoption and Policy Changes

Regulatory alteration related to renewable energy aims to promote sustainable energy adoption through standards, incentives, and policies. Global renewables capacity is expected to rise 50% by 2027 compared to 2022. Cleaner energy sources have flourished during the COVID-19 crisis, and the share of fossil fuels in the primary energy mix has declined. The United States is projecting a doubling of renewable electricity capacity over the next decade, making renewable energy the fastest growing rural power generation source.

Recent Straits Times coverage shows Thailand's government enhancing incentives for investments in solar, wind, and hydropower, with further measures expected to be finalized in 2024. Surging Russian gas prices are stimulating a diesel-to-PV-plus-storage energy shift in Ukraine. Solar power constitutes around 7% of U.S. electricity generation, while coal, natural gas, and nuclear remain the dominant sources. Direct CO₂ emissions by passenger vehicles in the United States have been decreasing yearly from 2007 to 2021, mainly due to electric vehicle adoption and increased fuel efficiency.

Globally, renewables ranks second after natural gas, comprising 45% of total installed generating capacity at the close of 2023. PV panels are expected to supply more power than any other technology in China, the United States, and the European Union by 2025. The China Photovoltaic Industry Association projects that solar energy will dominate China's power system in the mid-2030s. Rooftop solar PV adoption in the United Kingdom is forecasted to continue, owing to electrotechnical codes of practice, reduced equipment costs, and PV efficiency improvements. In Africa, investment trends in solar energy could shape the continent into a global production hub with positive outlooks for photovoltaic and photovoltaic-thermal applications. Integration of energy storage systems supports some renewables' intermittent fluctuations [1].

9. Conclusion

Renewable energy, derived from resources naturally replenishing on a human timescale, offers substantial advantages for medical equipment. The hospital environment benefits significantly from integrating renewable sources due to cost savings, environmental protection, and health improvements. Implementing renewable power systems has effectively supported critical applications, including dialysis machines, surgical lights, and patient monitors. Solar photovoltaic, wind, hydro, geothermal, and biomass energy systems have demonstrated potential for cost-effective, reliable electricity supply that reduces greenhouse gas emissions and reliance on fossil fuels.

Despite the numerous benefits, several challenges persist. High initial investment costs, complex

maintenance requirements, and uncertainty surrounding policies and regulations can impede widespread adoption. Nevertheless, advances in energy storage, smart grid technologies, and portable device design address many of these barriers. Hybrid renewable systems equipped with appropriate conservation strategies can enhance affordability, reliability, and sustain continuous operation of life-support devices.

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