

Environmental Sustainability through Renewable Energy Integration

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ABSTRACT—This work provides a comprehensive review of the integration of renewable energy into the infrastructure of smart cities. With the increasing concerns over climate change, green house effect and the depletion of fossil fuel reserves globally, there has been a growing interest in transitioning towards sustainable and renewable sources of energy. This work explores case studies of some of the latest technological developments in the use of solar, wind, hydroelectric, geothermal, and biomass sources of energy in advancing sustainability, resilience, and livability in smart cities, from Copenhagen's ambitious climate plan to various renewable energy initiatives worldwide, including those focused on economic, social, and environmental implications such as reductions in greenhouse gas emissions, enhanced energy security, job creation, and improved public health outcomes. Despite significant progress, challenges such as intermittency, grid integration, storage limitations, and resource constraints persist, highlighting the need for continued research and innovation in this field. Through an interdisciplinary approach, this paper aims to contribute to the understanding of the power of renewable resources and their role in achieving a sustainable energy future in smart cities globally.

Keywords— Renewable energy, Technology, Solar, Smart cities Wind, Hydroelectric, Biomass, Geothermal.

I. INTRODUCTION

In recent decades, the global energy source has undergone a whole new direction as a result of the increase in environmental concerns, geopolitical tensions, and technological advancements.

Fossil fuels that have long served as the primary source of energy, are being reviewed because of its waste disposal problems, safety

concerns and the limited supply of these fuels on Earth. With the everyday need for these fossil fuels to heat and power our homes, fuel our cars and solve our other energy needs, they are being used more rapidly than they are being created and gradually they will run out. In the meantime, the world's energy needs are growing day by day and in response to this growth, we can agree that there is an urgent need for the world to transition towards a cleaner, sustainable and renewable source of energy.

The integration of renewable energy into smart city infrastructure offers a multitude of benefits, ranging from environmental sustainability to economic prosperity. By making use of energy sources that are continually replenished by nature — the sun, the wind, water, organic waste, the Earth's heat, and plants, these smart cities have a sustainable alternative to fossil fuels for meeting their growing energy demand. Renewable energy technologies turn these fuels into usable forms of energy — most often electricity, but also heat, chemicals, or mechanical power and unlike fossil fuels, these renewable energy sources are abundant, widely distributed, and emit minimal greenhouse gas emissions during operation. [1].

In addition to environmental benefits, renewable energy integration in smart cities can also drive economic growth and innovation. Advancements in renewable energy technologies, coupled with declining costs and increasing efficiency, have made renewable energy increasingly innovative. Solar photovoltaic (PV) and wind power, in particular, have experienced rapid growth in deployment and cost reductions, becoming the main energy sources in many cities worldwide [2] [3].

By investing in renewable energy infrastructure, these cities can also attract investment, promote technological innovation, and simplify the lives of the individuals. In [4],

Reykjavik relied heavily on renewable energy sources, particularly geothermal and hydroelectric power. The city's abundant geothermal resources provide heating and electricity to its residents, making it one of the greenest cities in the world. Barcelona in [5] integrated renewable energy into its urban infrastructure through ways such as solar power installations, green building projects, and sustainable mobility programs.

Despite the clear advantages of renewable energy integration, significant challenges remain on the path to achieving widespread adoption in smart cities. Some of these challenges include the intermittency of renewable energy sources, the need for efficient energy storage solutions, and the complexities of integrating renewable energy into existing grid systems. Addressing these challenges requires collaboration among the government policymakers, urban planners, industry stakeholders, and communities to develop strategies that optimize energy production, distribution, and consumption in urban environments. All technical, economic, regulatory, and societal barriers must be addressed to realize the full potential of renewable energy deployment.

Renewable energy represents a pathway towards a sustainable energy future and this paper aims to provide a comprehensive overview of the relationship between renewable energy integration and smart cities, examining the opportunities, challenges, technologies, policies, and case studies that shape this dynamic connection.

II. RENEWABLE ENERGY SOURCES AND TECHNOLOGIES IN SMART CITIES

Renewable energy sources are natural energy resources that can be regenerated naturally such as sunlight, wind, water, biomass, geothermal heat, etc. These resources provide sustainable alternatives to fossil fuels and they have very little impact on the environment compared to fossil fuels [6]. The various methods these renewable energy sources use in the provision of renewable energy is known as renewable energy technology. Some of these technologies include the solar photovoltaic systems, wind turbines, biomass energy facilities, geothermal power stations and so many others [6]. These renewable energy sources and their technologies offer a wide range of solutions to meet global energy needs.

A . Solar Energy

Solar energy, derived from the sun's radiation, is abundant and crucial for the energy transition. It encompasses photovoltaic (PV) solar

and concentrating solar power (CSP) technologies. PV technology directly converts sunlight into electricity using semiconductor materials like silicon in solar panels, applicable from residential rooftops to expansive solar farms [7] [8]. CSP technology concentrates sunlight using mirrors or lenses onto a small area, generating heat for steam turbines, with configurations like parabolic troughs, power towers, and dish/engine systems [7]. Masdar City in Abu Dhabi integrates solar infrastructure like rooftop panels and solar-powered streetlights, with energy-efficient building features for reduced consumption [9]. Songdo International Business District, in Incheon, South Korea, incorporates solar panels on rooftops and facades, along with solar-powered street lighting and benches providing Wi-Fi and charging stations [10]. Copenhagen, Denmark, showcases solar projects on public buildings and streets, including solar heating systems. The Amager Resource Center (ARC) waste-to-energy plant features a ski slope with solar panels, exemplifying renewable energy integration [11].

B . Wind Energy

Wind energy, derived from the kinetic energy of moving air, has emerged as a leading renewable electricity source, with global installed capacity skyrocketing from 4.8 MW in 1995 to nearly 700 GW in 2024 [12]. Wind turbines, varying from small residential units to large-scale installations, utilize aerodynamic principles to convert wind energy into mechanical power, then into electricity through generators. Offshore wind farms, located in coastal or offshore waters, offer substantial potential due to higher wind speeds and less visual impact [12] [13]. Hamburg, Germany, a leader in wind power, has established numerous wind farms both onshore and offshore, like the Sandbank and Nordsee Ost wind farms, bolstering energy security [14]. Portland, Oregon, renowned for its green initiatives, prioritizes wind energy, erecting turbines in urban and rural areas and procuring wind power through agreements with local farms and businesses [15]. Copenhagen, Denmark, a proponent of renewable energy, invests in onshore and offshore wind farms, exemplified by the Middelgrunden Wind Farm. Wind energy also powers district heating systems, advancing environmentally friendly heating solutions [11].

C . Hydroelectric Energy

Hydroelectric power, tapping into the energy of flowing water, stands as one of the oldest and most prevalent renewable energy sources. Hydroelectric plants encompass various types,

including conventional dams, pumped storage facilities, and run-of-river systems. Conventional dams, like gravity and arch dams, store water in reservoirs, releasing it through turbines for electricity generation. Pumped storage facilities utilize surplus electricity to pump water between reservoirs for energy storage and release. Run-of-river systems generate electricity without altering natural river flow [17].

The world's largest hydroelectric plant, the Itaipu Dam on the Paraná River, jointly developed by Brazil and Paraguay, initially had a capacity of 12.6 GW in 1984, now increased to about 14 GW [16] [17]. Salzburg, Austria, known for its scenic landscapes, leverages hydroelectric energy from the Alps' rivers, like the Salzach and Saalach, using pumped storage plants such as the Kaprun Power Plant to enhance grid stability by storing excess energy [18]. Bergen, Norway, capitalizes on its abundant water resources, including fjords and rivers, to generate hydroelectric power. Utilizing local rivers like the Svartediket and Oselva, Bergen meets a significant portion of its electricity demand [19].

D. Geothermal Energy

Geothermal energy is a type of thermal energy that uses heat from the Earth's interior for electricity. Geothermal energy has a major advantage compared to wind and solar energy in that it is available 24 hours a day through the year [16].

Geothermal energy is derived from the natural heat coming from the Earth's core, which manifests in various forms such as volcanic activity, geysers, and hot springs. Hydrothermal systems, characterized by circulating hot water or steam reservoirs in permeable rock formations, are the most common and commercially viable type of geothermal resource.

Enhanced geothermal systems (EGS) utilize hydraulic fracturing techniques to stimulate heat extraction from deep, low-permeability reservoirs, expanding the geographical scope of geothermal energy development [20]. Geothermal power plants utilize steam or hot water from underground reservoirs to drive turbines and generate electricity. Different types of geothermal power plants, including dry steam, flash steam, and binary cycle plants, are deployed based on the characteristics of the resource and technological considerations. Geothermal heat pumps, on the other hand, transfer heat from the ground to buildings for space heating, water heating, and air conditioning, offering energy-efficient and

environmentally friendly heating and cooling solutions [20].

Rotorua, located in the North Island of New Zealand, is known for its abundant geothermal resources and Maori cultural heritage. Rotorua utilizes geothermal energy for district heating, tourism attractions (such as geothermal spas), and electricity generation through geothermal power plants. The Te Mihi Power Station is a significant geothermal facility in Rotorua, producing electricity from geothermal steam and providing heat to the local district heating network [21].

E. Biomass Energy

Biomass energy is the energy derived from organic materials such as plants, agricultural residues, and waste. After hydropower, biomass is the world's second-leading resource of renewable energy. Power generating companies with coal power plants have found that replacing some coal with biomass is a low-cost option to reduce undesirable emissions. As much as 15 percent of the coal may be replaced with biomass. Biomass has less sulphur than coal. Therefore, less sulphur dioxide is released into the air. A process called gasification, - the conversion of biomass into gas, which is burned in a gas turbine - is another way to generate electricity [16] [23].

Biofuels, such as ethanol and biodiesel, are produced through the fermentation or chemical conversion of biomass feedstock, while biogas is generated through anaerobic digestion of organic matter. Biomass power plants utilize combustion, gasification, or pyrolysis processes to convert biomass into heat and electricity, providing power to the grid [23] [24].

Stockholm, the capital city of Sweden, has implemented innovative biomass energy projects as part of its commitment to renewable energy. Stockholm utilizes biomass energy derived from organic waste, forestry residues, and agricultural by-products for district heating, combined heat and power (CHP) plants, and biofuel production. The Värtaverket plant is one of Europe's largest biomass-fired CHP plants, producing heat and electricity for Stockholm's district heating network while reducing greenhouse gas emissions [25].

Eugene, located in the Pacific Northwest of the United States, has embraced biomass energy as a renewable resource to meet its energy needs. Eugene utilizes biomass energy from wood waste, forestry residues, and agricultural biomass for district heating, bioenergy production, and renewable fuel blending. The Eugene Water & Electric Board (EWEB) operates a biomass cogeneration facility that generates electricity and

steam from wood waste, providing renewable energy for Eugene's utility customers [26].

Graz, the second-largest city in Austria, has embraced biomass energy as a sustainable alternative to fossil fuels. Graz utilizes biomass energy from wood chips, agricultural residues, and biogas for district heating, decentralized heating systems, and bioenergy production. The Fernwärme Graz biomass plant is a key component of the city's district heating network, providing heat to residential, commercial, and industrial buildings while promoting local biomass utilization [27].

III. THE ECONOMIC, SOCIAL, AND ENVIRONMENTAL IMPLICATIONS OF RENEWABLE ENERGY

The adoption of renewable energy sources brings about a multitude of economic, social, and environmental implications that shape the transition towards sustainable energy systems in smart cities.

Renewable energy adoption stimulates economic growth through job creation, investment opportunities, and technological innovation. The renewable energy sector offers employment across a wide range of fields, including manufacturing, installation, maintenance, and research and development. Also, investments in renewable energy projects spur economic development in local communities, driving infrastructure development, attracting investment, and fostering entrepreneurship for members of the world [16] [28].

Socially, renewable energy adoption promotes energy access and equity by providing clean and affordable energy solutions to underserved communities. Off-grid renewable energy systems, such as solar home systems and mini-grids, offer a reliable source of electricity to rural and remote areas, improving livelihoods, health outcomes, and educational opportunities [16] [29].

Environmental benefits of renewable energy adoption include mitigating greenhouse gas emissions, reducing air and water pollution, and conserving natural resources. By displacing fossil fuel-based electricity generation, renewable energy helps combat climate change and mitigate its adverse impacts on ecosystems, biodiversity, and human health [16] [29].

Policy frameworks play a critical role in shaping the economic, social, and environmental implications of renewable energy adoption. Governments can incentivize renewable energy deployment through feed-in tariffs, tax incentives, renewable portfolio standards, and public procurement programs. Additionally, regulatory mechanisms such as environmental regulations can

internalize the external costs of fossil fuel use and promote renewable energy [16].

CONCLUSION

The utilization of renewable energy sources offers multifaceted solutions to tackle climate change, ensure energy security, and foster sustainable development. This shift transcends technology, acting as a catalyst for transformative change in urban living. By tapping into abundant resources like the sun, wind, water, and earth, smart cities can reduce reliance on fossil fuels, cut carbon emissions, and cultivate more sustainable, resilient, and inclusive communities.

Throughout the paper, various renewable energy sources have been examined—solar, wind, hydroelectric, biomass, and geothermal energy—in different smart cities. Each contributes uniquely to the energy mix, mitigating greenhouse gas emissions, and promoting energy access and economic growth. Technological advancements have accelerated global deployment, driving a transition toward a cleaner, more resilient, and sustainable energy system.

Yet challenges persist, including intermittency, grid integration, environmental impacts, and social acceptance. Addressing these requires innovative solutions and coordinated efforts across sectors and regions. Continued research and innovation are crucial to enhance efficiency, reduce costs, and overcome technical barriers. Collaboration among stakeholders is essential for navigating the transition and realizing a cleaner, more prosperous world.

Looking ahead, prioritizing renewable energy is crucial in smart city development. Investments in clean energy infrastructure, innovation, equity, and resilience-building are vital for creating cities that are smarter, more efficient, greener, healthier, and more equitable for all.

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