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Egypt's Solar Revolution: A Dual Approach to Clean Energy with CSP and PV Technologies

MEDHAT ELKELAWY[1,2], AHMED MOHAMMED SAEED [1], and HUSSEIN SELEEM.[3,4]

[1]Mechanical Engineering Department, Faculty of Engineering, Pharos University in Alexandria, Alexandria, Egypt
[2]Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt (e-mail: medhatelkelawy@f-eng.tanta.edu.eg)
[3]Electrical Engineering Department, Pharos University in Alexandria, Alexandria, Egypt
[4]Electronics and Electrical Communications Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt
{medhat.elkelawy,202001565,hussein.eltaibee}@pua.edu.eg

Corresponding author: Medhat Elkelawy (e-mail: medhat.elkelawy@pua.edu.eg).

ABSTRACT The Egypt Solar Hybrid Initiative aims to revolutionize the nation's renewable energy landscape by integrating Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies. With an average solar irradiance of approximately 5.7 kWh/m²/day, Egypt possesses one of the most favorable climates for solar energy generation globally. This initiative seeks to achieve a combined capacity of 2 GW from CSP and PV systems, contributing significantly to Egypt's ambitious goal of generating 42% of its electricity from renewable sources by 2030.The project will leverage the existing infrastructure of the Benban Solar Park, which currently houses around 1.8 GW of PV capacity, alongside planned CSP installations that are projected to reach 1.5 GW. This hybrid approach will not only enhance energy generation reliability through CSP's thermal energy storage capabilities but also optimize land use by co-locating PV and CSP facilities, thus minimizing the environmental footprint. Financially; the project is anticipated to attract approximately $2 billion in investment, aligning with Egypt's broader renewable energy investment requirement of $10 billion to meet its 2030 targets. The integration of CSP and PV is expected to yield a combined annual electricity output of approximately 5.5 TWh, significantly reducing reliance on fossil fuels and lowering carbon emissions. This initiative is poised to create thousands of jobs, stimulate local economies, and position Egypt as a leader in renewable energy in the MENA region.

KEYWORDS Concentrated Solar Power (CSP); Photovoltaic (PV) Systems; Renewable Energy; Solar Energy; Hybrid Energy Systems; Sustainable development

I. INTRODUCTION

The rising demand for clean, renewable energy is increasingly recognized as essential for addressing climate change and reducing reliance on fossil fuels. Fossil fuels contribute over 75% of global greenhouse gas emissions, necessitating a shift to renewable energy (RE) sources, which can potentially eliminate carbon emissions from 90% of electricity generation by 2050. In 2023, global renewable capacity additions surged by nearly 50%, reaching 510 G-watts, marking the highest growth rate in two decades and underscoring the feasibility of tripling renewable capacity to 11,000 GW by 2030. Furthermore, renewable technologies such as solar, wind, and hydroelectric power not only mitigate climate change but also enhance energy security and promote sustainable development [1]–[3]. The transition to renewable has already shown significant impacts, with wind and solar meeting over three-quarters of electricity demand growth in early 2022, thereby preventing substantial fossil fuel emissions [4], [5].

Solar energy, particularly through advancements in solar photovoltaic (PV) and concentrating solar power (CSP) technologies, is emerging as a leading renewable energy source for large-scale generation. Recent innovations in PV technologies, such as multi-junction cells and perovskite materials, have significantly enhanced efficiency, with some cells achieving over 40% conversion rates [6]. The global installed capacity of solar PV reached approximately 940 GW by 2021, with Asia leading at 486 GW, underscoring its growing importance in energy supply and accessibility. Despite solar energy's current contribution of only 3.6% to global electricity production, projections suggest it could meet 25% of global electricity needs by 2050, driven by ongoing technological advancements and increased installations [7]–[10]. Furthermore, the environmental benefits of solar energy, including substantial reductions in greenhouse gas emissions, reinforce its role in sustainable development and energy independence [11]. As countries continue to invest in solar technologies, the potential for solar energy to become a cornerstone of the global energy landscape is increasingly evident [12], [13].

Egypt's strategic initiative to produce 42% of its electricity from renewable sources by 2030 is a critical step towards a clean energy transition (CET) that leverages its abundant solar and wind resources [14], [15]. The country has significant potential for solar photovoltaic (PV) and onshore wind energy, which are essential for achieving this target. However, achieving the International Renewable Energy Agency's (IRENA) more ambitious goal of 53% would require an additional investment of USD 16.4 billion by 2035, while also potentially saving 732 million tons of CO2 emissions over the long term [16]. The transition is further supported by a surge in renewable energy investments, totaling USD 4.4 billion, with an additional USD 6 billion anticipated, which could enhance Egypt's position as a major electricity exporter and alleviate economic pressures from energy [17]–[19]. Nonetheless, socio-economic challenges, including recent natural gas discoveries and political instability, pose risks to investor confidence and the overall transition process.

Egypt's favorable solar irradiance levels, averaging approximately 5.7 kWh/m²/day, position the country as a prime candidate for solar power initiatives. Research indicates that concentrated solar power (CSP) technologies, particularly solar towers, are optimal for various locations in Egypt, yielding higher annual power production and lower levelized costs compared to parabolic trough systems. Additionally, the performance of solar parabolic trough collectors (PTCs) has been extensively modeled, demonstrating their effectiveness in harnessing direct solar radiation under Egypt's climatic conditions [20]. The integration of thermal storage systems, such as molten salt, further enhances the efficiency of solar power plants, with Aswan identified as the most suitable site for large-scale installations. Moreover, solar-powered irrigation systems have shown promise in conserving water and energy, highlighting the versatility of solar technology in addressing Egypt's energy and agricultural needs [21], [22].

Concentrated Solar Power (CSP) and Photovoltaic (PV) systems each present distinct advantages and limitations, particularly concerning reliability during periods of intermittent sunlight. CSP systems, while generally more expensive, offer enhanced dispatchability due to their ability to store thermal energy, thus providing a more stable power output compared to PV systems, which are subject to fluctuations based on sunlight availability [23]. Hybridizing CSP with PV can mitigate these limitations, as demonstrated by studies showing that such combinations can reduce the levelized cost of electricity (LCOE) and improve overall system reliability [24]. However, PV systems face challenges related to component failures and operational uncertainties, which can compromise reliability in grid integration. Therefore, while CSP provides a more reliable output, the integration of both technologies can enhance overall system performance and resilience against intermittency [25].

Concentrated Solar Power (CSP) systems are distinguished by their integration of Thermal Energy Storage (TES), which enhances their operational flexibility and efficiency, particularly in managing fluctuations in solar energy availability. CSP utilizes various storage methods, such as sensible heat and phase change materials, to enable energy production even when sunlight is not directly available, thus facilitating a smoother energy supply and higher capacity factors, which can reach up to 87.2% with optimal configurations [26]. In contrast, photovoltaic (PV) systems, while cost-effective for direct power generation, typically lack inherent storage capabilities, necessitating additional battery systems for energy storage, which can be less economically viable in high solar penetration scenarios [27], [28]. The economic analysis indicates that CSP with TES can achieve lower levelized costs of electricity (LCOE) compared to PV-battery systems, especially in regions with high direct normal irradiance, making CSP a more attractive option for sustainable energy generation in such contexts [29].

The Egypt Solar Hybrid Initiative aims to enhance energy reliability and efficiency by integrating Concentrated Solar Power (CSP) and Photovoltaic (PV) systems. This hybrid approach capitalizes on the strengths of both technologies: CSP provides dispatchable energy through thermal storage, while PV offers low-cost electricity generation during daylight hours [30]. By employing innovative configurations, such as using excess PV energy to heat molten salts, the initiative can optimize energy storage and conversion efficiency, resulting in a significant reduction in the levelized cost of electricity (LCOE) by nearly 20% compared to traditional setups [31] Furthermore, hybrid systems can mitigate the intermittency of solar energy, ensuring a more stable power supply, which is crucial for meeting the growing energy demands in Egypt and the broader MENA region. Overall, this initiative represents a strategic move towards sustainable energy solutions, aligning with global decarbonization goals [23], [32].

The Benban Solar Park, with a total capacity of 1,600 MW AC, is a pivotal project in Egypt's strategy to generate 22% of its electricity from photovoltaic (PV) sources by 2035, producing approximately 3.8 TWh annually and significantly reducing greenhouse gas emissions [33]. To achieve a target capacity of 2 GW, integrating Concentrated Solar Power (CSP) with PV systems is advantageous, as hybrid configurations can enhance energy reliability and mitigate fluctuations in PV output [34]. The combination of CSP's thermal storage capabilities with PV's lower costs can optimize the overall system performance, ensuring a more stable energy supply while maintaining economic feasibility. This synergy is crucial for meeting the growing energy demands in Egypt, particularly in the context of the Benban Solar Park's existing infrastructure [35].

The integration of Concentrated Solar Power (CSP) and Photovoltaic (PV) systems in Egypt's renewable energy landscape is poised to yield substantial environmental, economic, and strategic benefits. Environmentally, this hybrid approach is expected to significantly reduce reliance on fossil fuels, thereby lowering greenhouse gas emissions and aiding in climate change mitigation efforts, as evidenced by studies showing a reduction in life cycle emissions from hybrid systems. Economically, the initiative could attract around $2 billion in investments, stimulating local industries and job creation while enhancing energy security through diversified sources [36]. Strategically, Egypt's commitment to large-scale solar development positions it as a leader in the MENA region, fostering international partnerships and serving as a model for sustainable energy policies in neighboring countries [37]. Collectively, these impacts underscore the potential of solar energy to drive economic growth, enhance environmental sustainability, and solidify Egypt's influence in the global renewable energy arena [38], [39].

The current landscape of solar technologies, particularly Concentrated Solar Power (CSP) and Photovoltaic's (PV), presents distinct advantages and challenges in renewable energy generation. CSP utilizes thermal energy storage, enhancing reliability, while PV systems are simpler and more widely deployed, yet both are crucial for sustainable energy solutions. Egypt's Solar Hybrid Initiative aims to leverage these technologies, targeting a capacity that could significantly contribute to the nation's energy needs, projected to meet 42% of energy demands through renewable by 2035 [37].This initiative is expected to generate economic benefits, including job creation and investment opportunities, thereby supporting local economies [40]. Furthermore, the hybridization of PV and CSP systems is gaining traction globally, offering a model for other nations to achieve sustainable energy targets and mitigate climate change impacts.

In this paper, we begin with an exploration of the current landscape of solar energy technologies, specifically examining the benefits and limitations of Photovoltaic (PV) and Concentrated Solar Power (CSP) systems. Following this, we analyze Egypt's Solar Hybrid Initiative, a pioneering project designed to integrate CSP and PV systems to achieve a combined capacity of 2 GW. We then assess the initiative's environmental, economic, and strategic impacts, focusing on the potential reduction in greenhouse gas emissions, the attraction of substantial investments, and Egypt's emerging role as a leader in renewable energy within the MENA region. Finally, we discuss the broader implications of hybrid CSP-PV systems on global renewable energy practices, highlighting how such approaches can serve as scalable models for sustainable energy transitions worldwide.

II. CURRENT SOLAR TECHNOLOGIES

Solar energy, particularly through Photovoltaic (PV) and Concentrated Solar Power (CSP) technologies, has gained prominence as a sustainable solution to mitigate greenhouse gas emissions and address energy demands. PV technology, which converts sunlight directly into electricity, has seen significant advancements, including the development of multi-junction cells and materials like perovskite and quantum dots, enhancing efficiency and reducing reliance on traditional silicon cells. Conversely, CSP utilizes mirrors or lenses to concentrate sunlight, generating heat that drives turbines for electricity production, yet it faces challenges related to energy storage and operational efficiency [7]. Despite solar energy's contribution to only 3.6% of global electricity production, projections suggest that with increased investment and infrastructure, solar could meet 25% of global energy needs by 2050. Both technologies play crucial roles in sustainable development, offering environmental benefits and potential job creation in the renewable energy sector. However, reliability and storage remain critical limitations that need addressing to maximize their potential [41].

A. PHOTOVOLTAIC (PV) SYSTEMS

Photovoltaic (PV) systems have gained prominence due to their cost-effectiveness and simplicity in converting sunlight into electricity using semiconductor materials. Recent advancements, particularly in multi-junction and perovskite solar cells, have significantly enhanced efficiency, with some cells exceeding 40% conversion rates [6]. Perovskite materials, known for their low production costs and flexibility, are pivotal in this evolution, although challenges remain in scaling and stability [42]. The integration of energy storage solutions, such as hybrid capacitors, is essential to mitigate the intermittency of solar energy production, albeit at the cost of increased complexity [43]. Furthermore, optimizing interface architectures within perovskite cells is crucial for improving performance and longevity, highlighting the importance of material choice in PV technology. Collectively, these advancements underscore the potential of PV systems in diverse applications, from residential to utility-scale installations, while addressing inherent limitations.

B. CONCENTRATED SOLAR POWER (CSP) SYSTEMS

Concentrated Solar Power (CSP) technology distinguishes itself from photovoltaic (PV) systems by utilizing mirrors to focus sunlight onto a receiver, converting thermal energy into electricity, often through steam turbines. A significant advantage of CSP is its ability to integrate Thermal Energy Storage (TES) systems, particularly molten salts, which allow for electricity generation even during non-sunny periods, enhancing reliability and dispatchability compared to PV systems. Recent advancements in molten salt formulations, including the incorporation of nano-particles, have improved thermal properties, enabling higher operational efficiencies and reduced costs [44]. However, CSP systems face challenges such as high initial costs and the need for optimal conditions, particularly in regions with high direct solar irradiance [45]. Innovations in freeze recovery strategies and material compatibility are crucial for enhancing the economic viability and resilience of CSP plants. Overall, CSP's potential for sustainable energy generation is significant, provided ongoing research addresses existing challenges [46]. Fig. 1 shows the four main concentrating solar power technologies.

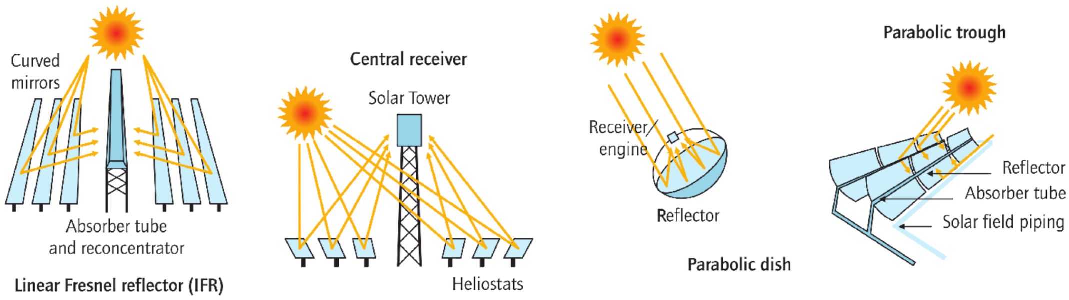

FIGURE 1. The four main CSP technologies [47]

C. COMPARING BENEFITS AND LIMITATIONS

Photovoltaic (PV) and Concentrated Solar Power (CSP) technologies exhibit complementary strengths that enhance renewable energy generation. PV systems are generally more cost-effective and adaptable, yet they face challenges in energy storage due to their intermittent nature. Conversely, CSP systems provide stable, grid-compatible energy through thermal energy storage, making them suitable for high-sunlight regions, although they are more complex and costlier. Hybrid solar projects that integrate PV and CSP capitalize on these advantages, optimizing energy reliability and reducing costs; for instance, a hybrid system in Ivanpah, California, achieved a 41% reduction in levelized cost of electricity (LCOE) compared to standalone CSP [23]. Furthermore, CSP's ability to store excess energy enhances overall system efficiency, particularly in high solar penetration scenarios, where it can lower net-LCOE by up to 65% [27]. This synergy is crucial for advancing sustainable energy solutions. As shown in Fig. 2, the efficiency and energy output of PV and CSP technologies differ significantly, highlighting how they can complement each other in Egypt's energy landscape.

III. EGYPT'S SOLAR HYBRID INITIATIVE

Egypt's Solar Hybrid Initiative, which integrates Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies, is pivotal for transforming the nation's energy landscape, aiming for 42% renewable electricity by 2030. The country's high solar irradiance of approximately 5.7 kWh/m²/day positions it favorably for large-scale solar energy production. The combination of CSP and PV addresses the limitations of each technology, enhancing reliability and stability in energy supply, crucial for meeting growing demands. Studies indicate that optimizing PV systems, such as through vertical axis tracking, can significantly increase energy output, with one scenario producing 2047 MWh annually [49]. Furthermore, innovative solutions like solar trees reduce land use while providing energy for urban applications, demonstrating the versatility of solar technologies in Egypt [50]. Overall, the initiative aligns with global efforts to reduce greenhouse gas emissions and supports Egypt's transition to a sustainable energy future [16].

A. OBJECTIVES AND GOALS

Egypt's Solar Hybrid Initiative aims to enhance solar energy generation reliability and efficiency by integrating Concentrated Solar Power (CSP) and Photovoltaic (PV) systems, targeting a combined capacity of 2 GW. CSP's thermal energy storage (TES) capabilities allow for continuous power generation, even during non-sunny periods, thus addressing the intermittency of solar energy and smoothing fluctuations in electricity supply [51]. In contrast, PV systems provide cost-effective electricity during peak sunlight hours, contributing to a balanced energy output that aligns with demand [36]. This hybrid approach not only optimizes energy production but also reduces reliance on fossil fuels, supporting Egypt's commitments to international climate agreements like the Paris Agreement by significantly cutting greenhouse gas emissions [30]. The integration of these technologies exemplifies a strategic move towards a sustainable energy future in the region.

B. PROJECT SITE AND INFRASTRUCTURE: BENBAN SOLAR PARK

The Solar Hybrid Initiative in Egypt aims to enhance the Benban Solar Park's capacity by integrating Concentrated Solar Power (CSP) alongside existing Photovoltaic (PV) systems, leveraging the site's high solar irradiance for optimal energy production. This co-location strategy not only maximizes land use and minimizes environmental impact but also improves energy stability, as CSP can provide power during non-sunlight hours, complementing PV output. Fig. 3 shows that the Benban Solar Park is strategically located in Egypt's western desert region, allowing for optimal integration of both PV and CSP technologies due to its high solar irradiance and vast available land area. The Benban Solar Park, with a current capacity of approximately 1.8 GW, is pivotal in Egypt's renewable energy strategy, which targets 42% of electricity from renewable sources by 2035 [17]. The integration of CSP and PV is expected to significantly reduce greenhouse gas emissions, with projections indicating that the park could avoid nearly 1.2 million tons of emissions annually [33]. Fig. 4 illustrates the schematic design of the park's 32 sub-systems connected to the national grid, each with designated transformers and energy capacities to support stable power distribution. This initiative aligns with Egypt's broader

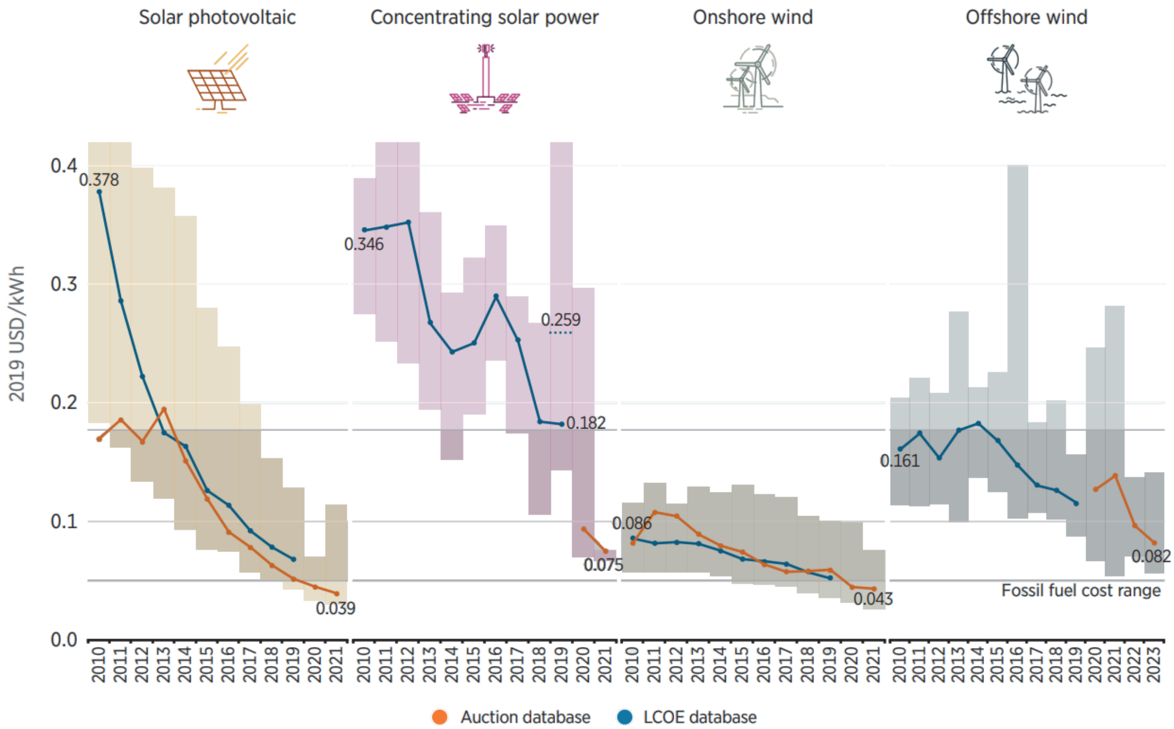

FIGURE 2. Efficiency and energy storage comparison of PV and CSP technologies, showing their respective advantages for Egypt's solar energy initiative [48].

TABLE 1. Effect of Integrating CSP with the PV.

Technology	Capacity	Capacity factor	Annual Energy Production
PV (1.8 GW)	1.8 GW	25%	3.94 TWh/year
CSP (500 MW)	500 MW	35%	1.53 TWh/year
Combined Total	2.3 GW	—	5.47 TWh/year

goals of achieving a clean energy transition and enhancing energy security while fostering economic growth through renewable investments. Integrating Concentrated Solar Power (CSP) with the Photovoltaic (PV) technology at Benban Solar Park could significantly increase its total energy production. The park's current 1.8 GW capacity using PV alone could be enhanced with the addition of 500 MW of CSP. With a higher capacity factor of about 35% for CSP compared to 25% for PV, this combination could boost overall energy production by about 38%. In terms of numbers, the current PV setup produces approximately 3.94 TWh/year, while the addition of CSP would generate an additional 1.53 TWh/year, resulting in a combined total of 5.47 TWh/year. This hybrid approach would not only increase energy output but also provide more reliable and dispatchable energy, reducing the park's dependence on intermittent sunlight and improving grid stability as shown in next table 1.

C. ECONOMIC AND SOCIETAL IMPACT

The Solar Hybrid Initiative in Egypt is poised to significantly enhance the country's renewable energy landscape, attracting an estimated $2 billion in investments, which could create thousands of jobs and stimulate local economic growth [17]. This initiative aims to reduce reliance on energy subsidies by providing a stable, affordable renewable energy source, thereby addressing the rising energy demands of Egypt's growing population. Furthermore, it aligns with Egypt's commitment to reducing greenhouse gas emissions and transitioning to a low-carbon economy, as the country seeks to generate 42% of its energy from renewable sources by 2035 [37]. By positioning itself as a regional leader in renewable energy within the MENA region, Egypt not only aims to attract international investors but also sets a benchmark for similar initiatives, potentially transforming its energy sector and enhancing its role in international energy transit.

D. ENVIRONMENTAL IMPACTS

The Solar Hybrid Initiative in Egypt is poised to significantly reduce greenhouse gas emissions by leveraging solar energy alongside fossil fuels, particularly through hybrid systems that incorporate thermal storage. This approach not only enhances energy generation during peak solar hours but also ensures continuous power supply during nighttime, thereby addressing solar intermittency issues. Studies indicate that solar photovoltaic (PV) systems can effectively replace fossil fuels, with one scenario demonstrating the potential to avoid nearly 19,000 tons of CO2 emissions annually in industrial applications [49]. Furthermore, the integration of renewable technologies, such as solar PV and concentrated solar power (CSP), is essential for Egypt's clean energy transition, with

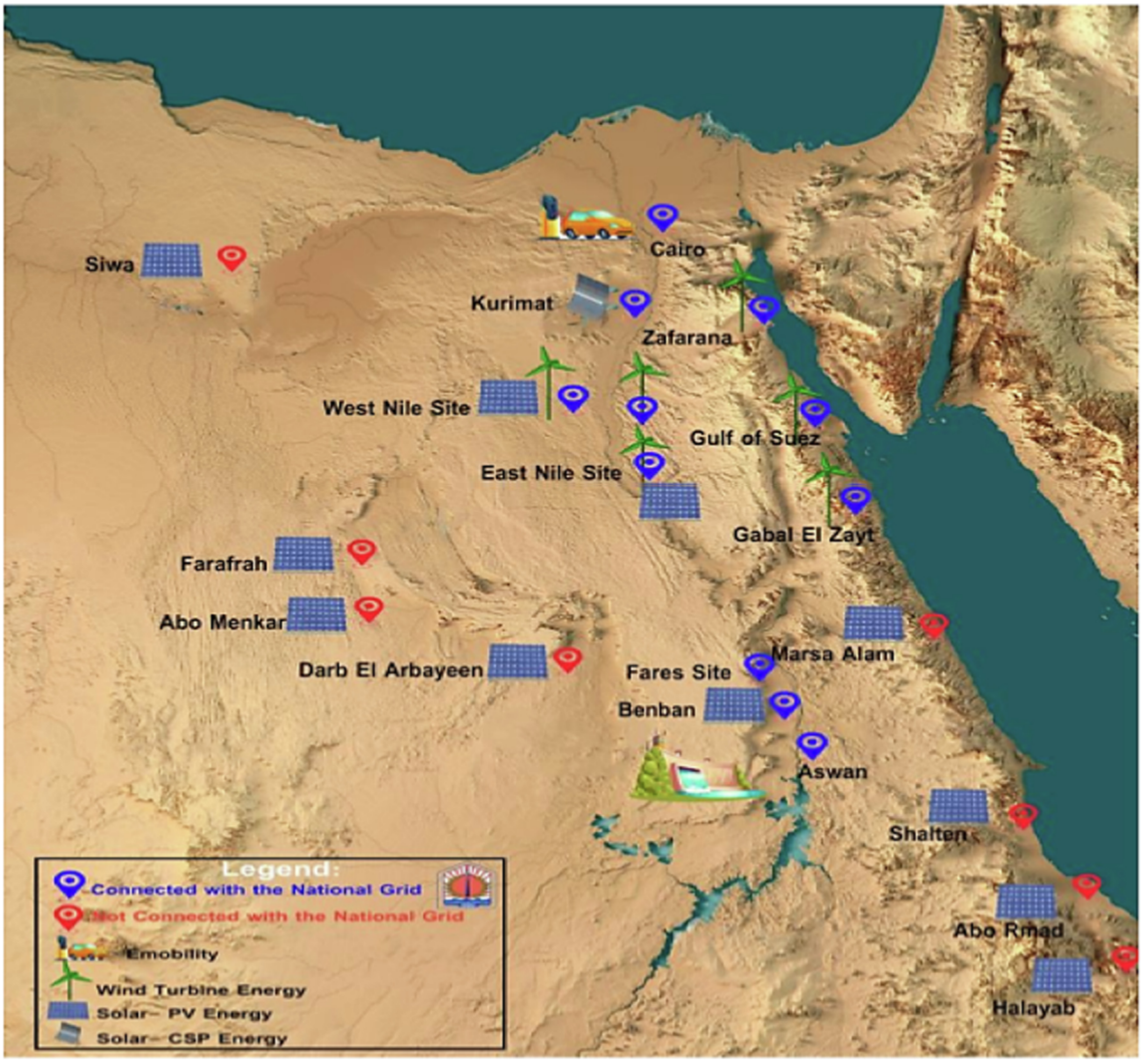

FIGURE 3. Location of Benban Solar Park [33].

projections suggesting that achieving a 53% renewable energy target could save approximately 732 million tons of CO2 by 2070 [16]. Overall, the hybrid system's resilience and efficiency contribute to a sustainable energy future for Egypt, aligning with global climate change mitigation efforts.

E. STRATEGIC IMPORTANCE

The successful implementation of Egypt's Solar Hybrid Initiative positions the country as a leader in large-scale solar hybrid systems within the MENA region, integrating Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies to address renewable energy intermittency challenges. This hybridization leverages the strengths of both systems, with CSP providing dispatchability and thermal storage capabilities, while PV offers lower levelized costs of electricity (LCOE) and ease of installation [30]. The initiative aligns with Egypt's goals to upscale renewable energy technologies, aiming for 53% of electricity from renewable by 2030, which could significantly reduce CO2 emissions [16]. By serving as a model for other nations with high solar potential, Egypt's approach not only enhances its influence in regional energy policies but also promotes sustainable energy solutions that can be replicated globally [36].

IV. ECONOMIC AND ENVIRONMENTAL IMPACTS

The Egypt Solar Hybrid Initiative, which integrates Concentrated Solar Power (CSP) and Photovoltaic (PV) systems, is poised to deliver significant economic and environmental advantages. By harnessing Egypt's abundant solar resources, this initiative aims to reduce reliance on fossil fuels, thereby mitigating projected CO2 emissions, which could rise by 125% by 2035 if conventional energy sources dominate [37]. The hybridization of CSP and PV technologies can lower the levelized cost of electricity (LCOE) by up to 41% compared to standalone CSP systems, enhancing economic viability while minimizing environmental impacts [23]. Furthermore, the initiative supports sustainable rural development by addressing energy and water supply challenges, crucial

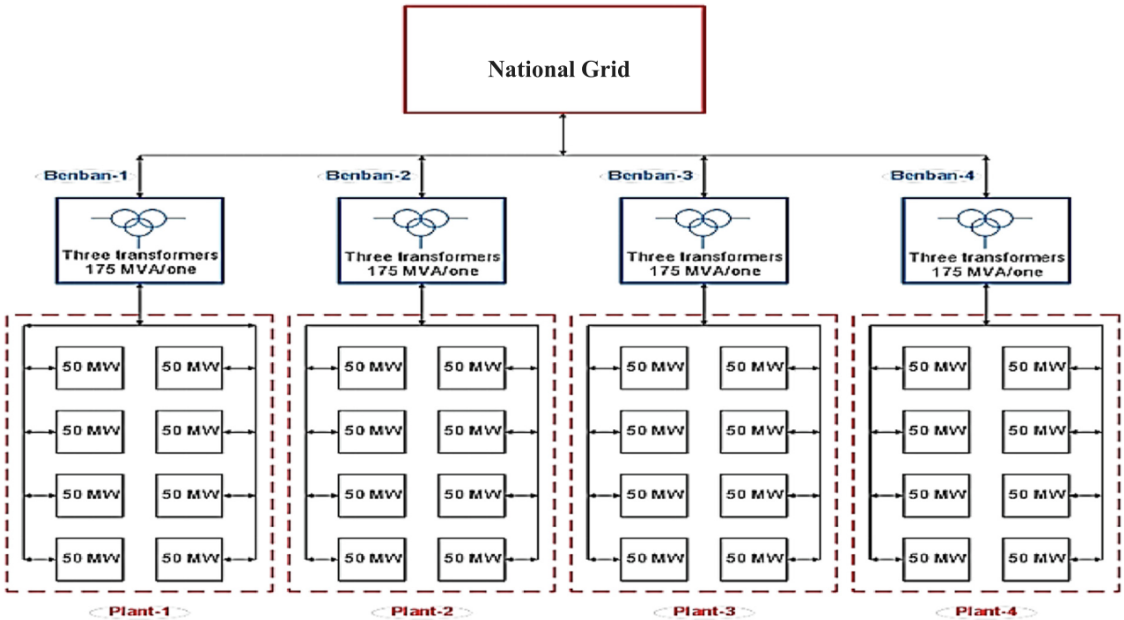

FIGURE 4. Schematic diagram of 32 sub-systems of Benban Solar Park [33].

for achieving the United Nations Sustainable Development Goals (SDGs) in Egypt [52]. Overall, the initiative aligns with Egypt's renewable energy targets, aiming for 42% of energy needs to be met through renewable by 2035 [36].

A. ECONOMIC IMPACT

The Solar Hybrid Initiative in Egypt is poised to generate substantial economic benefits beyond mere energy production, with projections indicating an influx of approximately $2 billion in both foreign and domestic investments, which will significantly enhance the renewable energy sector [17]. This initiative is expected to create thousands of jobs across various industries, including construction, manufacturing, and maintenance, thereby addressing high unemployment rates and fostering socioeconomic development [53]. Furthermore, the initiative will contribute to the development of a skilled workforce in renewable energy technologies, promoting expertise in solar energy and enhancing long-term economic resilience. As Egypt transitions to renewable energy, it not only aims to meet domestic energy demands but also positions itself as a potential electricity exporter, which could further stabilize its economy and reduce reliance on fossil fuels. Table 2 outlines the growth in renewable capacity, which can support economic benefits, highlighting Egypt's ongoing investments in renewable energy and job creation potential [54].

The hybrid project combining Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies presents a promising solution for Egypt's energy challenges, particularly in reducing reliance on costly fossil fuel imports and energy subsidies. By leveraging CSP's ability to provide stable, dispatchable energy alongside PV's cost-effective generation during peak sunlight, the project can significantly lower the Levelized Cost of Electricity (LCOE), with studies indicating potential reductions of up to 22% compared to standalone CSP systems [55]. Furthermore, the integration of supercritical CO2 cycles enhances efficiency, achieving LCOE figures as low as USD 171/MWh. This shift towards renewable energy not only alleviates financial burdens on the economy but also positions Egypt as an attractive destination for foreign investment, fostering economic growth and stabilizing energy prices for consumers and industries alike [17].

TABLE 2. Projected increases in renewable energy capacity in Egypt, demonstrating investment growth and potential for job creation.

Power Station	2009/10	2021/22	2029/30	2034/35
Hydro	2.8	2.8	2.9	2.9
Wind	0.5	13.3	20.6	20.6
PV	0.0	3.0	22.9	31.75
CSP	0.0	0.1	4.1	8.1
Total	3.3	19.2	50.5	62.6

Egypt's strategic focus on renewable energy positions it as a potential leader in the MENA region, capable of catalyzing trade partnerships and attracting international collaborations. With ongoing investments totaling USD 4.4 billion and prospective investments of an additional USD 6 billion, Egypt is set to significantly increase its renewable energy capacity, particularly in solar PV and wind technologies [16]. This transition is driven by high global energy demand and the need for decarbonization, which encourages Egypt to export surplus clean energy to neighboring regions, thereby enhancing its geopolitical influence. Furthermore, the internationalization of renewable energy businesses, supported by networking and collaborative competition, can facilitate

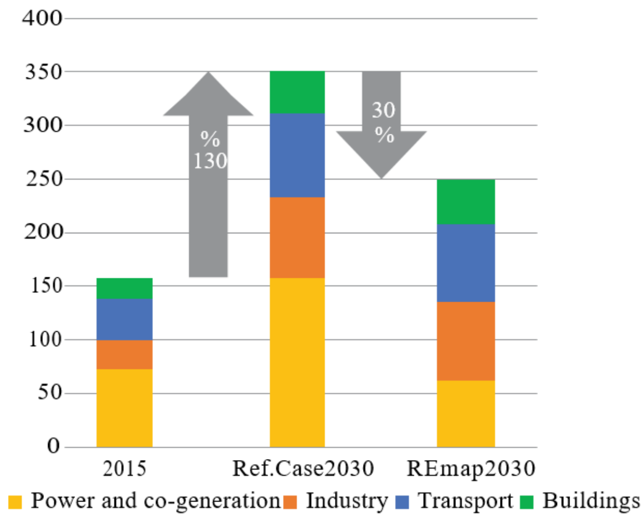

FIGURE 5. Changes in energy-related CO2 by sector, 2014, 2030 [17]

Egypt's entry into global markets, overcoming barriers to trade and fostering cross-border partnerships. By achieving ambitious renewable energy targets, Egypt not only aims to reduce greenhouse gas emissions but also to stabilize its economy through lower energy costs and increased foreign reserves.

B. ENVIRONMENTAL IMPACT

The hybrid project in Egypt is strategically positioned to significantly mitigate greenhouse gas emissions by transitioning from fossil fuels to solar energy for electricity generation. Currently, fossil fuels dominate Egypt's energy landscape, contributing to high CO2 emissions. As depicted in Fig. 5, CO2 emissions across different sectors are projected to decrease significantly by 2030 under Egypt's renewable energy plans, highlighting the environmental impact of renewable adoption. Egypt will see a significant increase in energy demand of almost 120% by 2030. Therefore, similar increases in energy-related CO2 are also seen, with an expected 126% increase in the Reference Case to 350 Mt annually by 2030. By integrating solar power, the initiative is projected to prevent millions of tons of CO2 emissions annually, aligning with Egypt's commitments under the Paris Agreement and its national carbon reduction targets [56].

Hybrid energy systems, which combine renewable sources with traditional energy, enhance reliability and efficiency, thereby facilitating a more sustainable energy supply [57]. For instance, similar systems have demonstrated substantial emissions reductions in various applications, such as dredging operations and industrial settings, showcasing the effectiveness of hybrid models in achieving environmental goals, This shift not only supports global climate change mitigation efforts but also promotes energy security and sustainability within Egypt [58].

The integration of Concentrated Solar Power (CSP) with Photovoltaic (PV) systems presents significant environmental benefits by enhancing energy reliability while minimizing land use. CSP's thermal energy storage capability allows for electricity generation during non-sunlight hours, effectively reducing reliance on fossil-fuel backup sources. The co-location of CSP and PV systems optimizes land use, as both technologies can share infrastructure and transmission lines, thereby decreasing the ecological footprint of large-scale solar installations. Moreover, hybrid systems have demonstrated a reduction in the Levelized Cost of Electricity (LCOE) by up to 22% compared to standalone CSP systems, highlighting their economic viability alongside environmental advantages [55]. This synergy not only enhances dispatchability but also contributes to a more sustainable energy landscape, particularly in regions with high solar potential [59].

The hybrid approach to energy generation, particularly through the integration of Concentrating Solar Power (CSP) and photovoltaic (PV) systems, significantly reduces water usage compared to traditional fossil fuel plants, which require substantial water for cooling. This reduction is crucial in arid regions like Egypt, where water conservation is a pressing concern. Studies indicate that hybrid systems can lead to a decrease in water demand by up to 3751 m^3 annually, while also preventing the emission of over 1340 tons of CO2 each year, thereby aligning with Egypt's environmental conservation goals [56]. Furthermore, the integration of renewable energy sources not only enhances energy efficiency but also supports sustainable urban energy management, contributing to a more resilient and environmentally friendly energy infrastructure. This multifaceted approach underscores the importance of hybrid systems in addressing both energy and water resource challenges in a sustainable manner.

V. STRATEGIC IMPACT AND LONG-TERM SUSTAINABILITY

The Solar Hybrid Initiative in Egypt aligns with the nation's Vision 2030, promoting long-term sustainability and energy security by establishing a robust renewable energy infrastructure. This initiative mitigates vulnerability to global fuel price fluctuations, enhancing energy independence and resilience, which is crucial for supporting the growing population and industrial sectors. The integration of solar technologies, such as photovoltaic and thermal systems, not only contributes to cleaner energy production but also demonstrates economic viability through favorable benefit-cost ratios and net present values[58]. Furthermore, hybrid systems, like those combining solar with fossil fuels, showcase effective energy storage solutions that ensure consistent power generation, thereby reducing reliance on traditional energy sources[54]. Overall, these developments position Egypt as a regional leader in sustainable practices, fostering economic growth while addressing environmental challenges.

Egypt's advancements in hybrid solar projects position it as a potential leader in renewable energy within the MENA region, showcasing the viability of hybrid systems in high-solar irradiance areas. The country's significant solar energy potential, particularly through photovoltaic (PV) and concentrated solar power (CSP) technologies, aligns with global decarbonization goals, as highlighted by the International Renewable Energy Agency's target of 53% renewable energy by 2030 [16]. Furthermore, the successful implementation of solar hybrid cooling systems in various MENA locations demonstrates the economic and environmental benefits of such technologies, with substantial reductions in CO2 emissions reported. Egypt's strategic initiatives could inspire neighboring countries to adopt similar frameworks, fostering regional collaboration in energy policy and accelerating the transition to sustainable energy systems.

VI. BROADER IMPLICATIONS FOR GLOBAL RENEWABLE ENERGY PRACTICES CONCLUSION

The Egypt Solar Hybrid Initiative, which combines Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies, exemplifies a transformative approach to renewable energy that can influence global practices. This initiative addresses the limitations of individual solar technologies by enhancing energy stability and resilience, as evidenced by studies demonstrating the superior performance of hybrid systems over standalone PV setups, particularly in terms of energy output and emissions reduction [49].The integration of diverse renewable sources, such as wind and hydrogen production, further underscores the potential for hybrid systems to meet varying energy demands while minimizing greenhouse gas emissions [16]. Moreover, the economic feasibility of these systems, highlighted by favorable levelized costs of energy and significant reductions in carbon emissions, positions them as viable solutions for countries aiming to achieve ambitious climate targets. Thus, the Egypt Solar Hybrid Initiative not only serves as a national model but also sets a precedent for global renewable energy strategies.

Hybrid solar technologies, particularly the integration of Concentrated Solar Power (CSP) and Photovoltaic (PV) systems, demonstrate significant feasibility in enhancing renewable energy output while addressing intermittency challenges. Projects like Egypt's exemplify how CSP's dispatchable energy complements PV's cost-effective daytime generation, thereby reducing reliance on fossil fuels and improving grid stability. Economic analyses reveal that hybrid systems can lower the levelized cost of energy (LCOE) significantly, with studies indicating reductions of up to 41% compared to standalone CSP systems [23]. Furthermore, the combination of solar and wind resources in hybrid systems enhances reliability and sustainability, as evidenced by simulations showing improved energy generation and reduced greenhouse gas emissions [60]. These systems not only optimize resource use but also present a viable solution for regions with high solar potential and limited energy storage options, ultimately supporting the transition towards a more sustainable energy landscape [61].

The hybrid approach to renewable energy, particularly through the integration of Concentrated Solar Power (CSP) and Photovoltaic (PV) systems, presents a scalable model for achieving international climate goals, as highlighted by the UNFCCC's emphasis on innovative solutions to meet Paris Agreement targets. For instance, Egypt's hybrid CSP-PV project exemplifies how such systems can significantly lower carbon emissions and reduce reliance on traditional energy sources, aligning with global decarbonization efforts [23]. Additionally, studies indicate that hybrid systems, such as PV-wind combinations, can optimize energy generation and reduce overall system costs, thereby enhancing deployment efficiency across various regions [60]. Furthermore, the implementation of strategic planning frameworks for PV installations can lead to substantial emissions reductions, demonstrating the potential of hybrid systems to adapt to local energy needs while contributing to broader sustainability objectives. Overall, these hybrid models not only support energy transition but also provide a robust framework for countries aiming to meet their climate commitments.

Hybrid solar systems, particularly those incorporating thermal storage, significantly enhance energy security and resilience, especially in regions prone to energy instability, such as the MENA region, Latin America, and parts of Asia. These systems provide consistent energy output, mitigating the impacts of fuel price fluctuations and supply disruptions. The integration of energy storage technologies, including underground energy storage systems (UESS) and hybrid energy storage systems combining batteries and fuel cells, further supports resilience by ensuring stability during extreme weather and operational contingencies. Additionally, the implementation of cybersecurity measures is crucial for protecting these systems from cyber threats, thereby safeguarding energy supply and enhancing overall system resilience [62]. By demonstrating the effectiveness of hybrid systems, successful projects can encourage broader adoption, ultimately reducing vulnerability to external energy shocks [63].

The integration of Concentrated Solar Power (CSP) and Photovoltaic (PV) systems presents a promising avenue for achieving cost-effective renewable energy solutions, particularly in regions with abundant solar resources. Hybrid systems can significantly reduce the Levelized Cost of Electricity (LCOE) by optimizing energy storage and distribution, as evidenced by studies showing up to a 22% reduction in LCOE when combining CSP with PV technologies [55]. Furthermore, the incorporation of Thermal Energy Storage (TES) enhances system performance, with configurations achieving substantial fuel savings and reduced operational costs [29]. For instance, a hybrid CSP-PV plant utilizing supercritical CO2 cycles demonstrated a competitive LCOE of USD 171/MWh, lower than traditional CSP plants. Additionally, multi-objective optimization in hybrid systems, including wind and solar, has shown potential for minimizing LCOE while maintaining reliable energy supply [61]. Overall, these findings underscore the economic viability of hybrid renewable energy systems in promoting sustainable energy deployment.

Egypt's Solar Hybrid Initiative exemplifies the critical role of supportive policies and investment in advancing hybrid renewable systems globally. The initiative highlights the necessity for robust regulatory frameworks that include financial incentives, such as tax credits and feed-in tariffs, which are essential for attracting investment in renewable technologies [64]. By demonstrating the economic viability of hybrid systems, particularly those combining solar and wind energy, Egypt's project can inspire international development banks and private investors to prioritize funding for similar initiatives, especially in regions facing energy shortages like Eastern and Southern Africa [64]. Furthermore, the initiative underscores the importance of international collaboration in sharing best practices and technical expertise, which is vital for optimizing system performance and achieving sustainable energy transitions globally. This multifaceted approach not only promotes investment but also enhances the overall efficiency and reliability of renewable energy systems, paving the way for a more sustainable future.

VII. CONCLUSION

The Egypt Solar Hybrid Initiative represents a pioneering step in advancing renewable energy through the integration of Concentrated Solar Power (CSP) and Photovoltaic (PV) technologies. This initiative not only aligns with Egypt's goal of producing 42% of its electricity from renewable sources by 2030 but also serves as a model for other nations striving to meet their climate and sustainability targets. By combining the dispatchability of CSP, with its thermal energy storage capabilities, and the cost-effectiveness of PV, this hybrid approach overcomes the limitations inherent in using these technologies independently. As demonstrated, the synergy between CSP and PV technologies provides a more stable and reliable power source, even in periods of intermittent sunlight, and minimizes environmental impact through optimized land and resource use. From an economic perspective, the project is projected to attract significant investments, stimulate job creation, and enhance Egypt's energy independence, positioning the country as a renewable energy leader within the MENA region. Environmentally, the hybrid model offers a viable pathway for reducing greenhouse gas emissions by displacing fossil-fuel-based energy production, contributing to global climate change mitigation efforts. Strategically, Egypt's commitment to hybrid solar technologies establishes a scalable and exportable model for other nations, especially those in regions with abundant solar resources.

This model demonstrates that hybrid CSP-PV systems are not only feasible but also economically and environmentally advantageous for countries looking to transition to clean energy while maintaining grid stability and energy security. Looking ahead, future research could focus on optimizing CSP-PV configurations to further reduce costs and enhance efficiency. Innovations in energy storage, such as advancements in molten salt technology or alternative thermal storage materials, could improve the operational flexibility of CSP systems, enabling them to store energy for even longer periods. Additionally, further studies are needed to assess the economic impacts of scaling hybrid systems to larger capacities, exploring how economies of scale could make such systems more accessible globally. Policymakers are encouraged to support hybrid renewable initiatives by developing incentives for investors, implementing favorable regulations, and promoting international collaboration to facilitate knowledge exchange. By addressing these areas, Egypt and other nations can continue to advance renewable energy systems that are both resilient and sustainable, paving the way toward a carbon-neutral future. The Egypt Solar Hybrid Initiative thus serves as a significant milestone in the global transition to renewable energy, underscoring the potential of hybrid solar technologies to drive economic growth, environmental protection, and energy security.

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