Research Article

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Transitioning from Oil Export to Hydrogen Via Solar, Wind, and Heccgt

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Abstract
The analysis focuses on a decarbonization strategy for an oil-exporting country, emphasizing the transition to renewable energy sources through two key scenarios. A baseline is provided, showing individual results for three power generation technologies: solar, wind, and helium closed-cycle gas turbines (HeCCGT). Building on this baseline, the first key scenario explores the combined potential of solar and wind energy, with the H2CCGT (Mean hydrogen combined gas turbine) serving as a backup power generation source when solar and wind resources are unavailable. This scenario provides insights into the combined capacities of solar and wind, their land requirements, and the necessary infrastructure to support continuous energy supply and large-scale hydrogen production. The second scenario advances the analysis by integrating HeCCGT helium closed-cycle gas turbines with solar and wind power, effectively eliminating the need for H2CCGT as a backup. The helium closed-cycle gas turbine works in tandem with solar and wind energy to provide a consistent and reliable power supply, even when solar and wind conditions are not optimal. This scenario also emphasizes the infrastructure required to support an export-oriented hydrogen production strategy, targeting an output of 2100 PJ or 17.5 MT of hydrogen. This strategic analysis serves as a comprehensive guide for understanding the technical and logistical requirements for transitioning from fossil fuels to a sustainable energy system. The study highlights the potential for the country to become a global leader in the hydrogen economy, supported by a diversified and resilient renewable energy infrastructure.

Keywords: Decarbonization, Wind Energy, Hydrogen Combined Cycle Gas Turbine, Hydrogen Production, Oil-Dependent Economies Transition, Renewable Energy Integration, Solar Photovoltaics (Pv), Helium Closed Cycle Gas Turbines

1. Introduction

The comprehensive global transition towards carbon reduction signifies a substantial transformation in energy paradigms, motivated by the imperative necessity to confront climate change and attain climate neutrality. This change is driven by the movement from relying on fossil fuels to welcoming renewable energy sources (RES), the application of tough energy regulations, and the fusion of groundbreaking technologies. Notably within the Asia-Pacific region, initiatives are focused on the gradual elimination of coal, bolstered by empirical data that underscores the efficacy of clean energy policies in diminishing CO2 intensity in electricity generation, particularly when buttressed by robust governance.Despite these advancements, numerous economies remain substantially dependent on fossil fuels, with forecasts suggesting that in the absence of expedited initiatives, global CO2 emissions may escalate markedly by the year 2050. This predicament is further exacerbated for oil and gas enterprises, which are compelled to reconcile climate objectives with persistent fossil fuel demand, thereby necessitating strategic transformations within their operational frameworks. Consequently, the attainment of net-zero emissions will demand comprehensive policy interventions and a fundamental reconfiguration of economic structures [1-5].

In this context, the transformation of economies reliant on oil towards renewable energy sources is imperative for achieving sustainable economic growth and ensuring energy security. Empirical research indicates that the shift towards renewable energy not only propels GDP growth, particularly in nations actively reforming their energy portfolios from fossil fuels to renewables, but also fosters job creation and stimulates technological innovation, thus disrupting conventional energy markets This transition not only promotes economic advancement but also generates employment opportunities and stimulates technological innovation, thereby disrupting conventional energy markets Moreover, the present worldwide movement towards renewable energy is intensified by geopolitical events, such as the war involving Russia and Ukraine, which have showcased the weaknesses linked to fossil fuel reliance and the critical demand for sustainable energy options. Although this transition entails challenges, such as the requisite investment in infrastructure and the management of energy supply intermittency, it concurrently presents considerable economic opportunities and fortifies energy security [6-9].

Customized policy frameworks and cooperative initiatives are critical to navigating these complexities and ensuring an equitable transition for regions that are dependent on traditional energy sources Hence, the shift to renewable energy represents a fundamental environmental responsibility alongside a pressing economic need.Hydrogen is emerging as a pivotal clean energy vector in the transition towards a sustainable energy system, providing considerable advantages such as high conversion efficiency and diminished local pollution when utilized in fuel cells, rendering it a feasible alternative to fossil fuels.

The evolution of Blue Hydrogen, integrating carbon capture technology, and Green Hydrogen, created from renewable energy options, is necessary for international decarbonization pursuits. The identification of natural hydrogen reservoirs further presents novel opportunities for clean energy production, potentially facilitating the decarbonization of energy-intensive sectors. Nevertheless, challenges persist, including elevated production costs and the necessity for robust infrastructure for storage and transportation. Surmounting these obstacles will necessitate effective policy frameworks and technological innovations, ensuring that hydrogen's role is complementary to other renewable technologies, particularly in addressing energy intermittency and storage challenges [10-16].

The global shift towards renewable energy constitutes a paramount initiative aimed at alleviating climate change and diminishing greenhouse gas emissions, with technologies such as solar energy, wind energy, and Helium Closed-Cycle Gas Turbines (HeCCGT) assuming essential roles. Solar energy, supported by rapidly decreasing costs and enhanced efficiency, has emerged as a fundamental element of renewable energy strategies globally. Solar power, driven by rapidly declining costs and increasing efficiency, has become a cornerstone of renewable energy strategies worldwide. Photovoltaic systems convert sunlight into electricity, making solar energy a clean and abundant source, though its production is limited to daylight hours, creating intermittency challenges.. Wind power, similarly, harnesses the natural movement of air to generate electricity and has seen significant growth, particularly in onshore and offshore wind farms, due to technological advancements and favourable policies aimed at reducing carbon emissions. However, like solar energy, wind power is also intermittent, with varying wind speeds across different seasons and times of day [17-21].

To address these fluctuations, backup systems such as HeCCGTs are essential. HeCCGTs use helium as a working fluid in a closed system, allowing for high-efficiency electricity generation by leveraging nuclear reactors or solar thermal energy as heat sources. These turbines provide reliable backup power, ensuring grid stability when renewable sources fall short, and can also be integrated with hydrogen production systems, using surplus renewable energy to generate and store hydrogen for later use. Together, these technologies—solar, wind, and HeCCGT—form a synergistic framework for reducing carbon emissions, enhancing energy security, and supporting a sustainable global energy transition.
[22-26].

As the global urgency for decarbonization intensifies, the need for substantial investments and comprehensive energy strategies has become more apparent than ever. These investments are not just financial but also strategic, aiming to sustain the progress achieved in reducing global poverty and ensuring continued economic development. Decarbonization involves more than just transitioning away from fossil fuels; it requires an integrated approach that includes renewable energy sources, technological innovation, and cross-border cooperation.The concept of global electricity interconnections, which fosters the sharing of renewable resources like solar and wind across different regions, is a significant component of this transition. This approach links environmental sustainability with sustained economic growth and the wise management of natural resources, illustrating the interconnectedness of these critical global priorities. In this context, oil-dependent economies are under pressure to pivot towards cleaner energy sources. This study is distinctive in its focus on the comprehensive decarbonization of an entire oil-exporting nation, a topic not widely explored in existing literature. While research has addressed decarbonization in certain industries like automotive, there is little examination of country-wide transitions. This work builds on that gap, exploring the shift from oil exports to hydrogen production through the integration of solar, wind, and HeCCGT technologies to achieve decarbonization [27-31].

2. Analysis Method

The analysis starts by organizing raw data on electricity demand and supply from solar, wind, and Helium Closed-Cycle Gas Turbines (HeCCGT) across different seasons, setting the stage for a detailed time-series analysis. This tracks fluctuations in energy production and consumption, helping to identify demand peaks, renewable energy variability, and the role of HeCCGT as a steady power source. The next step, supply-demand matching, compares energy produced by solar, wind, and HeCCGT to hourly demand, highlighting any shortfalls or surpluses. Scenario-based analysis follows, modeling different energy source combinations across seasons to illustrate system flexibility and the importance of a diverse energy mix for security. Efficiency and sustainability metrics are then calculated, measuring the performance of each energy source and its contribution to carbon reduction. A key part of the analysis examines the role of hydrogen, assessing its production during renewable energy surpluses, its storage, and usage across sectors, including in the Hydrogen Combined Cycle Gas Turbine (H2CCGT) system during power shortages. The effectiveness of hydrogen in stabilizing the grid and addressing renewable intermittency is evaluated.

To illustrate the results, the data are visualized through graphs and charts, which depict seasonal energy production versus demand, and the use of backup systems such as H2CCGT during deficits. Sensitivity analysis also tests the robustness of the system by adjusting variables such as demand and energy availability, ensuring its resilience under changing conditions. The method combines data analysis, scenario modeling, and visualization to assess how solar, wind, HeCCGT, and hydrogen backup systems can effectively drive decarbonization. The authors were unable to find such a comprehensive step-by-step analysis in existing research. To assist the country's efforts to decarbonize its energy system, national and international data were carefully analyzed to forecast future energy requirements, examine daily consumption patterns, and evaluate the integration of renewable energy sources through time series analysis, scenario modeling, and efficiency assessment.

3. Decarbonization Strategies in Oil-Dependent Countries

Decarbonizing oil-dependent countries is a unique challenge, but it's also a huge opportunity. Many of these nations rely heavily on fossil fuels for their economies, but they're recognizing the need to shift towards cleaner energy sources to address climate change and create more sustainable economies. One of the main strategies is transitioning to renewable energy. Countries like Saudi Arabia and the United Arab Emirates (UAE) are investing heavily in solar and wind power. Saudi Arabia, through its Vision 2030 plan, is working to diversify its energy sources and cut down on emissions by developing large-scale solar and wind projects. The UAE has also made significant strides, notably with its massive solar park projects like the Mohammed bin Rashid Al Maktoum Solar Park (REN21, 2020). These projects show that even oil-rich countries are starting to prioritize renewable energy as a path to a cleaner future [32-37].

Another approach is using carbon capture and storage (CCS) technology, which captures CO2 emissions from industries and stores them underground. Oil-dependent countries often have favorable conditions for this, thanks to their geological formations. Norway is leading the way with projects like Sleipner and Snøhvit, where CO2 from natural gas production is captured and stored beneath the seabed . This technology allows these nations to keep using fossil fuels while reducing their environmental impact. Developing a hydrogen economy is also seen as a promising solution. Hydrogen, especially when produced using renewable energy (green hydrogen), could play a significant role in clean energy for power generation, transportation, and industry. Countries like Saudi Arabia and the UAE are pouring resources into hydrogen production, aiming to be global leaders in this emerging market. Blending hydrogen with natural gas is one way these nations are slowly decarbonizing their energy systems while ensuring energy security [38-40].

Improving energy efficiency and pushing for electrification are also key elements of the decarbonization puzzle. Many oil-dependent nations, such as Kuwait and Qatar, are working on making their energy use more efficient across various sectors, from buildings to transport.Electrification, especially in transportation, is gaining traction as well. Oman and Bahrain are exploring electric vehicle infrastructure to help cut down on fossil fuel reliance. On a global scale, these countries are also taking part in international climate initiatives like the Paris Agreement. They're working with organizations such as the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) to create policies that support a low-carbon future. This collaboration helps them access the technology, financing, and expertise needed to make their energy transitions a reality[41-43].

The process of decarbonization in nations reliant on oil is inherently intricate, necessitating an amalgamation of advancements in renewable energy, the implementation of carbon capture technologies, the production of hydrogen, enhancements in energy efficiency, and the diversification of economies. Recent investigations conducted by various scholars elucidate the multifaceted challenges and potential benefits inherent in this transition, with particular emphasis on the Libyan context. Their 2023 research concentrated on the synergistic integration of hydrogen, wind energy, and gas turbine technologies, highlighting the extensive land utilization and infrastructural investment requisite for attaining energy autonomy and substituting oil exports with hydrogen. A subsequent 2024 investigation by the same researchers introduced an innovative methodology employing submersible power facilities equipped with closed-cycle helium gas turbines to further scrutinize these transitional dynamics[18] Additionally, another ongoing investigation by the same authors delves into the feasibility of amalgamating hydrogen, solar energy, and gas turbine technologies, with a pronounced focus on the substantial capital investments necessitated by such endeavours . The financial implications are also thoroughly analysed, with projections for solar, wind, and helium-cycle technologies estimated to range from several hundred billion to exceeding one trillion dollars. Collectively, these studies furnish a significant groundwork for policymakers and investors, underscoring the indispensable infrastructure and meticulous strategic planning necessary for the successful transition to a decarbonized economy within oil-exporting nations [44-46].

As mentioned in Section 1, this research is unique in the literature because it focuses on the decarbonization of an entire oil-exporting country—a subject that has not yet been extensively explored.

Despite extensive searches, no studies have been found that examine the decarbonization of a whole country, though similar research exists in specific industries, such as the automotive sector. Building on this foundational work, the current study investigates the transition from oil exports to hydrogen production by leveraging solar, wind, and HeCCGT technologies, and examines how these technologies can be combined to effectively decarbonize an oil-exporting nation. The comprehensive assessment presented here provides a critical assessment of the technological and economic implications associated with such a transition, emphasizing the need for significant investment and strategic foresight. The insights derived from this research are critical to guiding future policy formulation and ensuring effective implementation of decarbonization strategies within oil-exporting countries.

Decarbonization efforts in oil-dependent countries are inherently a diverse enterprise; however, they advance by integrating renewable energy innovations, decarbonization technologies, hydrogen production, energy efficiency improvements, and economic diversification. These frameworks not only help reduce carbon emissions, but also promise that these countries can evolve and succeed in a rapidly changing energy landscape.

4. Decarbonization Evaluations with Hydrogen Export

4.1 Energy Mix Analysis

Seasonal and hourly data highlight the contributions of solar, wind, and helium closed-cycle gas turbines (HeCCGT) to the overall energy mix in this study. Solar and wind peak during their respective seasons (solar in summer and wind in winter), while H2CCGT provides backup power, filling the gaps left by intermittent renewables. The data suggest a critical role for HeCCGT in grid stability and reliability.

4.2 Scenario-Based Projections

Two main decarbonization scenarios are examined considering the available data: - Scenario 1: In this scenario, solar and wind are identified as major contributors to power, with H2CCGTs acting as a backup system to compensate for periods of low renewable generation. This scenario underscores the importance of hydrogen in aligning power generation with consumption and export. A notable aspect of this scenario is the expected production and export of hydrogen, with Libya expected to export 17.5 million tonnes of hydrogen (2,100 PJ) per year, reflecting Libya's current oil production levels. Excess energy generated during peak periods will be allocated to solar and wind power generation to produce hydrogen for export, thereby generating economic benefits while facilitating global decarbonization initiatives. - Scenario 2: This scenario envisions a comprehensive integration of HeCCGT with solar and wind power systems, thus eliminating the need to use H2CCGT as a backup system. In this configuration, HeCCGT, in combination with renewables, provides a more reliable and stable electricity supply. Hydrogen production and export remain central, with Libya continuing to produce 17.5 million tonnes of hydrogen (2,100 PJ) for annual export. This scenario highlights the potential to decarbonize the domestic electricity grid while establishing Libya as a leader in the global hydrogen export market.

4.3 Carbon Emission Reduction

This investigation seeks to develop a comprehensive roadmap for decarbonizing Libya by 2050, demonstrating a critical change for a nation that is largely dependent on fossil fuel supplies. As illustrated in the Libya Energy Consumption in 2020 as shown in figure 1, carbon-intensive sectors, including transportation, jet fuel, and domestic gas consumption, play a significant role in the country's CO2 emissions profile [47-50].

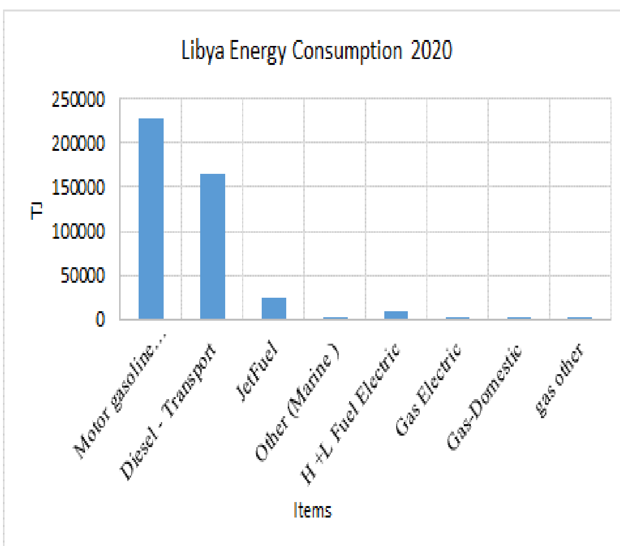


Figure 1: Libya energy consumption 2020

Libya intends to move away from its dependence on oil exports towards a future that highlights renewable energy, particularly solar, wind, and green hydrogen. The proposed decarbonization scenarios reveal the potential to mitigate carbon emissions by harnessing these renewable resources in conjunction with highly efficient combined cycle gas turbine (HeCCGT) systems for optimal power generation. By integrating renewable energy technologies, Libya intends to not only reduce its domestic carbon emissions but also make a meaningful contribution to global decarbonization initiatives through hydrogen exports. As the data presented suggests, sectors such as transportation, which currently account for a large share of energy consumption and emissions, are expected to benefit significantly from this shift towards green hydrogen. By moving away from sectors that produce high-carbon outputs and embracing renewable energy alternatives, Libya can help other countries reduce their fossil fuel needs, while maintaining its commitment to net-zero emissions by 2050, and ensuring it remains an energy supplier in a more sustainable global context.

5.1 Energy storage and hydrogen integration

The function of hydrogen as an energy storage mechanism is crucial for the decarbonization strategy outlined in both scenarios. The surplus energy generated by solar and wind during peak production periods is employed in the synthesis of green hydrogen. This hydrogen is then stored for use during energy deficits or exported to global markets. The production of 17.5 million tonnes of hydrogen (2100 PJ) for export constitutes a fundamental element of Libya's strategic approach to harness renewable energy for economic advancement and to support global decarbonization efforts.

5.2 Projections For The Year 2050

This study contributes to Libya's full transition to a renewable energy-based energy system, supported by solar, wind and HeCCGT, along with large-scale hydrogen production. Exporting 17.5 million tons of hydrogen (2100 PJ) per year will position Libya as a major source of clean energy, providing a sustainable economic future while contributing to global decarbonization efforts. This integrated approach to decarbonization combines the benefits of domestic energy stability with international market opportunities. Libya's decarbonization strategy involves a complex but well-planned transition from a fossil fuel-dependent economy to a leader in renewable energy and hydrogen exports. The combination of solar, wind and HeCCGT, supported by hydrogen production, ensures that the country not only meets its own energy needs, but also contributes significantly to global decarbonization efforts by exporting 17.5 million tons of hydrogen (2100 PJ) per year. This strategy provides a roadmap for other oil-dependent countries looking to transition to a green economy while maintaining economic growth and stability. Figure 2 shows current daily and seasonal consumption patterns to produce equivalent, carbon-free daily and seasonal consumption patterns for the year 2050[47], [48], [49], [50]. The year is assumed to consist of four seasons, each representing 91.25 "standard" 24-hour days. This step includes adjustments to ensure that daily and seasonal energy consumption patterns match the annual scenarios for Case 1 and Case 2.

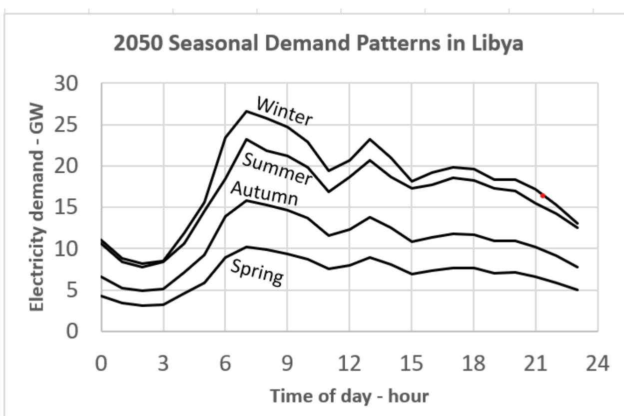
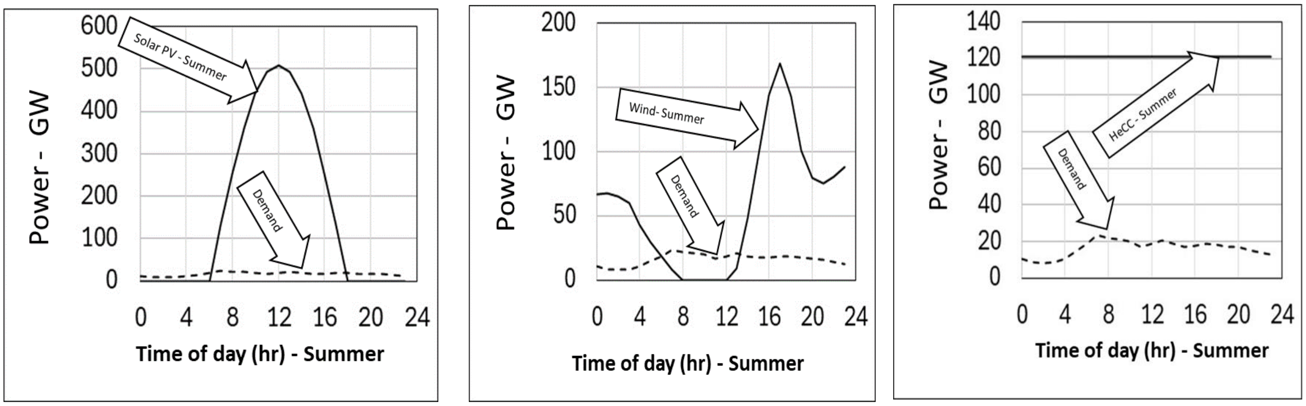


Figure 2: Demand curves for 2050 used in the study

5. Decarbonization Baseline: Comparative Case Studies for Solar, Wind, And Heccgt Integration with Hydrogen Export

This baseline represents a starting point for integrating three major electricity sources—solar photovoltaics, wind, and helium-powered closed-cycle gas turbines—in two decarbonization scenarios. The first scenario focuses on combining solar and wind power while exporting 17.5 million tons of hydrogen annually. The second scenario combines helium-powered closed-cycle gas turbines with solar and wind power, also aiming to export 17.5 million tons of hydrogen. These scenarios aim to achieve net-zero carbon emissions, meet domestic energy demand, and support economic growth through hydrogen exports. The following analysis assesses the effectiveness of each energy source in achieving these goals and lays the foundation for achieving decarbonization by 2050.

The baseline analysis focuses on three decarbonization case studies, each utilizing a different primary energy source: solar PV, wind energy, and HeCCGT. Figures 1 a, 3b, and 3c illustrate the performance of these energy sources during a typical summer day. The table accompanying these figures provides a detailed breakdown of the installed capacity, land area requirements, electrolyser capacity, hydrogen storage, and H2CCGT units needed to support both energy production and hydrogen export. This baseline serves as the foundation for understanding the infrastructure and output needed to transition away from fossil fuels.



3a 3b 3c

Figure 3a, b and c: comparative daily power generation and demand for solar, wind, and hecc in summer

In Figure 3a, the solar PV scenario shows how solar energy peaks during midday, generating nearly 500 GW of power when sunlight is at its maximum. However, this energy source is constrained by daylight hours, resulting in a gap between supply and demand during the night and early morning. The energy demand, represented by the dashed line, remains consistent throughout the day, highlighting the need for backup systems or energy storage to bridge the gap left by solar PV.

Power Generation	Installed Power GW	Area km²	Electrolyser GW	H_2 Storage tonnes	H_2CCGT units
Solar	657	7821	491	43500	54
Wind	340	37325	298	24000	44
HeCCGT	130	0	120	1080	0

Table 1: Power Generation Capacity, Infrastructure, and Hydrogen Production Summary

Table 1 presents an extensive overview of the power generation capabilities, necessary infrastructure, and hydrogen production potential for three predominant energy sources: solar, enhanced solar, wind, and helium closed-cycle gas turbines (HeCCGT). Solar energy leads with an established capacity of 657 GW, necessitating 7,821 km² of land, bolstered by 491 GW of electrolyser capacity and significant hydrogen storage of 43,500 tons, in addition to 54 H2CCGT units for supplementary support. Wind energy, which has an installed capacity of 340 GW, demands a larger expanse of 37,325 square kilometers, alongside 298 GW of electrolyser capacity and 24,000 tons of hydrogen storage, supported by 44 H2CCGT units. Although the HeCCGT system exhibits a lower capacity of 130 GW, it possesses the advantage of ensuring consistent power generation, complemented by 120 GW of electrolyser capacity and 1,080 tons of hydrogen storage, without necessitating additional H2CCGT units[18], [44], [45], [51].

The data presented in the table underscores the pivotal role that both standard and enhanced solar technologies play within the overarching energy generation framework. The solar power generation capacity stands at 657 GW, requiring 7,821 square kilometers of land. Notably, enhanced solar technology maintains the same capacity of 657 GW while achieving improved land utilization, decreasing the required area from an initial 12,100 square kilometers to 7,821 square kilometers. This signifies a substantial reduction in land utilization of approximately 35%, indicative of advancements in solar technologies that augment energy density and overall efficiency. The ramifications of this enhanced solar technology are substantial. By minimizing the land area necessary for equivalent energy output, Libya can optimize land utilization, particularly in regions where land availability poses a challenge. This increased efficiency also mitigates the ecological footprint associated with extensive solar farms, diminishing the necessity for large solar installations that could otherwise intrude upon critical ecosystems or agricultural zones. Furthermore, the reduced land demands facilitate more adaptable deployment of solar infrastructure, permitting integration of solar systems into urban or industrial locales where spatial constraints are present. Additionally, both configurations of solar contribute significantly to hydrogen production, with 491 GW of electrolyser capacity yielding 43,500 tons of stored hydrogen. The vast capacity for hydrogen storage highlights how crucial solar energy is in promoting hydrogen as a sustainable energy transport medium, which is key for reducing carbon emissions in areas like transport and heavy manufacturing. The presence of 54 H2CCGT modules associated with both solar systems exemplify the dependability of solar energy in furnishing stable, dispatchable power even in the absence of sunlight.

Nominal PV GW	Availability	Contingency	Fouling	Available PV	Weather assumption here is of 300 days of sunlight	Weather Availability PV	Efficiency of the PV Cell	Space of PV cells	Area needed km²
657	0.98	0.98	0.97	612.1	0.833	509.8	0.14	0.6	7821

Table 2: Solar PV System Performance and Land Use Overview

The solar energy system begins with a nominal installed capacity of 657 GW, which represents the maximum potential output under ideal conditions. However, several real-world factors reduce this theoretical capacity. Availability, contingency, and fouling, each with high values of 0.98 and 0.97, account for operational downtimes such as maintenance, which is often performed at night to minimize disruptions. After considering these factors, the available output is adjusted to 612.1 GW. Additionally, a weather factor of 0.833 is applied, based on the assumption that the region experiences 300 days of sunlight annually. This reduces the effective output to 509.8 GW, which reflects the impact of varying weather conditions on solar generation. The efficiency of the PV cells, at 14%, determines how much of the sunlight is converted into electricity, while the system's total installation requires an extensive land area of 7821 km². This includes the 0.6 fraction of the space occupied by the PV panels themselves. Together, these factors provide a realistic estimation of the solar energy system's actual output, considering both environmental and operational conditions as shown in table 2.

Figure 3b shows wind power as the primary energy source. Wind power shows a different pattern than solar power, with peak generation occurring in the early morning and evening. Wind power produces up to 150 GW in the summer season while peaking in the winter, generating about 311 GW of power when wind speeds are at their peak, but its variability is evident throughout the day. While wind power complements solar power by generating power during peak solar hours, it still struggles to meet the constant energy demand shown by the dotted line. Table 1 shows that 340 GW of wind power has been installed, requiring a vast land area of 37,325 km2. To achieve the hydrogen export targets, 298 GW of electrolyser capacity is needed, along with 24,000 tons of hydrogen storage. In this scenario, 44 H2CCGT units provide backup power when wind power is insufficient, especially during periods of low wind speed.

Nominal wind GW	Wind Factor	Maintenance	Fouling	Available wind GW	Wind Power Factor	Area Factor	Space of wind turbine	Area needed km²
340	0.04452381	0.90	0.97	305.3	1.632727	109.78	9.109	37325

Table 3: Wind System Performance and Land Use Overview

Table 3 provides an overview of the factors affecting wind energy generation. Starting with a nominal wind capacity of 340 GW, the actual available wind power is adjusted through several operational factors. The wind factor (0.0445), maintenance efficiency (0.90), and fouling adjustment (0.97) reduce the nominal capacity, resulting in an available wind generation capacity of 305.3 GW. Additionally, the wind power factor (1.6327) and the area factor influence the final layout of the wind turbines, requiring 9.109 km² of space for turbines and a total land area of 37,325 km² for the entire wind energy setup.

Figure 3c shows the HeCCGT scenario, where the helium-fired closed-cycle gas turbine provides a stable and reliable power output of 120 GW all day long in summer, while its cycle in winter is 130 GW, depending on the seawater temperature. Unlike solar and wind power, the HeCCGT is not affected by external conditions, providing continuous power that matches the ongoing energy demand. This makes the HeCCGT an essential component for ensuring energy stability, especially when renewable sources are not available. The table indicates the installation of 130 GW of HeCCGT capacity, with much lower ground requirements compared to solar and wind power. The electrolyzer capacity required for hydrogen production in this scenario is 120 GW, with 1,080 tons of hydrogen stored annually. It is worth noting that the HeCCGT system does not require any additional H_2CCGT backup units due to its reliable output.

Nominal Helium CC GW	Availability	GW-Power Available	Winter	Spring	Summer	Autumn	N0 of 1 GW Units
130	0.95	123	125.5	122.99	120.5	122.99	130

Table 4: Helium Closed Cycle System Performance Use Overview

Table 4. provides an insight into the performance of the HeCCGT system. With a nominal capacity of 130 GW, the system operates at 95% availability, providing an available power output of 123 GW. The system performance is consistent across seasons, with slight variations: 125.5 GW in winter, 122.99 GW in spring and autumn, and 120.5 GW in summer. The total number of 1 GW modules required for this setup is 130, ensuring a stable and reliable power supply throughout the year.

7. Case Studies 1

Case Studies 1 engages in a comprehensive examination of decarbonization strategies through the strategic incorporation of renewable energy resources. Within this context, solar and wind stand out as key energy sources, assessed for their joint impact on lowering carbon emissions and advancing energy sustainability. These case studies systematically assess the operational efficacy, capacity, and infrastructural prerequisites of solar and wind power generation in fulfilling energy demand while simultaneously facilitating the production and export of hydrogen as a viable clean energy carrier. The principal aim is to evaluate the collaborative functionality of solar and wind energy in establishing a resilient, decarbonized energy system, with hydrogen combined cycle gas turbines (H2CCGT) functioning as an auxiliary solution when solar and wind resources are inadequate.

7.1 Balancing Energy Demand with Solar, Wind, and H2CCGT Systems For four Seasons

The analysis provides a detailed explanation of energy production and consumption patterns across different seasons – winter, spring, summer and fall – with a focus on the integration of solar, wind and hydrogen energy systems. This analysis helps identify energy surplus or deficit for each hour of the day and shows how hydrogen is produced, stored and used to balance the energy grid.

7.2 Analysis for the Winter Season

The examination of the Winter season data provides a comprehensive analysis of the equilibrium between energy production and management, utilizing a hybrid of solar and wind energy, with hydrogen serving an integral function in upholding grid stability as shown in Table 5. The dataset initiates with solar irradiance (Column 1), quantified in watts per square meter (w/m²). During the Winter season, the maximum solar irradiance is recorded at 12 PM, attaining a value of 669 w/m², which corresponds to the zenith of solar power generation at 18 GW (Column 2). This solar input, albeit restricted to diurnal hours, is of paramount importance during its optimal operational periods.

Wind density (Column 4), articulated in kilowatts per square meter (kW/m²), remains consistently elevated throughout the diurnal cycle, which is crucial for the reliability of wind energy generation. The dataset indicates that wind power reaches its apex at 284 GW around midnight (Column 5), rendering it a dependable energy source, particularly during nocturnal hours when solar energy is non-existent. This constancy in wind energy contribution facilitates the overall power generation (Column 6) to maintain relative stability, with the highest total output of 293 GW occurring at 8 AM, amalgamating both solar and wind inputs. This culminates in the maximum total energy output (Column 7) of 1056 terajoules (TJ) at 9 AM, illustrating the synergy between the two energy sources in fulfilling demand.

Conversely, energy demand (Column 8), which reaches its zenith at 27 GW at 7 AM, generates a substantial energy requirement of 96 TJ during the corresponding hour (Column 9). Despite these peaks in demand, the system adeptly orchestrates an energy surplus, with the most significant surplus of 979 TJ manifesting at 8 AM (Column 10). This surplus is vital as it facilitates the generation of hydrogen, as depicted in Column 12, where the peak hydrogen production is recorded at 646 TJ, translating into 5382 tonnes of hydrogen (Column 13) at 9 AM.

The proficient storage and exportation of hydrogen are further emphasized within the dataset. Hydrogen storage reaches its apogee at 13,393 tonnes at midday (Column 16), guaranteeing an adequate reserve for periods of diminished energy output. This stored hydrogen is also allocated for export, with the maximum export level of 9,239 tonnes occurring at 3 AM (Column 17), exemplifying the system's capability to cater to both domestic energy requirements and generate economic advantages through hydrogen exports.

Notably, the dataset reveals an absence of necessity for the deployment of H2CCGT units (Columns 19 and 20) during the Winter season, highlighting the sufficiency of wind and solar energy in addressing demand without supplementary backup. This is corroborated by the electrolyser capacity (Column 21), which peaks at 276 GW at 2 AM, demonstrating the system's efficacy in transforming surplus energy into hydrogen during periods of excess availability.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Winter Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2 CCGT tonnes	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	0	0	4180	283	283	1018	11	40	979	0	636	5301	150	0	4956	3774	0	0	0	272
1	0	0	0	4200	284	284	1023	9	32	991	0	644	5370	150	0	6334	3774	0	0	0	275

2	0	0	0	4200	284	284	1023	8	29	994	0	646	5382	150	0	7780	3774	0	0	0	276
3	0	0	0	4200	284	284	1023	9	31	992	0	645	5376	150	0	9239	3774	0	0	0	276
4	0	0	0	4200	284	284	1023	12	43	980	0	637	5310	150	0	10691	3774	0	0	0	272
5	0	0	0	4200	284	284	1023	16	56	967	0	629	5239	150	0	12078	3774	0	0	0	269
6	0	0	0	4200	284	284	1023	23	84	939	0	610	5086	150	0	13393	3774	0	0	0	261
7	0	0	0	4200	284	284	1023	27	96	927	0	603	5024	150	0	14556	3774	0	0	0	258
8	335	9	0	4200	284	293	1056	26	93	963	0	626	5218	150	0	15656	3774	0	0	0	268
9	473	13	0	4146	281	293	1056	25	89	967	0	629	5240	150	0	16951	3774	0	0	0	269
10	579	16	0	3823	259	274	988	23	82	905	0	589	4904	150	0	18267	3774	0	0	0	252
11	646	18	0	3407	231	248	893	19	70	823	0	535	4459	150	0	19248	3774	0	0	0	229
12	669	18	0	3199	216	235	845	21	74	770	0	501	4173	150	0	19783	3774	0	0	0	214
13	646	18	0	3093	209	227	817	23	84	733	0	476	3971	150	0	20033	3774	0	0	0	204
14	579	16	0	2916	197	213	767	21	75	692	0	450	3747	150	0	20080	3774	0	0	0	192
15	473	13	0	2717	184	197	708	18	65	643	0	418	3482	150	0	19903	3774	0	0	0	179
16	335	9	0	2569	174	183	659	19	69	590	0	383	3194	150	0	19461	3774	0	0	0	164
17	0	0	0	2361	160	160	575	20	71	504	0	328	2730	150	0	18732	3774	0	0	0	140
18	0	0	0	2071	140	140	505	20	71	434	0	282	2351	150	0	17538	3774	0	0	0	121
19	0	0	0	1782	121	121	434	18	66	368	0	239	1994	150	0	15966	3774	0	0	0	102
20	0	0	0	1580	107	107	385	18	66	319	0	207	1726	150	0	14036	3774	0	0	0	89
21	0	0	0	1405	95	95	342	17	62	281	0	182	1520	150	0	11839	3774	0	0	0	78
22	0	0	0	1365	92	92	333	15	55	278	0	180	1503	150	0	9435	3774	0	0	0	77
23	0	0	0	1606	109	109	391	13	47	344	0	224	1865	150	0	7015	3774	0	0	0	96
Total							18932		1548	17384	0		94164	3592	0						
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Seasons Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	94	3.6		0	91		8593	328	0	8265											

Table 5. Analysis for the winter season

7.3 Analysis for the Spring Season

Table 6 shows that the spring solar energy data show a distinct dynamic when compared to winter, characterized by an increase in solar energy production due to the longer daylight hours and the intensification of solar radiation. Solar radiation (column 1) peaks at 906 W/m² at 12 noon and reaches a peak solar energy production of 25 GW (column 2) during the corresponding hour. This improvement in the solar energy contribution is significantly significant in contrast to winter, where solar energy assumed a more restricted role.

Wind energy (Columns 4 and 5) persists as a reliable source of energy, with the apex of wind power generation documented at 191 GW at 11 AM. While wind energy continues to exhibit reliability, its contribution is marginally diminished relative to Winter, owing to generally more tranquil wind conditions during the Spring. At 12 PM, the joint force of solar and wind energy reaches a high of 215 GW in total power output, which equals 774 terajoules of generated energy.

Energy demand (Columns 8 and 9) during the Spring season is typically lower than that observed in Winter, with the peak demand reaching 10 GW at 7 AM, resulting in an energy requirement of 37 TJ. Notwithstanding this diminished demand, the energy surplus (Column 10) remains robust, characterized by a peak surplus of 746 TJ at 11 AM, thereby facilitating significant hydrogen production. Hydrogen production (Columns 12 and 13) is notably vigorous in the Spring season, with the highest output recorded at 485 TJ, which translates to 4043 tonnes of hydrogen at 11 AM. This surplus production guarantees the maintenance of hydrogen storage (Column 16) and export (Column 17) levels, with 16,313 tonnes stored and 10,051 tonnes exported by the conclusion of the day.

Analogous to the Winter season, there exists a negligible reliance on H2CCGT units (Columns 19 and 20) during the Spring, reflecting the sufficiency of solar and wind energy in fulfilling the demand. The capacity of electrolysers (Column 21) peaks at 207 GW at 11 AM, signifying the effective conversion of surplus energy into hydrogen.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Spring Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2 CCGT	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	0	0	1150	78	78	280	4	15	265	0	172	1435	150	0	6775	1955	0	0	0	74
1	0	0	0	1697	115	115	413	3	12	401	0	261	2173	150	0	6106	1955	0	0	0	111
2	0	0	0	2258	153	153	550	3	11	539	0	350	2918	150	0	6175	1955	0	0	0	150
3	0	0	0	2242	152	152	546	3	12	535	0	347	2895	150	0	6989	1955	0	0	0	148
4	0	0	0	2061	139	139	502	5	16	486	0	316	2631	150	0	7779	1955	0	0	0	135
5	0	0	0	1742	118	118	424	6	21	403	0	262	2184	150	0	8306	1955	0	0	0	112
6	0	0	0	1901	129	129	463	9	32	431	0	280	2335	150	0	8386	1955	0	0	0	120
7	0	0	0	2344	159	159	571	10	37	534	0	347	2894	150	0	8616	1955	0	0	0	148
8	453	12	0	2649	179	192	690	10	35	654	0	425	3543	150	0	9405	1955	0	0	0	182
9	641	17	0	2752	186	204	733	9	34	699	0	455	3788	150	0	10844	1955	0	0	0	194
10	785	21	0	2809	190	211	761	9	31	730	0	474	3952	150	0	12527	1955	0	0	0	203
11	875	24	0	2824	191	215	774	8	27	746	0	485	4043	150	0	14375	1955	0	0	0	207
12	906	25	0	2807	190	215	772	8	29	744	0	483	4028	150	0	16313	1955	0	0	0	207
13	875	24	0	2759	187	210	758	9	32	726	0	472	3931	150	0	18236	1955	0	0	0	202
14	785	21	0	2101	142	163	589	8	29	560	0	364	3031	150	0	20063	1955	0	0	0	155
15	641	17	0	1456	99	116	417	7	25	393	0	255	2127	150	0	20989	1955	0	0	0	109
16	453	12	0	1058	72	84	302	7	26	276	0	179	1493	150	0	21012	1955	0	0	0	77
17	0	0	0	689	47	47	168	8	28	140	0	91	760	150	0	20400	1955	0	0	0	39
18	0	0	0	668	45	45	163	8	27	135	0	88	733	150	0	19055	1955	0	0	0	38
19	0	0	0	361	24	24	88	7	25	63	0	41	339	150	0	17684	1955	0	0	0	17
20	0	0	0	0	0	0	0	7	26	0	26	0	0	150	354	15918	1955	43	7	15	0
21	0	0	0	0	0	0	0	7	24	0	24	0	0	150	327	13459	1955	39	7	14	0
22	0	0	0	0	0	0	0	6	21	0	21	0	0	150	292	11028	1955	35	6	12	0
23	0	0	0	262	18	18	64	5	18	46	0	30	248	150	0	8631	1955	0	0	0	13
Total							10028		593	9504	70		51483	3592	973			117			
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Season Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	51.48	3.59		0.97	46.92		4698	328	89	4281											

Table 6: Analysis for the spring season

7.4 Analysis for the Summer and Autumn Season

The Summer and Autumn seasons present markedly different patterns of energy generation and consumption in comparison to Winter and Spring, predominantly attributable to fluctuations in solar irradiance and wind energy availability as shown in Table 7 and 8.

Summer Season: During the Summer season, solar energy assumes an increasingly significant role, with solar irradiance (Column 1) reaching a zenith of 999 w/m² at 12 PM. This phenomenon culminates in the apex of solar energy production at 27 GW during the identical hour (Column 2), which is substantially greater than the outputs recorded in Winter and Spring. Conversely, wind energy (Column 5) experiences a marked reduction, with the maximum observed wind energy generation being merely 156 GW at 5 PM, indicative of generally more tranquil wind conditions prevalent during the Summer.

Despite the augmented solar energy production, energy consumption (Columns 8 and 9) concurrently escalates, peaking at 23 GW at 7 AM, which corresponds to an energy requirement of 84 TJ. This heightened demand, primarily driven by cooling requirements, results in diminished energy surpluses (Column 10), with the highest surplus recorded at 197 TJ at 1 PM, which is significantly lower than the surpluses observed during Winter and Spring.

Hydrogen generation (Columns 12 and 13) remains considerable, achieving a peak of 339 TJ, translating to 2822 tonnes of hydrogen at 5 PM. Nonetheless, the curtailed surplus energy implies that the levels of hydrogen storage and exportation are correspondingly reduced, with 7,580 tonnes stored and 4,466 tonnes exported by the close of the day.

Fall Season: The Fall season witnesses a reduction in both solar and wind energy outputs in comparison to the Summer. Solar irradiance (Column 2) attains a peak of 906 w/m², leading to a maximum solar energy production of 25 GW (Column 3), comparable to Spring yet inferior to Summer. Wind energy (Column 5) remains at a moderate level, with the highest production registered at 146 GW at 5 PM.

Energy consumption (Columns 8 and 9) during the Fall is marginally lower than that of Summer, with the peak demand reaching 16 GW at 7 AM, equating to an energy utilization of 57 TJ. This diminished demand facilitates an increased energy surplus (Column 10), peaking at 594 TJ at midnight, which bolsters ongoing hydrogen production.

Hydrogen production (Columns 12 and 13) during the Fall is vigorous, achieving a peak output of 344 TJ, which converts to 2864 tonnes of hydrogen at 4 PM. The levels of hydrogen storage and exportation are sustained, with 6,867 tonnes stored and 3,336 tonnes exported by the conclusion of the day.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Summer Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2CCGT	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	0	0	920	62	62	224	11	38	186	0	121	1007	150	0	8001	729	0	0	0	52
1	0	0	0	932	63	63	227	8	30	197	0	128	1066	150	0	8130	729	0	0	0	55
2	0	0	0	893	60	60	218	8	28	190	0	123	1026	150	0	8318	729	0	0	0	53
3	0	0	0	824	56	56	201	8	30	170	0	111	923	150	0	8466	729	0	0	0	47
4	0	0	0	594	40	40	145	11	38	106	0	69	576	150	0	8511	729	0	0	0	30
5	0	0	0	404	27	27	98	15	52	46	0	30	250	150	0	8209	729	0	0	0	13
6	0	0	0	252	17	17	61	18	66	0	5	0	0	150	70	7580	729	8	1	3	0
7	259	7	0	111	8	15	52	23	84	0	31	0	0	150	434	6631	729	52	9	18	0
8	500	14	0	0	0	14	49	22	78	0	30	0	0	150	410	5319	729	49	8	17	0
9	707	19	0	0	0	19	69	21	76	0	7	0	0	150	98	4030	729	12	2	4	0
10	865	24	0	0	0	24	85	20	71	13	0	9	73	150	0	3053	729	0	0	0	4
11	965	26	0	0	0	26	94	17	61	34	0	22	183	150	0	2248	729	0	0	0	9
12	999	27	0	0	0	27	98	19	67	31	0	20	166	150	0	1553	729	0	0	0	9
13	965	26	0	121	8	34	124	21	74	50	0	32	269	150	0	840	729	0	0	0	14
14	865	24	0	658	45	68	245	19	67	178	0	116	963	150	0	230	729	0	0	0	49
15	707	19	0	1352	91	111	398	17	62	336	0	219	1822	150	0	315	729	0	0	0	93
16	500	14	0	1979	134	147	531	18	64	467	0	304	2531	150	0	1259	729	0	0	0	130
17	259	7	0	2308	156	163	588	18	67	521	0	339	2822	150	0	2912	729	0	0	0	145
18	0	0	0	1968	133	133	479	18	66	414	0	269	2242	150	0	4855	729	0	0	0	115
19	0	0	0	1379	93	93	336	17	62	274	0	178	1483	150	0	6219	729	0	0	0	76
20	0	0	0	1086	73	73	265	17	61	203	0	132	1102	150	0	6824	729	0	0	0	57
21	0	0	0	1030	70	70	251	15	56	195	0	127	1058	150	0	7047	729	0	0	0	54
22	0	0	0	1105	75	75	269	14	51	218	0	142	1180	150	0	7227	729	0	0	0	61
23	0	0	0	1209	82	82	295	13	45	249	0	162	1351	150	0	7529	729	0	0	0	69
Total							5401		1395	4079	73		94164	3592	0						
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Season Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	2209	3592		1013	22093	3592	1013	22093	3592	1013											

Table 7: Analysis for the summer season

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Autumn Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2CCGT	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	0	0	2537	172	172	618	7	24	594	0	386	3220	150	0	7172	1558	0	0	0	165
1	0	0	0	2421	164	164	590	5	19	571	0	371	3092	150	0	8684	1558	0	0	0	159
2	0	0	0	2111	143	143	514	5	18	497	0	323	2690	150	0	10068	1558	0	0	0	138
3	0	0	0	1736	117	117	423	5	18	405	0	263	2192	150	0	11051	1558	0	0	0	112
4	0	0	0	1439	97	97	351	7	25	325	0	211	1761	150	0	11535	1558	0	0	0	90
5	0	0	0	1185	80	80	289	9	33	255	0	166	1383	150	0	11588	1558	0	0	0	71
6	0	0	0	744	50	50	181	14	50	131	0	85	710	150	0	11263	1558	0	0	0	36
7	0	0	0	481	33	33	117	16	57	60	0	39	326	150	0	10266	1558	0	0	0	17
8	453	12	0	381	26	38	137	15	55	82	0	53	444	150	0	8884	1558	0	0	0	23
9	641	17	0	288	19	37	133	15	53	80	0	52	433	150	0	7621	1558	0	0	0	22
10	785	21	0	240	16	38	135	14	49	86	0	56	467	150	0	6346	1558	0	0	0	24
11	875	24	0	258	17	41	148	12	42	107	0	69	579	150	0	5105	1558	0	0	0	30
12	906	25	0	349	24	48	174	12	44	129	0	84	701	150	0	3976	1558	0	0	0	36
13	875	24	0	529	36	60	214	14	50	165	0	107	892	150	0	2968	1558	0	0	0	46
14	785	21	0	853	58	79	285	12	45	240	0	156	1298	150	0	2153	1558	0	0	0	67
15	641	17	0	1528	103	121	435	11	39	396	0	257	2145	150	0	1743	1558	0	0	0	110
16	453	12	0	2157	146	158	570	11	41	529	0	344	2864	150	0	2180	1558	0	0	0	147
17	0	0	0	2156	146	146	525	12	42	483	0	314	2615	150	0	3336	1558	0	0	0	134
18	0	0	0	1986	134	134	484	12	42	442	0	287	2393	150	0	4244	1558	0	0	0	123
19	0	0	0	1906	129	129	464	11	39	425	0	276	2302	150	0	4929	1558	0	0	0	118
20	0	0	0	1839	124	124	448	11	39	409	0	266	2213	150	0	5524	1558	0	0	0	113
21	0	0	0	1787	121	121	435	10	37	399	0	259	2159	150	0	6029	1558	0	0	0	111
22	0	0	0	1722	117	117	419	9	33	387	0	251	2095	150	0	6480	1558	0	0	0	107
23	0	0	0	1640	111	111	400	8	28	372	0	242	2013	150	0	6867	1558	0	0	0	103
Total							8489		922	7567	0		40988	3592	0						
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Season Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	41	3.6		0	37		3740	328	0	3412											

Table 8: Analysis for the autumn season

8.1 Maximizing the Efficiency of Solar and Wind Combination for Economical

The Tables 9 and 10 presented elucidate the iterative modifications of the nominal Photovoltaic (PV) GW and Wind GW variables, aimed at optimizing the energy composition while concurrently satisfying both domestic energy requirements and the export objective of 17.5 million tons of hydrogen annually (corresponding to 2100 PJ). The investigation was conducted under two distinct cost paradigms: the conventional pricing of solar PV and an alternative scenario wherein solar PV costs were diminished by 50%. The primary objective in both scenarios was to ascertain the most economically efficient amalgamation of solar and wind energy while concurrently minimizing the overall expenses associated with fulfilling the energy requirements and hydrogen export objectives.

8.2 At Standard Cost of Solar PV

In the initial scenario, characterized by the standard pricing of solar PV, a variety of combinations of solar and wind energy were scrutinized. For example, in the configuration of high solar and low wind (471 GW Solar, 70 GW Wind), the electrolyser capacity was established at 359 GW, necessitating a transmission capacity of 541 GW and hydrogen storage of 34,000 tonnes. This combination, while achieving the requisite energy production and export targets, culminated in the highest aggregate cost of 916 billion USD. As the equilibrium between solar and wind energy was altered, with an increase in wind energy and a corresponding reduction in solar (e.g., 330 GW Solar, 140 GW Wind), the total costs commenced a decline, reaching 799 billion USD. These adjustments exemplify an optimization approach that seeks to reconcile the elevated infrastructural expenses associated with solar energy against the more economically viable wind energy. In the scenario where wind energy was maximized and solar energy minimized (75 GW Solar, 270 GW Wind), the total cost further diminished to 625 billion USD, highlighting the substantial cost efficiencies attainable by favouring wind energy under the standard solar PV cost conditions.

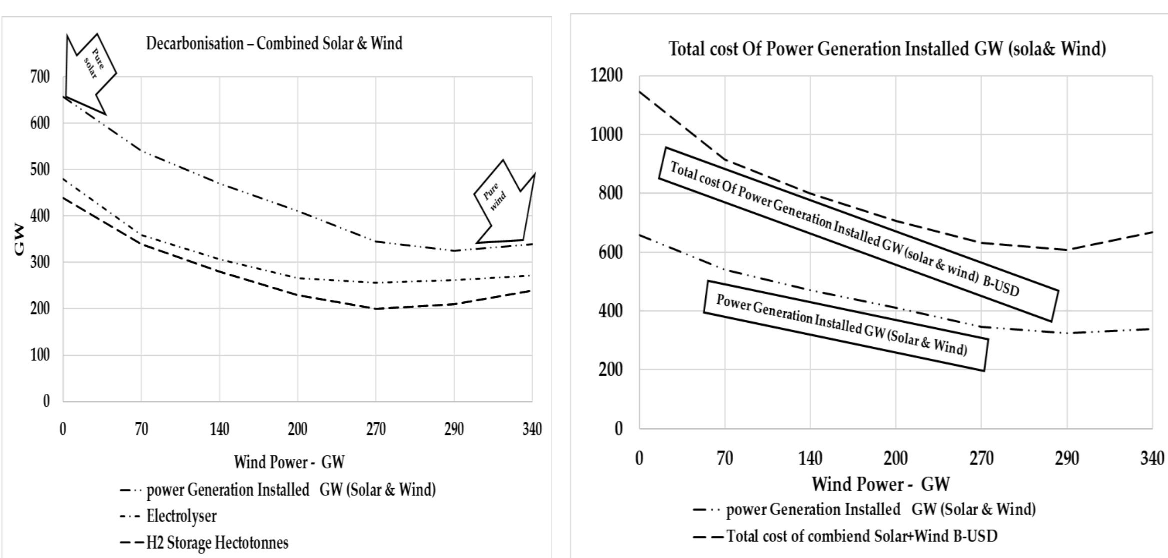
Nominal solar PV	Nominal wind	Electrolyser GW	Total installed GW and Transmission GW	H_2 Storage tonnes	H_2 CCGT units	Total cost of combined Solar Wind B-USD
657	0	491	657	43500	54	1145
471	70	359	541	34000	29	916
330	140	307	470	28000	21	799
211	200	266	411	23000	15	705
75	270	256	345	20000	15	625
35	290	261	325	21000	18	617
0	340	272	340	2400	44	667

Table 9: Analysis of Standard Solar panel Costs for Solar-Wind Power Combination

Based on Figures 4 a-b as well as Table 9, the examination elucidates a definitive correlation between the integration of solar and wind energy resources and the requisite infrastructure, alongside the associated costs necessary to fulfil decarbonization objectives, which include the exportation of 17.5 million tons of hydrogen annually (equivalent to 2,100 petajoules). Figure 4a illustrates the variations in total installed power generation, electrolyser capacity, transmission necessities, and hydrogen storage requirements as the contribution of wind energy escalates. As the capacity of wind energy expands, there is a marginal decline in total installed power generation and related infrastructure demands, signifying efficiency improvements. This pattern indicates that an equitable amalgamation of wind and solar energy is paramount to optimizing the energy system and diminishing infrastructure expenditures. Figure 4b concentrates on the overarching cost ramifications of the solar and wind energy combination. It demonstrates that the costs associated with power generation diminish as the proportion of wind energy elevates, with the most economical outcomes arising when the system is predominantly reliant on wind. This reduction is especially pronounced when juxtaposing the exclusive solar scenario with a more equitable or wind-centric blend. The prospects for economic viability from unifying wind and solar energy sources are unmistakable, since the total costs of a dual solar-wind operation are significantly less than those of systems that depend fully on either wind or solar power.

The corresponding table detailing standard solar photovoltaic costs corroborates these findings. It indicates that as the system transitions from a predominance of solar to a predominance of wind, the requirements for installed power, transmission, and hydrogen storage diminish, along with the quantity of H2CCGT units necessitated. This transition also culminates in a notable abatement in the total expenditure of a combined solar-wind system, with the most financially advantageous solution identified in the scenario exhibiting the highest wind contribution.

Significantly, such an analysis accentuates the critical necessity of optimizing the equilibrium between solar and wind energy to mitigate infrastructure costs and enhance efficiency in satisfying domestic energy demands and hydrogen export objectives.



4a 4b

Figure 4 A-B: Decarbonization - Solar and Wind Combined

8.1 Impact Of 50% Cost Reduction of Solar Pv On Combined Wind and Solar Systems

Table 10 and Figure 4- a,b provide a comprehensive analysis of the ramifications associated with a 50% diminution in solar photovoltaic (PV) costs concerning the overarching infrastructure and financial implications tied to a synergistic solar and wind power generation system aimed at fulfilling the hydrogen export objective of 17.5 million tons annually. The table delineates various configurations of solar and wind capacities, complemented by the requisite specifications for electrolyser capacity, transmission capacity, hydrogen storage, and hydrogen combined cycle gas turbine (H2CCGT) units. Furthermore, it encapsulates the cumulative total expenditure expressed in billions of United States dollars. In the figure, two distinct curves illustrate the total expenditures correlated with varying degrees of total installed power generation (measured in gigawatts), juxtaposing the initial standard solar PV cost against the 50% diminished solar PV cost. The dotted line signifies the standard solar PV cost scenario, while the dashed line represents the scenario incorporating the reduced solar PV cost.

Nominal solar PV	Nominal wind	Electrolyser GW	Total installed GW and Transmission GW	H_2 Storage tonnes	H_2 CCGT units	Total cost of combined Solar Wind B-USD
657	0	491	657	43500	54	743
471	70	359	541	34000	29	628
330	140	307	470	28000	21	598
211	200	266	411	23000	15	576
75	270	256	345	20000	15	585
35	290	261	325	21000	18	595
0	340	272	340	2400	44	667

Table 10: Analysis of 50% PV panel Costs for Solar-Wind Power Combination

The analysis reveals that a 50% reduction in solar PV costs engenders substantial cost efficiencies across all scenarios examined. For instance, in the scenario encompassing 471 GW of solar and 70 GW of wind, the total expenditure decreases from $916 billion under the standard PV costs to $628 billion under the reduced PV costs. The minimum cost observed in the scenario with a 50% reduction in PV costs is $576 billion, attained with a configuration comprising 211 GW of solar and 200 GW of wind. This analysis substantiates the notion that a reduction in solar PV costs catalyses significant declines in overall system costs, rendering solar-centric configurations increasingly economically viable. A combined solar and wind strategy, coupled with a 50% reduction in solar PV costs, consistently yields the most favourable cost outcomes while preserving the requisite infrastructure to satisfy hydrogen export targets.

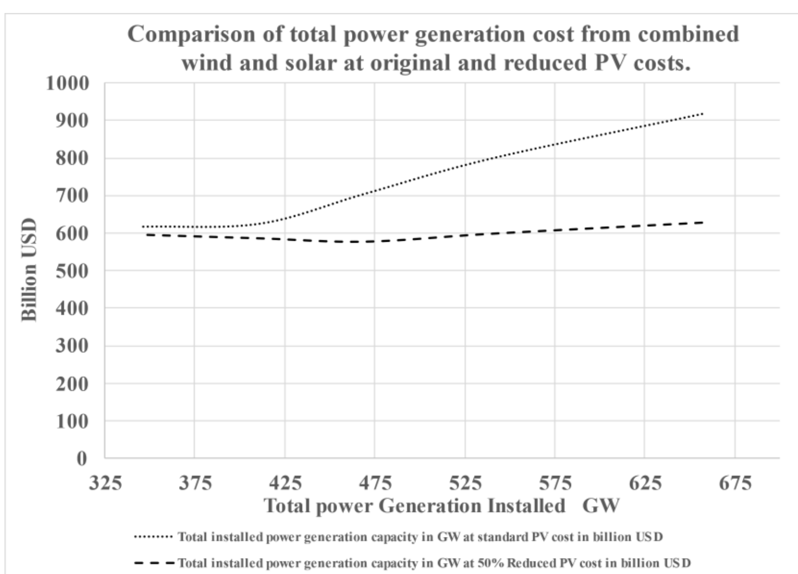


Figure 5: Comparison of total power generation cost

8.1 Case Studies 2 Integrating Wind, Solar, And Hecc

examine comprehensive decarbonization strategies through the strategic integration of renewable energy resources (wind and solar) and closed helium cycles. In this context, solar, wind and compressed helium energy emerge as key energy sources, and their combined impact on reducing carbon emissions and enhancing energy sustainability is evaluated. These case studies assess the operational effectiveness, capacity and infrastructure requirements of solar, wind and compressed helium power generation in meeting energy demand while simultaneously facilitating the production and export of hydrogen as a viable clean energy carrier. The main objective is to evaluate the collaborative functions of solar, wind and compressed helium energy in creating a flexible and carbon-free energy system, where hydrogen combined cycle gas turbines (H2CCGT), which were an auxiliary solution when solar and wind resources were insufficient in the first scenario, are eliminated.

8.2 Winter Season Analysis

During the winter season, the energy infrastructure is predominantly dependent on wind energy owing to the restricted solar irradiance, as demonstrated in Table 11. Solar energy achieves a moderate peak of 21 GW when irradiance ascends to 669 W/m² at noon. Conversely, wind energy delivers a consistent and substantial contribution, reaching a zenith of 216 GW, thereby maintaining the overall power generation stability. The highest total energy generation for a one-hour interval is documented at 911 TJ at 08:00 hours. The energy requirement during the winter months surges in the early morning hours, attaining 96 TJ, yet the system reliably generates an energy surplus, with the most significant surplus of 834 TJ recorded at 00:00 hours. This surplus facilitates considerable hydrogen production, with a peak output of 542 TJ, equating to 4516 tonnes of hydrogen at midnight. The proficient management of hydrogen storage is also observable, with storage capacities escalating to 13,393 tonnes by midday. Additionally, hydrogen exports reach a pinnacle of 9,239 tonnes at 03:00 hours, signifying the system's proficiency in producing surplus energy for hydrogen exportation. Importantly, the incorporation of compressed helium energy effectively obviates the necessity for Hydrogen Combined Cycle Gas Turbines (H2CCGT), showcasing the system's adeptness in addressing winter energy requirements exclusively through wind, solar, and helium storage.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Winter Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2 CCGT tonnes	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	28	4180	215	243	873	11	40	834	0	542	4516	150	0	3252	3313	0	0	0	232	0
1	0	27	4200	216	243	874	9	32	842	0	547	4562	150	0	4306	3313	0	0	0	234	0
2	0	27	4200	216	243	874	8	29	844	0	549	4574	150	0	5405	3313	0	0	0	235	0
3	0	27	4200	216	243	874	9	31	843	0	548	4567	150	0	6517	3313	0	0	0	234	0
4	0	27	4200	216	243	874	12	43	831	0	540	4502	150	0	7622	3313	0	0	0	231	0
5	0	27	4200	216	243	874	16	56	818	0	532	4430	150	0	8662	3313	0	0	0	227	0
6	0	27	4200	216	243	874	23	84	790	0	513	4278	150	0	9630	3313	0	0	0	219	0
7	0	27	4200	216	243	874	27	96	778	0	506	4216	150	0	10445	3313	0	0	0	216	0
8	10	27	4200	216	253	911	26	93	819	0	532	4435	150	0	11199	3313	0	0	0	227	10
9	15	27	4146	213	255	917	25	89	828	0	538	4485	150	0	12171	3313	0	0	0	230	15
10	18	27	3823	196	241	869	23	82	786	0	511	4260	150	0	13194	3313	0	0	0	218	18
11	20	27	3407	175	222	799	19	70	730	0	474	3952	150	0	13991	3313	0	0	0	203	20
12	21	27	3199	164	212	764	21	74	689	0	448	3734	150	0	14481	3313	0	0	0	191	21
13	20	27	3093	159	206	741	23	84	658	0	428	3564	150	0	14753	3313	0	0	0	183	20
14	18	27	2916	150	195	701	21	75	626	0	407	3391	150	0	14854	3313	0	0	0	174	18
15	15	27	2717	139	181	653	18	65	587	0	382	3182	150	0	14783	3313	0	0	0	163	15
16	10	27	2569	132	169	610	19	69	541	0	352	2931	150	0	14502	3313	0	0	0	150	10
17	0	27	2361	121	148	534	20	71	463	0	301	2507	150	0	13971	3313	0	0	0	129	0
18	0	27	2071	106	133	480	20	71	410	0	266	2221	150	0	13015	3313	0	0	0	114	0
19	0	27	1782	91	119	427	18	66	361	0	235	1956	150	0	11774	3313	0	0	0	100	0
20	0	27	1580	81	108	390	18	66	324	0	210	1752	150	0	10267	3313	0	0	0	90	0
21	0	27	1405	72	99	357	17	62	296	0	192	1602	150	0	8557	3313	0	0	0	82	0
22	0	27	1365	70	97	350	15	55	295	0	192	1598	150	0	6697	3313	0	0	0	82	0
23	0	27	1606	82	110	394	13	47	348	0	226	1882	150	0	4832	3313	0	0	0	97	0
Total							16889		1548	15340	0		83094	3592	0						
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Season Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	83	3.6	0	80		7582	328	0	7255	83											

Table 11. Analysis for the winter season

8.3 Spring Season Analysis

The vernal season experiences advantages from an augmentation of daylight duration, as illustrated in Table 12, culminating in an elevation of solar irradiance, which attains a zenith of 906 W/m² at solar noon, thereby facilitating the generation of solar power up to 28 GW. The contribution of wind energy remains pivotal, albeit with a marginal decrease relative to the winter months, exhibiting a maximal output of 145 GW at noon. Cumulatively, the total energy generation reaches 199 GW during peak operational hours, translating into an hourly energy yield of as much as 774 TJ. The energy consumption during spring is comparatively diminished in relation to winter, peaking at 37 TJ at 7 AM. The energy surplus in the spring season is also noteworthy, peaking at 746 TJ at 11 AM, which enables considerable hydrogen production, amounting to 447 TJ (4043 tonnes) at the same hour. The infrastructure for hydrogen storage and export is effectively upheld, with peak storage capacity reaching 16,313 tonnes and export quantities at 10,051 tonnes by the conclusion of the day. The compressed helium energy system continues to function proficiently, thereby obviating the necessity for H_2CCGT units, highlighting the system's operational efficiency, which relies solely on solar and wind energy inputs throughout the spring season.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Spring Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2 CCGT tonnes	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	0	27	1150	59	86	308	4	15	293	0	191	1588	150	0	4559	2006	0	0	0	81
1	0	0	27	1697	87	114	409	3	12	397	0	258	2152	150	0	3990	2006	0	0	0	110
2	0	0	27	2258	116	143	513	3	11	502	0	326	2718	150	0	3986	2006	0	0	0	139
3	0	0	27	2242	115	142	510	3	12	498	0	324	2700	150	0	4548	2006	0	0	0	138
4	0	0	27	2061	106	132	477	5	16	460	0	299	2493	150	0	5091	2006	0	0	0	128
5	0	0	27	1742	89	116	418	6	21	397	0	258	2148	150	0	5429	2006	0	0	0	110
6	0	0	27	1901	98	124	447	9	32	415	0	270	2248	150	0	5421	2006	0	0	0	115
7	0	0	27	2344	120	147	529	10	37	492	0	320	2666	150	0	5512	2006	0	0	0	137
8	453	14	27	2649	136	177	636	10	35	600	0	390	3253	150	0	6023	2006	0	0	0	167
9	641	20	27	2752	141	188	676	9	34	642	0	417	3478	150	0	7119	2006	0	0	0	178
10	785	24	27	2809	144	195	703	9	31	671	0	436	3636	150	0	8441	2006	0	0	0	186
11	875	27	27	2824	145	199	715	8	27	688	0	447	3729	150	0	9921	2006	0	0	0	191
12	906	28	27	2807	144	199	716	8	29	687	0	447	3721	150	0	11493	2006	0	0	0	191
13	875	27	27	2759	142	195	703	9	32	671	0	436	3637	150	0	13058	2006	0	0	0	187
14	785	24	27	2101	108	159	572	8	29	543	0	353	2940	150	0	14539	2006	0	0	0	151
15	641	20	27	1456	75	121	436	7	25	412	0	268	2230	150	0	15323	2006	0	0	0	114
16	453	14	27	1058	54	95	342	7	26	316	0	205	1709	150	0	15397	2006	0	0	0	88
17	0	0	27	689	35	62	223	8	28	195	0	127	1059	150	0	14950	2006	0	0	0	54
18	0	0	27	668	34	61	219	8	27	192	0	125	1039	150	0	13853	2006	0	0	0	53
19	0	0	27	361	19	45	162	7	25	137	0	89	743	150	0	12736	2006	0	0	0	38
20	0	0	27	0	0	27	96	7	26	70	0	46	380	150	0	11323	2006	0	0	0	20
21	0	0	27	0	0	27	96	7	24	72	0	47	391	150	0	9547	2006	0	0	0	20
22	0	0	27	0	0	27	96	6	21	75	0	49	405	150	0	7782	2006	0	0	0	21
23	0	0	27	262	13	40	144	5	18	126	0	82	684	150	0	6031	2006	0	0	0	35
Total							10147		593	9553	0		51746	3592	0						
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Season Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	52	3.6	0	48		4722	328	0	4394	52											

Table 12: Analysis for the spring season

8.4 Summer Season Analysis

As delineated in Table 13, the summer season witnesses the prominence of solar energy attributable to heightened solar irradiance, which attains a zenith of 999 W/m² at noon, culminating in a maximal solar power generation of 31 GW. The contribution of wind power is diminished during the summer months, exhibiting a peak output of 156 GW in the late afternoon. The overall energy production reaches its apex during midday, with a cumulative energy total of 515 TJ recorded at 4 PM. Nevertheless, the energy surplus during the summer is inferior to that of other seasons, with the most substantial surplus documented at 245 TJ at 2 PM. In spite of the diminished surplus, hydrogen production remains vigorous, peaking at 314 TJ (equivalent to 2615 tonnes) at 5 PM. The management of hydrogen storage and export levels is executed proficiently, with 7,580 tonnes retained and 4,466 tonnes dispatched by the conclusion of the day. The system's dependency on compressed helium serves to offset the reduced output of wind power, thereby ensuring grid stability and obviating the necessity for H_2CCGTs throughout the summer.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Summer Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2 CCGT tonnes	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	0	26	920	47	73	264	11	38	226	0	147	1222	150	0	5532	1033	0	0	0	63
1	0	0	26	932	48	74	266	8	30	236	0	153	1278	150	0	5572	1033	0	0	0	66
2	0	0	26	893	46	72	259	8	28	231	0	150	1250	150	0	5667	1033	0	0	0	64
3	0	0	26	824	42	68	246	8	30	216	0	140	1169	150	0	5735	1033	0	0	0	60
4	0	0	26	594	30	57	204	11	38	165	0	107	895	150	0	5722	1033	0	0	0	46
5	0	0	26	404	21	47	169	15	52	116	0	76	629	150	0	5434	1033	0	0	0	32
6	0	0	26	252	13	39	140	18	66	74	0	48	401	150	0	4881	1033	0	0	0	21
7	259	8	26	111	6	40	143	23	84	60	0	39	323	150	0	4099	1033	0	0	0	17
8	500	16	26	0	0	42	150	22	78	71	0	46	386	150	0	3240	1033	0	0	0	20
9	707	22	26	0	0	48	173	21	76	97	0	63	523	150	0	2443	1033	0	0	0	27
10	865	27	26	0	0	53	191	20	71	119	0	78	647	150	0	1784	1033	0	0	0	33
11	965	30	26	0	0	56	202	17	61	141	0	92	764	150	0	1248	1033	0	0	0	39
12	999	31	26	0	0	57	206	19	67	138	0	90	750	150	0	830	1033	0	0	0	38
13	965	30	26	121	6	62	224	21	74	150	0	97	811	150	0	397	1033	0	0	0	42
14	865	27	26	658	34	87	312	19	67	245	0	159	1327	150	0	26	1033	0	0	0	68
15	707	22	26	1352	69	117	423	17	62	361	0	234	1954	150	0	171	1033	0	0	0	100
16	500	16	26	1979	102	143	515	18	64	452	0	294	2447	150	0	942	1033	0	0	0	125
17	259	8	26	2308	118	153	549	18	67	483	0	314	2615	150	0	2206	1033	0	0	0	134
18	0	0	26	1968	101	127	458	18	66	392	0	255	2123	150	0	3638	1033	0	0	0	109
19	0	0	26	1379	71	97	349	17	62	287	0	186	1553	150	0	4579	1033	0	0	0	80
20	0	0	26	1086	56	82	295	17	61	233	0	152	1264	150	0	4949	1033	0	0	0	65
21	0	0	26	1030	53	79	284	15	56	229	0	149	1238	150	0	5031	1033	0	0	0	64
22	0	0	26	1105	57	83	298	14	51	247	0	160	1336	150	0	5087	1033	0	0	0	69
23	0	0	26	1209	62	88	317	13	45	272	0	177	1474	150	0	5241	1033	0	0	0	76
Total							6635		1395	5240	0		28381	3592	0			0			
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Season Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	28	3.6	0	25		2590	328	0	2262	28											

Table 13: Analysis for the summer season

8.5 Autumn Season Analysis

During the autumn season, the energy system undergoes an adaptation to the diminishing availability of solar and wind energy, as illustrated in Table 14. Solar irradiance attains a zenith of 906 W/m², facilitating the generation of up to 28 GW of solar power. Wind energy reaches a maximum output of 146 GW in the late afternoon, thereby contributing to an aggregate power generation of 545 TJ by 4 PM. The energy demand experienced in autumn is marginally lower compared to that of summer, with a peak demand of 57 TJ recorded at 7 AM. This reduced demand culminates in a more stable energy surplus, which peaks at 504 TJ by 4 PM. The production of hydrogen is effectively sustained, achieving a peak of 328 TJ (equivalent to 2730 tonnes) by 4 PM. The system adeptly manages the storage and export of hydrogen, with a maximum storage capacity of 6,867 tonnes and total exports amounting to 3,336 tonnes by the end of the day. Furthermore, the incorporation of compressed helium energy guarantees the seamless functionality of the system in the absence of H_2CCGT units, notwithstanding the decline in available solar and wind resources.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Autumn Hour	solar illumination w/m²	solar power produced GW	HeCC Power Produced GW	wind density kw/m²	wind power produced GW	total power produced GW	total energy produced for hour TJ	power demand for hour GW	energy demand for hour TJ	hourly energy surplus- TJ for elect	hourly energy deficit- TJ	H_2 produced TJ of FCV	H_2 produced tonnes	H_2 day demand tonnes	H_2 for H_2 CCGT tonnes	H_2 stored tonnes	H_2 export tonnes	H_2 FCV for CCGTs tones	H_2CCGTs GW	600 MW H_2CCGTs needed	electrolysis GW
0	0	0	27	2537	130	157	565	7	24	541	0	352	2931	150	0	4896	1669	0	0	0	150
1	0	0	27	2421	124	151	543	5	19	524	0	341	2840	150	0	6008	1669	0	0	0	146
2	0	0	27	2111	108	135	486	5	18	468	0	304	2537	150	0	7030	1669	0	0	0	130
3	0	0	27	1736	89	116	417	5	18	398	0	259	2158	150	0	7748	1669	0	0	0	111
4	0	0	27	1439	74	100	362	7	25	336	0	219	1821	150	0	8087	1669	0	0	0	93
5	0	0	27	1185	61	87	315	9	33	281	0	183	1524	150	0	8090	1669	0	0	0	78
6	0	0	27	744	38	65	233	14	50	183	0	119	992	150	0	7796	1669	0	0	0	51
7	0	0	27	481	25	51	185	16	57	128	0	83	692	150	0	6969	1669	0	0	0	35
8	453	14	27	381	20	60	217	15	55	162	0	105	876	150	0	5843	1669	0	0	0	45
9	641	20	27	288	15	61	221	15	53	168	0	109	909	150	0	4900	1669	0	0	0	47
10	785	24	27	240	12	63	228	14	49	179	0	116	968	150	0	3990	1669	0	0	0	50
11	875	27	27	258	13	67	241	12	42	200	0	130	1082	150	0	3140	1669	0	0	0	55
12	906	28	27	349	18	73	262	12	44	217	0	141	1177	150	0	2403	1669	0	0	0	60
13	875	27	27	529	27	81	291	14	50	242	0	157	1309	150	0	1762	1669	0	0	0	67
14	785	24	27	853	44	95	341	12	45	296	0	193	1604	150	0	1252	1669	0	0	0	82
15	641	20	27	1528	78	125	450	11	39	411	0	267	2226	150	0	1038	1669	0	0	0	114
16	453	14	27	2157	111	151	545	11	41	504	0	328	2730	150	0	1445	1669	0	0	0	140
17	0	0	27	2156	111	137	494	12	42	452	0	294	2447	150	0	2356	1669	0	0	0	126
18	0	0	27	1986	102	129	463	12	42	421	0	274	2279	150	0	2985	1669	0	0	0	117
19	0	0	27	1906	98	124	448	11	39	409	0	266	2214	150	0	3446	1669	0	0	0	114
20	0	0	27	1839	94	121	436	11	39	396	0	258	2146	150	0	3841	1669	0	0	0	110
21	0	0	27	1787	92	118	426	10	37	389	0	253	2109	150	0	4169	1669	0	0	0	108
22	0	0	27	1722	88	115	414	9	33	381	0	248	2065	150	0	4459	1669	0	0	0	106
23	0	0	27	1640	84	111	399	8	28	371	0	241	2009	150	0	4706	1669	0	0	0	103
Total							8979		922	8057	0		43643	3592	0			0			
Season Totals per day	H_2 Produced kt	Daily H_2 kt		H_2 for H_2CCGT kt	Export H_2 kt	Season Totals	H_2 Produced kt	Daily H_2 kt	$H_2$for H_2CCGT kt	Export H_2 kt											
	44	3.6	0	40		3982	328	0	3655	44											

Table 14: Analysis for the autumn season

9.1 Enhancing the integration of solar, wind, and hecc for efficient hydrogen generation and export at minimal costs.

The subsequent examination investigates the integration of solar, wind, and HeCC (Hybrid Energy Conversion Cycle) power generation systems to fulfil the dual objective of addressing domestic energy demands and facilitating the export of 17.5 million tons of hydrogen on an annual basis (which is equivalent to 2100 PJ). This investigation was undertaken within two distinct cost scenarios: the prevailing standard cost associated with solar photovoltaic technology and an alternative scenario wherein solar PV costs are diminished by 50%. The primary aim is to ascertain the most economically advantageous combination of solar, wind, and HeCC energy sources while concurrently minimizing the aggregate infrastructure expenditures necessary to achieve both energy production and hydrogen exportation goals.

9.2 Cost Analysis Under Standard Solar Pv Pricing

In the initial scenario, which presupposes conventional pricing for solar photovoltaic (PV) systems, diverse configurations encompassing solar PV, wind, and hydrogen electrolysis carbon capture (HeCC) power generation were scrutinized. Table 15 provides a comprehensive overview of these configurations alongside their respective financial implications. For instance, in a configuration predominantly reliant on solar energy with negligible wind contribution (475 GW Solar, 0 GW Wind, and 28 GW HeCC), the requisite electrolyser capacity is determined to be 365 GW, accompanied by a transmission capacity of 503 GW and hydrogen storage spanning 31,000 hectares. This arrangement culminates in an aggregate system expenditure of 817 billion USD.

As the ratio of wind energy escalates, concomitant with a reduction in solar capacity, the overall costs commence a downward trend. For instance, with 276 GW of solar, 100 GW of wind, and 28 GW of HeCC, the cumulative cost is diminished to 646 billion USD. The scenario exhibiting the most favourable cost is identified when wind energy is maximized and solar energy is minimized (78 GW Solar, 200 GW Wind, and 28 GW HeCC), which yields a total expenditure of 499 billion USD. This analysis underscores the substantial economic advantages realized by enhancing the share of wind energy within the composite power generation portfolio.

Nominal solar PV	Nominal wind	HeCC	power Generation Installed GW	Electrolyser GW	Transmission GW	H_2 Storage Hectotonnes	H_2CCGT units	Total cost of combined Solar, Wind and HeCC B-USD
475	0	28	503	365	503	31000	0	817
375	50	28	453	307	453	26000	0	724
276	100	28	404	271	404	22000	0	646
177	150	28	355	237	355	18000	0	570
78	200	28	306	211	306	15000	0	499
40	220	28	288	235	288	15360	0	494

Table 15: Cost Analysis of Solar-Wind-HeCC Power Integration at Standard Solar PV Prices

As depicted in Figures 6a and 6b, a discernible trend emerges, demonstrating that an augmentation in wind energy leads to a concomitant decrease in the overall infrastructure requirements and associated costs. This trend accentuates the necessity of achieving a harmonious balance between solar and wind energy to optimize the energy system, thereby facilitating cost efficiencies in both hydrogen production and exportation.

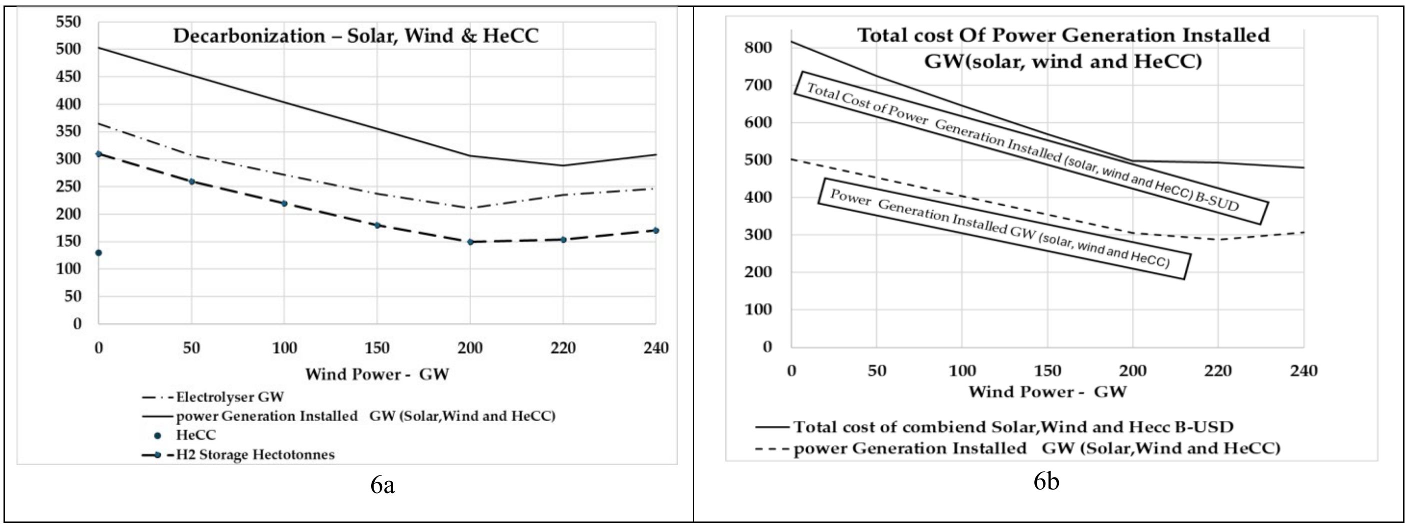


Figure 6 a-b: Decarbonization – Solar, Wind and HeCC.

9.3 Impact of A 50% Reduction in Solar Pv Costs on Solar-Wind-Hecc Power Systems

Table 16 and Figure 7 present a comprehensive analysis concerning the ramifications of a 50% reduction in solar PV expenditures on the cumulative system costs and infrastructure necessities pertinent to integrated solar, wind, and HeCC power generation. The table delineates a range of scenarios, emphasizing the total installed power generation capacity, electrolyser specifications, transmission capacity, hydrogen storage requirements, and the aggregate cost expressed in billions of USD. In the context of a 50% reduction in solar PV expenditures, the overall system costs exhibit a substantial decline across all scenarios analysed. For instance, within the scenario encompassing 475 GW of solar, 0 GW of wind, and 28 GW of HeCC, the total cost experiences a reduction from 817 billion USD to 527 billion USD. The most economical outcome in this scenario characterized by diminished PV costs is observed with 78 GW of solar, 200 GW of wind, and 28 GW of HeCC, culminating in a total expenditure of 499 billion USD. This reduction in costs illustrates that a decrease in solar PV expenditures can enhance the economic viability of solar-dominant configurations; however, the most cost-effective results continue to derive from a well-balanced integration of both wind and solar energy sources.

Nominal solar PV	Nominal wind	HeCC	power Generation Installed GW	Electrolyser GW	Transmission GW	H_2 Storage Hectotonnes	H2CCGT units	Total cost of combined Solar, Wind and HeCC B-USD
475	0	28	503	365	503	31000	0	527
375	50	28	453	307	453	26000	0	724
276	100	28	404	271	404	22000	0	646
177	150	28	355	237	355	18000	0	570
78	200	28	306	211	306	15000	0	499
40	220	28	288	235	288	15360	0	494

Table 16: Cost Analysis of Solar-Wind-HeCC Power Integration with 50% Reduced PV Costs

Figure 7 provides a visual representation comparing the overall power generation expenditures associated with standard solar photovoltaic (PV) costs versus those in reduced cost scenarios, thereby elucidating the economic advantages derived from diminished solar costs, particularly in the context of the integration of solar energy with wind and Hydrogen Energy with Carbon Capture (HeCC) power modalities.

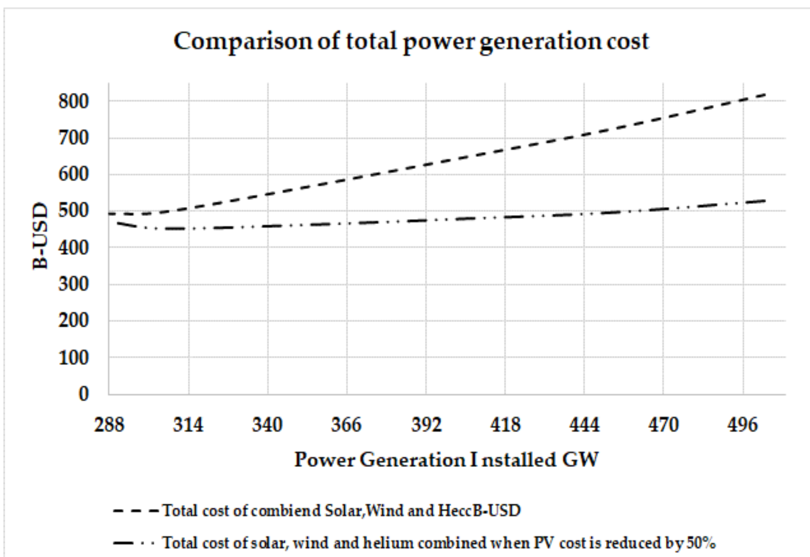


Figure 7: Comparison of total power generation cost

These evaluations underscore the imperative of optimizing the energy portfolio comprising solar, wind, and HeCC sources to facilitate economically viable hydrogen production and subsequent exportation, especially considering the fluctuations in solar PV cost scenarios.

10. Conclusion

This paper examines the feasibility of using solar PV, wind, and helium combined cycle gas turbines (HeCCGT) to achieve carbon emission reduction and boost hydrogen exports in oil-dependent countries. Two distinct scenarios are analyzed: the first scenario integrates hydrogen combined cycle gas turbines (H2CCGT) as a complementary power source to solar and wind, while the latter scenario replaces hydrogen combined cycle gas turbines (H2CCGT) with helium combined cycle gas turbines (HeCCGT), thereby increasing the overall system efficiency. The main results confirm that during peak operational periods, solar irradiance can rise to 999 W/m2, resulting in significant solar power generation, while wind power provides a steady contribution, especially in the winter months, peaking at 284 GW. The analysis also indicates that hydrogen combined cycle gas turbines effectively stabilize power production, thereby eliminating the need for backup power systems in the second scenario. Hydrogen production remains robust throughout all seasons, with peak production reaching

646 TJ in winter, equivalent to 5,382 tonnes of hydrogen (2,100 PJ, equivalent to Libya's annual oil production). Note 2100 PJ is equivalent to 17 500 000 tonnes, of H2 for oil export replacement From an economic perspective, the 50% cost reduction associated with solar PV systems significantly reduces the total system overhead, making solar-focused configurations more feasible, although the most economically beneficial approach remains a balanced integration of solar and wind energy sources. These findings provide a strategic framework for optimizing the energy portfolios of oil-dependent countries, thereby facilitating their transition towards sustainable energy systems while simultaneously advancing global decarbonization initiatives.

It is of interest that Libya, normally thought of as a sunny country requires double the solar capacity than wind generation capacity. This is primarily due to the low utilization arising from long periods of darkness. It is also of interest to note that the area required for solar power is a third of what is needed for wind energy, notwithstanding the much larger solar generation capacity needed. This presents a very interesting dilemma for energy planners. In particular it raises the matter of how land areas could offer additional utilization opportunities. Finally, the methods, although approximate, do reveal a need for vast investments in decarbonization.

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