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RESEARCH ARTICLE

Techno-economic Analysis of Large-scale Integration of Variable Renewable Energy Sources into Myanmar's National Grid with Interconnection and Energy Storage System

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Abstract

Myanmar’s abundant hydropower, solar, and wind resources present significant opportunities for a sustainable energy transition. Hydropower, with a potential capacity of 19,567 MW, currently forms the backbone of the energy strategy, though its seasonal variability necessitates improved transmission networks and planning. Solar energy, with an annual potential of 51,973.8 TWh, is increasingly utilized for both utility-scale and off-grid applications, while wind energy, with a theoretical potential of 80 TWh annually, requires further exploration. This study employs the EnergyPLAN modeling tool to analyze the techno-economic feasibility of integrating variable renewable energy sources (VRES) into Myanmar’s grid by 2030, targeting 11% of electricity generation from solar and wind. Five scenarios were examined, highlighting the role of grid flexibility solutions such as cross-border interconnections and energy storage system (ESS). Without flexibility measures, Critical Excess Electricity Production (CEEP) could reach 7.69 TWh annually. Introducing interconnections reduces CEEP to 0.57 TWh, while the combined deployment of interconnections and ESS further minimizes CEEP to 0.41 TWh and increases Exportable Excess Electricity Production (EEEP) to 7.29 TWh. These results underscore the importance of strategic investments in ESS and regional interconnections to address VRES variability, enhance grid stability, and reduce curtailment. Such measures are crucial for optimizing Myanmar’s renewable energy potential, advancing its energy transition, and reinforcing its position in the ASEAN regional energy market.

Keywords: EnergyPLAN modelling tool, energy storage system (ESS), interconnection, techno economic,variable renewable energy sources (VRES)

I. Introduction

Myanmar, rich in natural resources, is well-positioned for a transformative energy transition through the integration of variable renewable energy sources (VRES), such as solar and wind. Hydropower, currently the cornerstone of the energy mix, contributes significantly to electricity generation but is highly dependent on seasonal rainfall, leaving the grid vulnerable during dry periods. Solar energy, with substantial potential, is particularly advantageous for off-grid electrification in remote areas. Wind energy, though underdeveloped, holds promise for future expansion with site-specific studies. However, the inherent variability of VRES presents challenges to grid stability and reliability, necessitating advanced strategies for integration. Strengthening interconnections within Myanmar and with neighboring countries is vital for stabilizing power supply, enabling cross-border energy trade, and mitigating renewable energy fluctuations. Energy storage system (ESS) further enhances grid flexibility by storing surplus energy, reducing curtailment, and providing power during low-output periods. Myanmar’s grid infrastructure is not yet equipped to accommodate high VRES penetration. Challenges such as Critical Excess Electricity Production (CEEP) and curtailment reduce the efficiency of renewable energy utilization. While global studies emphasize the importance of flexibility solutions, there is limited research addressing Myanmar’s specific energy context. This study fills the gap by employing the EnergyPLAN modeling tool to evaluate five integration scenarios for 2030. It assesses the impact of interconnections and ESS on CEEP, exportable electricity, and grid reliability. The findings offer practical pathways to optimize renewable energy use, support Myanmar’s sustainable energy transition, and enhance its role in ASEAN’s regional energy market.

II. Methods

A. Renewable Energy Potential in Myanmar

Myanmar holds immense potential for renewable energy expansion, particularly in hydropower, solar, and wind. The country's favorable topography and climatic conditions create ideal opportunities to increase the contribution of renewables to its energy portfolio.

1) Hydropower: Hydropower plays a central role in Myanmar’s energy landscape. To fully harness its potential, the Ministry of Electric Power (MOEP) must revise the long-term Power Development Plan, factoring in peak demand and transmission capacity. Given that most hydropower projects are located in the northern regions, expanding transmission infrastructure is essential. Seasonal

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fluctuations between rainy and dry periods highlight the importance of strategic planning. While social and environmental considerations remain significant, Myanmar has identified a hydropower potential of 19,567 MW [1], with an installed capacity of 3,228 MW [2]. To ensure reliability and cost-efficiency during the dry season, it is crucial to explore diverse electricity procurement options, including thermal power generation and imports.

2) Solar Power: Solar energy has become a promising renewable solution in Myanmar, with the potential to meet the country's energy demands while reducing environmental impacts. Although challenges persist, such as inadequate infrastructure and regulatory limitations, Myanmar’s abundant solar resources—boasting an estimated annual potential of 51,973.8 TWh and over 5 average sun hours per day—highlight a significant opportunity for expansion [3]. Recent efforts to tap into this potential have led to a steady rise in solar projects, encompassing both utility-scale installations and off-grid systems designed to provide electricity to remote areas.

3) Wind Power: Wind energy in Myanmar is an emerging renewable resource with great potential to diversify the country’s energy mix and reduce dependence on fossil fuels. Myanmar's coastal and highland regions offer favorable wind conditions for power generation, making them ideal for development. However, wind energy remains in its infancy, with only a few pilot projects and minimal installed capacity. As part of its renewable energy strategy, Myanmar has set a goal to generate 11% of its electricity from solar and wind by 2030 [1]. With continued government support, international partnerships, and targeted investments, wind energy is expected to play a pivotal role in meeting the country’s rising energy demands and advancing its sustainable development objectives.

B. EnergyPLAN Modelling Tool

This study employs the EnergyPLAN tool to model Myanmar’s power system, simulating both current and future scenarios for integrating renewable energy sources (RES). The model incorporates key data, including electricity demand, generation capacity, fuel consumption, and greenhouse gas emissions, to create a comprehensive view of Myanmar's power landscape. Future scenarios are developed to assess the impact of cross-border interconnections on grid stability and RES penetration, providing insights into Myanmar’s pathway for renewable energy expansion.

The EnergyPLAN tool was chosen after reviewing several modelling options for its capabilities in large-scale renewable integration analysis. Designed to support regional or national energy strategies, EnergyPLAN conducts techno-economic assessments of various long-term planning alternatives. It uses a deterministic model with analytical programming, allowing for faster calculations than iterative models, and simulates an entire year with high temporal resolution to produce hourly outputs. Key inputs include system demands, RES capacities, power plant efficiencies, costs, and regulatory options, while outputs encompass annual energy production, electricity imports and exports, greenhouse gas (GHG) emissions, and surplus generation. Though capable of representing multiple energy sectors, this study applies EnergyPLAN solely to the power sector. More details and case studies on EnergyPLAN can be found in [8].

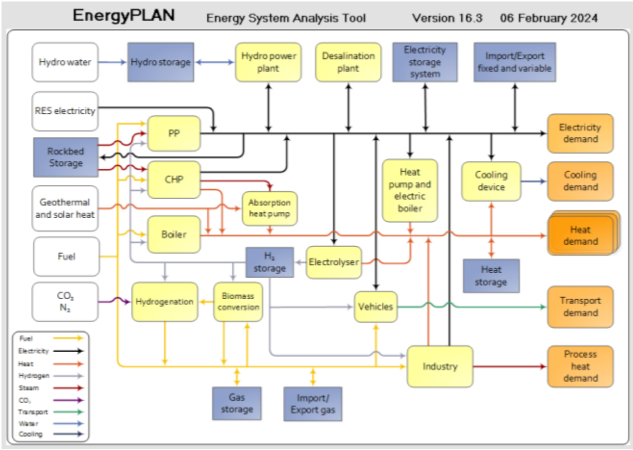

Fig. 1. Overview of the EnergyPLAN modelling tool [8]

C. Scenario Development

To assess the integration of variable renewable energy sources (VRES) into Myanmar's National Grid by 2030, five scenarios were developed, each aligned with national plans and international commitments. These scenarios explore various energy mixes and policy approaches:

1) Scenario 1: Business as Usual (BAU) 2030: Based on the 2014 National Electricity Master Plan (NEMP), this baseline scenario assumes no significant policy changes, with Myanmar continuing to rely predominantly on natural gas and hydropower as its primary energy sources. It provides the foundation for projecting future energy production, consumption, and greenhouse gas (GHG) emissions [4].

2) Scenario 2: MOEP RES Combination 2030: Based on proposals from the Ministry of Electric Power (MOEP), this scenario envisions a diversified energy mix that includes solar, wind, hydropower, and other renewable sources to enhance energy security and facilitate VRES integration. Additionally, nuclear power is incorporated as part of Myanmar’s long-term energy strategy [2].

3) Scenario 3: RES Combination 2030: Leveraging Myanmar’s high solar potential (51,973.8 TWh/year) [3] and wind potential (80 TWh/year) [9], this scenario proposes the assumed installed capacities for solar and wind based on their respective potentials: 29,600–33,170 MW of solar capacity (15–20% capacity factor) and 26,000–36,500 MW of wind capacity (25–35% capacity factor). It assumes significant penetration of solar and wind into Myanmar’s energy mix without relying on cross-border interconnections.

4) Scenario 4: RES Combination 2030 with Interconnection: Building on Scenario 3, this scenario integrates cross-border interconnections, enabling electricity exports during peak renewable production and imports during low production periods. These interconnections improve grid stability and facilitate greater solar and wind integration through connections with neighboring countries.

5) Scenario 5: RES Combination 2030 with Interconnection plus Energy Storage System: Expanding on Scenario 4, this scenario incorporates energy storage systems to manage surplus renewable generation and meet demand during periods of low production. By storing excess energy, this approach optimizes renewable integration, enhances grid flexibility and reliability, and significantly minimizes the occurrence of excess electricity.

Table I presents the EnergyPLAN model inputs for the reference year and future scenarios, with 2019 as the baseline, reflecting a total generation capacity of 4,945 MW—comprising hydropower (3,225 MW), natural gas (1,560 MW), coal (120 MW), and solar (40 MW). Scenario 1 initiates moderate growth by raising solar capacity to 1,300 MW and adding 700 MW of wind while expanding hydropower and natural gas. Scenario 2 further scales renewables to 4,175 MW for solar and 2,000 MW for wind. Scenarios 3, 4, and 5 push solar to 10,000 MW and wind to 6,000 MW, with scenario 5 also introducing a 600 MW energy storage system for enhanced grid flexibility. These scenarios collectively aim to optimize resources, bolster energy security, and support sustainable development, reflecting Myanmar's commitment to an increasingly renewable energy mix.

III. RESULTS AND DISCUSSION

A. Validation of Model

The EnergyPLAN model's accuracy in simulating Myanmar's energy system was validated against historical data by comparing outputs with actual monthly production, consumption, and emissions for 8,784 hours in the reference year. Table II shows the model's effectiveness, with most monthly average power production values closely matching actual data. For instance, in January, the model output was 2,427.00 MW, nearly identical to the actual 2,427.40 MW (0.02% difference). Similarly, April and December exhibited minimal differences of 0.14% and 0.40%, respectively. Although May and September showed slightly larger discrepancies (-0.44% and -0.66%), overall differences remained under 0.75%, indicating reliable forecasting accuracy of the model.

TABLE I. ENERGYPLAN INPUT DATA OF ELECTRICITY SUPPLY FOR THE REFERENCE MODEL AND FUTURE SCENARIOS

Descrip-tion	Ref. 2019 [MW]	Scenario [MW]				
		1	2	3	4	5
Hydro-power	3225	8896	8817	8817	8817	8817
Natural gas	1560	4758	4986	4986	4986	4986
Coal	120	7940	1000	1000	1000	1000
Solar	40	1300	4175	10000	10000	10000
Wind		700	2000	6000	6000	6000
Nuclear			330	330	330	330
Inter-connec-tion			2100		2100	2100
Energy stroage system						600
Total	**4945**	**23594**	**23408**	**31133**	**33233**	**33833**

[a] [2] [4] [5] [6] [9]

TABLE II. ENERGYPLAN MODEL VALIDATION RESULT FOR MONTHLY AVERAGE ELECTRIC POWER PRODUCTION

Month	Actual (MW)	EnergyPLAN (MW)	Difference	Percentage
January	2427.40	2427.00	0.40	0.02
February	2541.74	2547.00	-5.26	-0.21
March	2718.85	2725.00	-6.15	-0.23
April	2864.06	2860.00	4.06	0.14
May	3421.93	3437.00	-15.07	-0.44
June	2977.23	2956.00	21.23	0.71
July	2642.32	2645.00	-2.68	-0.10
August	2611.47	2601.00	10.47	0.40
September	2675.41	2693.00	-17.59	-0.66
October	2768.55	2770.00	-1.45	-0.05
November	2697.88	2682.00	15.88	0.59
December	2437.79	2428.00	9.79	0.40

The model's solar production estimate was slightly below actual figures, with a difference of -0.005 TWh/year (-14.29%), based on only six months of data, as Myanmar's first grid-connected solar plant began operation in July 2019. A full year's data might yield more accurate results. For load shedding, the model estimated 0.93 TWh/year, slightly above the actual 0.86 TWh/year (-0.07 TWh/year, -8.24%). Natural gas consumption was slightly underestimated at 33.36 TWh/year compared to the actual 34.55 TWh/year (3.45% difference), while coal consumption aligned closely, differing by only 0.02 TWh/year (3.39%). Overall, these variances validate the model's reliability, though adjustments, especially for hydropower and solar, could enhance precision. Integrating an advanced hydropower model into EnergyPLAN may further improve accuracy for hydropower estimates.

TABLE III. ENERGYPLAN MODEL VALIDATION RESULT FOR ANNUAL ELECTRICITY PRODUCTION

Descrip-tion	Actual	EnergyPLAN	Difference	Percentage
Electricity Production (TWh/year)				
Hydropower	10.48	11.15	-0.67	-6.37
Thermal	12.31	11.88	0.43	3.52
Solar	0.035	0.040	-0.005	-14.29
Load Shedding (TWh/year)				
Load Shedding	0.86	0.93	-0.07	-8.24
Fuel Consumption (TWh/year)				
Natural Gas	34.55	33.36	1.19	3.45
Coal	0.59	0.57	0.02	3.39

B. Scenario Analysis

This analysis explored the integration of variable renewable energy sources (VRES) into Myanmar's National Grid, focusing on technical, economic, and environmental aspects. It identified a peak demand period from May 17 to May 23, 2030, with hourly demands ranging from 3,265 to 3,432, underscoring the need for optimized grid operations during periods of high consumption and renewable variability, particularly for wind.

1) Scenario 1: Business as Usual (BAU) 2030: This scenario examined hourly energy demand and supply data, highlighting the dynamic interactions between different energy sources. The analysis revealed a significant dependence on natural gas and coal, with occasional contributions from renewable sources, emphasizing the challenges in achieving a balanced and sustainable energy mix in the BAU 2030 scenario.

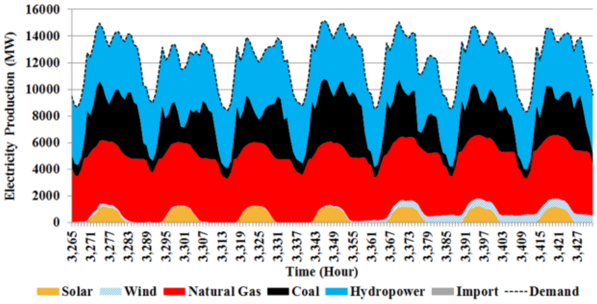

Fig. 2. Hourly data of demand and supply for the BAU 2030 scenario

2) Scenario 2: MOEP RES Combination 2030: This scenario analyzes hourly energy demand and supply, highlighting a balanced integration of renewable sources into the grid. It aims to reduce reliance on fossil fuels, enhance variable renewable energy source (VRES) penetration, and achieve significant greenhouse gas (GHG) emission reductions. The objective is to position Myanmar as a regional leader in renewable energy by 2030.

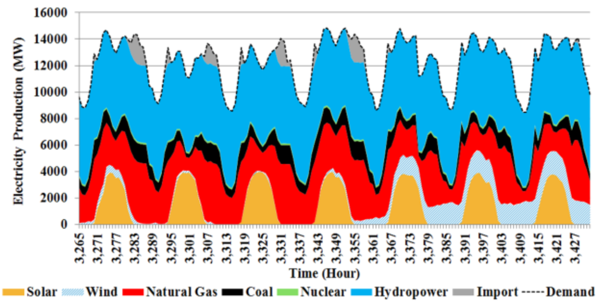

Fig. 3. Hourly data of demand and supply for the MOEP RES combination 2030 scenario

Scenario 3: RES Combination 2030: This scenario explores the impact of Critical Excess Electricity Production (CEEP) in Myanmar's energy landscape by 2030. The analysis shows a major increase in renewable energy integration, especially solar and wind, reducing reliance on fossil fuels. Solar output peaks over 9,000 MW during high demand hours, while wind energy supports grid stability. The mix of natural gas, coal, and hydropower ensures reliability and sustainability. CEEP also highlights the potential for significant energy exports during periods of peak renewable generation.

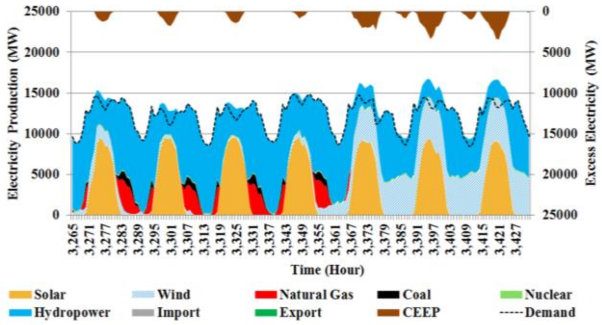

Fig. 4. Hourly data of demand and supply for the RES combination 2030 scenario

4) Scenario 4: RES Combination 2030 with Interconnection: This scenario demonstrates the potential for Exportable Excess Electricity Production (EEEP) by combining renewable and conventional energy sources. Variations in demand and production from solar, wind, natural gas, coal, nuclear, and hydropower reveal frequent surpluses, especially during peak renewable generation, which highlights export opportunities. High solar and wind outputs often exceed demand, underscoring the role of interconnection in optimizing distribution and supporting export strategies. This analysis emphasizes the importance of renewable integration in building a resilient energy infrastructure that meets local needs and enables exports.

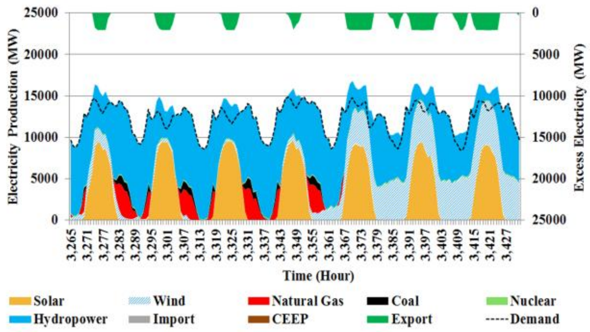

Fig. 5. Hourly data of demand and supply for the RES combination 2030 with interconnection scenario

5) Scenario 5: RES Combination 2030 with Interconnection plus Energy Storage System: This analysis demonstrates the potential for EEEP through a diversified mix of renewable and conventional sources, including solar, wind, natural gas, coal, nuclear, and hydropower. During lower-demand hours, hydropower and interconnection sources contribute significantly, while reliance on fossil fuels remains low. As demand rises, natural gas and coal plants ensure stability when renewable output is limited. The reduced CEEP and increased EEEP, compared to Scenario 4, reflect efficient management of excess generation through exports and storage. This integrated approach supports a resilient energy infrastructure, meeting local needs while enabling export potential.

C. Penetration of Renewable Energy into Myanmar's Generation Mix

From a technical perspective, integrating renewable energy into Myanmar's generation mix is essential for building a sustainable energy system. With proposed capacities of 10,000 MW for solar and 6,000 MW for wind, effective incorporation of these resources requires a strong technical framework to manage their variable generation profiles and maintain grid stability. Scenario 5 was analyzed to simulate gradual penetration increases, with solar ranging from 0% to 100% while wind penetration was fixed at 80%, and vice versa, with wind ranging from 0% to 100% while solar was maintained at 80%. These simulations provide critical insights into optimizing grid operations, evaluating system reliability, and determining the infrastructure upgrades necessary to support high levels of renewable energy integration.

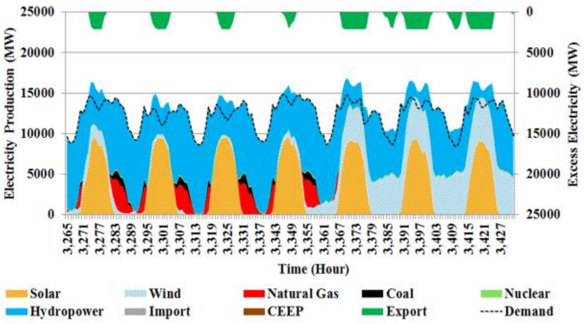

Fig. 6. Hourly data of demand and supply for the RES combination 2030 with interconnection plus energy storage system scenario

- As solar and wind penetration increase in Myanmar's generation mix, Exportable Excess Electricity Production (EEEP) grows, reflecting the potential for surplus electricity exports. For solar energy, EEEP remains negligible up to 30% penetration, indicating that most solar power is absorbed domestically. Beyond 50% penetration, however, EEEP begins to rise significantly as excess energy becomes available. At 80% penetration, solar EEEP reaches 1.9 TWh/year, and at 100%, it peaks at 4.14 TWh/year. This sharp increase highlights solar energy's potential to drive export opportunities at higher penetration levels. For wind energy, EEEP shows a more gradual and steady increase. It starts at 0.01 TWh/year at 10% penetration and grows consistently, with notable gains after 40% penetration. By 80%, wind EEEP reaches 0.18 TWh/year, peaking at 0.69 TWh/year at 100% penetration. While the surplus from wind is less pronounced than solar, it provides a stable contribution to Myanmar's export potential. These results underscore the importance of renewable energy integration in enabling Myanmar to develop substantial export capacity, particularly beyond 60% penetration. However, achieving this requires strategic investments in transmission infrastructure and regional export agreements to effectively manage and utilize surplus electricity, supporting Myanmar's sustainable energy goals and regional market participation.

- As solar and wind penetration increase in Myanmar's generation mix, Critical Excess Electricity Production (CEEP) shows a rising trend, reflecting a mismatch between renewable generation and demand. For solar energy, CEEP remains negligible up to 60% penetration, indicating effective grid absorption. Beyond this level, solar CEEP increases, reaching 0.01 TWh/year at 80%, 0.03 TWh/year at 90%, and peaking at 0.11 TWh/year at 100%. For wind energy, CEEP growth is more gradual, remaining at 0 TWh/year up to 80% penetration. It begins to rise at 90% with 0.01 TWh/year and peaks at 0.02 TWh/year at 100%. These trends highlight the need for flexibility measures such as storage and advanced grid management to reduce curtailment and manage surplus electricity effectively at higher renewable penetration levels.

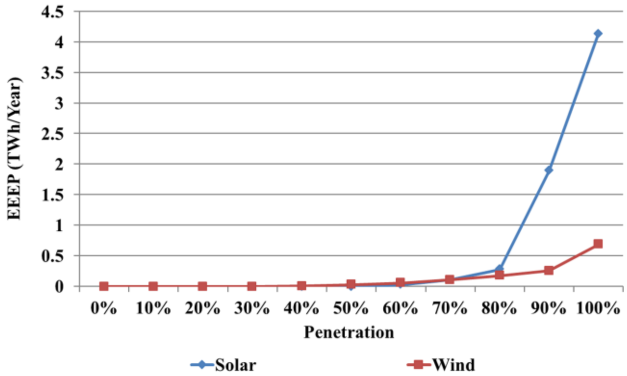

Fig. 7. Variation in EEEP as solar and wind penetration increases in Myanmar's generation mix

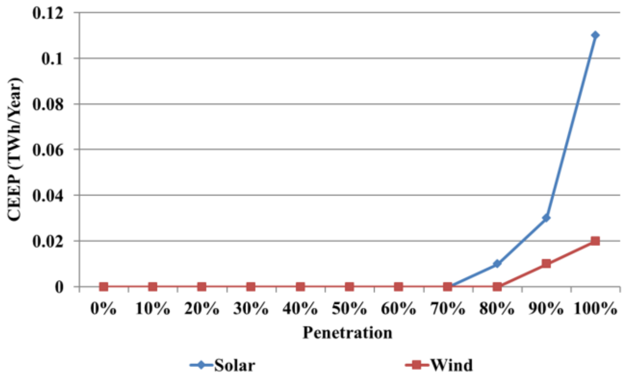

Fig. 8. Variation in CEEP as solar and wind penetration increases in Myanmar's generation mix

- As solar and wind penetration levels increase in Myanmar's generation mix, greenhouse gas (GHG) emissions, measured in $MtCO_{2e}$, exhibit a significant decline, showcasing the effectiveness of renewables in reducing emissions. For solar energy, emissions begin at 14.52 $MtCO_{2e}$ with 0% penetration and decrease steadily as penetration rises. By 50%, emissions are reduced to 6.69 $MtCO_{2e}$ and continue to decline, reaching 1.56 $MtCO_{2e}$ at 100%. This gradual reduction reflects the role of solar power in displacing fossil-fuel-based generation. For wind energy, emissions start at 9.34 $MtCO_{2e}$ at 0% penetration and decrease consistently, reaching 5.19 $MtCO_{2e}$ at 50% penetration. At full (100%) penetration, emissions drop further to 1.44 $MtCO_{2e}$. The more immediate impact of wind energy at lower penetration levels is likely due to its higher capacity factor and less variability compared to solar. These trends highlight the critical role of solar and wind in significantly reducing Myanmar's GHG emissions, particularly beyond 50% penetration. By incorporating higher renewable shares, Myanmar can achieve its low-carbon energy goals and contribute to global climate mitigation efforts.

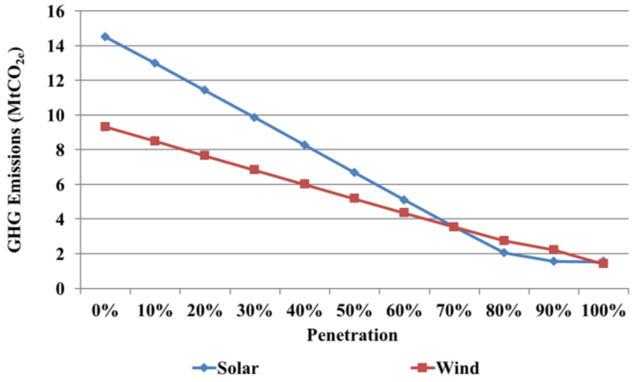

Fig. 9. Variation in GHG emission as solar and wind penetration increases in Myanmar's generation mix

D. *Impact of Renewable Energy Integration on EEEP and CEEP in Myanmar's Grid*

In Scenarios 1 and 2, there is no EEEP or CEEP, as the installed capacities and generation levels are sufficient to meet demand, with occasional electricity imports required. TABLE IV summarizes the monthly averages and annual totals of EEEP and CEEP in Scenarios 3, 4, and 5. In Scenario 3, with renewable penetration, CEEP remains high, particularly in January (1,466 MW) and December (1,298 MW), as the excess electricity generated cannot be absorbed by the grid. Scenario 4, which incorporates interconnection and flexibility measures, significantly reduces CEEP and introduces up to 1,130 MW of EEEP in January, which can potentially be exported. Annually, Scenario 3 results in 7.69 TWh of CEEP, while Scenario 4 reduces this to 0.57 TWh and exports 7.13 TWh of EEEP. Scenario 5, which further enhances renewable penetration, interconnection, and energy storage, reduces CEEP to 0.41 TWh and increases EEEP to 7.29 TWh, demonstrating that higher renewable shares, supported by grid flexibility and energy storage, can effectively manage surplus electricity, reduce curtailment, and contribute to export potential.

E. *Greenhouse Gas (GHG) Emissions*

The GHG emissions in Myanmar's 2030 energy scenarios are closely tied to the energy mix and infrastructure choices. In Scenario 1 (BAU 2030), emissions reach 27.82 $MtCO_{2e}$, primarily due to the high reliance on coal (23.16 TWh/year) and natural gas (8.9 TWh/year), even with significant hydropower (45.41 TWh/year). Scenario 2 (MOEP RES Combination 2030) reduces emissions to 11.04 $MtCO_{2e}$ by increasing hydropower to 50.51 TWh/year and introducing nuclear energy (1.02 TWh/year), while cutting coal use to 3.88 TWh/year. Scenario 3 (RES Combination 2030) achieves a further reduction to 1.35 $MtCO_{2e}$ by eliminating coal and ramping up wind (12.45 TWh/year) and solar (23.72 TWh/year). Scenarios 4 and 5, which add grid interconnection and energy storage, stabilize emissions at 1.35 $MtCO_{2e}$, showing that while these technologies enhance grid reliability and renewable integration, the primary driver of low emissions remains the shift toward renewable energy.

TABLE IV. MONTHLY AND YEARLY AVERAGE EEEP AND CEEP UNDER SCENARIOS 3, 4 AND 5 FOR MYANMAR'S GENERATION MIX

Description	Scenario 3		Scenario 4		Scenario 5	
	EEEP	CEEP	EEEP	CEEP	EEEP	CEEP
Monthly average (MW)						
January	0	1466	1130	215	1152	165
February	0	1237	1032	116	1052	82
March	0	879	830	72	849	50
April	0	824	787	24	807	14
May	0	274	425	0	437	0
June	0	502	601	15	617	10
July	0	600	685	3	702	1
August	0	752	738	11	757	6
September	0	823	791	27	811	17
October	0	917	792	38	810	22
November	0	950	849	89	867	61
December	0	1298	1081	167	1104	124
Yearly total (TWh/year)						
2030	0	7.69	7.13	0.57	7.29	0.41

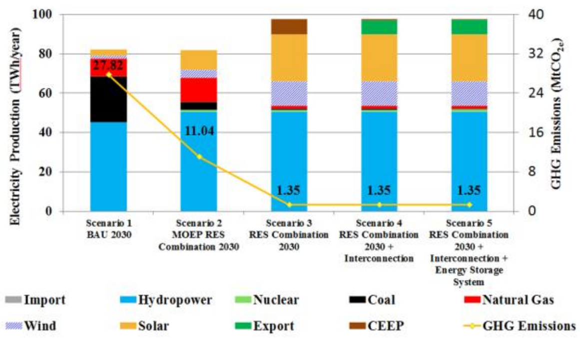

Fig. 10. Electricity production and GHG emissions for all the scenarios

F. *Cost Analysis*

The cost analysis for Myanmar's electricity export scenarios under ASEAN interconnections examines the balance between revenue generation and GHG emissions costs. With the average electricity price in ASEAN ranging from USD 0.10 to USD 0.15 per kWh, this study adopts a conservative estimate of USD 0.15 to calculate export revenue [11]. Simultaneously, a carbon price of USD 50 per tonne of CO_2 equivalent is used, aligning with Singapore's carbon tax policy, which is projected to increase to USD 37–60 per tCO_{2e} by 2030 [12]. In Scenario 1, with no export revenue and high GHG costs, the total cost results in a significant net loss of USD 1,391 million. Scenario 2 shows an improvement, with GHG costs reduced to USD 552 million, but still results in a negative net benefit of USD 552 million. Scenario 3 further reduces the GHG costs to USD 67.5 million, reflecting a small loss of USD 67.5 million. In contrast, Scenario 4 generates positive net benefits, yielding USD 1,002 million, driven by export revenue of USD 1,069.5 million and minimal GHG costs of USD 67.5 million. Scenario 5 shows a similar trend with a net benefit of USD 1,026 million, with export revenue of USD 1,093.5 million and the same low GHG costs. This analysis emphasizes the importance of integrating carbon pricing and maximizing export opportunities to enhance Myanmar's economic growth and sustainability through renewable energy integration, interconnection, and energy storage.

TABLE V. OVERVIEW OF EXPORT REVENUE, GHG EMISSION COSTS, AND TOTAL BENEFIT/COST IN VARIOUS SCENARIOS

Scenario	Export Revenue (MUSD)	GHG Cost (MUSD)	Total Benefit/Cost = Export Revenue – GHG Cost (MUSD)
Scenario 1	0	1391	-1391
Scenario 2	0	552	-552
Scenario 3	0	67.5	-67.5
Scenario 4	1069.5	67.5	1002
Scenario 5	1093.5	67.5	1026

G. Recommendation

From a techno-economic perspective, Scenario 4 is the more favorable for integrating Myanmar's renewable energy sources. Unlike Scenario 1, which incurs high GHG costs without export revenue, Scenario 4 balances financial sustainability with emissions reduction. It also outperforms Scenario 2, which, despite lower GHG costs, misses export opportunities, and Scenario 3, which offers only minor improvements. By optimizing the integration of renewable energy with interconnections, Scenario 4 positions Myanmar for regional energy collaboration and aligns with sustainable development goals.

Scenario 5 further enhances this by incorporating energy storage systems, which stabilize the grid, minimize curtailment of renewable energy, and increase the utilization of wind and solar resources. While the financial benefits of Scenario 5 are comparable to Scenario 4, with a slight increase in net benefit, the added grid flexibility and storage capacity improve the reliability of the renewable energy supply and reduce energy wastage. This makes Scenario 5 a highly strategic choice, maximizing renewable energy potential, strengthening energy security, and supporting long-term sustainability while reinforcing both economic and environmental objectives.

IV. CONCLUSION

In conclusion, Myanmar's abundant renewable energy potential provides a clear opportunity to transition toward a sustainable, low-carbon energy system. This study evaluates strategies to integrate variable renewable energy sources (VRES) into Myanmar's grid, addressing challenges such as Critical Excess Electricity Production (CEEP) and curtailment. The findings underscore the importance of flexibility solutions for maximizing renewable energy utilization. Without such measures, CEEP leads to significant energy wastage and underutilization of resources. Scenario 4, which incorporates cross-border interconnections, demonstrates substantial mitigation of CEEP by enabling electricity exports, improving grid stability, and fostering regional economic growth. Building on this, Scenario 5 highlights the effectiveness of combining energy storage systems (ESS) with interconnections, achieving a 94% reduction in CEEP, enhancing grid reliability, and optimizing VRES integration. While ESS requires significant upfront investment, its contribution to operational flexibility and system resilience is crucial. Strategic investments in interconnections and ESS are vital for Myanmar to achieve its renewable energy targets, minimize curtailment, and ensure system reliability. Policymakers must prioritize these measures to advance Myanmar's renewable energy transition. Future research should integrate market-driven economic simulations with technical modeling to provide a more comprehensive framework for decision-making. By adopting these strategies, Myanmar can fully harness its renewable energy potential, achieve its ASEAN energy objectives, and build a robust, resilient energy system aligned with global climate goals.

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