Article

On the Impacts of Renewable Energy Penetration on the Economic Dispatch and Sustainability of Power Systems

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ABSTRACT

This study investigates the penetration of Renewable Energy Sources (RES) in the Jordanian Power System (JPS) for the operation of many types of generating units. Several scenarios are analyzed, focusing on unit commitment and economic dispatch within the power system over time. As a special case, we used the JPS (High Voltage 400 kV and 32 kV). We use an economic dispatch and optimization method to minimize fuel cost with variable generation sources (conventional and renewable). Therefore, the load dispatch method is a process for scheduling the required demand among many types of power generation sources. A dedicated methodology is proposed to integrate RES, particularly photovoltaic (PV) and wind energy, to ensure effective management and cost minimization for the entire system. Unlike traditional generation units, most RES facilities are not directly dispatched by grid operators and cannot be controlled precisely. Their output is typically treated as (must-run or must-take generation. This research provides insights into accommodating these RES while maintaining economic sustainability and operational efficiency. Finally, to achieve the optimum Economic Dispatch and Unit Commitment needed for high-RES levels in the JPS, the installation of Energy Storage Systems (ESS), such as BESS or HPSS, is essential. The ESS provides an excellent solution not only for optimizing unit commitment but also for significantly enhancing the overall grid stability.

KEYWORDS: renewable energy; economic dispatch; unit commitment; power systems; power system stability

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INTRODUCTION

Sustainability of energy is key to the stability of any country. Jordan took this issue seriously and started developing many renewable energies resource projects in parallel with conventional generation resources. Consequently, there is a significant opportunity to utilize RES, particularly solar energy, which is considered sustainable, clean, environmentally friendly, and economically feasible. In addition, wind energy is a viable option because of the favorable wind speeds across many locations in

Jordan. As a non-oil-producing country, Jordan relies heavily on importing energy resources including oil, gas, and their derivatives. This dependence has adversely affected various sectors, depleting Jordan's financial resources and foreign currency reserves, increased the trade balance deficit, and contributed to the rise in public debt. Therefore, the utilization and enhancement of renewable energy resources is crucial. Wind and PV energy offer a significant comparative advantage owing to the continuous solar radiation and high number of sunny days annually. Moreover, the relatively low cost of land in Jordan makes renewable energy investment particularly attractive. At this stage, we acknowledge that the core content of this work originated from a master's thesis completed by my former student at German Jordanian University [1]. This paper also presents an extended version of our earlier conference [2]. The Updated Master Strategy for the energy sector (2007–2025), building on the foundational 2004 National Master Strategy, effectively highlights the significant challenges that may impede the successful implementation of various renewable energy projects, particularly in wind and solar PV systems [3]. To turn this ambitious vision into reality, a series of strategic steps has already been initiated, starting with the pivotal "Renewable Energy and Energy Efficiency" Law established in 2012. This groundbreaking legislation plays a crucial role in fostering the development of renewable energy resources in Jordan through innovative and diverse approaches. By committing to this strategy, we can unlock a sustainable energy future that benefits both the environment and the economy.

The first approach was implemented by allowing the Ministry of Energy and Mineral Resources to discuss tenders for the development of sites to generate electricity from renewable resources, particularly wind and solar PV. Additionally, investors are allowed to submit direct proposals to the ministry to develop any site for renewable energy utilization. Net metering and wheeling are the second and third approaches, respectively, targeting ordinary electricity customers to empower them in developing renewable energy resources. By implementing these three approaches to renewable energy development, it is anticipated that the installed capacity of renewable energy resources will reach approximately 3000 MW by 2025 for PV and wind projects.

Renewable energy resources are scattered across various locations in Jordan and are often situated far from consumption centers. To address this issue, a new transmission line is planned for the southern and eastern parts of Jordan to transport energy to regions with concentrated loads. This line is expected to be operational by the end of 2025. Although this connection will enhance energy distribution, it will also increase system losses and require significant investments and modifications to the national grid hierarchy. Figure 1 illustrates the locations of both PV and wind energy projects that will be utilized in the coming years, along with the committed projects.

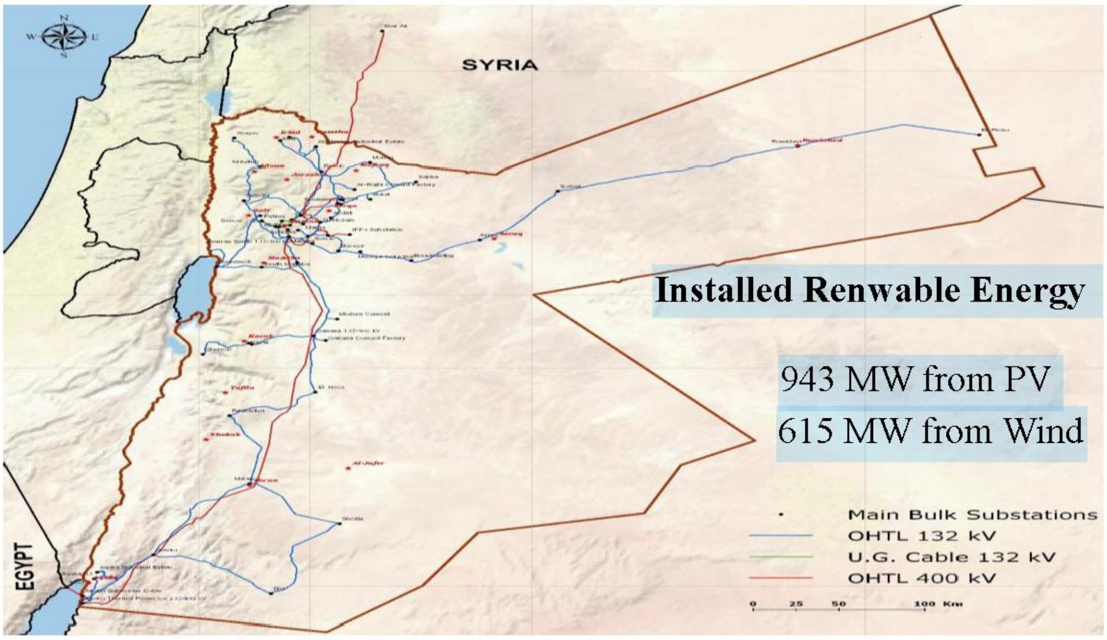

Figure 1. Wind and solar energy potential in Jordan, along with the distribution of large-scale renewable projects in the country.

Therefore, in this study, a comprehensive study will be conducted to determine the most appropriate renewable energy capacity and to identify the optimal operation of the JPS in the presence of renewable energy on an hourly, quarterly, and yearly basis. The economic feasibility of committed renewable energy projects (wind and solar PV) in Jordan in the coming years is simulated using a very robust computer software called PLEXOS [1,4] (for economic and operation studies) in addition to the models used by the National Electrical Power Company (NEPCO) in Jordan.

Finally, the central questions guiding this study are: How can the most optimal unit commitment solution be found for the JPS given the presence of RES? And why is the effect of RES penetration on the system's economic dispatch understood? To address these issues, we first establish the specific objectives of our research. The integration of PV and Wind energy (RES) into Jordan's power network began in the early 2000s under a government mandate. As one of the first adopters, the high-voltage power system (JPS) has seen that RES penetration rapidly climbs to almost 25% of its total generated power, a significantly high percentage. This high penetration level makes the question of optimizing Economic Dispatch in the presence of RES not only relevant, but also essential for the system's stability and economy. Many studies have addressed the stability of JPS in the presence of RES [5]. The next two sections are devoted to economic dispatch with RES, and briefly discusses the concept of unit commitment.

Economic Dispatch and Renewable Energy Integration

Generally, electrical systems exhibit daily load patterns characterized by significant variations between peak and off-peak hours, reflecting people's lifestyles. In Jordan, electricity consumption is lower on Thursday evenings, Fridays, and Saturdays than on the weekdays. Additionally, a trend shows reduced load during the late night and early morning hours compared with daytime usage [6]. Sufficient generation capacity was maintained on the grid throughout the day to meet the peak load demands. This often leads to the operation or shutdown of generating units, and some units may operate near their minimum loading limits during off-peak periods. This presents a challenge in deciding which units should be turned off and for how long. Many researchers have focused on unit commitment in the presence of RES [7–15]. Numerous studies have been conducted on the rapid integration of renewable energy into Jordan's electrical system. However, many of these studies overlooked the importance of the dispatch approach, which plays a crucial role in the system's operation. This study aims to explore methods for determining the optimal economic dispatch in the context of RES, specifically PV (solar) and wind energy. Furthermore, it seeks to identify the maximum allowable limit of renewable energy that can be accommodated within the Jordanian National Electrical Grid, and to recommend the most suitable size for any PV or wind energy plants to be integrated into this grid.

The main topics discussed in this paper are Unit Commitment and Economic Dispatch. They are focuses on determining when to start and shut down generation units to meet demand, considering the availability of RES. After the Unit Commitment decisions are finalized, the Economic Dispatch allocates the system's demand among the operating units, aiming to minimize the generation costs [16]. Economic dispatching plays a crucial role in modern energy systems. This involves effectively scheduling electricity production to minimize operational costs. The integration of substantial amounts of intermittent RES, such as PV and wind power, adds complexity to this process. Consequently, significant effort is required to ensure that the electricity supply remains stable and reliable for consumers.

Electricity-generating companies that operate power systems often face challenges in managing the varying demand for electricity, which fluctuates on hourly, daily, and weekly bases. To tackle this problem, they used short-term optimization strategies that focused on scheduling electricity generation to either minimize total fuel costs or maximize overall profit, typically over a one-day period. This optimization process must adhere to several constraints. Within any power system, two interconnected short-term optimization problems emerge: Unit Commitment and Economic Dispatch [17].

Unit Commitment

Unit commitment involves managing on/off generating units. Various methods have been developed to find effective solutions within a reasonable timeframe. These methods include priority lists, dynamic programming, Lagrangian relaxation, genetic algorithms, simulated annealing, and other computational techniques [1]. Economic Dispatch focuses on determining the power output of each power plant and each generating unit specifically to minimize the overall cost of meeting the system load. Power plants contain multiple generating units that require substantial financial investments. Operating costs are affected by several factors including general and administrative expenses, fuel costs, accumulated depreciation, interest, and maintenance costs. Among these factors, fuel cost is the most significant and controllable component. Therefore, for further analysis, we only considered the fuel cost. Each unit has an input-output curve that reflects the quantity of fuel used at different output power levels. This fuel quantity is measured in tons per hour, or millions of BTUs per hour. By determining the cost of fuel in terms of JD/ton or JD/million BTUs, the power generation cost can be expressed in JD/h. If *Ci* (in JD/h) is considered the input cost to generate a power output of *Pi* MW in unit (*i*), Figure 2 illustrates a typical input-output curve of a generating unit [17]. Each generating unit has a minimum power output of *Pi* min and a maximum power output of *Pi* max, which must be maintained.

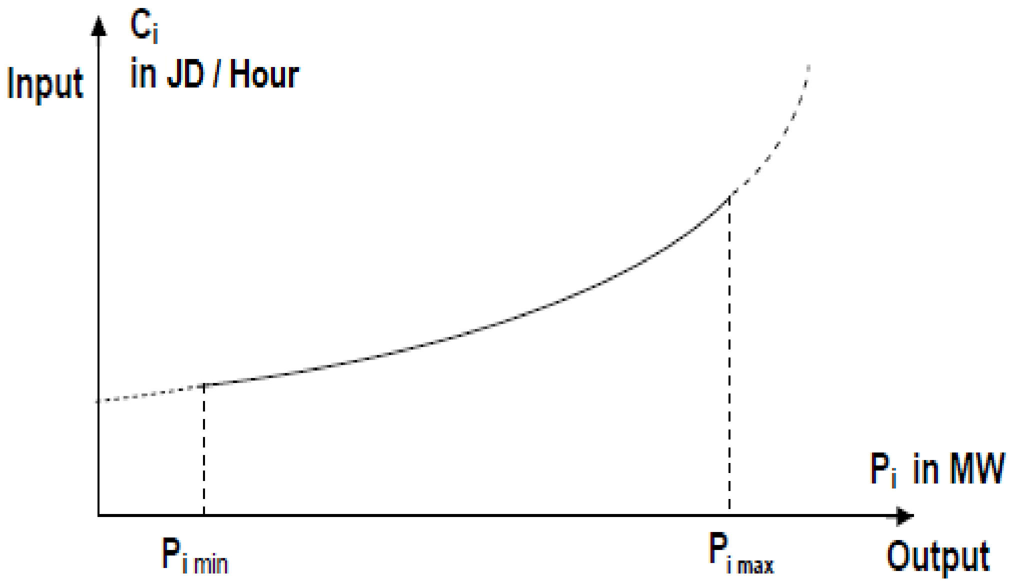

Figure 2. Input—Output curve of a generating unit (*i*).

The input-output curve can take various forms, including linear, quadratic, or cubic. However, a quadratic curve is often the preferred choice because of its effectiveness in accurately representing relationships [17]. This equation is expressed as follows:

$$C_i = \alpha_i P_i^2 + \beta_i P_i + \gamma_i \text{ (JD/H)} \quad (1)$$

A power station comprises multiple generating units, each of which has its own strengths and characteristics. When these units operate identically, the load is distributed evenly, thereby promoting efficiency. However, the true potential of the system emerges when we recognize that each generating unit possesses a unique input-output curve, which leads to a dynamic and varied demand distribution.

Enhancing the load on one unit typically results in a decreased load on the other, creating a balancing act that directly affects operational costs. To fully grasp the financial efficiency of the system, we can assess how input costs (ΔC_i) change in response to shifts in power output (ΔP_i) using the equation $dC_i/dP_i = \Delta C_i/\Delta P_i$. This allows us to express the costs effectively using $\Delta C_i = (dC_i/dP_i)*\Delta P_i$. In striving for excellence, optimizing our generation schedule hinges on understanding incremental cost (*IC*). This critical measure, represented by the slope of the input-output curve, is the key to unlocking greater efficiency, reducing costs, and maximizing resources. Emphasizing *IC* not only sharpens our operational strategy but also positions us to respond adeptly to fluctuating demands, ensuring a more sustainable and profitable future.

$$IC = dC_i / dP_i = 2\,\alpha_i\, P_i + \beta_i \quad (2)$$

α_i and β_i are known to be constant. A plot of the *IC* versus power output is shown in Figure 3.

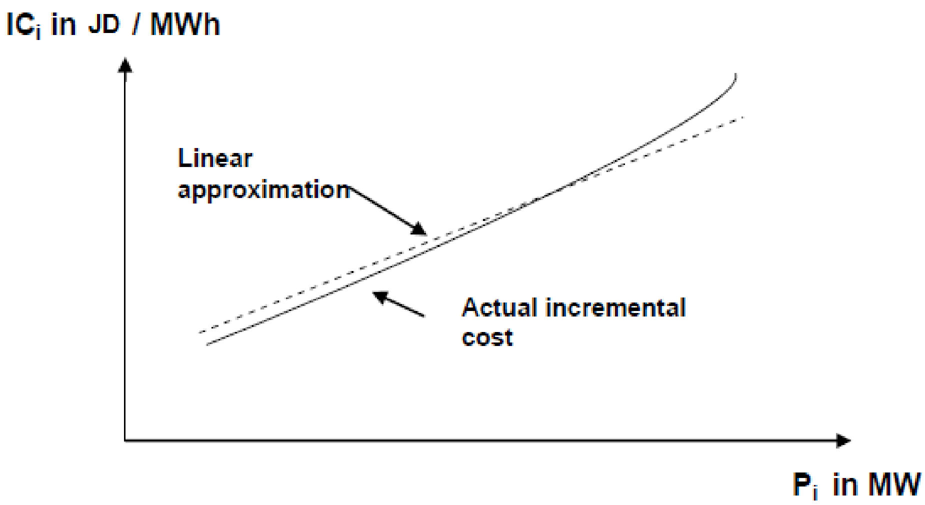

Figure 3. Incremental cost curves.

METHODOLOGY

In this paper, the methodology will be illustrated where various study cases take place based on many criteria, such as the load profile in each season for renewable energy, load growth percentage in each year, maintenance program for generating units, retirement and implementation of generating units, gas quantities, and any factor that may affect the operation of the JPS to show the best economic dispatch on an hourly basis. This paper outlines the research method, approach, data used, research process, type of data analysis, solving technique used, and computer software programming. The next subsections illustrate some concepts used in Unit Commitment and Economic Dispatch, such as power balance and peak load, with and without RES.

Power balance requires that a system's generating capacity always meets the maximum demand or peak load, which is the highest demand registered over a specified period (day, week, etc.). To guarantee reliability, all global electrical systems include a reserve margin, an intentional surplus of capacity tailored to the system's specific generation mix, and behavior. For example, Jordan's power system achieves this balance using a varied fleet of units, including gas turbines (GT), steam turbines (ST), combined-cycle plants, diesel engines (DE), and renewables. The reserve margin is mathematically defined as the difference between the available capacity and the peak load. When expressed as a percentage (surplus/peak load), a 20% margin indicates that the system holds 20% more capacity than the peak demand. This figure is crucial for long-term planning, as it must factor in all planned unit additions or retirements in the coming years.

$$\text{Reserve Margine (MW)} = \text{Available Generation Capacity (MW)} - \text{Peak Load(MW)} \quad (3)$$

$$\text{Reserve Margine (\%)} = \frac{\text{Reserve Margine (MW)}}{\text{Peak Load (MW)}} \quad (4)$$

The Electrical System Operator must continuously balance the supply and demand, matching the generating unit output to the load while maintaining the required reserve margin and controlling the system frequency.

The decision on which units to run is highly dependent on the daily load profile. While three seasons (winter, spring, and autumn) saw the load peak after sunset (Figure 4), the summer peak occurred at midday, followed by a slower decline. This marked seasonal difference in load patterns complicates the operator's task, primarily because of the financial and technical burden of cycling units, including startup, shutdown, and fuel marginal costs.

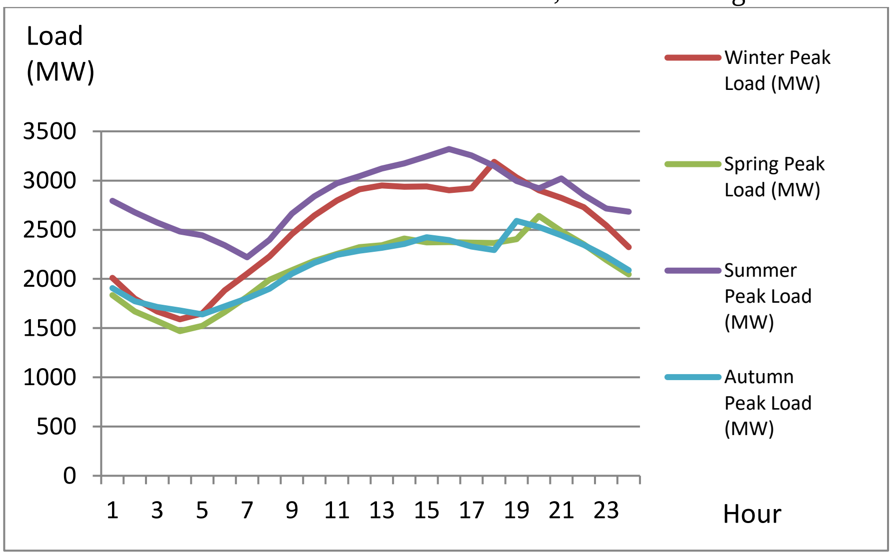

Figure 4. Seasonal peak load in 2017.

Knowing that conventional generation units act as a good follower to any such increase in the load to ease the operation of them, RES cannot afford a good and reliable source of energy due to its intermittency. As far as power balance with RES, the focus of this part is the projected impact of integrating additional intermittent PV and wind resources into the JPS, extending the analysis up to the year 2025. The central goal is to determine the economic feasibility of committing an additional 1620 MW of renewables (1005 MW PV and 615 MW wind). This study seeks to precisely determine the effect on economic dispatch, find the least-cost optimal percentage for renewable integration for the 2017–2025 timeframe, and advise on the best capacity for these projects. This work is motivated by the expected rapid growth of renewables, which is projected to increase from an estimated 17% in 2018 to 30% by 2025, as shown in Table 1.

Table 1. Installed capacity and renewable power plants capacity and share percentage from 2018–2025 in jordanian system [1].

Year	**2018**	**2019**	**2025**
System Installed Capacity (MW)	4920	5718	6145
PV Capacity (MW)	466	945	1005
Wind Capacity (MW)	372.2	515	615
Total Renewable Capacity (MW)	838.2	1460	1620
PV share to system Capacity (%)	9.5%	16.5%	16.4%
Wind share to system Capacity (%)	7.5%	9%	10%
Total Renewable share to system Capacity (%)	17%	25.5%	26.4%

Models that simulate electrical systems are influenced by a variety of factors (time horizon and generation unit modeling factors) that can significantly impact the accuracy and complexity of the results. In the Jordanian electrical system, these factors play a crucial role in shaping simulation outcomes. By conducting a thorough simulation covering the period from 2017 to 2025 on an hourly basis for each year (time horizon), we can achieve an insightful and precise understanding of how to meet energy demands in a cost-effective manner. This method carefully considers typical days, holidays, and regular working days to ensure a realistic assessment of the energy needs throughout the year.

It is essential to recognize that system load patterns fluctuate daily. In this simulation, we leveraged historical data on renewable energy load profiles to effectively capture these variations. The accompanying figures vividly illustrate the seasonal shifts in renewable resources; wind energy displays an unpredictable load profile, as shown in Figure 5, whereas PV energy often demonstrates a semi-predictable load profile that frequently aligns with the peak demand, as shown in Figure 6. By incorporating these insights, we can optimize our approach to energy management and enhance the sustainability of Jordanian electrical systems.

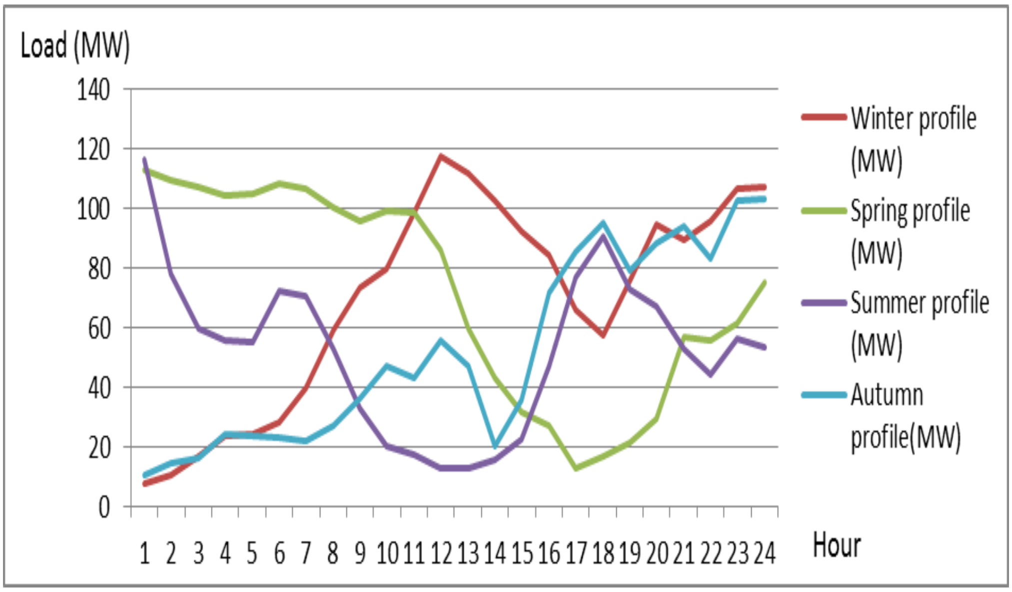

Figure 5. Seasonal daily generation profile for wind in Jordan.

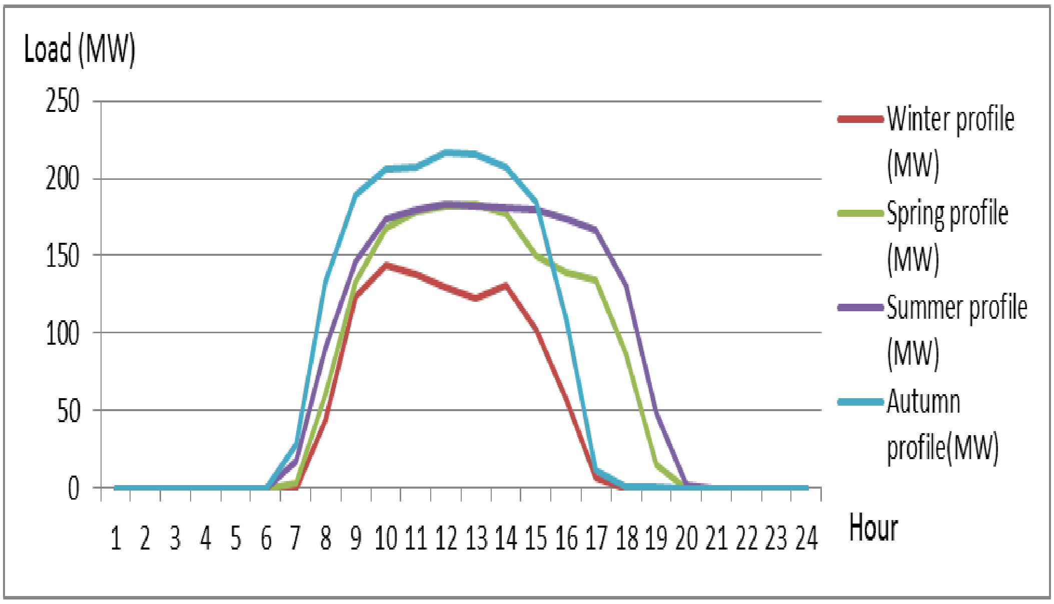

Figure 6. Seasonal daily generation profile for PV in Jordan.

Generating unit modeling in Jordan can be classified into two categories: conventional power plants, which consist of the following types: Combined Cycle (CC) units, which consist of two GTs and one ST; GT units, commonly known as simple cycle units; ST units; DE units, known as reciprocating engines, operating at full or zero load; and Oil Shale power plants, which will be in service during the year 2025. The CC units consisted of GTs with exhaust connected to a ST to utilize the higher temperature of the outlet air for electricity generation. These units were simulated in the model under different operational and transitional modes, such as one GT plus its ST (half CC). This simplifies the operation process of the Jordanian system, reduces constraints and transitions between states, and reduces the computational time for the software. The

DE units were modeled as one unit with a specific rated capacity. Conventional generation units in the JPS can be found in [1].

Renewable Energy Resources Panetration

The model treats all RES as must-take generation because the Power purchase Agreements (PPAs) in Jordan feature “take-or-pay” agreements, obligating the buyer NEPCO to pay for unused energy. The RES generation category includes wind and PV power plants. PV generation is restricted to daytime hours, with the output variability tied to factors such as irradiation and temperature. Wind power is available only when the wind is blowing, generally during times of lower system demand. Both sources were modeled using profiles derived from actual operational data. Specifically, the PV profile uses a 10 MW capacity from the Shamsuna project in Ma’an, and the wind profile uses a 117 MW capacity from the Tafillah power plant in the southwest.

Economic Dispatch and Unit Commitment Objective Function

Building on our work presented at IREC2019 [2], the central contribution of this study is determining the optimum Economic Dispatch for a power system incorporating renewable energy. The overarching goal (objective function) is the minimization of the total running costs, which covers fuel, variable O&M, and fixed startup/shutdown expenses.

Using the Linear Relaxation optimization approach for Unit Commitment and Economic Dispatch, we identify the optimal annual percentage of renewable energy integration and the maximum economic capacity for each renewable project. The economic viability of generation is quantified in $\MWh and is driven by the cost of the gas fuel consumed, proportional to the unit’s operating efficiency (heat rate), the variable cost of operation and maintenance per unit of energy generated, and the fixed charges associated with cycling units (startup/shutdown).

A detailed discussion about the input-output curve and fuel cost is found in [1]. The mathematical representation of fuel cost as a function of power is given by Equation (5):

$$Ci = a + bP + cP^2 \tag{5}$$

Were,
$Ci = \frac{\text{fuel}}{\text{hour}}$, or $\frac{\text{cost}}{\text{hour}}$ is the cost to produce electricity over one hour ($), *a, b*, and *c* are the constant coefficient of the generating unit; *P* = is the power or the generated energy in one hour (MW).

In Jordan, the equation is simplified to be linear, and the quadratic part is eliminated; thus, the fuel cost is given by Equation (6) will be:

$$Ci = a + bP \tag{6}$$

For more details on the variable operation and maintenance cost, startup cost, and RES cost, see [1].

Constraints on Unit Commitment and Economic Dispatch

The simulation of electrical systems has many constraints that control Unit Commitment and Economic Dispatch optimization, as the constraints increase the complexity of the model, herewith a list of common constraints that optimize electrical systems: Spinning Reserve, Unit level of Power, Minimum up time, minimum down time, generation and load balance, ramp rate, must run units, and renewable generation. As far as spinning reserve units are concerned, because of unexpected sudden increases in the load more than the predicted load, some system capacity must be maintained on the grid to match the sudden increase in the load or sudden outage of a generating unit known as the spinning reserve.

Generation and Load Balance

The balance between generation and load can be expressed by Equation (7):

$$\sum_{i=1}^{n} P(i,k,f) + shortage\ (k) - surplus\ (k) = load(k) \quad (7)$$

Where:
k: period of time,
Load (k): System load in MW at time period (*k*)
Shortage (k): Load shortage in MW at time period (*k*)
Surplus (k): surplus energy in excess of the load at time period (*k*).

This constraint affects the frequency deviation, which depends on the balance between the total energy production and its consumption for each time interval; worldwide energy production should always be greater than or equal to the load.

In Table 2, the data for conventional generation units, including the major constraints, are used for the simulation program (PLEXOS) and consist *of* P_{min}, P_{max}, a and b (constant coefficients of the generating units), VOM, Minimum up time, and minimum down time.

Table 2. Conventional generation units data, 2017–2025 [1].

Generation Unit	P_{min} (MW)	P_{max} (MW)	*a* (MMBTU/h)	*b* (MMBTU/MWh)	VOM (JD/MWh)	Min. up Time (Hours)	Min. down Time (Hours)
Oil shale 1	135	235	200	9.2	9.5	14	8
Oil shale 2	135	235	200	9.2	9.5	14	8
Aqaba 1 (ST)	55	121	150	9.3	0.6	14	8
Aqaba 2 (ST)	55	121	150	9.3	0.6	14	8
Aqaba 3 (ST)	55	121	150	9.3	0.6	14	8
Aqaba 4 (ST)	55	121	150	9.3	0.6	14	8
Aqaba 5 (ST)	55	121	150	9.3	0.6	14	8
Risha 1 (GT)	10	30	0	0.0	24	14	8
Risha 2 (GT)	10	30	0	0.0	24	14	8
Rehab 10 (GT)	10	25	119	10.3	3.0	2	2
Rehab 11 (GT)	10	25	119	10.3	3.0	2	2
Rehab 12 + ST14 (CC)	105	135	195	7.0	3.0	14	8
Rehab 13 + ST14 (CC)	105	135	195	7.0	3.0	14	8
Samra 1 GT1 + ST (CC)	110	154	280	6.2	0.1	14	8
Samra 1 GT2 + ST (CC)	110	154	280	6.2	0.1	14	8

Samra 2 GT3 + ST (CC)	110	150	280	6.4	0.1	14	8
Samra 2 GT4 + ST (CC)	110	150	280	6.4	0.1	14	8
AES 1 (CC)	140	212	380	5.8	0.1	14	8
AES 2 (CC)	140	212	380	5.8	0.1	14	8
Qatrana 1 (CC)	140	210	380	5.8	0.5	14	8
Qatrana 2 (CC)	140	210	380	5.8	0.5	14	8
Samra 31 (CC)	170	220	380	5.7	0.1	14	8
Samra 32 (CC)	170	220	380	5.7	0.1	14	8
Samra 4 (CC)	170	220	380	5.6	0.1	14	8
IPP 3,4 (DE)	0	813	0	8.7	10.1	2	2
ACWA 1 (CC)	120	160	300	5.7	0.2	14	8
ACWA 2 (CC)	120	160	300	5.7	0.2	14	8
ACWA 3 (CC)	120	160	300	5.7	0.2	14	8

Software Simulation

As mentioned earlier, PLEXOS [1,4] computer software was used to simulate generation units and related data in a model that solves optimization problems of the Jordanian system to achieve minimum cost. It was Developed in 1999 by Glenn Drayton, who founded Drayton Analytics in Adelaide, Australia, and was first released in 2000 by a team of experts in operational research and economics. The software gained significant traction in Europe by 2001, and it was adopted by the Irish SEM as the de facto “standard” simulator due to its ability to replicate the optimization-based market-clearing operation and its open, auditable solution methods.

By 2004, PLEXOS had evolved into a leading-edge transmission model and played a key role in the redesign of the California power market. PLEXOS Solutions also provides consulting and data services to the product. In 2006, the company expanded its reach into the Asia-Pacific region and southern Africa, and on June 29, 2006, Energy Exemplar Pty Ltd. registered and assumed the responsibilities of Drayton Analytics Pty Ltd. By January 2015, the number of installations of PLEXOS reached 1000, making it the most widely used commercial integrated energy market software globally.

PLEXOS is based on mixed-integer programming (MIP) optimization techniques, where Unit Commitment and Economic Dispatch are formulated as linear problems (after linearization) with integer variables representing the status of the generation units. In PLEXOS, the Medium-Term Schedule is executed and automatically linked to the Short-Term Schedule, ensuring that input data, such as constraints for minimum/maximum power generation, ramping, and transition actions, are properly accounted for to accommodate any increase in the load.

Case Study Selection

To select representative cases for this study, a specific analysis was conducted using the actual capacity factors and load profiles of the RES. The first objective of this study is to compare the economic dispatch results for the entire year, both with and without renewable energy, to quantify the effect on the total yearly energy yield.

Actual operational data are indispensable for accurate results that reflect real-world situations. The baseline data for this examination are summarized in Table 3, which provides the actual capacity factors for renewable energy power plants spanning the period from January 2017 to July 2018.

Table 3. Capacity factor of renewable energy power plants from January/2017 to July/2018 [1].

Month	PV (%)	Wind (%)
January/2017	20	29
February/2017	26	29
March/2017	30	30
April/2017	33	31
May/2017	36	28
June/2017	39	28
July/2017	35	28
August/2017	38	21
September/2017	42	17
October/2017	29	15
November/2017	21	17
December/2017	17	35
January/2018	20	39
February/2018	21	25
March/2018	30	33
April/2018	35	27
May/2018	35	39
June/2018	41	35
July/2018	41	43

It is clear from the table above that each season shows similar values of the capacity factor from renewable energy resources (PV and Wind); therefore, we can conduct our study on the period of each season to determine the impact of renewable energy in Jordan. This will allow us to evaluate the optimal percentage of the installed capacity and ultimately suggest the most appropriate size for any PV or Wind project. Next, the results and analysis are discussed in detail.

RESULTS AND ANALYSIS

The simulation results obtained from PLEXOS software version 1.1.0, optimize the Jordanian system on a yearly basis. The simulation was conducted hourly to determine the optimal economic dispatch and unit commitment with and without renewable energy. The first step involved simulating the system with and without renewables. In the second step, a sensitivity test is performed on the summer, winter, spring, and autumn days to assess how demand is matched with the best percentage of renewable energy. The third step evaluates the optimal capacity for a renewable project, whether it is PV or Wind. The simulation calculated the total system running cost, and the natural gas cost in the model was $6.5/MMBTU. The impact of integrating renewable energy power plants was assessed by comparing scenarios with and without renewable energy to determine the best economic dispatch with the lowest system running cost.

General Analysis of Economic Dispatch and Unit Commitment

To satisfy the first step, which focuses on the best economic dispatch in the presence of renewable energy, Table 4 summarizes the examined scenarios to identify the effect of integrating renewable energy versus not integrating it on the total cost due to economic dispatch and unit commitment optimization:

Table 4. Examined scenarios details [1].

Year	Scenario	Renewable Energy		Natural Gas Price ($/MMBTU)
		PV (MW)	Wind (MW)	
2020	Scenario 1	0	0	6.5
	Scenario 2	1005	615	6.5

The Economic Dispatch and Unit Commitment optimization results for each scenario are as follows:

- Economic Dispatch and Unit Commitment results, year 2020:
- The simulation and analysis of 2020 consist of two scenarios.

Scenario 1: The simulation was conducted without considering renewable energy power plants in service. Using the PLEXOS software, the results show that the total energy generated during the year 2020 is 21,230 GWh, with a total system cost of 1,474,698,040 JD.

Figure 7 shows the energy share percentage for each technology (Oil Shale, CC, Steam Cycle on gas, and DEs). It is clear that CC units contributed the most, covering 80.10% of the load, while oil shale contributed 19.62% as a must-run unit, STs contributed 0.21%, and DEs contributed 0.07%.

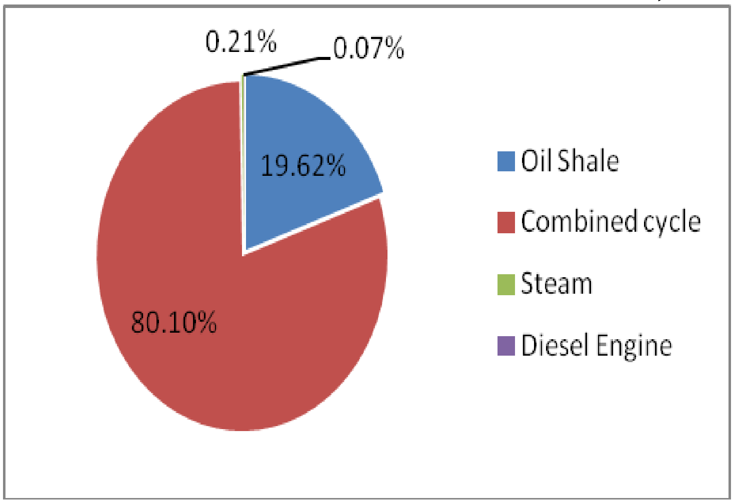

Figure 7. Energy shares per technology, scenario 1.

Scenario 2: The simulation was run with renewable energy power plants, including a 1005 MW PV power plant and a 615 MW Wind power plant. The results show that the total energy generated in 2020 is 21,230 GWh, with a total system cost of 1,568,799,478 JD in the presence of renewable energy.

Figure 8 shows the energy share percentage for each technology (CC, Steam Cycle for gas, Oil Shale, DE, PV, and Wind). It is clear that CC units contribute the most, covering 59.82% of the load, whereas oil shale contributes 19.62% as a must-run unit. ST burning gas contributed 0.04%, DEs contributed 0.03%, wind power contributed 8.99%, and PV power contributed 11.5%.

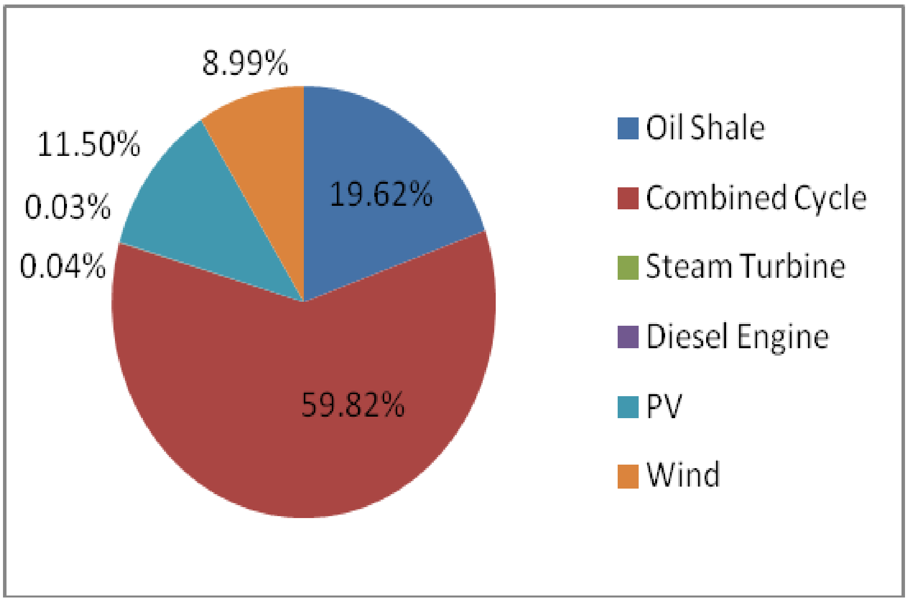

Figure 8. Energy shares per technology, scenario 2.

After comparing the two scenarios, the following results have been found:

- Economic Dispatch differs significantly when renewable energy is in service, as seen by the change in technology to share percentages. The CC loading decreased by approximately 20%, which was compensated for by renewable energy, whereas the share of STs and DEs remained approximately the same.
- The total system cost increased by 94,101,438 JD owing to the oil shale project, along with the implementation of renewable energy, particularly wind.

Therefore, the first objective of this study is satisfied and results in good economic dispatch in the presence of renewable energy, which will incur additional costs to the system when the price of renewable energy projects is high, but when prices decrease to around 50 $/MWh, it will be feasible. Yes, the results are influenced by several critical factors, most notably the structure of the PPA and price of the RES. It is important to note that a change in PPA conditions directly affected the findings.

Detail Analysis of Economic Dispatch with Renewable Energy Integration

The simulation of the Jordanian system using PLEXOS software shows economic dispatch on a daily basis. This study focuses on selected days across the four seasons (winter, summer, spring, and autumn) to evaluate how renewable energy affects the operation of other units. The analysis also discusses operational challenges these days and examines the impact of decreasing the percentage of renewable energy to 50% and 25% of the total installed capacity.

Winter Season: The day selected was the 5th of January. Table 5 shows the economic dispatch results, when dispatching the generating units with assumptions of 100%, 50%, and 25% committed RES.

Table 5. Dispatching units during the peak load in winter 2020 where renewable energy percentage is 100%, 50%, and 25% [1].

Station	Power Output when Renewable 100% (MW)	Power Output when Renewable 50% (MW)	Power Output when Renewable 25% (MW)
Qatrana	240	345	345
AES	343	345	345
Samra 1	0	172	298
Samra 2	0	189	297
Samra 3	413	413	413
Samra 4	204	204	204
PV	633	317	159
Wind	304	152	77
Acwa	477	477	477
Oil Shale	470	470	470
Total Load (MW)	3084	3084	3085

It was found that as the percentage of renewable energy decreased, the loading of conventional generating units increased, resulting in a more efficient operation with a higher capacity factor. Therefore, the optimal percentage of renewable energy for 2020 during the winter season is 25% of the installed capacity, which includes PV (1005 MW) and wind (615 MW).

Spring Season: the selected day was 10th of April 2020. Table 6 shows the best economic dispatch results when dispatching the generating units with assumptions of 100%, 50%, and 25% committed RES.

Table 6. Dispatching units during the peak load in spring 2020 where renewable energy percentage is 100%, 50%, and 25% [1].

Station	Power Output when Renewable 100% (MW)	Power Output when Renewable 50% (MW)	Power Output when Renewable 25% (MW)
Qatrana	120	302	345
AES	262	345	341
Samra 1	0	0	92
Samra 2	0	0	0
Samra 3	413	413	413
Samra 4	204	204	204
PV	482	241	121
wind	46	23	12
Acwa	477	477	477
Oil Shale	470	470	470
Total Load (MW)	2474	2475	2475

It was found that when the percentage of renewable energy decreased, the loading of conventional generating units such as AES, Samra 1, and Samra 2 increased, allowing them to operate more efficiently and flexibly from an operational standpoint. Therefore, the optimal percentage of renewable energy for 2020 during the spring season is 25% of the installed capacity, which includes PV (465 MW) and wind (372.2 MW), or potentially even lower.

Summer Season: The selected day was 10th of August 2020. Table 7 shows the best economic dispatch results when dispatching the generating units with assumptions of 100%, 50%, and 25% committed RES.

Table 7. Dispatching units during the peak load in Summer 2020 where renewable energy percentage is 100%, 50%, and 25% [1].

Station	Power Output when Renewable 100% (MW)	Power Output when Renewable 50% (MW)	Power Output when Renewable 25% (MW)
Qatrana	345	345	345
AES	345	345	345
Samra 1	133	299	298
Samra 2	30	297	296
Samra 3	413	413	413
Samra 4	204	204	204
Rehab	0	0	220
PV	784	392	197
Wind	84	42	21
Acwa	477	477	477
Oil Shale	470	470	470
Total Load (MW)	3285	3284	3286

It was found that when the percentage of renewable energy decreased, the loading of conventional generating units such as Samra 1 and Samra 2 increased, allowing them to operate more efficiently without shutting down or being turned off. Therefore, the optimal percentage of renewable energy for 2020 during the summer season is 25% of the installed capacity, which includes PV (1005 MW) and wind (615 MW), or potentially even lower.

Autumn Season: The selected day was the 2nd of November 2020. Table 8 shows the best economic dispatch results when dispatching the generating units with assumptions of 100%, 50%, and 25% committed RES.

Table 8. Dispatching units during the peak load in Autumn 2020 where renewable energy percentage 100%, 50% and 25% [1].

Station	Power Output when Renewable 100% (MW)	Power Output when Renewable 50% (MW)	Power Output when Renewable 25% (MW)
Qatrana	316	345	345
AES	238	345	345
Samra 1	0	150	241
Samra 2	0	122	236
Samra 3	413	413	413
Samra 4	204	204	204
PV	822	413	209
Wind	0	0	0
Acwa	477	477	477
Total Load (MW)	2470	2469	2470

It was found that when the percentage of renewable energy decreased, the compensation came from conventional generating units, resulting in a reduction in the total cost with higher capacity factor rates reaching 47%. Therefore, the optimal percentage of renewable energy for 2020 during the autumn season is 25% of the installed capacity, which includes PV (1005 MW) and wind (615 MW), or potentially even lower.

Based on the above analysis, one can say that the recommended capacity for any renewable project, whether wind or PV, depends on the transmission system, as the energy generated will be transferred to the grid and impact other components. In Jordan, the entire system can be enforced by upgrading conductor types to superheated ones, implementing new transmission lines, and building one substation (the Green Corridor, which includes two transmission lines from Ma'an to Qatrana and a Ma'an substation at 400/132 KV). This enhances the transmission capacity from the southern area to the load center. With these enhancements, the ideal renewable energy project size for 2020 is approximately 100–150 MW. Without such improvements, the recommended size ranges from 200 MW to 300 MW. The location of renewable energy projects should ideally be in the northern and central parts of Jordan because of the concentration of loads in these areas. From an operational perspective, it is preferable to minimize the size of each renewable project, aiming for 10 MW or 15 MW per project, and spreading them across different areas rather than concentrating them in one location. This strategy helps to reduce the risk of losing large amounts of energy at once and ensures a more balanced and reliable integration of renewable energy into the grid.

CONCLUSIONS

Economic Dispatch and Unit Commitment were used to study the impact of RES penetration on the power system. Many cases have been studied, and the following conclusions can be drawn. Adding 160 MW of new renewable projects (60 MW of PV and 100 MW of wind) alongside the oil shale project in 2020 to the Jordanian electrical system will increase the total generated energy cost by approximately 94 million JD, with daily operational losses estimated at approximately 250,000 JD. The optimal percentage of renewable energy for the year 2020 from an operational perspective is around 25% for the winter, summer, spring, and autumn seasons, depending on the PPA price. In the current situation without grid enforcement, the best capacity for renewable energy projects is between 100 MW and 150 MW in the southern area of Jordan. The wind project capacity can range from 200 to 300 MW if implemented in the northern area of Jordan, where the loads are concentrated and the system is stable in terms of voltage and operational criteria. In conclusion, it is preferable to limit the size of individual renewable energy projects to 10 MW or 15 MW and spread them geographically. This decentralized strategy minimizes the risk of losing a substantial block of generation capacity simultaneously, thereby ensuring more reliable and balanced renewable energy integration across the grid. However, there are some limitations to our work: one was mentioned early in conclusion, and the other might be to use new software.

After a comprehensive analysis, the authors recommend the following as future work: Invest more PV energy with storage technology to avoid uneconomical operation of the electrical system and to reuse energy during peak demand times. Robust forecasting programs for renewable energy help manage its variability throughout the day with minimal loss in economic dispatch and unit commitment. Delay investments in renewable energy until there is a significant increase in load growth to ensure efficient integration. Explore multiple markets to utilize excess renewable energy that will be connected to the grid to avoid wastage. Establishing a national reservoir, such as a hydropower storage system, to better manage energy fluctuations. Implementing more reinforcement plans for the grid to enable it to absorb large amounts of renewable energy. The interchange capacity is increased through the interconnection line with Egypt to reduce curtailment and provide more flexibility for system operators. Finally, it is strongly recommended that renewable energy projects be distributed across multiple locations in Jordan to reduce the impact of energy loss and enhance operational efficiency. In addition, it is recommended that future work use other software to study such problems. We used PELOXS because the software is available at the National Electric Power Company in Jordan. In addition, one can use different types of optimization methods, such as dynamic programming, genetic algorithms, or mixed integer programming, to address any limitations that might occur in the current method. Finally, addressing a valid reviewer comment, the impact of increased RES penetration on Jordan's long-term Energy Strategy (2030/2050) requires a strategic solution. To achieve the optimum Economic Dispatch and Unit Commitment needed for high-RES levels in the JPS, the installation of ESS, such as BESS or HPSS, is essential. The ESS provides an excellent solution not only for optimizing unit commitment but also for significantly enhancing the overall grid stability.

ETHICAL STATEMENT

Ethics Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Declaration of Helsinki STROBE Reporting Guideline

This study adhered to the Helsinki Declaration. The Strengthening the Reporting of Observational studies in Epidemiology (STROBE) reporting guideline was followed.

DATA AVAILABILITY

No data associated with paper (N/A).

AUTHOR CONTRIBUTIONS

AH contribution was in supervising, concept, Analysis reviewing, Final editing and writing. IAR, analysis, using sofwaer, writing a draft version of the article.

CONFLICTS OF INTEREST

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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