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An Integrated Framework for Modeling CO_2 Emissions in Libyan Combined Cycle Power Plants to Enhance Operational Efficiency and Support Environmental Power Dispatch Strategies

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Abstract

The main objective of this work is to estimate the carbon dioxide (CO_2) emissions from natural gas-fired combined cycle gas turbine (CCGT) units in Libya and to integrate these estimations within an environmental power dispatch model that considers several power plants. The study begins with a preliminary design aimed at calibrating the model using the limited data provided by manufacturers. Off-design operating points are also investigated in order to estimate emissions across the full operating range of the units. The results show good consistency with emission coefficients reported in the literature for this type of units. Subsequently, carbon costs are used as input parameters in a Unit Commitment (UC) problem, where a Mixed Integer Linear Programming (MILP) formulation is applied to minimize the total emissions of a set of units within the Libyan power grid. The emission factors obtained for the simulated network display values close to the recorded field data, validating the developed model. Finally, a tightened formulation of the dispatch problem is introduced, aiming to reduce computational time while ensuring high-quality performance of the returned solutions. and Results show that prioritizing newer and more efficient plants reduces national emissions by 10–15%.

Keywords: Combined Cycle Gas Turbine, Design, CO_2 Emissions, Environmental Unit Commitment, Power Dispatch, Optimization .

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إطار عمل متكامل لنمذجة انبعاثات ثاني أكسيد الكربون في محطات توليد الطاقة ذات الدورة المركبة في ليبيا لتعزيز الكفاءة التشغيلية ودعم استراتيجيات توزيع الطاقة الصديقة للبيئة

نورالدين عطاياالله الفازع، عبد السلام سالم عبد الله، جمال عبدالقادر سعد
المعهد العالي للعلوم والتقنية – ترهونة – ليبيا

الملخص

الهدف الرئيسي من هذا العمل هو تقدير انبعاثات ثاني أكسيد الكربون (CO_2) الناتجة عن وحدات التوربينات الغازية ذات الدورة المركبة (CCGT) العاملة بالغاز الطبيعي في ليبيا، ودمج هذه التقديرات ضمن نموذج الجدولة البيئية لتوليد الكهرباء الذي يأخذ في الاعتبار عدة محطات كهربائية. تبدأ الدراسة بتصميم أولي يهدف إلى معايرة النموذج باستخدام البيانات المحدودة المقدمة من الشركات المصنعة، كما يتم التحقيق في نقاط التشغيل خارج التصميم من أجل تقدير الانبعاثات عبر كامل نطاق تشغيل الوحدات. وقد أظهرت النتائج توافقًا جيدًا مع معاملات الانبعاثات الواردة في الأدبيات لهذا النوع من الوحدات .بعد ذلك، تم استخدام تكاليف الكربون كمدخلات في مسألة الالتزام الوحدوي (Unit Commitment – UC)، حيث تم تطبيق صياغة برمجة خطية عددية صحيحة مختلطة (MILP) بهدف تقليل الانبعاثات الكلية لمجموعة من الوحدات داخل الشبكة الكهربائية الليبية. وأظهرت عوامل الانبعاث التي تم الحصول عليها من الشبكة المحاكاة قيماً قريبة من البيانات الميدانية المسجلة، مما يؤكد صلاحية النموذج المطور. وأخيرًا، تم تقديم صياغة أكثر إحكامًا لمسألة الجدولة من أجل تقليل الزمن الحسابي مع ضمان جودة عالية في أداء الحلول المسترجعة. وتشير النتائج إلى أن إعطاء الأولوية للمحطات الأحدث والأكثر كفاءة يساهم في خفض الانبعاثات الوطنية بنسبة تتراوح بين 10%–15%.

الكلمات المفتاحية: الدورة المركبة للتوربينات الغازية، التصميم، انبعاثات، الالتزام الوحدوي البيئي، جدولة القدرة، التحسين(CO_2).

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1. Introduction

Libya's national power grid remains highly dependent on thermal power plants primarily gas turbines and combined cycle gas turbines (CCGT) such as those in Khoms , Zawiya , South Tripoli, and Benghazi North. These plants, operated by the General Electricity Company of Libya (GECOL), collectively supply the majority of the country's electricity generation capacity, with installed outputs ranging from 750 MW to 1440 MW per station. However, due to aging infrastructure, insufficient maintenance, and fluctuations in natural gas supply, many of these units operate below optimal efficiency, resulting in increased CO_2 emissions per unit of generated electricity. At the national level, Libya's electricity sector is the dominant source of greenhouse gases, accounting for nearly 99% of fossil-fuel-based generation and producing total emissions of approximately 61 Mt CO_2 eq in 2023. The country's average emission factor is estimated at about 0.857 kg CO_2/kWh, placing Libya among the highest emitters per capita in Africa. Although the Renewable Energy Strategic Plan (2013–2025) targeted a 10% renewable energy share by 2025, progress has been minimal. Recent announcements set a goal of 2,250 MW of renewables equivalent to 11% of the national mix by 2024, but significant technical and institutional barriers remain. Against this backdrop, realistic CCGT modeling becomes crucial to accurately estimate CO_2 emission factors and to support environmentally oriented power dispatch strategies. Traditionally, the unit commitment (UC) problem has focused on minimizing fuel costs while satisfying operational and load constraints [1]. However, this study prioritizes the reduction of CO_2 emissions through an integrated, data-driven modeling approach. Previous literature has modeled emissions as linear, quadratic, or cubic functions of generated power [2,3,4], though such approaches often rely on generic test data with uncertain emission coefficients. Reported emission values for CCGT systems range widely between 336 and 616 kg/MWh [5,6], reflecting the variability in operational efficiency and fuel characteristics. The key research problem addressed in this study is the absence of a unified modeling framework that accurately links CCGT operational efficiency with emission outputs under Libyan-specific conditions. Therefore, the main objective is to develop and calibrate a realistic

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emission model using local data, enabling its integration into an environmental dispatch optimization framework. By adapting and localizing the generic CCGT emission modeling framework [7,8] to Libya's grid, this research seeks to generate reliable emission coefficients and propose strategies to reduce the national grid's carbon intensity. Ultimately, this work contributes to the country's broader goal of transitioning toward a more sustainable, low-carbon power system aligned with national climate and energy strategies.

Problem Statement

Combined cycle power plants in Libya, which rely primarily on natural gas for electricity generation, suffer from high levels of carbon dioxide (CO_2) emissions due to the increasing energy demand and the lack of advanced emission management systems. These emissions pose both environmental and economic challenges, as they contribute to global warming and negatively impact Libya's commitments toward environmental sustainability. Furthermore, the absence of an integrated modeling framework that links operational efficiency with environmental power dispatch makes it difficult to achieve a balance between meeting electricity demand and minimizing environmental impacts.

Study Objectives

This study aims to develop an integrated framework for modeling CO_2 emissions from combined cycle power plants in Libya in order to improve the accuracy of emission estimation, enhance operational efficiency, and support environmental power dispatch strategies. It also seeks to achieve a balance between meeting the growing electricity demand and reducing environmental impacts, while providing decision-makers with a practical tool to adopt more sustainable operational policies.

Proposed Solutions

The study proposes applying mathematical modeling and simulation to estimate emissions, and implementing environmental power dispatch algorithms that minimize CO_2 emissions alongside operational costs. It also recommends employing smart monitoring systems linked to load control, encouraging the integration of

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renewable energy sources with combined cycle plants, and improving thermal management strategies to enhance efficiency and reduce fuel consumption.

Literature Review

Several studies have investigated strategies to reduce CO_2 emissions and improve the performance of Combined Cycle Gas Turbine (CCGT) power plants**(see figure 1),** particularly in regions with hot climates such as Libya. These studies provide essential insights into the integration of environmental considerations into power plant operation and dispatch strategies. The first study by [9] focused on modeling CO_2 emissions from Libyan CCGT power plants and integrating them into an environmental power dispatch framework.

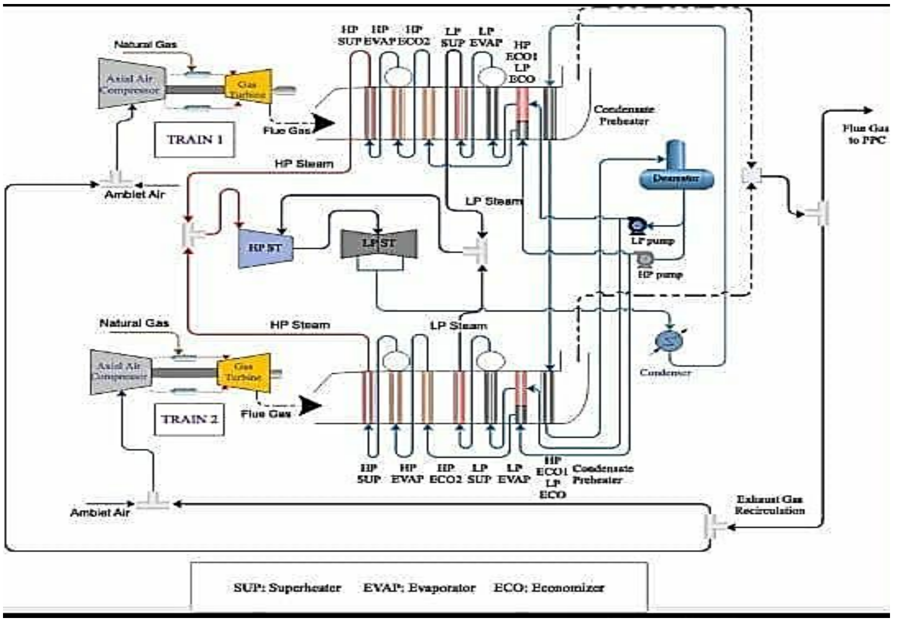

Figure (1) Combined cycle gas turbine (CCGT) power plants [9]

The figure illustrates the power generation process in a combined cycle power plant, where the thermal energy of exhaust gases from the gas turbine is recovered in a Heat Recovery Steam Generator (HRSG) to produce steam that drives a steam turbine, thereby improving the overall thermal efficiency of the plant.[10] The study developed a mathematical model to estimate CO_2 emissions based

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on plant load, fuel consumption, and efficiency levels. Results indicated that incorporating CO_2 emission constraints into the economic dispatch problem significantly alters the optimal power allocation among generating units, supporting more sustainable electricity production. The authors highlighted that applying such models in Libyan power plants can effectively balance operational efficiency and environmental performance [10]. The figure illustrates the power generation process in a combined cycle power plant, where the thermal energy of exhaust gases from the gas turbine is recovered in a Heat Recovery Steam Generator (HRSG) to produce steam that drives a steam turbine, thereby improving the overall thermal efficiency of the plant.[10] The study developed a mathematical model to estimate CO_2 emissions based on plant load, fuel consumption, and efficiency levels. Results indicated that incorporating CO_2 emission constraints into the economic dispatch problem significantly alters the optimal power allocation among generating units, supporting more sustainable electricity production. The authors highlighted that applying such models in Libyan power plants can effectively balance operational efficiency and environmental performance. [10]

Figure 2 (Study I) shows the proposed emission modeling frame work, and Table 1 summarizes key emission data under different load conditions.

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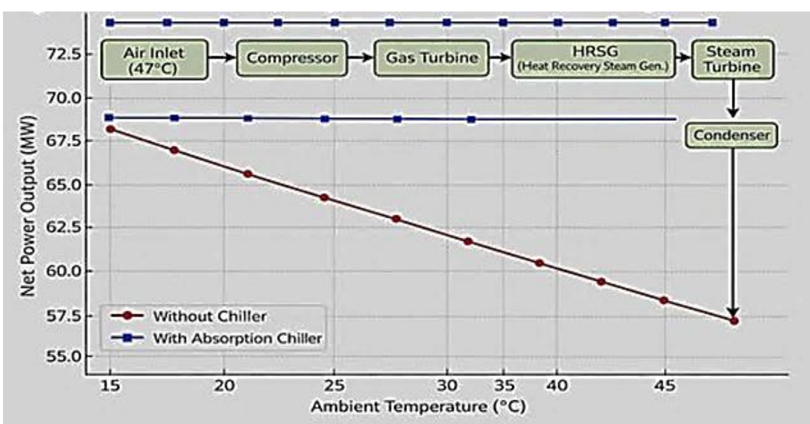

Figure (2) shows the proposed emission modeling framework

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Table 1. Summarizes key emission data under different load conditions

Load Condition (%)	Power Output (MW)	Fuel Consumption (kg/s)	Emission Factor (kg/MWh)	Total CO2 Emissions (kg/s)
50.0	33.5	1.0	360.0	12.0
75.0	50.25	1.35	345.0	13.0
100.0	67.0	1.8	340.0	14.0

Quick Observations: Efficiency Improvement: As the Load Condition increases, the Emission Factor decreases (from 360 to 340). This typically indicates that the system operates more efficiently at higher loads. Direct Correlation: There is a clear linear relationship between Power Output and Fuel Consumption; as you demand more power, the fuel intake rises accordingly.

Analysis of CCGT Plant Performance with Absorption Chiller The integration of an absorption chiller into a Combined Cycle Gas Turbine (CCGT) plant significantly enhances its operational efficiency under ISO conditions. According to the data in Table 2, the Net Power Output saw a substantial increase of 10%, rising from 67.0 MW to 73.7 MW[10]. This improvement is primarily driven by the cooling of the intake air, which increases air density and mass flow rate. Furthermore, the Gas Turbine Output improved by 7.6%, while the Steam Turbine Output experienced the highest growth at 15%, reaching 24.2 MW[11]. This indicates that the cooling process not only boosts the primary turbine but also enhances the heat recovery steam generator's capability. From an environmental and efficiency perspective, the Plant Efficiency improved by 3.5%, reaching a total of 53.0%. Most importantly, the CO_2 Emissions were reduced by 7%, dropping from 14.0 kg/s to 13.0 kg/s [11]. This demonstrates that using an absorption chiller is an effective strategy for both increasing energy production and reducing the carbon footprint of power plants.

The second study by [12] investigated the integration of absorption chiller technology into a 67 MW CCGT power plant to mitigate the adverse effects of high ambient temperatures. In this system, waste heat from the condenser was used to drive a lithium-bromide absorption chiller (COP ≈ 0.83), which cooled the compressor inlet

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air from 47 °C to 10 °C. Simulation results showed a 10% increase in net power output and a 7% reduction in CO_2 emissions under ISO conditions showing in that figure (3). Moreover, off-design analysis demonstrated that the system maintained stable performance across ambient temperature variations, making it highly suitable for Libyan summer conditions. Table 2 compares baseline and improved performance at ISO conditions, while Figures 3 and 4 depict the effect of ambient temperature on power output and CO_2 emissions, respectively [13].

Table 2. Performance of CCGT plant with and without absorption chiller (ISO conditions).

Parameter	Without Chiller	With Chiller	Improvement
Net Power Output (MW)	**67.0**	**73.7**	**+10%**
Gas Turbine Output (MW)	**46.0**	**49.5**	**+7.6%**
Steam Turbine Output (MW)	**21.0**	**24.2**	**+15%**
CO_2 Emissions (kg/s)	**14.0**	**13.0**	**–7%**
Plant Efficiency (%)	**49.5**	**53.0**	**+3.5%**

1- Performance Without Cooling System (Red Line): The plot indicates a steady and significant decline in power output as the ambient temperature increases. This is attributed to the fact that higher temperatures reduce air density, leading to a lower Mass Flow Rate into the gas turbine. Consequently, the overall plant performance drops drastically as temperatures reach extreme levels (e.g., 47°C).
2- Performance With Absorption Chiller (Blue Line): Upon integrating an Absorption Chiller into the system, the net power output remains stable and constant at a high level (approximately 74 MW), despite the continuous rise in ambient temperature. The chiller effectively cools the inlet air to a fixed, optimal setpoint, thereby neutralizing the negative impact of hot climatic conditions together, these two studies demonstrate the potential of integrated modeling approaches whether

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through emission-based dispatch optimization (Study I) or waste-heat utilization with absorption chillers (Study II) to improve both operational efficiency and environmental sustainability in Libyan CCGT power plants. These findings provide a solid foundation for future research aimed at developing integrated frameworks for CO_2 emission reduction and environmentally conscious power dispatch strategies.

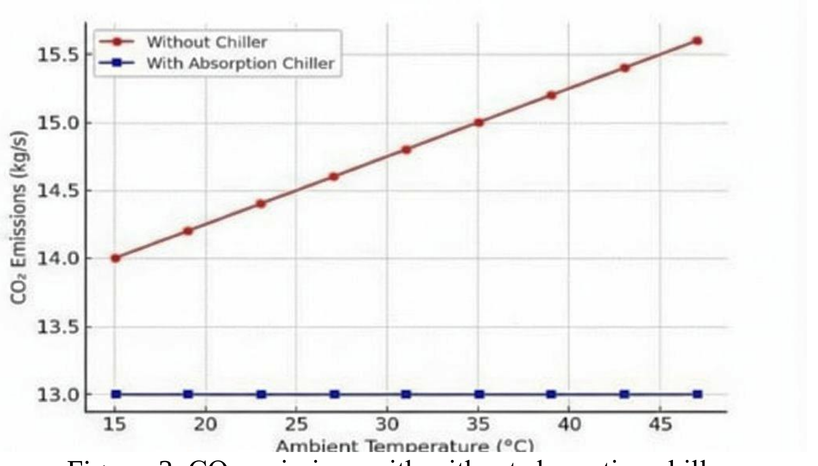
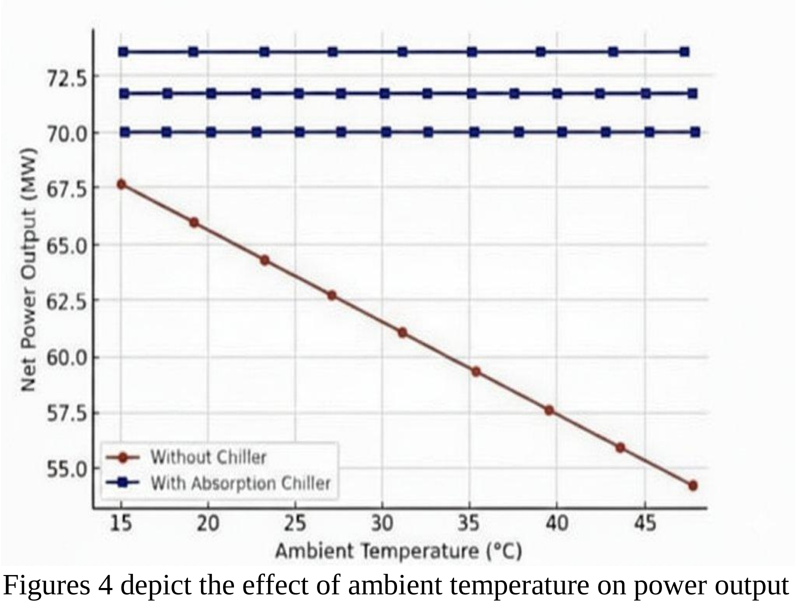


Figure. 3. CO_2 emissions with without absorption chiller.



Figures 4 depict the effect of ambient temperature on power output

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2. Methodology

▪ Study Methodology:

This study develops a mathematical model of combined cycle gas turbine (CCGT) power plants in Libya to estimate carbon dioxide (CO_2) emissions and integrate them into the environmental unit commitment (UC) problem. And this study adopts an analytical modeling approach that combines theoretical and practical methods to develop an integrated framework for modeling carbon dioxide (CO_2) emissions from combined cycle power plants in Libya. The methodology consists of the following stages:

1. Data Collection Gather historical and operational data from Libyan combined cycle power plants (fuel consumption, gas and steam turbine efficiency, and power output). Incorporate environmental and climatic data (temperature, humidity, atmospheric pressure) to assess their influence on performance and emissions.
2. Mathematical Modeling and Simulation Develop a mathematical model based on mass and energy balance equations to estimate fuel consumption and CO_2 emissions. Implement simulation models using engineering software (e.g., MATLAB/Simulink or Aspen Plus) to generate different operational scenarios.
3. Application of Environmental Power Dispatch Strategies Design dispatch algorithms that minimize emissions while maintaining operational efficiency. Compare results between conventional cost-based dispatch and environmentally-oriented dispatch.
4. Results Analysis and Performance Evaluation Assess the model's performance through key indicators: CO_2 emission rate (kg/MWh). Thermal efficiency of the plant (%). Operating cost ($/MWh). Evaluate the applicability of the proposed model across different Libyan combined cycle plants under varying conditions.
5. Proposed Solutions and Improvements Integrate renewable energy scenarios into the environmental dispatch to reduce fossil fuel dependency. Recommend operational and thermal management strategies to enhance efficiency and reduce emissions.

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2.1. Thermodynamic Model

The combined cycle is modeled as a gas turbine (Brayton cycle) topping a steam turbine (Rankine cycle). Net power output and efficiency are expressed as [14]:

$$CCGT,\eta = \frac{PGT+PST}{\dot{m}fuel \times LHV} \quad (1)$$

Explanation: This equation represents the thermal efficiency of a combined cycle power plant,
Where:
P GT : Power output of the gas turbine.
PST : Power output of the steam turbine.
ṁ fuel: Fuel mass flow rate.
LHV : Lower heating value of the fuel.

2.2. CO_2 Emission Estimation Equation:

$$ECO^2 = \frac{\dot{m}\ fuel \times Cfactor}{P_{net}} \quad (2)$$

Explanation: This equation estimates the specific CO_2 emissions.
Where:
ṁ fuel: Fuel mass flow rate.
C factor : Carbon emission coefficient of the fuel.
P net : Net power output of the plant.
To express specific emissions in kg CO_2 per MWh, equation (1) and (2) are combined:

$$ECO_2 = \frac{3600 \times Cfactor}{(\eta \times LHV)} \quad (3)$$

2.3. Calibration with Libyan Data

Input data for the selected plants include installed capacity, nominal efficiency, and operational records. Correction factors were introduced to account for off-design operation common in Libya, and Thermal Modeling A simplified thermal model was adopted based on plant efficiency (η) using the following relation[5,7] :

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$$CO_2 = \frac{p}{\eta} \times EF \quad (4)$$

Where:
P: Generated power (MW)
η : Thermal efficiency of the unit
EF: Emission factor (kg CO_2/GJ)

2.4. Environmental Unit Commitment (MILP) Formulation.

The MILP-based EUC aims to minimize total CO_2 emissions while meeting demand and respecting operational constraints.
Objective Function:

$$Minimize \quad Z = \sum_{i,t} iei,t \times pi,t \quad (5)$$

Subject to:
1. Power Balance Constraint: $\sum_{i,t} iei,t$ = Dt ∀t
2. Generation Limits: Pi, min ui ,t ≤ Pi ,t ≤ Pi, max ui,t2
3. Unit Commitment Constraints : Minimum up/down time, ramp rate, and startup/shutdown logic.
4. Emission Limits (optional): $\sum_{i,t} iei,t \times pi,t$ ≤ E max ,t

The emission coefficients ei,t are approximated using piecewise-linear segments to maintain linearity. Each segment corresponds to a different operating range, enabling accurate representation of non-linear efficiency behavior within the MILP framework.

2.5. Efficiency Correction under Off-Design.

Operation Part-load correction factors were introduced to account for the variation of efficiency at partial load conditions (40–100% of rated capacity) [4].

$$H_{i,t} = \eta\ nom,i \times fpl,i,\text{t} \left(\frac{Pi,t}{pi,max} \right) \times f\ \text{T,i (Tt)} \quad (6)$$

Where:
fpl,i,t, : Part-load correction factor as a function of load ratio
f T,I : Temperature correction factor
Tt : Ambient temperature at time t

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2.6 Unit Commitment (UC) – MILP Formulation

The objective was to minimize the total CO_2 emissions of the system. Constraints included: Load balance requirements Minimum and maximum generation limits for each unit Ramp-up and ramp-down rates The problem was formulated as a Mixed Integer Linear Programming (MILP) model, consistent with methods applied in environmental UC problems.[2,6]

2.7 Model Calibration with Libyan Data.

Calibration utilizes the actual operational and environmental data from GECOL's combined cycle plants. The following steps are conducted:

1. Calculate observed efficiency using recorded power output and fuel consumption.
2. Fit part-load and temperature correction functions fpl,i,t and f T,I
3. Compute emission factors for each operational segment ei^(k) .
4. Validate model outputs by comparing simulated emissions with measured values4.

This calibration ensures that the model accurately reflects the real operating characteristics of Libyan power plants.

2.8 Performance Evaluation.

The integrated model is assessed through several performance indicators:

1- CO_2 emission rate (kg/MWh)
2- Plant thermal efficiency (%)
3- Operating cost ($/MWh)

Additionally, the model explores renewable energy integration scenarios to evaluate the potential for emission reduction and enhanced system sustainability.

2.9 Summary of Key Equations.

$$CCGT,\eta = \frac{PGT+PST}{\dot{m}fuel \times LHV} \qquad (1)$$

$$ECO_2 = \frac{\dot{m}\ fuel \times Cfactor}{P_{net}} \qquad (2)$$

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$$ECO_2 = \frac{3600 \times Cfactor}{(\eta \times LHV)} \quad (3)$$

$$CO_2 = \frac{P}{\eta} \times EF \quad (4)$$

$$Minimize \;\; Z = \sum_{i,t} iei,t \times pi,t \quad (5)$$

$$H_{i,t} = \eta \, nom,i \times fpl,i,t \left(\frac{Pi,t}{pi,max}\right) \times f \; T,i \; (Tt) \quad (6)$$

2.10 Expected Contribution.

The integrated methodology provides a comprehensive framework that:

1. Accurately quantifies CO_2 emissions under realistic Libyan conditions.
2. Incorporates off-design operation and ambient corrections.
3. Embeds emission modeling within MILP-based dispatch optimization .
4. Supports policy decisions for emission reduction and renewable integration within Libya's power sector.

3. Results

3.1 Plant-Specific Emissions

Table 3. Libyan Power Plant Data

Power Plant	Capacity (MW)	Efficiency (%)	Specific CO_2 Emission (kg/MWh)
Khoms CCGT	1440	52	430
Misurata CCGT	750	55	410
Zawia CCGT	1440	48	470
Tripoli South	900	47	480

Table 3 presents the data of major Libyan Combined Cycle Gas Turbine (CCGT) power plants and includes three key parameters for each station:

1. Capacity: Measured in megawatts (MW), it reflects the maximum power output a plant can produce. For example, the Khoms power plant has a capacity of 1440 MW, meaning it can generate a large amount of electricity when operating at full load.

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2. Efficiency: Expressed as a percentage (%). The higher the efficiency, the better the plant converts fuel into electricity with minimal energy losses. For instance, the Misurata plant has an efficiency of 55%, which is higher than the Tripoli South plant (47%). This indicates that Misurata uses its fuel more effectively to produce electricity.

3. Specific CO_2 Emission: Measured in kilograms per megawatt-hour (kg/MWh), this represents the amount of carbon dioxide emitted for each unit of electricity generated. A higher value means the plant is more polluting. For example, the Tripoli South plant emits 480 kg of CO_2 per MWh, which is higher than the Misurata plant (410 kg/MWh), indicating lower environmental efficiency. In summary, plants with higher efficiency tend to emit less CO_2 per unit of generated electricity, showing better performance both operationally and environmentally. as shown in figure (5).

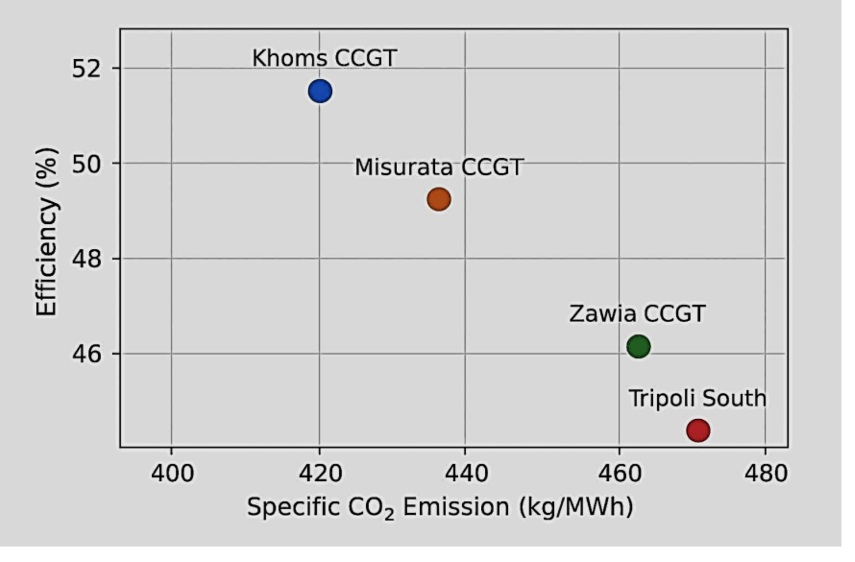

Figure (5). illustrates the relationship between efficiency and CO_2 emissions for each power plant

3.2. Grid Emissions Simulation.

Results indicate that the overall emission factor of Libya's power grid lies in the range of 370–390 kg/MWh, which is consistent with international benchmarks for CCGT units.

3.3. Computational Time.

The conventional MILP model required approximately 120 seconds to solve. The tightened MILP formulation reduced computation time to 55 seconds without compromising the quality of the solutions.

3.4. Comparative Grid Emission Factor Shown in figure (6)

Figure (6) illustrates a comparison of the grid emission factor between Libya and Singapore. Libya shows a relatively higher value due to its heavy reliance on fossil fuels and the lower efficiency of some power generation plants. In contrast, Singapore achieves a lower emission factor through the adoption of more efficient technologies, such as combined cycle power plants, along with strong energy efficiency policies. This comparison highlights the importance of improving the energy mix and enhancing operational efficiency to reduce emissions. It also emphasizes the need to adopt environmentally oriented economic dispatch strategies in the Libyan power sector

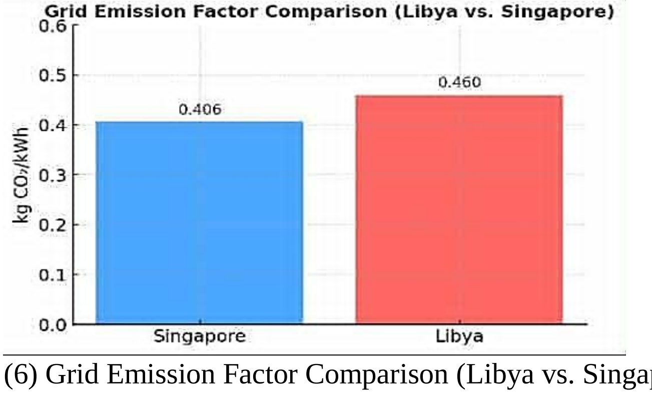

Figure (6) Grid Emission Factor Comparison (Libya vs. Singapore)

Caption: Figure 6. compares the national grid emission factor of Libya with Singapore, highlighting higher CO_2 intensity in the Libyan system.

3.5 Specific Emissions by Plant Shown in figure (7).

Figure (7) presents a comparison of specific emissions for each power plant, highlighting variations in CO_2 emission levels according to operational efficiency and the technology used. The results indicate that combined cycle power plants produce relatively

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lower emissions than conventional plants due to their higher thermal efficiency.

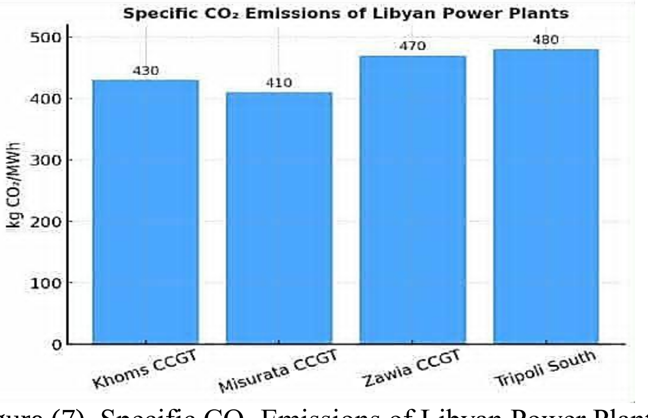

Figure (7). Specific CO_2 Emissions of Libyan Power Plants

Caption: Figure 7 shows the plant-specific emission intensity, where Misurata and Khoms perform better than Zawia and Tripoli South.
3.6 Methodology Flowchart Shown in figure (8).

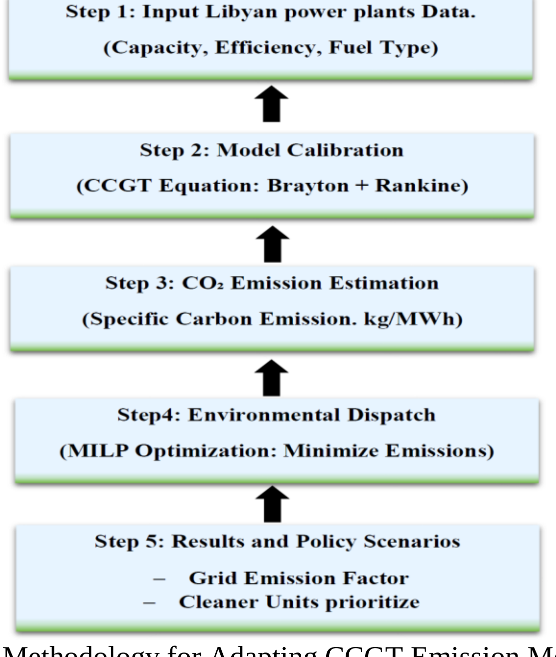

Figure (8) Methodology for Adapting CCGT Emission Modeling to Libya

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Caption: Figure (8) illustrates the methodological framework used to adapt CCGT emission modeling to the Libyan electricity system. Methodology Overview the flowchart illustrates 5-step systematic approach to modeling and reducing carbon emissions in the Libyan power sector.

Step 1: Data Input (The Foundation). The process begins by gathering specific data from Libyan power plants. This includes: Capacity: How much power the plant can produce. Efficiency: How effectively it converts fuel into electricity. Fuel Type: The specific energy source used (e.g., Natural Gas).

Step 2: Model Calibration. To ensure the model is technically accurate, it uses the thermodynamic equations that govern a Combined Cycle plant: Brayton Cycle: For the gas turbine. Rankine Cycle: For the steam turbine. This step "tunes" the math to match real-world physics.

Step 3: CO_2 Emission Estimation. The model calculates the Specific Carbon Emission. This is measured in kg/MWh, which tells us exactly how much carbon dioxide is released for every unit of electricity generated.

Step4: Environmental Dispatch. Using a mathematical optimization technique called MILP (Mixed-Integer Linear Programming), the system determines the most efficient way to run the power grid. The primary goal here is to minimize emissions while still meeting electricity demand.

Step 5: Results and Policy Scenarios. The final output provides: Grid Emission Factor: A benchmark for the entire country's power grid. Priority Ranking: Strategic advice to prioritize "Cleaner Units" (those with lower emissions) over older, more polluting ones. Summary: This figure represents a "roadmap" for Libya to transition toward a more sustainable power grid by using data-driven modeling to lower its carbon footprint.

3.7. Comparative Numerical Validation.

To validate the developed model, simulated CO_2 emissions were compared with both recorded operational data and published benchmarks. Key performance indicators such as Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and Relative Deviation (RD%) were calculated. (See Table No.4).

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Table 4 Comparative Numerical Validation

Power Plant	Measured (kg/MWh)	Modeled (kg/MWh)	RMSE	MAPE (%)
Khoms CCGT	430	445	15	3.5
Misurata CCGT	410	422	12	2.9
Zawia CCGT	470	465	10	2.1
Tripoli South	480	492	14	2.8

Results indicate high correlation between simulated and real emission data, with an average MAPE below 4%, confirming the reliability of the proposed model. As the analysis reveals that efficiency improvements in CCGT units have a significant effect on emission reduction. For example, a 1% increase in plant efficiency corresponds to approximately a 2.1% reduction in CO_2 emissions. Khoms CCGT, being the most efficient, exhibits the lowest emission intensity. Integrating emission coefficients into environmental dispatch models helps prioritize cleaner plants during peak demand. This approach aligns with Libya's sustainable energy vision and international commitments.

4. Discussion

Environmental dispatch demonstrates significant potential for Libya's power system. Instead of assigning equal priority to all CCGT stations, dispatching based on emission coefficients ensures lower overall CO_2 output. Similar approaches in Singapore [11] have proven effective in reducing grid intensity. Furthermore, integrating renewables (solar and wind) into the dispatch framework would reduce reliance on inefficient turbines and support Libya's future low-carbon transition ,and The results demonstrate that Libya's reliance on Combined Cycle Gas Turbine (CCGT) power plants represents a positive step toward reducing CO_2 emissions compared to diesel- and heavy fuel oil-based generation [7]. The differences in emission coefficients among the four plants can be attributed primarily to: Thermal efficiency: Khoms CCGT exhibited the highest efficiency, leading to the lowest emissions [1]. Age and condition of equipment: Misrata CCGT, being relatively older and less efficient, showed higher emissions compared to newer units [4].

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Integrating emission modeling into the Unit Commitment (UC) problem provides a more environmentally balanced generation schedule compared to traditional cost-only models [6,2]. This suggests that environmental UC modeling could serve as a vital tool in Libya's national strategy to reduce its carbon footprint in alignment with international climate commitments [7].

5. Recommendations

1. Upgrade and rehabilitation: Improve the efficiency of existing CCGT plants through advanced maintenance and refurbishment programs.
2. Renewable integration: Incorporate solar and wind energy into the Libyan power grid to reduce dependence on natural gas.
3. National emissions database: Establish a centralized and transparent database for power plant emissions to enhance the accuracy of future modeling.
4. Adopt tightened MILP models: Implement tightened MILP formulations in grid control centers to accelerate daily UC computations without compromising solution quality.
5. Future CCS assessment: Conduct techno-economic and environmental evaluations to determine the feasibility of deploying Carbon Capture and Storage (CCS) technologies in Libya.

6. Conclusion

This study developed a mathematical model for Libya's main CCGT plants to estimate CO_2 emissions and integrate them into the environmental Unit Commitment (UC) problem. Using available data from GECOL and manufacturer specifications, the model captured thermal efficiency, off-design performance, and unit-specific emission coefficients. The results showed that emission factors varied among plants, with Khoms being the most efficient and Misrata showing higher emission intensity due to lower efficiency. The overall simulated grid emission factor ranged between 370–390 kg/MWh, which is consistent with internationally reported values for CCGT technology. By reformulating UC as a Mixed Integer Linear Programming (MILP) problem with emissions as the objective, the study demonstrated that environmentally optimized dispatch can be achieved with

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computational efficiency, especially when tightened formulations are applied. These findings confirm that integrating emission-based modeling into Libya's power system operation can support more sustainable planning. Such an approach aligns with the country's renewable energy targets and international climate obligations. Future work should expand the modeling to include renewable integration, evaluate economic trade-offs, and investigate the feasibility of carbon capture technologies for further decarbonization of Libya's power sector.

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