Cost Optimization of Renewable Energy Installation in a Four-Microgrid System Using GBOML

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***Abstract*— The electrical power generation sector is undergoing a profound transformation, shifting from traditional large, centralized generators to a more decentralized model that integrates smaller, distributed generators directly into distribution networks. Initially designed as independent backup systems, these distributed generators are now being synchronized with the grid and increasingly utilized as primary electricity sources. This transition, driven by advancements in renewable and non-conventional energy technologies, is accelerating the development and widespread adoption of Microgrids, reshaping the future of power systems. Furthermore, interconnecting multiple Microgrids offers significant benefits, such as optimizing surplus renewable energy by transferring it to neighboring Microgrids, thereby reducing reliance on energy storage systems and enhancing the overall stability and efficiency of power distribution. In this paper, the Graph-Based Optimization Modelling Language (GBOML) is employed to optimize the overall installation cost of renewable energy technologies. The results obtained from GBOML are compared with Pyomo to evaluate the effectiveness of GBOML. For the purposes of this study, the load data, as well as solar and wind energy data, were collected for four distinct regions in India: Jharkhand, Chhattisgarh, Odisha, and West Bengal. These datasets serve as the foundation for analysing renewable energy integration and load management strategies within the proposed framework.**

Keywords—Microgrid; Grid Interconnection; Linear Optimization; GBOML; Global Electricity Grid

I. INTRODUCTION

Modern society and political frameworks are placing an increasing emphasis on achieving a sustainable and environmentally resilient future. This growing commitment is evident in the numerous climate change agreements that have been signed in recent years and those currently under negotiation [1]. A prominent example is the internationally binding Paris Agreement, which aims to limit the global average temperature rise to 2°C, with an aspirational target of keeping it below a 1.5°C increase relative to pre-industrial levels [2,3]. In a further demonstration of climate leadership, the European Union has introduced the European Green Deal, a comprehensive and ambitious policy framework designed to achieve carbon neutrality by 2050 while promoting sustainable economic growth and environmental protection.

One such promising solution for attaining sustainability in energy production is decentralization of electrical networks and one of the trends emerging in this regard is Microgrids. The EMS is an essential component in the optimal distribution of energy resources to satisfy load requirements in modern Microgrids [4,5]. These systems guarantee that the Microgrid keeps their activity within the technical and operational limits while pursuing a set objective.

The variability of Renewable Energy Sources (RES) like solar power, depending on the intensity of sunlight, represents one of the main problems in Microgrid operations [6]. This variability affects power quality and stability, especially when they are used to integrate solar power into grid systems where the system operator may consider its uncontrolled fluctuation as a liability. To tackle this problem, S. Chatzivasileiadis et al. 2013, proposed a Global Grid in where regional and national power grids are interconnected globally so that electric utilities can transfer electricity to others beyond countries and continents [7]. This system seeks to establish an interconnected mesh to tap energy-harnessing resources at far-off geographic locations: geothermal and solar energy from sun-drenched places, wind power from windy regions, hydroelectricity generated from water-abundant terrains enabling their efficient sharing on a global scale [8].

Microgrid systems have so many advantages with respect to the user as well as utility provider. Grid-connected Microgrids can improve power quality, minimize emissions, and reduce operational costs for users, while contributing to increased network reliability and higher efficiency for utility providers [9]. In addition, the interconnection of several

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Microgrids provides multiple benefits that can help make the electric power systems more efficient, sustainable, and reliable [10]. This cultivates better energy resource exploitation as sharing excess energy helps meet the overall energy demand through less energy storage solutions by interconnected Microgrids. Thus, in order to balance supply and demand across Microgrids, energy exchange will help improve overall grid stability and reduce energy waste. Interconnected Microgrids not only have the added redundancy of providing backup power during outages or high demand periods that allow them to support each other, but are also more resilient other utility grids when disturbances occur. Such interconnections also enable greater integration of renewable energy sources, facilitating a cleaner, more flexible, and cost-effective power network for both consumers and utility providers.

In 2021, M. Berger et al. proposed and developed Graph-Based Optimization Modeling Language (GBOML) which is applied to remote renewable energy hubs for carbon-neutral synthetic fuels production [11]. This novel approach illustrated the opportunity to make in situ optimizations to energy systems resource allocation and operational strategies on the fly [12]. Moreover, B. Miftary et al. delve into GBOML in detail and apply it to a mixed-integer linear optimization problem to analyze its performance [13].

The present research demonstrates the application of GBOML on individual Microgrid as well as interconnected Microgrid systems to identify the optimal costs for the implementation of renewable energy (RE) technology installations. In the case of the interconnected two-Microgrid system, the total cost consists of additional terms such as the costs for the converter pairs and HVDC transmission lines needed to enable energy transfer between the Microgrids.

The remainder of this paper is structured as follows: Section 2 provides an overview of the single Microgrid system and the interconnected two-Microgrid system. Section 3 presents the problem formulation, while Section 4 focuses on the analysis and discussion of results. Finally, Section 5 concludes the study and highlights key findings.

II. MICROGRID

The concept of Microgrids was first introduced in the technical literature, as noted in [14], as an innovative solution for the reliable integration of Distributed Energy Resources (DERs), including Energy Storage Systems (ESSs) and controllable loads. A Microgrid is viewed by the main power grid as a single, cohesive entity capable of responding dynamically to control signals to maintain stability and efficiency.

Although a universally accepted definition is still under debate in technical forums, a Microgrid can be broadly described as a coordinated network of interconnected loads, Distributed Generation (DG) units, and ESSs. This system operates in synchronization with the host power grid and interfaced at distribution side with single PCC. Microgrid implementation enables easy access to integrations of DERs with traditional power systems and also offers an alternative decentralized structure for tackling technical challenges, lessening the degree of dependency on complex centralized coordination and speeding up the process of achieving Smart Grid.

A. Single Microgrid System

In this paper, a single Microgrid system is configured with key components, including a Solar PV system, Wind Farm, Battery Energy Storage, load demand, and connection to the main grid. These elements are interconnected and operate in coordination through a power balance equation, ensuring efficient energy management and reliable supply within the Microgrid framework. Figure 1 illustrates the configuration of a single Microgrid system.

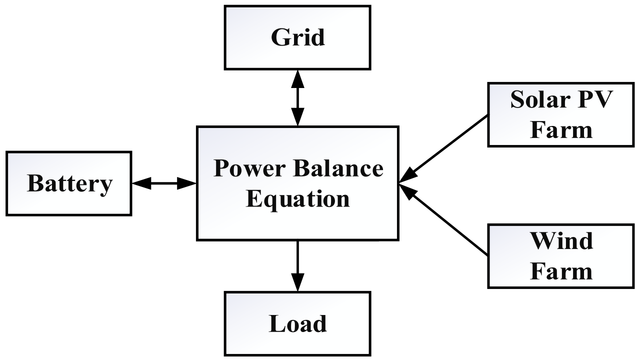

Fig.1. Single Microgrid System

B. Four Microgrid System

The four Microgrid system four microgrids are inter connected by a power balance equation which consist of Battery and main grid. The each individual microgrid are configured with key components, including a Solar PV system, Wind Farm, and load demand. These elements are interconnected and operate in coordination through a power balance equation, ensuring efficient energy management and reliable supply within the Microgrid framework. Figure 2 illustrates the configuration of a four microgrid system.

III. DATA COLLECTION

The data used in this study were sourced from reliable platforms to ensure accuracy in renewable energy optimization. Load demand data were obtained from the India Climate & Energy Dashboard [15], while solar irradiance and wind speed data were collected from Solcast, a DNV company [16]. Additionally, specifications for the Suzlon S144 3 MW wind turbine were taken from the Suzlon S144 3 MW Series [17]. These datasets serve as the foundation for analyzing renewable energy integration and load management strategies within the proposed framework.

IV. PROBLEM FORMULATION

A. Solar PV

The Irradiance on the Tilted Surface can be mathematically formulated as [18,19]:

$$I_t = DNI \times A + DHI \times B + GHI \times C$$

$$A = \cos\left(\theta z\right)$$

$$B = \left(\frac{1+\cos\left(\beta\right)}{2}\right)$$

$$C = \left(\frac{1-\cos\left(\beta\right)}{2}\right)$$

where, DNI, DHI, and GHI represents the Direct Normal Irradiance, Diffuse Horizontal Irradiance and Global

Horizontal Irradiance respectively. θz and β represents the Solar Zenith Angle and Tilt Angle respectively.

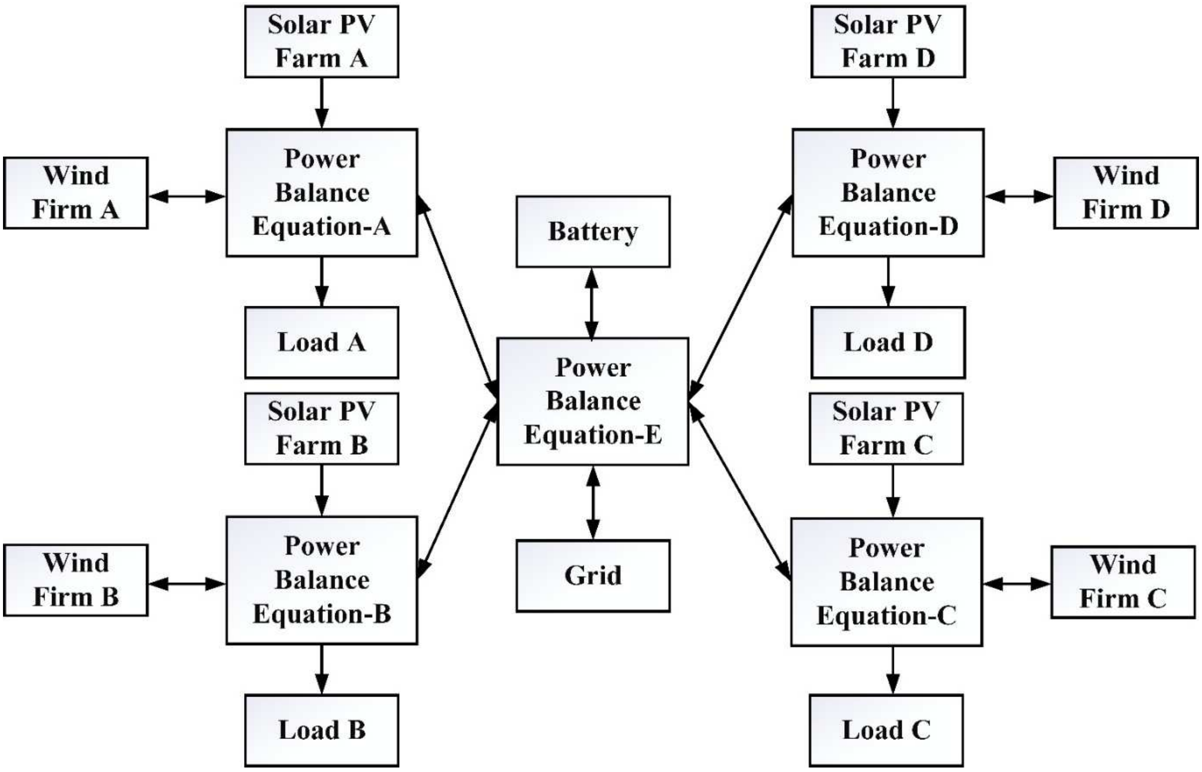

Fig.2. Four microgrid System

The power output of a PV panel decreases with increasing temperature. The temperature-corrected efficiency (ηT) can be calculated as:

$$T_{cell} = T_{air} + \left(\frac{NOCT - 20}{I_{ref}} \right) \times I_t$$

$$\eta_T = \eta_{STC} \times \left[1 - \Upsilon \times \left(T_{cell} - T_{STC} \right) \right]$$

where, T_{cell} and T_{air} represents the cell temperature and ambient air temperature. NOCT represents the nominal operating cell temperature. I_{ref} represents the reference irradiance. η_{STC} represents the efficiency at standard test condition. γ represents the temperature coefficient of the PV panel. T_{STC} is the cell temperature at standard test condition.

The power output of Solar PV Pannel can be mathematically represented as:

$$Pout = I_r \times A_{PV} \times \eta_T$$

where, A_{PV} represents the area of solar pannel.

The capacity Factor of solar PV can be mathematically formulated as:

$$CF_{PV} = \frac{P_{PV}^t}{\mathrm{P}_{PV}}$$

where, represents the Solar PV generation at any instant of time t, PPV represents the rated power that can be generated.

The total optimized investment cost of the solar PV (C_{PV}) system can be mathematically formulated as:

$$C_{PV} = \left(ACE_{PV} + OMC_{PV} \right) \times P_{PV}$$

where, PPV represents the total installation capacity of Solar PV, ACE_{PV} represents the annualized investment cost of solar PV and OMC_{PV} represents the annualized Operation and Maintenance cost of Solar PV.

At any instant of time P^t_{PV} always less than or equal to P_{PV}

$$P_{PV}^t \le P_{PV}$$

B. Wind Energy

The power output PW of a wind turbine can be calculated as follows [20]:

$$P_W = \frac{1}{2} \times \rho \times A_W \times V^3 \times C_P$$

Where, represents the air density, AW represents the swept area of the wind turbine, V represents the wind speed and the Cp represents the Betz coefficient.

The capacity Factor of Wind energy can be mathematically formulated as:

$$CF_W = \frac{P_W^t}{\mathrm{P}_W}$$

Where, represents the wind power generation at any instant of time t, PW represents the rated wind power of the wind turbine.

The total optimized investment cost of the wind generation (C_W) system can be mathematically formulated as:

$$C_W = \left(ACE_W + OMC_W \right) \times P_W$$

where, P_W represents the total installation capacity of wind turbine, ACE_W represents the annualized investment cost of wind turbine and OMC_W represents the annualized Operation and Maintenance cost of wind turbine.

At any instant of time P^t_W always less than or equal to P_W

$$P_W^t \leq P_W$$

C. Battery Energy Storage

The total optimized investment cost of the Battery (C_B) system can be mathematically formulated as [21]:

$$C_B = \left(ACE_B + OMC_B \right) \times P_B$$

where, P_B represents the total installation capacity of Battery, ACE_B represents the annualized investment cost of battery and OMC_B represents the annualized Operation and Maintenance cost of battery.

At any instant of time E^t_B always less than or equal to E_B

$$E_B^t \leq E_B$$

The State of charge (E_b^{t+1}) can be mathematically formulated as:

$$E_B^{t+1} = E_B^t + \eta E_{B+}^t - E_{B-}^t / \eta$$

where, η is the efficiency of battery regarding charging and discharging loss.

D. Main Grid

The Operating cost of power import at any instant of time t can be mathematically formulated as:

$$TC_G = \sum_{t=1}^{T} O_G \times P_G^t$$

where, O_G represents the per unit expenditure and P^t_G represents the microgrid power deficiency.

V. Graph Based Optimization modeling language

Graph Based Optimization modelling language (GBOML) is developed by M. Berger et al. in 2021. It is implemented in remote renewable energy hubs for the carbon-neutral production of synthetic fuels [10]. This novel approach showcased the potential for improving resource allocation and operational strategies in renewable energy systems. Furthermore, B. Miftary et al. conducted an in-depth study on GBOML, applying it to a mixed-integer linear optimization problem to evaluate its efficiency. Their research effectively demonstrated how GBOML enhances decision-making processes within intricate energy networks. The primary advantage of GBOML is its ability to break down a large optimization problem into multiple smaller sub-optimization problems, referred to as nodes. Equality constraints are considered the most stringent and rigid constraints in an optimization problem, as they significantly reduce the feasible solution space by strictly defining the conditions that must be met [22,23]. In this study, the equality constraint is handled by the hyperedge of GBOML. The steps for implementing GBOML is discussed below:

Step 1: Import gboml graph

In order to import the gboml graph we have to import GbomlGraph from gboml.

Step 2: Create gboml model

The gboml model can be created by assign a time horizon in GbomlGraph.

Step 3: Import nodes and hyperedges

In this step we have to mport al the nodes and hyperedges from the Linear Optimization Problem txt file.

Step 4: Add nodes and hyperedges in gboml model

In this step the nodes and hyperedges are assigned in the gboml model

Step 5: Update model

In this step the gboml model is updated by building the model

Step 6: Solve the model

In this step the solvers such as cplex and gurobi etc can be used to solve the optimization problem.

VI. Result Analysis

In this study, GBOML is implemented in single Microgrid system and four microgrid system to determine the total optimized cost of RE technology installations. The program is run in a pc having with a Core i7 CPU and 16 GB of RAM. In this study, four states in India Jharkhand, West Bengal, Chhatisgarh and Bihar were selected, and their one-year load data was analysed starting from 01/01/2022 to 31/12/2022. Additionally, wind speed and solar radiation data were collected for the same locations over the same period to ensure a comprehensive assessment of renewable energy potential and grid demand dynamics. In this study Suzlon S144 3 MW Wind Turbine is used for wind resources analysis and capacity factor calculation.

Case 1: Single microgrid system

In case study 1, GBOML is applied to a single microgrid system to determine the optimal renewable energy installation cost. As shown in Table 1, the total optimal installation cost required to meet the load demand in Jharkhand is ₹13,258.46755 crore, West Bengal is ₹65,056.24697 crore, Chhatisgarh is ₹38,833.16921 crore and Bihar is ₹46,587.93294 crore. The optimization process using GBOML takes 2 seconds for Jharkhand, 4 seconds for West Bengal, 2 seconds for Chhatisgarh, and 3 seconds for Bihar. In case of Pyomo the time taken to solve the optimization problems are 6 seconds for Jharkhand, 9 seconds for West Bengal, 7 seconds for Chhatisgarh, and 8 seconds for Bihar. In this case Plasmo can solve the optimization problems by 5 seconds for Jharkhand, 7 seconds for West Bengal, 6 seconds for Chhatisgarh, and 6 seconds for Bihar.

Case 2: Four microgrid system

In Case Study 2, GBOML is applied to a four-microgrid system to determine the optimal renewable energy installation cost. In this study, Jharkhand, West Bengal, Chhatisgarh and Bihar are interconnected.

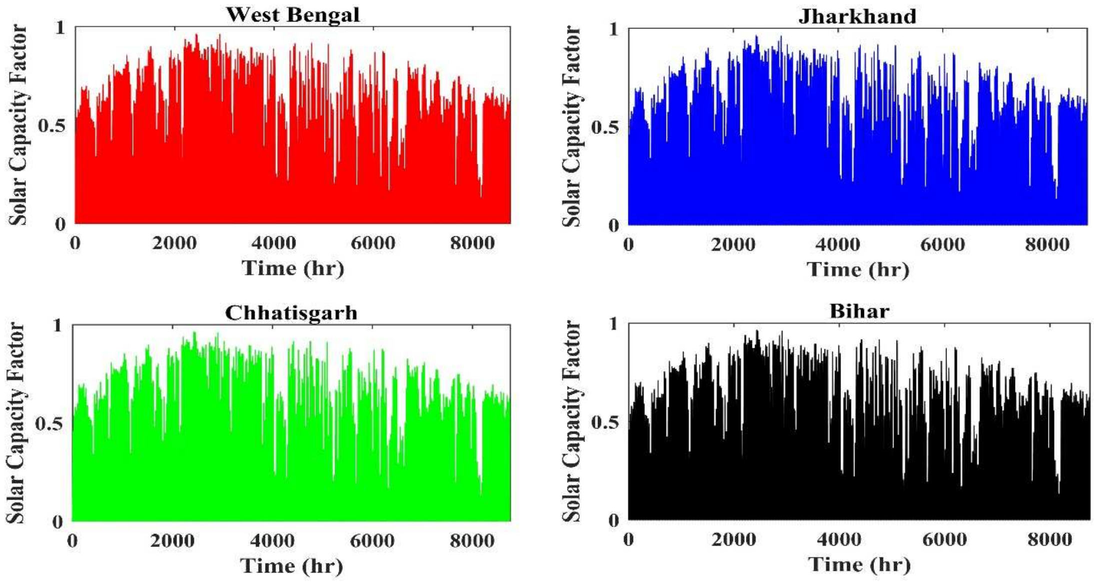

Fig.1. Solar Capacity Factor of all the four states

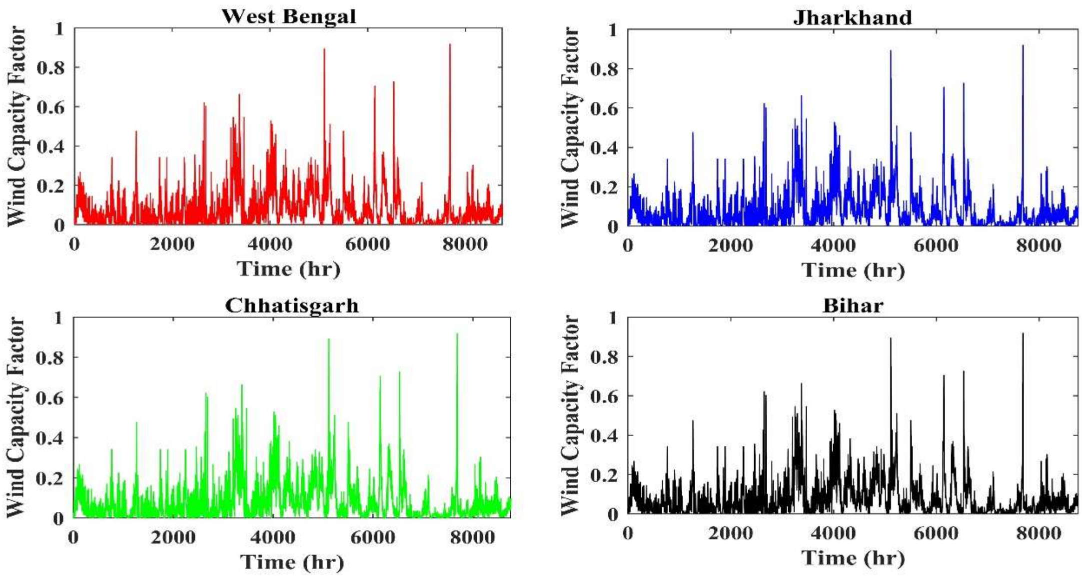

Fig.2. Wind Capacity Factor of all the four states

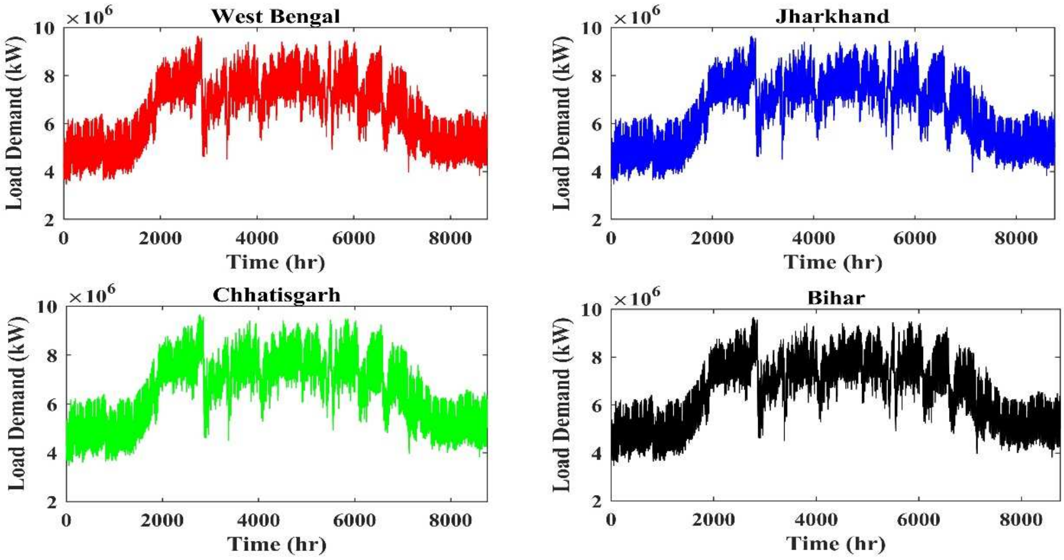

Fig.3. Load Demand of all the four states

Table 1. Total optimal renewable energy installation cost

Sl. No.	States	Installation Cost (Cr Rupees)	Simulation Time taken (sec)		
			GBOML	Pyomo	Plasmo
1	West Bengal	65056.24697	4	9	7
2	Jharkhand	13258.46755	2	6	5
3	Chhatisgarh	38833.16921	2	7	6
4	Bihar	46587.93294	3	8	6

Whenever the renewable energy power generation in any state is unable to supply the load demand the deficit is supplied by the rest of the states. If the tota demand of all the 4 states are not fulfilled then the load demand is supplied by the battery as well as main grid. The total optimal renewable energy installation cost obtained from GBOML for the two-microgrid system is ₹1,30,142.8813 crore. The optimization process using GBOML takes 8 seconds for the four-microgrid system. In casde of Pyomo and Plasmo the taime taken to sole the four microgrid system are 16 seconds and 11 seconds respectively This study demonstrates that the total optimal renewable energy installation cost for the interconnected four-microgrid system is significantly lower than the cost of designing four standalone microgrid systems.

VII. Conclusion

This research identifies the benefits of combining several microgrids to minimize renewable energy installation costs. Using the Graph-Based Optimization Modelling Language, the overall cost of renewable energy installation was analyzed for both independent and interconnected microgrid systems in Jharkhand, West Bengal, Chhatisgarh and Bihar. The findings show that interconnecting microgrids greatly minimizes overall installation costs as opposed to constructing independent systems. Particularly, the overall installation cost of the four isolated microgrids is ₹1,63,735.8167 crore, while the interconnected system costs only ₹1,30,142.8813 crore showing a cost saving through efficient energy sharing. In addition, interconnection of microgrids increases power system efficiency by facilitating surplus energy transfer between areas, minimizing reliance on energy storage, and enhancing grid stability. These results highlight the promise of interconnected microgrid networks in enabling cost-effective and sustainable integration of renewable energy, and thus are a promising solution for future power systems.

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