Social Factor in Quadrilemma Optimization of Grid-Connected Industrial Microgrid Sizing Supporting Socio-Economic Development

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DOI: https://dx.doi.org/10.47772/IJRISS.2025.909000235

Received: 02 September 2025; Accepted: 09 September 2025; Published: 07 October 2025

ABSTRACT

This paper presents a quadrilemma-based optimization approach for sizing an industrial microgrid, balancing technical, economic, environmental, and social objectives. The proposed method employs a multi-objective Iterative Pareto Fuzzy (IPF) technique, considering four critical factors: maximizing reliability, minimizing overall cost, reducing CO_2 emissions, and maximizing the job creation factor. The sizing optimization is applied to a case study of an industrial microgrid using MATLAB simulations, where photovoltaic (PV), wind turbine (WT), and battery energy storage system (BESS) units are strategically deployed. A comparative analysis with the trilemma approach reveals that the quadrilemma approach determines the optimal solution, achieving a higher reliability improvement of 11.04% while enhancing socio-economic benefits. Although this approach results in increased costs and emissions, the slightly larger PV and BESS capacities, which increased by 23.8% and 6.7%, respectively, contribute to improved scalability and system resilience. The findings demonstrate the effectiveness of the quadrilemma approach in achieving broader sustainability goals and supporting the development of resilient and socioeconomically beneficial industrial microgrid systems.

Keywords: quadrilemma optimization; industrial microgrid sizing; multi-objective; four-factor balance; renewable energy integration

INTRODUCTION

The integration of renewable energy sources (RESs) into microgrid systems has emerged as a critical solution to address the increasing demand for sustainable and resilient energy [1]. Microgrids, which utilize technologies such as photovoltaic (PV) systems, wind turbines (WT), and battery energy storage systems (BESS), provide a promising approach to enhancing energy independence and improving the reliability of the power supply. However, achieving optimal design and operation of these systems requires careful consideration of multiple, often conflicting objectives [2] across technical, economic, environmental, and social dimensions.

Previous optimization models for microgrids have predominantly focused on three main aspects: economic, technical, and environmental factors. Economic criteria typically involve evaluating the Net Present Cost (NPC) [3], Levelized Cost of Energy (LCOE) [4], and Total Cost (TC) [5] to assess financial viability and cost-effectiveness. Technical performance is often measured through indicators such as loss of power supply probability (LPSP) [6], renewable energy penetration factor (REPF), and unmet load (UL) [7], ensuring that the system can reliably meet demand and maintain operational standards. Environmental objectives, including the reduction of CO_2 emissions and an increased renewable energy fraction, are essential for evaluating the sustainability and environmental impact of the microgrid system [8]. Despite the growing awareness of the importance of social factors, many existing frameworks have rarely incorporated metrics like job creation (JC) and human development indices (HDI), which are critical for assessing the broader socio-economic benefits of microgrid systems [8], [9], [10], [11], [12].

Table 1 provides a comparative analysis of recent studies that incorporate the social factor and illustrates the distinct scope of this paper. Unlike previous works that primarily focus on off-grid or grid-connected hybrid renewable energy systems (HRES) or off-grid microgrids, this study examines a grid-connected industrial microgrid system. The focus on an industrial microgrid is motivated by the high energy demand, the need for a reliable power supply, and the potential for significant reductions in operational costs and greenhouse gas emissions within the industrial sector. By addressing these unique requirements, the proposed model aims to optimize the industrial microgrid system specifically for industrial applications, providing a tailored approach that enhance energy efficiency and socio-economic benefits.

Moreover, most existing optimization approaches only consider three dimensions, namely technical, economic, and environmental factors. In contrast, this study proposes an optimization model that incorporates a fourth dimension by including a social objective, specifically targeting job creation. By integrating this additional objective, the model aims to achieve balanced optimization that enhances technical performance while also providing significant socio-economic benefits.

The paper is structured as follows. Section II discusses the industrial microgrid case study, Section III details the objective function formulation, Section IV presents the results and discussion, and Section V concludes with key findings.

Table 1 Comparative Analysis of Recent Studies That Include the Social Factor

Ref.	Test System	Technical	Economic	Environmental	Social
[8]	Grid-connected HRES	-	TC	CO_2 emission	JC
[9]	Off-grid HRES	Renewable factor (RF), LPSP	Net present value (NPV), cost of energy (COE)	CO_2 pollution	JC
[10]	Off-grid Microgrid	Renewable dispersion (RD), UL	LCOE, NPC	Carbon emission (CE)	Human progress index (HPI), employment generation factor (EGF), local employment generation (LEG)
[11]	Off-grid Microgrid	REPF	LCOE	Greenhouse gas emission (GGE)	Employment creation factor (ECF)
[12]	Off-grid HRES	Energy efficiency	NPC, LCOE, payback period	Renewable fraction	HDI, job creation factor (JCF)
Proposed approach	**Grid-connected Industrial Microgrid**	Energy index of reliability (EIR)	Overall Cost	CO_2 emission	**JCF**

A Case Study in Industrial Microgrid

The grid-connected industrial microgrid analyzed in this study is based on Microgrid 2 (MG2) from a developed multi-microgrid (MMG) system comprising five interconnected microgrids in reference [13], where MG2 specifically caters to an industrial load. The configuration of industrial microgrid shown in Fig. 1 includes key components such as PV panels, wind turbines, and BESS, designed to meet the high energy demand and enhance the stability of the industrial sector. Detailed modeling of these components, including their characteristics and operating parameters, has been thoroughly discussed and is available in [13].

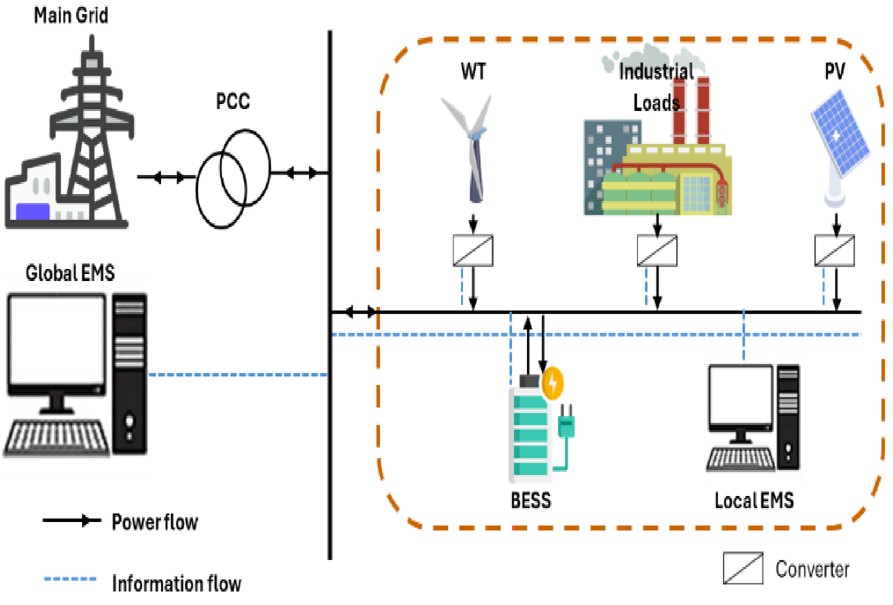

Figure 1. Industrial Microgrid Architecture

The renewable energy generation data and load profiles for the industrial microgrid were obtained from the Mersing site at Tanjung Resang, Malaysia [13]. Annual solar irradiance and wind speed data were collected for this location, providing a realistic basis for simulating the renewable energy potential of the industrial microgrid.

Additionally, the industrial load pattern was sourced from [14] to ensure accurate representation of typical demand patterns. Figures 2 to 4 illustrate the solar irradiance, wind speed, and load profiles (P_{load_demand}) used in this analysis.

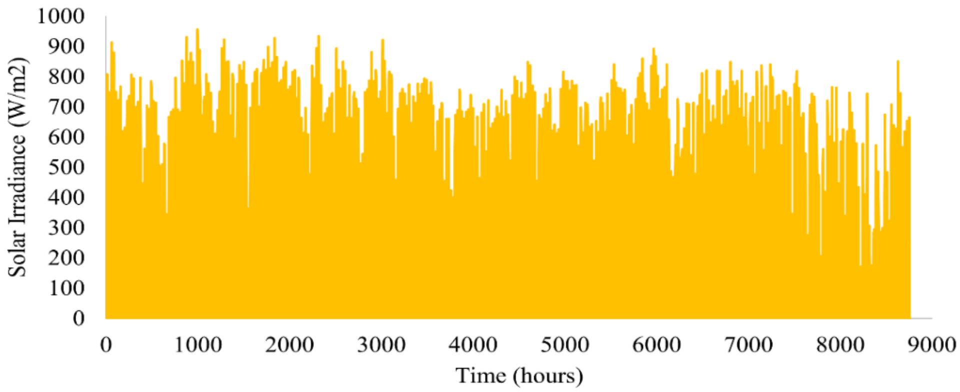

Figure 2. Annual solar irradiance

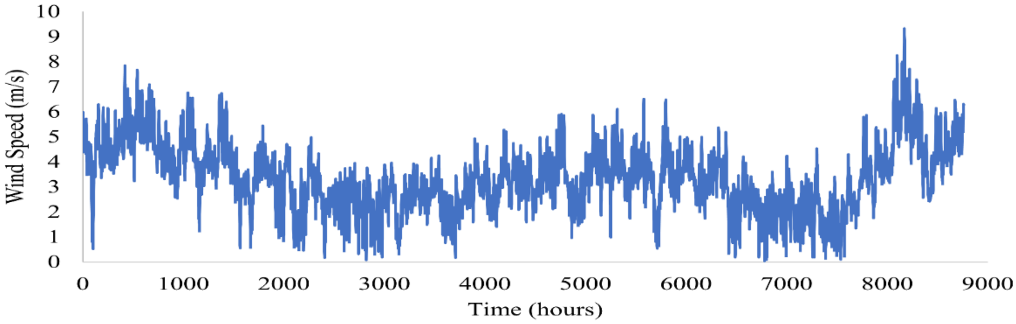

Figure 3. Annual wind speed

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue IIIS July 2025 | Special Issue on Education

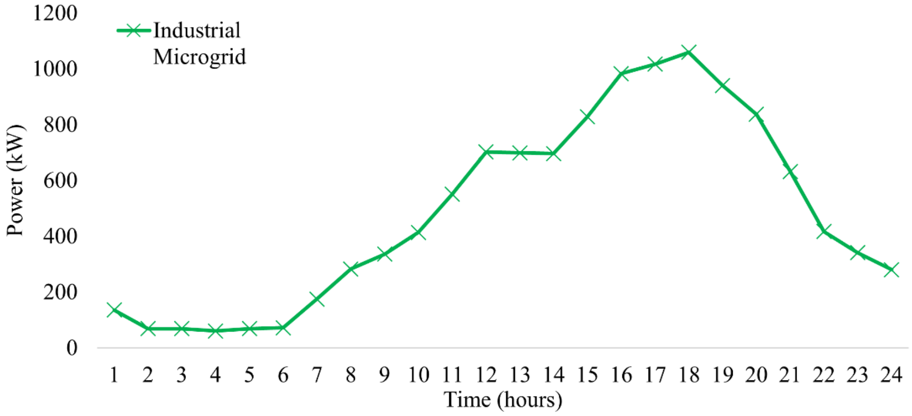

Figure 4. Daily load profile of an industrial microgrid

Objective Function Formulation

This study utilizes a multi-objective optimization framework based on the Iterative Pareto Fuzzy (IPF) technique [13], incorporating a comprehensive quadrilemma approach. This approach addresses four critical objectives, which are technical, economic, environmental, and social, with each representing a distinct aspect of sustainable industrial microgrid operation. The overall optimization process is illustrated in Fig. 5, which presents the flowchart of the proposed quadrilemma-based optimization for grid-connected industrial microgrid sizing.

The optimization problem is formulated subject to the operational constraints of the industrial microgrid system, including energy balance, state of charge (SoC) limits of the BESS, and capacity limits of renewable energy sources [13]. Each objective function is described in detail in the following subsections.

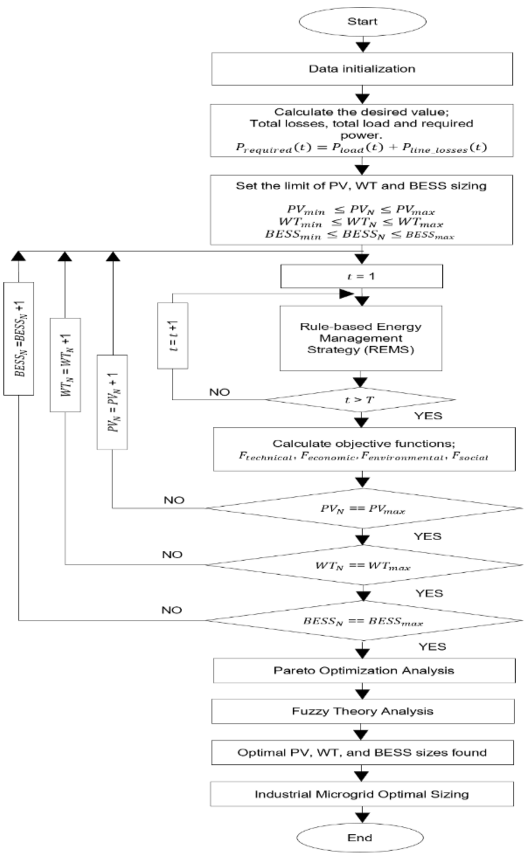

Figure 5. Flowchart of the proposed quadrilemma-based optimization for grid-connected industrial microgrid sizing

Technical Objective: Reliability Maximization

The technical objective focuses on maximizing the reliability of industrial microgrid using the energy index of reliability (EIR), which is defined as:

$$max\, F_{technical} = EIR = 1 - \frac{EENS}{P_{required}} \quad (1)$$

$$EENS = \sum_{t=1}^{T} \left[P_{required}(t) - \left(P_{total}(t) + P_{BESS_{SoC}}(t) - P_{BESS_{SoC\_min}}(t)\right)\right] \times U(t) \quad (2)$$

$$P_{total}(t) = P_{PV}(t) + P_{WT}(t) \quad (3)$$

$$P_{required}(t) = P_{load\_demand}(t) + P_{line\_losses}(t) \quad (4)$$

$$P_{line\_losses}(t) = |V_{i,t}|\,|V_{j,t}||Y_{ij}|cos(\theta_{ij} - \delta_{i,t} - \delta_{j,t}) \quad (5)$$

$$V_{min} \leq V_{i,t} \leq V_{max};\ i \neq 1, V_{i,t} = 1\angle 0 \quad (6)$$

where

$EENS$	: Expected energy not supplied
$P_{required}$	: Required power
P_{total}	: Total power
$P_{BESS_{SoC}}$	: SoC of BESS
$P_{BESS_{SoC\_min}}$	: SoC minimum of BESS
$U(t)$	: Time step

This function aims to minimize unserved energy, thereby increasing the reliability of the industrial microgrid. A higher EIR value indicates better system performance in meeting the load demand.

Economic Objective: Overall Cost Minimization

The economic objective seeks to minimize the overall cost denoted as $Overall\ Cost$ ($), which includes the initial cost (I_i), the operation and maintenance cost (OM_i), and the subtraction of the salvage value (S_i) for each components. The economic objective function is formulated as:

$$min\, F_{economic} = Overall\ Cost = \sum_{i=PV,\,WT,\,BESS} I_i - OM_i - S_i[X(t) \times Cost_{addWT}] \quad (7)$$

$$X(t) = WT_N - 1 \quad (8)$$

$$I_{PV} = \alpha_{PV} PV_N \quad (9)$$

$$I_{WT} = \alpha_{WT} A_{WT} WT_N \quad (10)$$

$$I_{BESS} = \alpha_{BESS} \times P_{BESS} \times BESS_N \times \sum_{i=1}^{Ybess} \left(\frac{1+v}{1+\beta}\right)^{(i-1)L_t} \quad (11)$$

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$$OM_{PV} = \alpha_{OMPV} \times PV_N \times \sum_{i=1}^{Lt} \left(\frac{1+v}{1+\gamma}\right)^i \quad (12)$$

$$OM_{WT} = \alpha_{OMWT} \times A_{WT} \times WT_N \times \sum_{i=1}^{Lt} \left(\frac{1+v}{1+\gamma}\right)^i \quad (13)$$

$$OM_{BESS} = \alpha_{OMBESS} \times P_{BESS} \times BESS_N \times \sum_{i=1}^{Lt} \left(\frac{1+v}{1+\gamma}\right)^i \quad (14)$$

$$S_{PV} = \alpha_{SPV} \times PV_N \times \left(\frac{1+\beta}{1+\gamma}\right)^{Lt} \quad (15)$$

$$S_{WT} = \alpha_{SWT} \times A_{WT} \times WT_N \times \left(\frac{1+\beta}{1+\gamma}\right)^{Lt} \quad (16)$$

where

$I_{PV,WT,BESS}$	: Initial cost of PV, WT, and BESS
$OM_{PV,WT,BESS}$	: Operation and maintenance cost of PV, WT, and BESS
$S_{PV,WT}$	: Salvage value of PV and WT
L_t	: Life span of the project

This function evaluates the long-term economic viability of industrial microgrid, aiming to optimize cost efficiency throughout the project lifecycle.

Environmental Objective: Carbon Emission Minimization

The environmental objective focuses on minimizing the carbon emissions generated by the industrial microgrid. The carbon emission function is expressed as:

$$min\ F_{environmental} = CO_2 = \sum_{h=1}^{8760} \beta_{PV} \times P_{PV} + \beta_{WT} \times P_{WT} \quad (17)$$

where

β_{PV}	: CO_2 emission per kWh consumption of solar PV
β_{WT}	: CO_2 emission per kWh consumption of WT
P_{PV}, P_{WT}	: Power produced by sources

The input parameters for CO_2 emission of different components are stated in Table 2.

Table 2 CO_2 Emission Parameters [8]

Components	**Factors (kg/kWh)**

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PV	0.05
Wind turbine	0.007

Social Objective: Job Creation Maximization

The social objective aims to enhance the social acceptance of the industrial microgrid system by increasing employment opportunities and supporting the adoption of renewable energy technologies. The social objective function can be expressed as: (18)

$$max\ F_{social} = JCF = (JCF_{PV} \times P_{PV}) + (JCF_{WT} \times P_{WT}) + (JCF_{BESS} \times E_{BESS})$$

where

JCF_{PV}	: Number of jobs per MW of solar PV
JCF_{WT}	: Number of jobs per MW of WT
JCF_{BESS}	: Number of jobs per MWh of the rated capacity of the BESS
P_{PV}, P_{WT}	: Power produced by sources
E_{BESS}	: Energy by BESS

The social objective, formulated in Equation (18), defines the job creation factors for solar PV and wind turbine technologies ($JCF_{PV}$and JCF_{WT}) in jobs per megawatt (MW) of installed capacity, while the factor for BESS (JCF_{BESS}) in jobs per megawatt-hour (MWh) of rated capacity. The installed capacities of PV and WT are denoted by P_{PV} and P_{WT}, and the rated storage capacity of BESS by E_{BESS}. Multiplying each technology's deployment scale with its corresponding job creation factor yields the total employment impact of the microgrid system. Since JCF values are commonly reported as annualized job-years, the resulting social objective F_{social} expresses the number of jobs per year. This function is designed to maximize social benefits, with higher values indicating greater acceptance and positive community impact. The input parameters for JCF of different components are stated in Table 3.

Table 3 JCF Parameters [8], [12]

Components	**Factors**
PV	2.7 job/MW
Wind turbine	1.1 job/MW
BESS	0.01 job/MWh/year

Constraints

The constraint ensures that the system functions within predefined limits by regulating the capacity of RESs, maintaining BESS SoC within safe thresholds, and restricting charging and discharging rates to prevent overloading and inefficiencies.

Capacity limits of RESs constraints:

$$PV_{min} \leq PV_N \leq PV_{max} \tag{19}$$

$$WT_{min} \leq WT_N \leq WT_{max} \tag{20}$$

$$BESS_{min} \leq BESS_N \leq BESS_{max} \tag{21}$$

BESS constraints:

$$BESS_{SoC\_min} \leq BESS_{SoC} \leq BESS_{SoC\_max} \tag{22}$$

BESS charging and discharging limit:

$$BESS_{cd} \leq BESS_{cd\_limit} \tag{23}$$

RESULTS AND DISCUSSION

The proposed method is tested on an industrial microgrid using MATLAB software. Optimal sizing of the PV, WT, and BESS is achieved by solving a multi-objective problem using the IPF technique [13]. A comparison is conducted between the existing trilemma approach [15] and the proposed quadrilemma approach, with both approaches defined as follows:

Trilemma approach [15]: Maximization of reliability, minimization of overall cost, and minimization of CO_2 emissions.

Quadrilemma approach: Maximization of reliability, minimization of overall cost, minimization of CO_2 emissions, and maximization of the job creation factor.

Optimal Sizing Comparison

In the quadrilemma optimization approach, the selected PV capacity for the industrial microgrid increased to 2,600 kW, compared to 2,100 kW in the trilemma approach, representing a 23.8% increase. This larger PV capacity facilitates greater renewable energy generation, contributing to a more sustainable and independent energy system by reducing reliance on non-renewable sources.

For wind turbines, both the quadrilemma and trilemma approaches suggest an optimal capacity of 4 kW, indicating that the inclusion of a social objective, such as job creation, does not influence the sizing of wind turbines. Meanwhile, the optimal size of the BESS is expanded from 7,500 kWh in the trilemma approach to 8,000 kWh in the quadrilemma approach, marking a 6.7% increase. This increase in BESS capacity enhances the system's energy storage capabilities, providing a more stable energy supply during periods of demand fluctuation and improving overall reliability. Table 4 summarizes the results of optimal sizing for the trilemma and quadrilemma approaches.

Table 4 Results of Optimal Sizing For Trilemma vs. Quadrilemma Approaches

Approach	Optimal size		
	PV size, kW	WT size, kW	BESS size, kWh
Trilemma [15]	2,100	4	7,500
Quadrilemma	2,600	4	8,000

Objective Functions Comparison

The analysis of the quadrilemma optimization approach demonstrates notable improvements across multiple performance metrics compared to the trilemma approach. Table 5 summarizes the results of objective function for the trilemma and quadrilemma approaches.

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In terms of reliability ($F_{technical}$), the quadrilemma approach achieves a score of 0.9382, significantly higher than the 0.8449 obtained in the trilemma approach. This increase reflects a more dependable system, which is crucial for maintaining a consistent energy supply within the industrial microgrid. Regarding the overall cost ($F_{economic}$), the quadrilemma approach shows a higher value of $12,602,027 compared to $10,629,727 in the trilemma approach. Although this represents a greater financial investment, it may be justified by the additional benefits gained across other objectives.

Table 5 Results of Objective Function for Trilemma vs. Quadrilemma Approaches

Approach	**Objective function**			
	$F_{technical}$	$F_{economic}$ (\$)	$F_{environmental}$ (kg/kWh)	F_{social} (jobs /year)
Trilemma [15]	0.8449	10,629,727	185,065.74	9,995
Quadrilemma	0.9382	12,602,027	229,126.30	12,374

While for CO_2 emissions ($F_{environmental}$), the quadrilemma approach records 229,126.30 kg/kWh, which is higher than the 185,065.74 kg/kWh seen in the trilemma approach. This increase suggests that emphasizing job creation may lead to a slight compromise in emissions reduction. Lastly, the job creation factor (F_{social}) is enhanced in the quadrilemma approach, with a value of 12,374 jobs/year, significantly surpassing the 9,995 jobs/year of the trilemma approach. This substantial increase underscores the potential socio-economic advantages of incorporating job creation into the optimization framework.

Advantages of the Quadrilemma Approach over the Trilemma Approach

The quadrilemma approach presents several key advantages for industrial microgrid system, particularly in enhancing reliability and promoting socio-economic benefits. First, it offers a higher reliability improvement of 11.04%, which is essential for industrial microgrids that need to provide an uninterrupted power supply. This reliability improvement makes the system more resilient, which is crucial for areas with unstable energy demands or those prone to power outages. The IPF result of the quadrilemma approach is illustrated in Fig. 6, which presents the Pareto-optimal front and highlights the best-compromised solution based on the highest normalized membership value. This figure showcases the trade-offs among technical, economic, environmental, and social objectives, with the best-compromised solution distinctly marked, demonstrating an optimal balance across these criteria while ensuring efficient system performance.

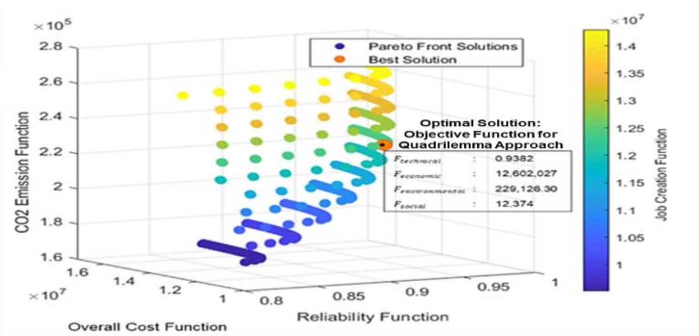

Figure 6. IPF results of quadrilemma approach

Additionally, the incorporation of the job creation factor aligns the system's objectives with broader societal goals, contributing to economic growth and creating employment opportunities in the renewable energy sector. This is especially beneficial in regions aiming to stimulate green job creation and sustainable economic development. Moreover, the slightly larger PV and BESS capacities in the quadrilemma approach better position the system for future expansion and growing demand. While this approach results in higher costs and

CO_2 emissions, the associated trade-offs are outweighed by the long-term benefits in reliability and job creation, making the quadrilemma a well-balanced and forward-looking strategy for industrial microgrid development.

CONCLUSION

In conclusion, this paper presents a comprehensive evaluation of an industrial microgrid system utilizing a quadrilemma approach, integrating reliability, overall cost, CO_2 emissions, and job creation as key objectives. The proposed quadrilemma approach determines the optimal solution, achieving a higher reliability improvement of 11.04% while increasing job creation. However, this approach also results in a 23.8% increase in PV capacity and a 6.7% increase in BESS capacity, leading to higher investment costs and CO_2 emissions compared to the trilemma approach. The larger PV and BESS sizes contribute to a more resilient system, ensuring future scalability and stability. Despite the trade-offs in cost and emissions, the quadrilemma approach offers a balanced and forward-looking solution for industrial microgrid design, emphasizing long-term benefits in reliability and community impact. These findings provide valuable insights for future industrial microgrid planning and policy, particularly in regions seeking to enhance energy efficiency while fostering economic, environmental, and social sustainability.

Future work could explore integrating advanced energy management strategies to further optimize resource allocation and emission trade-offs, such as demand-side management techniques and adaptive microgrid control. Additionally, further research could analyze the impact of alternative social factors, such as HDI and LEG, on microgrid reliability to provide a more comprehensive assessment of socio-technical trade-offs.

ACKNOWLEDGEMENTS

Funder by the Ministry of Higher Education under FRGS, Registration Proposal No: FRGS/1/2021/TK0/UTM/02/20.

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