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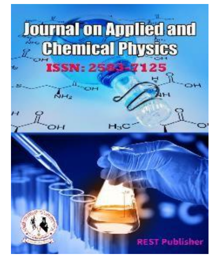

A Comparative Analysis of Renewable Energy Systems Using the COPRAS Method

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Abstract: *This paper presents an evaluation of five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—using the Complex Proportional Assessment (COPRAS) method. The analysis considers four key criteria: Energy Efficiency, Technology Maturity, Resource Availability, and Land Requirement. Each criterion is assigned equal weight, ensuring a balanced evaluation across technical, environmental, and spatial factors. The decision-making process involves normalizing the data and applying weighted scores to rank the systems based on both beneficial and non-beneficial criteria. Geothermal Energy emerges as the top-ranked renewable energy option, achieving the highest utility score (100%) due to its excellent balance of high energy efficiency, technology maturity, and minimal land use. Hydropower, while leading in energy efficiency and technological maturity, ranks second due to its high land requirement. Wind Energy follows in third place, providing moderate energy efficiency and land use but offering reliable technological performance. Solar PV ranks fourth, hindered by lower energy efficiency but benefitting from advanced technology and lower land use. Biomass ranks last, despite its high resource availability, due to its moderate energy efficiency and significant land requirement. This study highlights the trade-offs between different renewable energy systems, offering insights into how factors like land availability and technological maturity impact the feasibility of renewable energy integration. The results can guide decision-makers in selecting the most suitable energy systems for their specific needs, balancing both environmental and economic objectives. The application of the COPRAS method provides a structured and comprehensive approach to evaluating the performance of diverse renewable energy options, making it a valuable tool for policymakers and energy planners looking to optimize renewable energy integration strategies.*

Keywords: *Renewable Energy Systems, COPRAS Method, Energy Efficiency, Technology Maturity, Resource Availability, Land Requirement.*

1. INTRODUCTION

The increasing global demand for energy, coupled with the growing concerns over environmental degradation and climate change, has led to a significant shift toward renewable energy systems. Renewable energy, derived from natural and replenishable resources such as sunlight, wind, water, biomass, and geothermal heat, offers a sustainable solution to the world's energy needs while addressing environmental concerns. However, integrating renewable energy systems into existing energy infrastructure presents several technical, economic, and environmental challenges. This paper aims to explore the integration of renewable energy systems by evaluating five key alternatives: Solar Photovoltaic (PV), Wind Energy, Hydropower, Biomass, and Geothermal Energy, across multiple criteria, including benefits and non-benefit parameters. Renewable energy systems are increasingly being adopted as part of a global strategy to transition away from fossil fuel dependency and mitigate greenhouse gas emissions. The integration of these systems into national and regional grids involves the assessment of several factors, such as energy efficiency, resource availability, economic viability, and environmental impacts. These factors are critical in ensuring that renewable energy systems not only provide clean energy but also contribute to a stable and resilient energy infrastructure.The five systems considered in this paper—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—represent the most prominent renewable energy technologies available today. Each of these technologies has distinct advantages and disadvantages depending on the region, available resources, and energy demands. The comparative evaluation of these systems is essential for understanding how best to integrate them into broader energy systems. The evaluation of renewable energy systems requires the consideration of multiple criteria to ensure that the chosen technology meets both technical and economic requirements. For this study, we have divided the evaluation parameters into benefit and non-benefit criteria. The benefit parameters include energy efficiency, carbon emission reduction, resource availability, and technology maturity, while the non-benefit parameters comprise initial investment cost, operational and maintenance (O&M) cost, land requirement, and waste generation. Renewable energy systems integration has become a pivotal aspect of sustainable energy development, as it involves the coordination and incorporation of various renewable energy sources into existing or new energy grids. As the global demand for clean energy intensifies, the seamless integration of renewable systems such as solar photovoltaic (PV), wind energy, hydropower, biomass, and geothermal energy is becoming increasingly crucial. Renewable energy sources are inherently variable and geographically dispersed, presenting unique challenges in terms of grid stability, energy storage, transmission, and distribution. This paper focuses on five key renewable energy systems and evaluates them based on a set of critical benefit and non-benefit parameters, offering insights into their effectiveness, economic feasibility, and environmental impact. These renewable energy systems are evaluated using eight parameters: four benefit parameters, including energy efficiency, carbon emission reduction, resource availability, and technology maturity, and four non-benefit parameters, namely initial investment cost, operational and maintenance (O&M) costs, land requirements, and waste generation. Solar photovoltaic (PV) systems are one of the most widely deployed renewable energy technologies due to their scalability, declining costs, and ease of installation. The energy efficiency of solar PV systems is relatively lower than other renewable sources, typically ranging between 15% and 20%. In this analysis, solar PV is rated at 18% energy efficiency, a figure that reflects the real-world performance of most commercial solar modules. However, the ability of solar PV systems to reduce carbon emissions is significant, with an estimated reduction of 500 tons of CO_2 per year, as solar energy does not directly produce greenhouse gases during operation. Resource availability for solar energy is high, particularly in regions with abundant sunlight, and in this evaluation, it is rated an 8 out of 10, acknowledging that while sunlight is plentiful in many parts of the world, factors such as geographical location and seasonal variations can impact availability. Technology maturity for solar PV is rated at 9 out of 10, as the technology has evolved rapidly over the past few decades, with significant improvements in panel efficiency, energy storage integration, and grid compatibility. On the downside, solar PV systems have a moderately high initial investment cost, estimated at $3.5 million for a standard utility-scale installation, though these costs have been consistently decreasing. O&M costs are relatively low at $0.5 million per year, making solar PV systems economically competitive over their lifespan. The land requirement for solar farms is also significant, with this analysis estimating the need for 15 acres per installation. Waste generation from solar PV systems is minimal, particularly in comparison to biomass or fossil fuel systems, with an estimated waste generation of only 0.01 tons per year, mostly related to the eventual disposal of solar panels after their useful life. Wind energy is another prominent renewable energy system, particularly favored for its high energy efficiency, which in this study is rated at 35%. This high efficiency, combined with the ability to generate significant amounts of electricity in windy regions, makes wind energy one of the most attractive renewable options. Wind farms also offer substantial carbon emission reduction potential, with an estimated reduction of 800 tons of CO_2 per year, primarily because wind turbines harness kinetic energy from the wind without emitting any pollutants during operation. The availability of wind resources varies considerably depending on location, with coastal areas and high-altitude regions offering the best conditions; thus, wind energy's resource availability is rated 7 out of 10. The technology maturity of wind energy is rated at 8 out of 10, reflecting the decades of development and deployment of wind turbines, but there is still room for improvement in areas such as offshore wind technology and turbine efficiency. Wind energy systems tend to have lower initial investment costs than solar PV, with this analysis estimating $2.8 million for a typical wind farm installation. O&M costs are also low at $0.4 million per year, though maintenance can be more challenging in offshore environments. Wind farms require more land than solar PV systems, approximately 20 acres per installation, primarily due to the spacing required between turbines to avoid wake effects. Waste generation for wind energy is similarly low, at 0.02 tons per year, mostly consisting of turbine parts and materials that may require disposal or recycling at the end of their lifecycle. Hydropower is often considered the most mature and efficient renewable energy technology, with energy efficiency ratings as high as 90%. In this analysis, hydropower is evaluated with a 90% efficiency rate, which reflects the technology's ability to convert potential energy from water into electricity with minimal losses. Hydropower also boasts the highest carbon emission reduction potential of the systems considered, with an estimated reduction of 1200 tons of CO_2 per year. This is because once the infrastructure is in place, hydropower plants can generate large amounts of electricity without producing greenhouse gases. However, the availability of hydropower resources is more limited, earning it a 6 out of 10 in this evaluation, as suitable locations for dams and reservoirs are geographically constrained. Technology maturity for hydropower is rated at 10 out of 10, given the long history and well-established nature of hydropower plants. Despite these advantages, hydropower has the highest initial investment cost, estimated at $5.0 million for a new installation, largely due to the infrastructure required for dam construction and water management systems. O&M costs are moderate at $0.6 million per year. One of the significant drawbacks of hydropower is the large land requirement, estimated at 50 acres, as reservoirs and dams can have extensive footprints. Additionally, while hydropower plants generate relatively little waste during operation, they can cause ecological disruptions, and in this analysis, waste generation is rated at 0.1 tons per year, mostly related to maintenance and infrastructure upkeep. Biomass energy systems, which convert organic materials into electricity, are rated with a moderate energy efficiency of 30% in this analysis. Biomass systems can reduce carbon emissions by 600 tons per year, though this figure can vary significantly depending on the feedstock used and the efficiency of the combustion process. Resource availability for biomass is rated 9 out of 10, as organic materials such as agricultural waste, forest residues, and dedicated energy crops are widely available in many regions. Technology maturity for biomass is rated at 7 out of 10, as the technology is well-established but still faces challenges in scaling and improving efficiency. The initial investment cost for biomass systems is relatively low at $3.2 million, with O&M costs being the highest among the systems evaluated, at $0.8 million per year, due to the need for continuous feedstock supply and maintenance. Biomass systems also require significant land, approximately 25 acres, for both the energy facility and the cultivation of energy crops. Waste generation is a significant concern for biomass, with an estimated 20 tons of waste per year, primarily consisting of ash and other byproducts from the combustion process. Geothermal energy, which taps into the Earth's internal heat, offers a unique and consistent source of renewable energy. Its energy efficiency is rated at 70%, reflecting the high efficiency of converting geothermal heat into electricity. Geothermal systems can reduce carbon emissions by 700 tons per year, though this figure is contingent on the method of geothermal extraction and the associated environmental impacts. Resource availability is rated 6 out of 10, as geothermal resources are only viable in certain geological areas. Technology maturity for geothermal is rated at 9 out of 10, as the technology has been steadily improving, particularly in areas such as enhanced geothermal systems (EGS). The initial investment cost for geothermal energy is estimated at $4.0 million, with O&M costs at $0.7 million per year. Geothermal plants require the least land of the systems evaluated, with an estimated requirement of only 10 acres per installation. Waste generation from geothermal systems is also low, at 0.05 tons per year, mostly consisting of minerals and other byproducts from drilling operations.

2. METHODOLOGY

The integration of renewable energy systems is crucial for achieving sustainable energy development and reducing dependence on fossil fuels. With growing concerns over climate change and environmental degradation, the deployment of renewable energy technologies has become a key strategy for transitioning to a low-carbon future. However, selecting the most suitable renewable energy system for integration into a region or energy grid requires careful evaluation of multiple criteria, including both benefit-related and non-benefit-related factors. In this context, decision-makers face complex trade-offs between maximizing energy efficiency, minimizing environmental impacts, and ensuring economic viability. One of the robust multi-criteria decision-making (MCDM) approaches that can be employed for such evaluations is the COPRAS (Complex Proportional Assessment) method. The COPRAS method allows for the ranking and selection of alternatives based on their relative performance across various criteria, providing a systematic approach to integrate renewable energy systems effectively. In applying the COPRAS method to renewable energy systems integration, five alternatives representing different renewable technologies—Solar Photovoltaic (PV), Wind Energy, Hydropower, Biomass, and Geothermal Energy—can be evaluated across eight parameters. These parameters are divided into benefit-related criteria, which should be maximized, and non-benefit-related criteria, which should be minimized. The four benefit criteria include energy efficiency, carbon emission reduction, resource availability, and technology maturity. These parameters highlight the performance, environmental benefits, and technological readiness of the energy systems. On the other hand, the four non-benefit criteria include initial investment cost, operational and maintenance (O&M) costs, land requirement, and waste generation. These factors focus on economic feasibility and environmental footprint in terms of land use and waste output. The COPRAS method provides a structured means of handling such diverse criteria by assigning weights to each based on their importance to stakeholders or decision-makers. The core principle of COPRAS is to evaluate alternatives by calculating both positive and negative utility values, with the best alternatives exhibiting high positive utility and low negative impacts. This allows the decision-maker to choose a renewable energy system that not only provides maximum benefits but also incurs the least amount of costs or disadvantages. The dataset for this analysis provides performance data for the five renewable energy alternatives across the eight evaluation criteria. Solar PV, for instance, offers an energy efficiency of 18%, a carbon emission reduction of 500 tons per year, high resource availability (8/10), and strong technology maturity (9/10). However, its initial investment cost of $3.5 million and land requirement of 15 acres must also be considered. Wind energy demonstrates a higher energy efficiency of 35% and a carbon emission reduction of 800 tons per year, but it requires more land (20 acres) and a lower initial investment cost of $2.8 million. Hydropower, known for its high efficiency at 90% and significant carbon emission reduction of 1200 tons per year, also requires large land areas (50 acres) and comes with a higher initial investment cost of $5 million. Biomass, with an energy efficiency of 30% and carbon emission reduction of 600 tons per year, has high resource availability (9/10), though it generates considerable waste (20 tons/year). Geothermal energy offers a balance, with an energy efficiency of 70%, carbon emission reduction of 700 tons per year, moderate land requirement (10 acres), and waste generation of 0.05 tons/year, but its initial investment cost stands at $4 million. The COPRAS method is well-suited to integrate these diverse factors, as it not only considers the maximization of benefits such as energy efficiency and carbon emission reduction but also ensures that costs such as investment, land use, and waste generation are minimized. The first step in the COPRAS methodology is to normalize the decision matrix, which transforms the various criteria into comparable units. This normalization step ensures that each criterion, whether measured in percentages, tons, or dollars, can be evaluated on the same scale. Following normalization, the weighted significance of each criterion is applied, where decision-makers assign relative importance to each parameter based on policy objectives, environmental concerns, or budget constraints. For example, in regions prioritizing environmental sustainability, higher weights might be assigned to carbon emission reduction and energy efficiency, while in areas with limited land availability, the land requirement criterion may be given greater importance. Once the weights are applied, positive and negative utility values are calculated for each alternative. Positive utility values are derived from benefit criteria, while negative utility values correspond to non-benefit criteria. These values are then summed to obtain a total utility score for each renewable energy system. The alternative with the highest total utility is considered the most favorable for integration. The COPRAS method's strength lies in its ability to provide a proportional assessment of alternatives. This means that alternatives with higher positive utilities are rewarded proportionally, while those with higher negative utilities are penalized. Such a proportional system allows for a nuanced assessment, where trade-offs between different criteria are accounted for without disproportionately favoring any single parameter. For instance, although Hydropower has the highest energy efficiency and carbon emission reduction, its large land requirement and high initial cost may reduce its overall utility compared to alternatives like Wind or Solar PV, depending on the assigned weights. Similarly, Geothermal energy's relatively high efficiency and low land requirement could make it an attractive option, despite its higher initial cost compared to Wind energy. Therefore, the COPRAS method facilitates a balanced and transparent decision-making process that accounts for both the technical performance and economic and environmental impacts of renewable energy systems. The integration of renewable energy systems requires a comprehensive evaluation of multiple criteria that reflect both the benefits and costs associated with each alternative. The COPRAS method provides a robust framework for conducting such evaluations, enabling decision-makers to select the most appropriate renewable energy system based on proportional assessment. By applying the COPRAS method to five renewable energy technologies—Solar PV, Wind, Hydropower, Biomass, and Geothermal—across eight evaluation parameters, decision-makers can make informed choices that align with sustainability goals, economic constraints, and environmental protection. The result is a transparent, flexible, and systematic approach to renewable energy systems integration, which can be adapted to various contexts and regions worldwide.

Benefit Parameters:

Energy Efficiency: Energy efficiency measures how effectively a system converts natural resources into usable energy. Higher energy efficiency indicates a more productive system, reducing energy loss during the conversion process. Hydropower, for example, stands out with an energy efficiency of around 90%, making it one of the most efficient renewable energy sources. Wind energy and geothermal systems also demonstrate significant efficiency, whereas solar PV systems, though widely adopted, have relatively lower efficiency at around 18%. Biomass, despite its renewability, has moderate efficiency due to the energy-intensive processes involved in converting organic material into usable energy.

Carbon Emission Reduction: One of the primary motivations for integrating renewable energy systems is to reduce carbon emissions. Systems like wind, solar, and hydropower drastically reduce emissions compared to fossil fuels, with hydropower leading in terms of carbon offset due to its high capacity and consistent energy output. Wind and solar energy systems are also highly effective at reducing emissions, though their intermittency can limit total reductions. Biomass, while renewable, produces more emissions due to the combustion of organic material, though it is still considered more carbon-friendly than conventional fossil fuels. Geothermal energy provides moderate carbon reductions but requires careful management to avoid unintended emissions of gases like sulfur dioxide.

Resource Availability: The availability of renewable resources is highly dependent on geographic location and local climate conditions. Solar PV systems, for example, require ample sunlight, making them more effective in regions with high solar irradiance. Wind energy systems depend on consistent wind speeds, which vary by location. Hydropower requires a consistent water flow, limiting its potential to areas near rivers and large water bodies. Biomass relies on the availability of organic material, such as agricultural waste or forestry byproducts, and is therefore dependent on local industry and agricultural practices. Geothermal energy, while available in many regions, is most effective in areas with significant underground heat, such as volcanic zones.

Technology Maturity: The maturity of a technology is an important factor in determining its reliability and scalability. Hydropower, for example, is one of the most mature renewable energy technologies, with well-established infrastructure and operational practices. Solar PV and wind energy technologies have also reached a high level of maturity, driven by decades of research and development. Biomass and geothermal systems, while developed, are still less mature in terms of large-scale deployment and require further technological advances to improve efficiency and reduce environmental impacts.

Non-Benefit Parameters:

Initial Investment Cost: The cost of installing renewable energy systems can vary significantly depending on the technology. Solar PV systems have seen a dramatic reduction in costs over the last decade, making them one of the most affordable renewable energy options in terms of initial investment. Wind energy also benefits from relatively low installation costs, particularly for onshore wind farms. Hydropower, while highly efficient, requires significant upfront investment due to the need for large dams and reservoirs. Biomass and geothermal systems also have moderate to high initial costs, depending on the scale of the project and the required infrastructure.

Operational and Maintenance (O&M) Cost: The long-term costs of operating and maintaining renewable energy systems are critical to their economic viability. Solar PV and wind energy systems generally have low O&M costs, especially compared to fossil fuel power plants. Hydropower, while efficient, can have higher O&M costs due to the complexity of managing water flows and maintaining dam infrastructure. Biomass systems, which involve the continuous processing of organic material, have relatively high O&M costs. Geothermal systems also incur higher costs due to the need for maintaining underground drilling equipment and managing the heat extraction process.

Land Requirement: The land footprint of renewable energy systems is a major consideration, especially in densely populated areas or regions with limited land availability. Solar PV systems require large areas of land for installing panels, though rooftop installations can mitigate this issue. Wind farms also have a significant land footprint, though the land between turbines can often be used for other purposes, such as agriculture. Hydropower requires large reservoirs, which can inundate vast areas of land and displace local populations. Biomass systems require land for growing feedstock, while geothermal systems have a relatively small land footprint but may have localized environmental impacts due to drilling.

Waste Generation: The environmental impact of waste generated by renewable energy systems varies significantly across technologies. Solar PV systems, for instance, produce minimal waste during operation but can generate waste during manufacturing and at the end of their lifecycle, as solar panels need to be disposed of or recycled. Wind turbines also produce little operational waste but pose challenges in recycling the large turbine blades after their service life. Hydropower can generate waste in the form of sedimentation in reservoirs, which can impact aquatic ecosystems. Biomass systems generate waste in the form of ash and emissions, while geothermal systems can produce minimal emissions of sulfur dioxide and other gases.

Comparative Analysis of Alternatives

A comparative analysis of these five renewable energy systems across the eight evaluation parameters reveals distinct advantages and disadvantages for each technology. Solar PV and wind energy systems, for example, offer low O&M costs, significant carbon emission reductions, and growing resource availability, but they require substantial land areas and have intermittent energy production, necessitating energy storage solutions. Hydropower stands out for its high energy efficiency and carbon reductions, but the high initial investment cost and land requirement for reservoirs limit its widespread adoption. Biomass and geothermal energy systems, while offering moderate efficiency and carbon reductions, have higher operational costs and potential environmental impacts due to waste generation. The selection of an appropriate renewable energy system for integration into a national grid depends on balancing these factors according to regional priorities. For instance, regions with abundant sunlight may prioritize solar PV, while areas with consistent wind speeds may favor wind energy. Hydropower may be best suited for regions with ample water resources, while biomass and geothermal systems could be viable in areas with suitable organic material or underground heat. Integrating renewable energy systems into existing energy infrastructure is a complex process that requires careful evaluation of multiple criteria, including both technical and economic factors. The comparative analysis of Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy systems highlights the diverse strengths and weaknesses of each technology, suggesting that a mix of renewable energy sources is likely the most effective solution for achieving a sustainable and resilient energy future. Policymakers and energy planners must consider local resource availability, technological maturity, and economic constraints when making decisions on renewable energy integration. As technology advances and costs continue to decline, the role of renewable energy in meeting global energy demands will undoubtedly grow, providing cleaner and more sustainable solutions for generations to come.

3. ANALYSIS AND DISCUSSION

TABLE 1. Renewable Energy Systems Integration

	Energy Efficiency (%)	Technology Maturity (1-10)	Resource Availability (1-10)	Land Requirement (acres)
Solar PV	18	9	8	15
Wind Energy	35	8	7	20
Hydropower	90	10	6	50
Biomass	30	7	9	25
Geothermal Energy	70	9	6	10

Table 1 provides an overview of five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—evaluated using key parameters relevant to the COPRAS (Complex Proportional Assessment) method. These parameters include Energy Efficiency (%), Technology Maturity (1-10), Resource Availability (1-10), and Land Requirement (acres), which play a crucial role in assessing the feasibility and sustainability of each system. Hydropower stands out with the highest energy efficiency (90%) and top technology maturity (10), making it an attractive option for regions seeking to maximize output. However, its high land requirement (50 acres) could be a limitation in areas with constrained land resources. Geothermal Energy shows a balance between high energy efficiency (70%) and low land requirement (10 acres), making it suitable for areas with limited space. Solar PV and Wind Energy have moderate energy efficiency (18% and 35%, respectively) but benefit from high technology maturity and lower land requirements compared to Hydropower. Biomass, while offering high resource availability (9/10), presents a compromise with moderate energy efficiency (30%) and relatively high land use (25 acres). This comparative analysis highlights the trade-offs between land use, efficiency, and technological readiness, crucial for decision-makers when selecting a renewable energy system for integration.

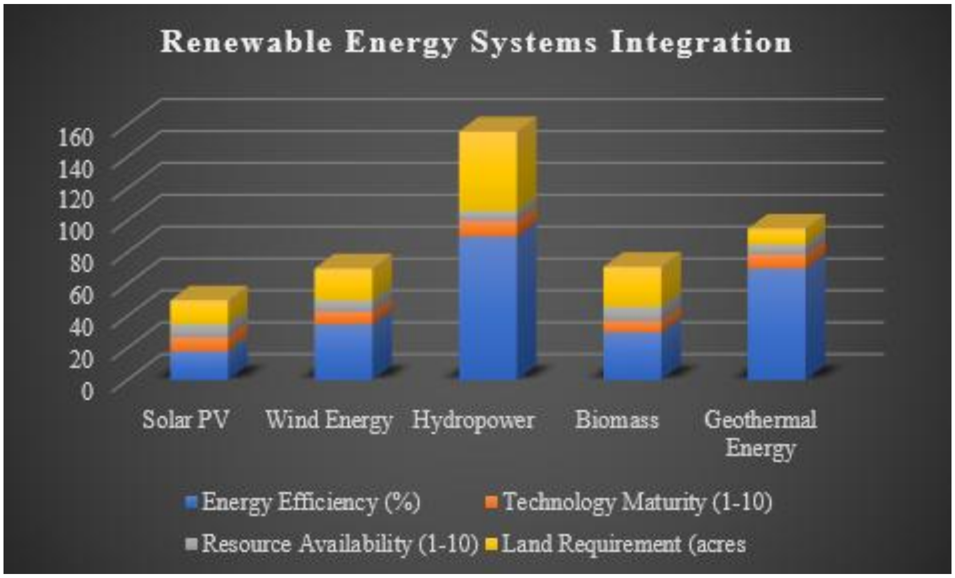

FIGURE 1. Renewable Energy Systems Integration

Figure 1 presents a stacked bar chart illustrating the integration of five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—evaluated using the COPRAS (Complex Proportional Assessment) method. The parameters displayed in the graph include Energy Efficiency (%), Technology Maturity (1-10), Resource Availability (1-10), and Land Requirement (acres). Hydropower stands out prominently with the largest total value, driven by its exceptionally high energy efficiency and technology maturity, although this is offset by a significant land requirement. Wind Energy, while showing moderate land use and high energy efficiency, is characterized by lower resource availability and technology maturity than Hydropower. Geothermal Energy exhibits a balanced performance, with relatively high energy efficiency and low land requirement, making it a competitive option. Biomass, though it has high resource availability, shows a moderate energy efficiency and considerable land use, positioning it as a middle-ground option. Solar PV, while offering the lowest energy efficiency, benefits from high technology maturity and lower land use. The figure effectively visualizes the trade-offs between energy efficiency and land requirements, highlighting that systems like Hydropower, despite their efficiency, may require more resources, whereas technologies like Geothermal offer balanced benefits with fewer resource demands.

TABLE 2. Normalized Data

Normalized Data				
	Energy Efficiency (%)	**Technology Maturity (1-10)**	**Resource Availability (1-10)**	**Land Requirement (acres)**
Solar PV	0.07407	0.2093	0.222222	0.13
Wind Energy	0.14403	0.186	0.194444	0.17
Hydropower	0.37037	0.2326	0.166667	0.42
Biomass	0.12346	0.1628	0.25	0.21
Geothermal Energy	0.28807	0.2093	0.166667	0.08

Table 2 presents the normalized data for five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—evaluated using the COPRAS (Complex Proportional Assessment) method. The normalization process transforms raw data into comparable units, allowing for a proportional assessment of the alternatives. For the Energy Efficiency criterion, Hydropower leads with the highest normalized value (0.37037), indicating its superior energy conversion capabilities compared to other systems. Geothermal Energy (0.28807) follows, offering strong efficiency, while Solar PV shows the lowest efficiency (0.07407). In terms of Technology Maturity, Hydropower again ranks highest (0.2326), reflecting its advanced technological readiness, followed closely by Geothermal Energy (0.2093) and Solar PV (0.2093). Resource Availability sees Biomass leading with a normalized value of 0.25, highlighting its abundant resources, whereas Hydropower and Geothermal Energy

(0.166667) lag behind in this criterion. The Land Requirement criterion, which should ideally be minimized, shows Geothermal Energy with the best performance (0.08), requiring the least land, while Hydropower demands the most (0.42). This normalized data allows for a fair comparison of renewable energy systems, enabling decision-makers to weigh energy efficiency, technological advancement, resource availability, and land use in determining the most appropriate system for integration.

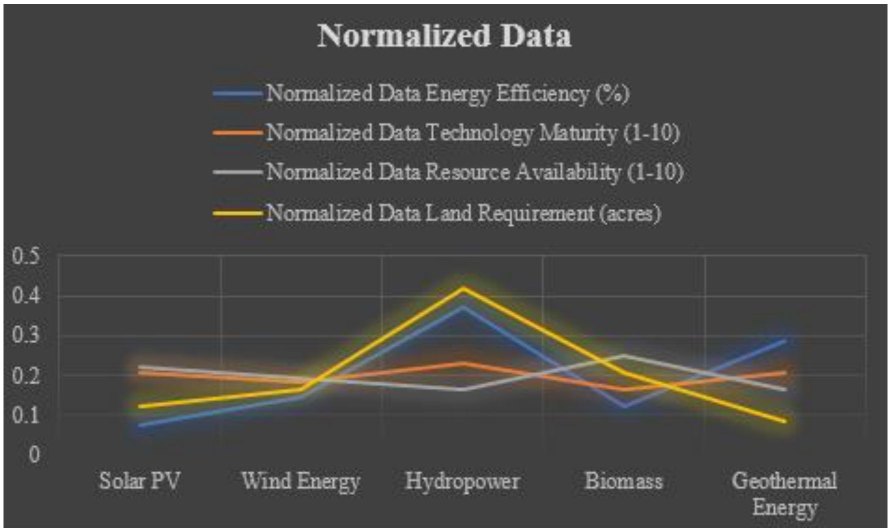

FIGURE 2. Normalized Data

Figure 2 illustrates the normalized data for five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—evaluated using the COPRAS (Complex Proportional Assessment) method across four criteria: Energy Efficiency (%), Technology Maturity (1-10), Resource Availability (1-10), and Land Requirement (acres). The graph shows that Hydropower leads significantly in both Energy Efficiency and Technology Maturity, as indicated by the peak values in blue and orange lines, making it a highly efficient and mature technology. However, Hydropower also has the highest land requirement (yellow line), highlighting its trade-off with land use. Geothermal Energy, represented towards the right, shows a balanced performance with relatively high Energy Efficiency and Technology Maturity while requiring the least land, making it an attractive option for areas with limited space. Biomass has the highest resource availability (grey line), reflecting its advantage in regions with abundant bio-resources, but its land requirement is moderately high. Solar PV, on the far left, exhibits the lowest energy efficiency but performs well in Technology Maturity and Land Requirement. Wind Energy shows moderate values across all parameters but does not excel in any single area. This visualization highlights the trade-offs between different criteria and helps decision-makers assess which system best meets their priorities for renewable energy integration.

TABLE 3. Weightages

Weight			
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25

Table 3 presents the weightages assigned to each evaluation criterion—Energy Efficiency, Technology Maturity, Resource Availability, and Land Requirement—in the COPRAS (Complex Proportional Assessment) method. Each criterion is equally weighted at 0.25, indicating that decision-makers have assigned equal importance to all four parameters. This balanced weighting suggests that no single criterion, such as energy efficiency or land requirement, is prioritized over the others in the decision-making process. The equal distribution reflects a neutral stance where all aspects—technical, environmental, and economic—are considered equally significant when evaluating and comparing renewable energy systems for integration.

TABLE 4. Weighted normalized decision matrix

Weighted normalized decision matrix				
	Energy Efficiency (%)	**Technology Maturity (1-10)**	**Resource Availability (1-10)**	**Land Requirement (acres)**
Solar PV	0.019	0.05233	0.06	0.03
Wind Energy	0.036	0.04651	0.05	0.04
Hydropower	0.093	0.05814	0.04	0.10
Biomass	0.031	0.0407	0.06	0.05
Geothermal Energy	0.072	0.05233	0.04	0.02

Table 4 presents the weighted normalized decision matrix for five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—using the COPRAS (Complex Proportional Assessment) method. The matrix represents the normalized data, weighted equally across four key criteria: Energy Efficiency, Technology Maturity, Resource Availability, and Land Requirement. Hydropower leads in Energy Efficiency (0.093), making it the most energy-efficient option. It also scores the highest in Technology Maturity (0.05814), reflecting its well-established technology. However, Hydropower's high Land Requirement (0.10) presents a notable drawback, emphasizing its need for significant land resources despite its technical superiority. Geothermal Energy stands out with a strong balance between Energy Efficiency (0.072), Technology Maturity (0.05233), and the lowest Land Requirement (0.02), making it an attractive option for areas with limited land availability. Wind Energy, while moderate in both Energy Efficiency (0.036) and Technology Maturity (0.04651), shows a relatively higher Land Requirement (0.04). Biomass, although performing well in Resource Availability (0.06), shows moderate performance in the other criteria, including a relatively high Land Requirement (0.05). Solar PV has the lowest Energy Efficiency (0.019) but benefits from high Technology Maturity (0.05233) and a relatively low Land Requirement (0.03). This matrix highlights the trade-offs between energy performance, technological maturity, and land use, guiding decision-makers in selecting the most suitable renewable energy system based on these balanced criteria.

TABLE 5. Renewable Energy Systems Integration Bi, Ci, & Min(Ci)/Ci

	Bi	**Ci**	**Min(Ci)/Ci**
Solar PV	0.0708441	0.086805556	0.72
Wind Energy	0.082519858	0.090277778	0.692
Hydropower	0.150732127	0.145833333	0.429
Biomass	0.071561872	0.114583333	0.545
Geothermal Energy	0.124342042	0.0625	1
	min(Ci)*sum(Ci)	0.0313	3.3863

Table 5 presents the Bi, Ci, and Min(Ci)/Ci values for five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—evaluated using the COPRAS (Complex Proportional Assessment) method. The Bi values represent the sum of the weighted beneficial criteria, while Ci represents the sum of the weighted non-beneficial criteria for each alternative. Geothermal Energy shows the highest Min(Ci)/Ci ratio of 1, indicating that it has the least negative impact relative to the other systems, making it an efficient option with a balanced trade-off between benefits and costs. Hydropower, despite having the highest Bi value (0.1507), reflecting its strong energy efficiency and technological maturity, has a low Min(Ci)/Ci ratio of 0.429 due to its high land requirement, reducing its overall appeal. Wind Energy and Solar PV offer moderate Bi and Ci values, with Solar PV having a Min(Ci)/Ci ratio of 0.72 and Wind Energy slightly lower at 0.692, indicating moderate performance with less significant drawbacks. Biomass, though strong in resource availability, has a relatively low Bi value and a Min(Ci)/Ci ratio of 0.545, indicating higher associated costs. The term min(Ci) * sum(Ci) (0.0313) helps in calculating the final ranking, where systems like Geothermal Energy rank higher due to favorable utility scores across both benefit and non-benefit criteria.

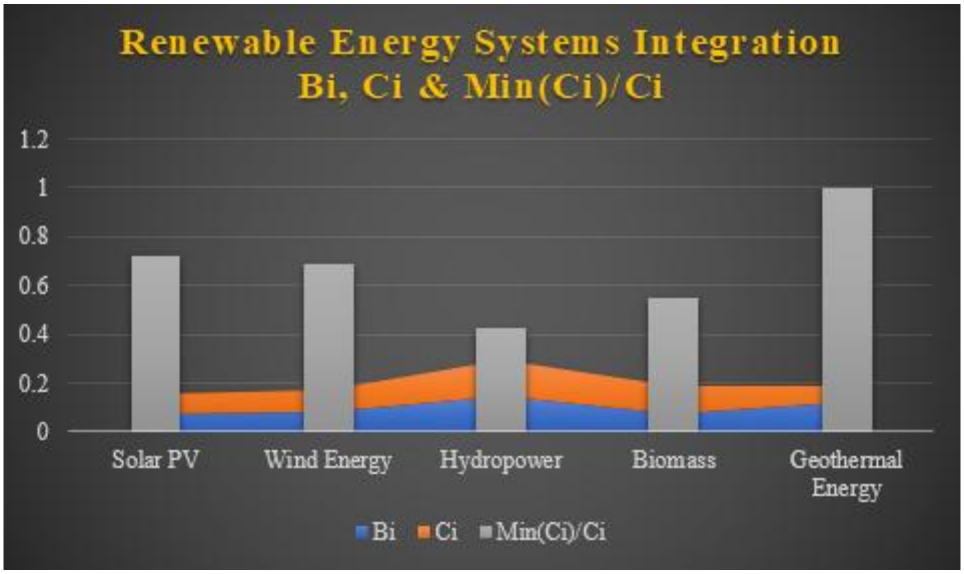

FIGURE 3. Renewable Energy Systems Integration Bi, Ci, & Min(Ci)/Ci

The chart titled "Renewable Energy Systems Integration: Bi, Ci & Min(Ci)/Ci" presents a comparative analysis of five renewable energy sources: Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy, using three key metrics—Bi (in blue), Ci (in orange), and Min(Ci)/Ci (in gray). These metrics are derived from the COPRAS (Complex Proportional Assessment) method, which is widely used in multi-criteria decision-making to evaluate different alternatives based on various criteria. Each energy source is evaluated across the three parameters. Solar PV and Wind Energy exhibit similar Bi values, which indicate their performance levels. Their Ci values are also close to each other, reflecting comparable competitiveness in their integration. Hydropower has lower values in all three metrics but shows a balanced proportion of Min(Ci)/Ci, indicating steady performance despite its lower scores. Biomass, while having lower Bi and Ci values than Solar PV and Wind, shows a Min(Ci)/Ci ratio comparable to Hydropower, suggesting it holds a stable potential in energy system integration. Geothermal Energy stands out with the highest Min(Ci)/Ci value, making it a promising option based on the COPRAS method. Although its Bi and Ci values are lower than those of Solar PV and Wind, its high Min(Ci)/Ci proportion suggests strong efficiency in integration. Overall, the chart highlights variations in the performance of different renewable energy systems, with Geothermal Energy emerging as a key contender in this multi-criteria assessment.

TABLE 6. Final Result **of** Renewable Energy Systems Integration

	Qi	Ui	Rank
Solar PV	0.177	65%	4
Wind Energy	0.185	68%	3
Hydropower	0.214	79%	2
Biomass	0.152	56%	5
Geothermal Energy	0.272	100%	1

Table 6 presents the final results of the renewable energy systems integration assessment using the COPRAS (Complex Proportional Assessment) method, displaying the Qi (utility degree), Ui (relative efficiency), and the ranking of each energy system. Geothermal Energy ranks first with the highest Qi value of 0.272 and a relative efficiency of 100%, making it the most favorable option for renewable energy integration due to its balanced performance across efficiency, resource availability, and low land requirement. Hydropower follows in second place with a Qi of 0.214 and 79% relative efficiency, reflecting its superior energy efficiency and technological maturity, though its high land requirement reduces its overall utility. Wind Energy secures the third position with a Qi of 0.185 and 68% relative efficiency, offering moderate benefits with fewer trade-offs compared to other alternatives. Solar PV ranks fourth with a Qi of 0.177 and 65% relative efficiency, indicating moderate performance, particularly due to lower energy efficiency despite high technology maturity. Biomass ranks last, with a Qi of 0.152 and 56% relative efficiency, due to moderate energy efficiency and relatively high land use, despite high resource availability. These final rankings provide decision-makers with a clear understanding of which renewable energy systems offer the best overall performance for integration.

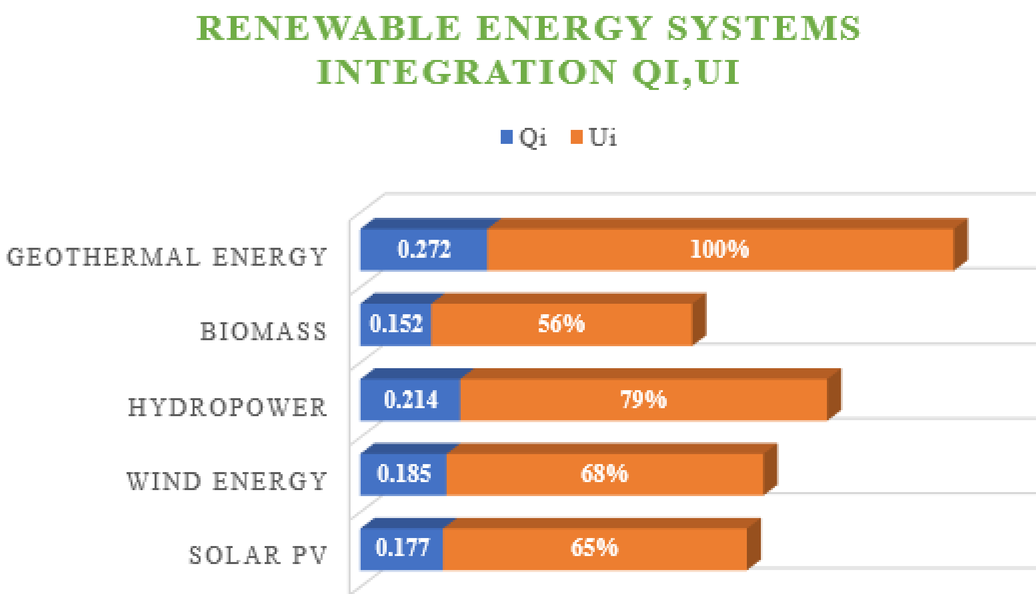

FIGURE 4. Renewable Energy Systems Integration Qi, Ui

The chart titled "Renewable Energy Systems Integration Qi, Ui" presents the performance of various renewable energy sources—Geothermal Energy, Biomass, Hydropower, Wind Energy, and Solar PV—using two metrics: Qi (in blue) and Ui (in orange), which are derived from the COPRAS (Complex Proportional Assessment) method. In this assessment, Geothermal Energy ranks the highest with a Qi value of 0.272 and a Ui score of 100%, making it the top-performing energy source in this comparison. This high Ui percentage reflects its optimal integration potential within renewable energy systems. Hydropower follows with a Qi of 0.214 and a Ui of 79%, demonstrating strong integration potential, though it falls short of geothermal's performance. Wind Energy and Solar PV have somewhat similar integration scores, with Wind Energy showing a Qi of 0.185 and a Ui of 68%, while Solar PV has a Qi of 0.177 and a Ui of 65%. Both energy sources are competitive but less efficient than hydropower and geothermal in this evaluation. Lastly, Biomass shows the lowest values, with a Qi of 0.152 and a Ui of 56%, indicating its relatively weaker performance in terms of integration potential within energy systems. Overall, Geothermal Energy stands out as the most favorable renewable energy source based on these metrics, followed by Hydropower, while Biomass appears less competitive in this particular assessment.

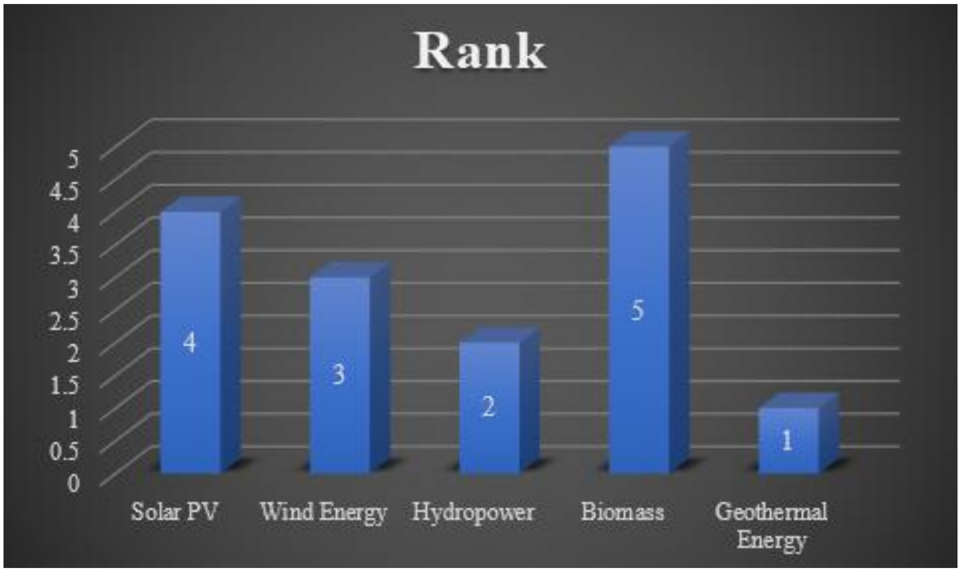

FIGURE 5. Rank

Figure 5 presents the ranking of five renewable energy systems—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—using the COPRAS (Complex Proportional Assessment) method. The bar chart visually represents the final rankings based on the evaluation of various criteria such as energy efficiency, technology maturity, resource availability, and land requirements. Geothermal Energy ranks first, as indicated by the shortest bar, reflecting its optimal performance across all evaluated parameters, particularly its balance of high energy efficiency and low land use. Hydropower comes in second, benefiting from its superior energy efficiency and mature technology, though its large land requirement pushes it behind Geothermal Energy. Wind Energy secures the third position, demonstrating moderate performance across the criteria, with a balance between efficiency and resource requirements. Solar PV ranks fourth, owing to its lower energy efficiency, though it maintains relatively high technological maturity. Biomass ranks last, shown by the tallest bar, due to its moderate energy efficiency and significant land requirements, despite its high resource availability. This ranking offers a clear visual summary of the comparative performance of these renewable energy systems, helping stakeholders and decision-makers easily identify the most efficient and viable options for integration based on the COPRAS methodology.

4. CONCLUSION

The evaluation of renewable energy systems using the Complex Proportional Assessment (COPRAS) method provides valuable insights into the performance and suitability of various energy alternatives. This study analyzed five distinct renewable energy sources—Solar PV, Wind Energy, Hydropower, Biomass, and Geothermal Energy—by considering crucial criteria such as Energy Efficiency, Technology Maturity, Resource Availability, and Land Requirement. The approach emphasized the importance of a balanced assessment, where all criteria were equally weighted to avoid bias and ensure a comprehensive evaluation. The results of the analysis revealed that Geothermal Energy ranks highest among the evaluated systems, primarily due to its impressive energy efficiency and minimal land use. This finding underscores Geothermal Energy's potential as a highly viable option for sustainable energy integration, particularly in areas with limited land availability. Hydropower, while rated second, demonstrated the highest energy efficiency and technological maturity; however, its substantial land requirement poses a challenge for its widespread implementation, particularly in densely populated or ecologically sensitive regions. Wind Energy and Solar PV followed in third and fourth positions, respectively. Wind Energy's moderate performance across criteria highlights its reliability and potential for contributing to a diverse energy portfolio. Meanwhile, Solar PV, despite its lower energy efficiency, benefits from advanced technology and lower land requirements, making it an attractive option in urban settings or regions with limited space. Biomass, while rich in resource availability, ranked last due to its moderate energy efficiency and higher land requirement, indicating that its implementation may be less favorable in certain contexts. This comprehensive evaluation not only illustrates the strengths and weaknesses of each renewable energy system but also emphasizes the need for decision-makers to consider a range of factors when selecting energy sources for integration. By utilizing the COPRAS method, stakeholders can make informed decisions that align with both environmental sustainability and economic viability. Ultimately, this study contributes to the ongoing discourse on renewable energy adoption, offering a structured framework that can facilitate future research and policy development in the field of renewable energy systems integration.

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