ABSTRAK

Akses energi listrik yang andal dan berkelanjutan masih menjadi tantangan signifikan di wilayah Papua Barat, khususnya di daerah pedesaan dan terpencil. Hambatan utama meliputi keterbatasan pengembangan jaringan distribusi, penyebaran penduduk yang tidak merata, kondisi ekonomi masyarakat yang rendah, tantangan geografis yang berat, serta ketergantungan tinggi pada bahan bakar fosil seperti diesel yang mahal, logistik yang sulit, dan berdampak negatif terhadap lingkungan. Penelitian ini bertujuan mengatasi masalah tersebut melalui dua pendekatan utama yaitu (1) pemetaan potensi energi terbarukan, khususnya tenaga air dan tenaga surya untuk menentukan besaran dan distribusi sumber daya di Provinsi Papua Barat dan (2) melakukan perancangan sistem energi terbarukan hibrida berbasis analisis teknis, ekonomi, lingkungan sesuai dengan sumber daya lokal.

Penelitian ini bertujuan untuk merancang dan mengoptimalkan sistem energi terbarukan hibrida yang andal dan berkelanjutan bagi wilayah pedesaan terpencil di Provinsi Papua Barat. Tahapan penelitian mencakup pemilihan lokasi berdasarkan kriteria sosial dan geografis yang koheren, pemetaan potensi energi (debit andalan, tinggi terjun, radiasi surya, dan ketersediaan lahan), peramalan beban, serta pemilihan teknologi pembangkit yang sesuai dengan karakteristik lokal. Pemetaan sumber energi dilakukan di tujuh kabupaten di Provinsi Papua Barat untuk mengidentifikasi daerah yang paling layak dikembangkan. Optimasi sistem energi terbarukan hibrida dilakukan dengan meminimalkan *Net Present Cost* (NPC) dan *Cost of Energy* (COE), serta memaksimalkan penetrasi energi terbarukan dengan mempertimbangkan batasan teknis, ekonomi, dan lingkungan. Model optimasi diformulasikan dan diimplementasikan menggunakan perangkat lunak HOMER guna menentukan konfigurasi sistem yang paling efisien, disertai analisis sensitivitas terhadap variabel utama seperti harga bahan bakar, debit air, tingkat inflasi, dan tingkat diskonto. Studi kasus diimplementasikan di Sistem Anggi-Sururey, Kabupaten Pegunungan Arfak, Provinsi Papua Barat dengan lima konfigurasi sistem, yaitu DG, DG/PV/Baterai, DG/Air/Baterai, DG/Air/PV/Baterai, dan PV/Air/Baterai, untuk menentukan solusi yang paling optimal berdasarkan konteks teknis, ekonomi, lingkungan, dan sosial masyarakat setempat.

Hasil pemetaan potensi sumber energi menunjukkan potensi energi surya bervariasi dari skala kecil-menengah (7-16 kWp) di lokasi seperti Distrik Syujak dan Distrik Mitimber, Kabupaten Tambrauw, Distrik Sararti, Kabupaten teluk Wondama, Distrik Sururey, Kabupaten Pegunungan Arfak hingga potensi besar seperti di Distrik Kokas (318,5k Wp) dan Distrik Bomberai (535,6 kWp), Kabupaten Fakfak. Potensi tersebut mendukung pengembangan microgrid komunal. Potensi energi air tersebar tidak merata di tujuh kabupaten, dengan Sorong Selatan mendominasi 46,19% dari total potensi 5,48 MW, diikuti Fakfak dan Tambrauw masing-masing 22,32% dan 22,16%, sedangkan Kabupaten Teluk Wondama, Manokwari Selatan dan Pegunungan Arfak memiliki kontribusi yang signifikan terhadap potensi yang ada. Data potensi energi air dan surya menjadi dasar rekomendasi pengembangan pembangkit berbasis energi terbarukan hibrida sesuai karakteristik lokal.

Hasil optimasi konfigurasi yang paling optimal berdasarkan analisis teknis, ekonomi dan lingkungan dengan studi kasus Sistem Anggi-Sururey adalah konfigurasi hibrida DG/Air/PV/Baterai. Konfigurasi DG/Air/PV/Baterai pada CS 0,1%, debit andalan 1.300L/detik, harga bahan bakar $0,917/Liter, tingkat inflasi 3% dan tingkat diskonto 4,8% mampu memproduksi energi sebesar 1.367.986 kWh/tahun (PV 1,67%, DG 174%

dan Air 81,3%) untuk konsumsi beban sebesar 1.197.894 kWh/tahun. Sistem ini menghasilkan COE sebesar $0,1562/kWh dan NPC $3,14M. Dari sisi teknis, konfigurasi ini menghasilkan kelebihan energi sebesar 12,2%, UL 0%, dan penetrasi energi terbarukan sebesar 80,5% serta penurunan emisi sebesar 75,78% setiap tahun sehingga berkontribusi langsung terhadap *Sustainabel Development Goal* (SGD) 7-*Affordable and Clean Energy* dan SDG 13-*Climate Action*.

Analisis sosial dengan pendekatan STEEP (*social, technical, economic, environmental, policy*) menunjukkan bahwa penerapan sistem energi terbarukan di wilayah pedesaan Papua Barat menghadapi tantangan berupa rendahnya partisipasi masyarakat, ketidakjelasan kepemilikan infrastruktur, dan keterbatasan kapasitas teknis. Namun, modal sosial lokal seperti kepemimpinan yang kuat, kerukunan antar warga, dan partisipasi komunitas yang konsisten menjadi landasan penting bagi keberhasilan pengembangan sistem energi terbarukan hibrida (DG/Air/PV/Baterai) di sistem Anggi-Sururey. Implementasi sistem ini secara empiris terbukti mampu menurunkan biaya operasi dan pemeliharaan hingga 71,84% dan mengurangi konsumsi bahan bakar sebesar 75,75% dibandingkan sistem konvensional sehingga meningkatkan efisiensi biaya energi dan kemandirian ekonomi lokal. Secara sosial, keberadaan listrik yang andal mendorong terbentuknya aktivitas ekonomi baru berbasis energi, seperti produksi kerajinan Noken, peningkatan produktivitas rumah tangga dan meningkatkan kualitas hidup masyarakat, di antaranya waktu belajar anak yang lebih lama, penggunaan perangkat digital di malam hari lewat pendampingan orang tua, serta penguatan fungsi sosial antar warga melalui kegiatan komunitas. Secara keseluruhan, hasil ini menegaskan peran transformatif sistem energi terbarukan hibrida dalam mendorong ketahanan sosial, pemberdayaan ekonomi, dan pembangunan pedesaan berkelanjutan di wilayah berkembang seperti Papua Barat.

Penelitian ini memberikan kebaruan melalui integrasi sistem energi terbarukan hibrida yang menggabungkan tenaga surya, air, diesel, dan baterai dengan potensi lokal, serta analisis sensitivitas yang mempertimbangkan faktor teknis dan ekonomi. Kontribusi penelitian meliputi penyediaan *framework* optimasi HYRES yang dapat di replikasi untuk pengembangan sistem serupa di wilayah pedesaan, mendukung mitigasi perubahan iklim melalui pengurangan emisi gas rumah kaca, dan memberikan rekomendasi kebijakan untuk mendorong transisi energi berkelanjutan.

Kata kunci: Sistem energi terbarukan hibrida, Elektrifikasi daerah berkembang, Pemetaan potensi energi, Software HOMER, Analisis STEEP

ABSTRACT

Reliable and sustainable access to electricity remains a significant challenge in West Papua Province, particularly in rural and remote areas. The main barriers include limited distribution network development, uneven population distribution, low household economic capacity, difficult geographic conditions, and a heavy dependence on fossil fuels such as diesel, which are costly, logistically constrained, and environmentally harmful. This research aims to address these issues through two main approaches: (1) mapping renewable energy potential, particularly hydropower and solar energy, to determine the magnitude and spatial distribution of renewable energy resources in West Papua Province, and (2) designing a hybrid renewable energy system based on technical, economic, and environmental analyses aligned with local resource characteristics.

The study aims to design and optimize a reliable and sustainable hybrid renewable energy system for rural and remote areas in West Papua Province. The research stages include selecting suitable locations based on coherent social and geographical criteria, mapping renewable energy potential (dependable flow, head height, solar radiation, and land availability), load forecasting, and selecting generation technologies that match local characteristics. Energy resource mapping was conducted across seven regencies in West Papua Province to identify the most feasible areas for development. The hybrid renewable energy system optimization was carried out by minimizing the Net Present Cost (NPC) and Cost of Energy (COE) while maximizing renewable energy penetration, taking into account technical, economic, and environmental constraints. The optimization model was formulated and implemented using Homer software to determine the most efficient system configuration, accompanied by sensitivity analysis of key variables such as fuel price, river flow rate, inflation rate, and discount rate. A case study was applied to the Anggi-Sururey system in Pegunungan Arfak Regency, West Papua Province, with five system configurations: DG, DG/PV/Battery, DG/Hydro/Battery, DG/Hydro/PV/Battery, and Hydro/PV/Battery, to determine the most optimal hybrid energy solution based on local technical, economic, environmental, and social contexts.

The mapping results indicate that solar energy potential varies from small to medium scales (7-16 kWp) in locations such as Syujak and Mitimber Districts (Tambrauw Regency), Sararti District (Teluk Wondama Regency), and Sururey District (Pegunungan Arfak Regency) to large-scale potential in Kokas District (318.5 kWp) and Bomberai District (535.6 kWp) in Fakfak Regency. These potentials support the development of community-based microgrids. Hydropower potential is unevenly distributed across the seven regencies, with South Sorong contributing 46.19% of the total 5.48 MW potential, followed by Fakfak and Tambrauw with 22.32% and 22.16%, respectively, while the Teluk Wondama, South Manokwari, and Pegunungan Arfak regencies also provide significant contributions. The hydropower and solar energy potential data form the basis for recommending hybrid renewable power plants that match local characteristics.

The appropriate configuration optimization results, derived from technical, economic, and environmental examination of the Anggi-Sururey System case study, indicate that the hybrid DG/Air/PV/Battery combination is significantly effective. The DG/Air/PV/Battery system at CS 0.1%, with a dependable discharge rate of 1,300 L/sec, a fuel cost of $0.917 per liter, an inflation rate of 3%, and a discount rate of 4.8%, may generate 1,367,986 kWh annually (comprising 1.67% from PV, 17.4% from DG, and 81.3% from water) with a load consumption of 1,197,894 kWh per year. This system generates a cost of energy (COE) of $0.1562/kWh and a net present cost (NPC) of $3.14

million. This configuration yields an energy surplus of 12.2%, a utilization level of 0%, a renewable energy penetration of 80.5%, and a yearly emission reduction of 75.78%, so it directly supports Sustainable Development Goals (SDGs). 7 - Economical and Unpolluted Energy and 13 - Environmental Action.

The STEEP (Social, Technical, Economic, Environmental, and Policy) analysis reveals that implementing renewable energy systems in rural areas of West Papua faces several persistent challenges, including limited community participation, unclear infrastructure ownership, and insufficient technical capacity. Nevertheless, strong local social capital, manifested in effective leadership, community cohesion, and consistent participation, serves as a crucial foundation for the successful deployment of a hybrid renewable energy system (DG/Hydro/PV/Battery) in the Anggi-Sururey system. Empirical findings demonstrate that this system can reduce operation and maintenance costs by 71.84% and fuel consumption by 75.75% compared with conventional systems, thereby enhancing energy cost efficiency and promoting local economic self-sufficiency. Socially, the availability of reliable electricity has stimulated new energy-driven economic activities, such as *Noken* handicraft production and household-scale enterprises, while improving the overall quality of life. Households experience longer study hours for children, increased access to digital technologies at night with parental support, and strengthened community interaction through collective social activities. Collectively, these outcomes highlight the transformative role of hybrid renewable energy systems in fostering social resilience, economic empowerment, and sustainable rural development in emerging regions such as West Papua.

This study provides novelty through the integration of hybrid renewable energy systems combining solar, hydro, diesel, and battery resources based on local potential, as well as sensitivity analysis that incorporates technical and economic factors. The research contributions include providing a replicable HYRES optimization framework for developing similar systems in rural areas, supporting climate change mitigation thru greenhouse gas emission reduction, and offering policy recommendations to promote a sustainable energy transition.

Keywords: Hybrid renewable energy systems, Electrification of developing regions, Energy resource mapping, HOMER software, STEEP framework analysis