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Pemodelan dan Simulasi Berbasis Agen dalam Penentual Adopsi dan Model Bisnis Residential Photovoltaic di Indonesia
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INTISARI

Adopsi *residential photovoltaic* (PV) di Indonesia masih jauh dari potensinya, dengan kontribusi sektor rumah tangga hanya sebesar 16,4% dari total kapasitas surya terpasang nasional (245 MWp). Rendahnya adopsi ini dipengaruhi oleh hambatan berlapis yang bersifat heterogen dan dinamis, meliputi keterjangkauan biaya investasi awal, keterbatasan pengetahuan masyarakat tentang PV, status kepemilikan rumah, pengaruh sosial, serta ketiadaan model bisnis yang sesuai dengan kondisi ekonomi rumah tangga. Pendekatan prediktif berbasis data historis sulit diterapkan karena data adopsi residensial masih sangat terbatas, sehingga dibutuhkan metode simulasi yang mampu merepresentasikan keragaman keputusan rumah tangga. Penelitian ini mengembangkan model *Agent-Based Modeling and Simulation* (ABMS) menggunakan Python dan Mesa, di mana setiap agen merepresentasikan satu rumah tangga dengan atribut sosial-ekonomi, status kepemilikan rumah, tingkat pengetahuan, pengaruh sosial, dan akses terhadap *service center*. Model mempertimbangkan empat model bisnis yaitu *Direct Purchase*, *Installment*, *Leasing*, dan *Pay-As-You-Go* (PAYG). Data primer diperoleh dari survei *stated preference* berbasis *vignette questionnaire* terhadap 138 responden valid (dari 257 awal) yang digunakan untuk membentuk atribut awal agen dan memvalidasi perilaku model. Sensitivitas model diuji melalui *parameter sweep* pada lima kelompok faktor: difusi sosial, infrastruktur, teknologi PV, pembiayaan, dan dinamika sosial-ekonomi, dengan analisis statistik menggunakan GLM/ANOVA.

Validasi model menghasilkan rata-rata RMSE ternormalisasi sebesar 0,102 (10,2%), menunjukkan bahwa model mampu merepresentasikan pola keputusan awal responden secara memadai. Analisis karakteristik responden mengungkapkan bahwa status kepemilikan rumah merupakan faktor paling kuat yang membedakan pilihan model bisnis (Cramer's $V^2 = 0{,}754$): rumah tangga tanpa rumah cenderung memilih PAYG atau tidak mengadopsi, sementara pemilik rumah dominan memilih *Direct Purchase* dan *Installment*. Hasil simulasi menunjukkan bahwa frekuensi pertimbangan adopsi dan laju pembelajaran pengetahuan tentang PV adalah dua pendorong adopsi paling kuat — peningkatan keduanya secara konsisten meningkatkan jumlah adopter secara signifikan. Sebaliknya, tarif PAYG yang tinggi dan harga rumah yang mahal menekan adopsi karena mempersulit keterjangkauan biaya dan peluang kepemilikan rumah. Parameter infrastruktur seperti jumlah dan aksesibilitas service center tidak selalu meningkatkan total adopsi, tetapi secara konsisten menggeser komposisi model bisnis dari *Leasing* menuju *Direct Purchase* dan *Installment*. Temuan ini menunjukkan bahwa adopsi *residential* PV di Indonesia merupakan fenomena yang muncul dari interaksi kompleks antara akses informasi, kepemilikan aset, kapasitas finansial, dan ketersediaan layanan teknis, bukan sekadar respons terhadap satu faktor tunggal.

Kata Kunci : *residential PV,* pemodelan dan simulasi berbasis agen*,* adopsi teknologi, model bisnis*, stated preference, parameter sweep*

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ABSTRACT

Residential photovoltaic (PV) adoption in Indonesia remains far below its potential, with the household sector contributing only 16.4% of the national installed solar capacity (245 MWp). This low adoption reflects layered and heterogeneous barriers, including high upfront investment costs, limited public knowledge of PV technology, homeownership constraints, social influence dynamics, and the absence of business models suited to diverse household economic conditions. Predictive approaches based on historical data are difficult to apply given the scarcity of residential adoption records, underscoring the need for a simulation method capable of capturing the heterogeneity of household decision-making. This study develops an Agent-Based Modeling and Simulation (ABMS) model using Python and Mesa, in which each agent represents one household with socioeconomic attributes, homeownership status, knowledge level, social influence, and access to service centers. The model evaluates four business models: Direct Purchase, Installment, Leasing, and Pay-As-You-Go (PAYG). Primary data were collected through a stated preference survey using vignette questionnaires, yielding 138 valid respondents (from 257 initial responses), which were used to initialize agent attributes and validate the model's behavioral logic. Model sensitivity was examined through parameter sweeps across five factor groups — social diffusion, infrastructure, PV technology, financing, and socioeconomic dynamics — with statistical analysis using GLM/ANOVA.

The cleaned survey data produced 138 valid respondents and were used as the basis for Model validation produced a mean normalized RMSE of 0.102 (10.2%), indicating that the model adequately represents respondents' initial decision patterns. Analysis of respondent characteristics revealed that homeownership status is the strongest differentiator of business model preference (Cramer's $V^2 = 0.754$): households without homeownership predominantly selected PAYG or chose not to adopt, while homeowners largely preferred Direct Purchase and Installment. Simulation results demonstrate that adoption consideration frequency and the rate of PV knowledge acquisition are the two most powerful drivers of adoption, with increases in both consistently and substantially raising the total number of adopters. Conversely, high PAYG tariffs and rising house prices suppressed adoption by constraining cost affordability and reducing the likelihood of homeownership transition. Infrastructure parameters such as the number and accessibility of service centers did not always increase total adoption rates, but consistently shifted the composition of chosen business models from Leasing toward Direct Purchase and Installment. These findings suggest that residential PV adoption in Indonesia is an emergent phenomenon arising from the complex interaction of information access, asset ownership, financial capacity, and technical service availability, rather than a response to any single determinant.

Keywords: residential PV, agent-based modeling and simulation, technology adoption, business model, stated preference, parameter sw