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An Agent-Based Modeling Approach to Support Site Selection for Renewable Power Plants in Kerman Province

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ABSTRACT

Objective: Tii s styyy aims to sppoort Ira'' s transition .o reeeaa ll e eergy by ieett ifyigg optimal sites for renewable power plant deployment in Kerman province. The aim is to design a decision-support framework incorporating stakeholder values and dynamic system behaviors to guide policy and investment under multiple scenarios.

Methods: An integrated Value-Focused Thinking (VFT) and Agent-Based Modeling (ABM) framework was developed. Phase 1 involved interviews with 15 experts (engineering, economics, and environmental science) to derive stakeholder values, translated into criteria like solar radiation, ecological sensitivity, cost, social acceptance, and grid resilience. Legal/environmental filters narrowed 39 locations to six feasible sites. Phase 2 employed ABM to simulate interactions among suppliers, government, and consumers under three policy scenarios: (1) limited local sales, (2) guaranteed government purchases, and (3) competitive energy market sales.

Results: The simulations demonstrated that Scenario 3 (energy market sales) resulted in the highest levels of energy output and job creation, particularly at high-potential locations E and F. The model also highlighted how adaptive financial mechanisms, such as targeted subsidies and tax incentives, can shape investor and supplier behavior in favor of sustainable deployment.

Conclusion: The proposed VFT-ABM framework offers a flexible and context-sensitive tool for renewable energy planning in decentralized systems. It effectively balances economic, social, and environmental goals and can be replicated in other regions facing similar energy transition challenges. Strategic policy design, especially market-driven approaches coupled with incentive structures, is critical for mobilizing private sector participation.

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Introduction

In recent years, Iran has faced a severe energy imbalance, with electricity consumption growing at an annual rate of 7%, while production has increased by less than half that rate over the past decade (Solaymani, 2021). This disparity has led to significant power shortages, particularly during peak summer months, where the electricity deficit surged to 20,000 megawatts in 2024. The situation is exacerbated by aging infrastructure, underinvestment, and the impact of international sanctions (Ramezani et al., 2024). Despite these domestic challenges, Iran continues to export electricity to neighboring countries, prioritizing long-term regional energy agreements and geopolitical interests over domestic supply stability (Abdolahinia et al., 2024). This paradoxical export behavior, even during periods of internal shortages, highlights the complexities of Iran's energy policies and the need for a strategic reevaluation to balance domestic needs with international commitments (Shikh Mohammadi & Hashemi, 2024). Addressing this chronic disequilibrium requires advancing localized renewable energy solutions and enhancing flexibility within the energy mix (Tahari-Mehrjardi et al., 2024). Without strategic reforms in production diversification and cross-border energy trade governance, Iran risks prolonged exposure to blackouts and economic inefficiencies (Eghlimi et al., 2022). The observed gaps between seasonal demand and supply underscore the urgency for adopting decentralized, renewable-based energy planning models.

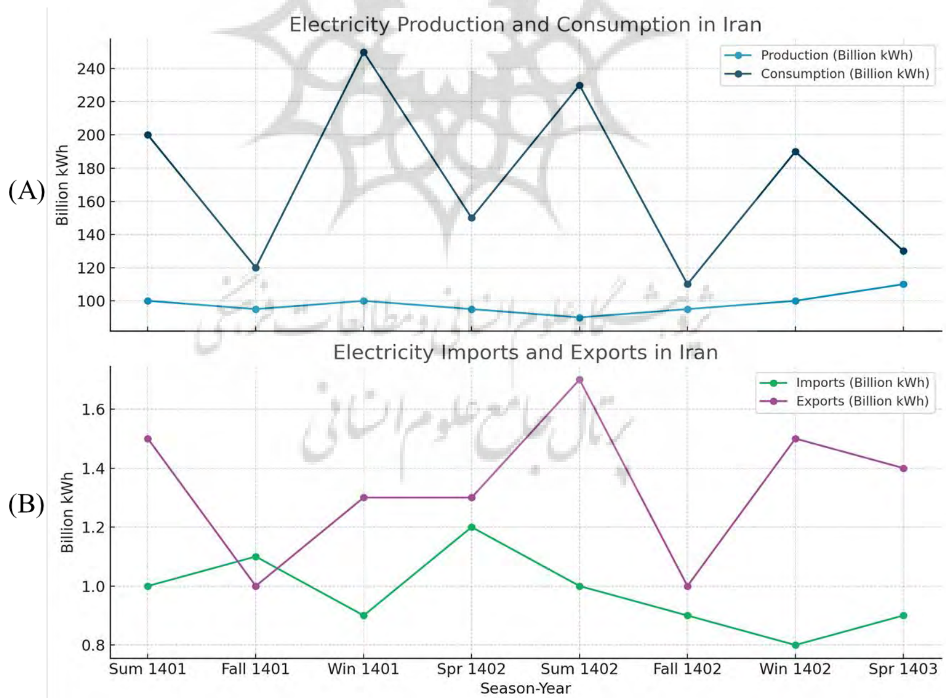


Figure 1. Electricity production and consumption (A), and electricity imports and exports (B) in Iran from Summer 1401 to Spring 1403 (Source: Ministry of Energy).

The data illustrated in Figure 1a highlights a recurring imbalance between electricity production and consumption across seasonal cycles in Iran (Asadi et al., 2023). This energy imbalance—most notably observed during summer and winter peaks—is primarily due to a growing mismatch between rising domestic demand and relatively constrained generation capacity (Chen et al., 2022). As shown, electricity consumption consistently surpasses production during high-demand seasons, indicating systemic strain on the national grid and underscoring the urgent need for structural improvements and demand-side management (Williams et al., 2023).

Contributing to this imbalance is the pattern of electricity imports and exports, depicted in Figure 1b. Iran continues to export electricity even in periods of domestic shortage, particularly during Summer 1401 and Summer 1402, when exports peaked despite ongoing consumption surges. This paradoxical export behavior suggests that long-term regional energy agreements or strategic geopolitical interests are prioritized over domestic supply stability (Ibekwe et al., 2024). Additionally, fluctuations in imports show limited buffering capacity, failing to compensate adequately during critical consumption periods (Khazaei, Gholian-Jouybari, Dolatabadi, et al., 2025).

Tii s chroii c diseuullirr ium in Iran’s electricity system uneerscores the imoortance of advancing localized renewable energy solutions and enhancing flexibility within the energy mix (Zaheb et al., 2023). Without strategic reforms—both in production diversification and cross-border energy trade governance—the nation risks prolonged exposure to blackouts and economic inefficiencies (Venizelou & Poullikkas, 2024). The observed gaps between seasonal demand and supply offer a compelling case for adopting decentralized, renewable-based energy planning models (Foukolaei et al., 2024), as explored in the present study.

Across nearly all provinces of Iran—including sun-rich regions (Hosseini & Javid, 2024) Like Kerman, electricity imbalances have emerged as a persistent challenge, impacting households, industries, and local economies. To mitigate this issue, a growing consensus is that private sector investment in renewable energy infrastructure, particularly solar power plants, is a critical pathway forward (Taghipour et al., 2023; Pourezzat et al., 2022). However, understanding how private investors behave under varying governmental incentives, tax policies, and the presence of competing actors is essential. This requires more than technical feasibility; it calls for a structured understanding of what truly matters to stakeholders. Therefore, the study first applies a soft decision-making method, Value-Focused Thinking (VFT), to elicit core objectives and screening criteria. These refined outputs then guide the identification of promising candidate sites for simulation and deeper analysis. Using an Agent-Based Modeling (ABM) approach, the study further investigates how investor behavior and system-level dynamics evolve under diverse policy and market scenarios (Niknami & Akhondzadeh Noughabi, 2024).

In the following sections, we present a detailed review of relevant literature, outline the integrated VFT–ABM methodology, discuss simulation results based on various investment and policy scenarios, and conclude with implications for regional energy planning in Kerman and beyond.

Literature review

The transition to renewable and low-carbon energy systems has garnered increasing scholarly attention, especially with the rise of environmental concerns (Taghipour et al., 2024), economic sustainability goals, and advancements in simulation-based decision-making (Ölmez et al., 2025; Haghighi et al., 2016: Nasrollahi et al., 2022; Ghasemi et al., 2016). This body of literature spans various perspectives—from financial and policy modeling to behavioral and technological analysis—reflecting the multidisciplinary nature of energy planning and innovation. Below, the literature is categorized into two major thematic areas: strategic and decision-making models in renewable energy systems, and the application of agent-based modeling and ESG-aligned frameworks (Keenan et al., 2021).

Strategic models and decision-making

Numerous studies have aimed to enhance strategic decision-making in renewable energy development through analytical, simulation-based, or hybrid models. Ölmez et al. (2025) Adopt a simulation-based approach to evaluate the role of energy storage in stabilizing power markets and reducing the intermittency of renewables. Their model highlights the value of storage integration in supporting decarbonization and improving price stability in renewable-dominant systems, particularly when coupled with demand response strategies. Complementing this operational focus, Więcooss ki et al. ())))) emphasize the importance of robustness in renewable energy decision-making through a multi-dimensional sensitivity analysis of MCDA methods across European nations. Their framework demonstrates how changing assumptions and data variability affect policy priorities and ranking stability) an approach that supports more resilient energy planning. Meanwhile, Tahir (2025) delivers a comprehensive systematic review of hybrid microgrid systems' optimization techniques and software tools. The analysis traces the evolution of classical, metaheuristic, and AI-based optimization methods and underscores the central role of tools like MATLAB/Simulink and HOMER.

Dinçer et al. (2022) developed a combined approach based on fuzzy DEMATEL, TOPSIS, and Shapley value to prioritize cost-related strategies in low-carbon projects. Similarly, Xia et al. (2023) explored financing decisions in competitive supply chains under low-carbon constraints. Kong et al. (2023) focused on uncertainties in low-carbon supply chains and analyzed how financial supports like green credit influence carbon emission reduction. Further studies, such as Zhang et al. (2019), emphasized the temporal dynamics of policy mixes, underlining the importance of well-timed and coherent policy packages. Mardani et al. (2015) broadly reviewed decision-making techniques in renewable energy planning.

Besides, recent advances in strategic decision-making for renewable energy development have increasingly incorporated hybrid frameworks and multi-criteria methodologies to address energy systems' environmental, economic, and governance complexities. For example, Khazaei et al. (2025) introduced the STRIDES framework to evaluate enablers in the hydrogen supply chain, integrating Critical Systems Heuristics, Robust Analysis, Importance-Performance Analysis, and Trends Impact Radar. Their approach aligns with ESG principles and emphasizes systemic critique and stakeholder engagement. Similarly, Solangi and Magazzino (2025) applied fuzzy AHP and fuzzy VIKOR to prioritize financial policies for renewable energy adoption in China, identifying key factors such as financial risk, social benefit, and economic viability. Their findings support targeted incentives like green finance and public-private partnerships. Furthermore, Richards et al. (2025) proposed an integrated methodology using AHP, fuzzy logic, and GIS to identify optimal sites for solar PV deployment in Jamaica. Their approach accounted for technical, environmental, and socio-economic factors, demonstrating how spatial decision tools can guide sustainable energy investments. These studies highlight a growing emphasis on stakeholder-centered, criteria-driven frameworks that enhance the robustness and transparency of renewable energy strategies.

Agent-based modeling and ESG-oriented approaches

Another branch of the literature emphasizes the role of ABM and ESG-focused innovation in accelerating renewable energy transitions. Baldauf and Jochem (2024) Using an agent-based market framework, explore the role of financing strategies—project finance vs. corporate finance—in influencing the pace of renewable energy transitions. Their findings underscore how policy tools like green credit easing (GCE) can mitigate investment slowdowns and support system-wide growth. Meanwhile, Zhu et al. (2024) leverage AI on China's ESG platform, combining Particle Swarm Optimization and Deep Q-Networks to optimize clean energy scheduling, achieving significant gains in efficiency and responsiveness. Wei et al. (2024) present a real options model incorporating ESG factors in photovoltaic investment decisions, showing enhanced project value and policy alignment. Complementing this, Garrido-Merchán et al. (2023) introduce Bayesian Optimization for ESG portfolio construction, outperforming traditional heuristics and enabling black-box investment decision-making under ESG constraints. Moreover, Lin et al. (2024) examine asymmetric spillover effects between fossil fuel markets, policy uncertainty, and ESG investments, revealing how economic and geopolitical shocks can variably affect ESG-focused capital flows across global markets.

Wu et al. (2023) showed that alignment in ESG preferences among institutional investors significantly fosters low-carbon innovation in family-owned enterprises. Abbasi et al. (2021) and Alola et al. (2023) used ABM to examine the benefits of improving non-renewable energy efficiency and expanding renewable energy sources, iii ch contribtt ed oo reccc ing C emissions in Thailand and India. Draycott et al. (2019) highlighted the importance of ABM in modeling marine renewable energy systems, particularly given their complex integration with existing oceanic ecosystems.

Gaps and novelties

Recent literature on renewable energy and power plant site optimization has primarily emphasized improving energy efficiency, reducing costs, and deploying innovative technologies. However, a notable gap remains in applying ABM for region-specific site selection—particularly in areas like Kerman Province, Iran, where local environmental, socio-economic, and infrastructural conditions play a crucial role. While previous studies used ABM to simulate renewable energy performance, they primarily focused on national-level scenarios without integrating local data or social dynamics. Additionally, although ESG-related research has highlighted governance and sustainability concerns, few have linked these to spatial decision-making. Furthermore, models incorporating interactions among multiple criteria—such as economic costs, environmental impact, and network integration—remain scarce. This study addresses these limitations by offering a localized, multi-criteria ABM framework tailored to the unique characteristics of Kerman Province.

- Uses high-resolution climatic, geographic, and socio-economic data specific to Kerman Province for accurate site modeling.
- Combines ABM with VFT to assess trade-offs across environmental, economic, and social criteria.
- Model's dynamic scenarios such as climate change, water resource limitations, and grid constraints to enhance decision-making for renewable energy deployment.

Methodology

Based on the theoretical foundations and objectives outlined in this study, the methodology section presents a sequential combination of approaches used to achieve the research goals (Khazaei et al., 2023). Initially, the VFT method analyzes interview data and identifies key goals and values. These insights, enriched by expert input, serve as the basis for the next phase: modeling and prioritizing identified factors using an ABM approach. This integrated methodological structure ensures the qualitative depth and the quantitative rigor required for optimal site selection of renewable power plants. In the following, the two primary methods used—VFT and ABM—are briefly introduced and explained in terms of their conceptual foundations and application steps.

VFT, as introduced by Keeney (Mushi, 2020), shifts the decision-making paradigm from focusing on alternatives to focusing on values. Rather than reacting to pre-defined choices, VFT proactively identifies core objectives and their means. This approach is efficient in participatory, multi-stakeholder contexts where understanding diverse value systems is crucial. By systematically identifying fundamental and means objectives, structuring goals hierarchically, and generating alternatives aligned with stakeholder values, VFT provides a clear conceptual map for complex decision problems—especially those related to infrastructure planning and sustainability (Selart & Johansen, 2011).

Implementing the VFT approach follows a structured set of steps emphasizing values over predefined alternatives, fostering more innovative and purpose-driven decision-making. The process begins with Step 1: defining the decision context, which clarifies the boundaries, stakeholders, and scope of the problem. Next, in Step 2, the core values are translated into objectives and performance measures, reflecting what the decision-makers truly care about achieving or avoiding. Then, in Step 3, instead of selecting from pre-existing solutions, decision-makers generate alternatives by asking how each objective might be best fulfilled—often encouraging bold, even idealistic ideas to spark creativity (Mushi, 2020). In Step 4, these alternatives are evaluated by mapping their consequences across each performance measure, exposing strengths and weaknesses concerning the stated goals. Step 5 analyzes trade-offs among conflicting objectives to surface the most balanced and value-aligned solutions. Once trade-offs are understood, Step 6 is the decision point, selecting the option that offers the most acceptable compromise among competing values. Finally, in Step 7, the chosen solution is implemented, with mechanisms for monitoring and learning in place, ensuring the system can adapt to new information or changing conditions. Through this methodical process, VFT ensures that decisions are grounded in what truly matters, not just in what is immediately feasible (Selart & Johansen, 2011).

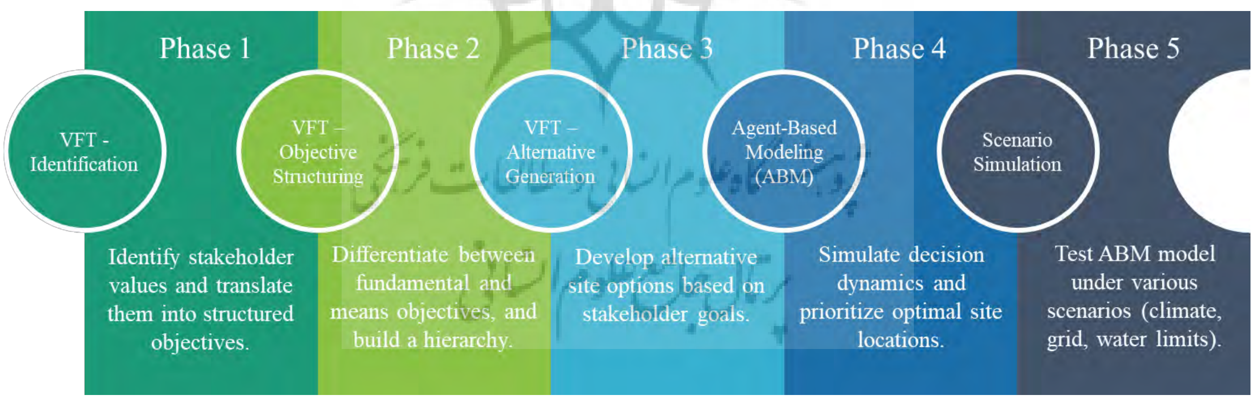


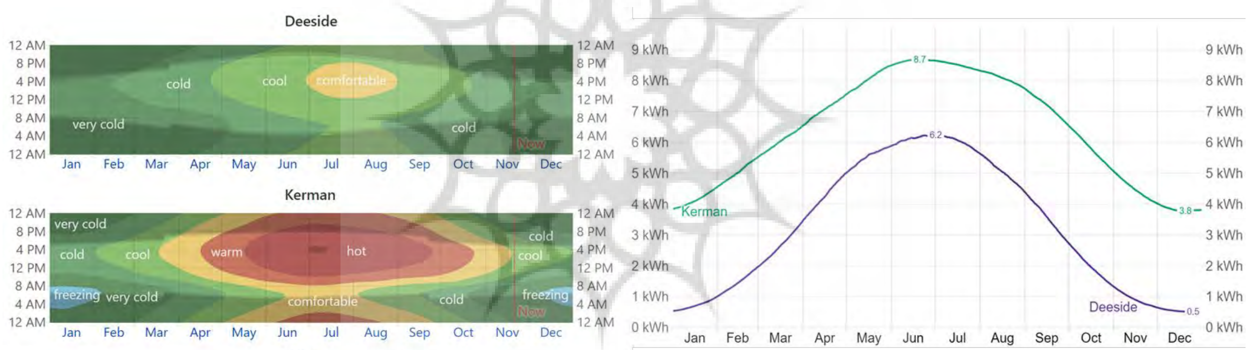
Figure 2. The five-phase research framework combines VFT and ABM for optimal site selection of renewable power plants under multiple stakeholder values and scenario constraints.

In the final phases, the research employs ABM to simulate the behaviors and interactions of various stakeholders (Maleki & Nilforoushan, 2024; Mohaghar et al., 2024a), environmental agents, and policy scenarios affecting renewable power plant siting in Kerman Province. ABM is particularly suitable for modeling complex systems with decentralized agents, adaptive behaviors, and dynamic environments (Mukherjee et al., 2021). This approach offers a bottomup perspective that complements the goal-driven structure of VFT, allowing the research to incorporate spatial, social, economic, and ecological dimensions into a single decision-support model (Koppelaar et al., 2021). By integrating qualitative insight and computational modeling, this methodology delivers a robust framework for informed and context-sensitive renewable energy planning (Gholian-Jouybari et al., 2024).

Results

Renewable potentials in Kerman province

To better understand the renewable energy potential of Kerman Province, this study undertakes a comparative case analysis between Kerman and an existing operational solar power site in Europe—specifically, the Deeside solar power plant in the United Kingdom. By examining real-world conditions such as solar radiation, temperature profiles, and seasonal variations, we aim to contextualize the capabilities of Kerman within a global benchmark. This comparison highlights Kerma’’s natrr al advantaees for solar energy generation. It provides valuable insights into how similar or less favorable regions have successfully leveraged technology and infrastructure to harness renewable energy.



(A) (B)

Figure 3. Comparison of temperature comfort zones (A) and monthly average solar radiation (B) between Deeside, UK, and Kerman, Iran (Source: Weatherspark).

Despite ee esiee in the UK beigg home ooone of Err oee’s lareest solar ooee r ll ants—with a capacity of 400 MW and annual generation of over 400 GWh—its average solar radiation is relatively modest, ranging between 0.5 and 6.2 kWh/m² per day. In contrast, Kerman Province in Iran demonstrates significantly higher solar potential, reaching 8.7 kWh/m² during peak months. The climate diagrams show how Kerman experiences consistently hot and sunny conditions, aarticularly in the summer, llll e ee esiee’s solar efficiecy is more constrained by its temperate and often cloudy weather. Iran’s vast eeserts—especially in regions like Lut Desert, Shahdad, and Tabas—offer a unique opportunity for solar power development. These areas report over 300 days of sunshine annually and radiation levels between 5 and 7 kWh/m²/day. As highlighted by current governmental initiatives in Kerman, including the 100 MW Shahdad solar plant and 50 MW wind project in Tabas, the region is well-positioned to become a renewable energy hub.

(A) (B)

Figure 4. Monthly percentage of clear or partly cloudy skies (A) and average daylight duration (B) in Kerman and Deeside throughout the year (Source: Weatherspark)

In addition to temperature and solar radiation levels, two key environmental variables—sky clarity and daylight hours—play a pivotal role in assessing solar energy feasibility. As illustrated in Figure 4 (A), Kerman enjoys significantly higher sky clarity year-round, reaching up to 99% during summer, compared to a peak of 55% in Deeside. This means solar panels in Kerman are exposed to far more direct sunlight, allowing for higher and more consistent electricity generation.

Figure 4 (B) shows that while Deeside benefits from longer daylight durations during peak summer months (up to 17 hours), Kerman maintains a more stable range of daylight hours throughout the year, around 10 to 14 hours daily. This stability and high sky clarity further reinforce Kerman's suitability for solar energy development. Even with fewer daylight hours in summer compared to Deeside, the superior clarity and intensity of sunlight in Kerman more than compensates for it.

These fiddisss eem. nstrate Kerma’’ s eccett ional and nneertt iiized ttt ential for reneaa ll e energy production, particularly solar power. By benchmarking it against a successful European model, the case for investment in solar infrastructure in Kerman becomes more compelling. In the next section, we explore how decision-makers can define and structure their objectives—starting with the VFT method—to guide sustainable and strategic site selection.

VFT analysis

In order to execute the first phase of the VFT method, we began by engaging a panel of 15 experts with diverse academic and professional backgrounds. These experts were selected based on their relevance to the research topic, representing industrial management, renewable energy engineering, environmental sciences, economics, and urban planning. Their professional experience ranged from 7 to 27 years, with a near-equal gender distribution (8 men and 7 women), and most holding doctoral degrees. This interdisciplinary group was carefully curated to ensure a balanced technical, managerial, economic, and environmental perspective. Through structured interviews and iterative workshops, the experts collaboratively identified and refined the core objectives for sustainable site selection of renewable power plants in Kerman Province.

Table 1. Hierarchical analysis of fundamental objectives and their sub-objectives for renewable power plants in Kerman Province.

Main Objective	Sub-Objectives
Maximize Renewable Energy Production	- Identify areas with high solar radiation - Evaluate wind speed and seasonal stability - Determine potential for hybrid solar-wind power plants
Minimize Environmental Impacts	- Avoid ecologically sensitive areas - Ensure minimal disruption to wildlife and local habitats - Assess impact on water resources
Ensure Economic Profitability	- Minimize construction and maintenance costs - Maximize proximity to existing infrastructure - Evaluate economic returns for local communities
Enhance Energy Security and Resilience	- Improve integration with existing power grids - Ensure geographic diversity of energy production sites
Promote Social Acceptance and Inclusion	- Engage with local communities in site selection - Ensure local populations benefit from the produced energy - Minimize displacement or disruption of local communities
Reduce Geopolitical and Legal Risks	- Ensure compliance with national and provincial regulations - Avoid areas with land ownership disputes - Minimize exposure to politically unstable regions

The first primary output of this process was a structured hierarchy of primary and secondary objectives (see Table 1). The main goals identified include maximizing renewable energy production, minimizing environmental impacts, ensuring economic profitability, enhancing energy security and resilience, promoting social acceptance, and reducing geopolitical and legal risks. Each main objective was further broken down into specific sub-objectives. For example, maximizing renewable energy involves identifying areas with high solar radiation, assessing seasonal wind conditions, and evaluating hybrid solar-wind plant feasibility. Meanwhile, environmental goals prioritize avoiding sensitive ecological zones and minimizing disruption to local habitats and water resources.

This hierarchical breakdown allows decision-makers to trace each overarching goal to measurable and actionable subcomponents. Such granularity enables a more precise site evaluation and prepares the foundation for simulation in later phases of the research. It aligns technical and economic considerations with broader environmental and social values, ensuring a sustainable planning framework. This step is pivotal in integrating multi-stakeholder priorities into a single decision-support model that will later be operationalized via agent-based modeling.

The second phase of the VFT methodology involved translating abstract strategic objectives into concrete, measurable criteria to support the decision-making process for optimal renewable power plant siting in Kerman Province. After identifying the fundamental objectives—from maximizing renewable energy production to ensuring environmental protection and social inclusion—each goal was disaggregated into actionable indicators. These indicators were carefully defined to allow systematic site suitability assessment while considering the province's diverse environmental, economic, and infrastructural conditions. For example, evaluating renewable energy potential involved measuring annual solar radiation and average wind speeds, while environmental impact was assessed using proximity to ecologically sensitive areas and water usage data.

Table 2. Summary of objectives and their corresponding measurable criteria for renewable energy site evaluation.

Objective	Criteria
Maximize Renewable Energy Potential	Solar radiation (kWh/m^2/year), Wind speed (m/s), Hybrid solar-wind plant potential
Minimize Environmental Impacts	Proximity to ecologically sensitive areas, Impact on wildlife (mortality rate), Water usage
Ensure Project Economic Viability	Project costs (USD/MW), Job creation potential (jobs per MW), Local community benefits
Strengthen Energy Grid Resilience	Energy storage capacity (MWh/MW), Grid upgrade requirements (km of lines, MW capacity)

This structured approach provided a consistent basis for comparing locations under the same evaluation framework. Economic viability was measured through project costs, job creation potential, and local community benefits. Network resilience was evaluated via energy storage capacity and the need for grid upgrades. These measurable criteria ensure that decisions align with stakeholder values and policy goals. More importantly, they allow future simulation phases to rely on robust, real-world metrics rather than vague assumptions, strengthening the credibility and relevance of the final site selection model.

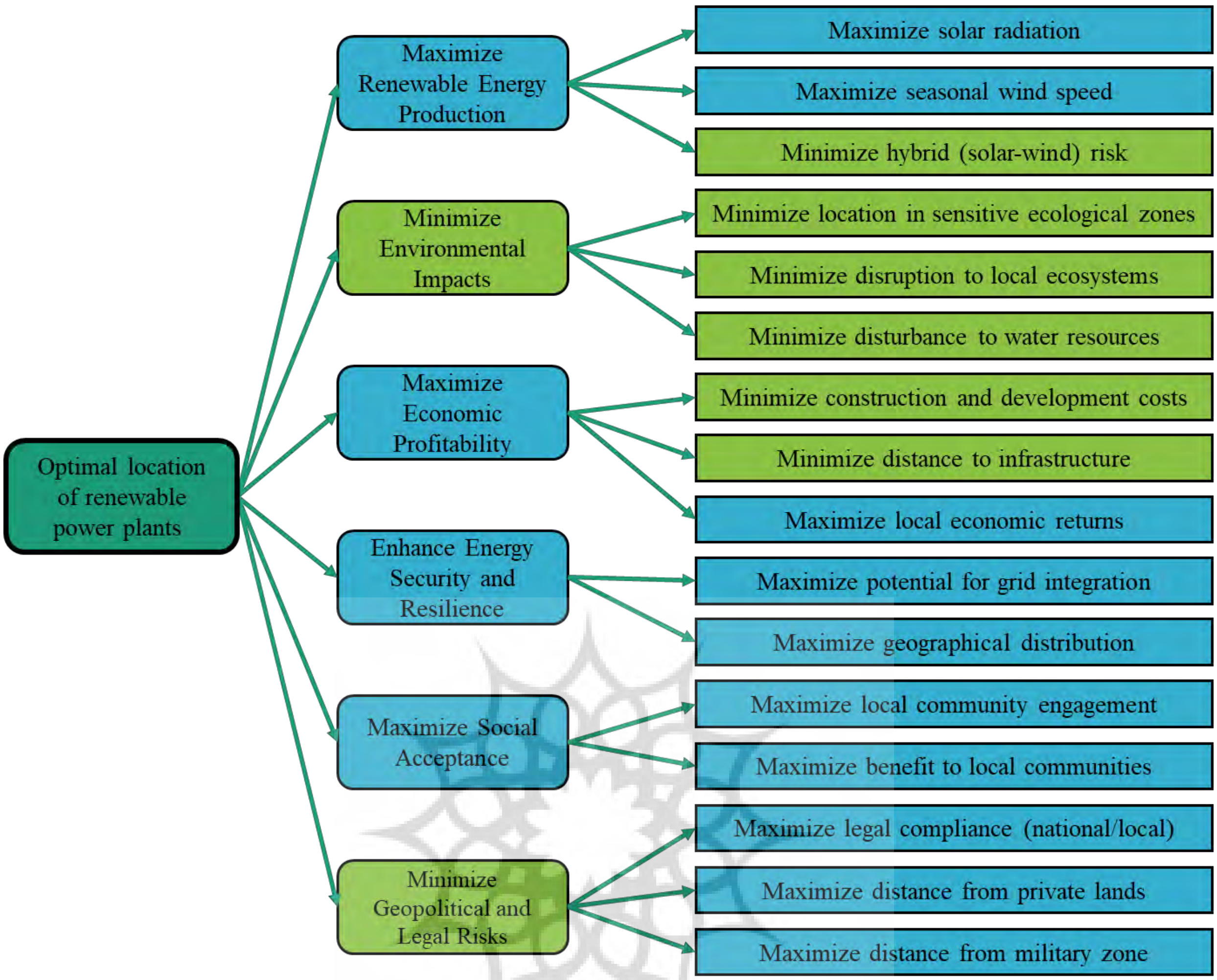
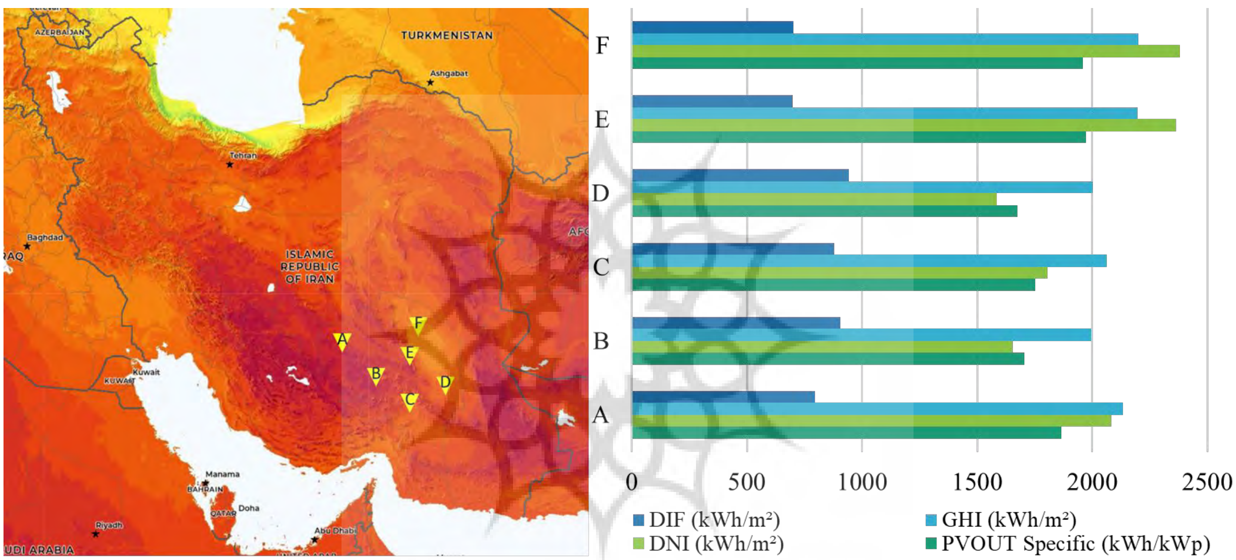


Figure 5. Hierarchical objective structure linking the optimal location of renewable power plants to specific sub-objectives and operational criteria.

In the third phase of the VFT process, the focus shifted to generating a set of viable site alternatives based on the structured objectives and corresponding criteria developed in earlier phases. Initially, 39 candidate locations across Kerman Province were identified through a preliminary geographic and technical screening. Two fundamental criteria—environmental impacts and geopolitical/legal risks—were applied as exclusionary filters to refine these options. This process led to eliminating unsuitable locations, narrowing the list to six high-potential sites that demonstrated minimal ecological disruption and aligned with relevant legal frameworks and land use restrictions. These six shortlisted sites were then evaluated using the remaining criteria: energy potential, economic viability, grid integration, and social acceptance. Rather than applying further complex filters, these criteria were incorporated into the ABM stage, where dynamic simulation of stakeholder behaviors and investment decisions was conducted. By focusing on the most context-sensitive and legally secure locations, this phase ensured that only feasible and strategically aligned options would enter the simulation phase for deeper scenario testing and optimization.

ABS implementation

The spatial visualization and accompanying bar chart illustrate six shortlisted locations in Kerman Province identified during the alternative generation phase. These candidate sites—A through F—were filtered based on environmental and legal criteria and evaluated for their solar potential using multiple performance indicators. The map on the left highlights the spatial oositioii gg of each site witii n Ira’’ s solar heatma,, hh ere aa rmer colors indicate ii gher solar irradiation. On the right, site-specific performance metrics such as PVOUT Specific (indicative of photovoltaic yield), Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI), and Diffuse Horizontal Irradiance (DIF) are compared to provide a holistic assessment of energy potential (Agbo et al., 2023).



(A) (B)

Figure 6. Geographic distribution of candidate sites (A) and comparison of key solar performance indicators across selected locations (B) (Source: Solargis)

Among these sites, Location E stands out with the highest PVOUT Specific value of 1973.6 kWh/kWp, closely followed by Location F (1957.9 kWh/kWp) and Location A (1864.6 kWh/kWp), marking them as top contenders for high-efficiency photovoltaic installations. Furthermore, E and F exhibit the highest DNI values—2363.8 and 2381.3 kWh/m², respectively—making them optimal for concentrated solar power (CSP) technologies (Zhang et al., 2013). Conversely, Location D, with the lowest PVOUT and DNI values, may pose challenges for efficient solar energy generation. Additionally, the GHI values reaffirm the superiority of sites F and E, while the DIF levels, particularly low in E and F, suggest excellent clarity and reduced atmospheric scattering—ideal for maximized solar harvesting.

Three policy-based scenarios were designed and simulated to evaluate the resilience and profitability of each shortlisted site. Each scenario reflects a unique regulatory framework and energy market mechanism that could shape investor decisions. In Scenario 1, only energy consumed by local users is sold, and any surplus is wasted—making it a scenario best suited for areas with high local demand. In contrast, Scenario 2 features a guaranteed purchase mechanism, where the government buys all the energy generated at a fixed rate, reducing investor risk and encouraging broader spatial investment. Scenario 3 introduces a dynamic pricing strategy where excess energy is sold on the national energy exchange at a premium rate, benefiting high-yield regions with surplus generation. Moreover, all scenarios, parameters, and modeling assumptions were developed and validated in close consultation with 15 domain experts.

Table 3. Comparison of three policy-driven scenarios for energy sales, pricing, and supplier behavior modeling.

Title	Scenario 1: Selling Energy to Local Customers	Scenario 2: Guaranteed Energy Purchase by Government	Scenario 3: Selling Excess Energy on the Energy Exchange
Energy Sales Model	Only the energy required by local customers is sold. Excess energy is wasted.	The government purchases all generated energy at a fixed price.	Excess energy is sold on the energy exchange at a higher price.
Energy Sales Calculation	Energy Sales = (Generated Energy - Excess Energy) × Unit Energy Price	Energy Sales = Generated Energy × Unit Energy Price	Energy Sales = (Energy Demand × Base Price) + (Excess Energy × Exchange Price)
Energy Pricing	Base price, e.g., $0.16 per kWh	Base price, e.g., $0.16 per kWh	Base price for local demand and exchange price (e.g., $0.21) for excess energy
Excess Energy Management	Excess energy is wasted.	The government purchases excess energy	Excess energy is sold on the energy exchange.
Impact of Subsidies & Taxes	Subsidies and taxes affect ROI.	Subsidies and taxes affect ROI.	Subsidies and taxes affect ROI.
ROI Formula	ROI = (Subsidy + Energy Sales) × (1 - Tax)^2 ÷ Proposed Investment	ROI = (Subsidy + Energy Sales) × (1 - Tax)^2 ÷ Proposed Investment	ROI = (Subsidy + Energy Sales) × (1 - Tax)^2 ÷ Proposed Investment
Advantages	- Suitable for areas with high energy demand	- Guaranteed sales for the supplier	- Optimized use of generated energy
Challenges	- Energy waste due to surplus	- High cost of guaranteed purchase for government	- Requires a strong infrastructure for energy exchange
Supplier Behavior	Invest in areas with high energy demand to reduce waste	Invest in areas with stronger government support and lower taxes	Invest in areas with high demand and potential for selling excess energy
Government Role	Set tax and subsidy policies for suppliers		

Each scenario affects the Return on Investment (ROI) through different energy sales formulas and pricing mechanisms and shapes supplier behavior and government involvement. For instance, in Scenario 1, investors are likely to concentrate in high-demand regions to avoid waste, whereas in Scenario 2, subsidies and purchase guarantees attract investors even in remote areas. Scenario 3, requiring robust infrastructure for market participation, pushes investment toward regions with strong grid connectivity and high production potential. By modeling each of the six candidate locations across these scenarios, the study captures how spatial viability, regulatory incentives, and energy market conditions interact to determine the most strategic sites for renewable energy development.

Table 4. Description of agents and their roles in the agent-based simulation model.

Agent	Role and Responsibilities	Key Decisions	Impacts and Interactions
Supplier	- Generate solar energy - Select investment location based on the highest ROI - Contribute to job creation in each region	- Decide on the investment amount in each region	- Supplies energy to local clients - Dependent on government subsidies and taxes
Government	- Set taxation and subsidy policies - Manage energy demand and supply through regulations	- Determine subsidy levels by region - Adjust tax rates based on population and jobs created	- Direct impact on sppll iers' ROI - Incentivizes suppliers through financial policies
Client	- Consume generated energy - Decide whether to stay or migrate based on job opportunities	- Decide to migrate to regions with more job opportunities	- Affects regional energy demand - Dependent on job creation by suppliers
Energy Exchange Market	- Enable sale of excess energy at higher prices - Provide infrastructure for energy trading	- Set market energy prices	- Encourages suppliers to utilize surplus energy - Reduces energy waste
Energy Infrastructure	- Transmit energy from producers to clients or markets - Store and manage surplus energy	- Decide whether to store or distribute excess energy	- Direct impact on supplier efficiency - Dependent on investments by the government or suppliers

In the simulation model, five distinct agent types were defined to represent the core components of the renewable energy investment ecosystem. Suppliers play a key role in sustainability (Sadeghi Moghadam et al., 2017; Jamalian et al., 2018); in particular, improving quality, reducing costs, on-time delivery, and flexibility (Mohaghar et al., 2011; Jafarnejad et al., 2014; Razavi et al., 2016; Mohaghar et al., 2024b; Ghasemi et al., 2025). The Supplier agents are private investors who decide where and how much to invest based on projected ROI, influencing job creation and energy availability. The Government agent plays a regulatory role, adjusting subsidies and tax rates according to regional development goals and population dynamics. The Client agents represent local populations who decide whether to remain or migrate based on job opportunities created by suppliers. Additionally, the Energy Exchange Market enables trade of surplus energy and sets pricing signals, thereby shaping supplier behavior. Lastly, the Energy Infrastructure agent determines the feasibility of energy transmission and storage, directly affecting the system's efficiency. These agents collectively create a dynamic simulation environment where policy interventions, spatial characteristics, and agent interactions drive investment flows and energy outcomes.

Scenario analysis

The demand patterns in each scenario reveal the impact of policy mechanisms on regional attractiveness and population dynamics. In Scenario 1, where excess energy is wasted and only local demand is fulfilled, Locations A and B maintain relatively high demand due to their favorable initial conditions. However, Locations C, E, and F experience sharp declines, indicating that insufficient investment and limited access to energy have led to population decline and demand loss. This uneven distribution highlights how neglecting surplus energy management exacerbates inequality between high- and low-demand regions.

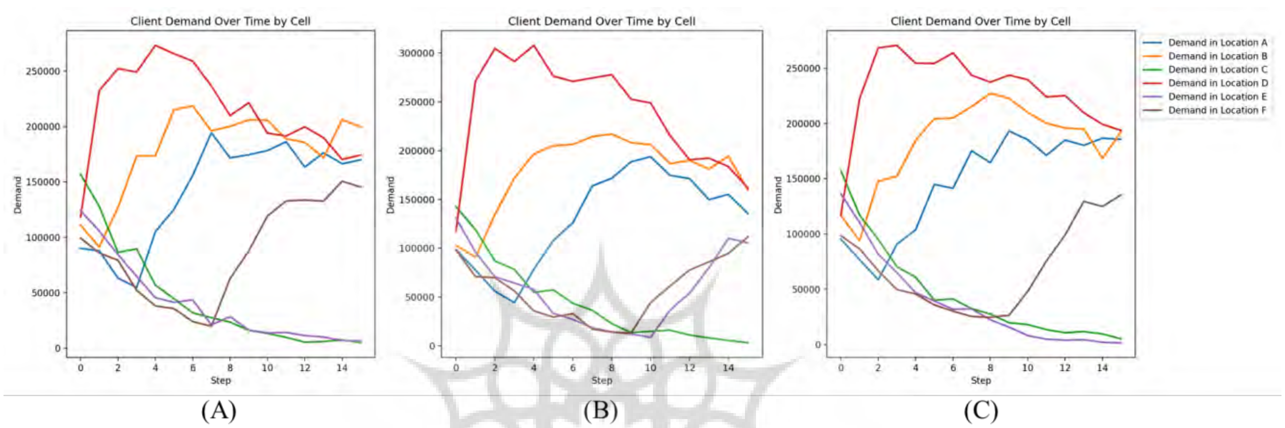
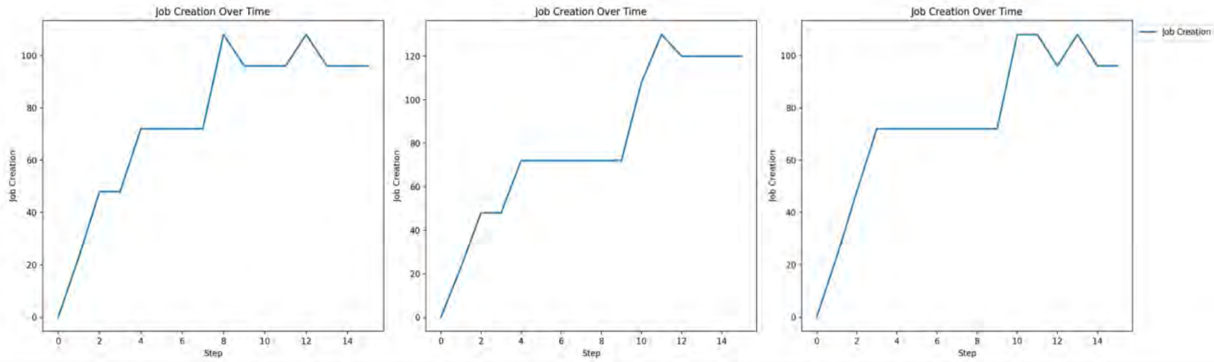


Figure 7. Client energy demand trends over time for each location under three different policy scenarios: (A) Scenario 1 – Local sales with excess wasted, (B) Scenario 2 – Government guaranteed purchase, and (C) Scenario 3 – Sale of excess energy on the energy exchange.

In contrast, Scenario 2, which includes government-guaranteed energy purchases, shows more balanced demand trajectories across locations. Although A and B still dominate, Locations E and F also witness gradual growth in demand due to improved investment incentives and lower risk for suppliers. Scenario 3 exhibits the most dynamic and efficient outcome, as the ability to sell surplus energy on the exchange platform motivates suppliers to invest in high-potential zones like F and E. As a result, these locations capture greater demand over time, suggesting that market-based mechanisms can help maximize regional energy utilization and population retention.



(A) (B) (C)

Figure 8. Job creation trends over time under three policy scenarios: (A) Scenario 1 – Local sales with excess waste, (B) Scenario 2 – Government guaranteed purchase, and (C) Scenario 3 – Energy exchange sales.

The job creation results across all three scenarios show a consistent increase in employment opportunities during the early stages, peaking around simulation steps 8 to 10. Scenario 2 yields the highest total job creation, indicating that government guarantees offer strong incentives for sustained investment and workforce growth. While Scenario 3 also supports substantial employment, its slight volatility suggests that job creation may be more sensitive to market fluctuations. In contrast, Scenario 1 demonstrates moderate job growth, reflecting the limited expansion potential when surplus energy is not efficiently utilized.

The visual analysis of subsidies over time across all three scenarios reveals a consistent upward trend, especially in high-potential areas like Locations A and F. These locations, due to their superior solar radiation and proximity to infrastructure, received increasingly higher subsidies as the simulation progressed. Notably, in all scenarios, a sudden dip or correction in subsidy allocation occurs around step 7 for Locations E and F, suggesting a policy recalibration or saturation threshold being triggered within the model logic. Conversely, lower-potential locations such as C and D experienced slower subsidy growth, indicating limited governmental incentive to stimulate investment in less attractive regions.

On the taxation side, the dynamics reflect a strategic attempt to redistribute investment incentives. In all scenarios, taxes decrease in low-demand locations like C and D—especially in Scenario 3—aiming to attract private investment through fiscal leniency. Locations A and B initially had higher tax burdens due to their early-stage population and investment influx. Eventually, they declined as subsidies rose and the system sought to stabilize ROI across regions. This inverse relationship between taxes and subsidies, evident in the middle and late stages of the simulation (steps 8–15), suggests an adaptive fiscal mechanism that modulates government intervention to promote spatial equity and optimize renewable energy deployment.

Discussion

The simulation results reveal significant differences among the three policy scenarios regarding spatial equity, energy efficiency, and investment behavior. Scenario 1, characterized by local energy sales without proper mechanisms for handling surplus, led to sharp population imbalances. High-demand areas like Locations A and B thrived. In contrast, others remained underdeveloped, particularly Location C. Suppliers in this scenario avoided risk by investing only in areas with high ROI, limiting the diffusion of renewable projects across the province. Additionally, the effect of subsidies and tax incentives in addressing regional disparities was minimal.

Scenario 2, the guaranteed energy purchase by the government, offered a more balanced outcome. Reduced investment risk led to broader supplier participation across various locations, including underdeveloped areas such as D and E. Tax reductions and subsidies proved more effective in this scenario, encouraging diversification and contributing to moderate improvements in energy efficiency. Scenario 3, involving energy exchange sales, produced the highest energy efficiency and concentrated investment in high-potential areas like Location F. While overall equity improved compared to Scenario 1, certain areas still lagged in population and investment attraction.

Table 5. Comparative performance of the three policy scenarios across key indicators.

Indicator	Scenario 1: Limited Energy Sales	Scenario 2: Guaranteed Energy Purchase	Scenario 3: Selling Excess Energy on the Exchange
Population Distribution	Unequal; high-demand areas attracted more population	More balanced; even moderate-demand areas saw population growth	More balanced than other scenarios, but some regions remained low-populated
Supplier Behavior	Invested only in high-ROI areas; ignored low-demand regions	Broader investment due to lower risk	Focused on high-production capacity areas for greater efficiency
Role of Taxation	Limited role in addressing inequality; low-demand areas had lower taxes	Reduced taxes in underdeveloped areas were effective	Continued tax cuts supported less attractive regions
Role of Subsidy	Attempted to reduce inequality, but with limited impact	Encouraged investment in lower-demand regions	Positive effect in attracting investment to underdeveloped areas
Attractive Regions	Locations A and B attracted the most population	Locations D and E also became more attractive	Location F attracted the most population
Underdeveloped Areas	The population declined in Locations C and E	Location C remained sparsely populated	Location C continued to have a low population
Energy Efficiency	Low; excess energy was wasted	Moderate; government guarantees improved efficiency	High; maximum efficiency via energy exchange sales
Investment Motivation	Limited to high-ROI areas	Increased across regions due to risk mitigation	Encouraged in regions with high production capacity

For policymakers aiming to stimulate renewable energy deployment in underdeveloped regions like parts of Kerman Province, Scenario 2 provides a viable middle ground. Government-backed purchase guarantees reduce investor uncertainty and promote regional equity. However, a hybrid model incorporating market mechanisms (as in Scenario 3) alongside targeted subsidies may be optimal to maximize efficiency and long-term sustainability. Effective design of incentive structures, coupled with strategic infrastructure development, is essential for unlocking decentralized renewable energy systems' full socio-economic and environmental benefits.

Conclusion

Sustainable development of countries pursues various goals such as economic development, social welfare (Firozabadi et al., 2010), and environmental improvement. Renewable energy is one of the prominent manifestations of such development (Mahbanooei & Ghasemi, 2024; Harta Nugraha Nur Rahayu et al., 2025). This study proposed an integrated VFT and ABM framework to support decision-making for the optimal siting of renewable energy power plants in Kerman Province. By first identifying stakeholder values and converting them into quantifiable criteria, and then simulating dynamic behaviors of agents such as suppliers, governments, and consumers under multiple policy scenarios, the model provided nuanced insights into how changes in subsidies, taxation, and energy pricing affect energy investment, job creation, and regional development. The results indicate that leveraging localized solar and wind potential, particularly in sites E and F, can significantly improve energy efficiency, spatial equity, and socioeconomic outcomes—especially when accompanied by adaptive fiscal mechanisms and infrastructure support.

One key limitation of the current study lies in the simplification of agent behavior. While the ABM framework incorporated core decision-making logics such as ROI optimization and policy responses, it did not fully capture more complex behavioral factors like risk aversion, institutional inertia, or social resistance, which could significantly influence real-world investment outcomes. Additionally, the model relied on historical and simulated data, and despite calibration efforts, may not fully reflect future fluctuations in climate, energy markets, or political regulations. Meanwhile, policymakers can consider investing in renewable energy to increase the country's goods market efficiency (Razavi et al., 2015).

Future studies could enhance the realism of the ABM by integrating behavioral economics principles and qualitative data from in-depth stakeholder interviews. Moreover, expanding the moeel's saatial scoee oo iccldde interrroii ncial rr id interactioss and trans-regional policy dynamics would provide a more comprehensive understanding of national energy strategy. Finally, embedding climate change projections and water scarcity scenarios into long-term simulations would help assess the resilience and sustainability of different site configurations under uncertain future conditions.

A sustainable approach in the field of renewable energy, like in other fields, with the help of Industry 4.0 technologies such as the Internet of Things (Ghasemi et al., 2025; Mohagahr et al., 2023; Karimi et al., 2022; Hoorshad et al., 2023; Yousefi et al., 2024; Mohaghar et al., 2025), can also help improve the competitiveness of countries (Jafarnejad et al., 2013; Mehregan et al., 2016; Ghasemi et al., 2018; Mahbanooei & Pourezzat, 2023; Tavakoli & Mahbanooei, 2014), which can be a topic for future research. Also, encouraging ethical issues as a driver for sustainable development (Pourezzat et al., 2019; Mahbanooei et al., 2019; Shojaei et al., 2023) for energy development can also be considered in future studies.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The authors have witnessed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work.

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Appendices

Appendix 1. Subsidy and Tax trends by location across scenarios.