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Intelligent Sustainable Energy Solution (ISES): An AI-Driven Residential Solar Assessment via Multimodal Vision, Interactive 3D Spatial Modeling, and Competitive Bidding Marketplace

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ABSTRACT
The Intelligent Sustainable Energy Solution (ISES) is an advanced artificial intelligence platform specifically designed to revolutionize and streamline the residential and small-commercial solar energy adoption ecosystem in Pakistan. The conventional process of installing photovoltaic (PV) solar systems in developing nations suffers from severe inefficiencies, including manual and error-prone electrical load calculations, inadequate rooftop physical assessments, opaque vendor pricing, and incorrect sizing of solar inverters, battery storage, and panel arrays. ISES addresses these multi-faceted challenges by providing a unified, data-driven digital platform integrating real-time energy load profiling, computer vision rooftop image analysis via Google Gemini Vision API, WebGL/Three.js-driven interactive 3D spatial visualization, and a transparent competitive bidding vendor marketplace.

Users input basic spatial and load specifications, including appliance usage parameters, property structural types, geographical coordinates, and rooftop orientation. The platform's Gemini Vision AI engine analyses uploaded rooftop images to automatically detect physical obstructions—such as concrete water tanks, staircase mumties, parapet walls, skylights, nearby building shadows, and vegetation—mapping out dead zones and isolating precise usable surface areas. Based on these spatial constraints and localized solar irradiance data, ISES calculates optimal system capacities, required panel counts, azimuth angles, and 25-degree south-facing tilt angles. Furthermore, an interactive 3D digital twin of the proposed installation allows users to preview equipment layouts prior to physical deployment. An integrated multi-vendor marketplace connects users with verified installers, facilitating transparent quote comparison and eliminating price monopolies. Managed by an enterprise backend architecture built on ASP.NET Core and SQL Server, ISES bridges the gap between technical complexity and user decision-making, accelerating clean energy adoption in South Asia.

General Terms
Artificial Intelligence, Computer Vision, Photovoltaic System Design, 3D Spatial Modeling, Vendor Marketplace, Sustainable Energy Systems.

Keywords
Sustainable Energy, Solar Photovoltaics, Gemini Vision API, Artificial Intelligence, 3D Spatial Visualization, Computer Vision, Load Profiling, Vendor Marketplace.

1. INTRODUCTION
Over the past decade, the global energy paradigm has witnessed an aggressive shift toward renewable energy sources, driven by the depletion of fossil fuel reserves and the accelerating threat of global climate change. In developing nations like Pakistan, this transition is not merely an environmental obligation but an urgent socio-economic necessity. Rapid urbanization, population expansion, and an increasing reliance on high-power residential electric appliances have pushed the national electrical grid to its operational limits. Consequently, consumers face severe grid instability, frequent scheduled load shedding, and escalating utility tariffs. Photovoltaic solar energy presents an abundant, clean, and economically viable alternative given Pakistan's geographic positioning within a high solar irradiance belt receiving over 5 to 6 peak sun hours per day.

Despite clear environmental and financial incentives, domestic solar adoption remains severely hindered by significant technical, physical, and commercial market barriers. Designing a residential solar system requires precise integration of electrical engineering parameters (peak load, continuous load, power factor, battery discharge rates) and structural spatial conditions (roof weight-bearing capacity, surface area, orientation, shading profiles). The average homeowner lacks the technical literacy required to make informed decisions regarding panel wattage, hybrid versus off-grid inverters, battery chemistry, and structural mounting.

Currently, consumers must rely on local solar vendors for site assessments and bill-of-materials (BOM) estimates. This creates a severe market information asymmetry. Unscrupulous vendors frequently provide inaccurate system sizing—either under-sizing systems leading to operational overload or over-sizing systems to inflate profit margins. Furthermore, physical rooftop conditions in urban Pakistani residential architectures present severe installation hurdles. Roofs are rarely wide, unobstructed open spaces; instead, they feature complex architectural anomalies including concrete overhead water storage tanks, elevated staircase enclosures (mumties), boundary walls, AC outdoor units, clotheslines, skylights, and shading from adjacent multi-story structures. Partial shading caused by these obstructions severely degrades PV array power output due to mismatch losses across series-connected solar cell strings.

To eliminate these systemic operational bottlenecks, this paper proposes the Intelligent Sustainable Energy Solution (ISES). ISES is a comprehensive, data-driven web platform designed to automate the entire solar journey from initial site audit to vendor installation management. By combining multimodal artificial intelligence (Google Gemini Vision API), physical load profiling, Three.js 3D web rendering, and an enterprise multi-vendor marketplace, ISES provides residential users with objective, highly accurate, and transparent solar installation blueprints.

2. LITERATURE REVIEW & RELATED WORK

To establish the theoretical and technological foundation of the ISES framework, we benchmarked existing global platforms, software tools, academic methodologies, and regional calculators across key functional parameters.

Global consumer-facing platforms such as Google Project Sunroof leverage high-resolution satellite imagery and machine learning to analyze roof geometry, solar exposure, and estimated financial savings. While Project Sunroof excels at macro-level spatial estimation, it lacks detailed internal household appliance profiling and does not account for localized urban rooftop anomalies prevalent in South Asian architecture.

In the professional engineering domain, software suites like PV*SOL Online and Aurora Solar offer highly sophisticated ray-tracing, dynamic shading simulation, and automated 3D modeling from high-definition aerial photography. However, these tools are tailored for commercial installers and solar engineers rather than end-user consumers, requiring high technical expertise and costly subscription models.

In terms of commercial matchmaking, platforms such as EnergySage Solar Marketplace have demonstrated the efficacy of open vendor bidding in reducing residential capital expenditure by up to 20% by breaking localized vendor monopolies. Locally in Pakistan, regional tools such as Reon Energy offer basic localized calculators; however, they rely entirely on manual text inputs without automated visual roof parsing or 3D spatial layout generation.

Recent academic research emphasizes the integration of AI models for photovoltaic management. Neural network architectures, including Artificial Neural Networks (ANN), Deep Reinforcement Learning (DRL), Convolutional Neural Networks (CNN), and Long Short-Term Memory (LSTM) networks, have been widely investigated for Maximum Power Point Tracking (MPPT) under partial shading conditions, short-term irradiance forecasting, and battery storage charge-discharge optimization. Furthermore, recent advancements in Weightless Neural Networks (WiSARD) and vision transformer edge compute demonstrate high accuracy in real-time fault detection and spatial obstacle recognition from RGB images.

2.1 Comparative Analysis Matrix

Table 1 provides a systematic comparative evaluation of existing literature, global platforms, local software, and the proposed ISES architecture across key operational capabilities.

Table 1. Comparative analysis matrix aligning ISES against established solutions across structural system parameters and location performance metrics.

S. No	System / Literature Work	User Input	Appliance Selection	Upload Image	AI Implemented	AI Suggestion (Dead/Usable)	Roof Status	Solar Zone	Peak Hours	Daily/Monthly Gen.
1	Google Project Sunroof	✓	✗	✗	✓	✓	✓	✓	✓	✓
2	PV*SOL Online	✓	✓	✗	✗	✗	✗	✓	✓	✓
3	Aurora Solar	✓	✓	✗	✓	✓	✓	✓	✓	✓
4	EnergySage Solar Marketplace	✓	✓	✗	✗	✗	✗	✗	✗	✓
5	Reon Energy	✓	✓	✗	✗	✗	✗	✗	✗	✓
6	AI Optimization Review	✗	✗	✗	✓	✓	✗	✓	✓	✓
7	DRL Energy Management	✓	✓	✗	✓	✗	✗	✗	✗	✓
8	Deep Learning Forecasting	✗	✗	✗	✓	✗	✗	✓	✓	✓

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S. No	System / Literature Work	User Input	Appliance Selection	Upload Image	AI Implemented	AI Suggestion (Dead/Usable)	Roof Status	Solar Zone	Peak Hours	Daily/Monthly Gen.
	Study									
9	LSTM Smart Grid Efficiency Research	✗	✗	✗	✓	✗	✗	✓	✓	✓
10	RL Utilization Review	✗	✗	✗	✓	✗	✗	✗	✗	✗
11	Macroeconomic AI Assessment	✗	✗	✗	✗	✗	✗	✗	✗	✗
12	Explainable AI Irradiance Study	✗	✗	✗	✓	✗	✗	✓	✓	✓
13	PV Applications Review	✗	✗	✗	✓	✓	✓	✓	✓	✓
14	ANN MPPT Optimization	✗	✗	✗	✓	✗	✗	✗	✗	✓
15	Shading Mitigation Study	✗	✗	✗	✓	✓	✓	✓	✓	✓
16	Weightless Neural Network Tracking	✗	✗	✓	✓	✓	✓	✗	✗	✗
17	OUR SYSTEM (ISES)	✓	✓	✓	✓	✓	✓	✓	✓	✓

3. PROPOSED MODEL & SYSTEM ARCHITECTURE

The Intelligent Sustainable Energy Solution (ISES) architecture is structured as an enterprise-grade multi-layer web application. The core backend relies on ASP.NET Core managing application logic, security protocols, API orchestrations, and data pipelines interacting with a relational SQL Server database.

The platform execution workflow encompasses four core technical modules:

Intelligent Load Profiler: Computes baseline and realistic power requirements based on user appliance counts, standard wattages, operational hours, power factors, and diversity coefficients. It calculates continuous versus surge loads to determine appropriate inverter kW ratings and battery storage Amp-hour requirements.

Multimodal Computer Vision Engine (Google Gemini Vision API): Analyzes user-uploaded high-resolution rooftop and surrounding context photographs. Using custom structured JSON prompting, Gemini Vision identifies architectural obstructions (concrete water tanks, stair rooms, pillars, adjacent building shadows, trees, skylights), calculates unusable "Dead Area" percentages, computes remaining net "Usable Area", and assesses overall roof space suitability.

3D Scene Orchestration Module (Three.js & WebGL): Converts dimensional data and AI obstacle boundaries into an interactive 3D digital twin rendered directly within the browser. The system automatically places solar panel arrays in clear zones, angling them at an optimal 25° south-facing tilt tailored for Pakistani geographical latitudes.

Bidding Marketplace & Documentation Engine: Packages technical findings into a verified PDF audit report using html2pdf.js, which is pushed to accredited local solar vendors for competitive quotation submission.

3.1 System Operational Workflow

Figure 1 illustrates the end-to-end data and process flow within the ISES platform across all system layers.

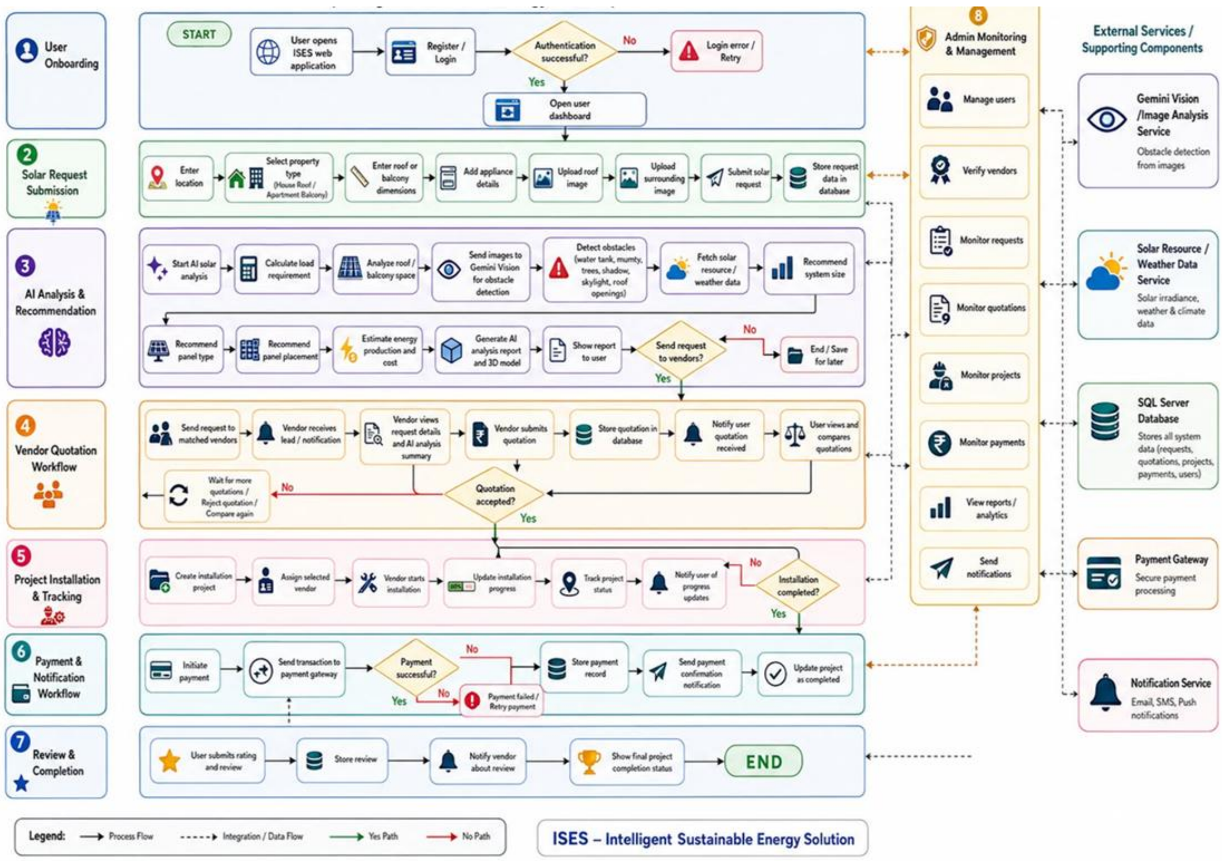

Fig 1: ISES Operational Workflow Diagram

[A comprehensive 7-stage architectural workflow detailing: (1) User Onboarding & Authentication, (2) Solar Request Submission, (3) AI Vision Analysis & Load Recommendation Engine, (4) Vendor Quotation Workflow, (5) Project Installation & Tracking, (6) Payment Gateway Integration, and (7) Admin Management & System Analytics.]

4. USE CASE SPECIFICATIONS

Figure 2 outlines the Unified Modeling Language (UML) Use Case Diagram depicting interactions between primary actors (User/Customer, Vendor, Admin) and external cloud services (Gemini Vision API, Solar Data Service, Maps API, Payment Gateway, Notification Engine).

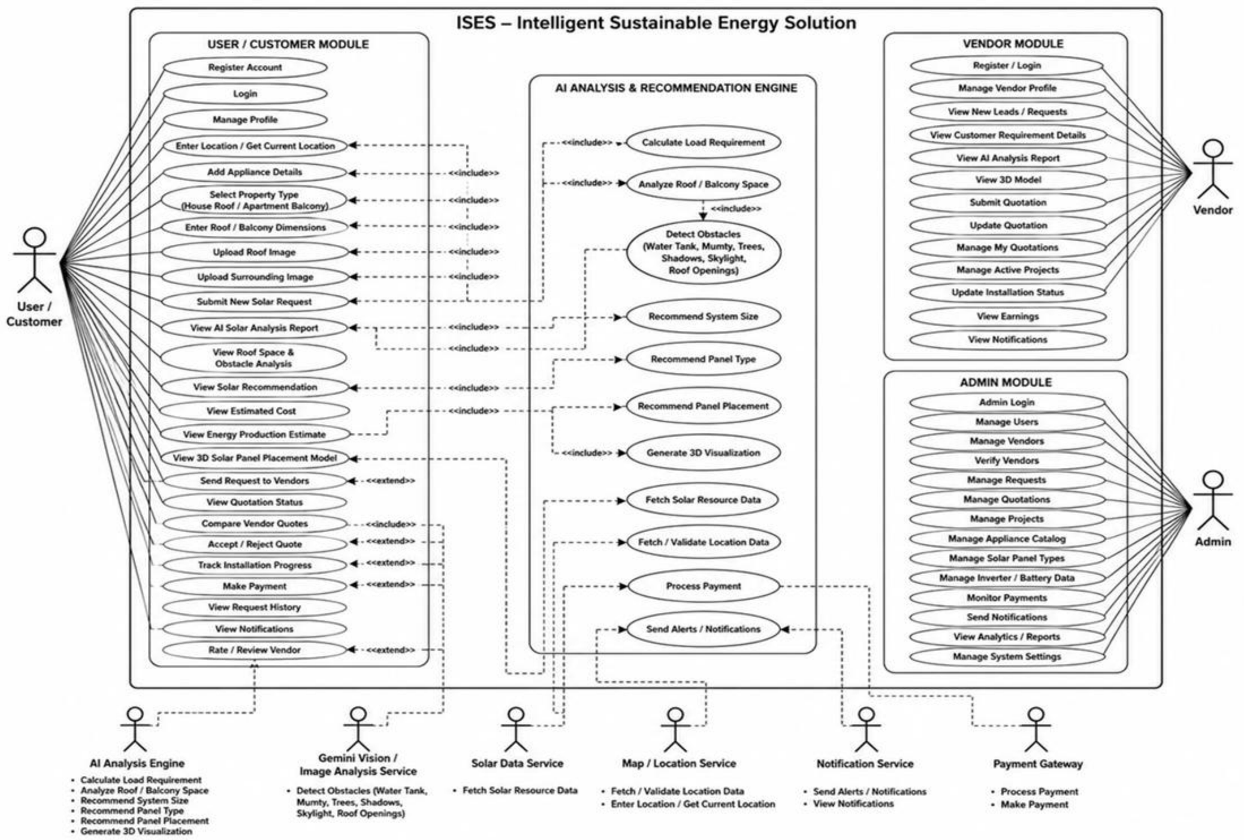

Fig 2: ISES Architecture Use Case Diagram

[Diagram detailing boundaries across User Module, Vendor Module, Admin Module, and the central AI Analysis & Recommendation Engine.]

4.1 Detailed User Module Use Cases

Use Case ID	UC-U01
Use Case Name	User Login
Primary Actor(s)	End User
Description	A registered user accesses the ISES platform using valid credentials or Google OAuth.
Preconditions	The user must possess an active, registered user account.
Main Flow	1. User enters registered email and password. 2. System validates credentials against SQL database. 3. System identifies role and instantiates authenticated HTTPS session. 4. User is redirected to the End User Dashboard.
Alternative Flow	1. Invalid credentials trigger an error alert. 2. Deactivated accounts display contact admin prompts.

Use Case ID	UC-U02
Use Case Name	View User Dashboard

Primary Actor(s)	End User
Description	Displays real-time overview of active requests, vendor bids, project statuses, and system alerts.
Main Flow	1. Fetch user solar requests. 2. Display statistical counters (Pending, Active, Completed). 3. Render quotation status feed and recent activity logs.

Use Case ID	UC-U03
Use Case Name	Create New Solar Request
Primary Actor(s)	End User
Description	User submits property dimensions, location, appliance inventories, and rooftop photographs.
Main Flow	1. User selects property type (House Roof / Apartment Balcony). 2. User inputs roof length, width, floor count, orientation. 3. User inputs appliance quantities (Inverter ACs, pumps, fans, lights). 4. User uploads high-resolution rooftop and context site photos. 5. Payload is sent to backend for AI processing.

Use Case ID	UC-U04
Use Case Name	Calculate Appliance Load
Primary Actor(s)	End User; Solar AI Engine
Description	Calculates base electrical load, realistic operational load, and recommended system kW rating.
Main Flow	1. Fetch wattage specs for selected appliances. 2. Multiply wattage by quantity and usage hours. 3. Apply diversity and power factor loss multipliers. 4. Output recommended kW capacity, panel count, and battery backup sizing.

Use Case ID	UC-U05
Use Case Name	Analyze Roof or Balcony Images
Primary Actor(s)	End User; AI Vision Service (Gemini API)
Description	Executes computer vision segmentation on uploaded images to isolate dead areas and usable surface space.
Main Flow	1. Transmit image payload to Gemini Vision API. 2. Detect water tanks, mumties, pillars, skylights, nearby building shadows. 3. Compute percentage dead area and net usable square footage. 4. Generate structural placement guidance and tilt recommendations.

Use Case ID	UC-U06
Use Case Name	View Solar Analysis Result
Primary Actor(s)	End User
Description	Displays comprehensive technical metrics including system capacity, daily generation, and ROI estimates.
Main Flow	1. Render load metrics (e.g., 3750W load requiring 4kW system). 2. Display required panel count (e.g., 8 x 550W panels). 3. Show local solar zone data (e.g., Karachi Coastal Zone, 5.65 peak hours/day, 19.39 kWh daily generation).

Use Case ID	UC-U07
Use Case Name	View 3D Solar Visualization
Primary Actor(s)	End User
Description	Renders an interactive Three.js 3D model of the user's roof with installed panels, mounting structures, and wiring.
Main Flow	1. Generate 3D roof canvas based on dimensions. 2. Place detected obstacles in precise coordinate space. 3. Mount virtual solar panels at 25° south-facing tilt angle. 4. Provide interactive rotation, panning, and zoom controls.

Table 2. Summary of Additional User Module Use Cases

ID	Use Case Name	Summary & Main Actions
UC-U08	Send Request to Vendors	Publishes verified technical analysis report to marketplace lead pool for vendor bidding.
UC-U09	Compare Vendor Bids	Side-by-side comparison matrix evaluating vendor quotes by price, inverter/panel brands, and warranties.
UC-U10	View Notifications	Fetches real-time alert logs regarding bid arrivals, project status updates, and admin notices.
UC-U11	Download Solar Report	Generates downloadable multi-page PDF summary detailing audit findings via html2pdf.js.
UC-U12	View Market Analysis	Displays current retail market trends for panels, inverters, and lithium battery storage equipment.
UC-U13	User Logout	Terminates authenticated session token and clears client state.

4.2 Detailed Vendor Module Use Cases

Table 3. Vendor Module Use Cases

Use Case ID	Use Case Name	Operational Description
UC-V01	Vendor Login	Authenticates registered solar installer credentials and verifies corporate KYC status.
UC-V02	View Vendor Dashboard	Displays active lead metrics, submitted proposal statuses, won projects, and total earnings.
UC-V03	View Available Leads	Browses public user solar requests filtered by geographic proximity and system size.
UC-V04	View Lead Details & 3D Model	Inspects user load profile, AI roof obstacle analysis, and interactive 3D layout prior to quoting.
UC-V05	Submit Quotation	Enters itemized pricing, panel/inverter brand selections, labor costs, and warranty terms.
UC-V06	Manage Active Projects	Updates milestone progress (e.g., Structure Mounting, Electrical Wiring, Inverter Commissioning).
UC-V07	Dispute & Communication	Exchanges direct project messages with customers and logs compliance records for admin review.

5. SYSTEM IMPLEMENTATION RESULTS & INTERFACE ANALYSIS

The operational prototype of ISES was implemented and evaluated across multiple residential scenarios in Karachi, Sindh. The user interface and technical outputs are demonstrated in the following modules.

5.1 User Authentication & Landing Experience

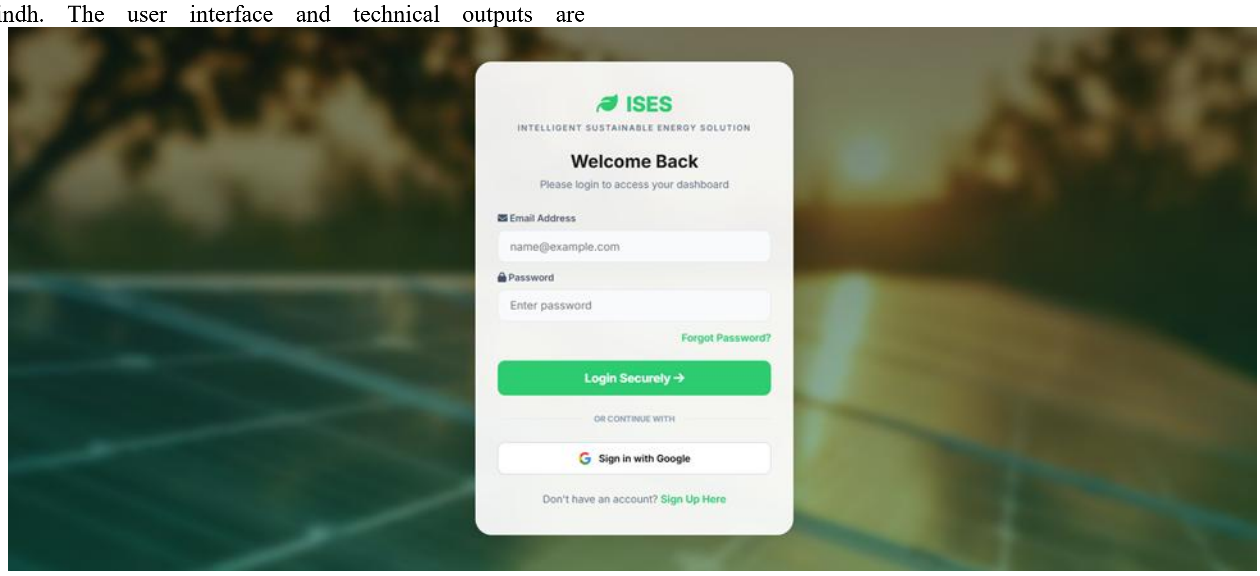

Fig 3: Secure User Login Interface

[Responsive authentication portal providing dual options for standard email/password credentials and Google Single Sign-On (SSO).]

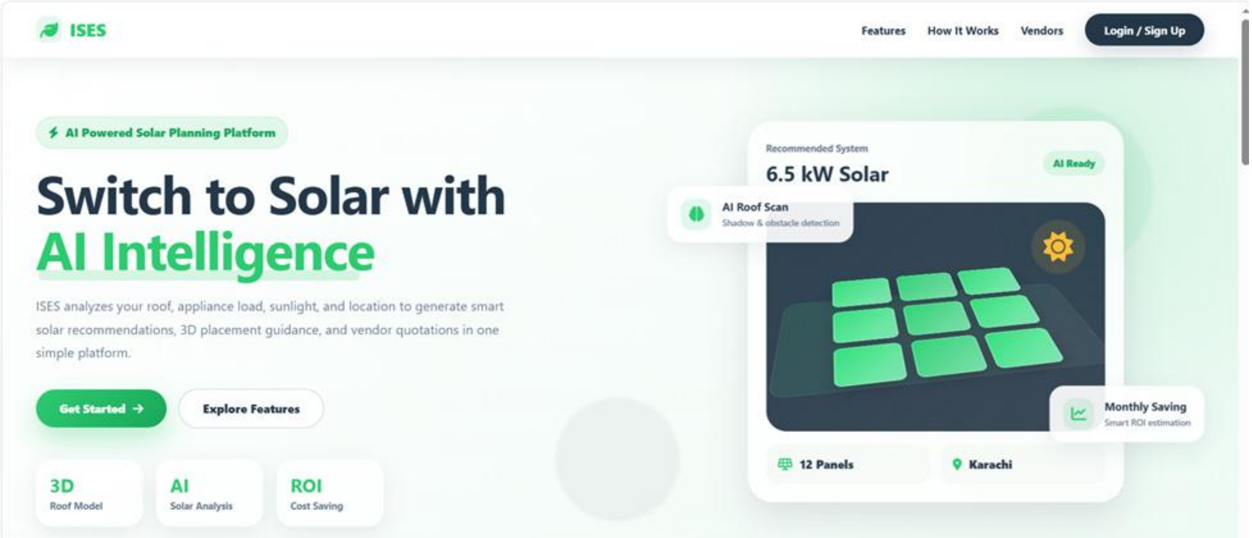

Fig 4: ISES Platform Landing Page

[Public landing interface introducing key features: AI 3D Rooftop Modeling, Automated ROI Calculations, and Competitive Multi-Vendor Marketplace.]

5.2 AI Roof Analysis & Performance Output Modules

When a user inputs their appliance load and uploads site photographs, the system executes combined computer vision and load estimation algorithms. The generated outputs are illustrated below:

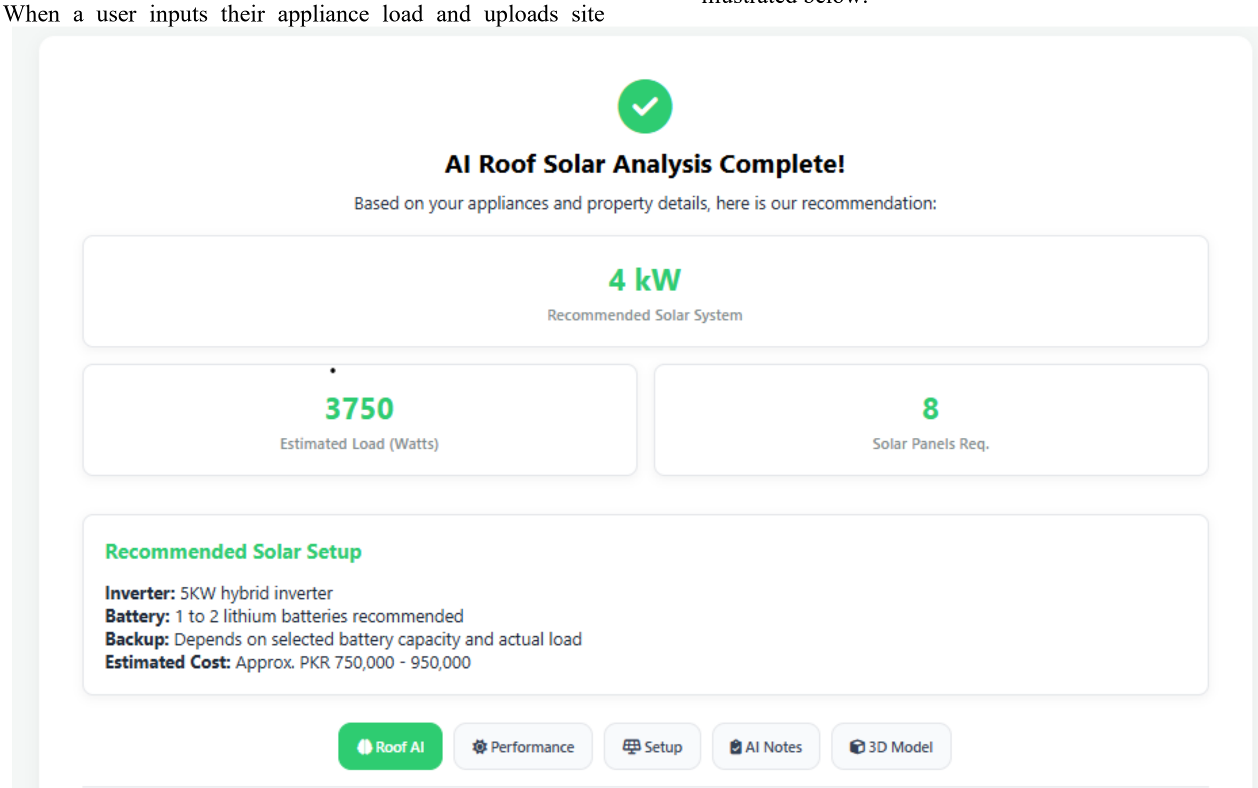

Fig 5: AI Roof Solar Analysis Overview

[Primary output card displaying recommended system capacity (4 kW), estimated continuous load (3750 Watts), required panel count (8 Panels), hybrid inverter rating (5 kW), lithium battery specs, and overall system cost estimate (PKR 750,000 - 950,000).]

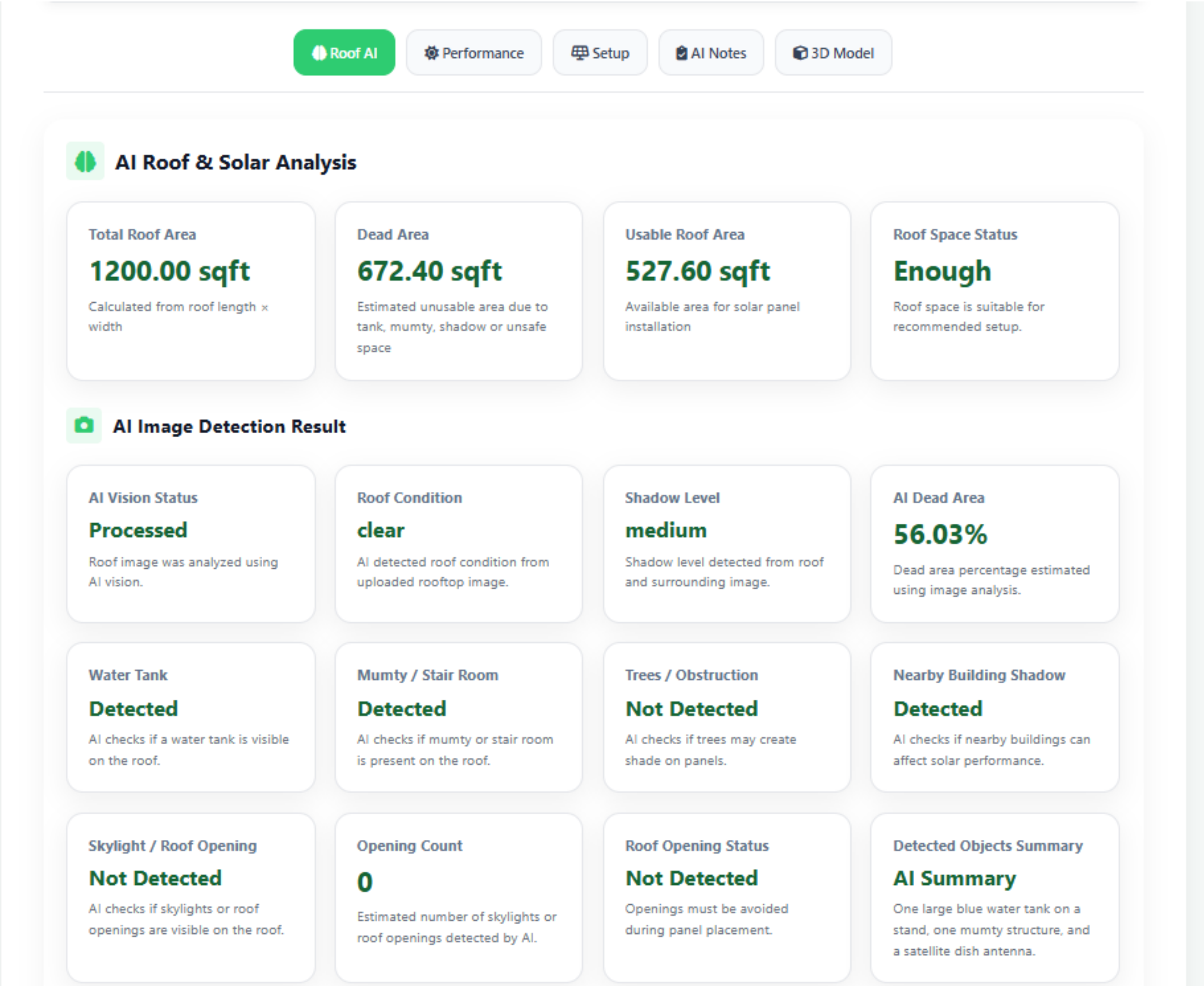

Fig 6: AI Image Detection & Surface Area Results

[Detailed computer vision breakdown showing Total Roof Area (1200.00 sqft), AI-calculated Dead Area (672.40 sqft / 56.03%), Net Usable Area (527.60 sqft), and detected structural obstacles (Water Tank: Detected, Mumty/Stair Room: Detected, Nearby Building Shadow: Detected, Skylight: Not Detected).]

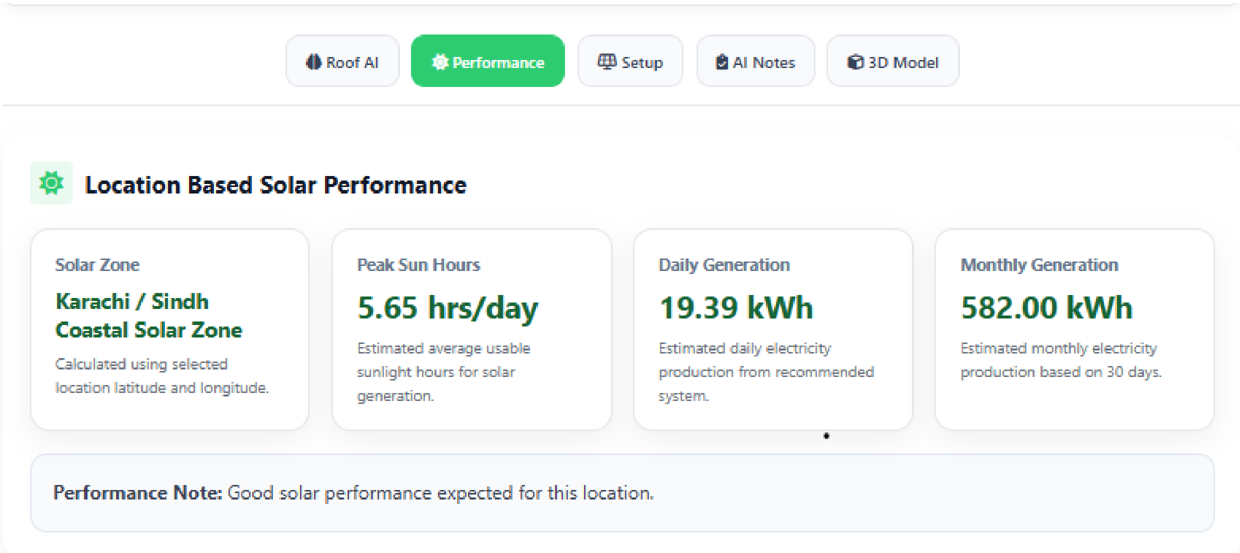

Fig 7: Location-Based Solar Performance Metrics

[Geospatial radiation analysis panel indicating location solar zone (Karachi / Sindh Coastal Solar Zone), Peak Sun Hours (5.65 hrs/day), Daily Generation Output (19.39 kWh), and Monthly Estimated Generation (582.00 kWh).]

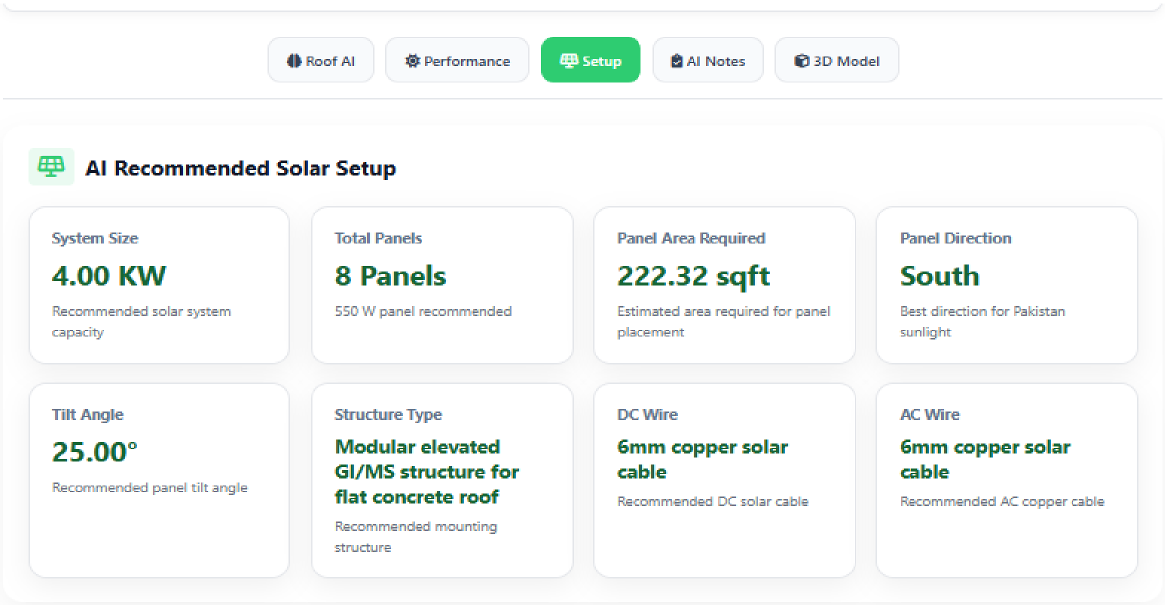

Fig 8: AI Recommended Solar Setup Specifications

[Hardware engineering specification breakdown showing required panel area (222.32 sqft), optimal facing direction (South), recommended tilt angle (25.00°), mounting structure type (Modular elevated GI/MS frame), and DC/AC cable standards (6mm copper solar cable).]

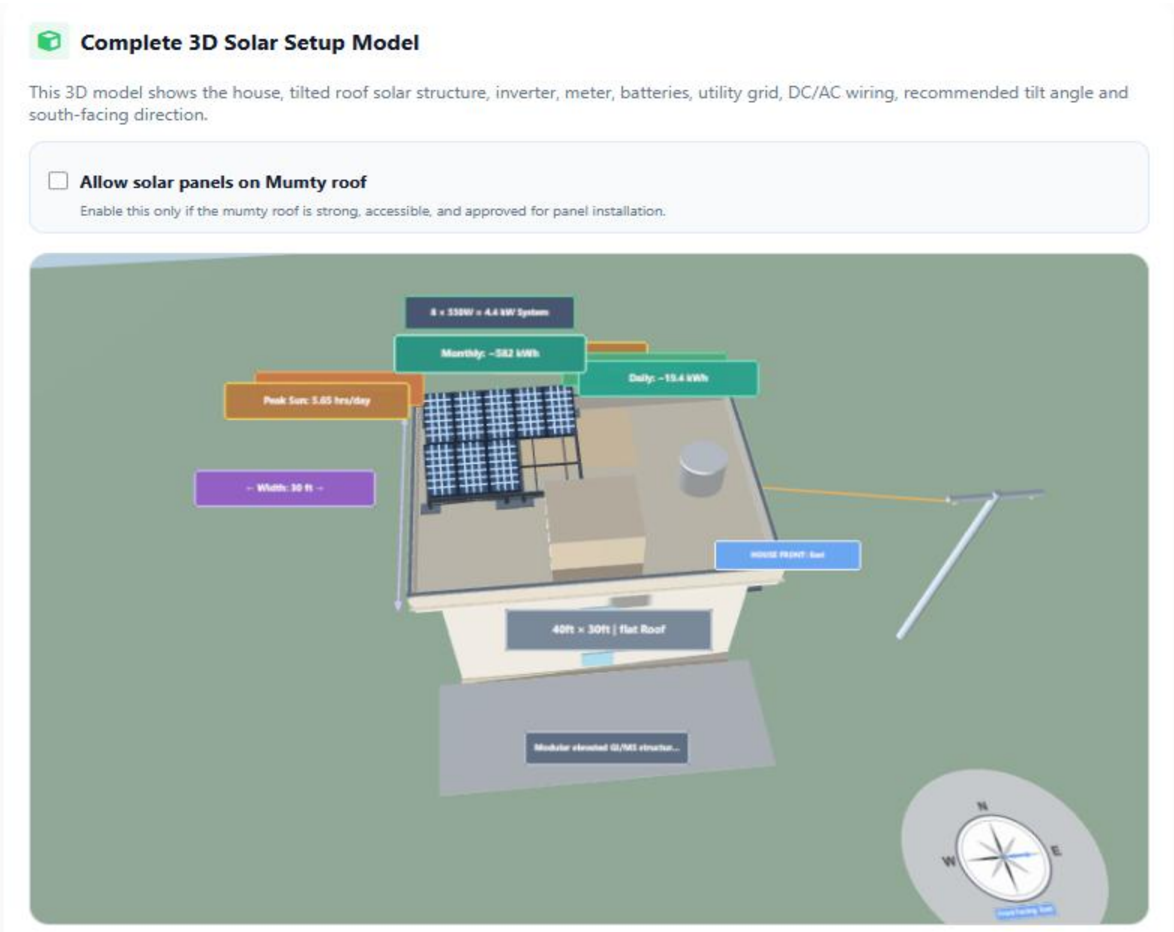

Fig 9: Interactive 3D Digital Twin Solar Model

[WebGL Three.js canvas rendering a 1:1 scale digital twin of the residential building, displaying placed solar panel arrays at 25° tilt, elevated mounting structures, mumty position, inverter/battery placement, utility pole wiring, and real-time compass orientation.]

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5.3 Property Submission & Vendor Marketplace Modules

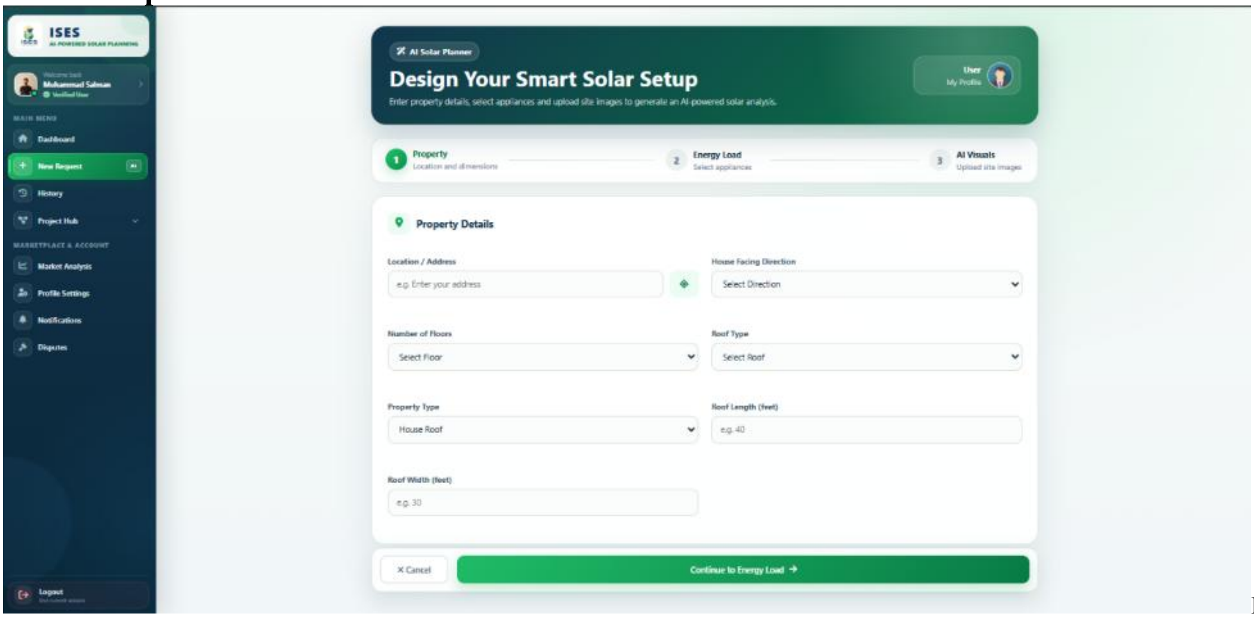

Fig 10: Property Details Entry Interface

[Multi-step request wizard capturing address, house orientation, floor count, roof type, and precise length/width dimensions.]

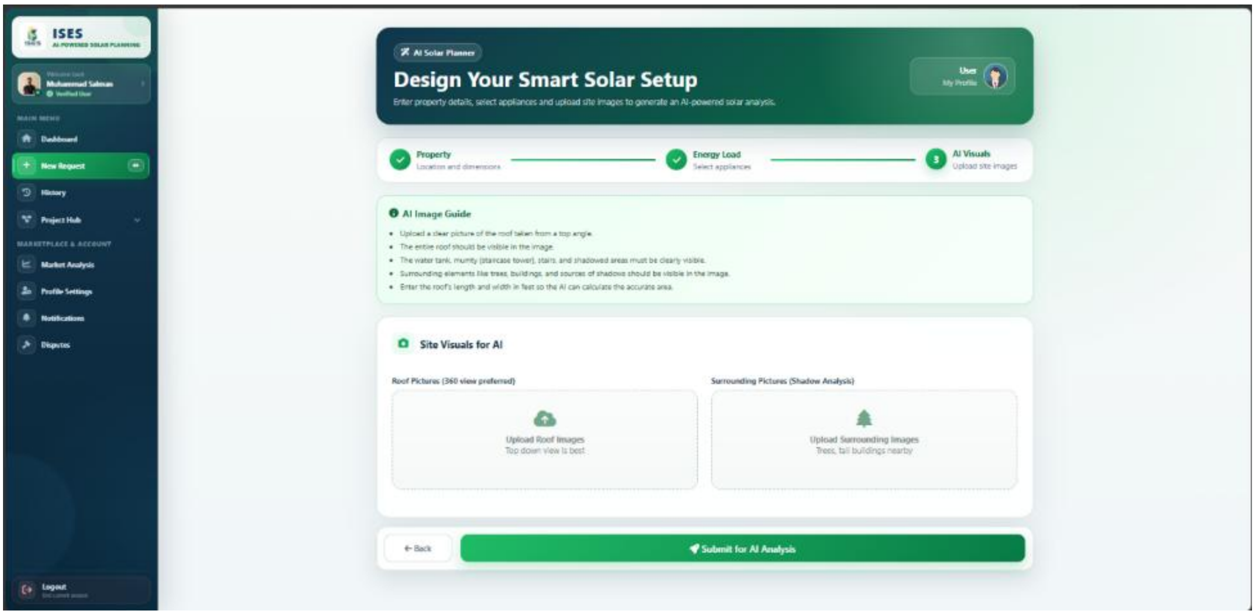

Fig 11: AI Visuals Upload Interface

[Drag-and-drop file upload interface equipped with automated image format validation and visual guidance criteria.]

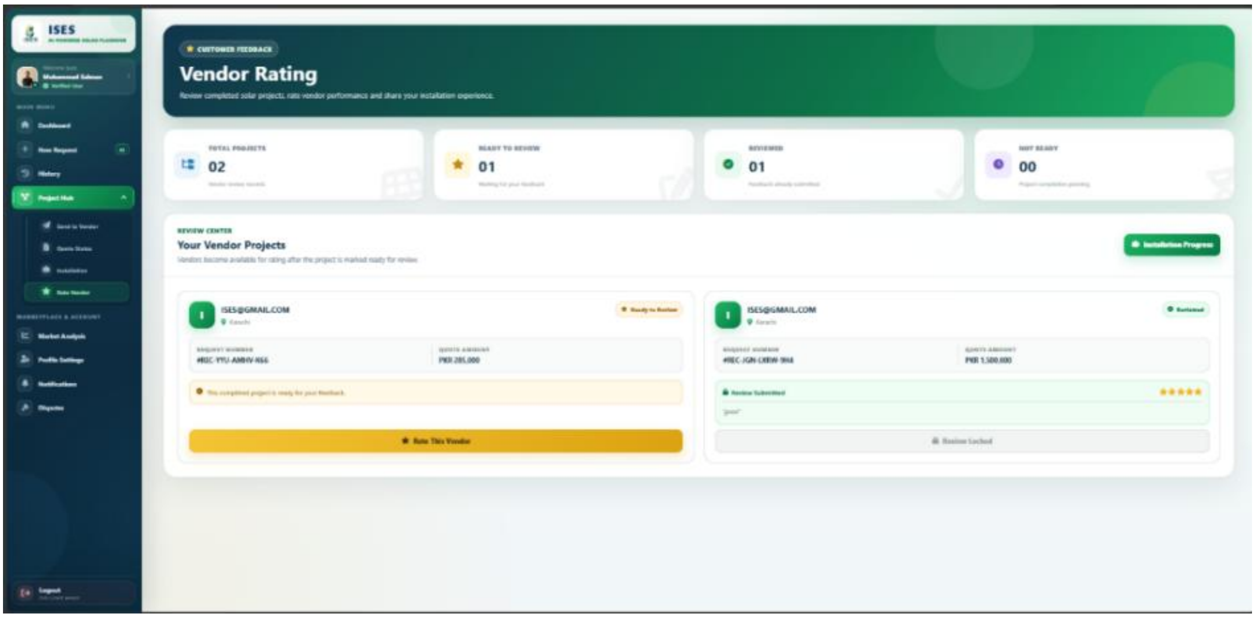

Fig 12: Installation Area Selection & Vendor Matchmaking

[Geographic map interface allowing users to pin installation coordinates and filter verified installers by proximity, reviews, and past ratings.]

6. CONCLUSION & FUTURE WORK

The Intelligent Sustainable Energy Solution (ISES) presents a robust, holistic, and scalable software framework that directly addresses the long-standing challenges of residential solar adoption in Pakistan. By bridging the gap between high technical complexity and end-user decision-making, ISES eliminates predatory vendor pricing, manual calculation errors, and improper array sizing. The integration of multimodal AI (Google Gemini Vision) for rooftop obstacle detection, deterministic electrical load engineering algorithms, WebGL 3D rendering, and a multi-vendor marketplace establishes a transparent digital ecosystem.

Experimental prototype deployments demonstrate high user engagement and significant improvements in system sizing precision. While ISES acts as an advisory and spatial planning tool rather than a substitute for final physical site engineering validations, it drastically reduces entry barriers for homeowners. Future work will focus on integrating drone-based high-resolution photogrammetry, expanding real-time weather API feeds for continuous power prediction, and integrating automated net-metering application tracking with national utility providers.

7. ACKNOWLEDGMENTS

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