Applied Energy 426 (2026) 128620

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A GIS-MCDA method for renewable energy prosumer integration in road construction compound siting: development, demonstration, and evaluation

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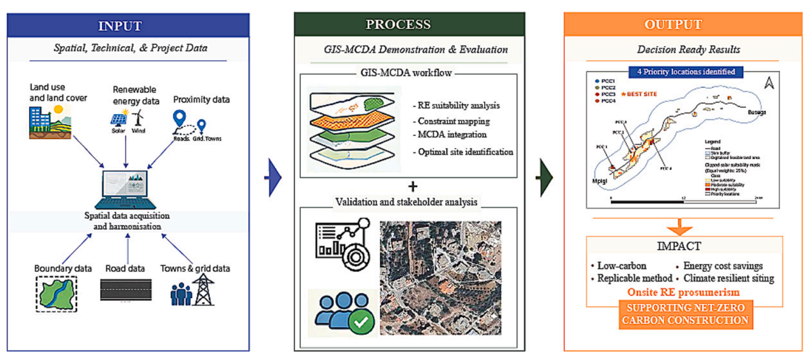
HIGHLIGHTS

- Transferable GIS-MCDA method for RE-integrated road construction compound siting.
- Optimal energy yields (+120 MWh/yr) and ~84 tCO_2 savings annually.
- Robust results confirmed across multiple weighting scenarios.
- High stakeholder acceptance and adoption readiness; barriers are transitional.
- Extension of prosumerism into temporary project-based contexts.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Construction compounds
GIS-MCDA
Renewable energy
Road infrastructure
Prosumer
Net zero carbon construction

ABSTRACT

The global transition to renewable energy (RE) is essential for sustainable development and climate change mitigation. However, integrating RE into road construction remains largely overlooked in both research and practice. Construction compounds—operational hubs for road projects, are energy-intensive; yet their siting is typically based on logistics, cost, and regulatory considerations, with minimal attention to onsite RE potential. This study develops, demonstrates, and evaluates a Geographic Information Systems-Multi-Criteria Decision Analysis (GIS-MCDA) method to identify optimal construction compound locations supporting RE prosumption, using Uganda's Busega–Mpigi Expressway as a case study. The method integrates constraint mapping with solar and wind suitability modelling using Weighted Linear Combination (WLC). Wind conditions (0.1–3.8 m/s; <4 m/s threshold) were infeasible, while solar analysis identified four priority construction compound locations (PCC1–PCC4), with PCC3 performing best, reflecting a distribution of 75% low, 21% moderate, and 4% high suitability classes. Sensitivity analysis confirmed robust spatial rankings across alternative weighting scenarios. Comparison with the existing compound revealed a recoverable energy gap of 8.3%, increasing annual output by ~120 MWh, yielding USD 42,000–48,000 savings and ~ 84 tCO_2/year avoided emissions. Stakeholder evaluation using the Technology Acceptance Model (TAM) showed strong intention to adopt (4.50/5.0) and support for

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https://doi.org/10.1016/j.apenergy.2026.128620
Received 1 May 2026; Received in revised form 16 July 2026; Accepted 2 August 2026
Available online 7 August 2026
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construction-phase prosumerism (4.45/5.0). Barriers including skills deficits, institutional fragmentation, and high capital costs, are transitional and addressable through training, coordination, and procurement reform. Overall, the study contributes a transferable spatial method for RE-informed compound siting, extends prosumer theory to temporary project-based infrastructure, and supports low-carbon construction in Sub-Saharan Africa and comparable contexts.

1. Introduction

Climate change mitigation has heightened the global urgency to reduce dependence on fossil fuels across all sectors, with the infrastructure sector emerging as a critical area of intervention. Road construction is among the most energy-intensive activities within the broader infrastructure sector and contributes significantly to carbon emissions, accounting for up to 85% of a road's whole lifecycle emissions [1]. In response, the concept of Net Zero Carbon Construction (NZCC) has gained prominence as a framework for aligning construction practices with global decarbonisation targets, yet it remains elusive especially in road projects. Even under carefully optimised mitigation scenarios, residual emissions of approximately 10–30% persist across the project lifecycle [2]. Strategies such as low-carbon materials substitution (2–12% emissions reduction), optimised fleet management (8.1% reduction), and biofuel substitution (up to 86% reduction), each deliver incremental improvements, but do not close this gap [3]. The integration of RE offers a more promising pathway by reducing construction dependence on fossil fuels. For example, in Australia, an electric concrete pumping solution powered by RE achieved zero operational emissions and reduced energy consumption by 67% [4]. Despite such successes, RE adoption in construction remains limited, largely project-specific, and rarely embedded within systemic planning processes, constrained by the absence of frameworks that consider energy at early project planning.

The prosumer model offers a conceptual pathway for integrating RE within construction. First coined by Toffler [5] and later developed in the energy literature [6,7], a prosumer generally refers to an entity that both produces and consumes energy—typically through on-site RE generation via solar photovoltaics (PV) or wind turbines, and where possible, supplies excess generation to nearby users or the wider grid [7]. Such prosumer systems are commonly implemented through RE microgrids, which integrate distributed generation, energy storage, and control technologies to manage local electricity supply and demand while operating either independently or in conjunction with the main grid [8]. Under this model, construction sites can transition from passive energy consumers into active participants in decentralised energy systems—an opportunity particularly suited to road construction, where corridors often traverse large, open, topographically varied landscapes with considerable solar and wind potential. Onsite generation could allow sites to meet their own demand while supplying surplus electricity to surrounding communities or national grids [8]. Given the scale and continuous pipeline of global infrastructure development, with transport investment in Sub-Saharan Africa (SSA) alone projected to exceed $130 billion annually in the period 2020–2040 [9], construction sites collectively represent a substantial, currently underutilised opportunity for distributed RE generation.

To date, microgrid applications have largely focused on residential, commercial, and community-scale settings [8,10], and their application to infrastructure projects—particularly temporary road construction operations characterised by high energy demands and significant RE integration potential, remains limited. However, comparable temporary and remote environments have demonstrated their feasibility. Military forward operating bases (FOBs), for example, have deployed hybrid microgrids combining solar PV, wind, diesel generation, and battery storage to support mission-critical loads under temporary and off-grid conditions [11,12], while disaster-relief and refugee camps have adopted modular solar microgrids to provide rapid, scalable, and resilient emergency power [13,14]. Similarly remote mining operations, particularly in Australia, have also implemented hybrid RE microgrids to reduce dependence on fuel supply chains [15]. Within construction, a notable example is the Sichuan–Tibet Railway project in China, which demonstrated the feasibility of deploying solar PV and battery storage microgrids to supply construction machinery and site facilities during project delivery [16]. Beyond the construction phase, broader applications across transport infrastructure including solar roadways, photovoltaic noise barriers (PVNBs), wind-powered lighting systems, PV-covered highways, and large-scale solar installations along highways, further demonstrate the potential for infrastructure systems to function as distributed energy assets [17–20]. However, these applications remain largely concentrated on permanent infrastructure or post-construction operations, leaving the planning of temporary construction compounds for RE prosumption largely unexplored.

One underexplored enabler of this transition is the siting of construction compounds. As temporary but operationally central facilities, construction compounds serve as logistical and energy hubs for road projects, accommodating machinery, workforce facilities, batching plants, and site offices throughout the construction phase. Despite their importance, compound siting decisions are made almost exclusively based on distance from the longitudinal mid-point of the road, land acquisition costs, regulatory compliance, and community relations, with energy supply typically treated as an operational afterthought rather than a strategic location determinant. This results in continued reliance on grid electricity and/or diesel generators, and represents a significant structural gap, as compound locations are established early in the project lifecycle and are rarely altered once operations commence. Neglecting RE potential at the siting stage therefore forecloses opportunities for construction-phase energy transition, since later integration often requires substantial logistical and financial adjustments. This challenge can be examined through socio-technical transitions (STT) theory—large-scale, co-evolutionary changes in energy systems, technologies, and daily societal practices [21], which researchers have approached through multiple lenses, including socio-technical, techno-economic, socio-ecological, and political-institutional [22–24]. This study adopts the STT theory, which frames transitions not merely as the adoption of new technologies but as broader systemic changes involving interactions between technological innovation, institutions, policies, economic structures, and social practice [21]. Road construction projects are thus viewed as STT systems comprising project actors, technologies (construction machinery and energy systems), and broader institutional structures, including environmental policies, land-use regulations, and energy markets.

Recent studies identify prosumerism as a core element of STT, shaped by the dynamic interplay of technological innovation, policy, behavioural change, and institutional arrangements [25,26]. In this context, RE-integrated construction compounds can be viewed as transition niches where prosumer-based energy systems are trialled and refined under real project conditions, and were successful, scaled to influence broader construction practice. Accordingly, this study reconceptualises construction compounds as temporary yet strategic distributed energy nodes (decentralised RE hubs), capable of generating and supplying electricity for construction operations while potentially contributing surplus energy to nearby communities or the national grid. This reconceptualisation rests on three grounds. First, the substantial and growing scale of global infrastructure investment, valued at approximately $79 trillion by 2040, with transport accounting for the largest share in many low-income regions [9], which presents a continuous pipeline of potential RE generation sites. Second, the operational flexibility and increasing cost competitiveness of modular RE systems centralised power plants, which can be rapidly deployed, scaled to meet the evolving construction energy needs, and relocated after project completion [27]. The declining technology costs (prices for solar PV modules and associated batteries fell by roughly 90% between 2010 and 2023), further enhance the suitability of RE systems particularly in SSA where fuel logistics, grid access, and reliability remain constrained [28,29]. Third, the opportunity to institutionalise RE integration within construction planning processes, such as Environmental and Social Management Plans (ESMPs). This could shift energy integration from an optional contractor-led initiative to a structured component of infrastructure delivery, supporting a move from isolated demonstration projects to systematic adoption.

Achieving this shift requires decision-support approaches that embed RE considerations into compound siting from the earliest planning stages. Multi-Criteria Decision Analysis (MCDA), grounded in decision theory, provides a structured means of simultaneously evaluating alternatives across multiple technical, economic, environmental, and social criteria [30]. When combined with Geographic Information Systems (GIS), it enables spatially explicit and data-driven assessment of RE suitability based on variables such solar irradiation, wind speed, topography, land use, and proximity to infrastructure within a unified analytical framework [31–33]. GIS-MCDA is well established for RE facility siting across diverse geographic and regulatory contexts [32–39]. However, a key methodological gap remains existing GIS-MCDA frameworks are designed predominantly for permanent RE facilities operating under relatively stable environmental, technical, and socio-economic conditions, and are not readily transferable to temporary construction compounds. Construction compounds typically operate over short durations (approximately 2–5 years), require modular, relocatable energy systems, and experience rapidly changing energy demands driven by project sequencing, equipment deployment, and evolving activities [8,40,41]. Suitability is therefore tied to project logistics as much as RE potential, requiring frameworks that also account for operational accessibility, temporary land-use constraints, and construction workflow. This distinct decision context makes existing GIS-MCDA frameworks inappropriate as they stand. Furthermore, stakeholder acceptance of such decision-support approaches within construction planning—particularly in low- and middle-income countries, remains insufficiently examined.

To address this gap, this paper advances a multidisciplinary conceptualisation of RE-informed siting for temporary road construction compounds by integrating insights from three complementary perspectives—STT theory, the prosumer model, and decision theory (GIS-MCDA). STT theory provides the macro-level rationale for repositioning construction compounds as transition niches within the broader system change; the prosumer model defines energy behaviour at the project-level, where compounds act as both consumers and potential producers of RE; and decision theory underpins how project actors balance beliefs, preferences, and operational constraints when selecting compound locations. GIS-based MCDA operationalises these considerations by systematically assessing technical, environmental, logistical, and spatial criteria, serving not only as a technical decision-support tool but also as a spatial governance mechanism aligning project-level decisions with wider NZCC objectives. The Busega–Mpigi Expressway in Uganda serves as a case study, representative of large-scale, multi-year road projects operating in a context of constrained grid reliability, high RE potential, and rapidly increasing infrastructure investment. The proposed approach is compared to prevailing construction compound siting practices, and its suitability for practical adoption is evaluated using the Technology Acceptance Model (TAM). The study is guided by two objectives:

i. To develop and demonstrate a GIS-MCDA method for identifying optimal construction compound locations for RE integration along road corridors; and,
ii. To evaluate the proposed GIS-MCDA method against conventional compound siting practices and assess stakeholder readiness for adoption.

The primary contribution of this paper is methodological: a transferable GIS-MCDA framework for RE-enabled siting of temporary road construction compounds that extends spatial decision-support methods to the unique operational context of temporary infrastructure. By embedding energy performance as an integral locational criterion from the earliest stages of project planning, this study positions construction compound siting as a strategic lever for construction-phase energy transitions—one that has been systematically overlooked yet holds significant potential to advance the NZCC agenda in infrastructure delivery. Specifically, it contributes: (i) a transferable GIS-MCDA method for RE-integrated project-compound siting; (ii) a practical demonstration of the method in a real-world infrastructure project; (iii) an extension of the prosumer concept to temporary project-based contexts; and (iv) TAM-based empirical evidence on adoption readiness from an SSA infrastructure context. By promoting more informed siting of construction project compounds to facilitate on-site RE deployment, the study aligns with SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action), and advances the NZCC agenda. Beyond the project level, the proposed method offers strategic value to policymakers and infrastructure authorities seeking to mainstream RE and prosumer approaches across construction and the wider built environment.

2. Methods

2.1. Study design and approach

This study adopts a Design Science Research (DSR) approach [42,43], which is appropriate when the primary goal is to design a practical, transferable artefact—in this case, a GIS-MCDA site selection method. DSR combines scientific rigour with practical relevance, requiring both the development of the artefact and a demonstration of its functionality and applicability in a real-world context [43]. Within this framework, the study follows a sequential mixed-methods approach with two main phases: development and evaluation. The development phase applies GIS-based spatial analysis alongside MCDA to map constraints, assess RE suitability, and identify the most appropriate locations for construction compounds. This was followed by the evaluation phase, which included a technical site assessment, sensitivity analysis, and a stakeholder-led adoption-readiness analysis. The combination of quantitative and qualitative methods provides a balanced approach that supports robust technical validation and real-world applicability, in line with best practices in applied energy and construction research [44].

2.2. Description of case study

The Busega–Mpigi Expressway is a 23.7 km four-lane dual carriageway that plays a critical role in regional connectivity along the Northern Corridor while reducing traffic congestion in Uganda. It spans three districts in the central region (Fig. 1), commencing at Busega (0.3111°N, 32.5217°E) in Kampala, passing through Wakiso District, and terminating at Mpigi District (0.2274°N, 32.3249°E). The project, which aims to improve mobility and regional connectivity along the Northern Corridor, comprises 13 bridges, four interchanges, four toll plazas, and new link roads. Construction was approximately 45% complete at the time of data collection [45]. This case study was chosen because it is representative of a large-scale, multi-year, energy-intensive project carried out in a high-solar-resource setting with limited grid reliability, and where the road corridor passes through a range of land-

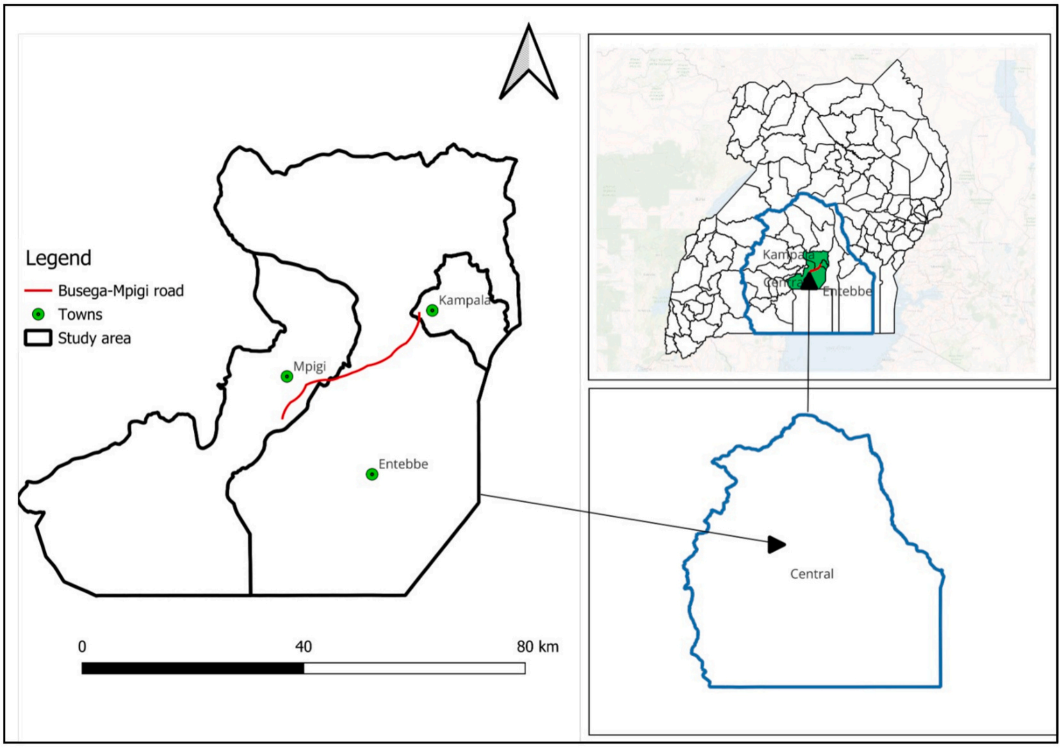

Fig. 1. Location of the study area showing the Busega–Mpigi Expressway corridor in central Uganda, with inset maps illustrating its regional and national context within Uganda.

use conditions suitable for testing constraint-based spatial modelling. While the spatial results are project-specific, the main contribution lies in the methodology developed. Most of the input data are publicly available from open sources, and the modelling process is clearly defined to facilitate adaptation across different geographic and regulatory contexts.

2.3. Proposed GIS-MCDA approach

The proposed method comprises five sequential, modular stages (Fig. 2), implemented in Quantum Geographic Information System (QGIS 3.44), an open-source platform widely recognised for its robustness and versatility in advanced spatial analysis [46]. While the overall workflow is designed as a transferable framework for RE-prosumer construction compound selection, the input parameters, suitability thresholds, weighting criteria, and decision rules adopted throughout this study are tailored to the Busega-Mpigi Expressway case study. The components are not fixed and can be modified according to the geographical, technical, environmental, and project-specific conditions of other construction contexts.

2.3.1. Spatial data acquisition and harmonisation

To optimise the selection of PV, WT, and hybrid RE sites, ten spatial criteria were identified and grouped into four categories: meteorological (Global Horizontal Irradiance (GHI), wind speed at 10 m, temperature); topographical (slope, hillshade); environmental (Land use and land cover (LULC) including built-up areas, commercial farmland, wetlands, forests, and protected areas); and proximity (distances to road alignment, powerlines, and towns). These were sourced from authoritative global and national databases, as summarised in Table 1. To enable accurate spatial overlay and analysis, all spatial datasets were projected into a common coordinate reference system (CRS) (EPSG:32636 – WGS 84/UTM zone 36 N) and resampled to compatible spatial resolutions to minimise scale-induced bias and ensure analytical consistency in overlay operations [47].

2.3.2. Study area delineation

The national administrative boundary of Uganda was processed using a dissolve geoprocessing operation to extract the central region, which contains the Busega–Mpigi road corridor. The road alignment was derived from GPS polyline survey data provided by the Ministry of Works and Transport (MoWT) and validated against Google Maps satellite imagery to confirm positional accuracy and spatial consistency. The spatial extent for analysis was then defined by generating a 5 km buffer around the road centreline, representing an established practical service radius for temporary construction activities and route corridor RE analysis [33].

2.3.3. Constraint mapping and land feasibility

A Boolean constraint-based exclusion approach was used to remove spatially unsuitable areas before suitability modelling—a methodological best practice that prevents artificial compensation of infeasible areas during weighted aggregation [48,49]. A comprehensive set of key constraints and their respective thresholds was identified as shown in Table 2. Each constraint layer was rasterised and reclassified into binary form (1 = suitable; 0 = unsuitable) based on the defined exclusion zones, followed by raster multiplication, which produced a combined feasibility mask identifying areas that satisfy all constraints simultaneously. Environmentally and operationally restricted land classes were extracted from the LULC dataset to generate individual exclusion layers, which were then merged into a unified land-use constraint layer. In addition, proximity constraints were applied to towns, powerlines, and the Busega–Mpigi road. For towns, a single exclusion buffer of 1000 m was applied, while dual buffer zones (minimum 20 m and maximum 1000 m) were generated to define acceptable proximity ranges for roads and powerlines. Each layer was rasterised and reclassified into binary form (1 = suitable; 0 = unsuitable), and raster multiplication produced a combined feasibility mask identifying areas that satisfy all constraints simultaneously and are thus potentially available for construction compound siting.

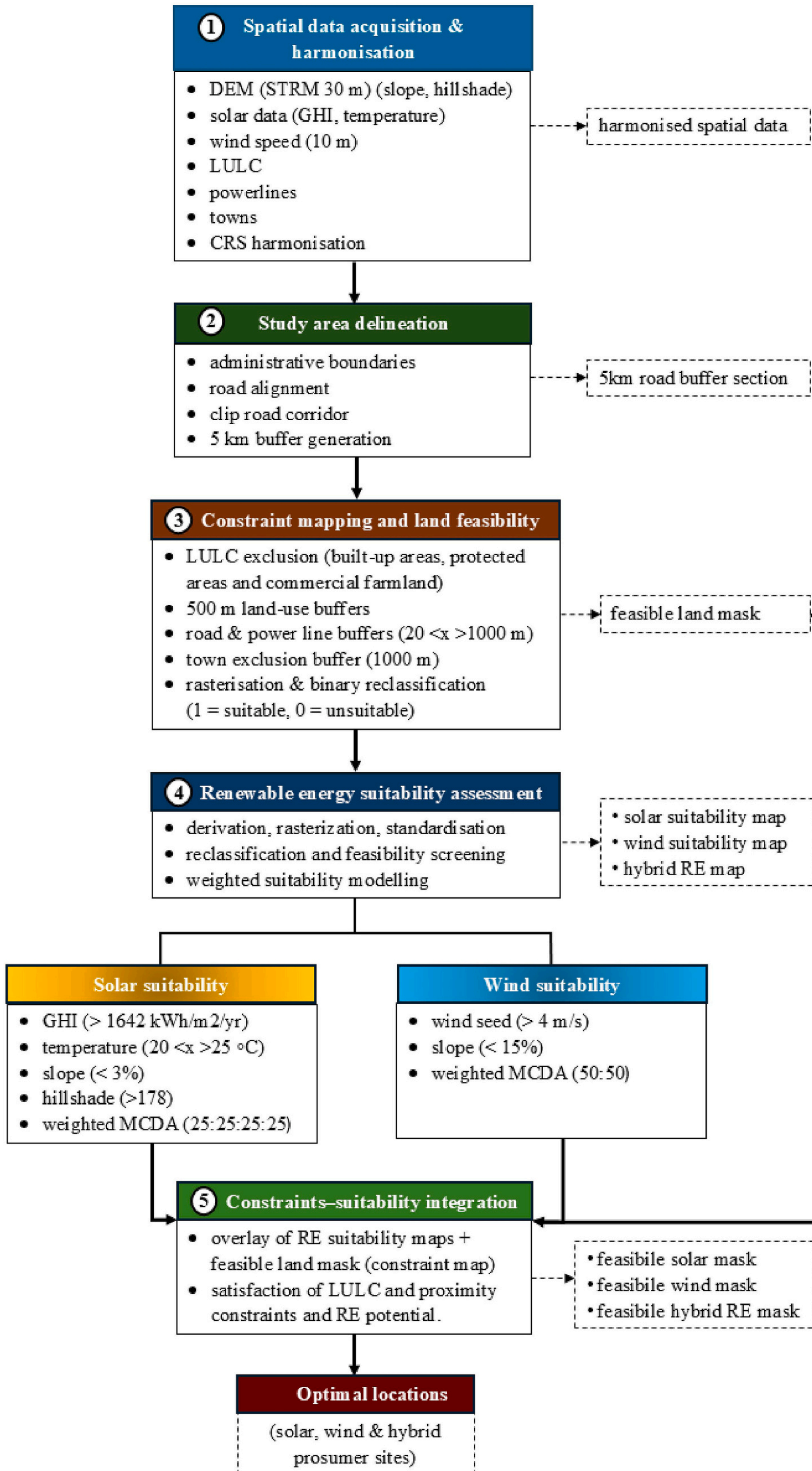

Fig. 2. Sequential GIS-based MCDA framework for RE-integrated construction compound siting. Parameters and thresholds are case-study specific and adaptable.

Table 1
Spatial criteria, categories, and data sources.

Category	Layer	Source of data
Meteorology	GHI, Temperature Wind speed (10 m)	SOLARGIS: https://solargis.com/resources/free-maps-and-gis-data?locality=uganda. Global wind Atlas: https://globalwindatlas.info/en/area/Uganda.
Topography	Slope, Hillshade	SRTM DEM 30 m—OpenTopography https://portal.opentopography.org/datasets.
Environment	LULC, Protected areas	Uganda Bureau of Statistics (UBOS)/MoWT
Proximity	Towns, Powerlines, Road alignment	MoWT GPS/CAD survey data

Table 2
Constraints/thresholds for spatial exclusion analysis.

Criteria	Threshold/ Constraints	Source/Justification
Solar irradiance	>1642 kWh/m^2/yr	[33,34] minimum solar irradiance required for economically viable PV deployment in GIS-based siting studies.
Temperature	20–25 °C	[35] optimal PV operating range to minimise efficiency losses and improve energy yield
Slope (solar)	<3%	[33,38]: improved PV siting efficiency through maximised energy capture and minimised construction and earthworks costs.
Slope (wind)	<15%	[35,50]: suitable terrain for wind energy siting and facilitation of turbine installation and maintenance.
Hillshade	>178	[33,51]: maximisation of solar exposure and identification of low-terrain shading areas for PV suitability.
Wind speed (10 m)	>4.0 m/s	[50]: minimum wind speed required for viable electricity generation.
Land use/protected areas	>500 m buffer	[34,52,53]: ecological protection through avoidance of sensitive habitats, and GIS-based setback for impact minimisation.
Proximity to roads and powerlines	20 < x < 1000 m	[33,54]: feasible grid connection constraints balanced with transmission safety requirements and minimised interconnection costs.
Proximity to towns	>1000 m	[52,55]; settlement setback to minimise community disturbance, ensure compatible land use, and reduce health, safety, and nuisance impacts.

2.3.4. Renewable energy suitability assessment

For this study, solar and wind technologies were the primary focus of the assessment, with each evaluated separately to support appropriate feasibility decisions. The suitability of both solar PV and wind was assessed using a two-stage WLC approach: criterion reclassification and feasibility screening, followed by weighted aggregation. In Stage 1, each spatial criterion was reclassified onto a standardised 0–5 scale (Table 3). Values below the minimum technical viability thresholds were assigned a score of zero, thereby excluding technically infeasible locations from further consideration, whereas higher values indicated greater energy-generation potential. This integrated approach enabled simultaneous screening for technical infeasibility and ranking of performance within a single, transparent operation, suited to continuous spatial domains. In Stage 2, the standardised suitability layers were combined using equal criterion weights as a baseline—GHI, slope, hillshade, and temperature were each assigned 25% for solar, while wind speed and slope were each assigned 50% for wind. This equal-weighting approach was adopted to provide a neutral, transparent, and reproducible baseline for the WLC-based GIS-MCDA in the absence of elicited expert preference weights. Given that the objective of this study was to develop and demonstrate a transferable GIS-MCDA framework rather than establish project-specific criterion weights, all criteria were assigned equal importance during framework development, consistent with established GIS-MCDA practice [32,56,57]. Construction professionals were subsequently engaged only to evaluate the framework's applicability and adoption potential rather than to derive criterion weights. The equal-weighting scheme was presented as a demonstration approach that can be tailored in future applications to reflect project-specific priorities or expert preferences.

The WLC constraint-based GIS-MCDA approach was selected over alternatives such as ELECTRE, PROMETHEE, and TOPSIS for its ease of use, transparency, computational efficiency, and widespread adoption in RE siting, including its combination with alternative weighting schemes such as the Analytic Hierarchy Process (AHP) [33,34]. Unlike these and many other alternatives, WLC explicitly enforces technical feasibility by applying suitability thresholds and constraint masking before aggregation [58]. This feature makes it particularly suitable for RE siting along linear infrastructure corridors, where spatial continuity and strict feasibility thresholds must be maintained. The final outputs are continuous, ranked suitability maps of solar and wind energy that provide a spatially explicit basis for identifying areas with high RE potential along the study corridor.

2.3.5. Constraint–suitability integration and optimal site identification

In the final stage, the ranked RE suitability maps were overlaid with the land feasibility mask derived from constraint mapping (Stage 3) to retain only locations that satisfy both land-use and proximity constraints and exhibit high RE potential. The resulting feasible–suitable areas were identified as candidate construction compounds capable of supporting on-site RE generation and prosumer-based energy practices. To enable robust site ranking and selection, candidate locations were further screened using a 95th-percentile suitability threshold. The remaining sites were ranked by overall suitability score and selected as the Priority Construction Compound (PCC) locations.

2.4. Method evaluation

The proposed GIS-MCDA method was evaluated using two approaches—technical site assessment and stakeholder evaluation. Together, these approaches provided a balanced assessment of technical performance, methodological robustness, and institutional feasibility, thereby strengthening the method's credibility and its potential for real-world adoption.

2.4.1. Technical evaluation

The technical evaluation of the PCCs comprised a quantitative GIS-based and satellite-based validation to assess real-world feasibility, a

Table 3
Reclassification scheme for assessing the suitability of solar and wind energy.

Criterion	Unsuitable (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
GHI (kWh/m^2·yr)	<1642	1642–1800	1801–1850	1851–1900	>1900
Temperature (°C)	<20 or >25	22–25	21–22	20.5–21	20.0–20.5
Slope (%) solar	>3	2–3	1–2	0.5–1	0–0.5
Hillshade	<178	178–190	190–205	205–220	>220
Wind Speed (m/s, 10 m)	<4.0	4.0–5.0	5.0–5.5	5.5–6.0	>6.0
Slope (%) wind	>15	10–15	5–10	3–5	0–3

sensitivity analysis to test the robustness of the spatial outputs, and an energy performance gap assessment to quantify the energy, cost, and carbon dioxide implications.

a. *Quantitative GIS-based site validation and satellite verification*

A quantitative GIS-based validation was undertaken to assess the suitability of the identified PCCs. Spatial measurements were extracted directly from GIS for each candidate site, including distances to the road alignment, nearest town, powerline, and land-use. These measurements were compiled into a validation table to provide an objective assessment of each PCC against the established site selection criteria. High-resolution satellite imagery was subsequently used to verify the GIS-derived results by confirming the physical characteristics of the short-listed identified PCCs. This involved digitising the PCCs and overlaying them on satellite imagery to examine their precise spatial positioning, surrounding space and land-use characteristics, and direct accessibility to the road alignment. The resultant satellite imagery provided supporting evidence to confirm the practical feasibility of the quantitatively validated locations, ensuring that the identified sites are both spatially compliant and practically suitable for construction compound installation.

b. *Sensitivity analysis*

A sensitivity analysis was conducted to assess the stability of GIS-MCDA results under different weighting assumptions, given the subjective nature of assigning criterion weights in WLC-based GIS-MCDA [33,35]. Two alternative scenarios were implemented alongside the equal-weight baseline (scenario 1). Scenario 2 used a resource-dominant weighting scheme adapted from Jiang et al. [33], placing greater emphasis on GHI (60%) than on other terrain-related factors (slope 15%, hillshade 15%, temperature 10%). Scenario 3 implemented a terrain-dominant weighting scheme (GHI 40%, slope 30%, hillshade 20%, temperature 10%), accounting for terrain conditions that affect installation feasibility and cost [59]. All constraint layers, classification thresholds, and spatial parameters were kept constant to isolate the weighting effect. Results were compared based on spatial distribution, persistence of high-suitability zones, and the stability of PCC rankings across all three scenarios. Consistency in site selection outcomes was used as an indicator of the method's robustness and reliability.

c. *Assessment of the energy performance gap*

A comparative energy performance assessment was conducted between the GIS-selected optimal location and the current project compound to quantify the practical implications of using the proposed GIS-based method for selecting construction compounds. The difference in composite suitability score from scenario 1 was converted into annual energy generation, cost savings, and avoided CO_2 emissions using solar resource data for the Busega-Mpigi road corridor and established photovoltaic (PV) performance assumptions and equations based on IEC 61724-1 [60]. The resulting estimates are intended to be indicative rather than bankable projections, with parameter inputs based on Eqs. (1)–(5).

The annual PV yield is estimated using Eq. (1):

$$E_{annual} = P_{PV} \times GHI \times PR \tag{1}$$

where E_{annual} is the annual energy yield (kWh/year), P_{PV} is the installed photovoltaic capacity (kWp), GHI is the annual global horizontal irradiance (kWh/m^2/year), and PR is the system performance ratio (−), as defined in IEC 61724–1 [60].

The relative improvement between the existing and optimal site is defined using Eq. (2):

$$RI = \frac{S_{opt} - S_{exist}}{S_{exist}} \tag{2}$$

where RI is the relative improvement in composite suitability, while S_{opt} and S_{exist} represent the GIS–MCDA composite suitability scores of the optimal and existing sites, respectively.

This factor is applied to the baseline energy yield to estimate the optimal site performance. The resulting energy performance gap is expressed in Eq. (3):

$$\Delta E = E_{opt} - E_{exist} \tag{3}$$

where ΔE denotes the incremental annual energy yield (kWh/year), and E_{opt} and E_{exist} represent the annual energy outputs of the optimal and existing compound locations.

The corresponding reduction in diesel-based energy costs is estimated using Eq. (4):

$$CS = \Delta E \times C_d \tag{4}$$

where CS is the annual cost saving (USD/year) and C_d is the diesel-based electricity generation cost (USD/kWh).

Finally, avoided emissions are calculated using Eq. (5):

$$CO_2 = (\Delta E \times EF_d)/1000 \tag{5}$$

where CO_2represents avoided carbon dioxide emissions (tonnes CO_2/year), and EF_d is the diesel emission factor (kgCO_2/kWh).

2.4.2. *Stakeholder evaluation*

Adoption readiness was assessed using a mixed-methods approach with a sample of eleven (11) key informants (KIs) drawn from the Busega–Mpigi expressway project. Participants were purposively selected across the client ($n = 4$), consultant (n = 4), and contractor ($n = 3$) roles, including project managers, engineers, surveyors, and environmental officers. Purposive sampling was used to capture institutionally grounded variations in adoption readiness across project roles, ensuring representation of perspectives from key actors involved in project management rather than aiming for statistical representation. This way, data collection focused on all available top management actors involved in project decision-making, thereby capturing the full set of relevant perspectives on decision-making, consistent with established guidance on purposive sampling in qualitative research [61]. The resulting $n = 11$ falls within the 8–15 informant range widely accepted as sufficient for saturation in expert, role-stratified designs.

The study employed a before-and-after design structured into three stages. The first stage comprised baseline semi-structured interviews to establish existing construction compound siting practices and awareness of RE integration. The second stage consisted of a video demonstration of the GIS–MCDA method, including the criteria, constraints, and resulting outputs. The final stage combined a post-exposure qualitative interview with a structured survey. Whereas the interview captured participants' initial reactions to the proposed method, their perceived differences from current compound selection and approval practices, anticipated benefits, potential implementation barriers, and suggestions for improving usability and institutional acceptance, the structured survey was based solely on the Technology Acceptance Model (TAM). It assessed perceived usefulness (PU), perceived ease of use (PEOU), attitude towards use (ATT), behavioural intention (BI), method content evaluation (M), and perceptions of prosumer energy adoption (PEA).

The combined use of qualitative feedback and TAM-based usability assessment has been widely adopted to evaluate similar decision-support tools and their potential for adoption [62]. It is therefore well suited to this study, as it supports the dual aim of assessing the proposed method's technical performance and its potential for institutional uptake. The analysis is case-specific and not designed to test structural relationships; rather, it is presented to offer construct-level evidence on adoption readiness across different role types. It is also consistent with Davis's [63] characterisation of TAM as amenable to small-sample, qualitative-dominant validation when applied to new decision contexts. In addition, descriptive statistics are presented as mean ± SD and a Wilcoxon signed-rank test is used to compare responses against the neutral midpoint (3.0).

3. Results

This section presents the GIS-MCDA outputs as a sequence of spatial analyses that progressively refine the study area, from the full corridor buffer through constraint exclusion and RE suitability assessment, to the integration of the resulting model outputs, and ultimately to the selection and ranking of technically feasible and RE-suitable PCC locations. This sequence provides a clear, replicable set of steps that can be adapted to other geographic and regulatory settings.

3.1. Constraint mapping and land feasibility outcomes

The first stage of the spatial analysis examined the effects of land-use and proximity constraints on the feasibility of construction compounds along the Busega–Mpigi road corridor. The resulting constraint maps clearly show the spatial distribution of land that is not suitable for construction compound siting across the corridor. Large portions of built-up areas, wetlands, commercial farmland, and forested zones were mapped and effectively excluded, along with areas within restricted proximity to towns, roads, and powerlines, based on buffer thresholds as depicted in Fig. 3.

As shown in Fig. 3(h), the combined constraint overlay substantially reduced the available corridor area. Of the total buffered study area, LULC constraints alone accounted for 30.3%, with wetlands accounting for the dominant share (77.27% of constrained land), followed by built-up areas (14.82%), forest cover (7.85%), and commercial farmland (0.06%). The dominance of wetlands indicates that the road corridor lies within the Lake Victoria catchment, which is characterised by seasonal flooding and environmental sensitivity. These conditions restrict planning or any form of development in accordance with national environmental laws and the World Bank's Environmental and Social Standards, which are applicable to this project [45]. On the other hand, the small share of commercial farmland indicates limited agricultural activity along the corridor, while the built-up area of approximately 15% reflects the peri-urban character of the Busega-Kampala section.

When land-use constraints were combined with road proximity (within 1 km) and powerline proximity buffers, the cumulative effect of exclusions was pronounced, substantially reducing the extent of land retained as feasible. The resulting feasible land mask (Fig. 4) retained only 10.5% of the total buffered area. This stark reduction—with 89.5% of the corridor excluded, demonstrates the essential and non-substitutable role of the constraint screening stage. If suitability analysis were conducted without prior feasibility screening, it would rank locations within excluded areas, producing sites that score highly but are legally or practically infeasible.

3.2. RE suitability assessment

3.2.1. Meteorological and topographic resource characterisation

The RE suitability assessment focused on solar and wind energy resources, with pronounced differences in RE viability along the road corridor (Fig. 5). Total annual solar irradiance (GHI) was notably high across the corridor, ranging between 1911.0 and 1934.7 kWh/m^2 per year (Fig. 5a), resulting in a minimum daily irradiance of approximately 5.24 kWh/m^2/day. This comfortably exceeds the 4.5 kWh/m^2/day threshold widely cited as the economic viability floor for solar PV in SSA [28,64]. At the same time, temperature varies minimally, ranging from 20.7 °C to 21.8 °C (Fig. 5b), consistent with the moderate temperatures typical of the elevated equatorial setting in central Uganda [65]. The low temperature indicates a low risk of deterioration in thermal efficiency, which is common in PV panels, whose output coefficient

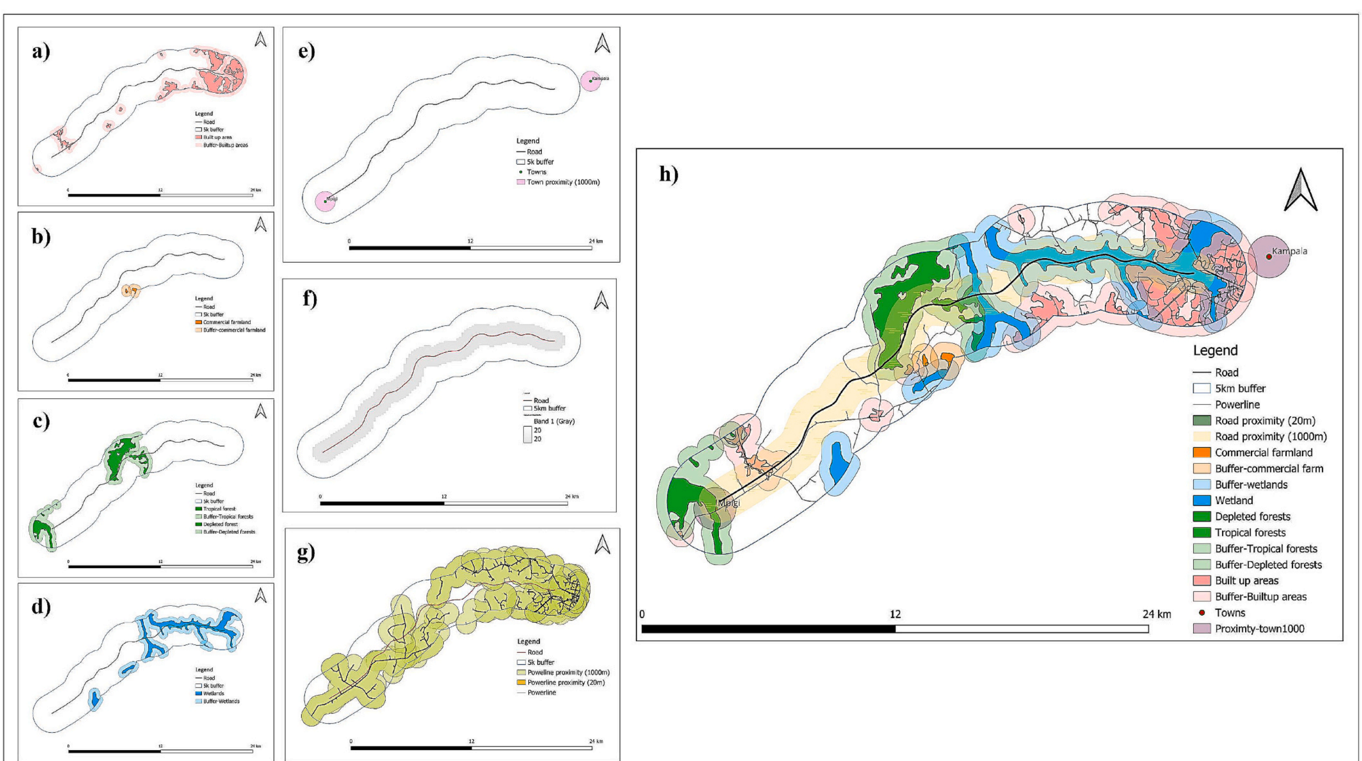

Fig. 3. Spatial constraint buffer maps - a) built-up areas, (b) commercial farmland, (c) forests, (d) wetlands, (e) towns, (f) road corridor, (g) powerlines, and (h) combined constraint overlay.

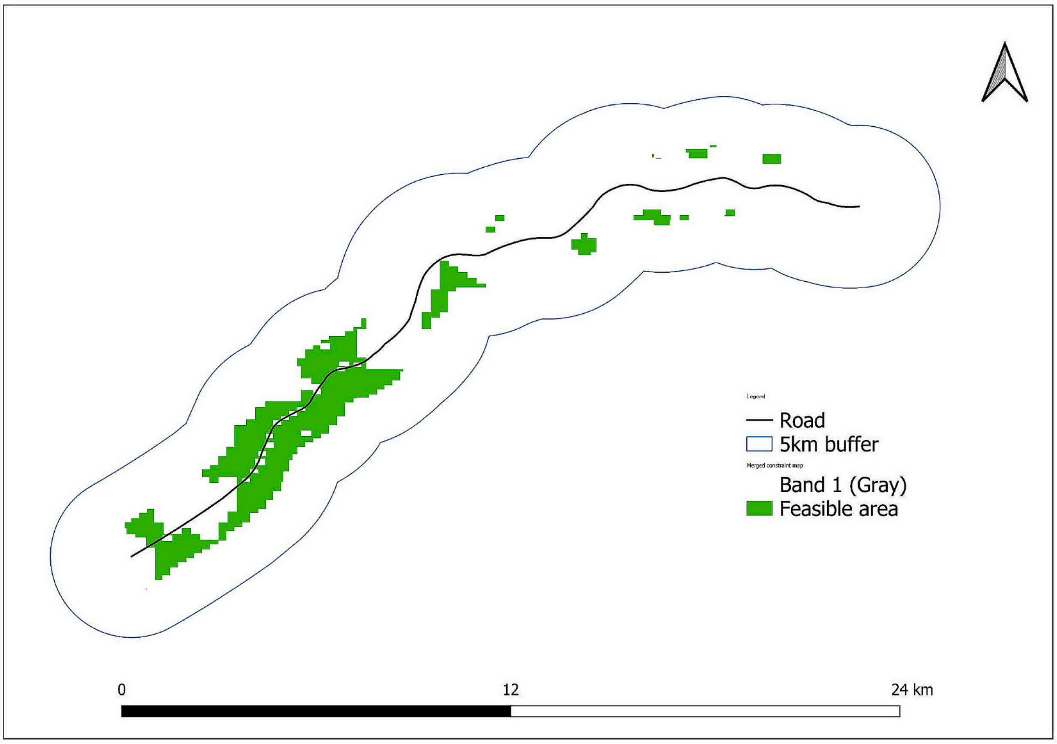

Fig. 4. Combined land feasibility mask showing areas retained after applying land-use and proximity constraints along the study corridor.

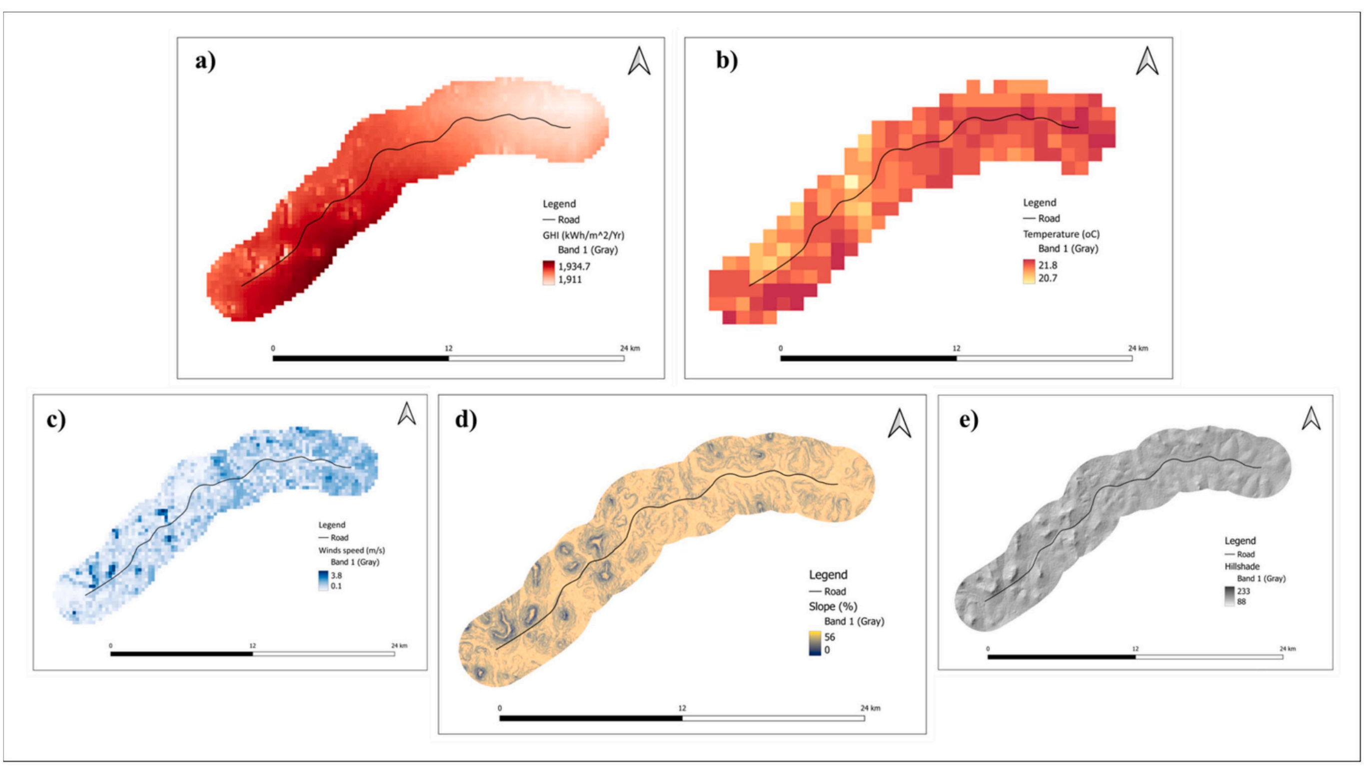

Fig. 5. Spatial distribution of meteorological and terrain parameters within the buffered study area: (a) temperature, (b) wind speed, (c) GHI, (d) slope, and (e) hillshade.

decreases noticeably above 25 °C [66]. The spatial uniformity of GHI and temperature found confirms that solar resource quality is consistently high across the entire corridor, reducing variability in energy yield estimation.

Wind speeds, however, varied from 0.1 to 3.8 m/s at 10 m reference height (Fig. 5c), which is far below the 4.0 m/s minimum requirement for small wind turbine viability, and far below the 6–7 m/s range associated with commercially productive small-scale wind deployment

[50]. This is representative of the generally low-wind conditions in equatorial East Africa, where terrain features and atmospheric patterns tend to limit sustained surface winds. This terrain characteristic is reflected in the slope distribution, which ranges from 0° to 50.5° (Fig. 5d), and in the hillshade values, ranging from 88 to 233 (Fig. 5e), indicating a heterogeneous corridor with localised steep terrain and shading conditions that directly affect PV installation feasibility and system performance.

3.2.2. Solar suitability

Following the meteorological and topographical assessment, the RE suitability analysis evaluated solar energy potential along the corridor. The WLC solar suitability model, with equal weights, was used to produce a spatially continuous suitability map (Fig. 6). Areas with high GHI values, gentle slopes, favourable hillshade conditions, and moderate temperatures received higher scores, forming clusters of high solar suitability along certain sections of the road.

As shown in Fig. 6, about 75% of the feasible land falls within the low suitability class (2.0–2.6), 21% within the moderate class (2.6–3.2), and only 4% within the high suitability class (>3.2). This spatial distribution reflects the interaction between solar resource availability and terrain characteristics across the corridor. Despite uniformly high GHI values (1911–1934.7 kWh/m^2/yr), overall suitability is strongly influenced by terrain variability. This is evidenced by discrete pockets of high suitability associated with favourable slope, hillshade, and temperature conditions. In contrast, areas classified as moderate and low suitability are constrained primarily by terrain factors that limit system performance despite adequate solar resource availability. These spatial patterns highlight the effectiveness of the GIS-MCDA approach in capturing multi-factor trade-offs influencing solar suitability for compound siting.

3.2.3. Wind suitability

In contrast to solar, all locations along the road corridor were classified as technically unsuitable for wind energy because observed wind speeds consistently fell below the 4.0 m/s minimum threshold. No wind-suitability zones were identified, thus, wind energy was excluded from further analysis. This outcome demonstrates the effectiveness of the proposed method's technology-screening logic, and should not be interpreted as an analytical failure. The screening mechanism embedded in the reclassification stage assigns a suitability score of 0 to locations that do not meet minimum technical thresholds, thereby preventing infeasible energy options from advancing to subsequent decision stages. In the absence of this step, a composite hybrid suitability map incorporating wind would have assigned low but non-zero scores across the corridor, falsely implying marginal wind potential and potentially misleading construction compound siting decisions. The exclusion of wind, therefore, maintains the integrity of the results and demonstrates the flexibility and transferability of the compound-selection method.

3.3. Constraint–suitability integration and optimal site identification

The spatial overlay of the solar suitability map with the combined land feasibility mask produced the final map shown in Fig. 7, which retains only locations that satisfy all land-use and proximity constraints and fall within the top 5% of the solar suitability distribution.

As shown in Fig. 7, the overlay refined the candidate areas into a limited set of spatially discrete zones along the corridor. The resulting feasible-and-suitable areas are spatially clustered rather than uniformly distributed, reflecting the combined influence of environmental constraints, proximity to towns and infrastructure, and solar resource potential. Four Priority Construction Compound locations (PCC1–PCC4) were identified from this intersection, collectively covering approximately 0.64 km^2. The presence of high solar suitability and road accessibility at these sites demonstrates the method's co-optimisation objective—simultaneously maximising energy performance and logistical functionality, is achievable along this corridor.

3.4. Technical evaluation of priority compound locations (PCCs)

The results of the technical evaluation of the GIS-MCDA selected compound locations are presented in three stages: (i) quantitative GIS-based site validation supported by satellite imagery verification, (ii)

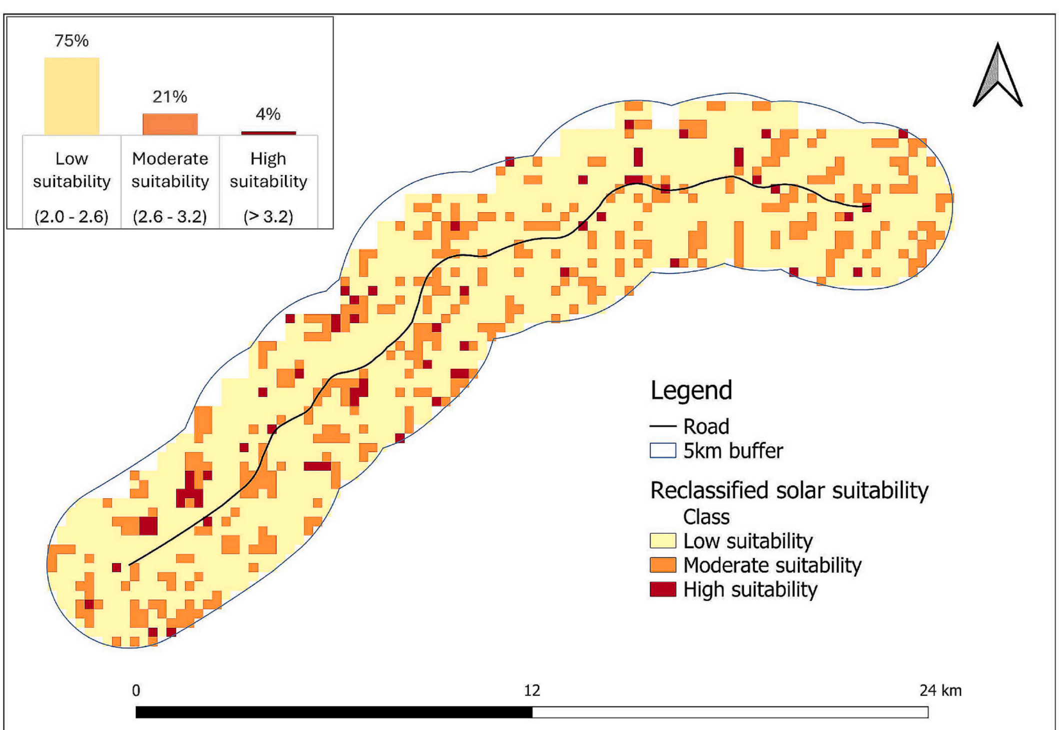

Fig. 6. Continuous map showing spatial variation in solar suitability across the study corridor.

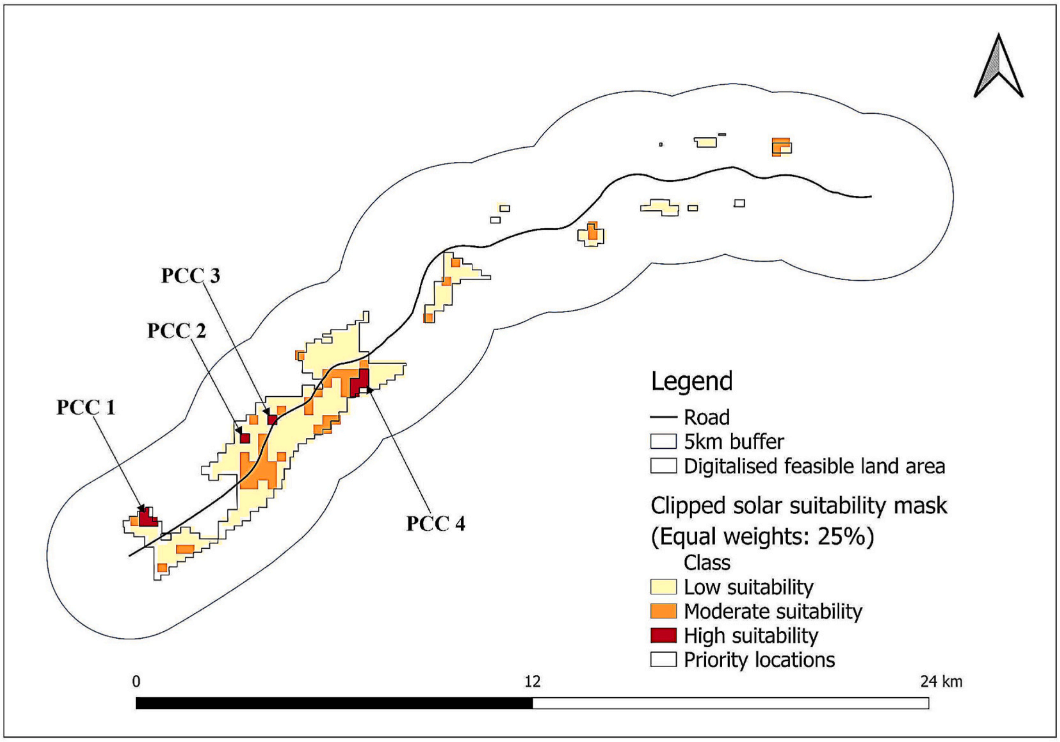

Fig. 7. Solar feasibility mask showing candidate construction compound locations.

robustness assessment through sensitivity analysis, and (iii) quantification of energy and carbon dioxide performance gains.

3.4.1. Quantitative GIS-based site validation and satellite verification

To verify the suitability of the GIS-identified PCCs, a quantitative validation was undertaken using spatial measurements extracted directly from the GIS environment. Each candidate site was assessed against the key siting criteria established in the GIS-MCDA model, namely proximity to the road alignment, nearest town, electricity network, and restricted land-use zones as shown in Table 4.

The quantitative assessment depicted in Table 4, revealed differences in the spatial suitability of the four shortlisted PCCs, despite all satisfying the GIS-MCDA suitability criteria (suitability score of 3.25). PCC3 demonstrated the strongest overall performance and was classified as having very high suitability, primarily due to its excellent road accessibility (20 m), adequate separation from nearby towns (6160 m), acceptable proximity to existing powerlines (508 m), and compatible land-use characteristics. PCC4 was classified as highly suitable, benefiting from the largest available area (294,994 m^2), good accessibility to both the road network (280 m) and power infrastructure (186 m), and the greatest separation from settlements (8610 m). PCC1 and PCC2 were both classified as moderately suitable. PCC1 offered immediate access to the electricity network (20 m) but was located considerably closer to nearby settlements (1348 m), while PCC2 exhibited the least favourable road accessibility (428 m) and was situated within woodland, which may require additional environmental assessment and regulatory approvals before development [67]. Overall, the validation confirmed that although all shortlisted sites were technically feasible, PCC3 provided the most balanced combination of accessibility, infrastructure connectivity, land-use compatibility, and operational practicality for RE-integrated construction compound development.

To complement the quantitative validation, high-resolution satellite imagery was used to visually verify the GIS-identified PCCs by assessing site accessibility, available working space, and surrounding land-use conditions (Fig. 8). This qualitative assessment provided additional insights into site characteristics that are not fully captured by the GIS–MCDA suitability model.

The satellite imagery largely corroborated the quantitative assessment of the shortlisted locations. Although PCC4 offers the largest contiguous land parcel, it lacks direct access to the road alignment and would require access through surrounding built-up areas, which may increase haulage distances and cause traffic-related disruptions to nearby settlements. In contrast, PCC3 provides direct road access, sufficient working space, and favourable surrounding land conditions, making it operationally more suitable for primary construction compound development. Overall, the satellite-based verification reinforces the quantitative findings and confirms PCC3 as the most practically feasible location for construction compound establishment.

3.4.2. Sensitivity analysis

A sensitivity analysis was conducted to assess the stability of the GIS–MCDA outputs under varying criterion weights. The results

Table 4
Quantitative GIS validation of candidate PCCs.

PCC	Area (m^2)	Distance to Road (m)	Distance to Town (m)	Distance to powerlines (m)	LULC type	Suitability
PCC1	187,980	328 (3)	1348 (4)	20 (1)	Subsistence farmland (SFL)	Moderate
PCC2	77,126	428 (4)	5178 (3)	508 (3)	Woodland	Moderate
PCC3	64,252	20 (1)	6160 (2)	508 (3)	SFL/Grassland	Very high
PCC4	294,994	280 (2)	8610 (1)	186 (2)	SFL/Grassland	High
Existing	52,805	30	8256	705	SFL/Woodland	

Note: Lower values indicate better overall spatial validation. Rankings were used only for validation and not in the GIS-MCDA suitability model.

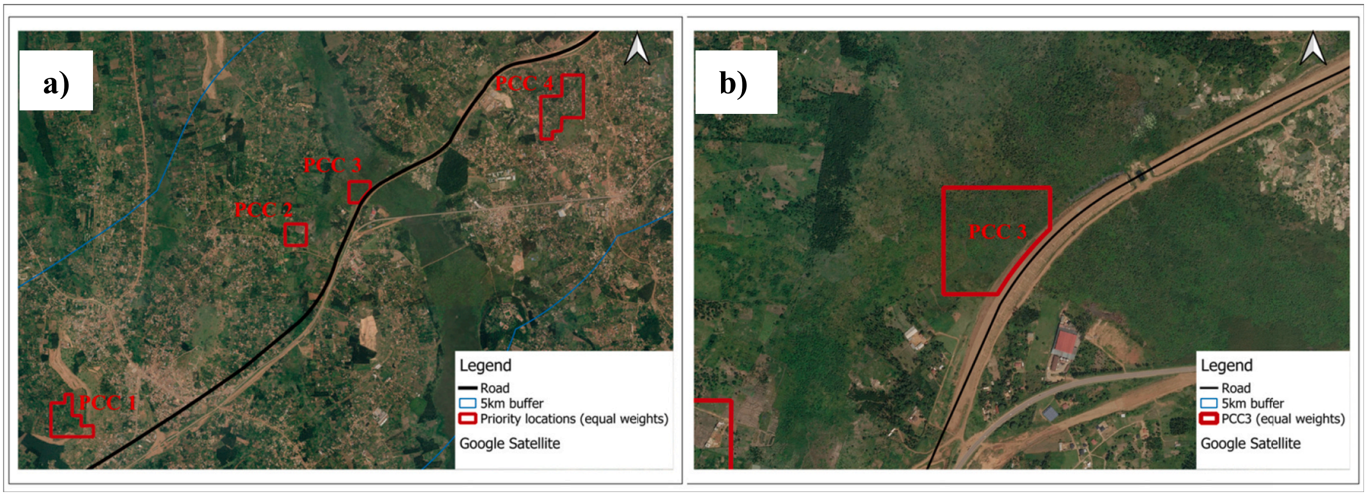

Fig. 8. Satellite imagery of PCCs. (a) Imagery of PCC1-PCC4, (b) Closer imagery of PCC3.

comparing the equal-weight baseline (Scenario 1) with the resource-dominant (Scenario 2) and terrain-dominant (Scenario 3) schemes are presented in Figs. 6 and 9a–b, and in Table 5. The comparison focused on the spatial distribution of suitability classes, the persistence of the highest-suitability zones, and the stability of PCC location rankings across the three weighting scenarios.

The sensitivity analysis shows that 74% of the feasible land falls within the low-suitability class across all weighting scenarios, indicating that suitability is primarily influenced by the constraint-screening stage rather than by changes in the MCDA model's weighting. This means that the weighting scheme primarily affects a small portion of the already-feasible land. Variations across scenarios are reflected in the number of PCCs identified. While the equal-weight scenario produced four PCCs, the resource-dominant scenario expanded this to six due to uniformly high GHI across the corridor, while the terrain-dominant scenario reduced it to two, reflecting stricter terrain constraints. Notably, PCC2 and PCC3 were consistently identified across all scenarios, indicating strong spatial consistency.

The ordinal ranking comparison confirms PCC3 as the top-ranked site across all weighting configurations, indicating that its suitability is structurally driven rather than dependent on specific weighting assumptions. PCC2 shows improved ranking under Scenario 3, while PCC1 and PCC4 remain stable across Scenarios 1 and 2. PCC5 and PCC6 only emerge under Scenario 2, indicating sensitivity to weighting configurations and lower relative suitability. On comparing the

Table 5
Sensitivity analysis results: comparison across three weighting scenarios.

Scenario	Criteria weights (%) GHI/ temp/ slope/ hillshade	Suitability distribution (Low/Mod/ High)	Identified PCCs and ranking (best → lowest)	Optimal location	Retention of baseline PCCs
1	25/25/ 25/25	74%/22%/ 4%	PCC3 (1), PCC1 (2), PCC2 (3), PCC4 (4)	PCC3	Baseline (4PCCs)
2	60/10/ 15/15	74%/21%/ 5%	PCC3 (1), PCC1 (2), PCC2 (3), PCC4 (4), PCC6 (5), PCC5 (6)	PCC3	100% retention + (PCCs 5 & 6 added)
3	40/10/ 30/20	74%/25%/ 1%	PCC3 (1), PCC2 (2)	PCC3	50% retention (PCCs 1 & 4 lost)

Note: Values in brackets indicate PCC priority ranking based on composite suitability score (1 = highest suitability).

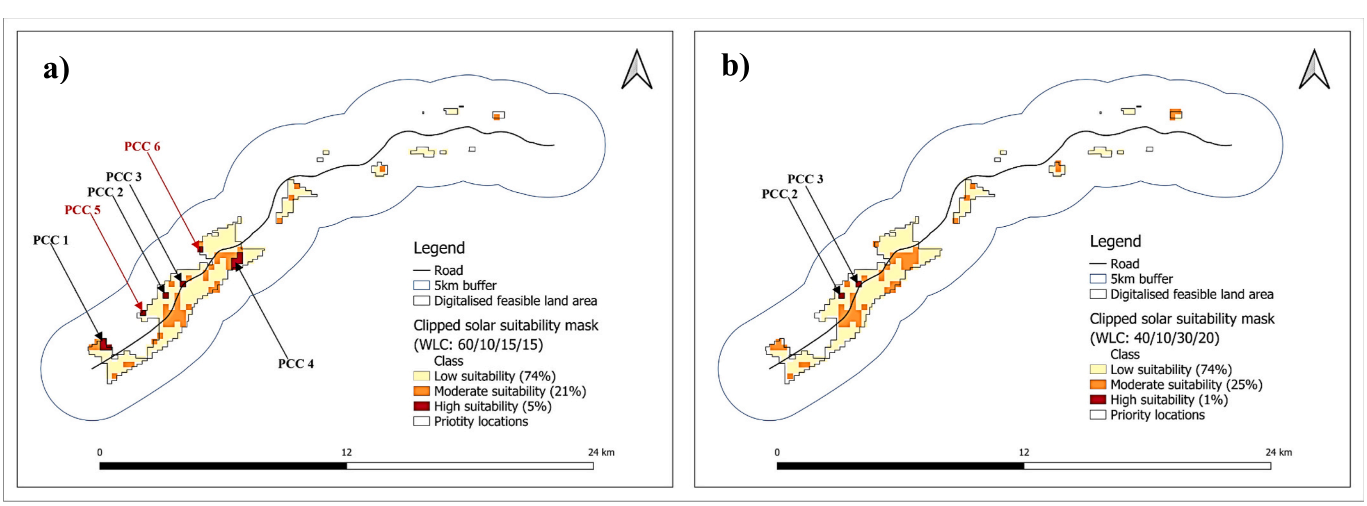

Fig. 9. Sensitivity analysis results for (a) Scenario 2 and (b) Scenario 3.

suitability gap between the existing compound and the optimal site (PCC3) across all three scenarios, the difference ranged from 8.3% under the equal-weight scenario, to 5.2% under the resource-dominant scenario, and 23.3% under the terrain-dominant scenario. The narrower gap under scenario 2 reflects the score-compressing effect of assigning a high weight to a relatively uniform variable (GHI), whereas the wider gap under scenario 3 reflects the greater influence of local terrain constraints on site performance. Scenario 1, however, provides a balanced and conservative representation of this difference and is therefore used in subsequent energy yield calculations.

Overall, the sensitivity results show that while weighting influences the number of candidate sites and their relative rankings, the optimal location (PCC3) remains consistently identified across scenarios, indicating a general robust GIS-MCDA outcome under the tested conditions. This consistency provides practical confidence for real-world application of the method, suggesting that site selection is primarily driven by underlying spatial and environmental conditions rather than subjective weighting assumptions. Given that GIS-MCDA outputs are often questioned for their sensitivity to analyst bias, the persistence of key PCC locations and the limited variation in suitability classes across scenarios provide a transparent and defensible basis for construction compound selection.

3.4.3. *Energy performance gap: existing vs proposed compound location*

A comparative assessment of the GIS-MCDA-identified optimal location (PCC3) and the existing project compound shows a measurable difference in both spatial configuration and composite suitability. PCC3 provides closer access to the road alignment (0.02 km compared to 0.03 km) and a larger available site area (0.068 km^2 versus 0.053 km^2), while maintaining a more favourable separation from surrounding settlements (6.2 km compared to 8.25 km for the existing site), as shown in Fig. 10. In terms of composite suitability, both locations fall within a comparable performance range ($S_{exist} = 3.0$ and $S_{opt} = 3.25$), although PCC3 demonstrates a modest improvement. While this difference is small at the scoring level, it reflects a more efficient spatial configuration that may translate into measurable gains in energy performance and associated carbon dioxide outcomes when propagated through operational demand and supply models over the project lifetime.

Building on the spatial comparison presented in Fig. 10, the energy performance implications of the existing and proposed configurations were quantified using solar resource data from the Busega–Mpigi corridor and representative operational cost data (Table 6). The annual GHI across the corridor ranges from 1911 to 1934.7 kWh/m^2/year, with an average of approximately 1920 kWh/m^2/year. Based on stakeholder-reported expenditure, the existing construction compound incurs annual energy costs of approximately UGX 2 billion (≈USD 526,000). Using typical diesel generation costs in Uganda of USD 0.35–0.40/kWh [28], this corresponds to an estimated annual energy demand of 1316–1504 MWh. Applying Eq. (1) and assuming a performance ratio (PR) of 0.75 in line with IEC guidelines [60], this translates to an installed PV capacity of approximately 0.9–1.0 MWp. Using this baseline, the existing compound (composite suitability score $S_{exist} = 3.0$) yields an estimated annual energy generation of approximately 1440 MWh/year. In comparison, PCC3, with a higher composite suitability score ($S_{opt} = 3.25$), is projected to achieve approximately 1560 MWh/year. This results in an energy performance gap of approximately 120 MWh/year (Eq. (3)), which corresponds to annual cost savings of USD 42,000–48,000 (Eq. (4)). Using a diesel emission factor of 0.7 kgCO_2/kWh [28], the corresponding reduction in emissions is estimated at approximately 84 tCO_2/year (Eq. (5)).

Although the figures in Table 6 are indicative rather than precise investment estimates, they demonstrate that a relatively small improvement in composite suitability can translate into tangible gains in energy output, cost savings, and emissions reductions. This confirms that the GIS-MCDA-derived suitability scores are not merely theoretical indicators but have direct operational and economic significance when linked to energy performance modelling. Importantly, the findings show that while the existing compound is situated within a moderately

Table 6
Comparison of the energy performance gap.

Metric	Existing compound (score 3.0)	Optimal site (score 3.25)	Difference
Annual yield	1440 MWh/yr	1560 MWh/yr	+120 MWh/yr
Financial value	$504,000–$576,000	$546,000–$624,000	+$42,000–$48,000
Avoided CO_2	1008 tCO_2/year	1092 tCO_2/year	+84 t CO_2

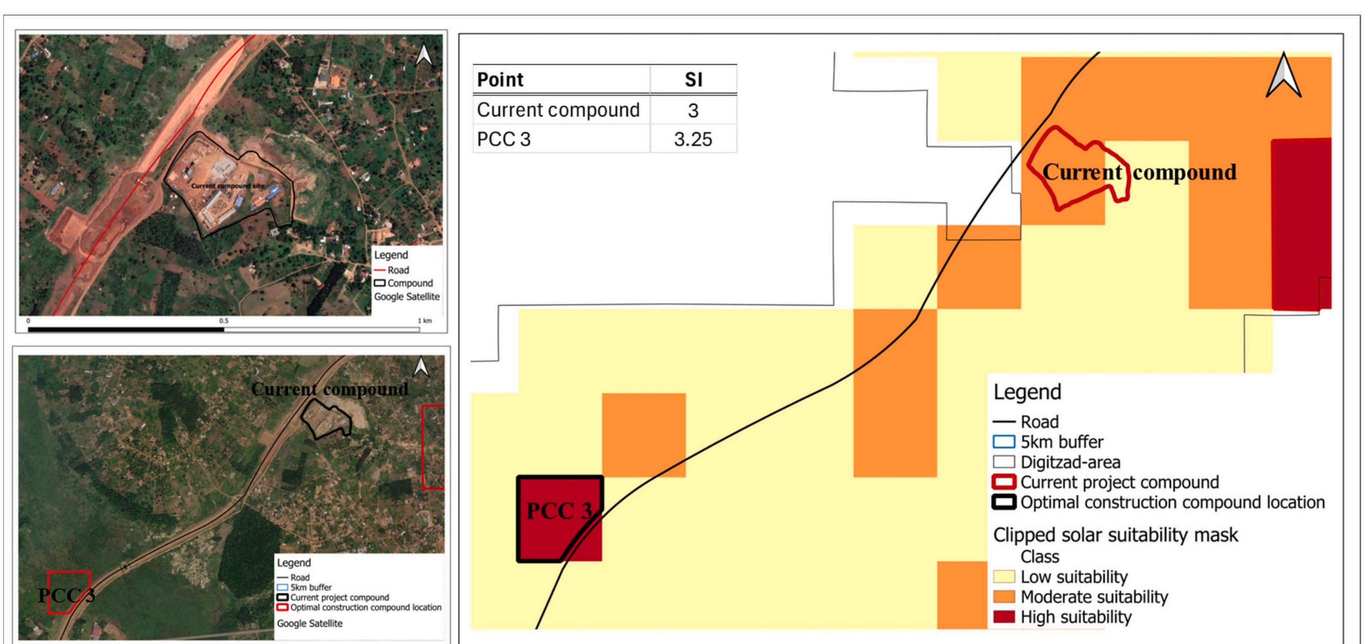

Fig. 10. Comparative analysis of GIS–MCDA-selected sites and the existing construction compound based on composite suitability scores.

suitable zone ($S = 3.0$), a higher-performing alternative location was available and would likely have been selected had energy performance criteria been incorporated into the siting decision from the outset. Overall, the results underscore the added value of incorporating spatial energy metrics into construction compound planning. Doing so enables decision-makers to capture otherwise overlooked trade-offs between location, energy performance, and lifecycle costs—an aspect that remains largely absent from current practice.

3.5. Stakeholder evaluation and adoption readiness

3.5.1. Participant profile

Eleven (11) key informants (KIs) with multidisciplinary expertise, primarily in civil engineering, surveying, and environmental management, working on the Busega-Mpigi Expressway, participated in the study. Their professional experience ranged from 8 to 15 years, with most having worked on the project for 2 to 5 years. The group was predominantly male (10 of 11), reflecting the demographics of the wider senior technical workforce. The KIs held key delivery and oversight roles, including Contract Manager, Project Engineer, and Assistant Resident Engineer, as well as specialist functions such as Bridge Engineer, Civil Engineer (earthworks and plant operations), Land Surveyor, and three Environmental Specialists from both the consultant and the client (MoWT) sides. Together, these roles covered core contractual, technical, environmental compliance, and community welfare functions. Only one KI had been involved in the original compound siting decision, so most participants provided independent views rather than reflecting or justifying past choices, thereby strengthening their perspectives. Despite their extensive professional backgrounds, none of the KIs had prior exposure to RE prosumer systems, particularly their practical integration into construction, making the idea of integrating RE into site operations a new concept for all participants.

3.5.2. Conventional siting practice: a structural critique

KIs described the current compound siting process as multifaceted and driven by a conventional hierarchy of factors, including road centrality, land cost, regulatory compliance, and community relations. Most framed compound selection in terms of operational needs, with little or no consideration given to energy supply. Three illustrative quotes capture the dominant logic, each followed by an analytical commentary that frames them within the study's broader argument.

On centrality and logistics, one Contract Manager stated:

> "You need to find a location that's close to the road and placed in the centre of the project. For example, if the project is 60 kilometres, the campsite should be placed at 30 km so that you can be able to move on either side and reduce the haulage."

This approach is practical and reflects a genuine logic of efficiency. However, it is limited, as focusing only on centrality overlooks the opportunity to optimise energy generation alongside location. The proposed method does not remove centrality; rather, it incorporates it via road-proximity constraints, while also capturing energy performance, environmental compliance, and land use within a multi-criteria GIS-MCDA matrix.

On cost and community relations, the same Contract Manager noted:

> "You find five acres of land amid an urban area, yet you have so many trucks and so many movements. So even the complaints from the stakeholders are so many. Otherwise, you rather go to a place where it's not highly settled, then you can be able to manoeuvre and do these things quietly."

This preference for peri-urban, low-density locations is, in fact, partially aligned with the GIS-MCDA method, as built-up areas are excluded through constraint mapping, leaving lower-density transitional zones as the main feasibility pool from which priority sites are selected. The gap is not the zone preference but the absence of an analytical tool that can pinpoint the specific sites within that zone with the highest energy performance.

On regulatory compliance and risk management, most KIs viewed these aspects not merely as procedural requirements but as part of a broader approach to managing risk, supporting sustainability, and ensuring smoother project delivery. In this context, one KI highlighted the role of the National Environment Management Authority (NEMA) and the requirement for an Environmental Impact Assessment (EIA) in the approval process for road construction activities, noting that:

> "You need to go to NEMA, which requires you to do an EIA, and if you want to operate a fuel camp, you need to go and acquire that license to operate a fuel station from the Ministry of Energy and Mineral Development."

This regulatory compliance narrative shows that practitioners are already required to engage with and obtain approvals from multiple regulatory bodies when establishing construction compounds. Embedding RE system approvals within this existing multi-agency compliance process, rather than presenting them as an additional burden, would reduce perceived regulatory complexity. Moreover, the method's spatial outputs can directly support EIAs and planning submissions by clearly justifying site selection decisions, thereby helping to streamline rather than complicate the approval process.

Across all narratives, energy supply is treated as an operational and logistical issue rather than a spatial planning factor. This is rational, as current procurement systems neither require nor prioritise energy performance at the compound level. Instead, traditional construction compound selection is largely driven by short-term considerations such as cost, logistics, and risk, with little systematic attention to energy efficiency or long-term sustainability. Therefore, improving siting practice requires more than a tool; it also demands changes to procurement and contract frameworks, alongside optimisation-based approaches such as the GIS-MCDA method proposed in this study.

3.5.3. Stakeholder acceptance of the method and the prosumer concept (TAM results)

The quantitative assessment, based on the TAM model, examined stakeholders' perceptions of the proposed GIS-based approach to selecting construction compounds and the broader concept of RE prosumption in road construction projects. The TAM construct scores are presented in Table 7, along with interpretive commentary. All six constructs scored significantly above the neutral midpoint of 3.0, as indicated by Wilcoxon signed-rank tests (all $p \leq 0.002$), suggesting a clear positive orientation towards the proposed method. The pattern of scores is analytically informative beyond the aggregate means, and together the constructs provide insight not only into whether stakeholders consider the method technically sound, but also into whether they view it as practical, acceptable, and likely to be adopted in real project contexts.

The behavioural intention score (BI = 4.50) is the most significant finding in the TAM analysis, and within TAM theory [62,63], BI is the strongest predictor of actual technology adoption. The fact that this score was achieved among practitioners with no prior exposure to the concept, following only a single video demonstration, suggests that the value of the proposed method is immediately apparent to its intended users without the need for extended sensitisation or pilot experience.

The difference between PEOU (3.88) and PU (4.24) is sometimes interpreted in technology acceptance literature as evidence of resistance, but this is not the case here. Lower PEOU scores were mainly reported by site-based operational staff with limited GIS experience, while the same respondents recorded PU and BI scores consistent with those of the rest. This gap suggests that while practitioners recognise and value the method, some are unsure about their ability to use it in practice. Rather than indicating rejection, this points to capacity-building and usability as the main barriers to adoption.

The PEA score (4.45) shows strong conceptual and practical support

Table 7
TAM construct scores: mean ± SD ($n = 11$; Likert scale: 1 = strongly disagree, 5 = strongly agree), and Wilcoxon signed-rank test.

Construct	Items	Mean score	SD	Wilcoxon vs 3.0	Analytical interpretation
Perceived Usefulness (PU)	PU1–PU3	4.24	0.40	W = 66, $p < 0.001$*	Strong, clear agreement on improved siting performance; highest among client/ consultant roles.
Perceived Ease of Use (PEOU)	PEOU1–PEOU3	3.88	0.62	W = 64, $p = 0.002$*	Moderate-high; generally usable; lower scores in site-based roles indicate a capacity gap, not conceptual rejection.
Attitude towards Use (ATT)	ATT1–ATT2	4.18	0.75	W = 54, p = 0.002*	Positive, favourable perception, stronger among roles familiar with spatial tools.
Behavioural Intention (BI)	BI1–BI2	4.50	0.59	W = 66, p < 0.001*	High; strongest construct; clear willingness to adopt across all roles, including those with lower PEOU scores
Method Content Evaluation (M)	M1–M4	4.18	0.51	W = 66, p < 0.001*	Strong, criteria and weights perceived as appropriate and adaptable across roles.
Prosumer Energy Adoption (PEA)	PEA1–PEA3	4.45	0.69	W = 55, $p = 0.001$*	Strong, high support despite no prior familiarity across roles.

Notes: Means are respondent-level construct averages. Wilcoxon signed-rank test (one-tailed, H_1: construct mean > 3.0, neutral midpoint). * $p \leq 0.05$; all remain significant.

for construction-phase prosumerism. Most participants agreed that integrating RE into construction compounds is feasible and supported trialling of PV and storage solutions. Notably, this high level of support was observed despite participants having no prior familiarity with the prosumer concept, suggesting that once introduced, it is relatively easy to understand. Its potential benefits, such as cost savings, improved energy reliability, and greater operational autonomy, directly address the existing site challenges, making it easy for practitioners to relate to in practical terms.

Overall, the TAM results indicate general acceptance of the GIS-MCDA approach and strong support for RE prosumer integration in road construction compounds. Participants perceived the method as useful and were willing to adopt it, with slightly lower ease-of-use scores reflecting limited technical familiarity rather than resistance. Statistical exploration of relationships between constructs did not yield clear evidence of strong associations. The main barrier to adoption of the approach therefore is not acceptance, but readiness to implement, particularly the need for training, practical demonstrations, and enabling policy support.

3.5.4. Perceived benefits: operational and strategic dimensions

The qualitative analysis shows strong agreement among stakeholders on the practicality of using solar power at construction compounds. Three operational benefits, each framed in commercial and operational rather than environmental terms stood out: (i) cost reduction through fuel displacement, (ii) improved energy reliability and reduced reliance on the national grid, and (iii) procurement competitiveness.

On lifecycle cost advantage, one project engineer observed:

> "If you're using fuel, it is more expensive to keep buying the fuel on a day-to-day basis. But when it comes to solar or RE, it would be less costly in the long run because once you put it up, it's about maintaining it."

This view is supported by evidence on the levelised cost of energy (LCOE). IRENA [28] reports that the LCOE of utility-scale solar PV in SSA fell below $0.05/kWh in 2023, much lower than the diesel generation costs of $0.35–0.45/kWh on construction sites in Uganda when all costs are included. In simple terms, RE has high capital costs but low running costs, while diesel is the reverse- cheaper to set up but expensive to run. Over a 36-month project, RE is likely to be more cost-effective, even without accounting for carbon costs or financing incentives.

On energy supply reliability, one informant explained:

> "If we are able to appreciate the RE idea, it is reliable in terms of supply... you don't have to rely on the national grid and its instabilities. If say we set out to crush, we know that we check our power capability for the given crushing that we want to do and we're able to crush within the time that we want without saying that maybe the power has gone off."

This argument for operational reliability is particularly persuasive in the Ugandan context, where grid reliability is constrained. Uganda's electrification rate remains uneven, and load-shedding events affect all areas country-wide [65]. On-site generation eliminates this dependency entirely, providing the energy certainty required for schedule-driven construction activities. Critically, this benefit accrues regardless of environmental motivation, as it is a purely operational advantage that improves project delivery performance.

Regarding procurement competitiveness, one project engineer noted that integrating RE could enable contractors to submit lower-cost bids by better controlling and stabilising energy costs. Thus, RE would not be seen as an extra cost but as a competitive advantage, since more predictable energy costs reduce financial risks in bids. It also suggests a mechanism through which RE adoption could penetrate the market, rather than relying solely on regulatory mandates.

Beyond immediate operational benefits, participants also highlighted broader advantages, including improved regulatory compliance and opportunities for community engagement, through corporate social responsibility, particularly by supplying excess power to nearby communities. In addition, the adoption of RE systems was seen as a way to reduce reliance on diesel generators, thereby minimising noise and harmful emissions, especially around office areas or other generator zones, where workers are more directly exposed. Overall, these perspectives show that RE prosumption is not merely a simple technical substitution, but a practical way to improve project operations, reduce costs, improve working conditions, and deliver social and environmental benefits.

3.5.5. Perceived barriers and mitigation pathways

Stakeholders identified several implementation barriers. Rather than accepting these at face value, the analysis examines them more closely to distinguish between genuine technical or economic limitations and those stemming from institutional inertia, such as information asymmetries or misaligned incentives. It then identifies practical mitigation pathways to address each of these challenges.

Skills and awareness gaps. KIs noted that most local and international contractors operating in Uganda have limited experience in RE integration, citing the need for sensitisation and education. One informant stated: *'Most of the contractors that we have in Uganda are international contractors. They come from countries which probably maybe [sic] have not interfaced with the RE campsite supplies.'* This is a valid diagnosis but reflects a localisation and mainstreaming deficit rather than an intrinsic constraint. International contractors operating under World Bank or AfDB financing are increasingly required to submit Energy Management Plans as ESMP conditions. Therefore, incorporating RE compound siting requirements into standard bidding documents would formalise them as contractual obligations rather than optional considerations, thereby reducing reliance on individual contractor initiative.

Institutional fragmentation. One contract manager highlighted the separation of mandates between key institutions—particularly the MoWT (road infrastructure), the Ministry of Energy and Mineral Development (MEMD) (energy regulation), NEMA (environmental oversight), and local council authorities, as an issue that would create procedural complexity, particularly anticipating delays linked to authorisation of on-site generation. While this concern reflects a real administrative challenge, it is primarily an issue of coordination rather than the lack of policy support. Uganda's RE Policy (updated 2021) and the National Development Plan III both explicitly support decentralised RE generation but do not clearly define the approval process for temporary, project-based systems. As a result, the fragmentation identified by participants translates into delays and uncertainty in practice. In this context, clearer inter-agency procedures—such as a joint administrative protocol between MoWT and MEMD could help align approvals without requiring major legislative changes.

Capital cost. The upfront cost of solar PV and battery storage was cited as a barrier, particularly when considered across the ministry's entire project portfolio, which comprises several concurrent infrastructure projects. *'You can imagine if you're doing 100 projects and everyone has to set up their solar panels… this becomes very expensive.'* This concern reflects a static cost assessment that does not account for: the 90% decline in PV module prices since 2010 [28]; Power Purchase Agreement (PPA) structures in which a third-party RE provider (or even the government itself) installs, owns, and operates the system at no capital cost to the contractor (already operational in comparable East African infrastructure projects); and blended finance instruments from multilateral development banks or international agencies that can subsidise or guarantee RE equipment procurement. Therefore, although capital costs are a real issue, under current procurement systems they can be greatly reduced through alternative financing models that do not require contractors to provide capital.

Linear corridor energy distribution. KIs also highlighted the logistical challenges of distributing power across long road corridors, especially those exceeding 100 km, and particularly for equipment operating far from the main construction compound, framing it as logistically impractical: *'I have equipment working at kilometre zero, and they want to recharge.'* This concern is more about system design than a fundamental limitation. Construction work is not spread evenly along the whole corridor but is concentrated at active work fronts that progress sequentially along the alignment. In this context, zone-based microgrid configurations that align with the construction programme phasing, combined with mobile charging units for equipment operating at a distance from the main compound, already exist and are technically feasible and commercially deployable. The issue is therefore not the feasibility of the prosumer model, but rather the design of the energy system.

Political economy of energy governance. Participants highlighted the governance challenge of integrating decentralised microgrid models into Uganda's centralised electricity system, managed by the Uganda Electricity Distribution Company Limited (UEDCL). There was concern that on-site RE generation could be perceived as diverting revenue from the state utility, creating political resistance. One KI further noted that the current separation of mandates between MoWT and MEMD could lead to inter-ministerial friction. This is the most substantive institutional barrier identified, reflecting a genuine political economy dynamic. It reflects the political economy of a centralised energy system in which distributed generation is perceived as a competitive threat rather than a complementary resource. However, the informants themselves proposed a constructive resolution: feeding surplus generation back into UEDCL through net-metering arrangements rather than selling directly to communities. This model aligns with the utility's commercial interests, avoids direct competition with centralised supply, and is operationally equivalent to net-metering frameworks in Kenya, Rwanda, and South Africa. It represents a politically feasible solution that requires only regulatory guidance, rather than any fundamental restructuring of Uganda's energy governance architecture.

3.5.6. Recommendations for operationalisation

Stakeholders converged on a set of recommendations that collectively define the institutional and design conditions for adoption. The most consistently cited technical requirement was a user-friendly interface without GIS expertise or coding requirements: 'Shouldn't be one that requires coding algorithms because these are end users that are ordinary. They do not have time to go into much of that.' This recommendation is partially addressed by the method's open-source implementation in QGIS, which offers substantial interface customisation and an established global user community, particularly in low-resource settings.

Beyond interface design, KIs recommended: embedding training requirements in contract ESMPs; formal inter-agency coordination protocols that formalise approval pathways; a broader method scope, encompassing full site establishment rather than energy siting alone; and the incorporation of emerging technologies, including fast-charging infrastructure for electric plants. One informant proposed that generated power be fed to UEDCL, the primary utility, rather than to a direct community supply, which represents a politically viable business model for the prosumer concept in the Ugandan regulatory context. These recommendations collectively define a product-development and policy-integration roadmap for moving from a demonstrated proof of concept to a deployable decision-support tool embedded within standard infrastructure project planning practice.

4. Discussion

4.1. Compound siting as a strategic energy planning decision

The central contribution of this study is to demonstrate that construction compound siting, conventionally treated as a logistics problem, can become an energy planning decision with measurable, recoverable consequences for project sustainability performance. The proposed GIS-MCDA-based method operationalises this reframing by embedding RE suitability criteria within the same spatial decision matrix as land feasibility and logistical accessibility, enabling co-optimisation rather than sequential trade-offs. The result is a compound location that is both logistics-feasible and energy-optimal, an outcome that conventional sequential planning cannot achieve because it provides no mechanism for considering energy performance as a spatial variable at the siting stage.

The 8.3% suitability score differential between the existing compound and the GIS-identified optimal site, while numerically modest, represents a structurally recoverable performance gap in the specific sense that it could have been avoided at zero additional logistical cost had energy criteria been embedded in the initial siting decision. This finding aligns with and extends prior GIS-MCDA literature demonstrating that experience-based or logistics-driven site selection produces 'good enough' rather than optimal outcomes [31,32,47]. Similar gaps between conventional, experience-driven practice and spatially optimised solutions have been documented in the RE infrastructure planning and related facility planning literature e.g., [30,36–39,55,56,59]. In temporary construction infrastructure, the implications extend beyond energy performance, establishing a concrete operational pathway for construction-phase decarbonisation. Importantly, the existing compound's score confirms strong solar viability, indicating that conventional siting can also yield good energy outcomes. However, the value-addition of the new GIS-MCDA method lies in identifying the subset of viable locations where performance is maximised, a precision increasingly critical as carbon budgets tighten.

Taken together, the results demonstrate that the primary contribution of this study is the development and demonstration of a transferable GIS-MCDA approach for RE-enabled siting of temporary road construction compounds. Beyond its methodological contribution, the approach reframes compound siting as an early decision opportunity for construction-phase energy transitions by embedding energy considerations as core locational criterion rather than a post-construction intervention. However, real-world impact will depend on translating this approach into user-friendly decision-support tools, aligning institutional arrangements between road and energy authorities, and supporting contractual and policy frameworks. This highlights the broader relevance of this approach for supporting the transition towards NZCC in infrastructure delivery.

4.2. Extending prosumer theory to temporary infrastructure

The prosumer model has been extensively studied and applied in permanent residential, commercial, and community settings [6,7,10]. This study extends prosumer theory to a qualitatively different context: temporary, project-based infrastructure such as construction sites, where energy demand is intensive but limited to installations designed for relocation, and contractual arrangements that are time-limited. Thus, this extension requires reconceptualising prosumer economics around the project lifecycle rather than the asset lifecycle. For example, instead of focusing on the traditional question of what the payback period is for a 25-year solar asset, the more relevant question becomes what the return on investment is over the project life for a system designed to be relocated and redeployed. This shift also highlights design priorities such as rapid deployment, modularity, portability, and recovery of residual value—factors that are less central in permanent prosumer applications but are critical in construction environments.

The strong stakeholder support for the prosumer concept (PEA = 4.45), even among practitioners with no prior exposure to it, suggests that its adoption potential has been constrained primarily by its invisibility within project planning practice rather than by fundamental economic or technical barriers. Many practitioners are already grappling with the underlying challenges, i.e. high energy costs, unreliable grid supply, and heavy reliance on diesel, but have not been exposed to the prosumer approach as a structured way to address them. This aligns with Everett Rogers' [68] characterisation of the awareness-knowledge gap as a primary driver of slow innovation diffusion. In other words, the issue is not resistance to adoption but a lack of visibility. Within this context, the GIS-MCDA approach developed in this study serves not only as a site-selection tool but also as a means of translating the prosumer concept into a practical, spatially grounded option that practitioners can realistically consider during project planning.

4.3. Barriers as transitional constraints: a policy-level reframing

The barriers identified by stakeholders closely align with the concept of 'transition friction' in the sustainability transitions literature [23–25]. This perspective distinguishes between barriers arising from genuine technical or economic limitations and those stemming from institutional inertia, information asymmetry, or misaligned incentives. The findings of this study suggest that most barriers fall into the latter category. In other words, while these constraints are real, they are not necessarily permanent. They reflect the current state of procurement processes and governance systems, not their theoretical limits. More importantly, each barrier identified can be addressed through practical mitigation pathways that operate within existing institutional capacities, without requiring major systemic reform.

One of the most practical interventions is to revise standard bidding documents and ESMPs for road construction projects financed by major development banks. These documents already set the conditions contractors must meet and the criteria against which compounds are approved. Introducing minimum RE performance targets for compound energy systems, similar to the minimum energy performance standards now governing building construction, in many jurisdictions, would shift RE integration from an optional innovation to a basic contractual expectation. Importantly, this could be achieved without new legislation or fundamental changes in contractor behaviour by leveraging the existing compliance-driven rationality of construction procurement—contractors work to satisfy the requirements set out in their contracts, thus, changing contract requirements directly influences contractors' actions and project delivery as a whole.

This observation is consistent with the argument in sustainability transitions literature that emerging innovations often need supportive governance arrangements before they can scale [21–26]. As theoretically argued by Geels [25], niche innovations typically require protective governance arrangements or policy support to achieve scale. In this context, the GIS-MCDA approach developed in this study provides the technical basis for implementing such support. However, its wider uptake ultimately depends on policy actions embedded within infrastructure procurement systems. The evidence from this study suggests that practitioners would welcome rather than resist such a mandate; in fact, the strong BI scores indicate readiness to adopt the approach once the appropriate institutional conditions are in place.

4.4. Limitations and future research

This study has several limitations that define the scope of its conclusions. First, the stakeholder sample was purposively selected to capture role diversity within the Busega–Mpigi project and is therefore explicitly exploratory rather than inferential. While the TAM scores provide useful insights into adoption readiness within this group, the findings should not be generalised without validation across multiple projects, institutions, and geographic contexts. The sample size ($n = 11$) was sufficient to achieve role saturation for qualitative analysis but remains below the threshold required for statistical inference on TAM relationships. Future research should extend the analysis to larger, multi-project and multi-country samples. Second, the study focuses on suitability assessment and does not extend to direct energy yield modelling. Converting suitability scores into bankable generation estimates would require detailed site-specific inputs, such as system sizing, storage, and demand profiles, which are beyond the scope of this study but essential for investment decisions. Third, the sensitivity analysis was restricted to three predefined weighting scenarios, without incorporating stochastic weight variation or expert-derived weights. Although relevant stakeholders were engaged in the study, their input was focused on TAM-based evaluation rather than structured MCDA weight elicitation (e.g., AHP). While this separation ensured methodological clarity and transferability based on the equal-weighting criteria, future work could incorporate formal expert elicitation and probabilistic weighting approaches to further test model robustness.

Future research should focus on three areas. First, integrating construction-phase energy demand profiling based on equipment schedules and activity programmes to enable demand–supply matching, rather than relying solely on supply-side suitability. Second, developing and field-testing a deployable, user-friendly decision-support tool based on the proposed method, tailored for non-GIS users in construction project environments, to address the usability challenges identified by stakeholders. Third, conducting post-occupancy performance monitoring of GIS-MCDA-selected versus conventionally selected compound sites to validate the energy performance differences identified in this study. This evidence can support the development of procurement guidelines and inform policy and regulatory frameworks for integrating RE and spatial optimisation into construction project planning.

5. Conclusions

This study sought to develop and evaluate a transferable GIS-MCDA method to optimise construction compound siting by integrating onsite RE prosumption considerations into road infrastructure projects, in line with NZCC objectives. By combining spatial, logistical, and energy performance criteria and applying the method to the Busega–Mpigi Expressway in Uganda, the study demonstrates how the selection of a compound location can shift from a purely logistical exercise to a strategic energy-planning decision. Through systematic spatial analysis, energy modelling, and stakeholder evaluation, the study reveals that:

1. Construction compound siting along the Busega-Mpigi expressway is highly spatially constrained, with constraint mapping reducing the feasible land area to just 10.5% of the total buffered corridor. This highlights the complexity of siting decisions and the need for structured, data-driven approaches such as the proposed GIS-MCDA-based method, to navigate competing spatial and infrastructural demands.
2. Solar suitability modelling effectively identifies four PCCs, with PCC3 emerging as the optimal location. Its combination of high solar potential and direct road access resulted in the highest composite suitability score. Sensitivity analysis further confirmed the robustness of this outcome, with PCC3 consistently ranking highest across varying weighting scenarios, thereby demonstrating the method's robustness as a decision-support tool for planning applications.
3. Integrating RE considerations into construction compound siting delivers measurable energy and environmental benefits, with PCC3 outperforming the conventionally selected site by 8.3%. This corresponds to an estimated additional generation of approximately 120 MWh/year and about 84 tonnes of avoided CO_2 emissions annually, reinforcing the role of siting decisions in achieving measurable operational and environmental benefits.
4. Stakeholder evaluation indicates strong acceptance and readiness to adopt RE-integrated compound siting, with high scores for perceived usefulness (4.24), behavioural intention (4.50), and support for the prosumer concept (4.45), despite participants having no prior exposure to RE-integrated compound design. This suggests that industry practitioners readily recognise the value of integrating spatial optimisation with energy performance criteria in construction compound siting decisions.
5. Implementation barriers to adoption are primarily transitional rather than structural, with key constraints including skills gaps, institutional fragmentation, capital cost considerations, and regulatory complexity. These can be addressed through targeted interventions, including capacity building, strengthening inter-agency coordination, adaptive procurement frameworks, and supportive financing mechanisms.

Overall, this paper contributes to both theory and practice by introducing a methodological approach to integrating RE considerations into temporary construction infrastructure planning. Primarily it extends GIS-MCDA applications to the underexplored domain of temporary road construction, by developing a transferable framework that incorporates energy performance alongside conventional logistical and spatial criteria in compound siting. Second, it provides a practical demonstration of the proposed method within a real-world road infrastructure project, illustrating its potential to support more informed and energy-conscious siting decisions. Third, it advances the prosumer energy concept by demonstrating its applicability to temporary, project-based contexts, where energy systems can be designed, deployed, and relocated over finite project lifecycles. Fourth, it provides empirical evidence of adoption readiness through TAM analysis in a Sub-Saharan African infrastructure context. As demonstrated, realising this potential will depend on supportive governance structures, alignment between road and energy authorities, and the integration of energy performance criteria into infrastructure planning and procurement processes. Integrating RE-informed decision-making into construction compound siting offers a practical pathway for advancing construction-phase energy transitions and achieving NZCC objectives in infrastructure delivery.

Data access statement

The data associated with this paper can be accessed via [69].

CRediT authorship contribution statement

Racheal Wesonga: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Apollo Tutesigensi:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the Faculty of Engineering & Physical Science, University of Leeds, United Kingdom.

Data availability

Data will be made available on request.

References

[1] Liu N, Wang Y, Bai Q, Liu Y, Wang P, Xue S, et al. Road life-cycle carbon dioxide emissions and emission reduction technologies: a review. J Traffic Transp Eng (Engl Ed) 2022;9(4):532–55. https://doi.org/10.1016/j.jtte.2022.06.001.
[2] Lokesh K, Densley-Tingley D, Marsden G. Measuring road infrastructure carbon. DecarboN8; 2022. . (report), https://decarbon8.org.uk.
[3] Hong B, Lü L. Assessment of emissions and energy consumption for construction machinery in earthwork activities. Sustainability 2022;14(9):5326. https://doi.org/10.3390/su14095326.
[4] Lendlease. Fossil fuel free construction: guidance for Lendlease Australia project team. Lendlease; 2023 (guidance report), https://www.lendlease.com.
[5] Toffler A. The third wave. Bantam Books; 1980.
[6] Parag Y, Sovacool BK. Electricity market design for the prosumer era. Nat Energy 2016;1:16032. https://doi.org/10.1038/nenergy.2016.32. https://doi.org/10.1038/nenergy.2016.32.
[7] Ford R, Maidment C, Fell M, Vigurs C, Morris M. A framework for understanding and conceptualising smart local energy systems. Glasgow (UK): University of Strathclyde Publishing; 2019. ISBN: 978-1–909522-57-2. Available from: https://www.energyrev.org.uk/media/1298/energyrev-sles-frameworkv4.pdf.
[8] Wesonga R, Tutesigensi A, Moodley K. Advancing net zero carbon construction: a techno-economic and environmental analysis of onsite microgrids and prosumer energy adoption. Appl Energy 2025;398:126453. https://doi.org/10.1016/j.apenergy.2025.126453.
[9] Global Infrastructure Hub. Global infrastructure outlook: forecasting investment needs to 2040. GI Hub; 2023. https://outlook.gihub.org.
[10] Kotilainen K. Energy prosumers' role in the sustainable energy system. In: Leal Filho W, Azul A, Brandli L, Özuyar P, Wall T, editors. Affordable and clean energy. Cham: Springer; 2020. p. 1–11. https://doi.org/10.1007/978-3-319-71057-0_11-1.
[11] Berardi U, Tomassoni E, Khaled K. A smart hybrid energy system grid for energy efficiency in remote areas for the army. Energies 2020;13. https://doi.org/10.3390/en13092279.
[12] SANDIA REPORT: deployable wind-hybrid power systems for defence and disaster response applications. California: Sandia National Laboratories, 2021. Available from: https://www.sandia.gov/app/uploads/sites/273/2022/01/D3T-Microgrid-Report-SAND2021-14967.pdf.
[13] International Renewable Energy Agency (IRENA). Renewables for refugee settlements: sustainable energy access in humanitarian situations. Abu Dhabi: IRENA; 2019. Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Dec/IRENA_Refugee_settlements_2019.pdf.

[14] United Nations High Commissioner for Refugees (UNHCR). Access to clean energy for refugees: Uganda case studies. UNHCR; 2019. Available from: https://www.unhcr.org/uk/media/access-clean-energy-refugees-uganda-case-studies.
[15] Ellabban O, Alassi A. Optimal hybrid microgrid sizing framework for the mining industry with three case studies from Australia. IET Renew Power Gener 2021;15:409–23. https://doi.org/10.1049/rpg2.12038.
[16] Shu N, Jiang S, Fan Z, Cao X, Zhang Z. Energy management strategy of microgrid based on photovoltaic and energy storage system in construction area of Sichuan-Tibet railway. Sci Technol Energy Transit 2024;79:49. https://doi.org/10.2516/stet/2024044.
[17] Manic N, Maslak E, Curic T, Vatic D, Nurkovic I. Historical development of solar road panels in pavement structures. Sylwan 2024. https://doi.org/10.59879/T4hj0.
[18] Kurz D, Bugała A, Głuchy D, Kasprzyk L, Szymenderski J, Tomczewski A, et al. The use of renewable energy sources in road construction and public transport: a review. Energies 2024;17(9):2141. https://doi.org/10.3390/en17092141.
[19] Ma T, Li S, Gu W, Weng S. Solar energy harvesting pavements on the road: comparative study and performance assessment. Sustain Cities Soc 2022;81:103868. https://doi.org/10.1016/j.scs.2022.103868.
[20] Chang Y, et al. Mitigating the greenhouse gas emissions from urban roadway lighting in China via energy-efficient luminaire adoption and renewable energy utilization. Resour Conserv Recycl 2021;164:105197. https://doi.org/10.1016/j.resconrec.2020.105197.
[21] Cherp A, Vinichenko V, Jewell J, Brutschin E, Sovacool BK. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework. Energy Res Soc Sci 2018;37:175–90. https://doi.org/10.1016/j.erss.2017.09.015.
[22] Geels FW. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 2002;31(8–9):1257–74. https://doi.org/10.1016/S0048-7333(02)00062-8.
[23] Köhler J, et al. An agenda for sustainability transitions research: state of the art and future directions. Environ Innov Soc Transit 2019;31:1–32. https://doi.org/10.1016/j.eist.2019.01.004.
[24] Markard J, Raven R, Truffer B. Sustainability transitions: an emerging field of research and its prospects. Res Policy 2012;41(6):955–67. https://doi.org/10.1016/j.respol.2012.02.013.
[25] Geels F. Disruption and low-carbon system transformation: progress and new challenges in socio-technical transitions research and the multi-level perspective. Energy Res Soc Sci 2018 Mar;37:224–31. Epub 2017 Oct 23, https://doi.org/10.1016/j.erss.2017.10.010.
[26] Smith A, Stirling A, Berkhout F. The governance of sustainable socio-technical transitions. Res Policy 2005;34(10):1491–511. https://doi.org/10.1016/j.respol.2005.07.005.
[27] Adegboyega AW, et al. DC microgrid deployments and challenges. A comprehensive review of academic and corporate implementations. Energies 2025;18(5):1064. https://doi.org/10.3390/en18051064.
[28] International renewable energy agency (IRENA). Renewable power generation costs in 2023. IRENA; 2023. https://www.irena.org/publications.
[29] African Development Bank. Climate change and green growth strategic framework 2021–2030. Abidjan: African Development Bank; 2022. Available form: https://www.afdb.org/sites/default/files/documents/publications/ccgg_strategy_en_v3.pdf.
[30] Belton V, Stewart TJ. Multiple criteria decision analysis. Kluwer; 2002. https://doi.org/10.1007/978-1-4615-1495-4.
[31] Malczewski J. GIS and multicriteria decision analysis. Wiley; 1999.
[32] Malczewski J. GIS-based multicriteria decision analysis: a survey. Int J Geogr Inf Sci 2006;20(7):703–26. https://doi.org/10.1080/13658810600661508.
[33] Jiang W, Zhang S, Wang T, Zhang Y, Sha A, Xiao J, et al. Evaluation of solar energy resources in road areas before route corridor planning. Appl Energy 2024;356:122260. https://doi.org/10.1016/j.apenergy.2023.122260.
[34] Elkadeem MR, Younes A, Sharshir SW, Campana PE, Wang S. Sustainable siting and design optimization of hybrid RE system: a geospatial multi-criteria analysis. Appl Energy 2021;295:117071. https://doi.org/10.1016/j.apenergy.2021.117071.
[35] Elkadeem MR, Younes A, Mazzeo D, Jurasz J, Campana PE, Sharshir SW, et al. Geospatial-assisted multi-criterion analysis of solar and wind power geographical-technical-economic potential assessment. Appl Energy 2022;322:119532. https://doi.org/10.1016/j.apenergy.2022.119532.
[36] Al Garni HZ, Awasthi A, Wright J. Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia. Appl Energy 2017;206(C):1225–1240. doi: https://doi.org/10.1016/j.apenergy.2017.10.024.
[37] Raza MA, et al. Site suitability for solar and wind energy in developing countries using combination of GIS-AHP; a case study of Pakistan. Renew Energy 2023;206:180–91. https://doi.org/10.1016/j.renene.2023.02.010.
[38] Aydin NY, Kentel E, Duzgun HS. GIS-based site selection methodology for hybrid renewable energy systems: a case study from western Turkey. Energy Convers Manag 2013;70:90–106. https://doi.org/10.1016/j.enconman.2013.02.004.
[39] Doorga JRS, Hall JW, Eyre N. Geospatial multi-criteria analysis for identifying optimum wind and solar sites in Africa: towards effective power sector decarbonization. Renew Sust Energ Rev 2022;163:112107. https://doi.org/10.1016/j.rser.2022.112107.
[40] Andayesh M, Sadeghpour F. Dynamic site layout planning through minimization of total potential energy. Autom Constr 2013;31:92–102. https://doi.org/10.1016/j.autcon.2012.11.039.
[41] Hickey J, Pimoult M, Liang F, O'Connor I, Gallagher J. Examining electricity demand profiles to inform sustainable on-site construction practices. Proc Inst Civ Eng Eng Sustainability 2026;179(2):115–26. https://doi.org/10.1680/jensu.25.00037.
[42] Peffers K, et al. A design science research methodology for information systems research. J Manag Inf Syst 2007;24(3):45–77. https://doi.org/10.2753/MIS0742-1222240302.
[43] Hevner AR, March ST, Park J, Ram S. Design science in information systems research. MIS Q 2004;28(1):75–105.
[44] Crowe S, et al. The case study approach. BMC Med Res Methodol 2011;11:100. https://doi.org/10.1186/1471-2288-11-100.
[45] Uganda National Roads Authority. Busega–Mpigi expressway progress report. Uganda National Roads Authority; 2024. https://www.unra.go.ug.
[46] Graser A, et al. QGIS: an open-source GIS platform. Open Source Geospatial Foundation; 2025. https://qgis.org.
[47] Jankowski P. Integrating GIS and multiple criteria decision-making methods. Int J Geogr Inf Syst 1995;9(3):251–73. https://doi.org/10.1080/02693799508902036.
[48] Atici KB, Simsek AB, Ulucan A, Tosun MU. A GIS-based multiple criteria decision analysis approach for wind power plant site selection. Util Policy 2015;37:86–96. https://doi.org/10.1016/j.jup.2015.06.001.
[49] Rahman MA, Rusteberg B, Gogu RC, Lobo Ferreira JP, Sauter M. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. J Environ Manag 2012;99:61–75. https://doi.org/10.1016/j.jenvman.2012.01.003.
[50] International renewable energy agency (IRENA). Wind energy technology brief. IRENA; 2022. https://www.irena.org.
[51] ESRI. Hillshade analysis for solar siting applications. ESRI Technical Documentation; 2025. URL: https://www.esri.com.
[52] Uganda Government. The National Environment Act, 2019 (act no. 5 of 2019). Kampala (UG): Government of Uganda; 2019.
[53] African Development Bank Group (AFDB). Proposed construction of Busega-Mpigi expressway (23.7KM): updated environmental and social impact statement (ESIS). Abidjan (Côte d'Ivoire): AFDB; 2024. Available from: https://www.afdb.org/sites/default/files/final-esia-update-for-busega-mpigi-expressway-with-comments-addressed-june-2024.pdf.
[54] Uganda Electricity Transmission Company Limited (UETCL). UETCL wayleaves management policy. Kampala (UG): UETCL; 2019.
[55] Kahatapitiya C, Jayasooriya VM, Muthukumaran S. GIS-based weighted overlay model for wind and solar farm locating in Sri Lanka. Environ Sci Pollut Res 2023;30:98947–65. https://doi.org/10.1007/s11356-022-24595-0.
[56] Georgiou A, Skarlatos D. Optimal site selection for solar energy plants using AHP and GIS. Renew Sust Energ Rev 2016;56:551–60.
[57] Zhao L, van Duynhoven A, Dragićević S. Machine learning for criteria weighting in GIS-based multi-criteria evaluation: a case study of urban suitability analysis. Land 2024;13(8):1288. https://doi.org/10.3390/land13081288.
[58] Kumar A, Sah B, Singh AR, Deng Y, He X, Kumar P, et al. A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. Renew Sust Energ Rev 2017;69:596–609. https://doi.org/10.1016/j.rser.2016.11.191.
[59] Chen Y, Yu J, Khan S. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. Environ Model Softw 2010;25(12):1582–91. https://doi.org/10.1016/j.envsoft.2010.06.001.
[60] International Electrotechnical Commission. IEC 61724-1: photovoltaic system performance – part 1: monitoring. Geneva: IEC; 2017.
[61] Guest G, Bunce A, Johnson L. How many interviews are enough?: an experiment with data saturation and variability. Field Methods 2006;18(1):59–82. https://doi.org/10.1177/1525822X05279903.
[62] Venkatesh V, Morris MG, Davis GB, Davis FD. User acceptance of IT: toward a unified view. MIS Q 2003;27(3):425–78.
[63] Davis FD. Perceived usefulness, perceived ease of use, and user acceptance of IT. MIS Q 1989;13(3):319–40. https://doi.org/10.2307/249008.
[64] Agoundedemba M, Kim CK, Kim HG. Energy status in Africa: challenges, progress and sustainable pathways. Energies 2023;16(23):7708. https://doi.org/10.3390/en16237708.
[65] World Bank. Uganda energy access and sector evaluation development report. World Bank; 2020.
[66] Sharaf M, Yousef MS, Huzayyin AS. Review of cooling techniques used to enhance the efficiency of photovoltaic power systems. Environ Sci Pollut Res Int 2022;29(18):26131–59. https://doi.org/10.1007/s11356-022-18719-9.
[67] Republic of Uganda. The National Forestry and Tree Planting Act, 2003. Kampala (UG): Government of Uganda; 2003. Available from: https://nfa.go.ug/.
[68] Rogers EM. Diffusion of innovations. 5th ed. Free Press; 2003.
[69] Wesonga R, Tutesigensi A. Dataset of an evaluation of a GIS-MCDA method for renewable energy prosumer integration in road construction compound siting. University of Leeds 2026;Dataset. https://doi.org/10.5518/1900.