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Integrating Energy Systems and Humanitarian Action for the Water–Energy–Environment Nexus: Evidence from India and Kenya

Mojtaba Sedaghat[1,*], **Nima Emami Kian**[2]

[1] Department of Mechanical Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong; Memojtabas@ust.hk.

[2] Department of Mechanical Engineering, Shahid Beheshti University, Tehran, Iran; n_emamikian@sbu.ac.ir.

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Abstract

This article introduces and applies an Integrated Index (II) to identify and prioritize the most suitable technologies for impoverished regions in the fields of water and energy, using India and Kenya as comparative case studies. A PRISMA-guided review and expert interviews inform the selection of prevalent technologies like energy (solar PV, biomass gasification, LPG, mini-hydro) and water (boreholes, rainwater harvesting, wastewater treatment). The indicators derive weights with the Best–Worst Method (BWM) and compute II scores to reflect social, economic, and environmental objectives. Results highlight efficiency (with 32% of total weights) as the dominant criterion for energy and cost/reliability (with 35%, and 20% of total weights) for water. Under the INI framework, LPG (0.84) and biomass (0.56) rank highest among energy options for near-term service delivery, while borehole extraction (0.83) outperforms other water options, followed by rainwater harvesting (0.58). This article translates these insights into actionable planning guidance for humanitarian–development settings, emphasizing service-based contracts, telemetry-enabled O&M, and circular resource strategies to enhance resilience to real-world challenges. The II provides a transparent, adaptable decision tool to prioritize technologies, reduce fragmentation, and steer SDG-aligned investments in poverty-affected regions.

Keywords: Energy systems, Humanitarian actions, Water-energy-environment Nexus, Sustainable development goals.

1 | Introduction

Population growth is tightly coupled with rising demand for energy, food, and water, and it is a key driver of global CO2 emissions [1-4]. Energy, in particular, underpins social and economic well-being: it enables

Corresponding Author: Memojtabas@ust.hk

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modern health care and is foundational to poverty alleviation [5-8]. Yet more than one billion people still lack reliable access to essential energy services and to basic resources such as safe water and nutritious food [9]. In many regions, poverty has deepened in recent years, amplifying exposure to cascading risks like blackouts, water scarcity, food insecurity, and climate-related challenges [10], [11]. These dynamics reinforce one another, creating cycles that are difficult to break with regular solutions. Global frameworks such as the 2030 Agenda for Sustainable Development were designed to confront these mixed challenges. However, implementation in real-world settings remains uneven. Policy fragmentation, financing gaps, the differentiation between theory and reality constraints, and context-specific technical limitations often dilute the impact [12-15]. Against this backdrop, integrated approaches that explicitly account for cross-sector dependencies are essential [16].

The MCDM (Multi-Criteria Decision-Making) offers a practical lens for designing solutions that deliver multiple benefits simultaneously. By optimizing trade-offs and co-benefits across sectors, MCDM strategies can strengthen energy system reliability, reduce water losses, improve agricultural productivity, and lower emissions [17, 18]. Two features make the MCDM approach particularly promising:

I. System reliability: Integrated planning reduces vulnerability to single-point failures (e.g., power outages that compromise electricity demand or cold/Thermal storage) and enhances redundancy through diversified resource pathways [19].

II. Resource efficiency: Circular strategies like wastewater reuse for irrigation, recovery of energy from organic residues, precision irrigation, and demand-side management lower overall resource intensity while maintaining or increasing output [20], [21].

To assess the state of knowledge and implementation barriers, the study employed a structured literature review that combined elements of the PRISMA framework with a SWOT analysis [22], [23]. Using the PRISMA approach, major academic databases and literature repositories were systematically searched with predefined keywords covering "water–energy–technology," "poverty reduction, "resilience, "decentralized energy systems," and "humanitarian actions. After removing duplicates, the study screened titles and abstracts against inclusion criteria focused on challenges with measurable outcomes related to access, reliability, resource efficiency, emissions, and socioeconomic indicators. In this vein, some of the most important articles in the field of energy systems and humanitarian actions are reviewed according to *Table 1*.

Table 1. A comprehensive review of water-energy-food nexus models towards sustainability.

Reference	Year	Methods/ Models	Short Description	Main Outcomes
Nielsen et al. [24]	2014	Qualitative interviews; design-tradeoff framework	Examines off-grid energy product design; identifies stakeholder misalignments.	• Imperatives: Do-no-harm; intuitive design; plan for maintenance/end-of-life. • Trade-offs: local capacity vs. low cost; market stimulation vs. donations • Barriers: short funding cycles, unclear requirements, limited end-user access.
Caniato et al. [25]	2017	Selective review; problem-tree for energy–food security in humanitarian contexts	Analyses how energy poverty undermines food security in crises; reviews barriers and outlines opportunities/innovations.	• Energy is integral to all four pillars of food security; fuel scarcity drives negative coping. • Opportunities: SAFE/MEI/SET4Food; LPG/ethanol/biogas/solar pumping. • Future areas: standardized inclusion of energy, WEF nexus, IFES, food preservation tech.

Table 1. Continued.

Reference	Year	Methods/ Models	Short Description	Main Outcomes
Thomas et al. [26]	2021	Conceptual synthesis using the IASC Cluster System; practitioner insights	Maps how energy interlinks with all humanitarian clusters and proposes ten cross-cluster actions.	• Energy is essential yet not fully integrated in cluster planning. • Clear links between different sectors: cooking/protection risks; lighting/safety; solar water pumping/WASH; • Ten recommendations for cluster-owned actions (standards, data, training, cash/vouchers for fuel, quality assurance, inclusive programming).
Robinson et al. [27]	2022	Rapid review; conceptual typology (“Spectrum of Co-Design”); retrospective analysis using TIME framework	Reviews co-design in humanitarian energy; proposes a spectrum and applies TIME to HEED lessons.	• Co-design improves inclusion and sustainability. • TIME helps align purpose, assumptions, engagement, and reflection. • Gaps: post-project support, funding rigidity, misaligned expectations.
Rosenberg-Jansen et al. [28]	2022	Literature Review; expert interviews; disciplinary mapping	Establishes the scope and growth of humanitarian energy literature and identifies major research gaps.	• Rapidly emerging field; strongest in social science and energy studies; clean cooking and solar dominate. • Gaps: qualitative, refugee-led research; IDPs/urban displacement. • Calls for disciplinary diversity, deeper empirical work.
Robinson et al. [29]	2022	Development of the Technology Implementation Model for Energy (TIME); synthesis of method; field validation (Nepal ICS)	Presents TIME, a formative and evaluative co-production model to increase sustained use of improved energy tech by addressing contextual barriers.	• Core factors: Co-production; Ownership; Utilization. • Strategic elements: Purpose & Need; Assumptions & Expectations. • Improves sustained use vs. adoption-only metrics.
Ray and Chakraborty [30]	2022	Techno-economic modelling (HOMER Pro); LCOE; demand response (OpenADR)	Assesses how demand flexibility and tiered resilience affect solar PV PPAs for off-grid camps; quantifies costs for e-cooking, water pumping, lighting, and facilities.	• 100% PV with DR + tiered resilience can power e-cooking, water pumping, lighting, and essentials at ~0.318–0.325 $/kWh; annual energy charge ~0.41M$ for ~15k people. • Recommends consumer-integrated PPAs (time-coupled supply).
Joireman et al. [31]	2023	Applied Case Study, Literature Review	Developing Humanitarian–Development–Peace Nexus for humanitarian scenarios.	Developing a plan to conserve the environment during humanitarian actions. Posing a comprehensive method considering different parameters rather than focusing on optimizing one.
Li et al. [32]	2024	QSAND, Survey	Decision-making based on analysis of renewable energy in humanitarian shelters.	Integration of the sustainability framework and local standards at an early stage. Developing the first solar-powered emergency shelter equipped with energy storage.
Alfandi et al. [33]	2025	Water Resource Platform	Investigate the effect of leveraging renewable energy for solving water and energy challenges in Syria.	Examining the Challenges and Opportunities of Renewable Energy in Water Supply. The integration of renewable energy enhances the efficiency, sustainability, and resilience of water supply systems.
Sun et al. [34]	2025	CS-ARDL	Analyze the effect of humanitarian actions on electricity generation in OECD countries.	Positive Correlation between the expansion of the economy, the provision of humanitarian assistance, and electricity production. Foreign direct investment restricts electricity generation capacity.

Rafa et al. [35] examined energy access and water systems in humanitarian camps for Rohingya refugees. Their study formalized national policies for energy technologies and proposed that addressing energy poverty requires integration with socioeconomic, environmental, and political dimensions. Schismenos et al. [36] investigated flood-related and renewable energy prototypes designed for humanitarian interventions in two locations of Greece and Nepal. The comprehensive framework they developed can be applied not only for early disaster warning but also to meet energy and water demands in otherwise inaccessible communities. In another research [37], this team evaluated the impact of micro-hydro power on local communities. The results indicate that a 300W generator is sufficient to meet demand under both regular and extreme conditions. Moreover, the use of outdoor sensors and lighting can save lives before and during adverse events.

Despite growing literature on humanitarian energy and the MCDM, most studies treat sectors in isolation (e.g., solar for electrification or biomass for cooking) and evaluate technologies with uniform, non-contextual weights. Existing approaches rarely operationalize multi-criteria trade-offs across social, economic, environmental, and reliability outcomes; they underrepresent real case evidence, and they seldom bridge short-term humanitarian needs with long-term development planning. Moreover, technology choices are often optimized on a single dimension (cost or emissions), overlooking service continuity, O&M feasibility, and local governance constraints in places like India and Kenya. Our innovation is a decision framework, the Integrated Index (II), that: 1) jointly evaluates water and energy options within a MCDM lens; 2) applies expert-elicited, context-specific weights via the Best–Worst Method instead of assuming equal importance; 3) integrates measurable indicators that capture service delivery (efficiency, capacity factor, reliability), affordability, environmental impact (carbon footprint), durability (lifetime), and livelihoods (employment); and 4) translates scores into actionable rankings for policy and humanitarian operations. This study presents a comparative application of the Integrated Index to India and Kenya. The article involves following steps: first a PRISMA-guided literature review to define indicators and technology sets; then elicitation of expert weights for water and energy dimensions; third computation of INI scores for common technologies (solar PV, biomass gasification, LPG, mini-hydro, boreholes, rainwater harvesting, and wastewater treatment); and final step is interpretation of the results into planning guidance and priority transitions.

2 | Methodology

The methodology comprises several well-defined sections. First, the study develops a new water–energy MCDM model and outlines the data collection approach. Next, it presents the weighting formulation and explains the application of the Best–Worst Method (BWM).

2.1 | Developing a New Framework and Data Gathering Method

Two case studies (India and Kenya) were selected due to their recurrent challenges and significant potential in water and energy, alongside ongoing environmental initiatives. The study proposes a new framework aligned with the Sustainable Development Goals, which evaluates not only economic aspects but also environmental and social dimensions. Guided by this framework, several indicators for water and energy technologies were defined. For data collection, an expert questionnaire was administered, complemented by interviews to capture practitioner insights and validate indicator weights.

2.2 | Weighting Concept

Unlike prior multi-criteria decision-making studies that focus on one parameter or technology in the impoverished zones, this study applies differentiated weights to energy and water technologies based on expert-judged importance. For each technology, indicator values and their weights are combined in a linear formulation according to *Eq. (1)*. The weights vary by objectives aligned with the Sustainable Development Goals. The term resulting composite metric is the Integrated Index (II).

$$\mathrm{II} = (\mathrm{W1} \times \mathrm{I1}) + (\mathrm{W2} \times \mathrm{I2}) + (\mathrm{W3} \times \mathrm{I3}) + (\mathrm{W4} \times \mathrm{I4}) + (\mathrm{W5} \times \mathrm{I5}) + (\mathrm{W6} \times \mathrm{I6}). \tag{1}$$

In *Eq. (1)*, the term "w" denotes the weights assigned to each indicator, and I denotes the normalized, dimensionless indicator values. For the energy sector, six indicators are used: efficiency, lifetime, capacity factor, cost, carbon footprint, and employment. For the water sector, the indicator set replaces energy- and cost-specific factors with water quality and reliability. Given that this study examines various technologies across both water and energy supply sectors, establishing common indicators is essential to facilitate a standardized comparison. Accordingly, *Table 2* presents the selected shared indicators.

Table 1. The general information of selected indicators [38], [39].

No.	Sectors	Indicators	Discription
1	Energy and Water	Capital Cost	This criterion represents the total initial investment required to implement a technology. It encompasses all upfront expenses, including equipment acquisition, land, engineering, construction, and installation, incurred before the system becomes operational.
2	Water	Water Quality	This criterion evaluates the biological characteristics of water. It determines the water's suitability for a specific intended use (e.g., irrigation or potable supply) based on compliance with established environmental and health standards.
3	Energy and Water	Carbon Footprint	This metric quantifies the total amount of greenhouse gases (GHGs) emitted directly or indirectly by the system.1 To facilitate comparison, all emissions are aggregated and expressed in units of carbon dioxide equivalent (CO2eq) based on their Global Warming Potential (GWP).
4	Energy and Water	Lifespan	This parameter denotes the expected useful economic life of the technology. It represents the time horizon over which the initial capital investment is amortized, and the system remains operational with standard maintenance.
5	Energy and Water	Labor Required	This criterion assesses the human resource inputs necessary for the continuous operation and maintenance of the system.
6	Water	Reliability	This criterion assesses the consistency and security of supply. It evaluates the system's ability to provide continuous output despite external fluctuations (e.g., weather dependence)
7	Energy	Efficiency	This criterion measures the performance of the technology by calculating the ratio of useful output to the total input resources required.
8	Energy	Capacity Factor	This metric is defined as the ratio of the actual output generated over a specific period to the theoretical maximum output if the system were to operate at full nameplate capacity continuously. It indicates how effectively the installed capacity is utilized.

3 | Case Study Description

3.1 | Study Area

Two developing countries, India in Asia and Kenya in Africa, were selected because they face persistent challenges in water, energy, and the environment, while also demonstrating significant potential for improvement. Briefly, their current situations are:

I. India (population: 1.43 billion) has near-universal electricity connections but uneven supply quality; per-capita electricity use is almost 1,300–1,400 kWh/year, with coal still 70% of power generation and fast-growing solar/wind [40], [41]. Clean cooking access has expanded via LPG, yet biomass use persists in rural areas. Water stress is acute: almost 80% of rural drinking water relies on groundwater, with declining tables and contamination hotspots. Urban utilities face high non-revenue water and intermittent supply; wastewater treatment coverage is improving, but is still insufficient. Climate variability drives cycles of droughts and floods, pressuring irrigation-heavy agriculture [42], [43].

II. Kenya (population: 55–57 million) has almost 75–80% electricity access nationally, with strong off-grid solar and mini-grids complementing grid expansion; per-capita electricity use is almost 200–250 kWh/year. Power mix is predominantly renewables like geothermal, hydro, and growing wind/solar. Yet tariffs are relatively high, and outages persist. Clean cooking relies heavily on biomass; LPG and electric cooking are growing but unevenly [44], [45]. Water security is challenged by arid/semi-arid lands, drought frequency, and urban non-revenue water; boreholes and small schemes are vital in rural areas, with fluoride and salinity issues in Rift Valley aquifers. Urban wastewater capacity lags demand, and floods periodically disrupt services [46], [47].

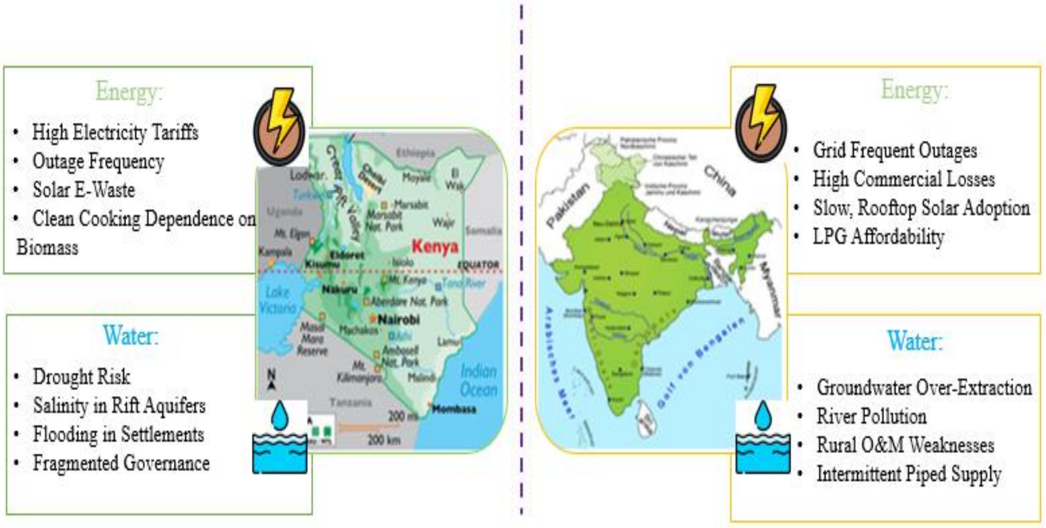


Fig. 1. Case study of India and Kenya and their challenges in the field of water and energy.

Fig. 1 shows the maps, locations, and key geographic features of the two case studies, alongside their energy and water challenges. In energy, both countries face frequent outages and gaps in clean cooking access. Kenya's power mix has a higher share of renewables, but reliability and cost remain issues [48]. In India, LPG affordability is a constraint, and the rollout of small-scale rooftop solar has been comparatively slow [49]. On the water infrastructure, both countries have meaningful resources, yet India struggles with over-extraction and pollution, while Kenya's fragmented regulations and climate variability hinder reliable supply. India also faces O&M and supply chain challenges for rural schemes [50]. In Kenya, soil conditions and intense rainfall make flooding a significant risk. Overall, given their resources, populations, and locations, these challenges are addressable through an integrated water–energy–environment approach. The result section outlines potential solutions within this framework.

3.2 | Selecting the Technology

Fig. 2 focuses on the water and energy technologies that are most widely adopted and thoroughly studied, ensuring the analysis remains practical. For water infrastructure, the selected technologies include boreholes, rainwater harvesting, and wastewater treatment. On the energy side, a review of 63 articles covering 10 different technologies highlights solar PV, biomass gasification, LPG, and mini-hydro as the options most commonly implemented in practice.

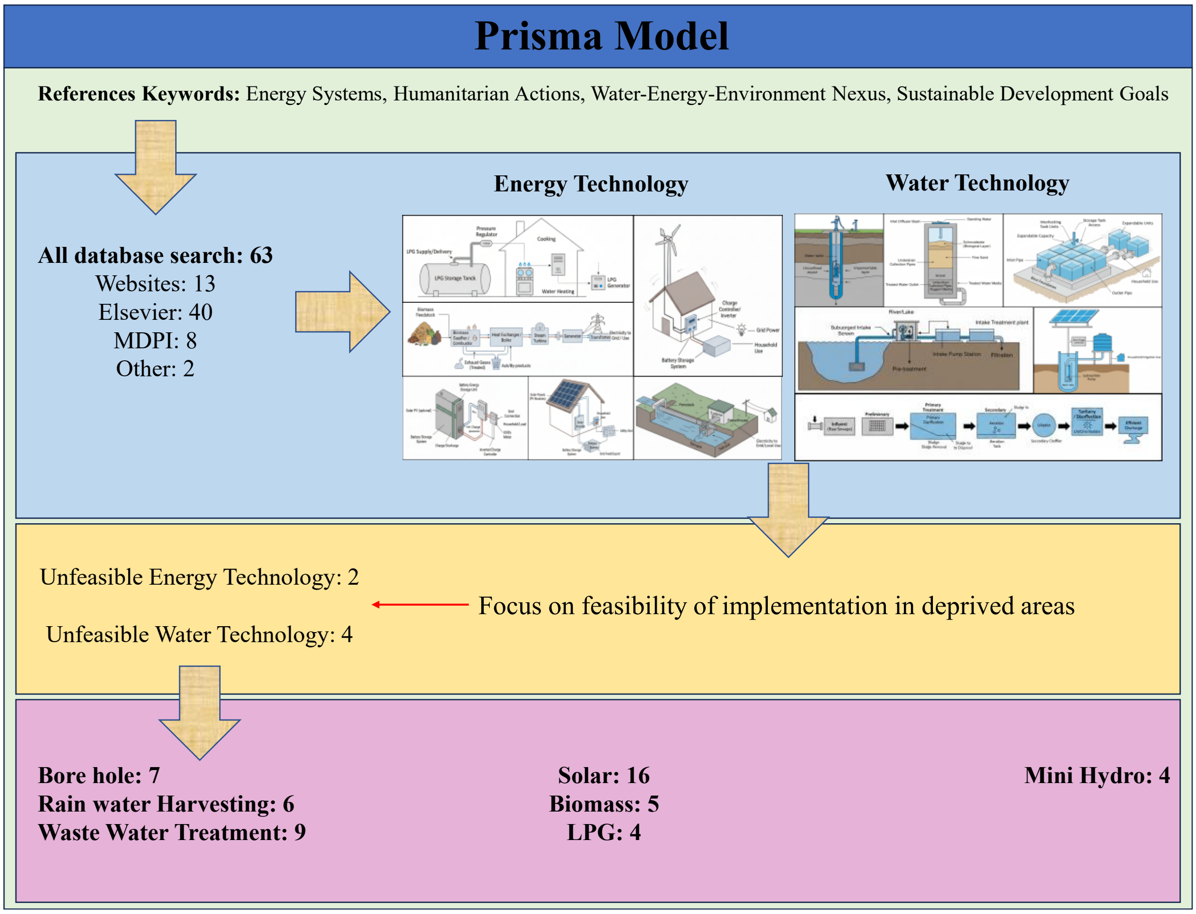
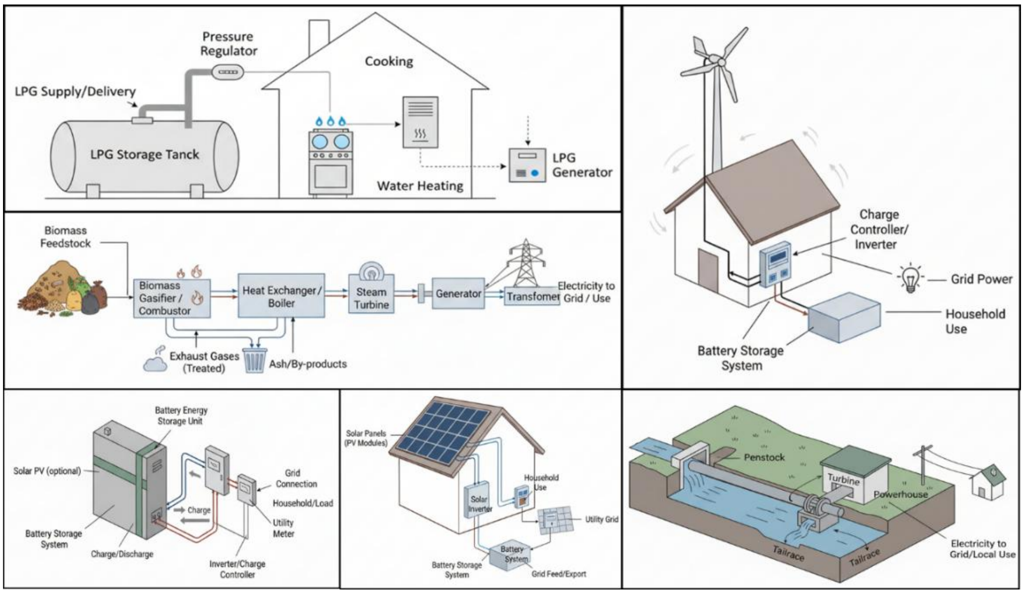


Fig. 2. Water-Energy technology criteria for selection

Fig. 3 then walks through how these technologies work over their life cycles, shown separately for (Fig. 3a) energy systems and (*Fig. 3.b*) water systems. It facilitates the linkage between technology choices and practical applications.



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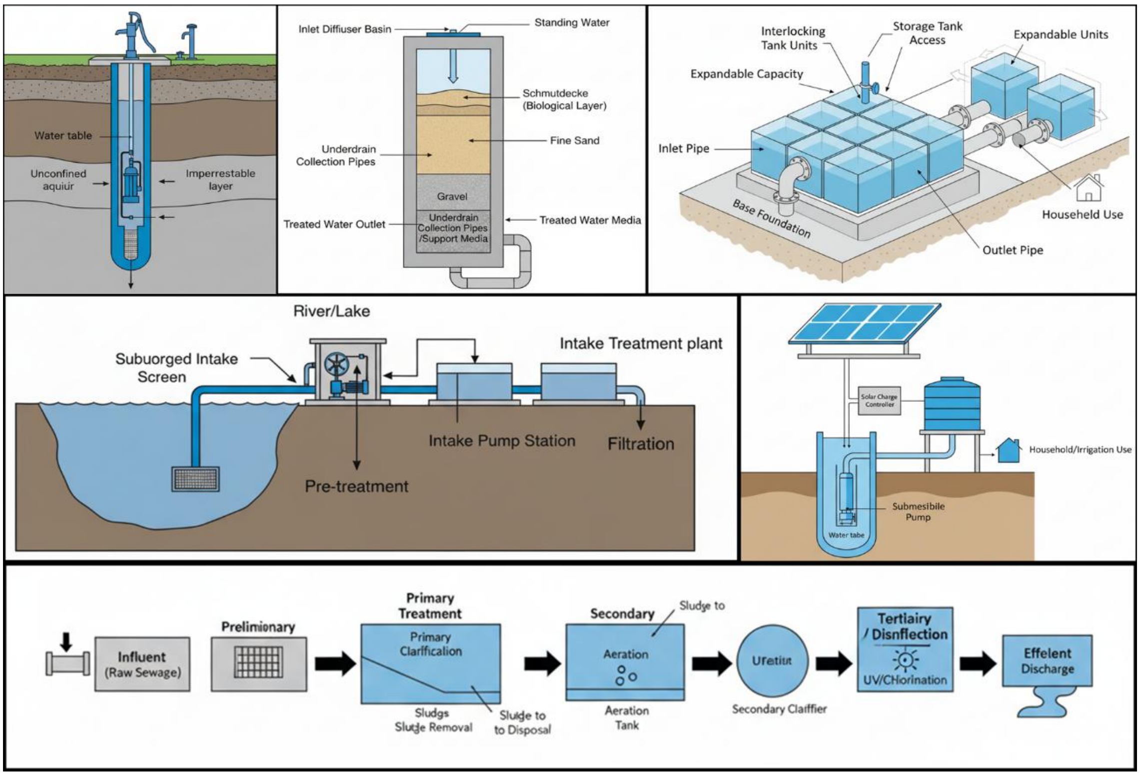


b.

Fig. 3. Technologies selected in the different cases; a. Energy, b. Water.

3.3 | Indicators

Based on the literature review and interviews with experts in both fields of water and energy, the indicators for each category have been defined, which are summarized in *Tables 3* and *4*. In the energy section (*Table 3*), mini-hydro stands out for the highest efficiency and the lowest carbon footprint. LPG, given its production and supply chain, scores best on lifetime, job creation, and price. Biomass gasification, meanwhile, offers the highest capacity factor.

Table 2. Metrics for prioritizing the Energy technologies.

Metric	Biomass Gasification [51], [52]	Solar PV [53], [54]	Mini Hydro [55], [56]	LPG [57], [58]
Efficiency (%)	70	25.2	80	65
Capacity Factor (%)	73	17.4	48	59.7
Cost ($/kW)	2,730	691	2,881	109
CO2eq Footprint (kg/kWh)	0.868	0.041	0.024	0.3
Lifetime (years)	20	30	25	30
Employment	1	0.3	0.25	2.1

According to Table 4, borehole water systems score best on delivered water quality and reliability, create the most jobs per unit capacity, and have the lowest carbon footprint. Rainwater harvesting is the most affordable in terms of upfront capital cost. By contrast, wastewater treatment has the longest lifespan, offering strong long-term performance, albeit with higher initial investment.

Table 3. Metrics for prioritizing the Water technologies.

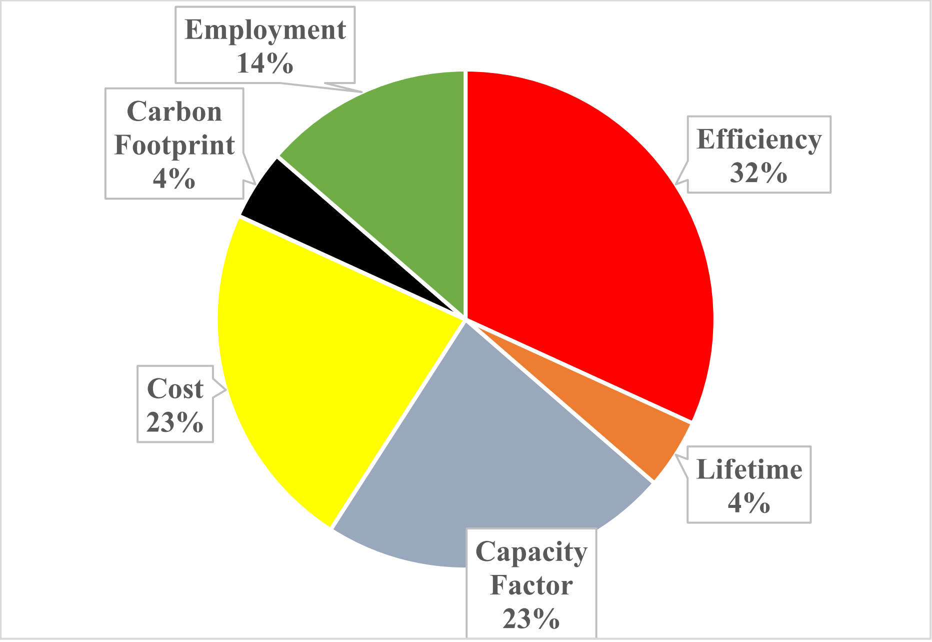
Criteria	Borehole [59], [60]	Rainwater Harvesting [61], [62]	Wastewater Treatment [63], [64]
Capital Cost ($\$/m^3$ capacity)	400	315	800 - 2500
Water Quality (mg/L BOD)	5	3.2	12.5
Carbon Footprint (kg CO_2/m^3)	0.5	0.25	0.6
Lifespan (years)	20 - 30	15	60
Labor Required (persons/$1m^3$/day)	4	1	0.9
Reliability (days/year)	350	200	350

4 | Result and Discussion

This section presents the key findings derived from the framework and the expert questionnaire, followed by the weighting approach and the resulting nexus analysis. Together, these elements identify the top water and energy technologies that policymakers and practitioners in India and Kenya can prioritize for transition. The study then offers practical recommendations to strengthen the framework's real-world applicability and to address on-the-ground challenges. Finally, mechanisms are outlined to scale solutions across the II nexus, enabling promising pilot projects to evolve into sustainable, system-wide programs.

4.1 | Questioner Results

Fig. 4 summarizes how our expert panel weighted the indicators for energy and water technologies. For energy (*Fig 4.a*), efficiency is the top priority at 32% of the total weight, followed by capacity factor and cost, each at 23%. For water infrastructure (*Fig 4.b*), project cost is most important at 35%, with water quality and reliability next, each at 20%. These weights reflect what matters most for service delivery in the two sectors and are used in *Eq. (1)* to compute the Integrated Index scores discussed in the next subsection.



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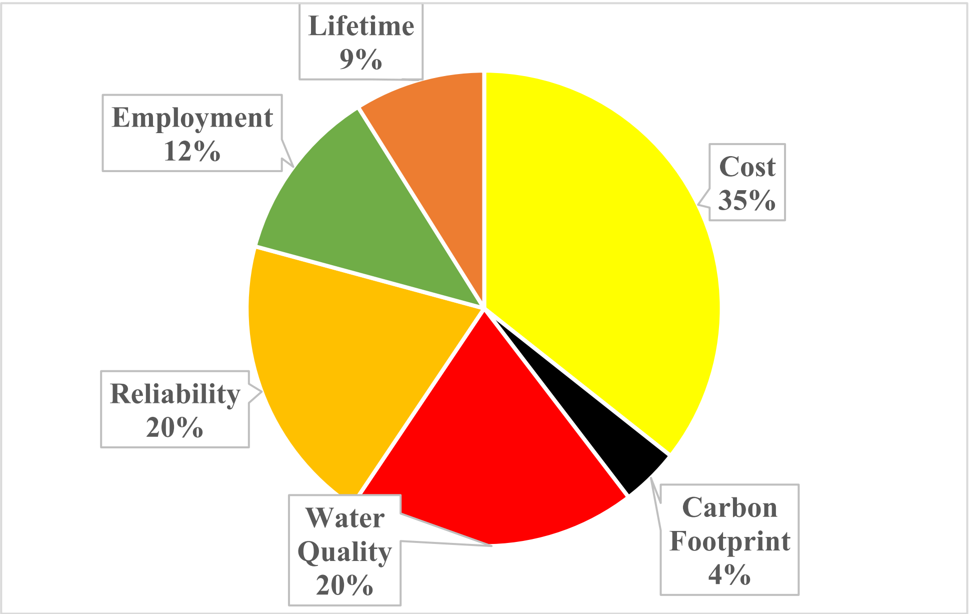
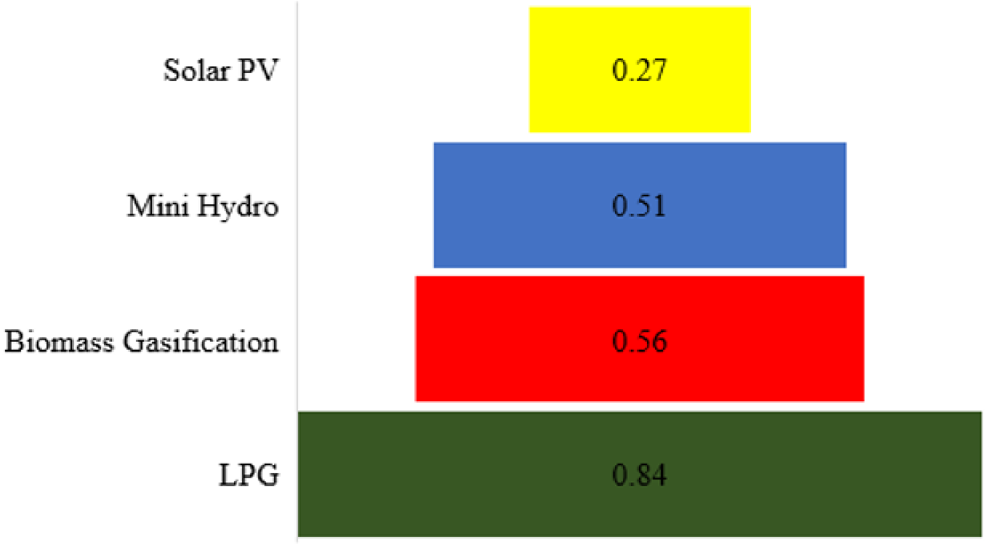


b.

Fig. 4. Weighting of the water and energy indicators by experts; a. Energy sector, b. Water infrastructure.

4.2 | Framework Result

Using *Eq. (1)*, the indicator values from *Tables 2* and *3*, and the expert weights from Section 4.1, we computed the Integrated Nexus Index (INI) scores. In energy (*Fig. 5.a*), LPG ranks first overall, with biomass gasification next. In water (*Fig. 5.b*), boreholes come out on top, followed by rainwater harvesting.



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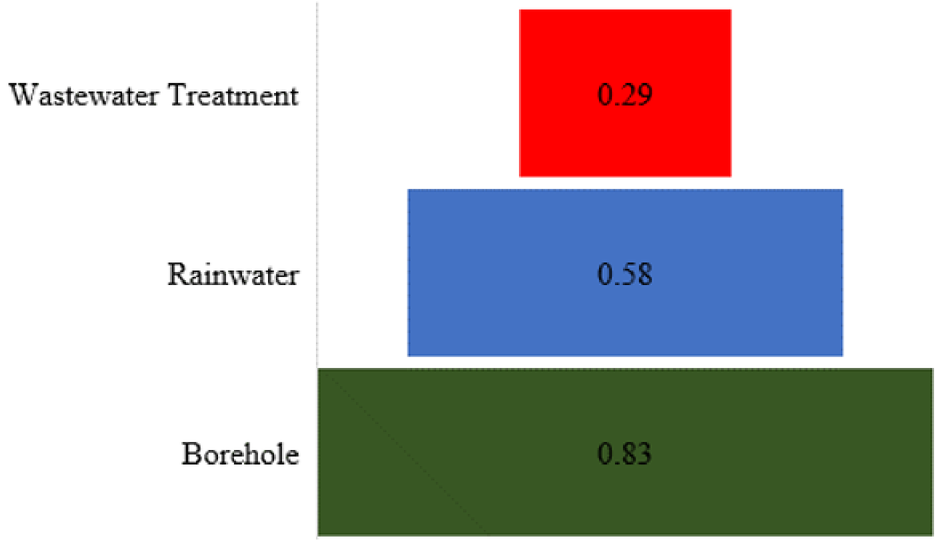

b.

Fig. 5. Integrated index results for; a. Energy sector, b. Water infrastructure.

The II framework results, grounded in expert-weighted indicators, point to boreholes as the leading water option and LPG as the top energy option for near-term deployment. It's recommended that policymakers and practitioners in India and Kenya prioritize these solutions, especially in high-need areas, to improve service reliability and access. Adopting this ranked approach can help align energy systems with humanitarian objectives and accelerate progress within the MCDM, fostering more integrated, service-oriented programs rather than isolated interventions.

4.3 | Future Planning

Based on these results, we offer practical recommendations for policymakers and communities in underserved areas. By following these steps, they can reduce energy, water, and environmental challenges while advancing progress toward the Sustainable Development Goals.

I. Moving from small scale to national level, which can be integrated in real-world challenges, can be a key. Investment in the implementation of the Integrated Index in impoverished areas of the world can save millions of people worldwide.

II. Building crisis-resilient supply chains in the water–energy–environment field by designing systems that can keep working during droughts, floods, or conflict. These systems are modular, easy to deploy quickly, and focused on delivering reliable services

III. Circular resources recovery in water-energy fields helps to reduce food and water waste, improve energy systems efficiency, which can be amplified by teaching people in those locations.

IV. Strengthen utilities and rural providers: Performance contracts, loss-reduction programs, and cost-reflective tariffs with pro-poor safeguards.

5 | Conclusion

This study introduced and applied the Integrated Index (II) to prioritize water and energy technologies in humanitarian and poverty-affected contexts through a WEE lens, using India and Kenya as case studies. Grounded in a PRISMA-informed review (82 references) and expert weighting via the Best–Worst Method, the II synthesized technical, economic, environmental, and social indicators into a transparent decision metric. Three overarching conclusions emerge.

I. First, decision salience differs by sector: Efficiency dominates technology choice in energy, while cost and reliability lead in water infrastructure.

II. Second, under the elicited weights and available performance data, LPG and biomass gasification rank highest for near-term, service-oriented energy delivery; for water, borehole development ranks first on reliability and service continuity, followed by rainwater harvesting, with wastewater treatment offering superior longevity but higher capital needs.

III. Third, these rankings align with on-the-ground constraints in India and Kenya like uneven electricity reliability, persistent clean-cooking gaps, groundwater dependence and depletion, intermittent urban supply, and limited wastewater capacity.

Policy and practice should prioritize service-based contracting with O&M process, and demand management to protect aquifers, and circular resource strategies (e.g., energy and nutrient recovery) to enhance resilience under droughts and floods. The INI framework is adaptable: weights and indicators can be localized, extended to include food and environmental co-benefits, and embedded in results-based financing.

Author Contribution

Mojtaba Sedaghat: Original draft, Conceptualization, Interview.

Nima Emami Kian: Writing, Visualization, Software, Conceptualization.

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Data Availability

All data have been included in the body of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest or personal relationships that affect this research.

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