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Feasibility of Developing Solar Power Parks in Uttarakhand: An ISM-MICMAC Approach

Pankaj Aswal[1] (Corresponding Author), Atul Rawat[2]

[1]*School of Business, University of Petroleum and Energy Studies, Kandoli, Dehradun 248001, India*
PANKAJ.113640@stu.upes.ac.in
[2]*School of Business, University of Petroleum and Energy Studies, Kandoli, Dehradun 248001, India*
a.rawat@ddn.upes.ac.in

Abstract :-Uttarakhand, a state blessed with great solar potential, has particular difficulties moving toward renewable energy. This research uses an Interpretative Structural Modelling (ISM) and MICMAC technique to identify and evaluate important obstacles, therefore investigating the viability of utility-scale solar power farms in Uttarakhand. The report identifies 19 key components: legislative gaps, financing sources, land acquisition challenges and geographic constraints. Depending upon ISM data, "lack of state-specific solar policies" and "multifaceted land-use regulations" show up as basic hurdles; "high initial investment" and "environmental concerns" occupy the top of the hierarchical structure. Highlighting the importance of particular policy actions, MICMAC study defines obstacles into driving, dependent, and linking categories. In line with Uttarakhand renewable energy aims and ecological preservation goals, the study provides officials practical insights to hasten solar park development.

Keywords: Solar parks, Uttarakhand, Feasibility analysis, ISM, MICMAC, Renewable energy policy.

1. Introduction

Uttarakhand boasts tremendous solar energy potential, with an average solar irradiation of 5.4 kWh/m²/day and 300 bright days yearly. Despite this, the state continues to depend largely on hydropower and thermal energy, which exposes it to risks during seasonal swings. The Uttarakhand Renewable Energy Development Agency (UREDA) aspires to develop 2,500 MW of solar power by 2030, however progress has been sluggish owing to many difficulties. Uttarakhand power consumption is roughly 1,500–1,600 MW, with a 52% gap in renewable energy supply (Roy & Bhatt, 2021). Approximately 50% of the state's energy demands are satisfied by imports, showing the dependency on hydropower (Roy & Bhatt, 2021). Issues such as high prices, poor service, and lack of infrastructure restrict solar energy implementation (Roy & Bhatt, 2021). A need for an integrated policy framework is underlined to support fast renewable energy adoption (Roy & Bhatt, 2021). The creation of solar parks in Uttarakhand is a viable strategy to manage energy deficits and lessen dependent on hydropower, which is subject to volatility. By harnessing solar energy, the state can tap into its renewable energy potential to meet the huge power supply gap. The following sections outline the benefits and issues of setting up solar parks in Uttarakhand. Energy production can make a great deal of contribution by solar parks. The total potential in Uttarakhand can be 8115 MW. Around 20 GW of solar parks can produce around 37.16 million MWh of solar energy per year which can displace over 34.67 million tons of CO_2 (Rajaram & Balamurugan, 2020). The lowest reported levelized cost of energy (LCOE) for solar PV technology is 32.23 €/MWh (Silva et al ., 2020). Investing in solar parks can

create economic opportunities and jobs, thus enhancing sustainable growth in rural areas (Ghosh et al ., 2023). Fixing problems with the quality of power due to grid connection could be managed by integrating solar parks (Kalal & Byalihal, 2024). Installing solar power plants in different areas can reduce the variations that may occur and help our grid to stay strong when there is less sunshine. However, the hilly areas, forest area, and other rules pose their own issues. This study utilizes the ISM-MICMAC framework to analyse the barriers to the implementation of solar parks and presents a contextual roadmap for energy transition in Uttarakhand.
Objectives of this work include identifying and analysing key barriers to solar power park implementation in Uttarakhand using ISM-MICMAC methodology. The novelty lies in the application of a structured modelling framework to a region-specific renewable energy challenge, offering a unique lens to evaluate feasibility.

2. Uttarakhand Energy Landscape

As of 2023, India hosts 61 solar parks across 18 states with a total capacity of 40 GW. The topography of Uttarakhand mountainous with steep gradients poses unique challenges, but areas like Haridwar, Udham Singh Nagar and Dehradun are relatively suitable due to flatter terrain and decent solar irradiance of around 5.4–6.0 kWh/m²/day. With renewable energy sources contributing only 18% (756 MW), solar power accounts for just 5% (210 MW), which is a relatively small share despite the state's favourable geographic conditions for solar energy generation. The slow adoption of solar power in Uttarakhand can be attributed to several key challenges, including land scarcity, inadequate grid connectivity, and policy gaps.(Zebra et.al, 2021) Addressing these barriers is crucial for expanding solar energy and enhancing the state's renewable energy portfolio as shown in Table (1).

2.1 Land Scarcity

One of the most major challenges to solar power growth in Uttarakhand is land availability. Nearly 65% of the state's entire land area is covered by woods, which hinders large-scale solar park construction. Unlike states with extensive spans of barren or dry territory, Uttarakhand hilly and environmentally sensitive terrain makes it difficult to assign big tracts of land for solar systems. Additionally, rigorous environmental rules further limit the conversion of forest area for energy projects. Land acquisition expenses are extremely significant, making utility-scale solar installations financially hard.
Given these limits, new solutions such as floating solar panels on reservoirs, rooftop solar installations, and agro-photovoltaics (where solar panels are combined with agricultural land) might give alternatives to typical land-based solar farms.(Garrod et.al, 2024) These measures may assist improve land use without sacrificing forest cover or agricultural yield.

2.2 Grid Connectivity Challenges

A significant hurdles to solar energy growth in Uttarakhand is insufficient grid infrastructure, especially in rural and mountainous locations. Many prospective solar project locations are situated in hilly terrain that require proper transmission and distribution networks.(Sadik-Zada et.al,2023) The difficult terrain increases the expense and complexity of installing transmission lines, resulting to delays and inefficiencies in power evacuation from solar systems to the main grid.
An additional solar power generated in distant locales cannot be successfully delivered to areas with greater energy demand without proper Grid connection.(Vaziri et.al,2023) This induces the less involvement of investors from starting significant solar projects and results in

underuse of solar potential. Making investments in smart grid technology and building distributed microgrids in Isolated or remote area locations might help to significantly increase the viability of solar power generating in Uttarakhand.

2.3 Policy Errors and Insufficient Motives

Unlike other Indian states such Gujarat, Rajasistan and Karnataka, which have set up subsidies, incentives, and land allocation rules for solar power projects, Uttarakhand lacks a specific framework to help solar park development. Another major problem is the absence of state specific guidelines and incentives meant to boost solar energy. For private investors and developers, the absence of financial incentives such as capital subsidies, viability gap loans or long-term power purchase agreements (PPAs) makes it less appealing. (Polzin et.al,2019) To offset this obstacle, the state government has to carry out specific legislative efforts include leasing land for solar projects, providing subsidies for rooftop solar systems, and streamlining of the approval procedure for renewable energy projects. Perhaps worthwhile projects include encouraging public-private partnerships (PPPs) and working with central government agencies to fund the development of solar infrastructure.

3. Identification of Key Barriers

3.1 Technical Barriers

1. Grid Instability (F4)

Uttarakhand hilly terrain and decentralized settlements pose significant challenges to grid stability. Frequent voltage fluctuations and transmission losses are exacerbated by outdated infrastructure, particularly in rural areas. Solar integration into the grid is further complicated by intermittent generation, which strains the existing power distribution network.(Denholm et al. 2021) highlight that regions with rugged topography, like Uttarakhand, require advanced grid management systems to balance renewable energy supply and demand.

2. Skilled Labour Shortage (F7)

The state suffers a scarcity of personnel and engineers qualified in solar panel installation, maintenance, and grid interconnection. This regional discrepancy is severe in outlying regions like as Chamoli and Pithoragarh, where migration of competent persons to metropolitan centres is prevalent.(IRENA 2021) stresses that distant locations in underdeveloped nations frequently lack particular training programs, impeding renewable energy employment creation.

3. Seasonal Weather Variability (F8)

Uttarakhand monsoon driven climate and winter fog diminish solar irradiation, resulting to seasonal declines in energy output. For instance, solar farms in Dehradun and Nainital report ~30% decreased production during peak monsoon months (July–September).(Pryor et al. 2020) indicate that mountainous locations with substantial seasonal weather fluctuation need adaptive energy storage and hybrid systems to maintain year-round dependability.

4. Inadequate R&D (F9)

Restricted investment in renewable energy research within Uttarakhand academic and industrial sectors has hampered the deployment of innovative technology like bifacial solar panels or AI-driven energy forecasting systems.(Nemet 2019) contends that underfunded R&D ecosystems in poor nations prolong dependence on old technology, impeding innovation.

5. Technological Obsolescence (F15)

Many solar projects in Uttarakhand employ decade-old photovoltaic (PV) technology with efficiency below 15%, compared to newer panels attaining >22%. This obsolescence is frequent in state-funded projects owing to financial restrictions. (Hoppmann et al. 2014) relate delayed policy revisions to the survival of outmoded technology in public-sector renewable projects.

6. Storage Limitations (F18)

Uttarakhand inhibits the deployment of solar energy during non-sunny hours owing to unavailability of economically appropriate battery storage devices. For example, distant settlements in Rudraprayag depend on diesel generators as backups, undercutting sustainability aspirations.(Larcher & Tarascon 2015) underline that mountainous areas demand decentralized, large capacity storage systems to address intermittency.

3.2 Financial Barriers

The development of solar energy sector in Uttarakhand has various financial barriers that limit large scale deployment and investment in renewable infrastructure. These financial challenges directly effect the viability of projects, investor confidence and the long term sustainability of solar energy efforts. The primary financial barriers are high initial investment costs, capital acquisition and market uncertainty.

1. High Initial Investment (F1)

One of the most major financial challenges to increasing solar energy in Uttarakhand is the high upfront cash necessary for building up solar power installations. Site purchase cost, equipment procurement and installation may be excessive, particularly for small and medium-sized enterprises (SMEs) and local investors. According to the International Energy Agency (IEA, 2020), the high initial costs of solar infrastructure usually discourage collaboration from diverse stakeholders, making big scale solar projects harder to accomplish.as the solar photovoltaic (PV) modules cost has been consistently compensating the complete expense of creating solar parks. However in the case of Uttarakhand it is difficult as logistical and infrastructural barriers creates costs even higher due to hilly terrain.

2. Financing Bottlenecks (F10)

Securing inexpensive, long term funding for solar installations is another big difficulty. Many investors and financial institutions consider renewable energy projects as high risk undertakings, resulting to restricted credit availability, high interest rates and tight loan requirements. As (Polzin & Sanders ,2020) stress, renewable energy companies typically face with financial uncertainties owing to ambiguous returns on investment, long payback times and difficulty in providing collateral for loans. In Uttarakhand, the lack of a well established finance ecosystem for solar energy projects further complicates the problem, making it difficult for developers to get the required financing for project execution and development.

3. Market Uncertainty (F17)

Change in energy prices, regulatory frameworks and unanticipated returns on ROI produce uncertainty in the solar energy market, prohibiting investors from investing. Government regulations, incentive structures and tariff limits considerably affect the renewable energy sector in Uttarakhand. As (Bohlmann & Inglesi-Lotz ,2021) stated about uncertainties hinders investor confidence, leading to delayed financial commitments and delays in project execution. Additionally, the absence of a steady demand supply structure for solar power in Uttarakhand leads to market instability, further hampering efforts to reach financial sustainability for solar energy initiatives.

3.3 Policy & Regulatory Barriers

Solar energy infrastructure in Uttarakhand has various governmental and regulatory difficulties that restrict investment, delaying project execution and generate ambiguity in the renewable energy industry. These barriers originate from policies and regulatory ineffectiveness which will create bureaucratic restrictions. The primary policy and regulatory constraints are lack of state funding, clearance from the environment delays, policy fragmentation, bureaucratic delays, forest preservation regulation and political prioritizing concerns.

1. Lack of State Subsidies (F5)

The lack of major financial incentives and subsidies for solar energy projects in Uttarakhand restricts the expansion of the industry. Many renewable energy entrepreneurs depend on government subsidies, tax exemptions and financial incentives to make projects commercially feasible. However due to uneven or inadequate support regimes discourage private investment. (Stokes 2020) notes that sustainable renewable energy policies need ongoing governmental support in the form of subsidies to stimulate adoption and build up the infrastructure. lack of financial assistance for solar power providers provides a barrier to entry in Uttarakhand even in case of small and medium companies (SMEs) and household solar users.

2. Environmental Clearance Delays (F6)

Environmental effect assessments (EIAs) and regulatory permissions typically delay solar energy projects in Uttarakhand. strict environmental rules & regulations and lengthy approval processes create project cancellations or severe delays among the developers side. (Sovacool & Dworkin, 2015) explains that even considering environmental issue. excessive bureaucratic red tape and lack of coordination among regulatory organizations hinder down renewable energy deployment.

3. Policy Fragmentation (F11)

Solar energy progress in Uttarakhand adds to regulatory inconsistency as the lack of a comprehensive and consistent policy framework. Indian government departments and state governing organizations manage different sections of solar energy regulation creates conflicting rules and unclear execution standards. (Lockwood et al. 2017) underline that regulatory fragmentation may damage investor confidence, generate inefficiencies and slow down the shift to renewable energy. In Uttarakhand, the absence of a clear, long term solar energy strategy has resulted in uneven tariff structures, regulatory overlaps and lack of coordination between state and national programs.

4. Bureaucratic Delays (F14)

Solar energy projects in Uttarakhand are often hindered by administrative inefficiencies, slow approval processes and excessive documentation requirements. Developers face challenges in obtaining land permits, grid connectivity approvals and financing clearances due to lengthy bureaucratic procedures. (Ahlborg & Hammar, 2014) argue that cumbersome bureaucratic processes deter private investors, increase project costs and delay infrastructure deployment. The requirement for many permissions from different government authorities without a simpler strategy further exacerbates project delays in Uttarakhand.

5. Forest Conservation Laws (F16)

Uttarakhand confronts legislative difficulties linked to land exploitation for solar energy projects, since Strict Forest protection rules limit the utilization of some land parcels for solar power systems, making site acquisition a considerable burden for developers. (Adams 2020) states that while environmental conservation is critical, inflexible land use policies can significantly limit renewable energy expansion. In Uttarakhand, the classification of land under forest reserves limits the availability of large tracts of land for solar parks, thereby increasing project costs and administrative hurdles.

6. Political Prioritization (F19)

The lack of strong political commitment and inconsistent government priorities pose challenges to solar energy expansion in Uttarakhand. Policy shifts due to changing governments, election cycles and lobbying by conventional energy sectors create uncertainty in the renewable energy sector. (Meckling et al. 2015) stress that political will plays a vital role in creating renewable energy policy and uneven prioritizing might hinder long term investment in the field. Solar energy policy in Uttarakhand are sometimes overshadowed by competing interests such as hydroelectric projects, reducing the emphasis on solar energy as a key energy source.

3.4 Social Barriers

The adoption of solar energy in Uttarakhand is driven not only by financial and policy related factors but also by sociocultural barriers that impact project execution and acceptance. These barriers are often connected to land acquisition constraints, geographic restrictions, community resistance and infrastructure inadequacies, which may severely delay or hamper solar energy deployment. Addressing these problems demands stakeholder involvement, social inclusion and localized policy initiatives to facilitate smooth project execution.(Norouzi et.al, 2022)

1. Land Acquisition Challenges (F2)

Complexity in ownership as high population density in certain locations and local community opposition. Acquiring land for solar power projects in Uttarakhand is rather difficult as solar parks covers vast areas of land, which often causes disputes on environmental issues, relocation and compensation. (Levenda et al. 2021) satiated about legal disputes even unclear property rights and opposition from affected people usually cause delays in land acquisition for renewable energy projects. In Uttarakhand, the situation is worsened by the existence of protected forest regions and agricultural land, where land use regulations further limit supply.

2. Geographic Constraints (F3)

Uttarakhand hilly terrain creates significant geographic challenges for solar energy deployment. the mountainous landscape of Uttarakhand hinders suitable locations for solar panel installation. (Hoogwijk et al. 2004) suggests that solar energy generating potential is proportionally dependent on geographic and climatic conditions, with mountainous areas added difficulties related to shading even land stability and transmission losses. The inaccessibility of remote locations further increases the costs of transporting and installation. This will create challenge in implementation and adoption of large scale solar parks.

3. Community Resistance (F12)

Public opposition and lack of social acceptance are key barriers to the successful implementation of solar energy projects in Uttarakhand. Large scale solar projects raise questions regarding land displacement, inadequate compensation and environmental effect, which makes many local governments dubious. According to (Wüstenhagen et al. 2007), effective stakeholder involvement, confidence in legislators and perceived advantages to the local community define societal acceptability of renewable energy. Fear of change in Uttarakhand is often connected to ignorance about solar energy advantages over insufficient interaction with local people during project development. To develop trust and support for solar projects by overcoming this barriers as per community awareness and participation in tends to better decision making process.

4. Infrastructure Gaps (F13)

Theme	Barrier	Code	Citation
Technology	Grid instability	F4	Denholm et.al (2021)
	Skilled labour shortage	F7	IRENA. (2021)
	Seasonal weather variability	F8	Pryor et.al,(2020)
	Inadequate R&D	F9	Nemet, (2019)
	Technological obsolescence	F15	Hoppmann et.al,(2014)
	Storage limitations	F18	Larcher & Tarascon (2015)
Financial	High initial investment	F1	IEA. (2020)
	Financing bottlenecks	F10	Polzin & Sanders (2020)
	Market uncertainty	F17	Bohlmann & Inglesi-Lotz (2021)
Policy & Regulatory	Lack of state subsidies	F5	Stokes (2020)
	Environmental clearance delays	F6	Sovacool & Dworkin (2015)
	Policy fragmentation	F11	Lockwood et.al, (2017)
	Bureaucratic delays	F14	Ahlborg & Hammar (2014)
	Forest conservation laws	F16	Adams (2020)
	Political prioritization	F19	Meckling et.al, (2015)
Social	Land acquisition challenges	F2	Levenda et.al, (2021)
	Geographic constraints	F3	Hoogwijk et.al,(2004)
	Community resistance	F12	Wüstenhagen et.al, (2007)
	Infrastructure gaps	F13	Bazilian et al, (2019)

Table1:-Barriers in SPP implementation in Uttarakhand

The absence of suitable infrastructure in Uttarakhand offers another key hurdle to solar energy growth. Limited road connections, outdated energy infrastructures and insufficient transmission capacity limit the incorporation of solar power into the state's electrical network. According to (Bazilian et al. 2019), poor infrastructure generally limits the acceptance of renewable energy in underdeveloped areas. This will cause inefficiencies in supply dependability and power distribution. In Uttarakhand, rural and distant regions suffer from insufficient grid connection, making it difficult to transmit produced solar electricity to places with high energy demand. To fill up these infrastructural voids, investments in smart energy management systems, battery storage and grid modernization are essential.

The data for identifying barriers were collected using semi-structured interviews with 12 energy experts, supported by secondary data from government reports and peer-reviewed literature. The 19 barriers were shortlisted using thematic analysis and expert consensus to ensure relevance to solar park implementation in Uttarakhand. Through literature review and expert consultations (n=12), 19 barriers were identified.

4 Research Method Approach

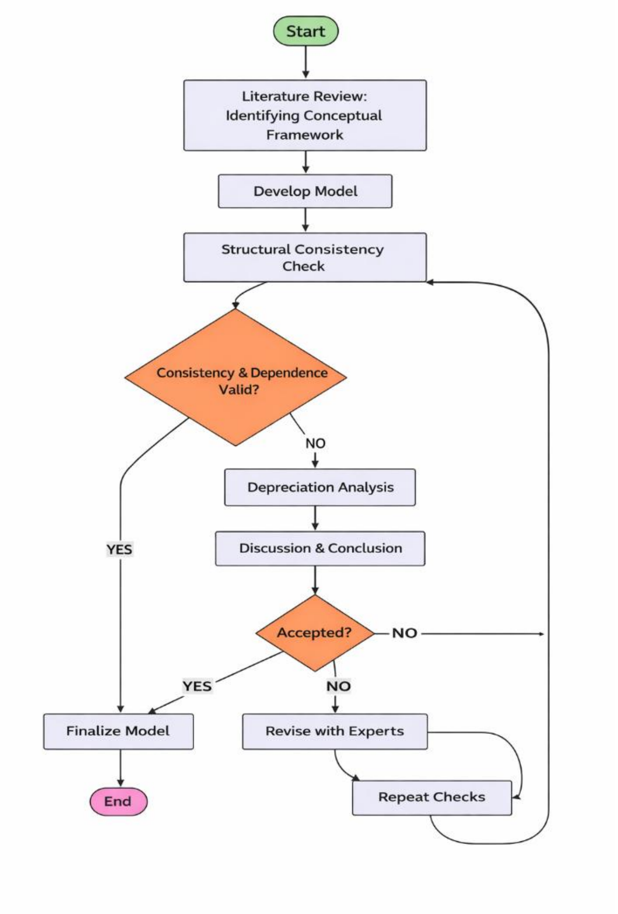

Figure (1):- Research framework

This flowchart depicts an organized research approach for building and evaluating a conceptual model. It starts with the Literature Review, which identifies the conceptual framework. Once a framework is defined,the following step is to construct the Model. After model development, a Structural Consistency Check is done to establish logical coherence. The decision point "Consistency & Dependence Valid?" assesses whether the model is structurally sound. If YES, the procedure continues immediately to Finalizing the Model. If NO, a Depreciation Analysis is undertaken to evaluate flaws. Following depreciation analysis, the study goes to Discussion & Conclusion, where insights and results are evaluated. Another judgment point, "Accepted?" assesses whether the model matches the needed requirements represented in figure (1) If YES, the model is finished. If NO, it is forwarded for Review with Experts to acquire expert perspectives.

The ISM and MICMAC analyses reveal that high initial investment, land acquisition challenges, and lack of state-specific policies are the foundational barriers. These trends align with national-level data where policy and land issues are reported as primary challenges for solar park development (MNRE, 2024). The classification of barriers into driving and dependent factors helps in identifying leverage points for intervention.

5. ISM and MICMAC Analysis

5.1 Structural Self-Interaction Matrix (SSIM)

The Structural Self-Interaction Matrix (SSIM) is used to evaluate the interactions between various barriers or elements in a system. It helps indicate the directional impact of one barrier over another using particular symbols:

• V: The row element effects the column element.

• A: The column element effects the row element.

• X: Both factors impact each other mutually.

• O: No direct link exists between the components.

By assigning these symbols to a matrix, SSIM offers a formal mechanism to examine relationships and interactions between barriers. This strategy is extensively used in Interpretive Structural Modelling (ISM) to construct hierarchical structures and comprehend complicated systems. The SSIM serves as the basis for turning qualitative interactions into a quantitative reachability matrix, facilitating in decision-making and strategy planning.

5.1.1 Interpretation of relationships:

- **High Initial Investment (F1)** → influences financing (F10), policy (F11), and infrastructure (F13).
- **Land Acquisition (F2)** → impacts policy (F11), bureaucracy (F14), and community resistance (F12).
- **Geographic Constraints (F3)** → affect infrastructure (F13), grid stability (F4), and environmental laws (F16).
- **Grid Instability (F4)** → affects market uncertainty (F17) and storage (F18).
- **Lack of State Subsidies (F5)** → influences financing (F10) and political prioritization (F19).
- **Environmental Clearance (F6)** → influences bureaucratic delays (F14) and policy fragmentation (F11).
- **Skilled Labour Shortage (F7)** → affects technology obsolescence (F15) and R&D (F9).
- **Seasonal Variability (F8)** → affects market uncertainty (F17) and storage (F18).
- **Inadequate R&D (F9)** → influences technology (F15) and financing (F10).
- **Financing Bottlenecks (F10)** → impacted by policy (F11) and subsidies (F5).

- **Policy Fragmentation (F11)** → affects multiple barriers like subsidies (F5), bureaucracy (F14), and political prioritization (F19).
- **Community Resistance (F12)** → linked to land acquisition (F2) and political prioritization (F19).
- **Infrastructure Gaps (F13)** → linked to geographic constraints (F3) and grid instability (F4).
- **Bureaucratic Delays (F14)** → linked to environmental clearance (F6), policy (F11), and subsidies (F5).
- **Technological Obsolescence (F15)** → influenced by R&D (F9) and financing (F10).
- **Forest Conservation Laws (F16)** → influenced by environmental clearance (F6) and land acquisition (F2).
- **Market Uncertainty (F17)** → affected by grid instability (F4), financing (F10), and seasonal weather (F8).
- **Storage Limitations (F18)** → affected by grid instability (F4) and market conditions (F17).
- **Political Prioritization (F19)** → affects subsidies (F5), policy (F11), and bureaucracy (F14).

Justification is analysed in SSIM Matrix and Initial reachability Matrix of the following barriers in implementation and adoption of solar power park in Uttarakhand as mentioned in Figure (2) and Figure (3).

5.1.2 SSIM Matrix for Solar Power Park Barriers in Uttarakhand

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
F1	O	O	V	V	V	V	O	O	O	V	V	O	V	V	V	V	V	V	V
F2	O	O	O	O	V	V	O	O	O	V	V	X	O	V	V	O	V	V	V
F3	A	O	O	V	O	O	O	O	O	O	O	O	X	O	O	V	V	V	O
F4	A	O	A	O	O	O	O	O	O	O	O	O	A	O	O	O	V	V	O
F5	A	A	O	O	O	A	O	O	O	V	A	A	O	A	V	O	V	O	X
F6	A	A	O	O	V	O	O	O	O	V	X	A	O	X	V	O	V	V	X
F7	O	O	O	O	O	O	O	O	V	V	O	O	O	O	V	O	V	O	O
F8	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	V	O
F9	O	O	O	O	O	O	A	O	O	V	O	O	O	O	V	O	V	O	O
F10	A	A	O	O	A	A	A	O	A	O	A	A	O	A	V	O	V	V	A
F11	A	A	O	O	V	X	O	O	O	V	O	A	O	X	O	O	V	V	X
F12	O	X	O	O	V	V	O	O	O	V	V	O	O	V	V	O	V	V	V
F13	A	O	X	V	O	O	O	O	O	O	O	O	O	O	O	V	V	V	O
F14	A	A	O	O	V	X	O	O	O	V	X	A	O	O	V	O	V	V	X
F15	A	A	O	O	A	A	A	O	A	A	O	A	O	A	O	O	O	O	A
F16	A	O	A	O	O	O	O	O	O	O	O	O	A	O	O	O	O	O	O
F17	A	A	A	A	A	A	A	A	A	A	A	A	A	A	O	O	O	V	A
F18	A	A	A	A	O	A	O	A	O	A	A	A	A	A	O	O	A	O	A
F19	A	A	O	O	X	X	O	O	O	V	X	A	O	X	V	O	V	V	O

Figure (2):- Full SSIM Matrix of Barriers

5.1.3 Initial reachability Matrix

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
F1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0
F2	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
F3	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
F4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
F5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
F6	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
F7	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
F8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
F9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
F10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
F11	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
F12	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
F13	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F14	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0
F15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
F18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F19	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0

Figure (3):- IRM of Barriers in Uttarakhand

Key Observations:

1. **Bidirectional Relationships** (e.g., F5 ↔ F19, F11 ↔ F19, F3 ↔ F13) indicate mutual influence.
2. **High Initial Investment (F1)** directly drives financing (F10), policy (F11), and infrastructure gaps (F13).
3. **Policy Fragmentation (F11)** is a central node influencing subsidies (F5), bureaucracy (F14), and political prioritization (F19).
4. **Technological Obsolescence (F15)** and **Forest Conservation Laws (F16)** are primarily influenced by other factors (F9/F10 and F6/F2, respectively) but do not influence others directly.
5. **Storage Limitations (F18)** are affected by grid instability (F4) and market uncertainty (F17).

5.1.4 Final reachability Matrix

Though there are various barriers in the implementation and adoption of solar power park in Uttarakhand. The following identified barriers are the most impactful which is responsible of effective implementation of SPP in Uttarakhand. The barriers are also linked with each other creating the transitivity condition as shown in Figure (4) final reachability matrix. The resulted Smart ISM matrix is shown in Figure (5).

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Driving Power
F1	1	0	1	1	1	1	0	0	0	1	1	0	1	1	1	1	1	1	1	14
F2	0	1	0	0	1	1	0	0	0	1	1	1	0	1	1	0	1	1	1	11
F3	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	6
F4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	3
F5	0	0	0	0	1	1*	0	0	0	1	1*	0	0	1*	1	0	1	1*	1	9
F6	0	0	0	0	1	1	0	0	0	1	1	0	0	1	1	0	1	1	1	9
F7	0	0	0	0	0	0	1	0	1	1	0	0	0	0	1	0	1	1*	0	6
F8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	3
F9	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	1	1*	0	5
F10	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	0	4
F11	0	0	0	0	1	1	0	0	0	1	1	0	0	1	1*	0	1	1	1	9
F12	0	1	0	0	1	1	0	0	0	1	1	1	0	1	1	0	1	1	1	11
F13	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	6
F14	0	0	0	0	1	1	0	0	0	1	1	0	0	1	1	0	1	1	1	9
F15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
F16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
F17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2
F18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
F19	0	0	0	0	1	1	0	0	0	1	1	0	0	1	1	0	1	1	1	9
Dependence Power	1	2	3	4	8	8	1	1	2	11	8	2	3	8	12	4	16	17	8	

Figure (4):- Final Reachability Matrix of Barriers

5.2 .ISM Hierarchy:

5.2.1 Smart ISM Matrix

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Variables
	O	V	V	V	V	O	O	O	V	V	O	V	V	V	V	V	V	V	High initial investment (F1)
		O	O	V	V	O	O	O	V	V	X	O	V	V	O	V	V	V	Land acquisition challenges (F2)
			V	O	O	O	O	O	O	O	O	X	O	O	V	V	V	O	Geographic constraints (F3)
				O	O	O	O	O	O	O	O	A	O	O	O	V	V	O	Grid instability (F4)
					A	O	O	O	V	A	A	O	A	V	O	V	O	X	Lack of state subsidies (F5)
						O	O	O	V	X	A	O	X	V	O	V	V	X	Environmental clearance delays (F6)

							O	V	V	O	O	O	O	V	O	V	O	O	Skilled labour shortage (F7)
								O	O	O	O	O	O	O	O	V	V	O	Seasonal weather variability (F8)
									V	O	O	O	O	V	O	V	O	O	Inadequate R&D (F9)
										A	A	O	A	V	O	V	V	A	Financing bottlenecks (F10)
											A	O	X	O	O	V	V	X	Policy fragmentation (F11)
												O	V	V	O	V	V	V	Community resistance (F12)
													O	O	V	V	V	O	Infrastructure gaps (F13)
														V	O	V	V	X	Bureaucratic delays (F14)
															O	O	O	A	Technological obsolescence (F15)
																O	O	O	Forest conservation laws (F16)
																	V	A	Market uncertainty (F17)
																		A	Storage limitations (F18)
																			Political prioritization (F19)

Figure (5):- Smart ISM Matrix of Barriers in SPP Implementation

5.3 .MICMAC Diagram

The Driving-Dependence Power Grid or MICMAC (Matrix Impact Cross-Reference Multiplication Applied to a Classification) diagram as shown in figure (6), divides the factors affecting the development of solar power parks in Uttarakhand into four quadrants according to their driving power (y-axis) and dependence power (x-axis).

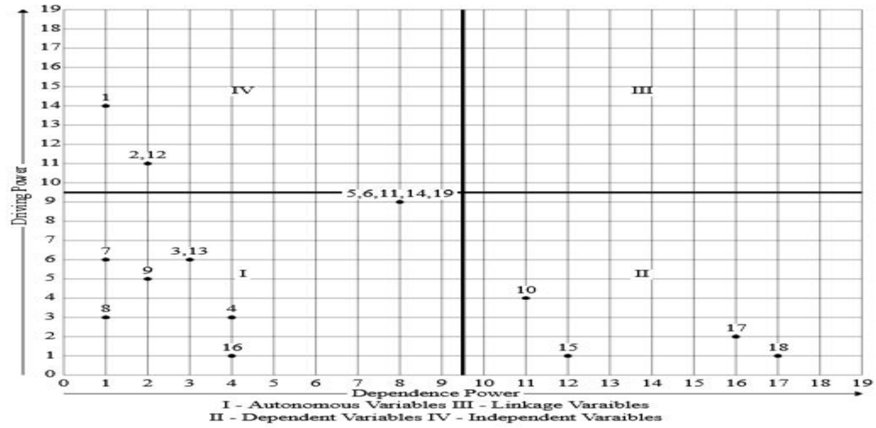

Figure (6):- MICMAC Analysis of Barriers

Quadrant I – Autonomous Variables

These variables (e.g., 3, 7, 8, 9, 13, 16) have low driving and dependency power, demonstrating they are weakly related to the system and do not appreciably impact other components. In Uttarakhand, they could signify less substantial limits like regional policy concerns or restricted budgetary restraints.

Quadrant II – Dependent Variables

These variables (e.g., 10, 15, 17, 18) indicate high reliance but low driving power, indicating they are strongly impacted by other factors.In Uttarakhand, barriers may include land acquisition issues, investor trust, and community animosity, which depend on greater financial and political outcomes.

Quadrant III – Linkage Variables

This group (e.g., 5, 6, 11, 14, 19) has strong driving and high dependence components, suggesting feedback loops and sensitivity to change. In Uttarakhand, these could include regulatory norms, financial arrangements, and grid dependability, which both affect and are impacted by other concerns.

Quadrant IV – Independent Variables

These variables (e.g., 1, 2, 12) have strong driving power but little dependence, meaning they are major drivers of the system. In Uttarakhand, these might include government policy, incentives, and technology acceptability, which strongly determine the development of solar power facilities.

For Uttarakhand, the independent and associated aspects are the most important intervention locations. Policies relating to land distribution, financial aid, and grid infrastructure must be strengthened to increase dependent variables like community acceptance and investor involvement. This MICMAC research supports in defining crucial methods for sustainable solar energy growth in the region.

5.3.1 Level Partitioning Iterations (First Iteration)

As mentioned in figure (7) level Partitioning is given of first Iteration highlighting the most impactful barriers in Level 1. The level partitioning has been done upto 5 levels as shown in Table (2).

Elements(Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi)∩A(Ni)	Level
1	1, 3, 4, 5, 6, 10, 11, 13, 14, 15, 16, 17, 18, 19,	1,	1,	
2	18, 19,	2, 12,	2, 12,	
3	3, 4, 13, 16, 17, 18,	1, 3, 13,	3, 13,	
4	4, 17, 18,	1, 3, 4, 13,	4,	
5	5, 6, 10, 11, 14, 15, 17, 18, 19,	1, 2, 5, 6, 11, 12, 14, 19,	5, 6, 11, 14, 19,	
6	5, 6, 10, 11, 14, 15, 17, 18, 19,	1, 2, 5, 6, 11, 12, 14, 19,	5, 6, 11, 14, 19,	
7	7, 9, 10, 15, 17, 18,	7,	7,	
8	8, 17, 18,	8,	8,	
9	9, 10, 15, 17, 18,	7, 9,	9,	
10	10, 15, 17, 18,	19,	10,	
11	5, 6, 10, 11, 14, 15, 17, 18, 19,	1, 2, 5, 6, 11, 12, 14, 19,	5, 6, 11, 14, 19,	
12	18, 19,	2, 12,	2, 12,	
13	3, 4, 13, 16, 17, 18,	1, 3, 13,	3, 13,	
14	5, 6, 10, 11, 14, 15, 17, 18, 19,	1, 2, 5, 6, 11, 12, 14, 19,	5, 6, 11, 14, 19,	
15	15,	15, 19,	15,	1
16	16,	1, 3, 13, 16,	16,	1
17	17, 18,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 17, 19,	17,	
18	18,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 17, 18, 19,	18,	1
19	5, 6, 10, 11, 14, 15, 17, 18, 19,	1, 2, 5, 6, 11, 12, 14, 19,	5, 6, 11, 14, 19,	

Figure (7):- Level Partitioning First Iteration

5.3.2 Final Model

The following diagram depicts the ISM (Interpretive Structural Modelling) Final Model evidently maps the interrelationships among numerous difficulties and impediments. These barriers impacting the deployment and uptake of solar power parks in the area. The approach is constructed hierarchically with basic impediments at the bottom impacting upper level difficulties. Ground level restrictions include costly initial investment (F1), land acquisition issues (F2), regional limits (F3) and absence of governmental subsidies (F5), which operate as the base factors producing cascading impacts on additional challenges. The intermediate layer includes of issues such as environmental clearance delays (F6), skilled labor scarcity (F7), insufficient R&D (F9), policy fragmentation (F11), infrastructural gaps (F13) and community rejection (F12). These characteristics are largely impacted by fundamental barriers but also contribute to upper level uncertainty. The top layer comprises of more abstract and overarching issues, such as: Market uncertainty (F17) ,Seasonal weather variability (F8) ,Financing constraints (F10) ,Political prioritization (F19) ,Technological obsolescence (F15) ,Forest conservation legislation (F16), Storage limits (F18) .These concerns are consequences of several lower and intermediate-level challenges, as shown in Figure (8) indicating how deep rooted constraints contribute to greater market and policy uncertainty. The arrows signifies direct effect and relationships between variables. Geographic limits (F3), land acquisition issues (F2) and costly initial investment (F1) are important triggering variables that cascade into infrastructural gaps, skilled labor shortages and finance impediments. Policy fragmentation (F11) and insufficient R&D (F9) seem to be significant variables coupling financial and market concerns with implementation issues. Community pushback (F12) and bureaucratic delays (F14) also appear as important impediments in the mid-to-high level impact, reflecting socio-political complications.

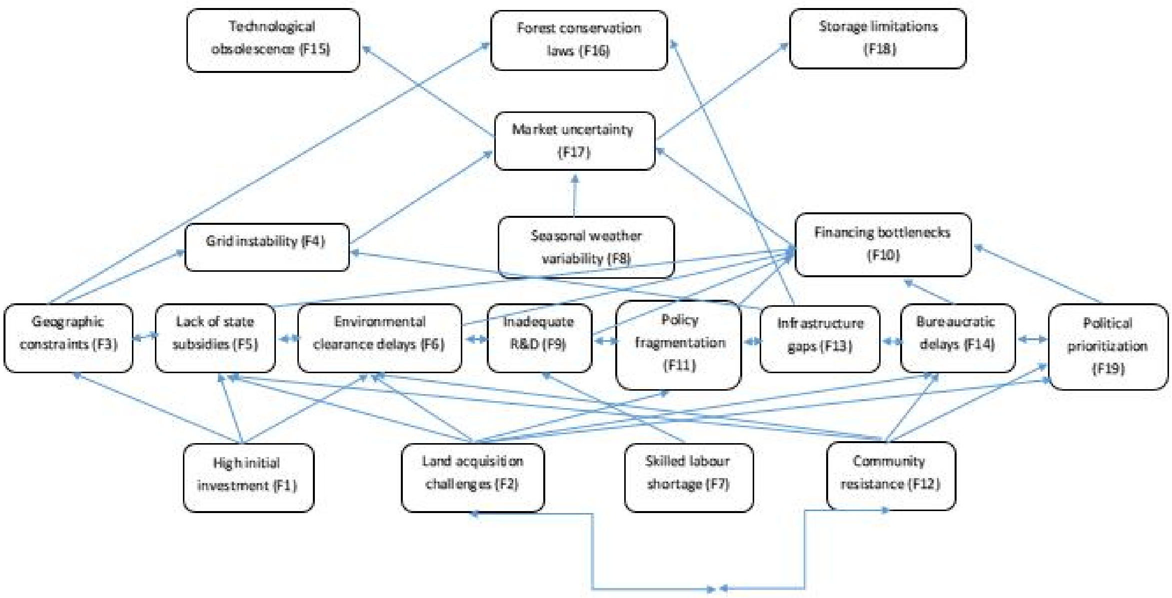

Figure (8):- Final Model structure of Barriers in Adoption and Implementation of SPP in Uttarakhand

5.3.3 Level Partitioning

S. No.	Level No.	Barriers
1	1st	• Technological obsolescence (F15) • Forest conservation laws (F16)

		• Storage limitations (F18)
2	2nd	• Market uncertainty (F17)
3	3rd	• Grid instability (F4) • Seasonal weather variability (F8) • Financing bottlenecks (F10)
4	4th	• Geographic constraints (F3) • Lack of state subsidies (F5) • Environmental clearance delays (F6) • Inadequate R&D (F9) • Policy fragmentation (F11) • Infrastructure gaps (F13) • Bureaucratic delays (F14) • Political prioritization (F19)
5	5th	• High initial investment (F1) • Land acquisition challenges (F2) • Skilled labour shortage (F7) • Community resistance (F12)

Table 2 Barriers levels for propagation the solar power plants in Uttarakhand.

The viability of establishing solar power parks in Uttarakhand, as investigated using the ISM (Interpretive Structural Modelling) framework, is dependent on overcoming a complex network of linked barriers. Storage constraints gap (F18) and obsolete technology gap (F15) are the key issues. Seasonal weather unpredictability (F8) and grid instability (F4) worsen these issues by reducing predictable energy generation and transmission. Forest protection guidelines (F16) further limit land availability generating conflict between environmental conservation and renewable energy objectives. Furthermore, environmental approval (F6) and bureaucratic delays (F14) are undermining investor confidence. Social problems, such as community denial (F12) and skilled labour shortages (F7), impede growth by stressing gaps in local engagement and capacity building. Uttarakhand has numerous critical elements in strategy design such as decreasing restrictions, boosting R&D (F9), strengthening grid resilience and fostering public-private collaboration. Resolving political priorities (F18) to align solar standards with state aspirations as well as community activities to minimize opposition, may utilize Uttarakhand renewable energy potential. The ISM model depicts about significant multi stakeholder cooperation is essential to overcome this challenging climate and allow for prolonged solar power growth.

6. Discussion and Policy Recommendations

In Uttarakhand, other viable renewable sources such as small hydro and biomass could be strategically integrated with solar through hybrid mini-grids and co-location. This could mitigate intermittency, improve efficiency, and ensure better land and resource utilization. In order to speed solar power plant growth in Uttarakhand, a coordinated and comprehensive approach is essential to overcome present hurdles.

1. Facilitating Land Use: Despite the geographic and environmental limitation in Uttarakhand. Discovering and assigning non forest wastelands for solar energy development by GIS mapping may boost usage of land while maintaining wooden forest.

2. State-Specific Incentives: Introducing capital subsidies and encouraging Public Private Partnership (PPP) models will attract investment by minimizing financial risks. This will overcome financial shortages to encourage private players to join in Uttarakhand renewable Energy achievement plan.

3. Strengthening Grid Infrastructure: Uttarakhand can use Central programs like the Green Energy Corridor to boost grid resilience and capacity. This procedure can guaranteeing effective transmission and distribution of solar energy despite the region's tough topography.

4. Social Engagement: benefit sharing initiatives helps to resolve disputes in local community. This will ensure that communities directly profit from solar installations. T&D programs and employment possibilities will improve public acceptability for promoting long term survival.

5. Policy Reforms: The fast monitoring environmental clearances and implementing a single window approval system may avoid bureaucratic bottlenecks, assuring timely project execution.

6. Conclusion

The rise of solar power parks in Uttarakhand demands for a diversified plan to handle connected problems. Long term success relies on overcoming technological, financial, policy and social constraints as per the ISM framework. Constant innovation and flexible laws assist to decrease technology obsolescence and storage inefficiencies thus insuring that solar projects continue viable despite quick improvements. Likewise, approaches for seasonal energy management and grid stability upgrades are vital in overcoming geographical and climatic limits.

Financially, easing investment procedures by means of subsidies, preserving policy continuity and consequently expanding access to funds would aid to strengthen investor confidence. Overcoming bureaucratic bottlenecks by fast approval processes and governance enhancements may further expedite project execution. Initiatives for community participation and skill development to overcome local opposition and worker shortages as a consequence in achieving a more inclusive energy change. Strong governmental commitment by innovative public-private collaboration and sustainable infrastructure design allow for harnessing Uttarakhand solar power potential.

The ISM model underscores the necessity of integrated stakeholder driven solutions. This process solar energy development satisfies environmental concerns, economic growth and energy security in the area. According to the ISM model, Uttarakhand solar park feasibility hinges on overcoming fundamental barriers including bureaucratic inefficiency and policy fragmentation. While physical and environmental limits exist, particular programs may exploit the state's solar potential. Future study should examine hybrid solar-hydro models for hilly places and assess these barriers using AHP.

8. Future Prospects

Particularly the mix of solar and wind power, hybrid energy systems provide a good way to improve sustainability and energy security. By including these renewable sources one guarantees a more continuous and steady energy supply as solar power is accessible throughout the day while wind energy may be used both day and night (Hassan et al., 2023). Because hybrid systems may help to reduce the intermittency problems related to individual renewable energy sources, they are a good choice for areas like Uttarakhand which suffers seasonal variations in solar radiation and varied weather.

Machine learning applications play a crucial role in improving the efficiency of solar energy systems. Even the application of Artificial intelligence driven smart solar tracking systems may optimum panel position to maximize daily energy output. A case study in Uttarakhand showed how machine learning based photovoltaic (PV) systems improved electrification in high altitude regions so addressing energy shortages in isolated communities (Das et.al, 2023).

Despite Uttarakhand tremendous potential for solar energy growth, the state's existing dependence on hydropower and thermal energy offers problems that need well structured governmental interventions. Hydropower remains the leading source of energy in the area although it is sensitive to climate induced unpredictability. Meanwhile, thermal electricity adds to environmental issues. Addressing these difficulties via deliberate policies investment in hybrid renewable systems and continuous technology breakthroughs will be necessary for Uttarakhand to transition toward a more sustainable and resilient energy future.

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