

Lessons Learned from Solar Irrigation Scaling in Asia and Africa

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Front cover photo: A woman stands with her cabbage harvest, irrigated using solar power, in Zimbabwe on June 8, 2016. (Credit: IWMI/David Brazier)

Back cover photo: SoLAR project beneficiaries in Nepal (Credit: IWMI/Nabin Baral)

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1. Introduction

1.1 Solar Irrigation and Its Relevance

Solar-powered irrigation systems (SPIS) are reshaping smallholder farming across Asia and Africa. By harnessing renewable energy, they reduce farmers' dependence on costly and polluting diesel pumps and provide more reliable access to water for crop production. This technology directly addresses some of the most persistent constraints in rural areas: energy insecurity, erratic rainfall, and limited irrigation infrastructure. For many smallholders, especially in dryland and remote settings, solar irrigation represents both an entry point into modern farming and a safeguard against climate shocks.

From a development perspective, solar irrigation sits at the intersection of the water–energy–food (WEF) nexus. It supports higher productivity, income diversification, and climate adaptation while cutting greenhouse gas (GHG) emissions. These attributes make it a central focus of international agricultural research and investment programs. Within the CGIAR system, solar irrigation connects to the broader agenda of climate-resilient food systems and the transition to clean energy in rural economies. The International Water Management Institute (IWMI) has been a leading actor in this field, pioneering technical, policy, governance, market, and financial innovations. Its work spans from early pilots of solar pump adoption to the creation of decision-support tools, groundwater monitoring systems, and gender-responsive business models. By linking research to practice, IWMI demonstrates how science-based insights can translate into accessible technologies and services for smallholders.

The growing interest in solar irrigation also reflects its potential for inclusive and sustainable growth. When embedded in supportive governance and financing frameworks, SPIS can enhance the agency of women and youth, expand opportunities for rural enterprises, and reduce public subsidy burdens. Yet scaling these benefits requires coordinated action, integrating technology, institutions, and finance into adaptable, country-led models. This report contributes to that agenda by synthesizing practical lessons from IWMI's regional experiences.

1.2 About the Report and Methodology

This brief on *Lessons Learned from Scaling Solar Irrigation in Asia and Africa* is an output of the Solar Irrigation Scaling Challenge organized under the CGIAR Scaling for Impact Program. The Challenge was conceptualized through a structured approach to understand the existing scaling pathways of IWMI's country teams in different locations and accelerate the integration of scaling approaches and country-specific innovations across key countries in Asia and Africa.

Approach and Process:

The Scaling Challenge followed a three-stage format that combined preparatory work, in-person collaboration, and post-event synthesis:

- **Pre-Workshop (Online, August 2025):** Introduced the challenge concept, presented two innovations relevant for solar irrigation, namely the Solar Pump Sizing Tool and Groundwater Management Information System (GMIS), and formed multidisciplinary country teams. Participants assessed the enabling environment and how these tools could be adapted for their local contexts.
- **Main Workshop (In-Person and Hybrid, September 2025, Sri Lanka):** During the “Asia Scaling Week,” teams developed innovation bundles, mapped scaling pathways, and refined their strategies through guided templates (Alignment Canvas, Partner & Scaling Pathway Canvas, and Targets Sheet). The process culminated in short pitch presentations of all country teams which were evaluated by peer researchers.
- **Post Workshop Phase:** Promising scaling pathways were reviewed and incorporated into IWMI's planning for 2026–2028 solar irrigation flagships, with follow up support for refinement and scaling.

The present brief summarized the outputs of all sessions to distill country specific insights and cross-regional lessons. It reflects both the diversity of contexts and the shared potential pathways for scaling solar irrigation across different governance and market environments.

2. Country and Regional Analyses

2.1 Nepal

Problem and Opportunity

Agricultural productivity in Nepal is constrained by limited and uneven access to irrigation. Only around 20 percent of arable land is irrigated throughout the year, and the remainder depends on erratic rainfall. In the Terai plains, irrigation relies heavily on diesel pumps, increasing costs and emissions. In contrast, the mid-hills face water scarcity linked to declining springs and inadequate storage infrastructure. These spatial disparities in water access deepen social inequities, particularly affecting women and youth farmers who are disconnected from decision-making and the market.

Solar irrigation provides an opportunity to address these challenges. Declining technology costs and government commitments to renewable energy create favorable conditions for adoption. High farmer demand for solar systems demonstrates readiness for scaling, but subsidy programs currently reach only a small share of applicants. Expanding access requires innovative, multi-stakeholder delivery mechanisms that combine public, private, and community investments (Shrestha et al. 2021).

Policy frameworks continue to restrict private engagement in large irrigation services, and the government's solar irrigation subsidy program is both limited and declining, currently supporting about 500 installations per year against a demand exceeding 5,000 applications. Technically, there is insufficient local capacity for operation and maintenance (O&M) of solar systems, leading to performance inefficiencies and underutilization. Financially, solar technologies remain expensive and heavily dependent on subsidies, with few accessible credit or blended finance mechanisms available to smallholders. Although the **National Irrigation Policy 2023** introduces a framework for functional volumetric water allocation, the mechanisms and systems required to operationalize such a framework is still unavailable.

Innovations

Nepal's solar irrigation scaling approach is anchored in a set of innovations that integrate technology, policy, finance, and inclusion to create an enabling environment for sustainable irrigation. The focus is not only on deploying solar systems but also on transforming how irrigation services are financed, managed, and governed:

1. Public–Private–Community Partnerships (PPCP) for Decentralized Solar Irrigation: This model establishes shared ownership and co-financing mechanisms among municipalities, cooperatives, and private suppliers. By combining local investments with private-sector expertise, PPCP ensures long-term maintenance and financial viability. It also embeds gender and social inclusion (GESI) principles, enabling women and youth to engage in irrigation service delivery and enterprise development.

2. Smart Irrigation Information System and Dashboard: Developed under the new National Irrigation Policy 2023, this digital innovation provides real-time monitoring of canal flows for volumetric water allocation. The dashboard supports evidence-based irrigation planning and allocation for Babai irrigation system (36,000 ha). The prototype is already hosted by the Department of Water Resources and Irrigation (DWRI) and represents a scalable model for data-driven irrigation governance.

3. Solar-Lift Multiple Use Water Systems (MUS): This innovation addresses water scarcity in the mid-hills and mountain regions by integrating domestic and productive water uses. Powered by solar-lift technology, MUS systems enhance water-use efficiency and livelihood diversification, particularly for women-led households that benefit from reduced labor burdens and expanded income opportunities.

4. GESI-Responsive Business and Capacity-Building Models: Complementing these technologies are training programs for local technicians and cooperatives to strengthen operation and maintenance (O&M) capacity. The inclusion of women and youth in technical roles and irrigation management ensures equitable participation and sustainability.

Together, these innovations provide a comprehensive solution bundle, linking digital tools, social inclusion, and institutional reform, demonstrating how solar irrigation can enhance both productivity and climate resilience in Nepal's diverse agro-ecological zones.

Scaling Pathways and Partners

Scaling efforts in Nepal follow three main pathways: financial, institutional, and technological. The financial pathway involves blending public subsidies with microfinance and cooperative-based credit to increase affordability. Local governments and cooperatives co-invest in solar irrigation infrastructure, ensuring shared responsibility for operation and maintenance. Innovative financing models, such as revolving municipal funds and results-based grants, are increasingly applied to leverage private investment. The institutional pathway focuses on embedding solar irrigation within municipal planning and agricultural development programs, aligning it with water-use regulations and local adaptation strategies. The technological pathway promotes digitalization and

interoperability through the Smart Irrigation Dashboard, enabling evidence-based water allocation and resource monitoring across districts.

Partnerships for scaling are diverse and structured around complementary roles. The Alternative Energy Promotion Centre (AEPC) leads on renewable energy policy and subsidy frameworks, while the Department of Water Resources and Irrigation (DWRI) ensures integration into irrigation planning and groundwater management. Local governments and municipalities act as key implementing partners, responsible for coordinating with farmer cooperatives and private suppliers to deliver and manage such new systems. Private sector actors such as banks and photovoltaic companies provide technology, financing, and technical support. Development partners and donors, including IWMI, UNDP, and the World Bank, support research, data systems, and capacity development. This multi-layered partnership structure connects policy, finance, and field-level implementation, creating a sustainable ecosystem for scaling solar irrigation.

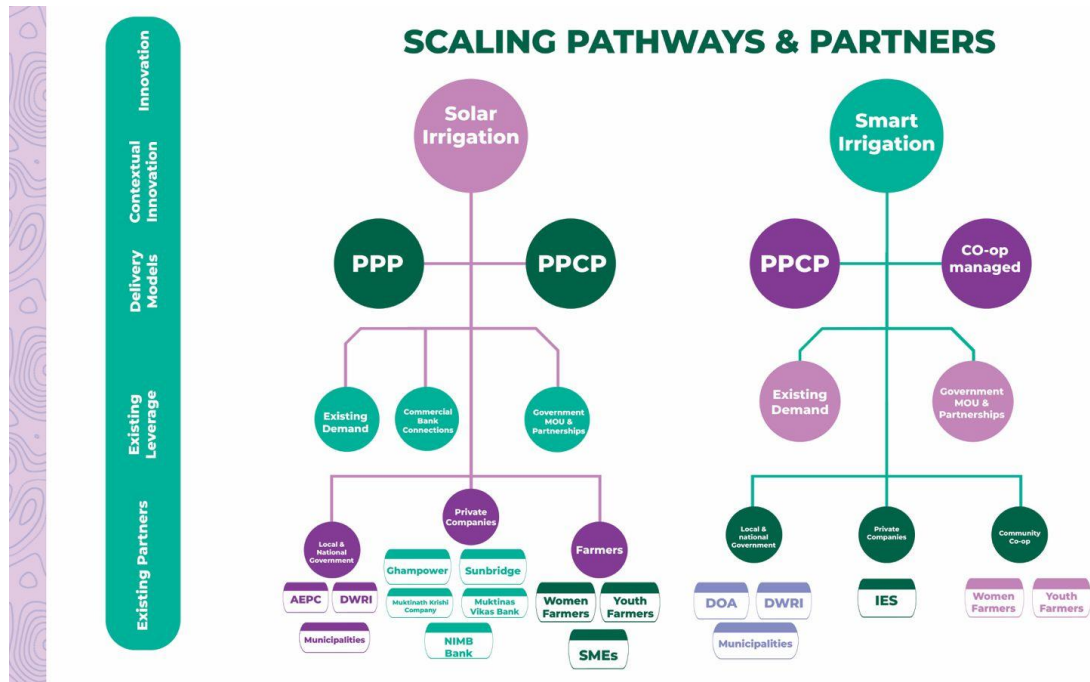


Figure 1: Scaling pathways and partners in Nepal (Source: authors)

Note: PPP = Public-Private Partnership, PPCP = Public-Private-Community Partnership; Co-op = Co-operative; MoU = Memorandum of Understanding, WUA = Water Users' Association

Unique Contribution

Nepal's unique contribution to the Solar Irrigation Innovation Bundle lies in its integration of decentralized governance, inclusive financing, and digital water management. The country's Public-Private-Community Partnership (PPCP) model demonstrates how local governments, cooperatives, and private firms can jointly finance and manage solar irrigation, ensuring both ownership and sustainability. This approach is distinguished by its gender and social inclusion (GESI) focus, embedding women and youth in service delivery and enterprise development.

Technologically, Nepal is advancing a Smart Irrigation Information System and Dashboard, developed with the Department of Water Resources and Irrigation (DWRI), to support volumetric water allocation and evidence-based planning. This prototype, alongside community-managed Solar-Lift Multiple Use Water Systems, links solar irrigation to groundwater governance, climate adaptation, and livelihood diversification.

By introducing these innovations, Nepal offers a promising example of how solar irrigation can be expanded through the involvement of local institutions, the use of blended finance, and the adoption of digital governance. This approach highlights Nepal's growing role in promoting more inclusive and climate-resilient irrigation development, which may inspire similar efforts in other parts of Asia and Africa.

2.2 Pakistan

Problem and Opportunity

Pakistan's agricultural economy relies heavily on groundwater, which supplies over 60 percent of irrigation but is increasingly under stress. Declining water tables, salinity intrusion, and deteriorating quality are widespread, particularly in Punjab and Sindh. Although national policies and provincial water acts emphasize sustainable groundwater management, weak enforcement and limited monitoring capacity make abstraction control difficult.

Solar irrigation offers an opportunity to reduce diesel dependence and energy costs, yet without proper regulation it could accelerate groundwater depletion. The challenge, therefore, is to link solar expansion with robust governance, deploying technology and data systems that enable efficiency, accountability, and farmer awareness.

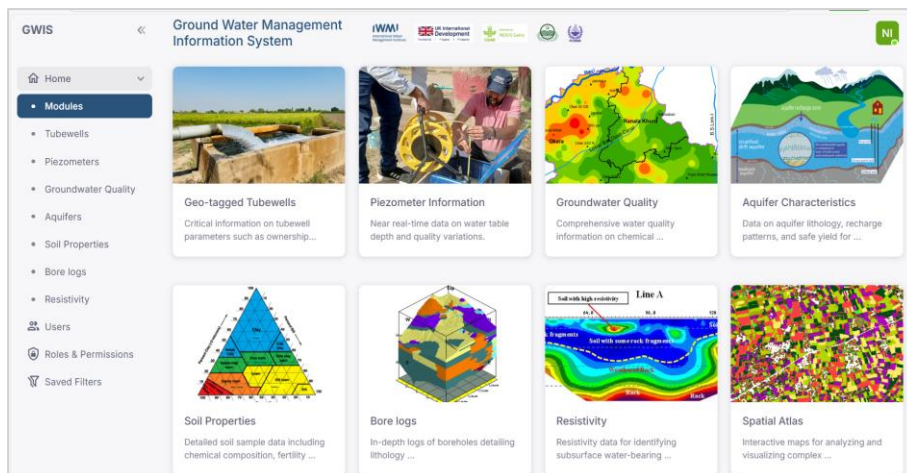


Figure 2: Digital platform of Pakistan's Groundwater Management Information System (GMIS) (Source: IWMI)

Innovations

Pakistan's scaling strategy uses a digital governance bundle that integrates groundwater monitoring, solar site selection, and pump sizing to support sustainable solar irrigation. A set of digital tools has been developed to strengthen data-based decision-making for groundwater management and solar irrigation planning. The Groundwater Management Information System (GMIS) tracks abstraction rates and identifies critical zones where pumping exceeds recharge. The Solar Suitability Mapping (SSM) tool integrates data on aquifer depth, solar radiation, and land use to determine appropriate areas for solar pump installation. The Solar Irrigation Pump Sizing Tool (SIP-ST) supports efficient pump selection to minimize energy use and water extraction. Together, these tools contribute to more sustainable allocation of groundwater resources.

1. Groundwater Management Information System (GMIS): Developed under FCDO-WRAP and CGIAR's Policy Innovations Initiative, GMIS is a decision-support tool that integrates fragmented groundwater datasets into a single digital platform (Figure 2). It has been adopted and operationalized by the Punjab Irrigation Department (PID) within its Water Resources Zone (WRZ) to support the Water Services Regulatory Authority (WSRA) in implementing the Punjab Water Act 2019 (CGIAR Research Initiative on NEXUS Gains 2024). GMIS now underpins hotspot mapping, abstraction analysis, and investment planning, including for nature-based recharge programs. Accessible through government portals (PID, PCRWR, and the Living Indus Initiative), it links geotagged tubewell inventories, groundwater quality, and pilot sensor data for evidence-based decision-making. A Farmer Awareness Module is currently being piloted to extend GMIS to end users through a mobile dashboard and WhatsApp/SMS advisories. The module is designed to reach about 100,000 farmers with localized information on groundwater levels and quality, strengthening behavioural change and promoting sustainable irrigation practices.

2. Solar Suitability Mapping (SSM): SSM identifies hydro-geologically appropriate areas for solar irrigation by combining data on aquifer depth, solar radiation, and socio-economic parameters (Figure 3). Responding to government demand the tool has been validated in Punjab and is being extended to Khyber Pakhtunkhwa (KP) and Balochistan to guide large-scale solarization programs and prevent over-extraction in sensitive zones. Additionally, this expansion is expected to significantly strengthen the provincial capacities for evidence-based planning and catalyse widespread adoption of climate-smart solar irrigation solutions across Pakistan.

3. Solar Irrigation Pump Sizing Tool (SIP-ST): SIP-ST optimizes pump selection using parameters such as crop type, groundwater depth, and solar intensity, minimizing energy use and water extraction (Figure 4). Piloted with provincial agencies and private suppliers, it supports efficient, right-sized investments in solar irrigation systems. The innovation is recognized by the Government of Pakistan (GoP) as powerful planning tool enabling line departments to scale solar irrigation sustainably.

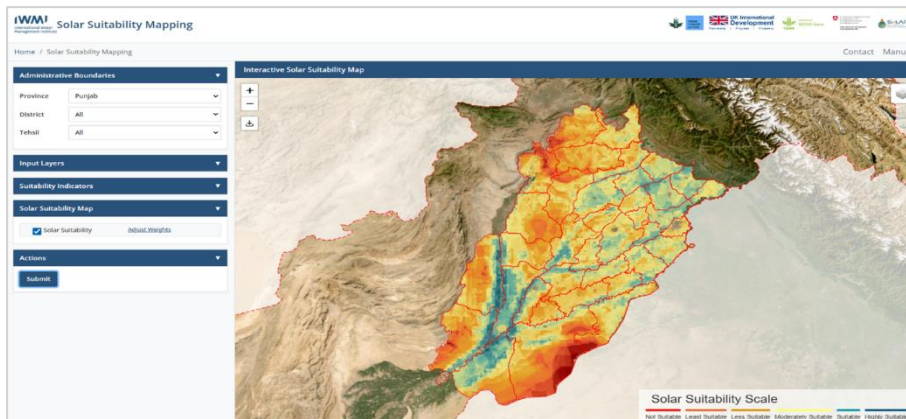


Figure 3: Web-based Module on Solar Suitability Mapping - Pakistan (Source: IWMI).

Scaling Pathways and Partners

Scaling efforts are structured around both technological and institutional pathways. Technological scaling focuses on integrating digital platforms into provincial planning systems, enabling evidence-based groundwater regulation and solar irrigation siting. Financial scaling is supported through public-private partnerships and blended finance mechanisms that facilitate access to affordable solar equipment. These efforts are reinforced by policy coordination at national and provincial levels to align renewable energy programs with groundwater conservation goals.

Institutional collaboration plays a critical role in the scaling process. Provincial irrigation and agriculture departments, along with Planning and Development (P&D) ministries, oversee integration of digital monitoring into water policy frameworks. Partnerships with the World Bank, European Union (EU), FCDO, and local private solar firms provide technical expertise and funding for pilot projects. Coordination among these actors supports the design of regulatory mechanisms for abstraction monitoring, linking solar irrigation deployment with groundwater management reforms and water governance modernization.

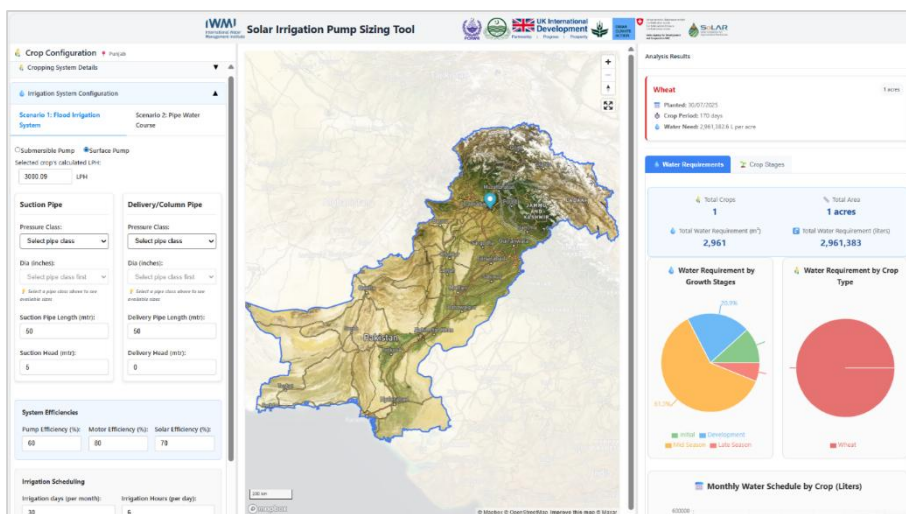


Figure 4: Web-based Module on Solar Irrigation Pump Sizing Tool - Pakistan (Source: IWMI).

Unique Contribution

Pakistan provides a leading example of how digital innovation and policy integration can transform groundwater governance. By linking solar irrigation expansion to real-time monitoring and data-driven decision-making, the country demonstrates how technology can simultaneously advance productivity and resource conservation. The combination of digital systems for monitoring and awareness (GMIS), spatial tools for solar irrigation siting (SSM), and analytical instruments for solar irrigation pump sizing (SIP-ST) creates an integrated framework that connects policy, technology, and farmer behavior. Embedded within provincial institutions and gradually extended to farmers through awareness and advisory platforms, this approach bridges the gap between regulation and practice, showing how solar irrigation can be scaled responsibly while ensuring the long-term sustainability of Pakistan's groundwater resources.

2.3 India

Problem and Opportunity

India has the most extensive experience in managing the interlinkages between solar irrigation and groundwater use. The country's groundwater-dependent agricultural systems have long faced challenges of over-extraction, declining water tables, and uneven energy access. Solar irrigation, if scaled without governance safeguards, risks intensifying groundwater depletion. At the same time, India has pioneered institutional and policy mechanisms to address this nexus, supported by IWMI's long-term research on groundwater-energy dynamics and solar irrigation planning. Programs such as PM-KUSUM provide significant opportunities to transition from diesel to solar irrigation while promoting sustainable groundwater use. Integrating solar pump deployment with groundwater monitoring and demand management remains a national priority. The adoption of digital tools such as the Solar Pump Sizing Tool allows for improved matching between water availability and pumping capacity, helping ensure that technological expansion does not lead to resource stress.

Innovations

Institutional mechanisms remain central to India's approach. The **Energy Extension Agent (EEA)** model embeds trained facilitators within Krishi Vigyan Kendras (KVKs) to deliver technical and financial guidance. **Self-Help Groups (SHGs)** improve affordability by supporting collective credit and ownership, while **Citizen Service Centres (CSCs)** operate as decentralized service hubs providing access to subsidies, maintenance, and after-sales services. The **Solar Pump Sizing Tool**, developed in partnership with IWMI and national agencies, provides data-driven recommendations for optimal pump capacity, integrating hydrological data to align solar irrigation with groundwater sustainability.

Scaling Pathways and Partners

The expansion of solar irrigation in India involves several interrelated pathways. Figure 5 demonstrates this complex scaling process. Financial scaling is facilitated by subsidy programs and microcredit initiatives, which lower the initial investment required for pumps and promote wider adoption among smallholder farmers. Technological scaling is supported through digital solutions and integrated service platforms that assist with site assessment, pump selection, and ongoing performance monitoring. Social scaling is achieved via self-help groups (SHGs) and cooperatives, which foster collective ownership and shared infrastructure arrangements.

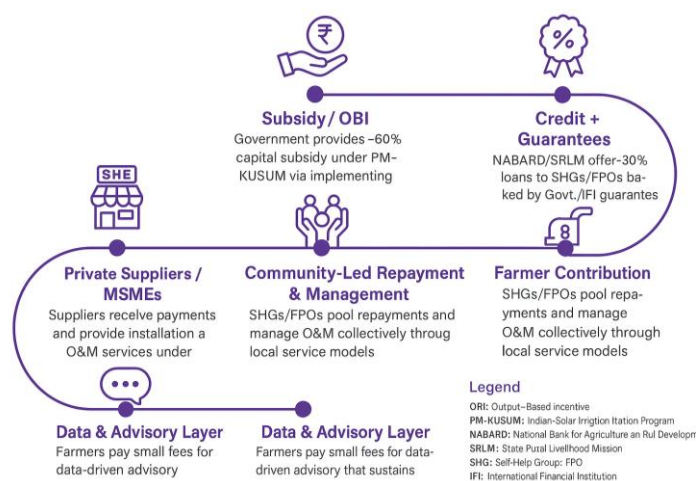


Figure 5: Solar irrigation scaling pathways in India (Source: authors)

Partnerships are extensive and cross-sectoral. National agencies such as the Ministry of New and Renewable Energy (MNRE), Ministry of Agriculture and Farmers Welfare (MoAFW), and National Bank for Agriculture and Rural Development (NABARD) collaborate with ICAR, State Rural Livelihood Missions (SRLMs), and local extension systems. IWMI contributes through applied research, training, and policy support, particularly on groundwater governance and solar irrigation design. Together, these actors promote a balanced approach combining technology, finance, and groundwater sustainability.

Unique Contribution

India's experience demonstrates a mature model for integrating groundwater governance within solar irrigation programs. The country's use of digital tools for pump sizing and water management, combined with institutional convergence and social inclusion mechanisms, provides a best-practice template for sustainable and equitable solar irrigation scaling that could be replicated across Asia and Africa.

2.4 Ghana and Nigeria

Problem and Opportunity

In Ghana and Nigeria, irrigation development faces significant challenges, including unreliable rainfall, high pumping costs, and variable groundwater availability. Many smallholders depend on shallow aquifers that fluctuate seasonally with rainfall, making irrigation unpredictable and risky. While solar pumps have reduced dependence on costly diesel systems, their uptake is constrained by high initial investment costs, limited access to affordable finance, and inadequate maintenance networks (Ojeleye et al. 2025). Although solar irrigation can

reduce energy costs and enhance agricultural productivity, it is only truly sustainable when paired with effective groundwater management and careful planning to prevent resource depletion. Many smallholder farmers struggle with technical sizing and matching pump capacity to groundwater yields and seasonal water demand.

Innovations

Solar irrigation initiatives in both countries integrate technological and financial solutions to improve water and energy efficiency. Innovations focus on derisking farmers' investments in solar irrigation and reducing uncertainty in public investment decisions. Solar-Based Irrigation Bundles (SBIB) providers combine hardware with digital tools, including the **Solar Pump Sizing Tool (SPST)** and **Suitability Mapping Tool**, to guide system design based on local hydrogeological conditions and ensure that pump capacity aligns with groundwater depth and recharge potential. The sizing tool supports extension officers, suppliers, and farmer groups, while partnerships with public agencies and financial institutions use suitability mapping to guide investment prioritization and develop irrigation credit products. Financial innovations, such as **Pay-as-You-Go (PAYGo)** and **group ownership schemes**, make systems more affordable for smallholders and encourage shared management of water and equipment (Gbodji et al. 2025).

Scaling Pathways and Partners

The pathway focuses on two complementary strategies: de-risking farmer investments and strengthening public decision-making. To de-risk farmer investments, the approach engages sales and service networks, including agricultural extension officers, Solar-Based Irrigation Bundles (SBIB) agents, input dealers, farmer cooperatives, and private suppliers, to deliver accurate solar pump sizing services to farmers intending to invest in SBIB. This ensures that each system is technically and economically optimized for local conditions, reducing performance risk and improving farmer confidence. On the policy and finance side, the pathway emphasizes managing uncertainty in public investment by partnering with government agencies and financial institutions to leverage suitability mapping and SPST tools. These tools help identify priority zones for solar irrigation expansion, guide efficient allocation of public resources, and support the design of credit or loan products tailored to SBIB investors, thereby aligning technology, finance, and governance toward sustainable irrigation scaling.

Partnerships underpin the scaling process through coordination between research, policy, and finance actors. Key collaborators include the **Ghana Cocoa Board**, the **MasterCard Foundation**, and **Access Bank in Ghana**, while **National Cereals Research Institute (NCRI)**, and **Bank of Agriculture** in Nigeria, along with private suppliers and service providers. IWMI supports these efforts through applied research on groundwater-solar linkages, system performance monitoring, and capacity development for local institutions. Together, these actors align national renewable energy goals with irrigation development strategies, promoting sustainable solar irrigation expansion across both countries.

Unique Contribution

Ghana and Nigeria demonstrate how integrating groundwater-informed planning with digital and financial innovations can unlock scalable solar irrigation. By combining hydrological suitability assessments with accessible financing, their experience provides a replicable framework for expanding climate-resilient irrigation while protecting groundwater resources.

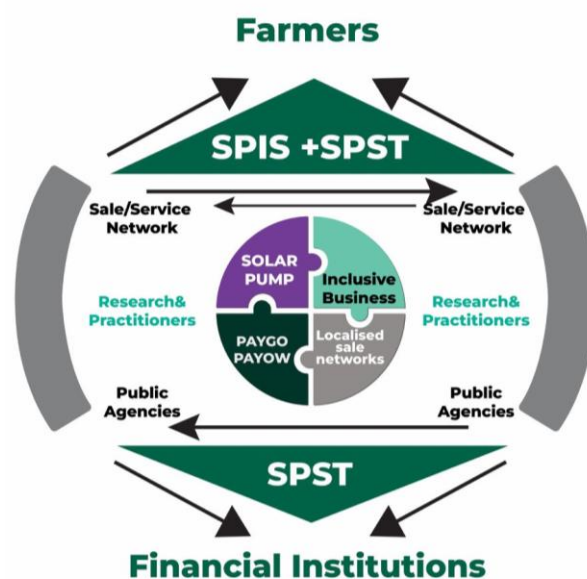


Figure 6: Conceptual framework illustrating the integration of technological and financial innovations within Solar-Based Irrigation Bundles (SBIB) in Ghana and Nigeria (Source: authors)

Note: This integration aims at de-risking farmer investments (upper triangle) and managing uncertainty in public and private sector decision-making. Solar-Powered Irrigation Systems (SPIS) integrate hardware and digital tools such as the Solar Pump Sizing Tool (SPST) and Suitability Mapping Tool to align pump capacity with groundwater potential. Bundle providers collaborate with farmers, service networks, financial institutions, and public agencies to ensure proper system design and informed investment choices. Continuous feedback between researchers and practitioners enhances learning and reduces risks for smallholders and institutions alike.

Table 1: Partner roles and functions in Ghana's and Nigeria's solar irrigation pathways (Source: authors)

| Partner/Institution | Country | Primary Role | Specific Functions/Contributions |
|--|-----------------|---|---|
| International Water Management Institute (IWMI) | Ghana & Nigeria | Research, coordination, and capacity building | Leads applied research on groundwater–solar linkages, monitors system performance, supports evidence-based policy engagement, and builds institutional capacity for scaling solar irrigation sustainably. |
| Ghana Cocoa Board (COCOBOD) | Ghana | Policy alignment and farmer support | Integrates solar irrigation into cocoa production programs; facilitates farmer outreach and training through extension services; aligns irrigation with climate-smart cocoa strategies. |
| MasterCard Foundation | Ghana | Financing through Access bank | Provides blended finance and grants to de-risk farmer investments; supports youth entrepreneurship and job creation in the solar irrigation value chain. |
| Access Bank | Ghana | Financial intermediation | Develops tailored credit and loan products for farmers and suppliers investing in solar irrigation technologies. |
| National Cereals Research Institute (NCRI) | Nigeria | Research and technology validation | Tests solar irrigation technologies for cereal-based systems; generates evidence on productivity and water use efficiency impacts. |
| Bank of Agriculture | Nigeria | Agricultural finance | Offers concessional loans and financial support schemes for smallholders and cooperatives investing in solar irrigation systems. |
| Private Suppliers & Service Providers | Ghana & Nigeria | Technology supply and maintenance | Supply, install, and maintain solar irrigation systems; provide technical support, after-sales services, and training to ensure long-term system performance. |

2.5 East and Southern Africa

Problem and Opportunity

Across East and Southern Africa (ESA), the potential for irrigation remains significantly underutilized despite abundant solar resources and substantial groundwater and surface water availability (Figure 7). Mapping of renewable groundwater across Africa indicates that the eastern region, in which many ESA countries lie, has significant potential for expansion of groundwater-based irrigation (Altchenko and Villholth 2015). Major barriers to realizing this potential include high upfront capital costs for irrigation infrastructure, weak coordination between water, energy, and agricultural policy institutions, and limited digital capacity at both farm and institutional levels for data-driven irrigation management and governance.

Recent evidence from Ethiopia shows that the cost of small solar-pump systems can reach 150,000 ETB (about US\$ 950), creating a financial barrier for most smallholders (Dejen et al. 2025). Furthermore, solar irrigation adoption remains low despite clear economic benefits, reflecting similar constraints across ESA (Negera et al. 2025). However, increasing private sector participation, donor investment, and innovative business models have created new opportunities to coordinate regional progress in solar irrigation, groundwater monitoring, and climate-resilient agriculture. For example, the International Water Management Institute (IWMI) reports that its *Solar Irrigation for Agricultural Resilience (SoLAR)* project is expanding to Kenya and Ethiopia to promote solar irrigation as a pathway for enhanced climate resilience (Bhaduri 2025). Solar Irrigation Living Labs in Hawassa Zuria, Adami Tulu, and Meskan demonstrate how co-designed pilots can accelerate integrated solar-water innovations (Dejen et al. 2025).

Innovations

In the ESA region, innovations are increasingly bundling **solar pumping, digital irrigation scheduling, soil/soil-moisture monitoring** and **climate-smart governance**. For instance, recent work



Figure 7: Solar pumps in Zambia (Credits: Adam Öjdahl/IWMI)

under IWMI's scaling solar irrigation challenge emphasizes how solar pumping must be integrated with governance of groundwater to avoid over-extraction. In Ethiopia, six innovation-bundling elements, namely policy, financing, hardware, water–agronomic integration, capacity development, and market linkages, were identified as essential for sustainable scaling (Dejen et al. 2025; see Figure 9). Empirical data show that bundling solar pumps with agronomic support and water-harvesting technologies significantly increases food security, improving both household food consumption score (HFCS) and household dietary diversity score (HDDS) for smallholder farmer families (Negera et al. 2025). Economic studies from Ethiopia further show that solar pumps deliver strong economic returns, with Benefit–cost ratio (BCR) above 1.0 and net water value (NWV) reaching USD 1.53/m³ for specific crops (Negera et al. 2025), underscoring the viability of integrated solar irrigation systems (Figure 9).

The model of a “**Smart Water System for Climate Adaptation**” could thus bring together solar-powered irrigation pumps, real-time soil-moisture sensors, farmer decision-support apps and water-carbon credit trading mechanisms (via monitoring of water productivity and reduced emissions). Co-design “Living Labs” in Kenya, Ethiopia and Zambia engage farmers, agribusinesses and research partners to tailor such integrated systems. Alongside, **citizen science** initiatives enable local communities to engage in groundwater monitoring (e.g., measuring water-table depth fluctuations) thereby strengthening accountability, resilience and local capacity. Ethiopian pilots confirm that farmer-generated groundwater data are now used in digital dashboards to inform local groundwater governance (Dejen et al. 2025).

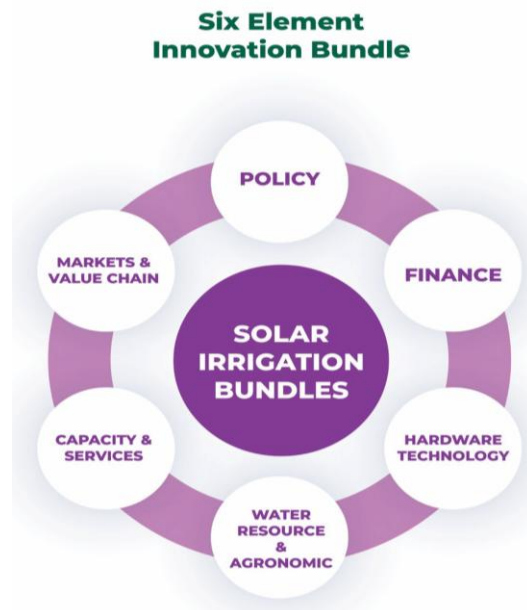


Figure 8: Six-element innovation bundle for inclusive solar irrigation scaling in Ethiopia (Dejen et al. 2025).

Scaling Pathways and Partners

Scaling in ESA emphasizes two parallel pathways. First, sustainable adoption of solar-based irrigation as a productivity and resilience measure for smallholder and medium-scale farms. Second, embedding this growth within sustainable groundwater management, monitoring abstraction and recharge, as part of the wider system. Living Labs act as multi-stakeholder learning platforms: water abstraction, recharge dynamics and irrigation performance are jointly analyzed, enabling local authorities, farmer cooperatives and service providers to use granular data (including citizen-collected groundwater data) to inform policy and practice. In Ethiopia, four farmer-centered scaling pathways have been prioritized, cooperative-based systems, shared solar farms, irrigation service providers, and individual smallholder investment, verified through multi-stakeholder consultations (Dejen et al. 2025).

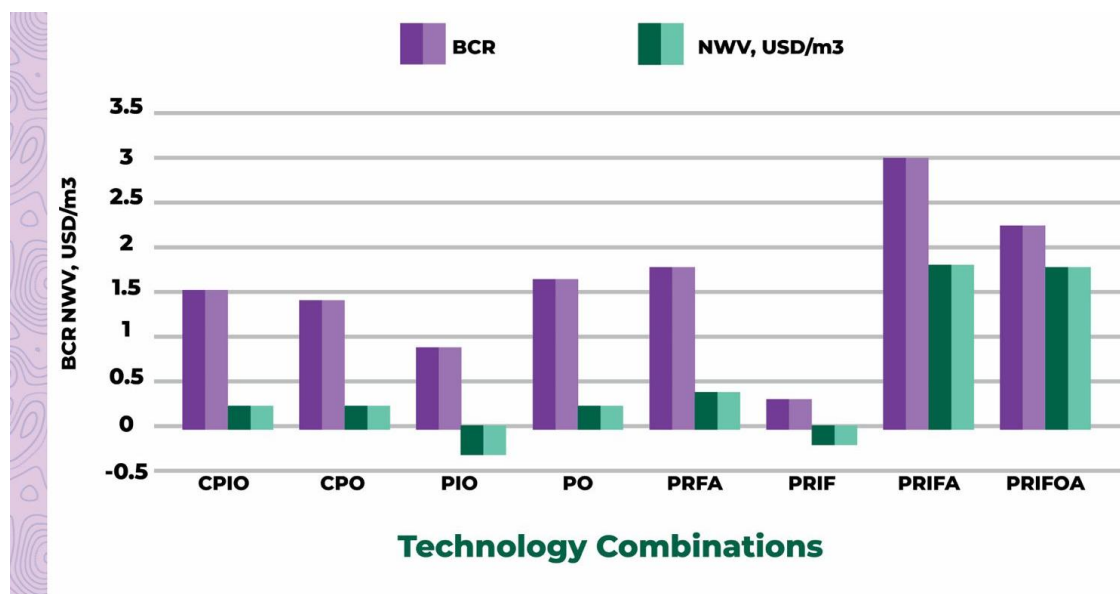


Figure 9: Economic returns, namely net water value (NWV) and benefit–cost ratio (BCR), of solar pump irrigation vs. water-harvesting irrigation technologies in Ethiopia (Negera et al. 2025).

Note: C = intercropping, P = row planting, R = crop rotation, I = improved seed/seedlings, F = chemical fertilizer, O = organic fertilizer, and A = agrochemicals.

Citizen science initiatives supplement formal monitoring systems; communities contribute water-table data that are visualized in digital dashboards to monitor groundwater fluctuations across pilot zones. Scaling also relies on inclusion of managed aquifer recharge (MAR) zones and sustainable pumping guidelines, supported by research institutions, NGOs national water agencies and regional donor programs, e.g., *SADC groundwater management project* (World Bank 2023).

Partnerships driving this scaling model include national ministries of agriculture and water, the International Fund for Agricultural Development (IFAD), World Bank, Shell Foundation, The Global Off-Grid Lighting Association (GOGLA), and regional SMEs. These actors align investment, policy, and technical support to expand solar irrigation while maintaining groundwater balance. Evidence from Ethiopia indicates that financial readiness, through revolving funds, contract farming and group lending, can accelerate adoption and ensures long-term viability (Dejen et al. 2025). Collaboration between different actors ensures that monitoring data inform water-allocation policies and that deployment of solar technologies aligns with national climate adaptation and resilience strategies.

Unique Contribution

The ESA experience demonstrates how integrating groundwater monitoring and recharge management into solar irrigation systems can ensure long-term sustainability. By linking digital advisory platforms, community participation, and institutional coordination, the region offers a replicable example of adaptive water governance that supports both agricultural productivity and environmental outcomes. Through the layering of farm-level solar irrigation, groundwater monitoring platforms and policy frameworks, ESA stands at the frontier of what might be called “smart, climate-resilient water-agriculture systems”.

3. Cross-Country Synthesis

The cross-country synthesis reveals how diverse contextual realities have shaped the pathways, pace, and outcomes of scaling solar irrigation across Asia and Africa. Evidence from the Solar Irrigation Scaling Challenge shows that scaling is not a linear process of technology transfer but rather an adaptive systems transformation – driven by how technology, governance, policy, finance, and inclusion are integrated within each country's institutional and ecological landscape. Table 2 provides a summary of country specific innovations, scaling strategies and the unique approaches. The following more in-depth discussion of cross-country learning also serves as a resource for policymakers and stakeholders as they plan how to expand sustainable and inclusive solar irrigation solutions in the future.

At the core, the experience confirms that solar irrigation is not a standalone technology solution, but a nexus innovation linking energy access, water sustainability, and rural livelihoods. Countries that treated solar irrigation as part of broader resource management reforms, such as India and Pakistan, where solar irrigation deployment is anchored in groundwater and agricultural policy frameworks, were able to align renewable energy expansion with sustainable resource use. By contrast, context like Ghana, Nigeria, and Nepal, where groundwater regulation is weaker, relied more on financial innovation and decentralized partnerships to accelerate adoption. This contrast highlights a critical trade-off between speed of diffusion and depth of sustainability integration: rapid market expansion can widen access but risks over-extraction if governance frameworks lag.

Technology and Innovation: Digitalization has become a key driver in scaling solar irrigation by enabling smarter and more accountable water management. For example, Pakistan's GMIS and SSM systems, India's Solar Pump Sizing Tool, and Nepal's Smart Irrigation Dashboard demonstrate how integrated data platforms support targeted investment and adaptive management. As a result, data-enabled governance allows policymakers and stakeholders to make informed choices about solar irrigation interventions and policy adjustments, ensuring sustainable and efficient use of resources. In East and Southern Africa, Living Labs and citizen science initiatives have extended innovation systems to the grassroots, linking farmer knowledge with hydrological data. Collectively, these cases underline that digital tools are most transformative when embedded in learning systems rather than introduced as stand-alone technologies.

Policy and Governance: Comparative analysis underscores that institutional coherence is the foundation of sustainable scaling. Where strong government leadership and cross-sector coordination existed, solar irrigation evolved from pilot interventions into structural reforms. Emerging success stories are Pakistan's integration of solar programs into groundwater management, India's policy convergence of energy, agriculture, and water policies, and Nepal's incorporation of solar irrigation into municipal development plans. On the other hand, countries with less coordinated mandates found it challenging to fully align incentives, which sometimes resulted in more limited or donor-driven adoption. This variation underscores an ongoing governance challenge: while achieving policy alignment across ministries can be a gradual process, it remains important for balancing energy and water needs to support long-term sustainability.

Finance and Inclusion: Access to affordable finance emerged as both a barrier and an innovation frontier. Blended finance mechanisms, including microcredit, PAYGo, and cooperative ownership schemes, is proving decisive in expanding access for smallholders. Ghana and Nigeria's partnerships with Access Bank and the Mastercard Foundation, and Nepal's cooperative finance models show that financial innovation can reduce entry barriers where subsidies are limited. However, financial scaling also entails social trade-offs: without deliberate design, credit-based models may privilege wealthier or male farmers. Integrating gender-responsive and community-based ownership mechanisms helps mitigate exclusion and enhance collective resource stewardship.

Climate Sustainability: Across contexts, the integration of solar irrigation with groundwater and soil management policies has emerged as a key determinant of climate resilience. India's groundwater-solar management pilots and East Africa's aquifer recharge monitoring illustrate how renewable energy transitions can simultaneously strengthen climate adaptation and mitigation. However, without robust monitoring and incentive structures, solar irrigation can unintentionally intensify groundwater depletion. The evidence points to the need for co-regulation of energy and water, linking subsidies, tariffs, and abstraction limits, to sustain the dual benefits of productivity and resilience.

Partnerships and Systems Thinking: Finally, the synthesis affirms that scaling is a collective process, requiring alignment across sector and diverse actors. Countries that foster multi-actor platforms, spanning governments, private firms, and farmer organizations, achieved more coherent scaling trajectories and greater adaptive capacity. These partnerships illustrate that the durability of scaling outcomes depends less on the volume of investment and more on the quality of institutional collaboration and feedback loops. IWMI's facilitator role is pivotal in translating innovative scaling approaches into implementation strategies and support cross-country peer learning.

Taken together, these insights point to a systems-based model for scaling solar irrigation sustainably anchored in data-driven governance, inclusive finance, and policy convergence across the energy-water-food nexus. Comparative experiences from Asia and Africa demonstrate that while the entry points differ, the enabling factors are universal: coherent institutions, adaptive learning, and partnerships that connect innovation with equity. The

table below summarizes the comparative contributions and innovations across all regions, serving as a reference for future scaling initiatives.

Table 2: Country summary of key Innovations, scaling pathways and unique contribution

| Country / Region | Key Innovations | Unique Contribution |
|-----------------------------------|--|--|
| Nepal | Decentralized solar irrigation under Public-Private-Community Partnerships; Smart Irrigation Dashboard; Solar-Lift Multiple Use Water Systems (MUS): | Integration of technology, finance, and gender-responsive governance; evidence-based irrigation planning |
| Pakistan | Groundwater Management Information System (GMIS); Solar Suitability Mapping (SSM); Solar Irrigation Pump Sizing Tool (SIP-ST) | Data-driven groundwater management and policy integration for sustainable solar expansion |
| India | Energy Extension Agents (EEAs); Self-Help Groups (SHGs); Citizen Service Centers (CSCs) | Institutional convergence leveraging social infrastructure for inclusive scale-up |
| Ghana & Nigeria | SPIS Bundles with Sizing & Suitability Tools; Pay-as-You-Go, partnerships with private institutions (suppliers and finance); Group Ownership Models | Financing innovation using digital tools to derisk lending and increase access |
| East & Southern Africa | Smart Water Systems; Living Labs; Citizen Science Monitoring | Systems-based approach integrating climate-smart irrigation, finance, and landscape management |

4. Conclusions and Way Forward

Scaling solar irrigation requires an integrated and adaptive approach that links technology, finance, governance, and inclusive partnerships within a coherent systems framework. Evidence from Asia and Africa demonstrates that scaling is most successful where solar irrigation initiatives are grounded in water resource sustainability, gender and social inclusion, and institutional alignment. Across diverse contexts, solar irrigation has proven to enhance not only agricultural productivity but also groundwater conservation and climate resilience -when guided by sound policy, data-driven management, and inclusive business models.

Through its facilitation of the Solar Irrigation Scaling Challenge, IWMI has strengthened cross-country learning and fostered a shared understanding of effective scaling mechanisms. The key conclusion is that solar irrigation systems must evolve from isolated energy or agricultural projects into integral components of national water, energy, and climate systems. This transition from technology deployment to systems transformation ensures that innovation contributes to sustainable and equitable resource use, rather than exacerbating existing pressures.

To scale solar irrigation sustainably and inclusively, countries need a coordinated, multifaceted strategy that integrates institutional reform, financial innovation, digital integration, and social equity. The following recommendations summarize the critical enablers for responsible scaling:

1. **Institutional Coordination:** Strengthen cross-sector collaboration between the ministries of water, energy, and agriculture to embed solar irrigation within national water, food and climate strategies. Institutional convergence ensures that renewable energy expansion reinforces, rather than undermines groundwater and ecosystem sustainability.

2. **Partnerships:** Collaborative partnerships involving government agencies, private sector stakeholders, community organizations, financial institutions, and research entities are essential to firmly embed solar irrigation within national frameworks and existing market systems. Partnerships should support co-investment models, strengthen operation and maintenance capacity, enable integration of digital tools, and ensure that solar irrigation contributes to sustainable groundwater and water resource management.

3. **Financial Innovation:** Expand blended finance, microcredit, and results-based grant mechanisms to improve affordability for smallholders while incentivizing private sector participation. Linking finance with sustainability metrics, such as groundwater monitoring or efficiency performance, can further align economic and environmental outcomes.

4. **Digital Integration:** Leverage digital tools and platforms – including suitability maps, dashboards, and pump sizing applications to improve decision-making, optimize resource allocation, and support transparent monitoring of water use and performance.

5. **Inclusive Access:** Design programs that actively increase participation of women and youth-led enterprises, through targeted capacity development, financial literacy training, and inclusive ownership models. Embedding social equity within scaling frameworks strengthens both adoption and long-term sustainability.

6. **Regional collaboration:** Promote South–South learning and cross-country collaboration through regional platforms that harmonize technical standards, disseminate innovations, and enable peer-to-peer knowledge exchange.

In summary, scaling solar irrigation responsibly depends on six interconnected pillars: coordinated institutions, strong partnerships, innovative financing, digital integration, inclusive access, and regional collaboration, as illustrated in Figure 10. Together, these elements ensure solar irrigation is sustainably, equitably, and effectively embedded within national systems.



Figure 10: Responsible Scaling Framework for Solar Irrigation (Source: authors)

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