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Irrigation as a system shaping load: technoeconomic and policy pathways for water energy food nexus

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ABSTRACT

Solar powered irrigation systems (SPIS) offer a pathway to expand agricultural water access while supporting national electrification objectives. This study develops a spatially explicit, temporally resolved planning and analysis framework that integrates hillside irrigation energy demand as a system shaping load within Rwanda's national electricity system. Two deployment pathways are assessed: behind-the-meter solar powered irrigation systems (BTM-SPIS) and grid-integrated solar powered irrigation systems (GI-SPIS). The Irrigation load profile is derived using elevation based pumping requirements and is coupled with hourly national economic dispatch model to evaluate grid interactions, system cost, and export tariff sensitivity across a range of photovoltaic deployment levels.

Results show that GI-SPIS achieves the lowest system cost at early deployment stages because gravity storage can be charged using low cost off peak generation and irrigation schedules can be coordinated with national dispatch. BTM-SPIS becomes competitive only when photovoltaic capacity exceeds irrigation demand and surplus electricity is exported. At high photovoltaic penetration, surplus production exceeds 55 GWh yr^{-1}, causing the marginal system value of exports to decline sharply, with export values falling to approximately 0.005 USD kWh^{-1}. At moderate sizing levels, photovoltaic irrigation reduces annual system cost by displacing high-cost daytime thermal generation and flattening the net load profile.

These findings demonstrate that surplus management, coordination mechanisms and tariff design rather than photovoltaic deployment alone are central to integrating solar irrigation into power-system planning. The results provide relevant planning evidence for aligning irrigation electrification with least cost generation expansion and export pricing strategies.

1. Introduction

Efforts to expand access to modern energy services and improve food security increasingly recognize the interdependence between electricity access, agricultural productivity, and water availability [1–5]. Within nexus contexts, irrigation is an energy intensive and water intensive productive use activity crucial in stabilizing yields, reducing climate risk, and improving rural livelihoods [6–8].

Achieving global development objectives therefore requires integrated planning across the water energy food (WEF) nexus [8]. Solar powered irrigation systems (SPIS) have emerged as a promising pathway for expanding irrigation access while reducing dependence on diesel pumps and increasing farmer income [7,9–11].

At the same time, solar energy deployment across SSA is entering a phase of rapid scale up, driven by declining photovoltaic (PV) costs, national electrification targets, and growing interest in productive uses of electricity. Utility scale solar capacity is expanding at the national level, while distributed PV systems are increasingly deployed in rural and *peri* urban areas. As solar penetration rises, questions of surplus generation, temporal mismatch, and system coordination become increasingly salient, particularly in contexts where demand profiles are highly seasonal [12]. Within this evolving landscape, irrigation occupies a distinctive position: it represents both a major source of electricity demand and one of the few flexible, daytime aligned uses capable of absorbing large volumes of solar energy [10,13,14].

Prior studies consistently show that irrigation constitutes the largest

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share of on farm electricity demand. Farthing et al. (2023) [10] estimate that irrigation accounts for >60 percent of agricultural electricity consumption across several SSA countries, and their geospatial groundwater pumping analysis highlights pronounced seasonality. Nilsson et al. (2021) [8] similarly develop a GIS-based framework to estimate groundwater pumping requirements across East Africa, reinforcing that pumping head and seasonal water demand are primary drivers of electricity needs. Falchetta et al. (2022) [3] extend this perspective by emphasizing renewable energy strategies that explicitly incorporate agricultural water use. However, these insights become more operationally binding in hillside settings, where pumping head varies sharply with terrain and timing of pumping can create short duration peaks even when annual energy demand is moderate. In such contexts, PV sizing and irrigation scheduling are inseparable from storage and coordination choices since oversizing can shift the challenge from meeting irrigation demand to managing surplus [15].

Solar energy research strongly supports the need for high resolution temporal modelling and explicit surplus management rules, but these insights have only partially migrated into agricultural and agrivoltaic contexts. Systematic agrivoltaic reviews highlight engineering and yield optimisation, but they also emphasise the lack of comprehensive financial and policy coordination models, as well as the limited attention given to large scale solar facilities [16,17]. Empirical work on seasonal performance and large PV samples quantifies temperature/season effects and performanceratio dynamics, which are useful for parameterising agrivoltaic yield models [18,19]. While these studies are not agricultural in focus, they establish important methodological foundations for linking temporal dynamics, resource availability, and energy system performance, particularly in contexts where surplus generation and tariff based compensation mechanisms are central. Parallel work in agricultural systems modelling, such as Asmelita et al. [20], applies system dynamics approaches to irrigation optimisation and food self-sufficiency, emphasising feedbacks between water allocation, crop productivity, and resource constraints. Spatial planning studies for large scale PV show how ignoring agriculture and biodiversity generates conflicts, and point to agrivoltaics and spatially explicit planning as key but still under developed coordination tools [16,17,21].

Moreover, most energy system and tariff studies continue to focus on household or commercial rooftop photovoltaic (PV) systems, with limited attention to agricultural loads [9,10]. Net metering and tariff optimization analyses typically rely on standard residential or commercial demand profiles and therefore fail to capture the diurnal and seasonal characteristics of irrigation demand [22–24]. Some studies address this limitation by integrating irrigation explicitly into hybrid minigrid dispatch models [25–28], but these approaches are generally confined to local system design and operation. More fundamentally, irrigation is typically treated as an exogenous passive load to be supplied, rather than as a system shaping demand that can alter generation profiles, surplus availability, and power system operation. Consequently, existing studies remain limited in their ability to assess how large scale irrigation electrification interacts with national dispatch, export compensation, and long term planning [29].

Once irrigation demand is met, surplus energy and peak coordination effects extend beyond the farm level and increasingly interact with electric grid [10,30]. At this point, irrigation can no longer be treated as a passive or purely absorptive load; it becomes a system shaping actor that influences storage requirements, dispatch patterns, and tariff design. Capturing this transition requires moving beyond local optimisation toward planning oriented approaches that explicitly consider grid interaction, surplus valuation, and system level coordination [30,31]. Taken together, this literature point toward an emerging need for which generation, demand, and coordination mechanisms co-evolve at scale beyond farm level [16,17,31]. However, very few studies engages with hillside irrigation load quantification or its integration into national electricity dispatch or tariff frameworks [16,17].

Understanding a country's economic-complexity outlook is increasingly used to anticipate how production structures evolve, which technologies diffuse, and how future product characterisation may shift under industrial upgrading and environmental pressures. Recent evidence shows that economic complexity and environmental-related technologies are central to sustainability trajectories, while economic complexity pathways can still amplify environmental stress if technology and governance do not co-evolve [32]. Against this backdrop, Rwanda provides a policy salient context in which to examine these issues. Agriculture employs >70 percent of the population, yet irrigated land remains limited relative to its potential. Vision 2050 prioritizes irrigation expansion in water stressed regions as a pillar of agricultural transformation [33]. At the same time, the National Electrification Plan targets universal access by 2030, with nearly half of new connections expected to come from off grid systems [34]. These parallel priorities place solar powered irrigation at the intersection of agricultural development and national energy planning, with irrigation expansion offering a potential pathway for scaling distributed solar capacity.

Two broad deployment pathways shape the integration of SPIS into national electricity systems. The first is behind-the-meter SPIS (BTM-SPIS), in which farmers own and operate on-site PV systems and may export surplus electricity to the grid. The second is utility-operated grid-integrated SPIS (GI-SPIS), in which irrigation pumping and storage are centrally coordinated. Each pathway has distinct implications for dispatch, system cost, and export compensation.

International experience shows that BTM-SPIS can benefit from prosumer incentives, but requires advanced metering, tariff design, and governance mechanisms to manage exports effectively [22,23,35]. Export compensation approaches such as India's SKY and PM-KUSUM show that tariff design can reward electricity export and thereby moderate incentives for excessive pumping [36,37]. GI-SPIS leverages economies of scale and coordinated dispatch, but may curtail unused solar energy if flexibility or storage are limited.

Against this background, the gaps in the literature can be summarised in three areas. First, most tariff and dispatch models are built on household or commercial load profiles, with limited attention to irrigation specific demand dynamics. Second, few studies integrate SPIS into national economic dispatch models that reflect actual generation mixes and system-level constraints. Third, existing work rarely quantifies tariff sensitivity in a way that links export pricing to grid cost recovery and WEF-nexus planning. In response, this study is guided by three planning questions: **(i) how irrigation electrification becomes system shaping for national grid dispatch; (ii) how alternative SPIS pathways and deployment scales reshape system costs and (iii) How export compensation levels bound utility's valuation of surplus electricity as SPIS scales?**

This study addresses these gaps by developing a planning oriented irrigation energy framework that treats irrigation as a system shaping load rather than as a passive demand. The framework integrates spatially explicit irrigation energy estimation with an hourly national electricity dispatch model and uses tariffs and dispatch outcomes as analytical probes to explore coordination pathways rather than as direct policy prescriptions. Using this framework, the study compares BTM-SPIS and GI-SPIS configurations in Table 1 across varying PV capacities and irrigated areas and evaluates system costs, export-

Table 1
Operational distinctions between BTM-SPIS and GI-SPIS configurations.

Feature	BTM - SPIS	GI - SPIS
Ownership	Farmer managed on site system; operational decisions made locally	Utility managed SPIS; operational decisions coordinated centrally
Gravity pond charging	Only from on site PV	From any on grid generators
Storage control	Local autonomy	Centrally optimised
Export and import logic	Surplus is exported to grid	Surplus is curtailed.

compensation requirements, and breakeven-tariff levels across different deployment scales.

By combining spatial elevation stratification, irrigation-energy estimation, scenario-based tariff analysis, and national dispatch simulation, the study contributes an integrated analytical structure linking agricultural water use and electricity planning. The results provide planning relevant insights for regulators, utilities, and agricultural institutions seeking to align irrigation expansion with grid studies.

2. Methodology

This study develops a spatially and temporally explicit planning and analysis framework to assess the technoeconomic performance of powering hillside irrigation through either grid supply or solar powered irrigation systems. The framework evaluates how irrigation electrification interacts with national power system costs and export compensation, interpreted as the utility's marginal value of purchasing surplus electricity from SPIS. The analysis is positioned at the national planning level and does not represent feeder level operation.

Methodologically, Fig. 1 summarizes the whole workflow used for quantification, national dispatch and tariff sensitivity. First, pumping head is derived from terrain and a hydrologically representative intake, defined as the lowest river /lake elevation point within each subbasin, and lift is computed as the relative elevation of cropland above that intake. Related studies have often assumed constant groundwater pumping head, using a hypothetical head value in the calculation [8, 10]. Next, daily irrigation water volumes are computed from crop water requirements and crop area within each elevation band. Then, daily water volumes and terrain-derived lift are converted into pumping energy and an hourly pumping-demand profile by defining a fixed daytime pumping window and computing the corresponding pumping flow rate as daily volume divided by the number of pumping hours. Subsequently, gravity storage is used to decouple irrigation service from real time electricity supply by buffering PV pumping mismatches and avoiding peak coincidence with morning and evening national demand. This gravity storage assumption is practically feasible and can be seen in Farthing et al.,(2023) [10]. Finally, the resulting hourly net load time series are evaluated in a cost minimising national dispatch and tariff sensitivity model.

2.1. Data collection and spatial preprocessing

This subsection defines how pumping head is determined from geolocation by locating a representative river intake elevation and computing cropland lift from DEM and ESA WorldCover [38]. The hydrological boundaries and river extents are obtained from Level-12 HydroBASINS [39] and HydroSHEDS [40]. Within each Level-12 subbasin, a representative pumping intake elevation is defined by sampling the minimum SRTM elevation within a narrow corridor buffered around the HydroSHEDS river network, as shown in Fig. 2; and cropland is then stratified into relative elevation as illustrated in Fig. 3.

Terrain characteristics are extracted from the 30 m SRTM digital elevation model [41], and cropland extent is sourced from ESA WorldCover at 10 m resolution [38]. Monthly rainfall and reference evapotranspiration are retrieved from CLIMWAT and CROPWAT [42,43]. Normalized hourly photovoltaic (PV) generation profiles are derived using the time series methods presented in Huld (2017) [44], and the hourly national load profile is sourced from the Rwanda Energy Group for 2022. All spatial datasets are harmonized in a common coordinate reference system prior to analysis. These inputs form the basis for estimating spatially differentiated irrigation demand and its temporal alignment with solar generation.

2.2. Irrigation water requirement and hourly pumping load construction

Crop water requirements are computed using the FAO Penman–Monteith method [42]. For each month, the analysis first determines monthly crop water demand, with banana selected as the representative crop due to its irrigation responsiveness (high crop coefficient) [45] and policy relevance in the region of interest [46]. Monthly effective rainfall is accounted for to estimate the portion of crop water demand met by precipitation. The remaining unmet demand is interpreted as the monthly net irrigation requirement. To reflect real pumping needs, the analysis converts net irrigation requirement into a monthly gross irrigation requirement by applying standard field efficiency assumptions [42].

The resulting monthly gross irrigation requirement is converted into a representative daily irrigation water volume by dividing the monthly irrigation volume by the number of days in the corresponding month. This produces a daily irrigation water volume time series in which

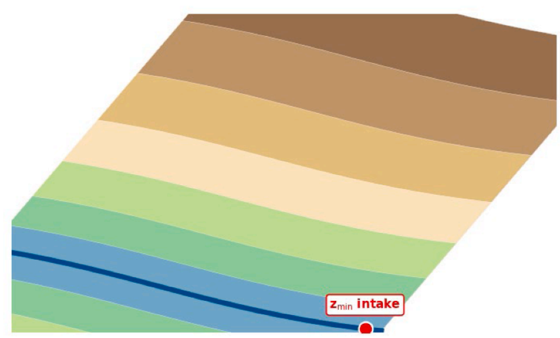

Fig. 2. Hillside perspective view.

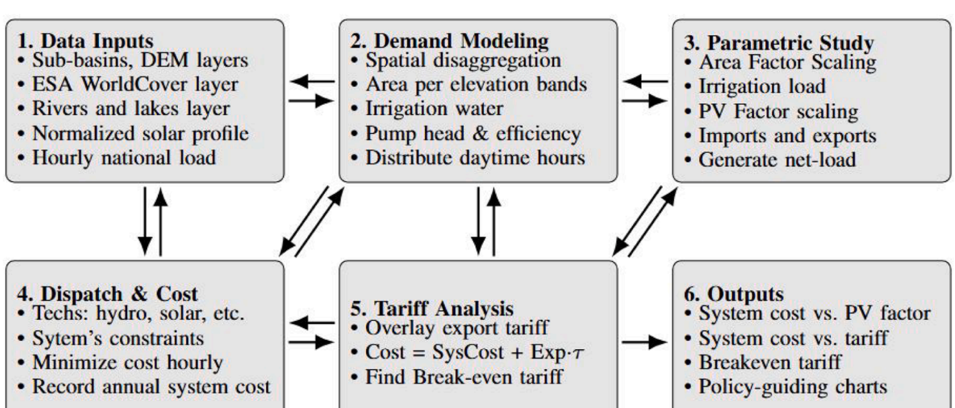

Fig. 1. Workflow for irrigation energy estimation and electricity system analysis.

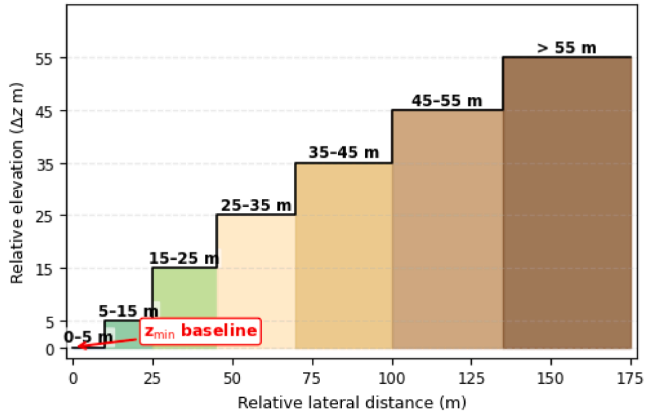

Fig. 3. Hillside elevation bands discretization.

values vary by month according to climate conditions, but are expressed on a daily basis to enable hourly load construction. In this way, monthly climate variability is retained while the irrigation requirement is represented in a temporal form compatible with hourly electricity dispatch modelling.

Daily irrigation water volumes are translated into daily pumping requirements by combining the daily water volume with the pumping head and pump efficiency assumptions. Pumping head is determined from the geolocation based lift method described in Section 2.1, where river intake elevations and cropland elevations define the terrain driven lift requirements for hillside irrigation within each Level-12 subbasin.

To reflect prevailing solar powered irrigation practices, pumping is restricted to a fixed daytime window from 06:00 to 18:00. The operational pumping flowrate is therefore defined directly from the daily irrigation water volume by dividing that volume by the total number of pumping hours within the daytime window. The corresponding daily pumping energy requirement is then converted into an hourly pumping electricity demand profile by allocating pumping uniformly across the daytime pumping hours. This yields an hourly pumping load time series that is temporally consistent with monthly climate drivers, daily irrigation water needs, and a transparent operational pumping rule, and that can be integrated directly into the national net load construction and the economic dispatch and tariff sensitivity analysis that follow.

2.3. Dispatch model

To represent a realistic solar pumping operating logic while avoiding non-dispatchable morning and evening peaks in the national net load profile, pumping is restricted to the fixed daytime window (06:00–18:00) described in Section 2.2. Irrigation service, however, is not assumed to occur only during pumping hours. Instead, pumped water stored in an elevated reservoir could be withdrawn for irrigation application without requiring simultaneous pumping. This representation reflects hillside gravity ponds practices used in hilly and terraced landscapes.

For each hour in the pumping window, the scheduled pumping demand is compared to the available PV generation. When PV generation exceeds scheduled pumping demand, the surplus is interpreted as additional pumping into storage, increasing the gravity storage inventory. When PV generation is below the scheduled pumping demand, the model first uses gravitystored water and imports from grid only when a residual unmet demand remains, thereby prioritizing self-consumption. This rule ensures that PV variability is buffered using gravity storage before the grid is used as the balancing resource, and it provides a consistent basis for computing hourly net load time series for system dispatch analysis.

Two deployment pathways are represented through alternative rules for surplus handling and system control as shown in Table 1. In BTM-SPIS configuration, the grid is treated as an infinite battery where surplus PV electricity not required for pumping or storage may be exported to the grid, and deficits may be imported. This configuration represents an upper bound planning case in which prosumers can fully interact with the grid. In the grid integrated configuration (GI-SPIS), surplus PV electricity is curtailed whenever it is not required for pumping or charging storage, representing a utility-managed scheme where PV generation is dedicated to irrigation service and does not participate in export markets.

2.4. Scenario design and scaling parameters

This subsection defines how irrigation deployment scale and PV sizing are varied to generate a planning relevant design space of net load outcomes. Two parameters are used to explore how SPIS deployment reshapes net demand, surplus generation, and export requirements. The first is the Area Factor, defined as the proportion of irrigable land that is developed, ranging from 0.25 to 1.0. The second is the PV Factor, defined as the ratio of installed PV capacity to peak power ranging from 0 to 3.0. For each combination of Area Factor and PV Factor, hourly pumping loads and PV generation profiles are simulated using the operational rules in Section 2.3 to generate hourly net load time series. Rather than identifying a single optimal configuration, the parameter sweep maps trade-offs between irrigation expansion, PV deployment, and grid interaction outcomes under national planning conditions [47, 48].

2.5. National economic dispatch and export compensation analysis

This subsection integrates the resulting hourly net load profiles into a national economic dispatch model and quantifies system cost sensitivity under alternative export compensation levels. Hourly net load profiles are supplied to a cost minimising national economic dispatch model representing hydropower, solar, peat, gas, and diesel generation. The dispatch model minimises total system cost subject to generation capacity and availability constraints and does not represent feeder-level power flows or network congestion, consistent with the planning-level focus of the study. Export compensation is represented through export tariff applied to surplus electricity exported to the grid under the BTM-SPIS configuration. Total system cost is defined as:

$$\text{Total cost} = \text{System cost} + \text{Exports}\cdot\tau \quad (1)$$

where τ is the export tariff in USD per kWh. The tariff is varied over a defined range to perform a planning-oriented export-compensation sensitivity analysis, informed by cost-reflective levels observed in auction-based procurement in developing countries [49]. The breakeven tariff is defined as the value of τ for which total system cost equals the baseline case without irrigation electrification. In this context, breakeven tariffs are interpreted as planning indicators of system value and surplus absorption rather than as proposed feed in tariffs.

3. Results and discussion

The results are organized as a planning sequence that links spatial feasibility, operational load shaping, system cost response, surplus valuation, export tariff exposure, and pathway comparison between BTM-SPIS and GI-SPIS. First, the analysis identifies the irrigable area which load can be added to the national load baseline without violating dispatch feasibility under existing generation capacity and availability constraints. Second, it quantifies how SPIS operating rules, namely PV aligned pumping and gravity pond buffering, reshape national grid electricity requirements. Third, it evaluates how deployment scale (Area Factor) and PV sizing (PV Factor) jointly determine total system cost and the threshold at which irrigation becomes cost neutral. The final set of results evaluates surplus energy value, derives cost neutral export tariff bounds, tests dynamic versus flat compensation rules, and compares BTM-SPIS and GI-SPIS performance under realistic pricing logic [22]. Consistent with the study scope, results are interpreted as system level outcomes in the hourly dispatch model rather than feeder-level operational behavior.

3.1. Spatial distribution of irrigable cropland

The extent of irrigable land must be established to quantify irrigation energy demand. Since irrigation is load intensive, the analysis first screens which irrigable areas can be added without exceeding installed generation capacity and hourly availability constraints in the dispatch model. Pumping requirements are mapped to elevation based steps and tested for dispatch feasibility under the baseline generation mix, yielding a prioritized set of elevation bands that remain feasible to serve. Fig. 4 summarizes the elevation distribution of cropland in the Eastern and Southern provinces of Rwanda [46] and provides the basis for elevation bands prioritization. Cropland is concentrated at low elevations, with progressively smaller areas at higher bands. In the dispatch simulations, a 55 m lift threshold is applied as an indicative capacity consistency limit. Prioritizing cropland within this low lift range keeps the combined load within the feasible envelope set by installed capacity and hourly operational constraints, whereas expanding to higher lift bands increases pumping demand and can push peak hour requirements beyond available capacity, rendering dispatch infeasible. Around one fifth of total cropland lies within the low lift range, while the remainder is distributed across higher elevation zones where pumping energy requirements rise rapidly. Fig. 4 therefore defines the dispatch feasible irrigation deployment space used in later sections to evaluate how PV integration changes grid demand, system cost, and tariff exposure.

Pumping lift is a primary determinant of irrigation energy cost, and hillside irrigation contrasts with many settings where irrigation commonly involves high lift pumping. Technical studies show that modern SPIS can operate reliably at total dynamic heads of 50–80 m [50, 51]. Commercially SPIS units marketed frequently specify operational heads of 60–70 m when paired with adequately sized PV arrays and inverters [52]. Recent reviews similarly confirm that high head solar pumping is technically feasible but requires larger PV arrays and higher investment to maintain target discharge rates as lift increases [53,54]. Technoeconomic studies of solar irrigation in SSA similarly report that system costs escalate rapidly as lift or pressure requirements increase, often becoming the dominant cost driver in high head environments [55].

These results point to a favourable and underexploited opportunity for hillside irrigation. In many SSA settings, solar irrigation is deployed under hydraulically demanding conditions, where high pumping heads require substantial PV oversizing and higher investment to maintain discharge targets. Therefore, Fig. 4 shows that a meaningful share of cropland is located in low lift zones, implying lower pumping energy intensity, smaller PV system requirements, and improved compatibility with the national dispatch feasibility envelope. This prioritization defines the deployment logic used in Section 3.2 to examine how SPIS operating rules reshape grid electricity requirements.

3.2. National grid electricity demand under SPIS operating rules

Solar pumping supported by gravity pond buffering, progressively reduces the national grid electricity required to supply irrigation as PV sizing increases. When the PV Factor is zero, all pumping depends on the national grid, resulting in the highest annual grid energy requirement. As PV Factor increases, a growing share of pumping energy is supplied by on site PV generation, reducing the portion imported from the grid. Pumping is restricted to daylight hours and therefore aligns with periods of solar availability [50,51]. This operating rule is the first mechanism that makes irrigation demand more dispatch friendly.

The near linear decline in Fig. 5 reflects the mechanism by which gravity ponds provide short term buffering within the day. Gravity

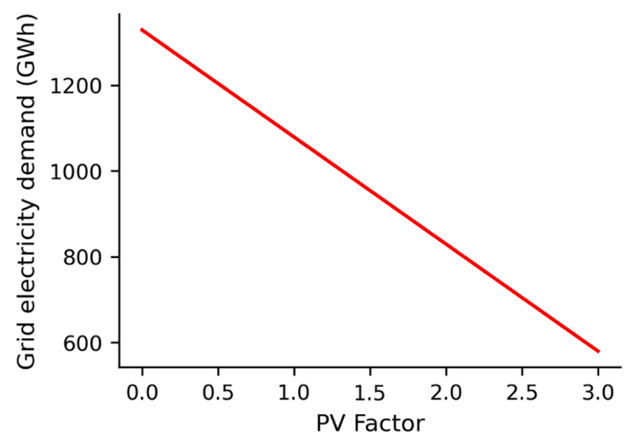

Fig. 5. Grid electricity demand (in GWh) as a function of the PV sizing factor.

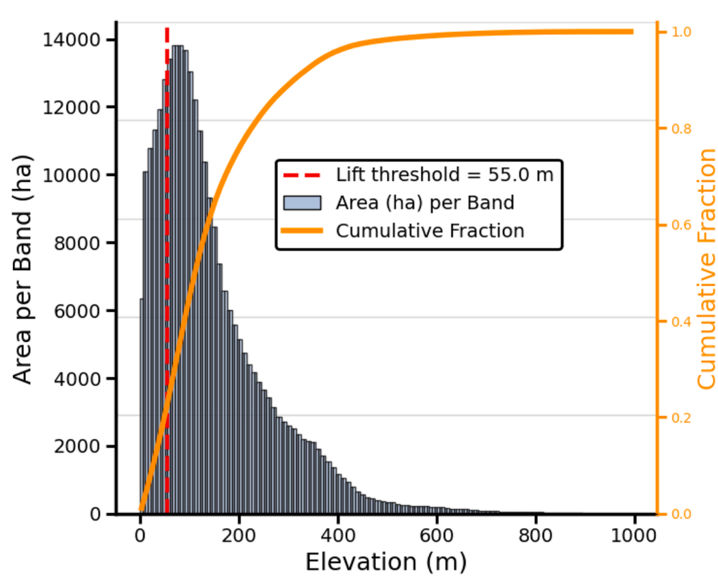

Fig. 4. Area and cumulative fraction of cropland versus elevation in the Southern and Eastern provinces.

ponds store water pumped during high irradiance periods and release it during morning and late afternoon intervals when PV output is lower. Because irrigation is served from stored water rather than requiring pumping, most PV energy produced during the irrigation window can be utilized [30]. As a result, successive increments of PV capacity displace a roughly constant amount of annual grid electricity, even though both irradiance and irrigation requirements vary seasonally.

At PV Factors above roughly 1.5, most irrigation energy is supplied by PV generation and the residual grid demand increasingly reflects the non-irrigation load. In planning terms, this indicates that once PV capacity and gravity buffering are appropriately sized, irrigation becomes independent of the central system's energy supply, reducing seasonal pressure on generators and limiting peak period requirements. This grid demand response provides the mechanism that underpins the system cost results.

3.3. System cost for BTM-spis across PV and area factors

Deployment scale (Area Factor) and PV penetration (PV Factor) jointly determine whether irrigation electrification increases national system cost or can be integrated at cost parity. The PV Sensitivity analysis provides a structured design space where the Area Factor scales the proportion of dispatchable land developed, while the PV Factor specifies installed PV capacity relative to peak irrigation load. Together, these parameters determine the split between grid supplied and PV supplied pumping and therefore the extent to which irrigation increases dispatch requirements or is served largely by on site generation.

Fig. 6 shows a consistent response across all Area Factors. Total system cost declines as PV Factor increases because PV displaces grid supplied pumping power during daytime hours. When PV is undersized relative to irrigation demand, pumping relies heavily on grid electricity, increasing operating cost and at higher development levels, potentially requiring dispatch of higher marginal cost units during solar hours. As PV Factor rises, a larger share of pumping is supplied by on site PV within the pumping window, producing the steepest cost reductions between PV Factors of roughly 0.8 and 1.5. Beyond this range, the curves flatten because most daytime pumping demand is already met, shifting the system response from import toward surplus exports.

Scale effects are visible without changing the underlying mechanism. Higher Area Factors shift the curves upward because larger irrigated areas require more annual pumping energy. This is most evident at PV Factor equal to zero, where the full deployment case (Area Factor = 1.0) has nearly double the system cost of the low deployment case (Area Factor = 0.25). The curves retain a similar overall shape, but the absolute cost reductions with increasing PV Factor are larger at higher Area Factors because more grid electricity is displaced.

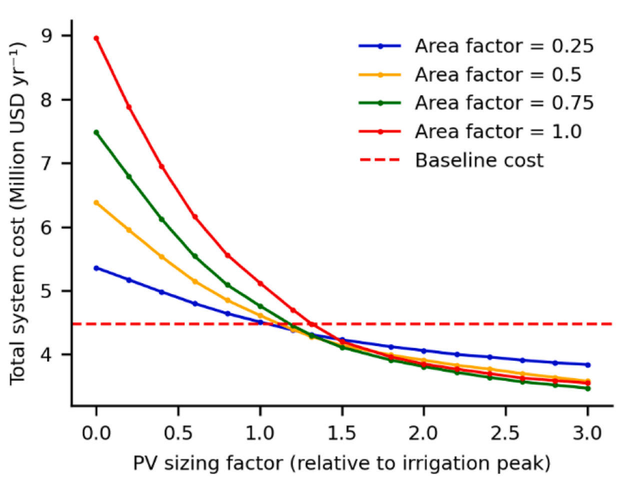

Fig. 6. System cost versus PV factor for different area factors.

The dashed horizontal line in Fig. 6 indicates the baseline system cost without irrigation pumping and provides a planning relevant parity benchmark. The intersections show that cost parity is reached at PV Factor close to one for Area Factors below 0.5, while full irrigation development requires only modest oversizing, with parity around PV Factor 1.2–1.3. A second planning threshold is apparent in the full deployment case. As PV Factor approaches roughly 1.5, irrigation becomes cost neutral or slightly system-saving relative to the baseline, after which further PV additions deliver diminishing returns. In this higher PV range, additional generation increasingly appears as surplus exports rather than further displacement of irrigation related grid imports, so system cost reductions are limited by the declining marginal value of midday surplus as PV penetration rises.

3.4. Value of surplus exports from BTM-SPIS

A key planning question is what happens once PV capacity exceeds on site irrigation needs and surplus electricity begins to appear, and what its system value is. Under the BTM-SPIS configuration, any surplus PV is exported to the grid and credited based on the generation it displaces in the national dispatch, consistent with the export valuation approach discussed in [56,57]. Fig. 7 reports the resulting export value, which reflects both when surplus occurs and the marginal cost of the displaced generation.

Export value is zero at low PV Factors because PV output is fully absorbed by irrigation pumping. As PV Factor increases beyond about 1.32, pumping requirements are largely met and surplus begins to emerge. Export value then rises rapidly between PV Factors of roughly 1.3 and 1.8 because early surplus exports occur during hours when the system still relies on relatively high marginal-cost generation, so displacement yields high value. Export value reaches a maximum near PV Factor 2.0. Beyond this point, additional PV continues to increase surplus energy volumes, but the associated value declines as exports increasingly coincide with lower marginal cost periods and contribute to system wide surplus conditions. Although exports still displace some thermal generation, the value per additional exported kilowatt hour decreases as the marginal displaced unit shifts toward lower cost supply.

This bending shape reflects the interaction between increasing export volume and declining marginal system value. Surplus PV can remain system beneficial, but its monetary contribution becomes progressively smaller as PV capacity grows further beyond irrigation requirements. This has direct implications for export compensation where a single fixed export tariff cannot reflect the declining marginal value of surplus as PV penetration increases, motivating the tariff-bound analysis and compensation.

A practical consideration is that SPIS is often sized to maintain a multi-day water buffer in tanks or ponds, keeping pumping concentrated

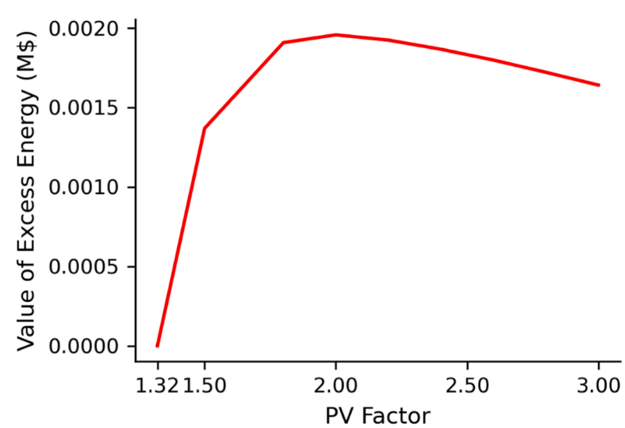

Fig. 7. Value of excess energy paid to the farmer as a function of the PV sizing factor.

in solar hours for reliability. In that operating regime, early "oversizing" is first absorbed by recharging water storage rather than appearing immediately as electricity exports. Once storage is routinely replenished, additional PV increasingly becomes surplus electricity that must be exported or curtailed, and its marginal system value declines as surplus conditions become more frequent.

From a planning perspective, SPIS can contribute to national supply by displacing marginal thermal generation and reducing operational pressure on higher cost units. However, that the value of this contribution is concentrated in the range where PV first begins to exceed irrigation demand and then declines as surplus conditions become more frequent, reinforcing the need to treat surplus remuneration as a system value problem rather than a uniform incentive.

3.5. Breakeven export tariffs for BTM-SPIS

This subsection addresses the planning question: for each PV Factor and deployment scale, what export tariff keeps the utility cost neutral. Sections 3.4 and 3.5 showed that PV integration can bring irrigation to cost parity and that surplus export value is non monotonic as PV Factor increases. Because surplus volumes grow rapidly once PV exceeds irrigation requirements, the system-level outcome depends strongly on how exported energy is compensated. To quantify this sensitivity, breakeven export tariffs are evaluated across PV Factors, defined here as the maximum uniform export payment that maintains cost neutrality for the utility under the dispatch model implicitly mentioned in tariffs studies [22,56,57].

At low PV Factors, the export tariff has limited influence on total system cost because surplus energy is negligible. Nearly all PV generation is absorbed by irrigation pumping and therefore does not enter the export mechanism. As PV deployment rises beyond irrigation requirements, the system becomes increasingly sensitive to export pricing because a growing share of PV output is exported. Under these conditions, export payments contribute directly to total system cost.

Fig. 8 shows that the breakeven tariff declines as PV Factor increases. Larger PV systems generate more surplus energy, so compensation for exports becomes a larger component of total cost. For moderate oversizing, roughly PV Factors of 1.3 to 2.0, sensitivity to tariff levels remains noticeable but bounded because export volumes are still limited. At high PV penetration, particularly near PV Factor 3.0, sensitivity increases sharply: total system cost rises steeply with tariff increases because export volumes are large and compensation is paid for every kilowatt-hour exported [49,57]. In this regime, uniform export tariffs become progressively less viable because they can generate substantial increases in system cost even when the marginal system value of midday exports is low.

The structure of Fig. 8 has direct planning implications. A flat export tariff compensates all exported energy equally regardless of time, yet surplus PV from irrigation-linked systems is concentrated around midday and can coincide with periods when marginal system value is declining. The breakeven results therefore indicate that the system gains relatively little from compensating large export volumes produced in lower-value hours. In this framework, breakeven tariffs should be interpreted as planning indicators of surplus value and fiscal exposure, rather than as recommended tariff levels. Therefore, breakeven tariff is the maximum cost neutral price the utility can pay given their declining marginal system value, and any higher payment would be an explicit subsidy rather than a cost-reflective purchase price [22].

Overall, Fig. 8 indicates that moderate PV oversizing can be accommodated under export compensation without destabilizing system costs, whereas very high PV penetration requires carefully calibrated pricing below cost reflective levels observed in auction based procurement in developing countries [49] to avoid unintended cost increases. This motivates moving beyond uniform tariffs toward compensation rules that track system value more closely, which is examined in Section 3.7.

3.6. System cost under dynamic versus flat export tariffs

This subsection addresses the planning question: if fixed tariffs are risky, can export pricing be tied to the system's marginal value. Building on the breakeven bounds in Section 3.6, Fig. 9 tests how alternative export compensation rules translate into total national system cost under BTM-SPIS when PV deployment increases beyond irrigation requirements.

Fig. 9 compares total annual system cost under two export compensation schemes: a dynamic export tariff linked to the hourly marginal cost from the dispatch model, and a flat export tariff of 0.05 USD/kWh. The red dashed line indicates the baseline cost without irrigation (4.48 Million USD). The flat tariff is selected as a representative value within commonly reported ranges for utility-scale PV costs and feed-in tariffs, where levelised costs and auction prices around 0.04–0.06 USD/kWh in 2016 as shown in Dobrotkova et al. [49]. At PV Factor equal to zero, both schemes coincide at approximately 8.9 MUSD because there is no PV generation and therefore no exported surplus.

As PV capacity is added, the dynamic-tariff curve drops sharply. Total cost falls to around 6.2 MUSD for PV Factors between approximately 0.8 and 1.3, reflecting displacement of higher marginal cost daytime generation by PV while export payments remain modest. In this range, most PV output is consumed by irrigation or displaces relatively

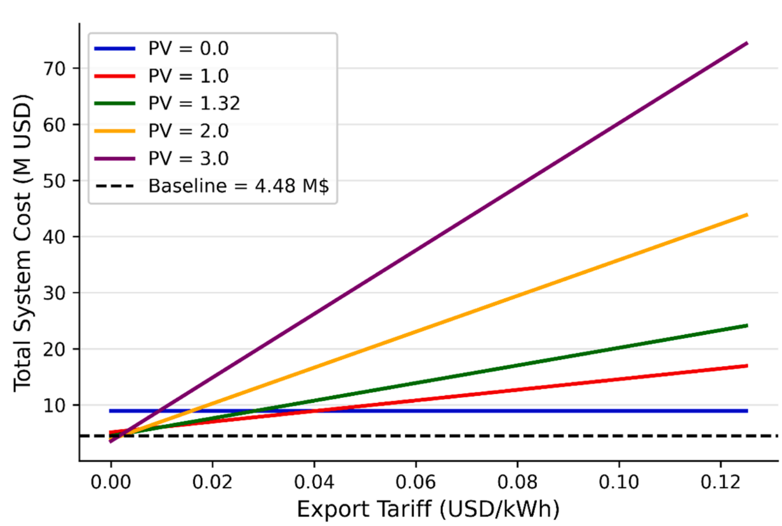

Fig. 8. Export tariffs above breakeven thresholds for BTM-SPIS.

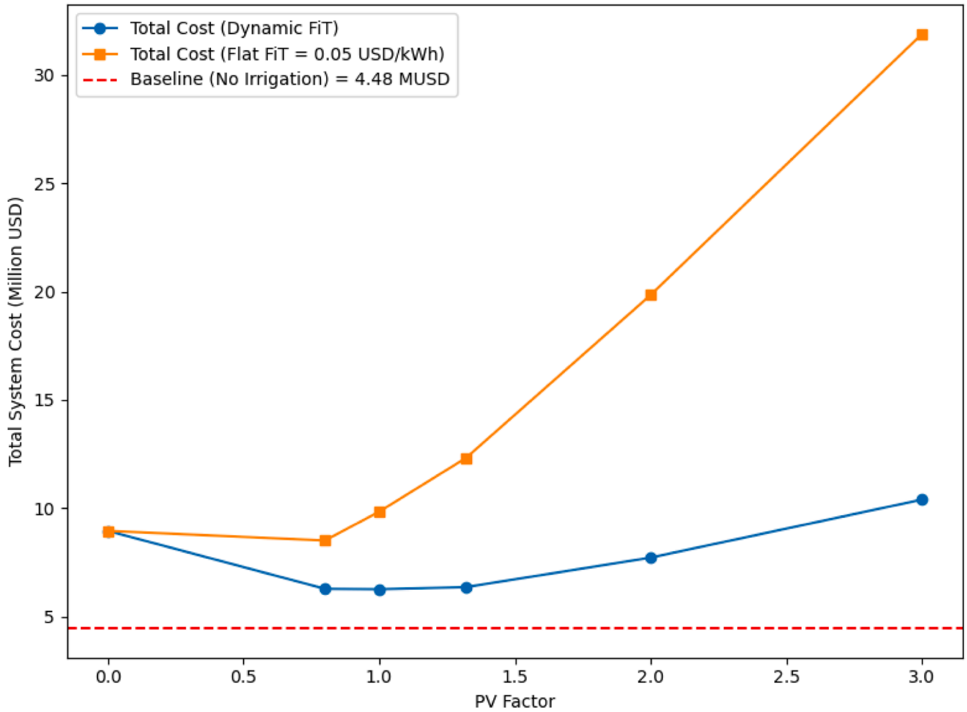

Fig. 9. System cost vs PV factor under dynamic vs flat FiT.

expensive generation, and the dynamic tariff closely tracks the underlying marginal system value. As a result, average payments for surplus energy remain low, close to 0.012 USD/kWh.

The flat 0.05 USD/kWh tariff behaves differently once surplus exports emerge. System cost decreases only slightly at low PV Factors and then rises steeply as PV deployment increases further. At PV Factors around 1.0 and 1.32, total cost under the flat tariff already exceeds the dynamic case by a substantial margin. At high PV penetration the divergence becomes extreme: by PV Factor 3.0, total system cost increases dramatically under the flat tariff while remaining far lower under the dynamic scheme. This escalation is driven almost entirely by export payments that scale linearly with exported energy, independent of whether the system can use that energy to displace high cost generation.

The dynamic-tariff curve indicates that for PV Factors roughly between 0.8 and 1.3, irrigation can be supplied while keeping total system cost within a relatively narrow band above the no-irrigation baseline. Beyond PV Factors near 2.0, total cost under the dynamic scheme rises more noticeably as surplus exports accumulate in lower-value hours, but the increase remains moderate compared with the flat tariff case. This confirms that marginal-cost-based remuneration naturally limits fiscal exposure to large midday surpluses, whereas generous flat tariffs become increasingly unsustainable as PV capacity approaches two to three times irrigation peak load.

Taken together with the breakeven analysis in Section 3.6, Fig. 9 shows that flat export tariffs that appear reasonable at low PV penetration can lead to substantial cost overruns once irrigation-linked PV is widely deployed, consistent with documented challenges in net metering and feed-in tariff schemes in emerging power systems [49,54]. Dynamic or time-differentiated export pricing therefore emerges as a key instrument for integrating BTM-SPIS at scale while maintaining system level cost efficiency.

3.7. Comparison of BTM-SPIS and GI-SPIS

This subsection addresses the planning question: if export payments are dynamic and surplus value declines at high PV penetration, should the preferred pathway shift toward GI-SPIS. The preceding results established that PV-integrated irrigation affects the national system through two channels: displacement of grid-supplied pumping energy and, once PV exceeds irrigation requirements, surplus exports whose marginal value declines and whose net cost to the utility depends on the export tariff rule. Fig. 10 compares BTM-SPIS and GI-SPIS to clarify how alternative coordination architectures perform across PV Factors under these system interactions.

Both configurations show declining system costs as PV capacity increases, reflecting the alignment between irrigation pumping and solar availability and the ability of gravity ponds to buffer intra-day timing differences. The distinction is that BTM-SPIS relies on decentralized PV production with exports treated through a compensation mechanism, whereas GI-SPIS represents coordinated operation in which pumping and gravity storage charging can be scheduled by a central operator relative to national dispatch priorities. As a result, performance differs across PV Factors, particularly in the low-PV regime and in the surplus-dominated regime.

At low PV Factors, GI-SPIS achieves lower system cost because the system operator can charge gravity ponds using low-cost off-peak generation and coordinate pumping with national dispatch objectives [58, 57]. Under BTM-SPIS, irrigation must be served at prevailing marginal cost when PV is insufficient, and the configuration lacks system-wide coordination. Consequently, GI-SPIS has a clear cost advantage when PV deployment is limited and grid supplied pumping remains important. As PV deployment increases, the two curves converge and may intersect. Beyond this point, BTM-SPIS can appear more cost-effective within the model because surplus PV exports are assigned positive value through the export mechanism, while GI-SPIS curtails surplus when it is not required for pumping or storage charging.

A central interpretation is that the apparent high PV advantage of BTM-SPIS is contingent on export absorptive capacity and compensation assumptions. In the model, surplus PV is exported without curtailment, implying that the grid can absorb all farm level midday exports. Under practical grid conditions, this assumption is unlikely to hold at high PV penetration, particularly where distribution constraints and midday saturation limit export acceptance. In such conditions, the advantage of

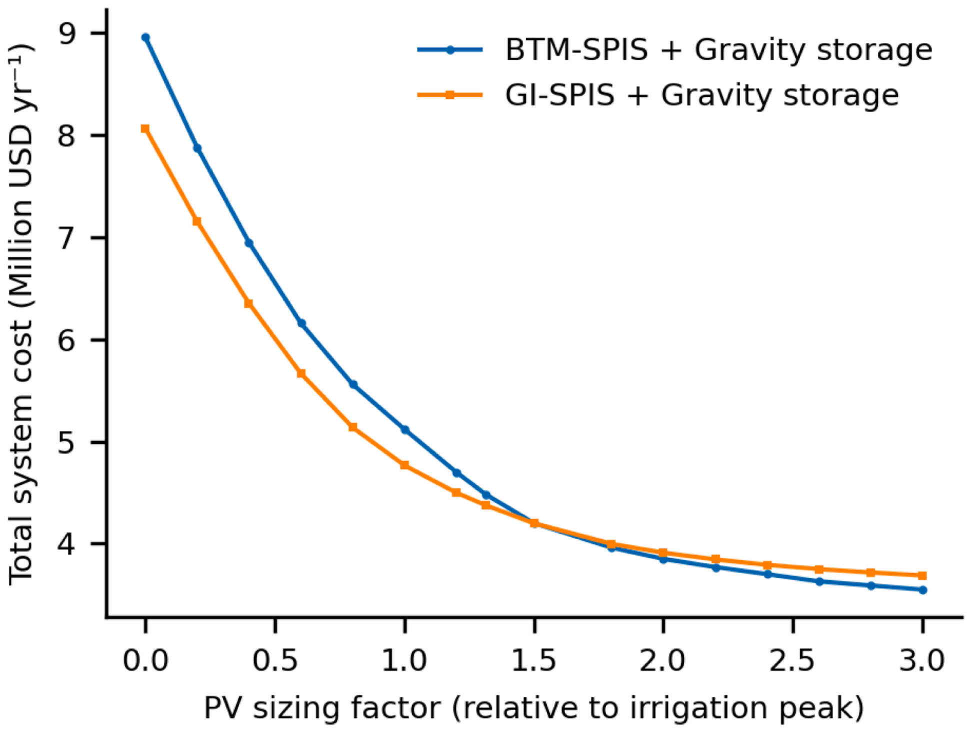

Fig. 10. BTM-SPIS versus GI-SPIS: system cost versus PV factor.

BTM-SPIS would be smaller, and could reverse if curtailment becomes significant. GI-SPIS is structurally more robust to this limitation because coordinated charging of gravity storage and coordinated pumping allow surplus energy to be absorbed within system objectives rather than treated as uncoordinated exports [30,52].

At very high PV Factors, marginal value declines for both architectures. Irrigation demand is fully met, gravity ponds approach saturation, and the national system has limited ability to benefit from additional midday energy. Outcomes then depend primarily on tariff design, curtailment constraints, and the availability of grid-tied storage or other flexible loads capable of absorbing surplus energy. In this regime, the distinction between architectures becomes less about whether PV is present and more about whether coordination and pricing rules can prevent low-value surplus from translating into either curtailment or fiscal exposure.

Overall, Fig. 10 highlights complementary strengths. GI-SPIS performs best when PV deployment is limited and system-level coordination can exploit low-cost generation to charge gravity storage and schedule pumping. BTM-SPIS can appear attractive at high PV penetration in an unconstrained export setting, but would create large uncoordinated midday surpluses in practice unless supported by storage, demand shifting, aggregation, and time-differentiated remuneration [59]. These results suggest that Rwanda's long-term strategy will benefit from coordinated architectures in which storage, flexible irrigation scheduling, and export compensation are designed jointly to limit curtailment and maintain system-level value as distributed PV scales.

4. Policy insights: toward a grid ready irrigation electrification strategy

The policy implications map directly onto the study's three planning questions. First, irrigation becomes system shaping when it is scaled because feasibility and cost outcomes depend on spatial and temporal coordination, storage buffering, and the grid's ability to absorb midday surplus (Figs. 4–5). Second, alternative SPIS pathways and deployment scales reshape national system costs differently (Figs. 6–7 and Fig. 10). Third, export compensation bounds are central to system performance, since the marginal value of surplus declines at higher PV penetration and flat remuneration can create substantial utility cost exposure once exports scale (Figs. 8–9). The subsections below translate these findings into actionable priorities for siting, coordination, tariff design, and phased system evolution especially with planning directions in which solar becomes a larger share of supply of flexibility resources, including battery storage and pumped storage for self-sufficiency and reliable system integration.

4.1. *Agricultural hubs and coordinated water delivery*

The spatial feasibility indicates that dispatch feasible irrigation expansion is concentrated in low-lift terrain (Fig. 4). This lowers pumping energy intensity and reduces the risk that incremental irrigation demand exceeds dispatch feasibility under existing generation constraints. It also creates a practical entry point for coordinated delivery models in which agricultural hubs centralize intake pumping, shared gravity storage, and water scheduling, with distribution implemented through piped networks or other locally appropriate logistics. Hub based designs reduce duplication of pumping and generation assets, increase storage utilization through sharing, and make disciplined scheduling more credible, including daytime pumping aligned with solar availability and coordinated release from shared gravity storage. In planning terms, hubs convert the spatial advantage of low lift cropland into an irrigation system that can be integrated into electricity planning as a coordinated load rather than many independent pumping points.

Hub based delivery is also compatible with agrivoltaic irrigation concepts, co-locating PV generation with irrigated production can reduce land competition and treat irrigation demand as a purposeful sink for daytime solar output, strengthening coherence between land use priorities and renewable integration [59].

4.2. *Soft infrastructure and institutional capacity*

The grid demand mechanism identified in the results depends on disciplined operation, particularly SPIS and buffering through gravity storage that reduces pumping in lower PV hours (Fig. 5). These benefits do not arise automatically from equipment deployment and require soft infrastructure that supports predictable collective operation. Shared schemes typically depend on clear governance structures, transparent metering, enforceable scheduling rules, and reliable communication between operators and users. Training programmes, irrigation committees, and data sharing arrangements should accompany investments in shared pumping and storage.

This institutional layer is central to performance because the system level benefits in the modelling rely on predictable scheduling behavior and credible enforcement of operating and compensation rules. Without such arrangements, irrigation can revert to pumping behavior that amplifies peak stress, and PV surplus can become unmanaged injections rather than coordinated contributions [60,61].

4.3. Coordination models and system level performance

The pathway comparison indicates that BTM-SPIS and GI-SPIS interact with the grid through different coordination pathways (Fig. 10). GI-SPIS can provide scheduled and controllable operation, enabling pumping and storage charging to be aligned with national dispatch priorities and low cost periods. This coordination advantage explains strong GI-SPIS performance when PV deployment is limited and grid energy remains part of the pumping supply [57].

BTM-SPIS can appear attractive at higher PV penetration because surplus exports are credited through the export mechanism, but this outcome depends on optimistic assumptions about export absorption. In practical systems, simultaneous midday exports from dispersed systems become more difficult to integrate as PV penetration rises, especially when local network constraints and system level midday saturation increase curtailment risk. Furthermore, such excess can lead to over-pumping. Centralized SPIS offers more robust and controllable system benefits because it internalizes flexibility through coordinated pumping, and curtailment decisions aligned with system needs. A planning implication is that export policy should be treated as part of a broader coordination design, including aggregation, controllability provisions, and settlement rules, rather than as a standalone incentive.

4.4. Phased evolution and future system architecture

A staged approach aligns deployment with the thresholds observed in the results and with governance capacity. Early deployment can prioritize low lift zones and coordinated rollout, where GI-SPIS can exploit scheduling and shared storage to manage grid interaction effectively (Figs. 4, 5, and 10). As PV deployment approaches the cost neutral range identified in the system cost results (Figs. 6 and 7), irrigation expansion can proceed without increasing national system costs, provided operating rules preserve peak avoidance and storage buffering.

At higher PV penetration, the binding constraint shifts from energy supply to system flexibility because surplus exports scale while marginal value declines (Fig. 8) and compensation rules become decisive for total system cost (Figs. 9 and 10). In this regime, larger flexibility resources become central to maintaining value, including batteries and pumped storage that shift surplus solar energy into higher value hours. Irrigation linked PV can evolve from pumping electrification into a coordinated PV load storage opportunity where irrigation provides a controllable daytime demand, gravity storage provides short term buffering, and system level storage converts surplus solar into dispatchable value. Agrivoltaic irrigation strengthens this pathway by coupling agricultural production with solar generation, creating a predictable daytime sink for PV output and reinforcing the system value of flexibility investment for both agricultural reliability and grid adequacy.

4.5. Political alignment, least cost planning, and rwanda pathways

Rwanda's Vision 2050 [33], the National Land Use Plan [62], and the Least Cost Power Development Plan (LCPDP) [63] each set clear sectoral directions, but they are typically operationalized through separate planning and implementation tracks. The modelling results show that this separation is increasingly problematic once irrigation electrification scales, because irrigation is both seen as a crucial food and energy systems shaping [46]. These are cross-sector effects that cannot be resolved within agriculture or electricity planning alone. The central implication is therefore an institutional one where irrigation electrification requires a joint planning interface that links land and irrigation development decisions to grid adequacy, flexibility planning, and export pricing rules.

In practical terms, coordinated architectures remain more robust under realistic export absorption limits because they enable disciplined pumping schedules, shared storage operation, and controllability that aligns irrigation demand and PV output with system needs. This does not require creating a new agency, but it does require formal coordination between institutions that already hold mandates. Energy system planners and the utility should lead on dispatch feasibility screening, flexibility investment needs, and tariff or remuneration design, while agricultural agencies should lead on scheme siting, farmer organisation, water allocation rules, and governance of shared infrastructure. SPIS can still complement national objectives by mobilising farmer-led PV uptake, but only within a governance framework that links export participation to system value and integration conditions, such as aggregation or storage-backed controllability, so that distributed PV contributes dispatchable value rather than unmanaged midday surplus.

As solar becomes a larger share of the generation mix, flexibility resources such as battery storage, pumped storage, and other controllable loads become increasingly important for preserving the value of midday generation and limiting curtailment and excess export payment risk. Irrigation electrification policy should therefore be developed through a combined electricity–irrigation planning process, so that irrigation-driven PV growth supports decarbonisation, adequacy, and agricultural productivity through coordinated operation rather than siloed implementation.

4.6. From access policy to energy governance

The findings imply a shift from access oriented deployment toward energy governance. As irrigation linked PV scales, system outcomes depend increasingly on how surplus is integrated, priced, controlled, and absorbed. Flat export tariffs become progressively risky [22] at high PV penetration because they can scale payments when marginal system value is declining and export volumes are growing. Time differentiated or marginal value linked export pricing can better align incentives with system value and reduce utility cost exposure under large scale exports (Figs. 8 and 9).

More broadly, irrigation electrification requires governance arrangements that integrate tariff design, storage investment, coordinated operation of gravity storage, and long term planning for solar and water variability. The success of this transition will determine whether solar powered irrigation becomes a flexible system asset supporting national decarbonization and agricultural development, or a source of unmanaged surplus that increases curtailment, over pumping or utility cost exposure.

5. Conclusion

This study sets out to address three questions by treating irrigation electrification as a planning relevant load and testing its implications under an hourly national dispatch framework.

First, the results show how irrigation becomes system shaping for national grid dispatch. Even when annual irrigation energy is moderate, the potential irrigated scale and the timing of pumping introduce peak hour requirements that interact directly with the installed capacity envelope and operational constraints of the generation fleet. Under hard dispatch feasibility, irrigation cannot simply be added to the national load without verifying hourly dispatchability and peak capacity limits. The feasible deployment scale is instead defined by whether the combined national and irrigation demand remains dispatchable, which motivates spatial prioritization of lower-lift cropland and coordinated pumping assumptions in planning-oriented analysis.

Second, alternative SPIS pathways and deployment scales produce significantly different system-cost outcomes. Grid integrated configurations increase system cost and highlight the capacity-feasibility boundary as irrigated area expands, while BTM-SPIS configurations reshape the net load profile through imports and exports. Across deployment scales, PV integration reduces total system cost relative to grid only irrigation by displacing higher cost marginal generation, but the magnitude of savings depends on how irrigation is deployed and how surplus is managed, especially, at higher PV penetration.

Third, export compensation levels bound the utility's cost exposure to surplus purchases as SPIS scales. As PV penetration rises and exports increase, compensation rules become a system-level design variable that can shift costs from prosumers to the utility. The study quantifies the compensation marginal value that maintains cost recovery under increasing surplus volumes and shows that export pricing must be aligned with system value to avoid uneconomic outcomes.

Overall, the findings position SPIS integration as a coordination and valuation problem at national-planning level. Planning frameworks that combine spatial screening, hourly dispatch feasibility, and export compensation sensitivity provide a practical basis for regulators and utilities to scale irrigation electrification while maintaining grid feasibility and financial sustainability. This study is subject to limitations consistent with its planning oriented scope. The dispatch model does not represent feeder level power flows or voltage constraints and treats export absorption as an upper-bound case; in practice, curtailment and local network limits would reduce the value of exports, particularly at high PV factors. Water availability and sustainability constraints are discussed from a geolocation, governance and incentive design perspective but overextraction is not studied in the model. Pumping operations are represented by using hardcoded rules and storage rules rather than observed farm level behavior. Results are therefore most directly transferable as a replicable workflow, while quantitative outcomes remain contingent on Rwanda specific data, generation mix, and institutional conditions.

CRediT authorship contribution statement

Pierre Damien Uwitije: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jimmy Ehnberg:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **J.M.V. Bikorimana:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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