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LICENTIATE THESIS

PIERRE DAMIEN UWITIJE • Planning Irrigation Electrification • 2026

Planning Irrigation Electrification

Demand Formation, Dispatch Feasibility, and Solar Integration in Rwanda

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DEPARTMENT OF ELECTRICAL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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Printed by Chalmers Digital Printing
Gothenburg, Sweden, 2026

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Abstract

Irrigation electrification is a critical pathway for enhancing agricultural productivity and climate resilience; however, its broader implications for power-system planning remain insufficiently understood. In many load-assessment studies, irrigation is treated either as a farm-level technical sizing problem or as an exogenous electricity demand, which limits its usefulness for national-scale planning, infrastructure deployment, and system-level decision-making. This reveals a gap between irrigation development strategies and electricity-system feasibility assessment.

This thesis addresses that gap by developing a planning-oriented framework for analysing large-scale irrigation electrification as a coupled irrigation–electricity system shaped by spatial, temporal, and operational constraints. It links geospatial terrain screening, lift-conditioned irrigation water demand, pumping schedules, and operational strategies to the formation of hourly demand profiles, generation and storage configurations, and grid-exchange conditions. These configurations are evaluated against dispatch-constrained electricity-system operation to examine utility-level generation-capacity feasibility, cost, surplus, and system-planning implications.

The results show that irrigation electrification is not defined by energy use alone, but by the spatial, temporal, and operational configuration through which irrigation demand, on-farm solar generation, storage operation, and grid exchange are jointly shaped under power-system constraints. The demand-formation process provides decision-relevant hourly profiles that reveal where irrigation demand becomes system-relevant, when it becomes compatible or incompatible with existing electricity-system operation, and how storage and solar-powered irrigation strategies reshape feasibility. Moderate irrigation electricity demand can become infeasible when concentrated in peak-coincident pumping windows, whereas coordinated scheduling and storage buffering can restore feasibility without reducing irrigation service. Storage does not remove constraints; rather, it shifts them toward charging behaviour, service reliability, and import–export balance. At larger scales, on-farm solar-powered irrigation introduces structural surplus, making deployment strategies and export valuation important determinants of system performance.

Applied to Rwanda, the computational framework bridges local irrigation engineering with national electricity planning. It illustrates that irrigation acts as a system-shaping load in which demand, generation, storage, and grid exchange are co-dependent. The findings provide a methodological basis for integrated energy and agricultural planning in Sub-Saharan Africa, where irrigation expansion is increasingly central to food security, climate adaptation, and sustainable energy access.

Keywords: irrigation electrification, demand formation, dispatch feasibility, solar-powered irrigation, storage, PV export valuation, Rwanda

List of Publications

This thesis is based on the following publications:

[I] **P. D. Uwitije**, J. Ehnberg, J. M. V. Bikorimana, “Microgrid and Farming Activities: Strategy for Sustainable Productive Uses in Rural Areas”. 2023 IEEE PES/IAS PowerAfrica, Marrakech, Morocco, 2023, pp. 1-5, doi: 10.1109/PowerAfrica57932.2023.10363323.

[II] **P. D. Uwitije**, J. Ehnberg, J. M. V. Bikorimana, J. P. Iradukunda, E. O. Ahlgren, “Planning Irrigation Electrification Through Demand Formation: Dispatch-Based Feasibility Assessment in Rwanda”. Manuscript.

[III] **P. D. Uwitije**, J. Ehnberg, J. M. V. Bikorimana, “Irrigation as a System Shaping Load: Technoeconomic and Policy Pathways for Water Energy Food Nexus”. Published in Energy Nexus, vol. 22, article 100707, 2026.doi: 10.1016/j.nexus.2026.100707..

Other publications by the author, not included in this thesis, are:

[IV] **P. D. Uwitije**, J. Ehnberg, J. Bikorimana, “Modelling Large-Scale Solar Irrigation Deployment: Costs and Grid Implications in Rwanda”. *2025 IEEE PES/IAS PowerAfrica*, Cairo, Egypt, 2025.

[V] **P. D. Uwitije**, J. Ehnberg, “Mutual Gain of Electric Markets and Agricultural Microgrids”. *5th International Conference on Solar Technologies & Hybrid Mini-Grids to Improve Energy Access*, Palma de Mallorca, Spain, Sept. 4–6, 2024.

[VI] N. Pettersson, A. Nilsson, A. Bergum, **P. D. Uwitije**, J. Ehnberg, “Impact of Climate Change on Energy Need and Cost of Sustainable Electrified Irrigation”. *2025 IEEE PES/IAS PowerAfrica, Cairo, Egypt, 2025*, doi: 10.1109/PowerAfrica65840.2025.11289089.

[VII] J. Ehnberg, M. A. Gelchu, **P. D. Uwitije**, “Assessing Cable Sizing for PV Microgrids: Economic and Environmental Factors in Focus – A Case Study of Ethiopia and Rwanda”. *2024 IEEE PES/IAS PowerAfrica, Johannesburg, South Africa, 2024*, doi: 10.1109/PowerAfrica61624.2024.10759427.

[VIII] M. Fernández, J. Ehnberg, **P. Uwitije**, L. Beniken, R. Mrabet, O. Santander, J. Morató, “On Improvements for Sustainable Energy System for Drip Irrigation – Study Case Kenitra Morocco”. *2023 IEEE PES/IAS PowerAfrica, Marrakech, Morocco, 2023*, doi: 10.1109/PowerAfrica57932.2023.10363332.

[IX] R. Busse, F. Davidsson, J. Ehnberg, I. Holtzhausen, **P. Uwitije**, “On Grid and Solar Hybrid Connection of a Nut Processing Plant in Mozambique”. *2023 IEEE PES/IAS PowerAfrica, Marrakech, Morocco, 2023*, doi: 10.1109/PowerAfrica57932.2023.10363247.

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Acknowledgments

I would like to express my sincere gratitude to all those who have supported my education and accompanied me throughout this licentiate work.

First, I wish to thank my supervisor, Associate Professor Jimmy Ehnberg, for his dedicated guidance, continuous encouragement, and constructive feedback throughout this work. His trust, generosity with time, and openness to discussion have shaped both this research and my development as a scholar.

I am equally grateful to my co-supervisor, Associate Professor Jean Marie Vianney Bikorimana, for his valuable support, thoughtful discussions, and continued encouragement. I also sincerely thank Professor Erik O. Ahlgren, my examiner, and Associate Professor Helene Ahlborg for their support, insights, and encouragement.

My sincere thanks go to colleagues at Chalmers University of Technology for providing a stimulating and supportive research environment. I am also grateful to my collaborators and co-authors, as well as to colleagues at the University of Rwanda, for their support, discussions, and contributions to different parts of this research.

I gratefully acknowledge the Sida-funded bilateral collaboration programme, whose support has made this licentiate work possible. Through this collaboration, I have benefited not only from financial support but also from a wider academic and institutional partnership that continues to strengthen higher education and research capacity. I therefore extend my sincere appreciation to Sida and to all the professors, experts, and partners who contribute their knowledge, time, and commitment to supporting research and education in Rwanda.

Finally, I would like to express my deepest gratitude to my family and friends for their patience, love, and encouragement. I am especially grateful to Siboniyo Felix for his unwavering support, guidance, and generosity throughout this journey. Above all, I thank my mother and my wife, whose love, strength, and constant support have carried me through this work.

Acronyms

BTM	Behind-the-Meter
CROPWAT	FAO crop water requirement model
DEM	Digital Elevation Model
ESA	European Space Agency
FiT	Feed-in Tariff
GI	Grid-Integrated
GIS	Geographic Information System
L12	HydroBASINS Level 12
PPA	Power Purchase Agreement
PV	Photovoltaic
REG	Rwanda Energy Group
RQ	Research Question
SPIS	Solar-Powered Irrigation System
SSA	Sub-Saharan Africa
WEF	Water-Energy-Food

CHAPTER 1

Introduction

1.1 Background and problem statement

Irrigation expansion lies at the intersection of food security, climate resilience, and modern energy access [1], [2]. In rainfed agricultural regions, irrigation stabilises yields, reduces drought vulnerability, and supports rural livelihoods [3]. When irrigation relies on pumping, however, agricultural water delivery becomes linked to energy infrastructure. Water must be abstracted, lifted, conveyed, and delivered at the required time, which makes irrigation planning dependent not only on agronomic conditions, but also on electricity supply, system operation, and infrastructure capacity [4], [5].

This connection is especially important in Sub-Saharan Africa, where irrigation expansion is promoted while electricity systems often remain capacity constrained and spatially uneven. In Rwanda, the challenge is intensified by hillside agriculture. Many potential irrigation areas lie above rivers or valley-bottom water sources, so pumping energy depends strongly on terrain-conditioned lift [6], [7], [8]. Irrigation electrification therefore creates a productive electricity demand whose system relevance depends on where irrigation is located, when pumping occurs, and how pumping, storage, solar generation, and grid exchange are organised.

Earlier studies provide important foundations for this problem, but they often remain sectoral. Irrigation studies commonly estimate crop-water requirements, pumping energy, groundwater pumping potential, or farm-level solar-powered irrigation feasibility [8], [9]. Electricity-planning studies commonly represent future demand through aggregate estimates, scenarios, or exogenous forecasts [10], [11]. These approaches are useful for demand estimation and forecasting, but they do not fully explain how irrigation demand is formed before it enters the electricity system. In particular, they provide limited insight into how terrain, water access, abstraction structure, pumping schedules, storage logic, and local solar generation jointly shape the timing, magnitude, flexibility, and feasibility of irrigation electricity demand.

This licentiate thesis therefore approaches irrigation electrification as a demand-formation problem. The central issue is not only how much electricity irrigation may require, but how irrigation becomes an electricity-system-relevant configuration. This requires linking spatial conditions, water-service requirements, operating rules, storage behaviour, photovoltaic generation, and grid interaction within a common planning framework.

Rwanda provides a relevant case for examining this problem. The country combines strong policy interest in irrigation expansion, ambitious electrification targets, and a terrain structure in which hillside farming makes pumping energy particularly important [12], [13]. At the same time, Rwanda's interest in solar energy creates an opportunity to examine solar-powered irrigation systems (SPIS) not only as farm-level pumping technologies, but also as grid-interactive assets. When combined with storage and suitable grid import–export arrangements, SPIS can support irrigation service, reduce grid-supplied pumping demand, export surplus electricity, and contribute to a higher renewable-energy share in the national electricity mix. This makes irrigation electrification in Rwanda an interface between agricultural development, distributed solar deployment, storage integration, and electricity-system planning.

1.2 Research gap and thesis positioning

This licentiate thesis starts from the position that irrigation electrification is likely to become an important productive end-use activity in regions where irrigation expansion, food security, climate resilience, and energy access are pursued together. Once irrigation depends on electrically driven pumping, it needs to be represented not only as an agricultural intervention, but also as a power-system-relevant configuration. For top-level infrastructure planning, farm-level electrification knowledge must therefore be translated into national water–energy–food nexus analysis and electricity-system insight. Planners need to understand where irrigation demand is spatially formed, when it appears in hourly operation, and how it changes when storage, solar-powered irrigation, and grid import–export rules are introduced.

Existing research provides important partial insights. Farm-scale studies clarify the technical and economic feasibility of solar pumping and component sizing. Geospatial studies help in territorial irrigation suitability assessment by linking land cover, topography, and water availability. Crop-water models such as FAO CROPWAT support the estimation of crop-water requirements under climatic and agronomic assumptions. Productive-use and rural electrification studies show that agricultural loads can influence system design. Power-system studies provide methods for dispatch, flexibility, and system-cost evaluation. However, these perspectives are not yet fully integrated into a planning-oriented representation of irrigation demand, local generation, storage operation, and grid exchange.

This missing integration matters because irrigation demand is not a fixed input to the electricity system. It is shaped by the way irrigation is spatially sited, hydraulically represented, temporally scheduled, and operationally coordinated. A hectare of irrigated land does not automatically imply one fixed electricity load. The resulting demand depends on the water source, elevation difference, pumping window, storage option, solar contribution, and grid-interaction rule. The same irrigation service can therefore create different electricity-system outcomes depending on how it is formed.

This licentiate thesis is positioned in the intermediate planning space between farm-scale irrigation design and national electricity-system assessment. It does not seek to model the full water–energy–food nexus as one integrated system. Instead, it focuses on the energy–food interaction created by irrigation electrification, with water represented through hydrological terrain, surface-water access, pumping lift, and storage potential. It also does not remain at the level of farm-scale pumping design or component sizing. Rather, it develops a computational, planning-oriented framework for analysing irrigation electrification as a coupled irrigation–electricity system shaped by spatial, temporal, and operational constraints.

Moreover, irrigation is described as a system-shaping load when its spatial distribution, hourly timing, storage operation, and local generation affect electricity-system feasibility, cost, surplus, or grid exchange. The term does not imply that irrigation always dominates the power system. It means that irrigation can change system outcomes when its demand is formed in particular ways. The relevant planning object is therefore not the irrigation load alone, but the configuration through which irrigation demand, photovoltaic generation, storage operation, and grid exchange interact with the electricity system.

1.3 Aim, research questions, and scope

The aim of this licentiate thesis is to develop and apply a planning-oriented framework for analysing irrigation electrification as a coupled irrigation–electricity configuration formed through spatial, temporal, and operational rules. The framework evaluates how this configuration interacts with power-system constraints and alternative solar-powered irrigation strategies.

The thesis is organised around three dimensions of demand formation. The first is spatial: where irrigation demand becomes system-relevant. The second is temporal: when the formed demand becomes compatible or incompatible with electricity-system operation. The third is operational: how storage, solar-powered irrigation, and export rules reshape feasibility, cost, surplus, and reliability.

In this licentiate thesis, demand formation refers to the computational process through which irrigation service requirements become electricity-system-relevant demand. It describes how spatial elements such as cropland, terrain, water access, and abstraction points; temporal elements such as seasons, irrigation windows, and hourly schedules; and operational elements such as pumping logic, gravity storage, photovoltaic generation, grid import, grid export, and dispatch constraints collectively shape system demand, generation, storage behaviour, and grid interaction.

Demand formation builds on conventional demand assessment, load estimation, and system sizing, but it extends them toward system-compatible planning. End-use demand studies are essential because they reveal how electricity consumption varies across sectors, locations, productive uses, appliance ownership, and levels of access. In irrigation electrification, however, the planning question is not only how much electricity irrigation may consume. It is also how the same irrigation service can be spatially organised, temporally scheduled, and operationally coordinated before it enters the power system.

This distinction reflects a shift from a hardware-heavy and supply-centric view of electrification toward a software-enabled and system-aware approach. A brute-force interpretation would treat irrigation as an additional load to be supplied by more generation and network capacity. A demand-formation interpretation instead asks how irrigation service can be shaped through siting, pumping windows, storage, solar generation, and grid exchange so that it becomes more compatible with electricity-system constraints.

The main research question is:

- How does irrigation electrification become a system-shaping load when water-service requirements, terrain, pumping operation, storage, and solar deployment are represented together, and what does this imply for electricity-system planning?

This question is addressed through three sub-questions:

- **RQ1:** Where does irrigation electricity demand become system-relevant when cropland, water access, and terrain-conditioned pumping lift are jointly considered?
- **RQ2:** When does formed irrigation demand become compatible or incompatible with the existing electricity system under alternative pumping schedules and storage-mediated operation?
- **RQ3:** How do gravity storage, SPIS deployment strategies, and export rules reshape the interaction among irrigation service, grid imports, surplus electricity, system cost, and reliability?

The licentiate thesis adopts a system-of-systems perspective in which complex interactions are represented through a sequence of coupled subsystems, geospatial overlays, and explicit modelling rules [14], [15]. The system of interest is narrower than the full water–energy–food nexus. It focuses on a coupled irrigation–electricity configuration evaluated against existing centralised electricity-system constraints. Within this scope, the work considers surface-water-based irrigation opportunities, terrain-conditioned pumping requirements, hourly load formation, buffering logic, and photovoltaic-assisted irrigation strategies.

Figure 1.1 provides a conceptual illustration of the successive tensions that motivate the licentiate thesis. Irrigation can reduce water stress but creates electricity demand. Solar-powered irrigation can reduce grid dependence but introduces temporal mismatch and possible surplus. Storage can buffer this mismatch, but it also introduces new questions about sizing, charging, reliability, and coordination. The figure therefore frames irrigation electrification as a sequence of linked planning tensions rather than as a single technology-supply problem.

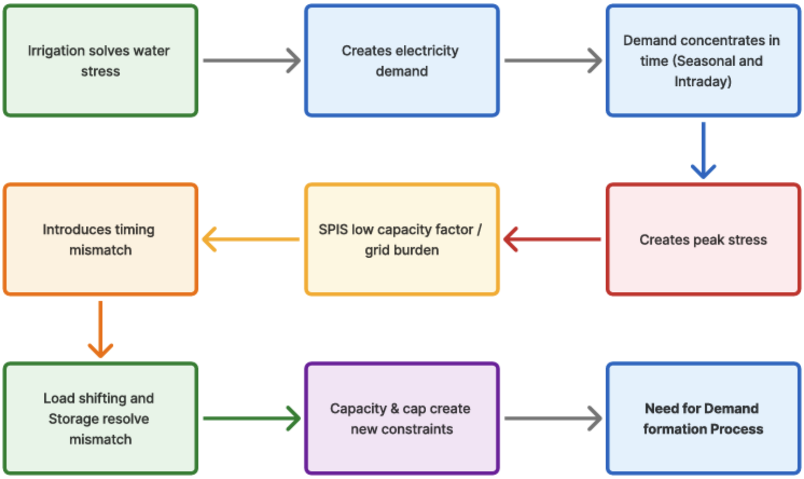

Figure 1.1: Demand-formation tension ladder in irrigation electrification.

The analytical boundary of the licentiate thesis is defined by several deliberate modelling choices. The irrigation demand-formation system is treated as a computationally represented and analytically bounded system that integrates selected domain-level models to explain how irrigation service requirements become electricity-system-relevant demand. It is analytical because it abstracts the components needed to compare irrigation-electrification configurations and their associated trade-offs and constraints. It is bounded because logical rules determine which mechanisms are included in the analysis and which contextual drivers remain external.

Within this boundary, demand formation is organised through three analytical layers: spatial feasibility, temporal feasibility, and operational feasibility. Spatial feasibility determines which cropland–water configurations enter the system through abstraction location, elevation bands, and pumping head. Temporal feasibility determines how irrigation service is scheduled through pumping windows, storage charging, and discharge logic. Operational feasibility determines whether the resulting hourly demand can be accommodated by the existing electricity system, including generation capacity, SPIS contribution, storage behaviour, imports, and exports.

The framework includes first-order spatial, hydraulic, operational, storage, photovoltaic, and dispatch mechanisms, while excluding detailed crop optimisation, stochastic hydrology, farmer behavioural adaptation, transient hydraulic control, equipment outages, and institutional adaptation. These exclusions are deliberate scope choices that allow the licentiate thesis to focus on how irrigation-related demand, generation, storage, and operation are formed and tested at planning scale.

1.4 Thesis structure and included papers

This licentiate thesis is organised around the three research questions as a summary of the three appended papers. The papers provide the empirical and modelling basis for the licentiate thesis, while the synthesis developed here integrates them into one planning framework. In this framework, irrigation demand is first spatially formed, then temporally scheduled, then evaluated under dispatch constraints, and finally reshaped through storage, photovoltaic deployment, and export rules.

Chapter 2 reviews related work on irrigation, energy access, solar-powered irrigation, geospatial irrigation-energy modelling, productive-use demand, and power-system planning. It identifies the literature gaps that motivate the demand-formation perspective. Chapter 3 presents the methodological framework, including the five-stage pipeline linking local engineering grounding, spatial-hydraulic screening, hourly demand formation, dispatch feasibility, and pathway analysis. Chapter 4 presents representative results from the included papers. Chapter 5 discusses the methodological and planning implications of the results. Chapter 6 states the conclusions, scientific contributions, methodological contributions, and research continuation directions.

The licentiate thesis therefore shows how local irrigation mechanisms, national-scale demand formation, dispatch feasibility, and policy-sensitive solar strategies connect into one planning argument for irrigation electrification. The three included papers are appended in full at the end of the licentiate thesis.

The author acknowledges the use of ChatGPT (OpenAI, 2024) to assist with language refinement and editing. The final manuscript reflects the author's original work and judgment.

CHAPTER 2

Background and Related Work

This chapter motivates the research questions and the stage-based methodological framework through a review of related work. The literature moves from irrigation and energy development studies, to farm-scale solar-powered irrigation, irrigation feasibility, geospatial irrigation-energy quantification, and finally to the need for representing irrigation as an electricity-system planning problem in Sub-Saharan Africa. The synthesis at the end of the chapter links literature gaps to the thesis positioning, methodological framework, and research questions.

2.1 Irrigation, energy, and development pathways in SSA

Irrigation is widely recognised as a cornerstone of agricultural transformation, yield stabilisation, and climate resilience, particularly in regions where crop production is highly exposed to rainfall variability [16], [17]. In Sub-Saharan Africa (SSA), this importance is amplified by the continued dominance of rainfed agriculture and the vulnerability of rural livelihoods to drought and rainfall irregularity [3], [18]. At the same time, large gaps persist between irrigation expansion needs and actual irrigated area [19]. As a result, expanding irrigation is frequently framed as a pathway toward improved food security, higher rural incomes, and reduced climate vulnerability.

The development significance of irrigation in the region cannot, however, be understood independently of energy. Irrigation is not only a water intervention; it is an energy-dependent service whose feasibility depends on whether water can be abstracted, lifted, conveyed, and delivered with sufficient reliability and at acceptable cost [2], [4]. In many Sub-Saharan African contexts, limited access to affordable and reliable energy remains a practical bottleneck even where land and water resources are physically available [5]. This interdependence situates irrigation within a broader water–energy–food nexus, in which agricultural productivity, energy systems, and infrastructure development evolve jointly rather than independently [20].

This interdependence becomes sharper as irrigation shifts from manual or diesel-based pumping toward electrically powered and solar-powered systems. Historically, irrigation in the region has relied on gravity-fed systems, diesel pumping, or small motorised solutions [21]. Diesel pumping offers flexibility, but it also exposes users to fuel price volatility, high operating costs, and environmental burdens [21], [22]. These constraints have intensified interest in solar-powered irrigation systems, which promise lower operating costs, modular deployment, and reduced dependence on imported fuels [22], [23].

Once irrigation is electrified, however, it becomes more than a farm technology choice. It becomes a spatially distributed source of electricity demand whose magnitude, timing, and concentration may influence generation adequacy, network expansion, and system operation [8], [11]. The relevant analytical question is therefore not only whether irrigation improves agricultural production, but under what conditions irrigation expansion becomes consequential for electricity systems. This motivates a planning-oriented perspective in which irrigation is examined not only as a water service, but as an infrastructure-dependent activity shaped by territorial conditions, hydraulic requirements, energy provision, and wider system constraints [24], [25].

2.2 Farm-scale studies on solar-powered irrigation

The literature on solar-powered irrigation systems has developed most strongly at the farm scale, where the central questions are practical: whether solar pumping can replace diesel, how systems should be sized, and what costs and savings can be expected [21], [26]. Reviews of sustainable solar irrigation in Sub-Saharan Africa and of solar-powered water pumping systems show substantial progress in technology choice, component sizing, and pumping performance [23], [26]. These studies also assess techno-economic feasibility under site-specific conditions [21], [23]. Comparative analyses of solar and diesel pumping further reinforce the attractiveness of solar solutions in weak-grid and off-grid settings [20].

One of the main strengths of this literature is its grounding in physical and engineering relationships. Farm-scale studies typically derive electricity demand from crop water requirements, hydraulic head, and pumping conditions rather than assuming it exogenously [26], [27]. This engineering-based approach gives the literature strong analytical depth and practical relevance for system design [23], [28].

At the same time, the farm-scale SPIS literature is closely aligned with the logic of smallholder or individual-farm deployment. This is consistent with the broader trajectory of irrigation development in Sub-Saharan Africa, where small-scale and farmer-led irrigation has expanded more rapidly than large, centrally managed schemes. Solar pumping has reinforced this trend by enabling modular and distributed systems that can be deployed without major grid or fuel infrastructure [16], [19], [21]. In this sense, the farm-scale literature has been indispensable in establishing solar irrigation as a credible development pathway in settings where distributed deployment is institutionally and economically attractive.

However, the same strength also reveals a limit. Most farm-scale studies implicitly assume that irrigation systems are designed and operated at the level of individual farms or plots, with parameters such as water source, pumping head, command area, and operating configuration inherited from site-specific observation or expert appraisal. This is entirely appropriate for project-level engineering. Yet it means that the literature is much less developed on whether irrigation might instead emerge through clustered or shared configurations, such as coordinated command areas, common abstraction points, or centralized pumping. Such configurations may offer important economies of scale in abstraction, conveyance, or energy provision, particularly where cropland is spatially clustered or where terrain and water access favour collective rather than purely individual solutions.

A further limitation concerns the design process itself. Farm-scale analyses generally depend on domain-expert sizing or detailed local measurements, but there remain relatively few integrated tools that allow farmer-led or planner-led design to emerge from generalisable representations of area, head, flowrate, and operating conditions. In other words, the literature is strong on engineering feasibility once the key design parameters are known, but weaker on how those parameters can be systematically abstracted and reconstructed when planning moves beyond the observed farm. As a result, the farm-scale literature explains local feasibility well, but only partially addresses how irrigation systems could become planning-relevant electricity loads once many local systems are considered together.

2.3 Scaling irrigation from local systems to planning problems

The transition from farm-scale analysis to territorial planning introduces a fundamental change in the analytical problem. At the level of an individual farm or scheme, many of the relevant parameters are directly observed: water source, field size, pumping head, irrigation technology, and operating schedule are typically known through measurement, farmer information, or site appraisal. Planning-oriented models face a different task. They must infer these parameters from heterogeneous territorial data and explicit selection rules rather than inherit them as given.

This scaling challenge is not merely a matter of aggregating many local systems. It requires translating dispersed and heterogeneous agricultural landscapes into plausible irrigation systems with defined abstraction points, service areas, and hydraulic characteristics. It also requires deciding whether irrigation should be represented as many isolated farm-level systems or as clustered opportunities that may justify shared pumping, storage, or generation infrastructure. In that sense, the planning problem is one of system construction rather than system description.

This distinction matters because spatial organisation affects both infrastructure requirements and electricity demand. Centralized or semi-centralized pumping configurations may exploit economies of scale in abstraction, conveyance, and energy provision, especially where water sources are spatially concentrated or where terrain favours grouped command areas. Dispersed farm-level systems, by contrast, may provide greater autonomy and align better with farmer-led adoption pathways, but they can also increase redundancy and obscure the aggregate implications for power systems. The analytical problem at planning scale is therefore not only how much irrigation may develop, but also how that development is spatially organised and infrastructurally configured.

Once this point is recognised, irrigation can no longer be treated as a simple extension of farm engineering to a larger map. Planning requires explicit rules for selecting croplands, associating them with water sources, defining likely service areas, and inferring the resulting hydraulic requirements. This motivates the move toward geospatial methods that attempt to represent irrigation beyond the individual farm, first through suitability and master-planning approaches, and then through irrigation-energy quantification [25], [29].

2.4 Geospatial irrigation suitability and master planning in SSA

A major strand of large-scale irrigation literature focuses on suitability assessment and irrigation master planning. These approaches combine climatic conditions, soils, water availability, topography, accessibility, and sometimes policy priorities to identify areas where irrigation development may be feasible, desirable, or strategically important [9], [13]. Such frameworks play an essential role in national planning, donor-supported programming, and investment screening because they help structure where irrigation expansion should be prioritised.

This planning tradition is important because it shifts irrigation from the level of isolated projects toward territorial strategy. In regions where irrigation remains underdeveloped relative to potential, suitability maps and master plans provide a first-order territorial logic for expansion. They can identify broad opportunity zones, highlight regional disparities in irrigation potential, and support decisions about where public and private investment should be directed. In that sense, they are indispensable to the planning discourse surrounding irrigation development in Sub-Saharan Africa.

At the same time, suitability and master-planning approaches generally operate at a level of abstraction that does not explicitly represent irrigation systems as physical infrastructure. They identify where irrigation could or should be developed, but they typically do not specify how water is abstracted, how it is conveyed, how service areas are structured, or how terrain conditions affect the hydraulic form of those systems. Their outputs are therefore usually territorial priorities rather than explicit irrigation-energy configurations.

A related limitation appears in broader irrigation-related nexus frameworks. Water–energy–food nexus analyses are valuable because they clarify interdependence across sectors and show that irrigation expansion cannot be understood in isolation from energy access, agricultural productivity, and resource governance [2], [4], [5]. However, these frameworks often privilege resource balances, cross-sector interactions, or high-level development indicators over the more specific variables that determine infrastructure planning. In particular, they tend to give less analytical attention to abstraction geometry, conveyance pathways, elevation differences, and service-area structure despite being the very variables that determine pumping requirements and infrastructure configuration.

As a result, there remains a gap between planning frameworks that identify where irrigation should occur and modelling approaches that specify how irrigation systems are physically configured and how they generate electricity demand. Identifying suitable areas for irrigation does not by itself determine how irrigation development will manifest as hydraulic requirement, electrical demand, or infrastructure need. Bridging this gap requires moving from territorial suitability toward explicit representation of irrigation system configuration and operation.

2.5 Geospatial quantification of irrigation energy demand

Another strand of literature builds on geospatial methods to estimate irrigation water requirements and translate them into spatially distributed energy demand. These models typically combine crop and climate data with land-use information to estimate irrigation needs, which are then converted into pumping energy using assumptions about hydraulic head, efficiency, and operating conditions. In doing so, they move beyond the question of where irrigation is suitable and begin to treat irrigation as an energy-demand problem [9], [20], [24].

This shift is a major advance. Rather than focusing only on suitability or profitability, geospatial irrigation-energy models quantify how much electricity would be required to support irrigation across large areas. Recent spatially explicit work on solar irrigation in Sub-Saharan Africa shows that substantial portions of currently rainfed cropland may be hydrologically and economically viable for solar irrigation, while also demonstrating that profitability varies significantly across crops, regions, and cost assumptions [19], [20]. GIS-based viability studies likewise show that irrigation power demand and solar irrigation costs are spatially heterogeneous, reinforcing the need for geographically differentiated planning [9].

Yet many of these models still rely on stylised representations of irrigation systems. A central methodological challenge is that hydraulic variables such as pumping head and flowrate are no longer directly observed, as they often are in farm engineering studies. Instead, they must be derived from spatial data and modelling assumptions. This creates a need for abstraction: engineering relationships must be reformulated in a way that allows them to be applied consistently across heterogeneous landscapes using geospatial inputs [10], [30].

This is especially important for pumping energy estimation. At a basic level, pumping requirements can be framed through gravitational potential energy, where the energy needed depends on the volume of water lifted, the elevation difference between source and command area, and the temporal distribution of pumping. Once this logic is adopted, variables such as farm area, elevation, abstraction point, and pumping window become central modelling inputs rather than background context. By linking crop water requirements to geospatially estimated irrigated area, terrain-derived head, and operating windows, it becomes possible to derive flowrates and pumping requirements in a transparent and scalable way. Such an approach moves beyond uniform or generic assumptions toward a representation in which hydraulic variables are constructed from terrain and service relationships rather than imposed exogenously [6], [7].

A further limitation of much existing geospatial irrigation-energy literature is its strong emphasis on groundwater-based irrigation. In many studies, pumping head is approximated using groundwater depth, and irrigation systems are implicitly assumed to draw from subsurface sources [8], [20]. This is an understandable choice, given the importance of groundwater irrigation in farmer-led expansion and the relative availability of groundwater-based proxy variables. However, it does not capture the full diversity of irrigation configurations in Sub-Saharan Africa, especially in settings where surface water resources are available.

In terrain-sensitive landscapes, hillside or surface-water-based irrigation may involve fundamentally different abstraction and conveyance structures. Here, pumping requirements are determined not by groundwater depth alone, but by the elevation differences between rivers, reservoirs, and cultivated areas, together with the spatial structure of service areas. These configurations are analytically more demanding because head becomes a function of terrain relations and spatial arrangement rather than a single vertical parameter. As a result, models that focus primarily on groundwater pumping may overlook important opportunities and constraints associated with hillside or surface-water irrigation, particularly in regions where surface water is available but cropland lies above the source.

Finally, most geospatial irrigation-energy assessments still focus on seasonal energy quantities, aggregate energy use, and, in some cases, peak power estimates. They rarely construct detailed hourly demand profiles or represent the operational strategies through which irrigation systems are used. Consequently, they stop short of representing irrigation as a dynamically formed electricity load. Even when irrigation energy demand is quantified spatially, it is not yet fully represented as a spatially constructed infrastructure system whose demand evolves through terrain, abstraction structure, flowrate requirements, and operating rules.

2.6 From energy estimation to demand formation under constraints

The distinction between energy estimation and demand formation is central to the present licentiate thesis. Energy estimation asks how much electricity, power, or energy irrigation may require under a given set of assumptions. Demand formation asks a broader planning question: where, when, and how irrigation electrification becomes an electricity-system-relevant configuration. Estimating energy demand therefore remains necessary, but it is not sufficient for understanding how irrigation interacts with power-system constraints.

In the context of irrigation, demand is not a predefined quantity waiting to be measured. It emerges from a sequence of modelling and infrastructural decisions: which croplands are included, where water is abstracted, how far and how high it must be conveyed, how irrigation service is scheduled, and over what time windows pumping takes place. Structural siting determines the potential lifting requirement. Service-area definition determines how much land is associated with a given source. Irrigation timing and pumping windows determine hourly flowrates. Together, these choices shape not only total energy use, but also the timing, concentration, and spatial distribution of electricity demand.

In this sense, demand formation is not limited to the construction of an hourly load profile. It concerns the formation of a coupled irrigation–electricity configuration in which spatial elements, temporal operating windows, and operational rules jointly shape demand, generation, storage behaviour, and grid interaction. This distinction is important because irrigation electrification may involve not only pumping demand, but also photovoltaic generation, gravity storage, grid imports, grid exports, and dispatch constraints.

Existing literature provides only partial coverage of this process. Geospatial models improve territorial realism but often remain focused on energy demand estimation or viability screening [31], [32]. Productive-use and rural electrification studies introduce temporal resolution and show that agricultural demand can materially influence energy system design [24], [33]. However, these studies often represent irrigation as a generic productive load rather than deriving it from explicit irrigation-system structure, creating a gap between physically grounded irrigation-energy estimation and electricity-system-relevant demand formation.

That gap matters because infrastructure planning depends not only on electricity quantities, but also on where demand appears, how concentrated it is, when it occurs, and how flexible it is under different operating strategies [11], [25]. It also depends on whether irrigation is represented purely as load or as a configuration that may include local generation, storage, and grid interaction [11]. In this sense, irrigation electricity demand should be understood as something formed under constraints rather than simply observed. It emerges from the interaction of terrain, abstraction structure, hydraulic requirements, operating rules, storage logic, photovoltaic deployment, and system limits [14], [15], [34]. This demand-formation perspective provides the conceptual bridge between geospatial irrigation modelling and power-system analysis.

2.7 Irrigation as a distinct class of electricity load

From a power-system perspective, irrigation electrification introduces a distinctive class of load whose characteristics differ from conventional residential or commercial demand. Irrigation demand is productive rather than purely consumptive, often partly flexible rather than fully fixed, and in many settings correlated with daytime solar availability because pumping frequently occurs during daylight hours. At the same time, irrigation can generate concentrated peaks when pumping is synchronised across farms or schemes, when operating windows are narrow, or when high lifting requirements compress pumping into limited periods.

The relevance of irrigation to electricity systems therefore depends not only on energy use, but on the timing, coincidence, and controllability of load. A given electricity quantity may be relatively easy to absorb if pumping is temporally distributed, coordinated with solar generation, or buffered through storage. The same quantity may become operationally problematic if pumping is concentrated into common peaks or shaped by steep terrain and tight irrigation windows. The planning issue is therefore not simply whether irrigation adds load, but what kind of system interaction irrigation creates when demand, generation, storage, and operation are represented together.

Despite this, irrigation is often weakly represented in electricity planning as an exogenous demand increment or an aggregated productive-use category. More broadly, the power-system literature has shown that multisector modelling outcomes depend strongly on how loads are represented, not only on their total size. Reviews of power-system operational models argue that core process representation is decisive when energy systems interact with other sectors, and that operational detail alone does not solve the problem if the structure of demand is poorly specified [11]. In the case of irrigation, this means that compatibility with electricity systems cannot be judged credibly unless irrigation is represented as a spatially and temporally structured load rather than a simple demand increment.

Recognising irrigation as a distinct load class therefore requires moving beyond aggregate energy metrics toward representations that capture its spatial distribution, temporal structure, operating flexibility, and possible clustering.

This is particularly important where irrigation may evolve through centralized or semi-centralized pumping, where shared infrastructure and economies of scale can change both hydraulic requirements and load shape. It is also important where solar-powered irrigation creates the possibility of daytime alignment, surplus generation, and new interactions between local pumping behaviour and wider system operation. In this sense, irrigation is not merely another end-use category. It is a structurally formed and potentially coordinated load whose system relevance depends on how territorial conditions, hydraulic requirements, and operating strategies are translated into manageable electricity demand.

2.8 Synthesis of literature gaps and thesis positioning

The literature reviewed in this chapter shows that the planning challenge is not only to estimate irrigation electricity use, but to represent how irrigation electrification becomes a spatially located, temporally scheduled, and operationally coordinated electricity-system configuration. For top-level planners, this translates into deciding where irrigation should be developed, when its demand can be accommodated, and how generation, storage, and grid interaction should be configured to ensure feasibility and cost-effectiveness. Table 2.1 summarises how the identified gaps motivate the thesis positioning, the corresponding methodological stages, and the research questions introduced in Chapter 1.

Table 2.1: Synthesis of literature gaps and thesis positioning.

Identified gap in the literature	Thesis positioning
Farm-scale dominance and weak scale transition: SPIS studies are strong on local feasibility, but provide limited guidance on how irrigation becomes system-relevant electricity demand at larger scales.	Connect local irrigation-service logic with planning-scale representation, so that seasonal demand, component sizing, and surplus can be interpreted beyond individual farm systems.

Continued on next page

Table 2.1 continued from previous page

Identified gap in the literature	Thesis positioning
Weak transition from local engineering inputs to territorial representation: Farm-scale studies rely on observed site parameters and expert sizing, while planning models rarely reconstruct engineering inputs such as area, head, and flowrate explicitly.	Represent local engineering variables through generalisable spatial relationships linking cropland, water access, abstraction points, elevation bands, pumping head, and flowrate requirements.
Suitability and master-planning approaches rarely represent irrigation as infrastructure: Spatial planning studies identify where irrigation could be developed, but usually stop short of specifying abstraction structure, conveyance logic, clustering, or electrical implications.	Extend territorial suitability toward irrigation-system representation by considering candidate irrigation units, terrain-conditioned lift, and the hydraulic structure from which electricity demand can be formed.
Irrigation-energy assessments often simplify hydraulics and stop at energy estimation: Large-scale studies frequently rely on stylised, fixed, or groundwater-dominated pumping assumptions, with limited representation of terrain-conditioned surface-water lifting and limited treatment of hourly demand formation.	Represent pumping requirements as spatially heterogeneous and temporally explicit by linking terrain-conditioned head, water-service requirements, pumping windows, and storage-mediated operation.
Irrigation is weakly represented as a special load: Power-system studies often treat irrigation as an exogenous load increment rather than as a productive, partly flexible, and spatially clustered demand category.	Treat irrigation as a formed electricity-system configuration whose compatibility can be evaluated through timing, peak coincidence, storage operation, and dispatch constraints rather than energy use alone.
Irrigation-specific surplus and policy design remain underdeveloped: Most PV export and compensation studies focus on residential or commercial systems rather than irrigation-driven PV and seasonal surplus.	Position photovoltaic-powered irrigation as a pathway-coordination problem involving gravity storage, SPIS deployment options, grid import–export rules, surplus valuation, and system-cost implications.

CHAPTER 3

Research approach and methodological framework

3.1 Five-stage methodological pipeline

This chapter presents the methodological framework used to analyse irrigation electrification in five-stage methodological pipeline. The framework is developed in direct response to the gaps identified in Chapter 2, particularly the weak connection between spatial irrigation planning, hydraulic representation, hourly load formation, and electricity-system evaluation. Methodologically, the licentiate thesis is organised as a five-stage modular pipeline linking local engineering grounding, geospatial siting, hourly demand construction, dispatch-constrained feasibility analysis, and policy extension.

The system of interest is an analytically bounded irrigation demand-formation system. It is defined as a coupled irrigation–electricity system in which irrigation service requirements are transformed into electricity-system-relevant demand through spatial, temporal, and operational rules. The system is analysed computationally through analytical abstraction and operational elements needed to compare feasible irrigation-electrification configurations, trade-offs, and constraints.

Within this system, irrigation demand is progressively formed through three analytical layers: spatial feasibility, temporal feasibility, and operational feasibility. Spatial feasibility determines which cropland–water configurations can enter the system through abstraction location, elevation bands, and pumping head. Temporal feasibility determines how irrigation service is scheduled over time through pumping windows, storage charging, and discharge logic. Operational feasibility determines whether the resulting hourly demand can be accommodated by the electricity system, including generation capacity, storage behaviour, SPIS contribution, grid imports, and exports.

The methodological framework operationalises this system through a five-stage computational pipeline visualised in Figure 3.1. The stages are sequential in information flow but modular in analytical purpose. Although the framework is presented as a forward-moving pipeline, Figure 3.1 also indicates the possibility of closing the loop from Stage 5 to Stage 1, whereby insights from later modelling and policy stages can feed back into computations as interventions to refine earlier assumptions, local design choices, and planning priorities.

The framework should be read in relation to the three research questions. Stage 2 corresponds primarily to the question of where irrigation electricity demand becomes system-relevant. Stages 3 and 4 correspond primarily to the question of when formed demand becomes compatible or incompatible with the electricity system. Stage 5 corresponds primarily to the question of how storage, SPIS deployment pathways, and export rules reshape the interaction between irrigation service and power-system operation.

The five-stage methodological pipeline is further presented in Table 3.1, which highlights the inputs, computations, and outputs for each stage. Detailed explanation of the computational logic is provided in the stage discussions that follow the table. This avoids overloading the table while still making clear what is computed in each stage and how the outputs contribute to the research questions.

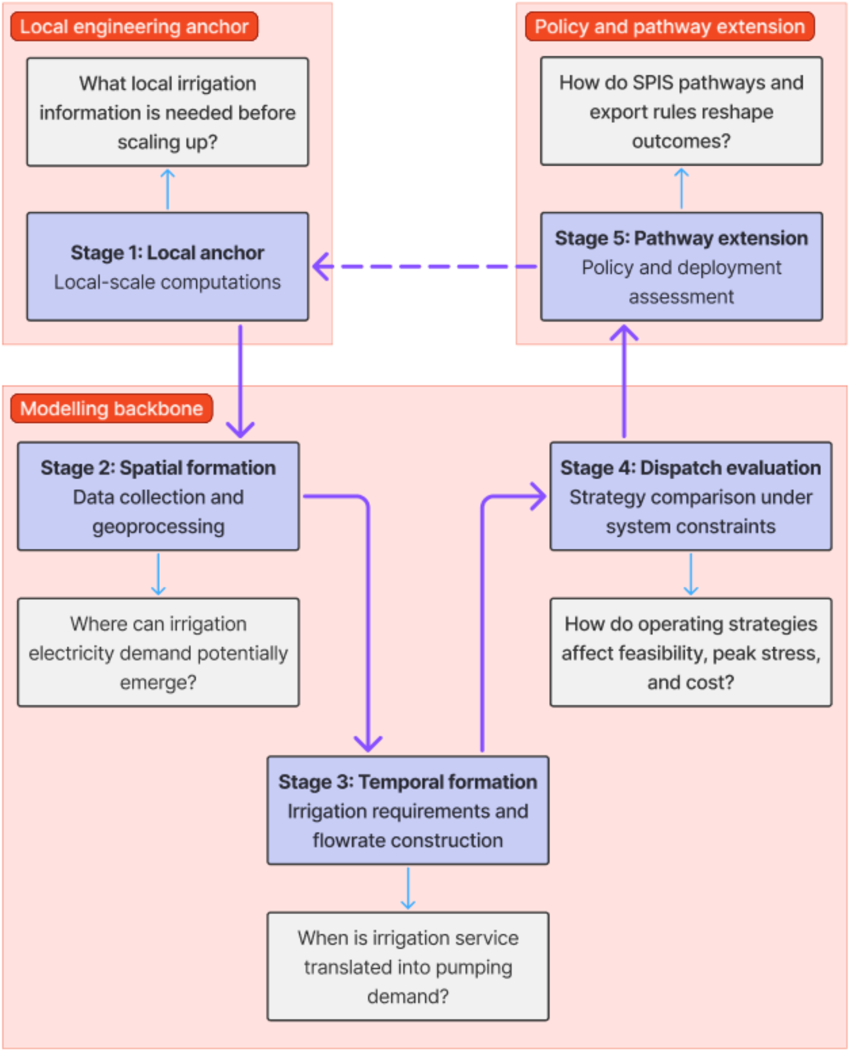

Figure 3.1: Five-stage methodological pipeline linking guiding planning questions to analytical stages.

Table 3.1: Simplified stage-wise methodological specification linking inputs, computations, and outputs.

Stage	Inputs	Computation	Outputs
Stage 1	Local irrigation suitability, crop choice, topography, water requirement, pumping and PV/microgrid inputs.	Derive irrigation energy demand and seasonal surplus from local service and sizing logic.	Local demand profile, surplus signal, and productive-use motivation.
Stage 2	Cropland, rivers/lakes, DEM, and subbasins.	Assign representative intake elevation, calculate relative lift, and group cropland into elevation bands.	Area by lift band, candidate irrigation units, and hydraulic demand structure.
Stage 3	Crop-water demand, pumping head, efficiency, pumping windows, and storage assumptions.	Convert water service into pumping energy, flowrate, hourly load, and storage-mediated profiles.	Hourly irrigation load profiles and storage operation variants.
Stage 4	Baseline load, irrigation load, generation capacities, costs, and solar availability.	Solve least-cost dispatch under fixed capacity constraints and compare system response across operating strategies.	Feasibility status, peak/capacity ratio, generation mix, and cost.
Stage 5	Formed load, PV profile, SPIS sizing, storage, export rules, and tariffs.	Construct net-load variants and evaluate system costs, imports, exports, and surplus valuation.	Grid imports, exports, surplus value, pathway comparison, and coordination insights.

Stage 1: Local mechanism anchor

Stage 1 serves as the local mechanism anchor of the licentiate thesis. Its purpose is not to provide a nationally representative result, but to clarify the local engineering logic through which irrigation service requirements become electricity-system relevant. At this stage, irrigation suitability, crop choice, topography, pumping head, water requirement, and PV or microgrid sizing assumptions are combined to estimate the electricity required for irrigation service and the seasonal surplus that may emerge when systems are sized for dry-period reliability.

The key computation is the conversion of local irrigation service requirements into pumping energy and sizing implications. This stage therefore establishes the first mechanism used later in the thesis: irrigation electrification can create both electricity demand and surplus generation. The output is not only a local demand profile, but a mechanism showing why irrigation should be analysed as a demand–generation–storage problem rather than as a pumping load alone.

The output of Stage 1 is mainly interpretive rather than directly transferred as a numerical input to the national modelling backbone. It motivates the later treatment of solar-powered irrigation as a configuration that can create seasonal mismatch, productive-use opportunities, and surplus electricity. In this sense, Stage 1 supports RQ1 by grounding the local origin of irrigation demand and supports RQ3 by showing why surplus and coordination become relevant once irrigation systems are sized for service reliability.

Stage 2: Spatial siting and terrain-conditioned pumping structure

Stage 2 defines where irrigation demand can plausibly emerge at planning scale. It uses cropland data, rivers or lakes, digital elevation data, and hydrological boundaries to construct a spatial-hydraulic representation of irrigation opportunity. The computation assigns representative intake elevation, calculates relative lift between cropland and the water source, and groups cropland into elevation bands.

This stage transforms the planning problem from a general question of irrigable land into a hydraulic-electricity question. The output is not simply a suitability map, but an area-by-lift structure that indicates where irrigation electricity demand becomes system-relevant. This directly addresses RQ1 by showing that demand formation begins with spatial filtering through water access, terrain, and pumping burden.

Computationally, the output of Stage 2 provides the spatial and hydraulic basis for the next stage. Area by lift band determines how much irrigation water requirement must be associated with different pumping heads. Candidate irrigation units define the spatial aggregation used for subsequent water-service translation. The stage therefore creates the structural input needed to convert irrigation opportunity into electricity demand.

Stage 3: Water-service translation and hourly demand formation

Stage 3 translates water-service requirements into hourly electricity demand. Crop-water demand, pumping head, pump efficiency, operating windows, and storage assumptions are used to convert irrigation service into pumping energy, flowrate, hourly load profiles, and storage-mediated operating variants.

This stage is where demand formation becomes temporal. The same irrigation service can produce different electricity-system effects depending on whether pumping is concentrated in narrow windows, shifted to daytime hours, or mediated through gravity storage. The output is therefore not only an energy quantity, but a set of hourly demand profiles that can be tested against system constraints. This stage addresses RQ2 by defining when irrigation demand appears in the electricity system.

Computationally, the stage first estimates irrigation water requirements from crop and climate assumptions. These water requirements are converted into pumping energy using water volume, terrain-conditioned head, pump efficiency, and pressure or loss allowances. The pumping energy is then distributed into hourly profiles according to operating windows and storage rules. When storage is represented, the model tracks charging, discharge, storage availability, and unmet irrigation service so that irrigation delivery can be decoupled from real-time electricity consumption.

The downstream output of Stage 3 is the set of hourly irrigation load profiles and storage-mediated operating variants. These profiles are passed to Stage 4, where they are added to the baseline electricity load and tested against dispatch constraints.

Stage 4: Dispatch feasibility and generation response

Stage 4 evaluates whether the hourly irrigation profiles formed in Stage 3 are compatible with the existing electricity system. The computation adds each irrigation profile to the baseline national load and solves a least-cost dispatch problem under fixed generation-capacity constraints. The resulting system response is assessed through feasibility status, peak-to-capacity ratio, generation mix, and cost.

This stage is mainly the feasibility test of the licentiate thesis. It shows whether formed irrigation demand can be supplied under the assumed dispatch-constrained system boundary. It also reveals how the generation fleet responds to different irrigation operating strategies. For this reason, Stage 4 primarily answers RQ2, because it identifies when demand becomes compatible or incompatible, but it also supports RQ3 by showing how generation response, solar availability, and operating strategy reshape system outcomes.

Computationally, the formed irrigation load is combined with baseline electricity demand for each hour. The dispatch model then allocates available generation according to capacity and cost assumptions. A scenario becomes infeasible when the system cannot meet the combined load within the fixed generation envelope. The resulting indicators, including feasibility status, peak/capacity ratio, generation mix, and cost, are used to compare operating strategies and identify feasibility boundaries.

The output of Stage 4 is both diagnostic and interpretive. Feasibility status and peak/capacity ratios indicate whether a demand formation is compatible with the existing system. Generation mix and cost indicate how the system responds when compatibility is possible. These outputs support the later synthesis by showing that the same irrigation service can produce different system consequences depending on timing and operating logic.

Stage 5: Intervention pathways

Stage 5 extends the formed irrigation configuration by examining how variations in storage capacity, SPIS generation capacity, and export rules reshape system outcomes. At this stage, hourly irrigation demand is combined with PV profiles, SPIS sizing assumptions, storage operation, grid import–export rules, and tariff assumptions. The computation constructs net-load variants and evaluates system cost, grid imports, exports, surplus value, and pathway performance.

This stage addresses how irrigation electrification changes once it is no longer treated only as load. Behind-the-meter and grid-integrated SPIS pathways create different interactions among pumping demand, PV generation, gravity storage, grid imports, exports, and surplus valuation. The purpose is to show how deployment architecture, storage coupling, and export rules reshape the planning problem. This directly addresses RQ3 by linking storage, solar pathways, and policy rules to system cost, reliability, and coordination needs.

Computationally, Stage 5 studies the effect of supplying irrigation with different fractions of onsite SPIS generation and storage-mediated operation. Depending on the SPIS fraction and dispatch conditions, PV generation may serve local irrigation demand, support storage charging, be exported to the grid, or be curtailed. Export-compensation assumptions then influence the economic value of surplus and the relative attractiveness of different intervention pathways from the national utility perspective.

The output of this stage is an intervention-pathway comparison rather than a single optimal design. Grid imports, exports, surplus value, system cost, and reliability indicators are used to interpret how storage, SPIS deployment, and tariff rules reshape the interaction between irrigation service and the electricity system. These outputs provide the main evidence for the "how" research question.

3.2 Relationship between stages, research questions, and included publications

The appended publications are cumulative rather than parallel, but the main organising logic of the licentiate thesis is the relationship between research questions and methodological stages. The local mechanism anchor supports the understanding of how irrigation service requirements can create both electricity demand and seasonal surplus. The spatial and hourly demand-formation stages extend this logic to national-scale planning by linking cropland, water access, terrain-conditioned lift, operating windows, and storage logic. The dispatch stage tests whether the resulting demand profiles remain compatible with the existing electricity system. The pathway stage then examines how storage, SPIS deployment, export rules, and compensation mechanisms reshape system outcomes.

This structure means that the publications provide evidence for different parts of one connected methodological framework. The licentiate thesis adds value by integrating these contributions into a single sequence: where irrigation demand becomes system-relevant, when it becomes feasible or infeasible under dispatch constraints, and how storage, photovoltaic pathways, and export valuation reshape the planning problem. In this way, the relationship among the included publications is expressed through the stages and research questions rather than through a simple chronological summary.

3.3 Internal consistency and scenario logic

Consistency is maintained by verifying each stage before outputs are passed downstream. Spatial representations are first checked for plausible irrigation structure, including cropland selection, abstraction logic, and terrain-conditioned pumping relations. Water-service and pumping calculations are then checked for internal coherence with efficiency assumptions and scenario definitions. Hourly demand profiles are verified against daily service requirements and operating rules. Feasibility assessment is undertaken only after these upstream checks are satisfied.

Scenario logic serves the same purpose. Rather than embedding uncertainty in hidden parameter choices, the framework exposes key assumptions through explicitly defined scenarios involving siting rules, elevation bands, pumping schedules, storage logic, photovoltaic deployment pathways, and export-compensation arrangements. This makes it possible to trace a given result back to the structural or operational assumptions that produced it.

The scenarios are therefore not separate case studies, but controlled variations of the same demand-formation framework. Each scenario changes one or more spatial, temporal, or operational rules and then traces how that change propagates through hourly demand formation, dispatch feasibility, storage behaviour, and pathway outcomes. This makes the framework auditable: a result can be linked back to the siting rule, pumping window, storage assumption, PV pathway, or export rule that generated it.

3.4 Summary

This chapter has presented the methodological framework of the licentiate thesis as a five-stage, modular pipeline linking local engineering feasibility, spatial siting, hourly demand formation, dispatch-constrained system evaluation, and policy extension. The framework treats irrigation electrification not as a predefined electricity-demand category, but as a demand-formation problem under spatial, hydraulic, operational, and system constraints. The cross-stage synthesis logic introduced in this chapter connects the five stages to the three research questions: where irrigation demand becomes system-relevant, when it becomes compatible or incompatible with dispatch-constrained electricity systems, and how storage, photovoltaic pathways, and export rules reshape the resulting system interaction. The following chapter uses this structure to organise the representative results and to synthesise their implications for planning and policy.

CHAPTER 4

Results

This chapter presents representative results that support the main argument of the licentiate thesis. It does not reproduce the full numerical detail of the appended papers. Instead, it focuses on selected results that show how irrigation electrification becomes spatially formed, temporally consequential, and operationally shaped within the electricity system.

The chapter is organised around the main result mechanisms. The first results show how local irrigation service creates seasonal demand and surplus. The second set shows how cropland, water access, and relative elevation determine where irrigation electricity demand becomes system-relevant. The third set shows how pumping schedules and dispatch constraints determine when formed demand becomes feasible or infeasible. The final results show how storage, SPIS pathways, and export valuation reshape system cost, imports, exports, and reliability.

4.1 Local mechanism: seasonal irrigation demand and surplus

The first representative result concerns the local mechanism through which irrigation electrification creates both demand and surplus. Irrigation service is not required uniformly throughout the year and throughout space. It is activated when crop-water deficit appears, and therefore electricity demand is seasonal rather than constant. When a PV or microgrid-supported irrigation system is sized to satisfy irrigation needs during high-demand periods, the same installed capacity can produce surplus during lower-demand periods.

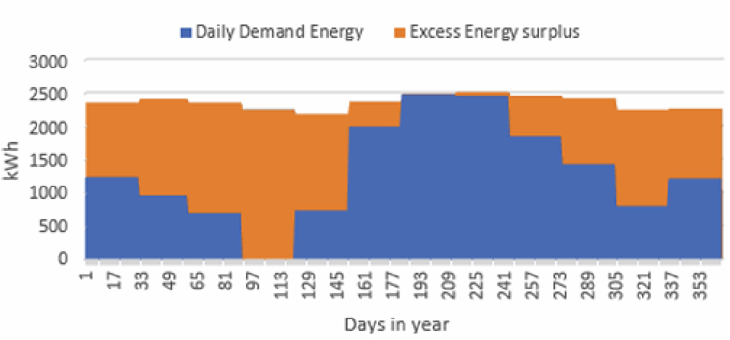

Figure 4.1: Seasonal irrigation demand and surplus under local irrigation-oriented sizing.

Figure 4.1 makes the local mechanism visible. The blue area represents daily irrigation demand energy, while the orange area represents surplus energy. The result shows that surplus is not an accidental by-product. It emerges structurally when system sizing is driven by irrigation service adequacy rather than by average utilisation.

This result supports RQ1 and RQ3. It supports RQ1 because it shows that irrigation electricity demand begins from a local water-service requirement rather than from an abstract electricity quantity. It supports RQ3 because the surplus created by irrigation-oriented sizing later becomes a coordination issue involving productive use, storage, export, or curtailment.

The broader implication is that irrigation electrification should not be interpreted only as a pumping-load problem. Even at the local scale, it creates a coupled configuration involving service demand, generation sizing, utilisation, and surplus handling. This mechanism provides the starting point for analysing irrigation electrification as a demand–generation–storage problem.

4.2 Spatial-hydraulic formation of irrigation demand

The second representative result concerns where irrigation electricity demand becomes system-relevant. At planning scale, demand does not emerge from cropland area alone. It emerges from the relation among cropland, water access, terrain, and abstraction structure. The spatial-hydraulic screening therefore determines which land is carried forward into electricity-system analysis and what pumping burden it implies.

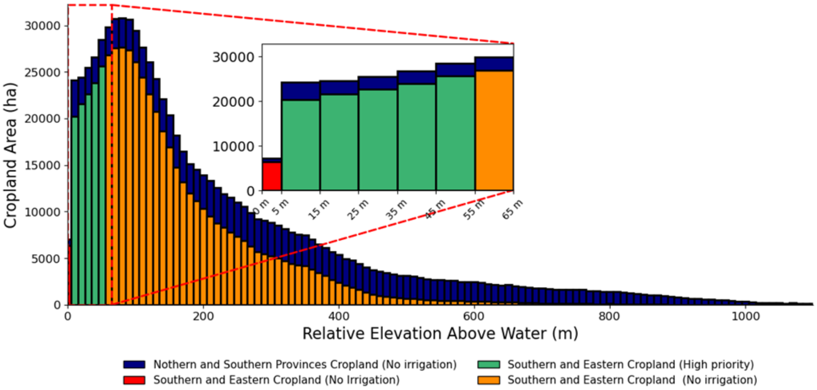

Figure 4.2: Cropland area by relative elevation above water sources.

Figure 4.2 shows the cropland area distribution across relative elevation above water sources. The green highlights the lower-lift bands that are most relevant for priority pumped-irrigation analysis. This result is important because it separates general cropland availability from electricity-system-relevant irrigation opportunity. The red highlights cropland lie close to water sources with high potential for flood irrigation followed by moderate lift ranges in green color. Other croplands in yellowish color remain technically irrigable but imply higher pumping burden or weaker suitability for coordinated electrification.

This result directly answers RQ1. It shows that irrigation electricity demand becomes system-relevant only after cropland is filtered through water access, relative lift, and spatial concentration. The figure therefore converts the question of irrigable land into a hydraulic-electricity planning question.

The spatial result is therefore not simply that irrigation is possible in some areas and not in others. Rather, it shows that irrigation electricity demand is formed by a spatial filter. Water-access conditions, abstraction elevation, terrain-conditioned lift, and cropland concentration define the hydraulic demand structure that later determines pumping energy, hourly load, storage requirement, and dispatch feasibility.

4.3 Operational timing and dispatch feasibility

The third representative result concerns when formed irrigation demand becomes compatible or incompatible with the existing electricity system. Once water-service requirements are translated into hourly electricity profiles, the same irrigation service can produce different system outcomes depending on pumping schedules and storage operation.

The dispatch results show that direct farmer-practical pumping can create severe system stress even when the increase in total irrigation energy is moderate. Under the direct morning-and-evening pumping strategy (relative pumping lifts), leads in aggregated pumping in few hours resulting in high pumping load spikes that coincide with existing national demand peaks. In the reported results, demand increases to only 1.18 times the baseline, but peak load reaches 124% of installed capacity and the dispatch problem becomes infeasible. This result demonstrates that feasibility is governed by timing and peak coincidence, not by energy use alone.

Table 4.1: Normalised performance of irrigation strategies.

Metric	**A**	**B**	**C**	**D**	**E**
Demand (GWh) / A	1.00	1.18	1.18	1.22	1.00
Peak load (MW) / A	1.00	2.00	1.42	1.26	1.26
Total cost ($M) / A	1.00	n/a	1.77	1.90	1.30
Cost intensity ($/MWh)	3.60	n/a	5.46	5.67	4.90
Peak / installed capacity (%)	56.0	124.0	80.1	71.0	71.0
Feasibility	Optimal	Infeasible	Optimal	Optimal	Optimal

Table 4.1 summarises the feasibility contrast across operating strategies. Strategy B is infeasible because the peak demand exceeds installed capacity. Strategy C restores feasibility by spreading the same irrigation service across daytime hours. Strategies D and E further reduce the peak-to-capacity ratio through storage-mediated operation, with Strategy E reducing cost relative to the grid-only storage case (Strategies D) by adding SPIS support (Strategies E).

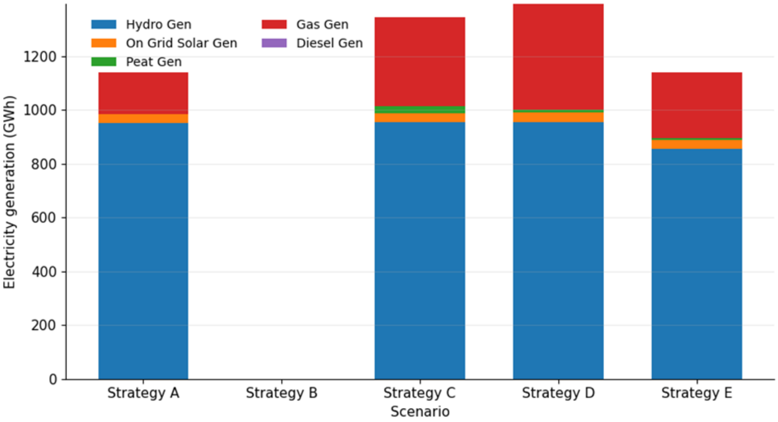

Figure 4.3: Dispatch feasibility and generation response by strategy.

Figure 4.3 shows the corresponding generation response. The infeasible strategy does not appear as a dispatched generation mix because the system cannot meet the peak-coincident load under the fixed capacity envelope. For the feasible strategies, irrigation changes not only the amount of electricity required but also how the generation fleet is used.

This result directly answers RQ2. It shows that the same irrigation service can be feasible or infeasible depending on when pumping demand appears in the power system. Feasibility is therefore governed by timing, peak coincidence, and dispatch constraints. Beyond capacity feasibility, total cost and cost intensity in Table 4.1 shows that feasible strategies are not cost-equivalent: once a strategy can be dispatched, its attractiveness depends on how it changes the use of lower-cost and higher-cost generation in the system.

4.4 Storage duration and charging flexibility

The fourth representative result concerns the role of storage. Storage-mediated strategies decouple irrigation delivery from real-time electricity consumption. This means that water can be delivered during farmer-practical irrigation periods while pumping or charging occurs at more system-compatible times. However, the results show that storage does not remove constraints. It shifts them toward storage duration, charging flexibility, unmet service, grid imports, and PV export tradeoffs.

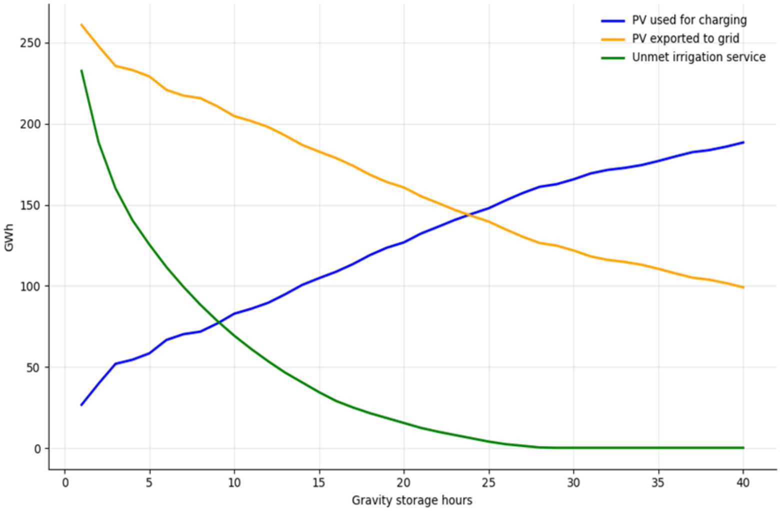

Figure 4.4: Storage-duration sensitivity.

Figure 4.4 shows that increasing storage duration reduces unmet irrigation service, increases PV used for charging, and reduces PV exported to the grid. Under the adopted charging assumptions, unmet irrigation service becomes negligible around 28–30 hours of storage. Beyond this point, additional storage mainly increases local PV self-use and reduces exports rather than materially improving service reliability. Storage therefore exhibits threshold behaviour: before the threshold, it primarily improves reliability; after the threshold, it mainly reallocates energy between local irrigation use and export.

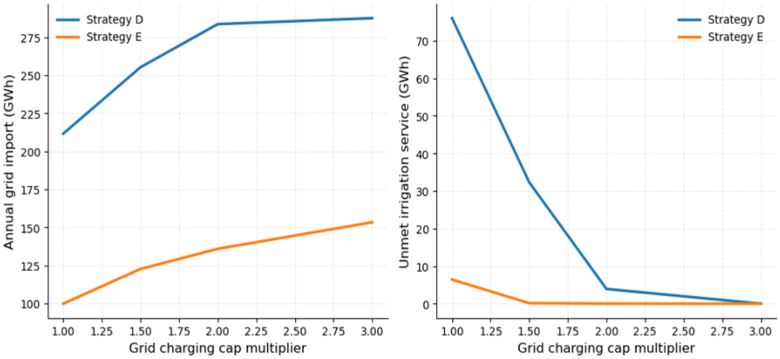

Figure 4.5: Charging-cap sensitivity.

Figure 4.5 isolates the effect of charging flexibility. Increasing the grid charging-cap multiplier reduces unmet irrigation service, especially for the grid-charged storage strategy, but it also increases annual grid imports. This result shows that reliability can be improved by allowing faster or more flexible charging, but this can shift burden back to the centralised electricity system. Charging discipline is therefore part of the system design problem.

These results contribute to RQ2 and RQ3. They contribute to RQ2 by showing how storage duration and charging flexibility affect service reliability and compatibility with system operation. They contribute to RQ3 by showing that storage reshapes the balance among PV self-use, grid imports, grid export, and unmet irrigation service.

Together, the storage results show that storage should not be described simply as a smoothing device. It is a constraint-shifting mechanism. It can reduce delivery-time stress and restore irrigation reliability, but it also creates new questions about charging windows, grid imports, PV self-use, and export reduction.

4.5 SPIS export-valuation outcomes

The fifth representative result concerns how export rules reshape system outcomes once irrigation is coupled to photovoltaic generation. At this stage, the planning problem is no longer only how to supply pumping demand. It becomes a question of how surplus electricity is valued once PV-supported irrigation begins to generate electricity beyond direct irrigation requirements.

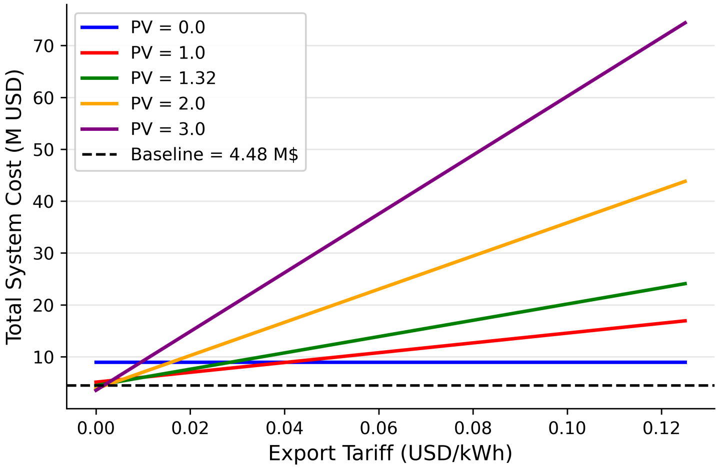

Figure 4.6: System cost sensitivity to flat export tariff under BTM-SPIS.

Figure 4.6 shows how total system cost changes as the export tariff increases under different PV sizing factors for BTM-SPIS. The dashed horizontal line indicates the baseline system cost without irrigation. When PV Factor is zero, export compensation has no effect because no PV electricity is exported. As PV capacity increases, however, system cost becomes increasingly sensitive to the export tariff because a growing share of generated electricity is exported rather than used directly for irrigation.

The figure shows that this sensitivity is strongly dependent on the level of PV deployment. At PV Factor 1.0, the increase in total system cost with export tariff remains moderate because most PV generation is still absorbed by irrigation demand. At PV Factors around 1.32 and 2.0, the slope becomes steeper, indicating that export compensation begins to materially affect total system cost. At PV Factor 3.0, the effect becomes very strong: system cost rises sharply with tariff level because export volumes are large and compensation is paid for every exported kilowatt-hour.

This result directly answers part of RQ3. It shows that once SPIS deployment exceeds direct irrigation requirements, export rules become a central determinant of system performance. The result also shows that export valuation cannot be treated as an external policy detail added after technical design. It becomes part of the technical-economic structure of photovoltaic-powered irrigation itself.

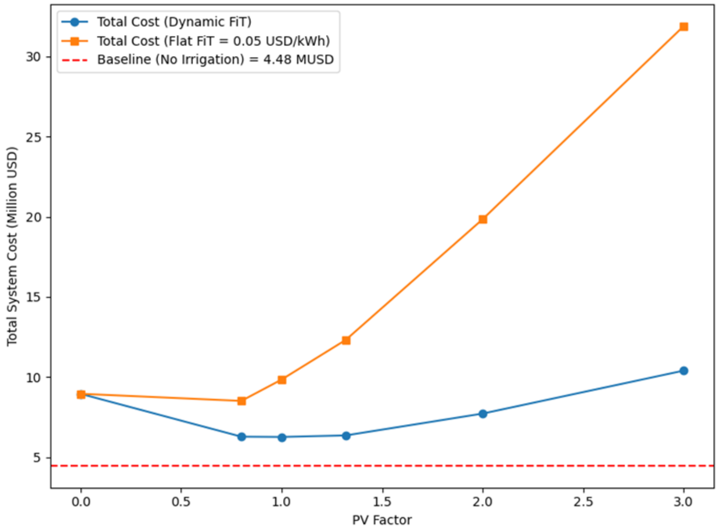

Figure 4.7: System cost under dynamic and flat export compensation.

Figure 4.7 extends this result by comparing a dynamic export tariff with a flat export tariff. The dynamic scheme ties compensation more closely to system value, while the flat tariff pays the same rate for all exported electricity. As PV deployment grows, the dynamic tariff produces lower system cost because it better reflects the declining marginal value of surplus electricity at higher export levels.

Taken together, Figures 4.6 and 4.7 show that PV-supported irrigation introduces a valuation and coordination problem. Moderate PV oversizing can be accommodated with limited cost impact, but high PV penetration becomes highly sensitive to export pricing. A flat and generous export tariff may appear attractive at low deployment levels, but it becomes increasingly costly as surplus expands. Dynamic or value-linked export compensation therefore provides a more system-consistent way of integrating exported surplus from irrigation-linked PV systems.

These results answer RQ3. They show that PV-supported irrigation is shaped not only by generation and storage, but also by the rules governing exported surplus. Export compensation affects system cost, surplus value, and the attractiveness of high-PV deployment. The broader implication is that SPIS planning must consider not only how much electricity is produced, but also how exported electricity is valued once irrigation systems begin to generate structural surplus.

4.6 Summary of results by research question

The results presented in this chapter answer the three research questions in a compact form. RQ1 asked where irrigation electricity demand becomes system-relevant. The answer is that demand becomes system-relevant only after cropland is filtered through water access, terrain-conditioned lift, and spatial-hydraulic structure. RQ2 asked when formed irrigation demand becomes compatible or incompatible with the electricity system. The answer is that compatibility depends on strategies timing and costs emerging from peak coincidence, storage duration, charging flexibility, and dispatch-constrained generation response. RQ3 asked how storage, SPIS pathways, and export rules reshape the system interaction. The answer is that these mechanisms redistribute constraints among reliability, grid imports, PV self-use, surplus exports, system cost, and coordination requirements.

The chapter therefore shows that irrigation electrification is not defined by energy use alone. It is defined by the spatial, temporal, and operational configuration through which demand, generation, storage, and grid exchange are jointly shaped. The next chapter discusses what these results mean for the methodological contribution, system interpretation, planning implications, and future research.

CHAPTER 5

Discussion and synthesis

This chapter discusses the results of the licentiate thesis together with the methodological framework that produced them. Its purpose is to explain how the integration of geospatial processing, temporal operation, dispatch modelling, storage logic, and photovoltaic pathway analysis creates planning insight. The chapter therefore discusses both what the results show and why the methodology is able to reveal those results.

The central argument is that irrigation electrification is best understood as a formed system interaction. It is not only a matter of estimating pumping energy or sizing components. It is a process in which exogenous factors such as climate, terrain, cropland, water access, and existing electricity-system conditions interact with endogenous design choices such as siting rules, pumping windows, storage capacity, charging limits, photovoltaic deployment, and export rules. The methodology brings these factors together into spatial, temporal, and operational configurations that can be tested for feasibility, cost, reliability, surplus, and policy relevance.

5.1 Geospatial integration and the formation of spatial design envelopes

The first synthesis concerns the role of geospatial integration in forming the spatial design space for irrigation electrification. In the framework developed in this licentiate thesis, cropland, rivers, lakes, digital elevation data, hydrological boundaries, and climate-related water-service requirements are not treated as separate background layers. They are processed together to define where irrigation can plausibly emerge as an electricity-system-relevant activity.

This integration brings together exogenous physical conditions and endogenous modelling choices. Exogenous conditions include terrain, water access, land cover, climate, crop-water requirements, and the existing geography of agricultural opportunity. These factors describe the physical and environmental context within which irrigation electrification must operate. Endogenous choices include the abstraction rule, the selection of elevation bands, the definition of candidate irrigation units, and the planning envelope within which pumping is considered. These choices do not invent the physical opportunity, but they determine how the opportunity is represented as an infrastructure problem.

The result is a spatial design envelope rather than a simple suitability map. A suitability map can indicate where irrigation may be possible, but the spatial design envelope defines how cropland, water source, elevation, and pumping burden are organised into candidate irrigation structures. This is why the question of where is both methodological and empirical. It asks not only where irrigation demand may be located, but how heterogeneous land and water conditions can be translated into spatial configurations that later determine energy-demand formation, generation strategy, storage design, and dispatch evaluation.

In this sense, the spatial layer defines more than location. It defines the magnitude and character of the irrigation demand that enters the subsequent stages. The amount of cropland retained within selected lift bands affects water demand. The elevation difference affects pumping energy. The abstraction structure affects whether irrigation is represented as individual pumping, shared pumping, or semi-centralised infrastructure. The spatial envelope therefore already begins to shape generation requirements, storage needs, and possible grid interaction before any hourly dispatch calculation is performed.

The main insight from the spatial part of the methodology and results is that demand formation begins before electricity demand is calculated. It begins when geospatial datasets are processed into a structured design space. The resulting spatial structures are tunable because the planner can vary elevation bands, siting criteria, abstraction logic, and priority domains. They are architectural because they define the physical arrangement through which irrigation may later become demand, generation, storage, and grid exchange.

5.2 Temporal operation and dispatch feasibility

The second synthesis concerns the translation of spatially formed irrigation opportunities into temporal operating profiles. Once cropland, water access, lift, and service requirements are defined, the question becomes when the electricity system experiences irrigation demand. This is where the methodology moves from spatial structure to temporal feasibility.

The temporal stage integrates climate-driven water-service requirements with endogenous operating strategies. Climate and crop-water needs define when irrigation service is required. Pumping windows, storage operation, charging caps, and SPIS support define how the service is converted into hourly electricity profiles. The same spatial irrigation opportunity can therefore produce different power-system consequences depending on the operating strategy used to deliver the water service.

The dispatch model then tests these formed profiles against the existing electricity-system boundary. In this licentiate thesis, the dispatch analysis is implemented as a Python-based modelling workflow that combines baseline electricity demand, irrigation load profiles, generation capacities, variable costs, and solar availability. The purpose is not only to calculate cost, but to determine whether a given irrigation configuration is feasible under fixed dispatch-constrained conditions.

This is where the methodology produces one of the strongest system insights. Moderate irrigation energy use can become infeasible when pumping is concentrated in peak-coincident windows. Conversely, the same irrigation service can become feasible when pumping is shifted, buffered, or supported by SPIS. The dispatch model therefore turns timing into a planning decision. It shows that feasibility is not determined only by the amount of irrigation demand, but by the temporal pattern through which that demand appears in relation to the generation fleet.

The cost and peak indicators produced by the dispatch model provide decision-relevant information. Peak-to-capacity ratios identify stress on the fixed generation envelope. Dispatch feasibility identifies whether the system can satisfy the combined load. Generation mix and cost reveal how different irrigation strategies change the use of existing resources. These outputs make the methodology useful for comparing operational strategies rather than only reporting energy totals.

5.3 Storage-coupled systems and the shaping of SPIS pathways

The third synthesis concerns the explicit treatment of storage-coupled irrigation operation. Storage changes the role of irrigation electrification because it decouples water delivery from real-time electricity consumption. This creates a new design space in which irrigation service can be maintained while pumping, charging, importing, exporting, or using PV generation at different times.

The results show that storage does not simply remove constraints. It transforms them. Without storage, irrigation demand appears directly as pumping load. With storage, the constraint shifts toward storage capacity, charging flexibility, charging timing, PV self-use, grid imports, and unmet service. This is why storage has to be discussed as both a technical and operational variable. It is not only a reservoir size or a battery-like buffer; it is a rule that determines how the irrigation system interacts with the electricity system over time.

Storage-coupled SPIS strategies reveal different pathway orientations. One orientation is export-led. In this pathway, PV capacity can exceed immediate irrigation needs, and surplus electricity becomes valuable only if export rules and system absorption allow it to be used. Another orientation is resilience-oriented. In this pathway, PV and storage are used primarily to reduce unmet irrigation service, improve autonomy, and protect irrigation delivery from grid constraints. The same SPIS technology can therefore support different planning objectives depending on how storage and export rules are designed.

This is why the distinction between behind-the-meter and grid-integrated

SPIS is important. Behind-the-meter systems emphasise local self-supply and may become attractive when surplus can be exported or when autonomy is valued. Grid-integrated systems allow more coordinated use of generation, storage, and grid resources, especially when PV deployment is moderate and system-level optimisation matters. The pathway choice is therefore not simply a technical configuration. It is a decision about how irrigation service, PV generation, storage, imports, exports, and compensation rules interact.

The methodology is able to reveal these mechanisms because it does not stop at system sizing. It connects sizing to operation, operation to dispatch feasibility, and dispatch feasibility to pathway valuation. As a result, the analysis can show how a storage-coupled irrigation system may be designed toward export, resilience, peak reduction, cost minimisation, or some balance among these objectives.

5.4 Balancing reinforcing mechanisms and trade-offs

A key synthesis from the licentiate thesis is that the methodology reveals reinforcing mechanisms as well as trade-offs, as illustrated conceptually in Figure ??. Several mechanisms reinforce each other positively. Low-lift spatial opportunities reduce pumping burden. Daytime pumping can align irrigation demand with solar availability. Storage can reduce peak-coincident stress. SPIS can reduce grid dependence. Dynamic export valuation can reduce the risk of overcompensating surplus generation.

However, the same mechanisms can also create new tensions. Concentrating irrigation in favourable spatial corridors may improve infrastructure efficiency, but it may also require coordination across farms or institutions. Increasing storage can improve reliability, but it may reduce exports or increase charging requirements. Increasing charging flexibility can reduce unmet irrigation service, but it may increase grid imports. Increasing PV capacity can support irrigation, but it may create structural surplus whose value declines as deployment grows.

The value of the methodology is that it makes these reinforcing and counteracting mechanisms visible. It does not only show that irrigation electrification is technically possible. It shows how different design choices reinforce or weaken each other across spatial, temporal, and operational layers. This makes it possible to ask a more useful planning question: not simply whether irrigation can be electrified, but which configuration balances demand, generation, storage, reliability, cost, and grid interaction under the chosen planning objective.

This balancing logic is central for future policy scenarios. A policy scenario that prioritises rapid farmer-led adoption may favour behind-the-meter SPIS, local autonomy, and simple compensation rules. A scenario that prioritises system coordination may favour grid-integrated SPIS, shared storage, controlled charging, and dynamic export valuation. A resilience-oriented scenario may prioritise storage autonomy and reliability over export revenue. An export-led scenario may prioritise surplus valuation and grid absorption. The methodology provides a way to compare these scenarios because it links spatial opportunity, operational control, and system consequences.

5.5 Implications for planning and policy

Several planning implications follow from this synthesis. Irrigation electrification is best represented in electricity planning as a spatially structured and hourly resolved system configuration rather than as an aggregate energy increment. The most important system effects arise through terrain-conditioned pumping burdens, peak coincidence, storage operation, and operating rules. This means that top-level planners need to ask not only how much electricity irrigation may require, but where the demand is formed, when it appears in the power system, and how it can be coordinated through generation, storage, and grid interaction.

Spatial screening needs to precede electrification decisions. Structurally favourable low-lift areas can provide more manageable and potentially more economical pathways than dispersed high-lift configurations. This does not imply that higher-lift areas are excluded, but it does mean that the energy and infrastructure consequences of lift need to be visible before planning commitments are made. In this sense, irrigation planning and electricity planning require a shared spatial logic rather than separate sectoral exercises.

The crop representation used in planning also has implications for electricity-system assessment. Irrigation studies often estimate water and energy requirements separately for different crops because crop coefficients, growing seasons, and water needs vary by crop. However, in many Sub-Saharan African farming systems, crop choices can change over time in response to markets, household needs, policy priorities, and climate conditions. For long-term irrigation infrastructure planning, it is therefore useful to test the system against relatively water-intensive and high-value crops rather than only against a single expected crop pattern. In this licentiate thesis, banana is used as a representative high-water-demand crop to stress-test irrigation electricity demand under planning-scale conditions. This is not a prediction that future irrigation expansion will be banana-based, but a way of assessing whether long-lived pumping, storage, and electricity infrastructure can accommodate demanding irrigation-service conditions.

Buffering and operating rules are better treated as planning variables than as implementation details. Moderate irrigation energy use can still become infeasible under narrow and coincident pumping windows, while the same irrigation service can remain feasible when pumping is shifted or buffered. Storage therefore has to be understood as an operational planning mechanism rather than only as an added component. It changes the relationship between irrigation delivery and electricity withdrawal, but it also introduces new questions about charging behaviour, grid imports, PV self-use, and reliability.

Surplus management needs to be treated as a structural planning issue from the outset. Once PV sizing is driven by irrigation reliability rather than average utilisation, surplus becomes a persistent feature of the system. Export-compensation policy is therefore better linked to system value than set independently of scale. Flat compensation may be simple, but it can become misaligned with system economics as surplus grows and marginal export value declines.

More broadly, irrigation electrification requires coordination between agricultural development institutions, electrification planners, utilities, and policy actors. Irrigation demand is formed partly in agricultural and hydrological space, while its consequences appear in the electricity system. Planning therefore needs to connect land, water, energy, storage, and institutional rules rather than treating irrigation electrification as only an agricultural technology choice or only an electricity-supply problem.

5.6 Analytical scope and limitations

The findings are best interpreted as planning-oriented mechanisms rather than deterministic forecasts. The framework is designed to reveal first-order spatial, temporal, and operational relationships, not to replace detailed project design. Its value lies in making the main mechanisms visible and traceable under explicit modelling assumptions.

One limitation concerns data and representation. The framework combines high-resolution structural data, such as land-cover and elevation datasets, with more aggregated crop-water and climate assumptions. This is appropriate for national-scale screening, but it cannot capture all field-level soil-water dynamics, micro-topography, or local irrigation scheduling constraints. The use of a representative high-water-demand crop is therefore best understood as a planning-level stress test rather than a detailed crop optimisation exercise. This choice is especially relevant for infrastructure-driven irrigation planning, where long-lived pumping, storage, and grid assets need to be assessed against demanding service conditions rather than only against a single crop calendar.

A second limitation concerns cost dynamics and market realism. The dispatch and SPIS pathway analysis use static cost assumptions for technology, fuel, and operation. In reality, declining solar costs, fuel price volatility, plant-specific contractual conditions, and changing tariff structures could alter the economic balance between grid-supported, storage-supported, and SPIS-supported pathways. The cost results are therefore structured comparisons under defined assumptions rather than fixed predictions of future technology economics.

A third limitation concerns behaviour and institutions. The model represents irrigation units as coordinated configurations governed by explicit operating rules. In practice, farmer behaviour, maintenance routines, compliance with pumping schedules, tariff response, ownership arrangements, and local governance may introduce additional variation. Individual pumping decisions may also produce stochastic load fluctuations that differ from the aggregated profiles used in the framework. These factors are not ignored conceptually, but they are treated as external to the analytical boundary of the present framework.

A fourth limitation concerns the electricity-system boundary. The dispatch analysis evaluates compatibility under a fixed generation-capacity envelope and does not include full AC power-flow modelling, feeder voltage limits, transformer loading, or detailed grid-extension design. These exclusions are deliberate because the focus is on demand formation and system compatibility at planning scale, rather than on final grid-connection design or distribution-network reinforcement.

A fifth limitation concerns uncertainty. The framework uses deterministic scenarios and tunable assumptions rather than probabilistic representation of river flow, climate variability, equipment outages, or institutional adaptation. This choice makes the modelling transparent and interpretable, but it also means that the results are structured scenario insights rather than probabilistic forecasts.

These limitations define how the results are to be interpreted. The framework does not claim to predict exact implementation outcomes. Instead, it provides a traceable planning logic in which each result can be linked back to the siting rule, pumping window, storage assumption, PV deployment pathway, or export rule that produced it. The results are therefore most useful for identifying mechanisms, trade-offs, and planning sensitivities that can guide more detailed project-level, institutional, or network-specific analysis.

5.7 Summary

This chapter has discussed the methodology and results of the licentiate thesis as parts of one planning argument. The geospatial layer integrates heterogeneous datasets and modelling rules to define spatial design envelopes. The temporal and operational layers translate irrigation service into hourly profiles and storage-coupled strategies. The dispatch layer evaluates feasibility, cost, peak stress, and generation response. The pathway layer shows how SPIS strategies can become export-led, resilience-oriented, or system-coordinated depending on storage and export rules.

Taken together, the discussion shows that irrigation electrification is not a fixed load or a simple component-sizing problem. It is a formed system interaction in which spatial structure, temporal operation, generation strategy, storage design, and policy rules jointly shape demand, reliability, surplus, cost, and grid compatibility. The next chapter draws the formal conclusions and states the scientific and methodological contributions of the licentiate thesis.

CHAPTER 6

Conclusions and contributions

6.1 Conclusions by research question

This licentiate thesis has examined how irrigation electrification can be represented and evaluated as a formed interaction between irrigation service, spatial conditions, operational strategies, storage, photovoltaic generation, and electricity-system constraints. The main conclusion is that irrigation electrification is best analysed not as an exogenous electricity-demand increment, but as a demand-formation process in which electricity demand, generation, storage, and grid exchange are jointly shaped by spatial, temporal, and operational rules.

The first research question asked where irrigation electricity demand becomes system-relevant when cropland, water access, and terrain-conditioned pumping lift are jointly considered. The thesis shows that this occurs only after cropland is filtered through water access, abstraction logic, terrain-conditioned lift, and spatial concentration. The answer to the question of *where* is therefore not only a map of irrigable land, but a spatial-hydraulic design envelope that defines the magnitude and structure of later electricity demand.

The second research question asked when formed irrigation demand becomes compatible or incompatible with the electricity system under alternative pumping schedules and storage-mediated operation. The results show that compatibility depends on timing, peak coincidence, storage-mediated operation, and the dispatch-constrained generation envelope. The same irrigation service can become infeasible when concentrated in peak-coincident pumping windows, while coordinated scheduling and buffering can restore feasibility without reducing irrigation service.

The third research question asked how gravity storage, SPIS deployment, and export rules reshape the interaction among irrigation service, grid imports, surplus electricity, system cost, and reliability. The thesis shows that these mechanisms do not remove constraints; they redistribute them. Storage changes when electricity is required, SPIS changes how irrigation is supplied, and export rules determine whether surplus becomes system value, fiscal exposure, or a signal for curtailment and additional flexibility.

Taken together, the answers to the research questions show that irrigation electrification needs to be planned as demand formation under constraints. The relevant planning object is the coupled configuration through which irrigation demand, photovoltaic generation, storage operation, and grid exchange are formed and tested together.

6.2 Scientific contributions

The scientific contributions of the licentiate thesis follow from the literature gaps identified in Chapter 2 and the results presented in Chapter 4. They add to previous research by extending how irrigation electrification is represented, evaluated, and interpreted in electricity-system planning.

The thesis first contributes a planning-scale interpretation of irrigation electrification that connects local irrigation-service logic, component sizing, seasonal surplus, and electricity-system relevance. Farm-scale SPIS studies have provided important insight into local feasibility and technical sizing, but they offer less guidance on how many local irrigation systems become relevant for wider electricity-system planning. This thesis addresses that gap by showing how local irrigation mechanisms can be interpreted beyond individual systems and linked to planning-scale demand formation.

A second contribution is the spatial-hydraulic representation of irrigation demand formation. Suitability and master-planning studies identify broad territorial opportunities for irrigation, but they often stop short of representing abstraction structure, elevation differences, pumping head, and candidate irrigation units as infrastructure variables. This thesis extends that literature by showing how irrigable land becomes an electricity-system-relevant planning object once it is organised through water access, intake logic, lift bands, and hydraulic demand structure.

A third contribution is the hourly demand-formation perspective for irrigation electrification. Geospatial irrigation-energy assessments often estimate energy quantities, and sometimes peak power, but they less often represent how irrigation service becomes an hourly electricity load under operating schedules and storage rules. This thesis adds to that literature by showing how terrain-conditioned water service becomes temporally structured demand, and why timing can determine whether a moderate energy requirement becomes system-compatible or infeasible.

A fourth contribution is the dispatch-based interpretation of irrigation as a distinct electricity load. Power-system studies often represent productive uses as generic or exogenous demand increments. This thesis shows that irrigation compatibility depends on timing, peak coincidence, storage-mediated operation, and generation constraints rather than on energy use alone. Irrigation is therefore better understood as a system-shaping load whose significance depends on how it is formed spatially, temporally, and operationally.

A fifth contribution is the irrigation-specific treatment of photovoltaic surplus and export valuation. Existing PV export and compensation studies often focus on residential or commercial systems, while irrigation-driven PV has different seasonal and operational characteristics. This thesis shows that reliability-sized irrigation PV can create structural surplus and that export rules become part of the technical-economic planning problem. In this sense, policy design is not only an external assumption added after technical sizing, but part of the system interaction that shapes cost, surplus value, and coordination.

6.3 Methodological and planning contributions

The methodological contribution of the licentiate thesis is the development of a five-stage framework that links local engineering grounding, geospatial processing, hourly demand formation, dispatch feasibility, and intervention-pathway analysis. The framework makes irrigation electricity demand traceable from spatial and hydraulic assumptions to hourly operation and system outcomes.

This traceability gives the framework its planning value. Geospatial processing defines where irrigation can emerge and what hydraulic structure it carries. Water-service translation defines the magnitude and timing of irrigation demand. Operational strategies define whether this demand is concentrated, shifted, or buffered. Dispatch modelling defines whether the formed profile is feasible under the existing electricity system. Storage and SPIS pathway analysis define whether the system becomes export-led, resilience-oriented, grid-supporting, or cost-sensitive.

The framework can inform decisions on demand, generation, storage, and policy because it shows how each decision depends on the others. Demand is shaped by spatial and temporal rules. Generation strategy is shaped by irrigation timing and PV deployment. Storage value is shaped by reliability needs, charging limits, and surplus allocation. Policy value is shaped by whether exports support the system or become costly compensation.

A further planning contribution is that the framework supports comparison between alternative irrigation-electrification configurations without treating one pathway as universally preferable. The same irrigation service can become a peak-stressing grid load, a storage-buffered demand, a PV-supported local system, or a coordinated grid-interactive pathway depending on the spatial, temporal, operational, and policy rules applied. This makes the framework useful for identifying trade-offs rather than only calculating technical potential.

The framework also clarifies why crop representation matters for electricity-system planning. Irrigation studies often estimate water demand separately for different crops because crop coefficients and growing seasons differ. However, for long-lived infrastructure planning, especially in large, shared, or centralised schemes, electricity-system studies need to test demanding irrigation-service conditions rather than assume that future crop choices remain fixed. The use of a representative high-water-demand crop therefore supports planning-scale stress testing of pumping, storage, and grid requirements.

6.4 Future research directions

The licentiate thesis establishes a planning-oriented framework for irrigation electrification under constraints, but it also identifies several directions for research continuation.

A first direction is to move from the present centralised feasibility perspective toward patch-scale irrigation potentials linked to grid planning and river infrastructure. Future work could identify geographically explicit irrigation patches based on geolocation, pumping conditions, pumped-hydro or gravity-storage potential, grid proximity, and nearby village productive uses, and connect these patches to distribution and expansion analysis using tools such as PyPSA or pandapower. This would allow the framework to assess local grid loading, feeder and transformer stress, hosting capacity, and reinforcement needs, while moving beyond aggregate national compatibility toward local potentials evaluated for coordinated electrification, storage, and productive-use integration.

A second direction is to move from dispatch-feasibility analysis toward investment-oriented design. The present licentiate thesis identifies where irrigation electrification is structurally plausible, how demand is formed, and under what conditions it remains compatible with existing system constraints. The next step could translate feasibility zones into investment propositions through sub-basin or cluster-level design, costed infrastructure packages, financing assumptions, and sensitivity to agricultural revenue streams. This would extend the framework toward bankability metrics such as levelised cost of irrigation water, CAPEX–reliability trade-offs, and sensitivity of NPV or IRR to tariffs, subsidies, and export compensation.

A third direction concerns coordination mechanisms and institutional design. The results show that deployment pathways and export-compensation rules materially alter system costs, surplus value, and incentives, but the framework does not yet represent the full institutional arrangements through which coordination would be implemented. Future work could therefore investigate questions of ownership, aggregation, metering, tariff design, and operational control more explicitly. The aim would be to understand how decentralised farmer-led deployment can be aligned with grid stability, cost recovery, and wider planning objectives without assuming that policy instruments operate independently of demand realism and system constraints.

A fourth direction is to translate the demand-formation framework into digital-twin representations in which key variables can be updated as real-life conditions change. Such an extension would connect the simplified workflow developed in this licentiate thesis with dynamic data streams on climate, water availability, crop conditions, pumping behaviour, storage state, PV production, grid imports, exports, and system constraints. The value of a digital-twin direction is that it preserves the structured logic of the framework while allowing the involved parameters to be updated, monitored, and recalibrated over time. This would support more adaptive planning by linking spatial, temporal, operational, and policy variables to observed system dynamics rather than treating them only as fixed scenario assumptions.

Taken together, these directions show that the research can continue on firmer conceptual ground. The licentiate thesis has established the demand-formation architecture, identified feasibility boundaries, and shown why storage, surplus, and coordination matter. Further work can therefore move more precisely toward investment design, network integration, digital-twin development, and implementable coordination models.

6.5 Final perspective

The broader implication of this licentiate thesis is that infrastructure planning for emerging electrified services requires stronger attention to formation. The challenge is not only to electrify more services, but to understand how new services become loads, how they reshape system operation, and how they can be coordinated with generation, storage, and policy rules.

Irrigation is the case through which this thesis develops that point, but the lesson extends beyond irrigation itself. Whenever a service is weakly observed, physically conditioned, operationally flexible, and potentially surplus-coupled, it cannot be represented adequately as a simple exogenous demand increment. It has to be traced through the territorial, technical, operational, and institutional relations that produce it.

This licentiate thesis has shown one way of doing that under constrained planning conditions. Its concluding contribution is therefore not only a set of results for irrigation electrification in Rwanda, but a more disciplined way of thinking about how emerging electrified infrastructures can be studied, compared, and coordinated within wider energy-system planning.

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