Unveiling Interdependencies in Infrastructure Transitions: Cross- sectoral Learning in the Water-Energy Nexus

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Unveiling Interdependencies in Infrastructure Transitions: Cross- sectoral Learning in the Water-Energy Nexus

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Abstract. Cross-domain coordination and nexus thinking are increasingly recognized as vital for addressing complex sustainability challenges in infrastructure systems. Transitions in one infrastructure system often reshape others through socio-technical interactions, revealing critical interdependencies. However, research on these interdependencies during transitions frequently focuses on technological innovation within specific regimes (e.g., renewables in energy) and lacks insights into how strategic ambitions are translated into operational realities. In this study, two different infrastructure regimes, as electricity and drinking water, will be investigated which will explore how the energy and water transitions influence each other by focusing on two Dutch public utility providers to identify cross-learning opportunities. Using the theoretical lens of socio-technical interdependencies and multi-regime interactions, the research investigates the mechanisms behind implementing electrification for renewables and sustainable water management strategies, as well as the common and unique challenges these systems face in achieving their transition goals. Drawing on 23 semi-structured interviews and secondary data, the study employs qualitative system dynamics models to highlight key interdependencies and challenges. The research identifies four critical interaction moments: (1) *competition* for limited space and resources, (2) *symbiosis* in aging infrastructure renovation, (3) *integration* through shared funding and political support, and (4) *spill-over* effects from grid congestion and social prioritization. By uncovering lock-in mechanisms, interdependencies, and cross-sectoral interactions, the study provides insights into fostering collaboration within infrastructure systems undergoing transitions.

1. Introduction

Sustainability transitions are vital for addressing the pressing challenges of climate change, resource scarcity, and growing societal demands. Research in sustainability transitions highlights the sociotechnical interdependencies of infrastructure systems, which both shape and are shaped by social dynamics and practices (1). For instance, societal consumption patterns of heating influences energy system operations, while new technologies such as renewable energy sources and smart meters raises awareness on social practices like energy use thereby influencing demand levels.

These interdependencies extend beyond individual systems to a "system-of-systems" framework, where large-scale networks—including energy, transport, water, and the built environment—are interconnected through technical and social interactions (2). Understanding these interactions is critical to avoiding unintended consequences, enhancing resilience, and overcoming systemic lock-ins (3). While significant research has advanced knowledge of socio-technical interdependencies towards the transitions within individual sectors such as energy, water, and mobility (e.g., 4; 5; 6), most studies focus on sustainability transitions within each isolated domain of that particular infrastructure. Recent research has begun to explore interdependent sustainability transitions in infrastructure (7,8), yet much remains sector-specific, focusing on how low-carbon innovations—electric batteries, hydrogen, natural gas—interact within energy systems. This narrow scope leaves critical gaps in understanding broader system-of-systems dynamics, which is essential for guiding integrated transitions strategies.

Without particularly focusing on sustainability transitions, the nexus framework—highlighting the interdependencies between critical sectors such as water, energy, and food—offers a practical approach to understand the complexity behind the system-of-systems of infrastructure, by promoting integrated management to optimize resources and reduce trade-offs across siloed domains (9).For example, the water-energy nexus has gained prominence as rising demand, industry reforms, and climate change create threats to each other's supply security, since electricity generation relies on water, while water treatment and distribution depend on electricity (10). Advances in methods such as life cycle assessments, system dynamics modelling, and input-output analyses have quantified these interdependencies and their environmental impacts (11). Nevertheless considering the sustainable management of infrastructure, much of the existing research focuses on the technical aspects, often neglecting the institutional, social, and governance challenges that complicate the transitions, particularly in urban contexts where socio-technical lock-ins further hinder progress (12). Moreover, while nexus thinking highlights synergies between resources like water and energy, it often prioritizes strategic-level governance, focusing on policy design and long-term pathways (9;13). Such emphasis overlooks operational realities—like infrastructure capacity, space, and coordination—crucial for translating strategy into action (14). Capacity planning, a key activity for aligning infrastructure with immediate needs and long-term goals, ensures future adaptiveness in infrastructure planning and fosters transformative capacity for sustainability innovations (15; 16), yet remains underexplored in nexus studies.

This paper addresses these gaps by examining the interdependencies between energy and drinking water infrastructure transitions in the Netherlands, such as renewable integration, distributed energy, rising electricity demand, climate change impacts, and sustainable water management. Using socio-technical interdependencies and multi-regime interactions as a lens, it explores how these transitions shape cross-sectoral learning in capacity planning. Specifically, it asks

How do transitions in energy and water grid infrastructures influence each other, and what interdependencies shape cross-sectoral learning opportunities during sustainability transitions ?

By addressing this question, the study seeks to advance an integrated understanding of how interconnected infrastructure systems can collaboratively manage capacity challenges and drive sustainability transitions. **Section 2** provides the theoretical framing, covering socio-technical interdependencies and multi-regime interactions. **Section 3** outlines the qualitative methods and systems thinking approach used to examine sectoral interdependencies, while **Section 4** presents the main findings.

2. Theoretical Framing

Infrastructure Interdependencies and Regime Interactions

Infrastructure interdependencies play a crucial role in sustainability transitions, influencing essential systems such as energy, water, transport, and communication, and while they can amplify risks like cascading failures, they also present opportunities for resilience, integrated risk management, R&D spillovers, and new urban functions (17).
As an early study to catalogue the interdependencies of infrastructure, (18) introduced four types of infrastructure interdependencies as: physical interdependencies, involving material input-output processes; cyber interdependencies, focusing on data and information exchange; spatial interdependencies, related to geographic proximity and shared spaces (19); and logical interdependencies, which originally addressed social influences like policy and markets. Recognizing the complexity of social dimensions, this category was later expanded to include policy/procedural, societal, economic and market interdependencies. Also physical and cyber interdependencies are further integrated into functional interdependency to reflect the growing role of ICT in infrastructure systems (20). In our study, we build on these theoretical frameworks to focus specifically on the sustainability-driven transitions of two distinct infrastructure systems (similarly proposed and utilized by (8), aiming to identify the key **social *(policy, market, cultural/norm)* and technical interdependencies *(functional, spatial*)** between water and energy grid infrastructures.
In the context of sustainability transitions, (21) redefined infrastructure interdependencies by shifting focus from physical and managerial links to interactions between socio-technical regimes, such as electricity and natural gas systems. Building on material input-output dependencies (19), the authors proposed four types of interactions: ***competition***, where systems fulfil similar needs; ***symbiosis*,** involving mutual benefits like long-term contracts; ***integration*,** where systems operate as one through shared ownership, actors or technologies; and ***spill-over***, where rules or norms from one system are replicated in another. The first three interaction types involve varying degrees of direct cooperation, whereas spill-over represents an indirect connection—referred to in this research as 'indirect communication' between infrastructure providers. Guided by these socio-technical classifications (17-21), our fieldwork and analysis aim to explore interdependencies and cross-sectoral learning opportunities between electricity and water infrastructure in sustainability transitions.

3. Methods

3.1. Case Description
The case study examines two major Dutch infrastructure providers—one for energy distribution and the other for drinking water supply—operating in overlapping regions. The energy provider manages extensive electricity and gas grids across Gelderland, Friesland, Noord-Holland, and Amsterdam, while the water provider serves Gelderland, Overijssel, Utrecht, and Flevoland, relying primarily on groundwater for water extraction. Their interdependence can be clearly shown, because electricity powers water treatment and distribution, and water resources support electricity generation. **Fig. 1** illustrates their overlapping service areas, highlighting this connection. Although they collaborate on sustainability projects or in strategic programs, their shared socio-technical interdependencies remain largely unexplored in the context of sustainability transitions.

This study examines capacity planning in the context of sustainability transitions, uncovering interdependencies and opportunities for cross-sectoral learning. Using qualitative empirical data from interviews and document analysis, it explores how energy and water providers manage capacity challenges within their overlapping regions.

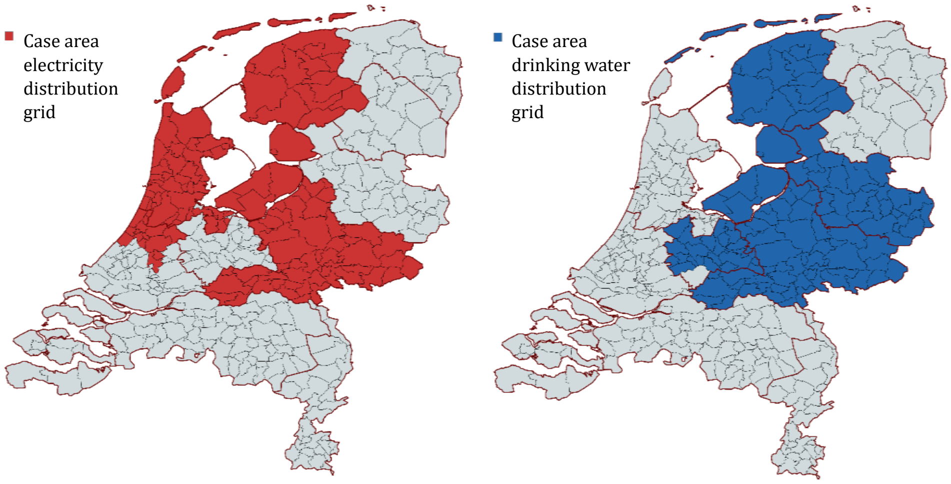

Figure 1. Case areas of electricity and water infrastructure

3.2. Qualitative Data Collection and Analysis

This research employs qualitative methods, including semi-structured interviews and document analysis, to examine capacity planning in energy and water infrastructure. A total of 23 interviews were conducted between December 2023 and July 2024: 11 with the energy provider and 12 with the water provider **(Table 1).**

Table 1: Participant List

		Responsibility	Years in Industry	1st Interviews	2nd Interviews	Validation/ Feedbacks
Energy	Int.1	CSR Director	10	X	X	X
	Int.2	Region Lead	5	X	X	X
	Int.3	Lab Manager/Researcher in Grid AI	15		X	
	Int.4	Epic Owner/System Operator	17		X	X
	Int.5	Senior Policy Advisor	15		X	X
	Int.6	Consultant in Energy Transition	9		X	
	Int.7	Product Owner and Developer	7		X	
	Int.8	Team Leader in Grid Strategy	12		X	
	Int.9	Product Owner and Developer	10		X	X
	Int.10	Consultant Product Development	10		X	
	Int.11	Team Manager in Grid Operations	5		X	
Water	Int.1	Strategic Asset Manager	38	X	X	X
	Int.2	Program Manager	13		X	
	Int.3	Strategist	15		X	
	Int.4	Legal Advisor	25			
	Int.5	Marketing Advisor/Team Manager	10		X	
	Int.6	Portfolio Manager	13		X	
	Int.7	Policy Advisor/Strategist	5		X	
	Int.8	Program Manager Sustainability	11		X	
	Int.9	Asset Manager	22		X	
	Int.10	Program Manager	25		X	
	Int.11	Policy Advisor	5		X	
	Int.12	Strategist	7		X	

Interviews, lasting 45 minutes to an hour, were recorded, transcribed, and analysed using Atlas.ti. The initial round examined interdependencies between water and energy infrastructure transitions to pinpoint areas for deeper investigation. Energy sector interviews addressed corporate social responsibility, transition pathways, regional operations, electrification challenges, distributed energy, and grid capacity. Water sector interviews focused on asset management, policy, and water supply reliability under climate change. Both sectors anticipate capacity constraints due to societal and environmental pressures. These findings informed subsequent interviews with capacity planning experts and additional data collection from documents and secondary sources.

Table 2. Reviewed Documents

Name	Reviewed Document	Description	Organization	Date
Climate Agreement	National Climate Agreement	Dutch climate policy, government's central goals	Ministry of Economic Affairs	2019
Energy DSO Strategy Document	2023 Results	Key highlights, strategies, concerns, and steps of 2023	Electricity Distribution Grid Organization	2023
E-Directive (2019) (contains E-Act (1998)	Law and Regulation of Electricity in Netherlands	Provides the basis of electricity market and regulation	European Parliament and Dutch Government	Electricity Act (1998) E-Directive, (2019)
Water Act (Netherlands)	Waterwet	Establishes the legal framework for water management	Ministry of Infrastructure and Water Management	2009
Drinking Water Strategy Document	Long-Term Vision 2020-2050 Infrastructure	Provides strategic insights into sustainable water management, including interdependencies between energy and water.	Drinking Water Grid Organization	2020

The research explores each organization's perception of its connection to the other and the mutual impact of their transitions. The water provider reflects on the energy transition, future outlook, and interdependencies shaped by market rules, policies, and societal changes. Qualitative data is categorized into technical (functional, spatial) and social (policy, market, cultural/norm) interdependencies, revealing interactions that are symbiotic, competitive, integrative, or involve knowledge spillovers, as detailed in **Section 2.**

3.3. Systems Thinking and Modelling
Systems thinking is essential for analysing interdependencies in interconnected infrastructure systems like energy and water networks. System dynamics (SD), developed by (22), captures feedback loops, emergent behaviours, and causal relationships in complex systems, identifying leverage points for policy intervention (23). While SD has been widely applied to infrastructure interdependencies (24) and increasingly in socio-technical transitions research (25), particularly for uncovering hidden feedback mechanisms to anticipate unintended consequences, its use in studying system-of-systems interactions during sustainability transitions remains limited. This study employs SD modelling to visualize interdependencies and feedback loops in energy and water grids, revealing cross-sectoral opportunities and challenges. Qualitative data, collected through interviews and document reviews, is analysed using typologies of socio-technical interdependencies and regime interactions, represented in causal loop diagrams. Positive links indicate changes in the same direction, while negative links show opposite changes; reinforcing loops drive exponential growth or collapse over time, while balancing loops stabilize systems by counteracting changes. Validation sessions involved discussing the impact of modelling with participants.

4. Results and discussion

4.1. What sustainability transitions mean for each infrastructure? Similarities and Differences

The interviews explored sustainability transitions in the energy grid and drinking water infrastructure, highlighting shared challenges and differences. For the energy distribution grid operator, the sustainability transition focuses on increasing renewable energy use and managing the exponential growth in electrification demand, which outpaces grid expansion capabilities. This shift requires moving from simply "laying cables" to becoming a "distribution service operator," transforming the grid from a traditionally passive infrastructure to an actively managed system. Drinking water infrastructure prioritizes long-term availability, quality, and accessibility, with strategies shaped by external environmental factors, facing challenges like climate change impacts, such as the 2018-2020 droughts (26), which strain resources and increase demand pressure. The case organization relies entirely on groundwater, raising concerns about availability due to climate change and competing land uses, while stricter regulations like Natura 2000 limit extraction to protect natural habitats.

Both systems share a "splintered" nature in the Dutch context. Historically, over 100 municipalities independently managed drinking water, creating a decentralized system that remains locked in. Sustainable water management now optimizes extraction locations while shifting toward centralized regulation for climate adaptation. This results in a decentralized physical system with centralized regulatory control. However, deregulated private extractions add uncertainty, especially in dry periods. Participants emphasized the benefit of stricter regulations, opposing privatization. In energy, unbundling since the late 1990s has made proactive planning difficult. Under the "copper plate" principle, energy production and supply operate freely, while grid operators, tightly regulated and publicly owned, must manage increasing renewable energy demand and grid congestion costs. Also, both sectors exhibit risk-averse capacity management due to financial constraints. In the water sector, strict tariff regulations and resistance to proactive investments (e.g.,from provinces and municipalities) foster an efficiency-oriented culture. Similarly, electricity grid operators, benchmarked on efficiency, face penalties for unused capacity, complicating investments for decentralized energy sources. However, rising congestion has spurred innovative flexibility solutions in the energy sector.

A key difference is the drinking water grid's deep interconnection with the broader water system, both physically and governance-wise, unlike the more independent energy grid. On the contrary, stricter water sector regulations, seen as beneficial, provide clear service criteria that support sustainable management, contrasting with the energy sector's first-come-first-serve approach.

4.2.Interdependencies between Water-Energy Transitions

- **Functional Interdependencies**

The primary functional interdependency identified in the case study involves energy grid congestion and its impact on the water system, particularly due to the growing energy needs of water extraction plants. This highlights the necessity of integrated planning to anticipate periods of increased water demand and inform energy supply and distribution accordingly for future.
Especially the water participants indicated that currently, in the case of the need for building new drinking water extraction plant, they are looking for their access to the electricity grid, and network operator (in this case the energy grid infrastructure provider of this study) may decline their request to the energy congestion. This had also direct influence on the sustainable energy strategies of the water company as well, since they also demand for sustainable energy from windmills or solar parks . This issue has been indicated as the main conflict between the energy and water transitions, as of competition for shared resources.

Functional interdependency is also evident as electricity grids anticipate a shift to district heating for most homes. While this increases flexibility and reduces low-voltage network load, it raises concerns for water organizations, such as groundwater contamination risks and competition for underground space. Thus, the energy transition may conflict with drinking water needs. Unlike simple competition, this interdependency resembles parasitism (27), where energy infrastructure benefits while potentially hindering water infrastructure.

- **Spatial Interdependencies**

Maintenance is crucial for both grid infrastructures, creating a key spatial interdependency in sustainability transitions. For instance, the aging electricity grid, over 100 years old, faces frequent outages due to infrequent inspections. Given their geographical proximity, renovation offers an opportunity for **symbiosis,** where both sectors benefit as indicated in interviews. Coordinated planning allows energy cables to be installed alongside water pipes, optimizing space, permits, and contractor availability. Still limited space in the Netherlands poses a major challenge for infrastructure providers. In energy, grid expansion is needed to meet growing electricity demand, driven by distributed renewables, fluctuating production peaks, and difficulties securing space and permits. Similarly, the water sector faces rising demand for drinking water extraction, but spatial claims for extraction plants require exclusive use to protect water quality, complicating licensing. A participant emphasized that energy and water, both essential public services, must compete for scarce space, requiring prioritization in infrastructure transitions. This issue is often framed as **competition** over physical and permitted space, negatively impacting both systems. However, it also presents an opportunity for integration, as water and electricity infrastructure regimes could collaborate more closely. Given their shared dependence on regional authorities for permits and financial support (e.g., from provinces) and overlapping spatial constraints, they could function more effectively as integrated providers.

- **Market Interdependencies**

The main market interdependency lies in the labour market, a shortage of personnel for growing workloads and sustainability projects has created mutual dependency among infrastructure providers, as an interaction of **competition** for contractors. This challenge emerged in both interview rounds, with experts noting that competition extends beyond individual sectors—energy grid and drinking water infrastructure now vie for the same workforce. A participant described how construction firms prioritize easier or more attractive projects, driving up costs and causing delays for both transitions. Limited availability of specialized contractors underscores the need for greater coordination among utility providers on social prioritization—deciding which projects, such as wastewater treatment, drinking water or district heating, should take precedence. Regional disparities also pose challenges, with most skilled workers concentrated in the west while the east requires more development. Building trust among agencies and integrating efforts on projects, rather than competing for transitions, were proposed as promising approaches.

- **Cultural/Normative Interdependencies**

The primary cultural interdependency stems from societal norms driving increased demand and consumption. Both sectors have introduced new departments and strategies to promote demand reduction. Water experts, in particular, emphasized learning from energy congestion to take a more proactive approach in preventing similar challenges in water infrastructure.

Rising housing demand has further intensified dependencies between drinking water and energy, with both sectors seeking stronger political support for integrating urban and infrastructure planning. Experts noted that shared reliance on the same authorities for political backing and funding has increasingly aligned the previously separate water and energy regimes, create an

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integration interaction. Capacity challenges have reinforced their common stakes in climate impact, demand reduction, flexibility solutions.

- **Policy/Procedural Interdependencies**

The shift from the 'first-come-first-serve' policy in energy distribution to social prioritization has sparked debates, particularly as drinking water companies—ranked third despite their essential role—argue for higher priority. This shift underscores procedural and policy interdependencies between energy and water, especially regarding grid congestion and the high energy demand of water pumping. Political support, shaped by climate policies and infrastructure tariffs, has driven greater integration between the sectors, evident in sustainability programs and climate agreements. Specific regulatory instruments, such as prioritization frameworks and joint permitting procedures, could further foster proactive collaboration between water and energy operators. Capacity challenges and demand reduction efforts have also fostered cross-sector learning, particularly in flexibility solutions. Water infrastructure is now adopting smart meters, following the lead of energy networks, while energy operators have drawn from water sector insights on prioritization rules, moving beyond procedural 'copper plate' or 'first-come-first-serve' approaches. These spill-over effects emerge not from direct collaboration but through implicit learning from shared cross-sectoral uncertainties.

4.3. System Dynamics Modelling and Insights on Interaction

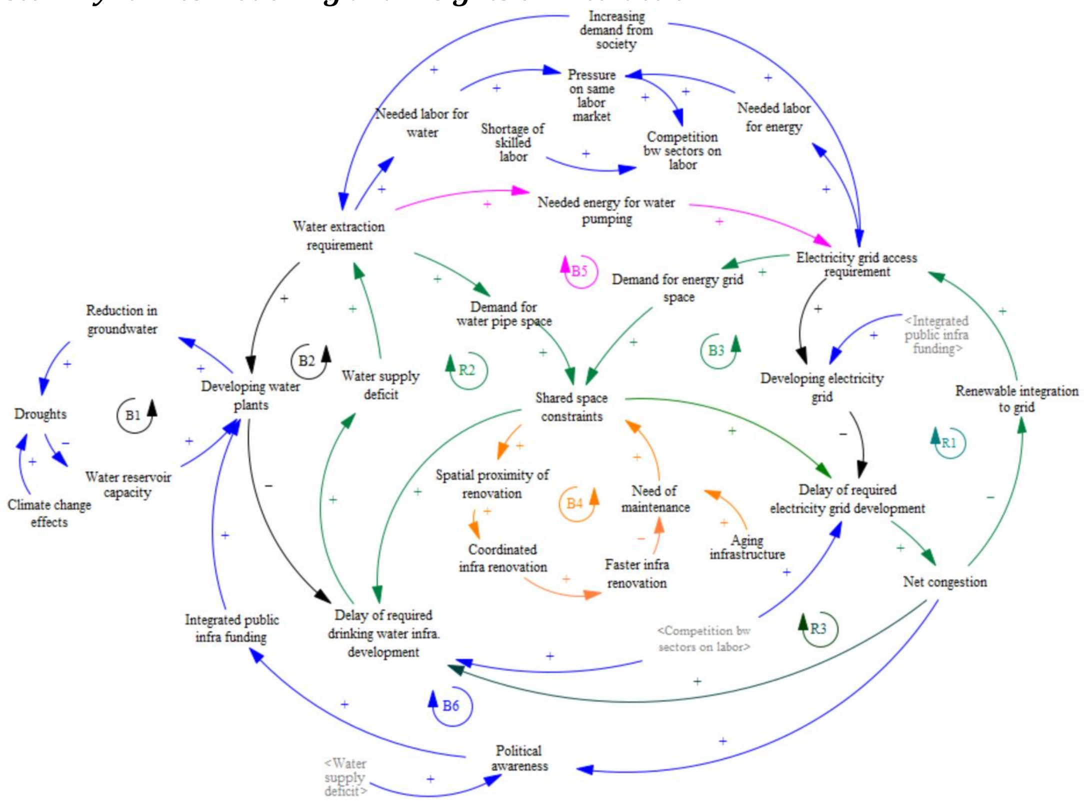

Figure 2: CLD Model

The model illustrates key interdependencies between energy and water infrastructures, validated by participants as effective in visualizing systemic interactions. Energy and water sectors primarily compete for limited space and skilled labour, creating market and spatial interdependencies. For water infrastructure, developing water extraction plants creates a contradiction due to groundwater reduction caused by climate change effects (B1),which may compromise another sustainability transition strategy as accessibility for society. Similarly, increasing societal demand exacerbates delays in water infrastructure development (B2), driven by interconnected challenges such as shared space constraints (R2) and grid congestion (R3). In the energy sector, rising demand for renewable integration leads to delays in grid development (R1), causing congestion and hindering the energy transition. Grid development is further challenged by space limitations, intensifying delays (B3). Additionally, increased water demand raises energy needs for pumping, which is constrained by grid congestion (B5). A significant interaction is the growing pressure on the labour market, where both sectors compete for skilled workers. However, shared space constraints could foster collaboration on renovation challenges (B4), as maintenance for water and energy is often done together, creating a symbiotic relationship. Congestion in both water and energy sectors may raise political awareness, potentially leading to public infrastructure funding. This funding is often referred to as "integrated" during interviews, as both sectors depend on the same actors. Such integration can balance delays by accelerating development (B6). Spill-over interactions occur indirectly through mutual dependency on societal demand, promoting cross-sectoral learning. Energy is increasingly adopting efficiency measures and social prioritization, learned from water sector practices. Conversely, water is learning congestion management and flexibility strategies from energy, as congestion becomes a growing issue for water systems. The system dynamics modelling improves decision-making by revealing unintended consequences and feedback loops, such as how delays in one sector exacerbate challenges in the other. This approach highlights the importance of integrated planning and collaboration to address shared challenges.

5. Conclusion

This research addresses the gap in understanding cross-sectoral interdependencies and regime interactions between energy and water infrastructure during sustainability transitions. Unlike technical-focused nexus studies, this study adopts a socio-technical perspective, examining how strategies like renewable integration and climate-adaptive water systems face operational capacity challenges. It identifies key interdependencies—competition for space and labour, symbiosis in renovation, integration through shared funding, and spill-over effects in policy—revealing areas for future coordination and knowledge exchange. Methodologically, qualitative system dynamics (SD) modelling visualizes interactions between water and electricity grids, identifying leverage points for intervention and fostering cross-sectoral learning. The findings highlight the importance of integrated planning to mitigate unintended consequences and enhance resilience. For example, shared space constraints and labour shortages create competition but also opportunities for collaboration, while policy spill-overs enable learning between sectors. Future research could quantify causal loops to assess the cost, time, and resource impacts of interdependencies (e.g., space and labour competition) through expert ranking and agency prioritization, and expand the nexus to include infrastructures such as transport and waste management. By understanding these interactions, stakeholders can anticipate challenges, build adaptive capacity, and strengthen infrastructure resilience. This study offers actionable insights for policymakers and practitioners by identifying key socio-technical interdependencies driving infrastructure transitions and emphasizing the need for collaborative, cross-sectoral strategies to achieve long-term sustainability goals.

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