
Infrastructure Digital Twins for Innovation in Rural Energy Systems

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Abstract: This paper conceptualizes Infrastructure Digital Twins (IDTs) to function as innovation-enabling boundary objects for early-stage coordination in rural energy systems. Rural regions face significant coordination challenges due to fragmented actors, sectoral silos, and limited shared situational awareness. Using a design-science approach applied in the German State of Brandenburg, the study shows how IDTs integrate heterogeneous spatial and actor data into a modular, GIS-based artefact. Emerging insights indicate that IDTs facilitate cross-sector dialogue through interpretive flexibility, support AI-assisted exploration rather than optimization, and enable collective sensemaking. An illustrative corridor co-use scenario demonstrates how IDTs reveal ecosystem structures and enable alignment prior to formal commitments, addressing coordination failures in infrastructure innovation.

Keywords: Infrastructure Digital Twins (IDTs); Boundary Object Theory; Rural Energy Systems; Innovation Coordination; Cross-Sector Ecosystems; Design Science Research; GIS-Based Spatial Integration; Ecosystem Alignment (Ecosystem-as-Structure); Collective Sensemaking; AI-Supported Exploration

1 Introduction

Rural energy systems are central to renewable energy transitions since rural regions host substantial renewable generation potential, but face innovation management challenges related to spatial dispersion, fragmented infrastructure ownership, and limited coordination capacity across actors (Mattes et al., 2015). Those challenges can hinder innovation in infrastructure developments due to heterogeneous data sources, sectoral silos, and a lack of shared situational awareness (McLellan et al., 2016). Planning and decision-making are traditionally approached top-down, project-specific, and sector-bound, thereby creating obstacles for cross-sector experimentation in early-stage exploration.

Infrastructure innovations can fail to materialise not because of technical infeasibility but because of limited transparency, lacking coordination, a high perceived risk in early project phases, and unrealized cooperation opportunities (Rogge and Reichardt, 2016). Especially in the rural context, where fragmented actors operate in sectoral silos due to geographical isolation, missed opportunities of collaborations are particularly present and can hinder potential innovation processes.

From an innovation management perspective, this highlights the need for artefacts which are defined as purposeful, human-created (including AI-based human-in-the-loop) objects that support transparency, joint-problem framing, exploration, and stakeholder engagement before formal investments or governance arrangements are established. This is not a conventional engineering problem but a coordination problem in a fragmented technical infrastructure context. Digital artefacts that make distributed actors visible to each other and across sectoral boundaries thereby hold the potential to foster collaboration efforts and to act as an ecosystem for innovation. An ecosystem is defined by Adner (2017) as “the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize”.

Digital Twins (DTs) are increasingly invoked in this regard which are defined by Fuller et al. (2020) as a “digital representation of an existing physical object in which the data flow between physical- and digital object are fully integrated in both directions”. DTs are predominantly applied during operational project phases for optimization, forecasting, monitoring, and control (Fuller et al., 2020). Although recent work has connected DTs to innovation processes, the coordination-enabling function of such digital artefacts has not been systematically theorized (Holopainen et al., 2024). This paper conceptualizes and defines Infrastructure Digital Twins (IDTs) not just a technical tool, but an innovation-enabling digital artefact based on boundary object theory, asking the following question:

How can Infrastructure Digital Twins function as boundary objects that support early-stage innovation processes in rural energy systems by enhancing transparency, stakeholder engagement, and cross-sector coordination?

2 Theoretical Background

2.1 Infrastructure Digital Twins

Digital Twin research in energy and infrastructure systems mostly treat DTs as technical instruments tightly coupled to physical systems through real-time data flows (Fuller et al., 2020). This framing has produced substantial advances in predictive maintenance, fault detection, monitoring, and simulation, but it leaves early-stage innovation processes largely outside the analytical frame. More recent work has shown that DTs can support exploration, experimentation, and the discovery of new business opportunities, particularly by integrating previously siloed information and enabling network-level collaboration (Holopainen et al., 2024). It positions DTs not only as tools for running existing systems more efficiently, but as digital artefacts that can shape how new systems become possible. Moshood et. al. (2024) introduce the term IDT in the context of the fragmented construction industry in which technology adoption has been slow and explicitly identify DTs value in streamlining coordination and facilitating data sharing across actors. IDTs are similarly not just framed as a tool but as a paradigm shift (Moshood et. al., 2024).

2.2 Rural Energy Transitions

Sustainability transitions literature conceptualizes systemic change through the multi-level perspective, with niches generating radical novelty, regimes providing stability, and landscape pressures opening windows for change (Geels, 2002). Rural energy innovations are small-scale, experimental, and dependent on alignment across actors who are not yet integrated into regime structures. Current landscape pressure such as climate change and rising oil prices due to ongoing wars create opportunities for regional renewable energy systems which hold great potential for driving decentralized solutions with distinct dynamics that national-level transition analyses miss (Mattes et al., 2015).

2.3 Boundary objects and ecosystem alignment

Star and Griesemer (1989) introduced boundary objects as artefacts that are plastic enough to adapt to the local needs of different social worlds (or social actors) and robust enough to maintain a shared identity across them which are weakly structured in common use and strongly structured in specific use. Boundary objects include different uses and attributed meanings to it (interpretive flexibility), a concrete or abstract information structure that various groups can engage with, and relational properties (how the object functions in interaction between groups) (Star and Griesemer, 1989). Boundary objects enable coordination without requiring full consensus on goals or methods, which matters in fragmented settings where prior agreement cannot be assumed (Star and Griesemer, 1989).

Ecosystem-as-structure adds a complementary lens. Four elements characterize the structure: activities, actors, positions (who hands off to whom), and links (transfers of materials, information, influence, or funds) (Adner, 2017). Ecosystems require alignment, not merely participation; and alignment requires visibility of positions and flows before commitments are made. In rural infrastructure settings, this precondition is often lacking. Actors know their own position but not the structure they sit within.

Together these lenses suggest a mechanism: plastic-yet-robust shared artefacts (boundary objects) enable visibility of positions and flows (ecosystem structure), which is the precondition for alignment before formal project commitments.

2.4 Research Gap

Digital twins in rural energy contexts are typically framed as technical planning or monitoring instruments (Fuller et al., 2020). They are commonly not conceptualized as innovation-enabling artefacts that mediate between distributed actors and heterogeneous data to support early-stage exploration and ecosystem formation (Moshood et. al., 2024). The gap is both conceptual and practical: DT research has not absorbed boundary-object or ecosystem-structure thinking and rural infrastructure actors lack digital artefacts that make cross-sector alignment possible before commitment. This paper addresses the gap by conceptualizing and prototyping an IDT that operates at this intersection.

3 Conceptualizing the Infrastructure Digital Twin

An Infrastructure Digital Twin (IDT) is defined here as a modular, GIS-based digital representation of regional energy infrastructure that integrates heterogeneous datasets on assets, actors, and contextual indicators into a continuously updatable analytical and visualization prototype. Each element of the definition is deliberate. Modular means the artefact is assembled from loosely coupled layers that can be extended or substituted without redesigning the whole. GIS-based anchors the representation in space, which is the dimension along which infrastructure actors already organize their thinking. Regional analysis at the subnational level shifts the focus towards where cross-sector coordination actually takes place. Heterogeneous datasets acknowledge that no single source suffices: assets (generation, grid, storage) come from registries; actors and relations come from public records and qualitative work; contextual indicators (land use, demographics, regulatory boundaries) come from geospatial and statistical sources. Continuously updatable distinguishes the IDT from static planning maps and points out its iterative nature. Analytical and visualization prototype signals its dual role as an object for computation and for shared viewing.

The IDT is explicitly bounded. It is not a real-time operational control twin; it is not a full dynamic simulation model; it is not a GIS-only visualization tool; and it is not a dashboard reporting predefined KPIs. Its unit of analysis is the region; its intended users are municipal actors, infrastructure operators, and regional coordinators; the decisions it supports are exploratory ones taken before formal project initiation. It can adopt functions of operational DTs in later project-stages, therefore complementing conventional DTs rather than replacing them.

AI-supported analytics are similarly scoped as an innovation-enabling tool. AI refers to human-in-the-loop methods such as rule-based data harmonization, clustering, and heuristic pattern detection. The idea is to support exploration and screening approaches. This scoping is not a limitation but a design principle: the artefact must preserve

interpretive flexibility across social worlds, which is incompatible with outputs that prescribe single optimal answers.

The proposed conceptual IDT architecture is illustrated in Figure 1.

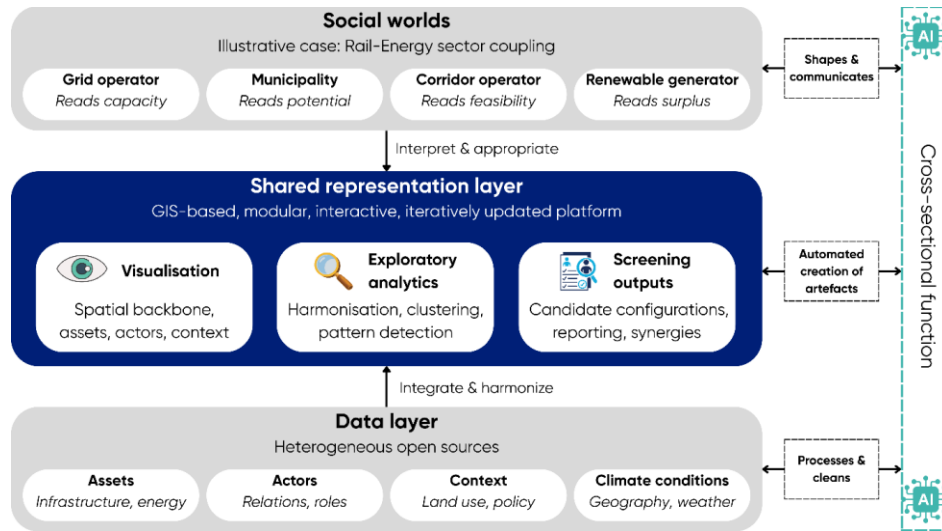


Figure 1 IDT conceptual architecture.

4 Research Design and Empirical Setting

The study follows a design-science research approach (Hevner et al., 2004), in which knowledge is produced through the construction and evaluation of a purposeful artefact that addresses a defined problem. The design-science frame fits the research question because the contribution is neither a behavioral theory to be tested nor a policy evaluation to be conducted, but an artefact whose conceptualization and early use generate insight into how such artefacts function in practice.

The empirical setting is the German federal state of Brandenburg, selected as a model region for rural energy transitions. Brandenburg combines high wind and solar generation potential with dispersed settlement structures, fragmented infrastructure ownership, and active regional coordination challenges. The state's energy strategy 2040 provides a formal regulatory frame in which rural actors operate; the Multi-Level Governance structure common across German states supports transferability of findings. The IDT prototype draws on nationally available open data, particularly the Marktstammdatenregister for energy infrastructure assets, supplemented by geospatial and actor-relational sources. This open-data foundation is a deliberate design choice for transferability.

The current empirical basis consists of iterative prototype development together with qualitative observations from stakeholder interactions, focused on how digital representations are interpreted, appropriated, and used in early-stage innovation

discussions . A first map-based and interactive artefact for exploring rural energy systems in Brandenburg as part of the IDT has been developed and is shown in Figure 2.

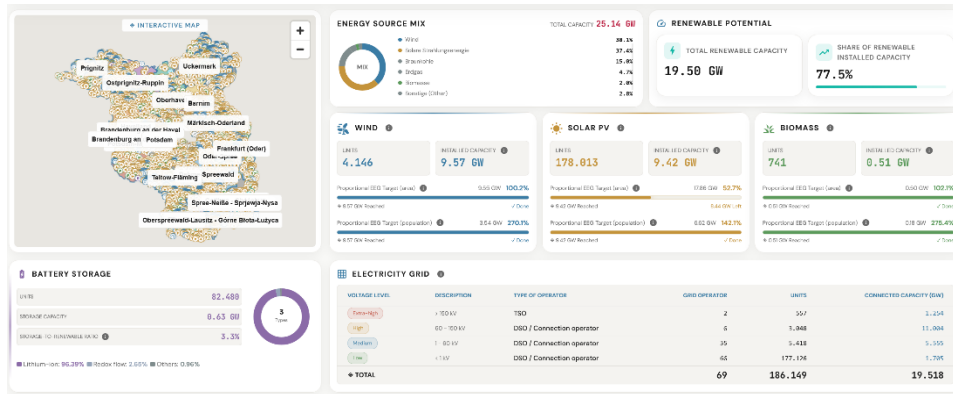


Figure 2 Regional energy report aggregated down to municipal level.

An illustrative scenario concerning cross-sector co-use of existing transport corridors for regional electricity distribution anchors the analysis (see Section 5.4). Systematic empirical validation is ongoing through expert interviews, exploratory and structured workshops as well as comparative case work. 4 interviews and 5 workshops with relevant actors and networks have been conducted. Additional 8 workshops and 2 round tables are planned for late 2026.

5 Emerging insights

The insights presented here are provisional, drawn from prototype development and stakeholder interactions rather than from systematic empirical validation. They are framed as emerging propositions to guide the next research phase.

5.1 IDT function as boundary object

A more specific mechanism emerges when the IDT is used as an interactive visual artefact in stakeholder settings. Different actors read different structures from the same representation: a grid operator reads capacity and congestion; a municipality reads regional generation potential and local revenue flows; a transport infrastructure operator reads corridor feasibility and co-location opportunity. This interpretive flexibility combined with a stable spatial and data backbone is the defining signature of a boundary object (Star and Griesemer, 1989). The IDT enables cross-sector dialogue without requiring prior agreement on goals, methods, or outcomes. What it requires is the coexistence of plasticity in local interpretation with robustness in shared reference.

5.2 AI-assisted exploration rather than optimization

Embedded analytics in the IDT facilitate the identification of cross-sector infrastructure concepts by aggregating heterogeneous datasets and screening possible constellations. Crucially, these analytics do not produce optimized or predictive outputs; they surface candidate configurations for discussion. This matters for the boundary-object function: outputs that prescribe a single optimal answer collapse interpretive flexibility and foreclose dialogue. Screening outputs that surface multiple candidate structures preserve the space in which different actors can engage. Limitations and potential biases of such screening particularly in underrepresented data domains remain open questions.

5.3 Collective sensemaking across sectoral silos

Integrating fragmented infrastructure and actor data into a single spatial representation enables actors who otherwise operate in sectoral silos to develop shared situational awareness. The mechanism is not that the representation resolves disagreements, but that it makes the terrain of disagreement visible. Municipal actors, grid operators, and generation-site operators typically hold partial, non-overlapping pictures of the same region. A representation that renders their respective domains within a shared spatial frame surfaces adjacencies and dependencies that were previously obscure. Sensemaking becomes collective not because actors agree, but because they now see the same object.

5.4 Illustrative scenario: cross-sector corridor co-use

A scenario concerning the potential co-use of existing transport corridors for regional electricity distribution illustrates how the three mechanisms combine. The relevant ecosystem, in Adner's (2017) sense, comprises renewable generators (upstream), transport infrastructure operators (corridor position), grid operators (network links), and municipal or industrial consumers (downstream). Historically, these actors have interacted bilaterally, if at all. Co-use as a value proposition requires alignment across all four positions, which in turn requires that each actor can see the others' positions within a shared representation. The IDT makes this alignment structure possible: generation surplus zones, corridor routes, grid constraint points, and consumer locations appear within a single frame. Prior map-based infrastructure analysis conducted by the authors has functioned as a first form of validation: structured spatial representations have supported strategic dialogue among distributed actors and moved initial coordination beyond bilateral conversation. The scenario remains exploratory rather than implemented, but the mechanism is observable.

6 Discussion

6.1 Preliminary answer to the research question

IDTs can support early-stage innovation in rural energy systems by functioning as boundary objects that make fragmented infrastructure and actor configurations visible as a plastic-yet-robust shared artefact. This visibility enables cross-sector dialogue and ecosystem alignment before formal project commitments, addressing the coordination failure that underlies much rural infrastructure innovation.

6.2 Theoretical contribution

The paper contributes to innovation management in three ways. First, it conceptualizes Infrastructure Digital Twins from technical optimization instruments toward innovation-enabling boundary objects, extending recent work connecting DTs to innovation (Holopainen et al., 2024) into the infrastructure-scale rural context. Second, it integrates boundary-object theory (Star and Griesemer, 1989) with ecosystem-as-structure thinking (Adner, 2017), showing how plasticity-with-robustness and visibility-of-alignment are complementary mechanisms. Third, it positions AI as a supplementary tool with cross-sectional functionality under the condition of established human-in-the-loop processes to maintain human oversight to ensure safety according to EU AI Act.

6.3 Practical implications and transferability

For infrastructure operators, municipalities, and regional policymakers, IDTs are expected to reduce coordination costs, support partner identification, and structure exploration before major investments. Because the approach builds on open, nationally available data and a modular architecture, transferability to other rural regions with comparable data infrastructure and Multi-Level Governance structures seem plausible. Boundary conditions matter: regions with weaker data access or governance capacity may face higher implementation barriers.

6.4 Limitations

The insights presented are conceptual and drawn from early prototype work. Empirical validation at this stage is limited to qualitative observations. The single-region case constrains generalisation. AI-supported transparency tools risk reproducing information asymmetries they aim to address; structural safeguards require further work.

7 Conclusion

Conceptualizing Infrastructure Digital Twins as boundary objects for early-stage innovation offers a productive direction for innovation management research on rural energy transitions. By integrating boundary-object theory with ecosystem-as-structure thinking, and by grounding the artefact in open regional data, this paper clarifies a mechanism that connects DT research to coordination-based innovation theory. The unique combination of theoretical and technological grounding in this rural energy context highlights a new approach to visibility-enabled actor alignment. The three emerging insights and the illustrative transport-corridor scenario remain provisional. Systematic empirical validation, comparative work across regions, and further theoretical refinement are next steps.

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Areas for Feedback and Development

The authors seek feedback on five areas:

1. Conceptual positioning. Does the reframing of IDTs as boundary objects rather than planning or monitoring tools productively bridge DT research and innovation management, or does it overextend either literature?
2. Theoretical integration. The paper pairs Star and Griesemer's boundary object theory with Adner's ecosystem-as-structure perspective. Is this coupling coherent, or are there tensions between the two lenses we have not surfaced?
3. Empirical validation design. How can the boundary-object function of IDTs be empirically assessed beyond qualitative observation? What counts as evidence of coordination without consensus?
4. Transferability. Which contextual conditions (data infrastructure, governance capacity, actor constellations) matter most for transferring the approach to other rural regions?
5. Information asymmetries. AI-supported transparency tools risk reproducing the asymmetries they aim to address. What structural safeguards should be built into the artefact rather than layered on afterwards?