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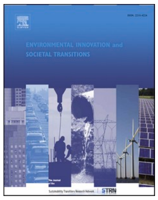

Creating actionable knowledge one step at a time: An analytical framework for tracing systems and agency in niche innovation pathways

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ABSTRACT

We present a practice-oriented analytical framework that supports the generation of actionable knowledge for practice and policy actors to facilitate sustainable niche innovations to emerge and mature. Originating from an applied research context, the framework combines and operationalises existing transition-related concepts and frameworks to build on their respective strengths and make them more relevant for practice. The framework facilitates tracing the development pathways of niche innovations from *system-centred* and *agency-centred* perspectives to yield insights into both the complex dynamics of innovation processes and the options for actions by different actors. We apply the framework to three cases of innovative coupled infrastructures in Germany and reflect on the extent to which these gauged actionable knowledge. Far from being a silver bullet to realising transformative change, making theoretical frameworks applicable to practice, and applying them in collaborative ways is nevertheless an important step when aiming to generate actionable knowledge for sustainability transitions.

1. Introduction

Sustainability transitions research aims at both, understanding and supporting sustainability transitions. First, sustainability transitions research aims at understanding the patterns and dynamics of transitions to sustainability - i.e., the radical, non-linear, and systemic changes that are needed to shift existing unsustainable systems towards sustainable ones (Grin et al. 2010). A focus is on the emergence and development of innovative solutions, which provide new ways of doing, thinking, and organising (Hildén et al. 2017; Kivimaa et al. 2017; Raven et al. 2016a). To contribute to sustainability transitions, such innovative solutions must challenge, alter, and often replace (parts of) the established socio-technical regime (Loorbach et al. 2020). This leads to complex dynamics, not least because regimes inevitably resist radical change, but also because innovations tend to reproduce existing regimes or can have adverse

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consequences (Pel 2021). To the end of understanding such transition dynamics, sustainability transitions research offers a repertoire of concepts and frameworks to identify underlying patterns, driving forces and the role of agency in such systemic change process, where individually, existing frameworks tend to take either a system-centred or agency-centred perspective (e.g., Geels et al. 2018; Köhler et al. 2019; Levidow and Upham 2017; Upham et al. 2018; Zolfagharian et al. 2019).

Second, considering the urgency of contemporary persistent problems, sustainability transitions research aims to support or contribute to shaping transition dynamics towards sustainability (Zolfagharian et al. 2019; Loorbach et al. 2017; Köhler et al. 2019). This comes along with an increasing uptake of transition concepts in policy circles boosting sustainability transitions research in an applied and knowledge co-production context (e.g., Hebinck et al. 2022; Kemp & Rotmans 2009; Turnheim et al. 2020; Voβ et al. 2009). As thus, sustainability transitions research engages in ongoing debates about how research can yield “both intellectual scientific contributions and radical real-world changes in behaviours, values, institutions etc.” (Hölscher et al. 2021: 4).

We focus on the combination of both aims, i.e. to the end of shaping transition dynamics, transition frameworks and concepts also need to be of practical use, and yield knowledge which is alternatively referred to as action-oriented, practical, solution-oriented, usable, or actionable knowledge (cf. Caniglia et al. 2020). Such knowledge in the context of persistent sustainability problems is the knowledge “that supports actors’ understanding of how to create transformative change towards sustainability” related to the design, agency, and realisation of their actions (ibid.). For some authors, this implies a perception of action and knowledge as being co-constitutive, where knowledge is co-produced through action-oriented, transdisciplinary, or other kinds of transformative research approaches (Frantzeskaki and Rok 2018; Popa et al. 2015; Greenwood and Levin 2007). For others, actionable knowledge can also be generated separate from action (Mach et al. 2020), which holds true for most research in which those for whom the knowledge is intended are only marginally involved (Kirchhoff et al. 2013). Thus, actionable knowledge, which supports practice actors in acting upon sustainability transitions dynamics can be produced through different kinds of research approaches with different degrees of science-policy-society interaction: knowledge-first and process-oriented ones (Miller 2013). However, the extent to which frameworks allow to generate actionable knowledge on sustainability transitions depends on (a) whether and how they allow one to understand the complexity of transition dynamics and the options for action, and (b) whether and how policy or practice actors are involved in the research process.

Faced with the challenge of producing actionable knowledge in an applied research context - i.e. a research project funded by the German Environment Agency (UBA) to mobilise innovative coupled infrastructure solutions for achieving sustainability transitions - the question arose: *What does an analytical framework look like that provides insights into systemic contexts of societal challenges as well as options to act within those (i.e. actionable knowledge)?* Answering this question, this paper works from the premise that the generation of actionable knowledge, whether through a knowledge-first or process-oriented knowledge approach, can be supported through connecting system-centred and agency-centred perspectives into a single analytical framework that enables policy and practice actors understand both the complexity of innovation processes as well as the options for action they have at hand.

In this paper, we present the analytical framework we have developed to respond to our question and illustrate how we have used it to generate actionable knowledge for, and with practice and policy actors at national, regional, and local levels involved in the development of innovative coupled infrastructure solutions. In the remainder of this paper, we present our analytical framework to analyse the development pathways of niche innovations (Section 2). To illustrate its application, we introduce three cases of coupled infrastructure innovations in Germany from our applied research context (Section 3), outline resulting insights (Section 4) and discuss the extent to which it served to generate actionable knowledge in terms of policy and practice recommendations through knowledge-

Steps	**Step 0: System definition and description**	**Step 1: Identifying critical development moments**	**Step 2: Identifying system factors**	**Step 3: Identifying actors and activities**	**Step 4: Assessing contribution to sustainability transitions**
Questions	**System boundaries** *What are geographical, functional and temporal system boundaries for the niche innovation?* **System elements** *What innovation is being developed (niche)? What are dominant structures, cultures and practices (regime)? What are societal trends and developments (landscape)?*	**Critical development moments** *What were critical moments (key events, phases, steps etc.) in the development of the innovation? What were its effects?*	**System factors** *What factors supported or hindered the development moments?*	**Actors** *Which actors take up roles in the development moments?* **Activities** *By which activities did the actors mobilise or respond to the influencing factors?*	**Sustainability impact** *What is the impact of the innovation on (different dimensions of) sustainability?* **Transformative impact** *Which elements of the existing regime does the innovation question, alter or replace? Which does it reinforce?*
Insights	Baseline for development pathway analysis: what system is being looked at and what innovation is being developed	Overview of development pathway of the niche innovation until current state	Identification of system factors supporting or hindering each development moment	Identification of key actors and activities to respond to system factors	Assessment of sustainability impact and changes brought about in the regime

Fig. 1. Analytical framework: analysis steps, questions, and insights.

first and process-oriented research approaches (Section 5). We close with next steps for the generation and uptake of actionable knowledge for sustainability transitions (Section 6).

2. Development pathways of niche innovations: an analytical framework

The analytical framework we propose traces the development pathways of niche innovations from both system-centred and agency-centred perspectives in a - parallel and iterative - stepwise process to arrive at actionable knowledge for policy and practice. Like the Multi-Level Perspective (MLP), our focus on pathways employs 'process theory' as explanatory style and thus turns to narrative explanation to capture the complex interactions between innovation, agency and changing contexts, time, and events (Geels 2011; Garud and Gehmann 2012). There are different concepts for operationalising such a process perspective, for example innovation journeys (Van de Ven et al. 1999), Regional Transition Paths to Sustainability' (RTPS) (Strambach and Pflitsch 2020) or socio-technical transition paths (Geels and Schot 2007).

We have chosen to focus on the concept of 'pathways' as it has been developed by Leach et al. (2010) since this aids in making sense of patterns of change while harbouring an explicit action perspective that guides strategy development to respond to and proactively address context dynamics from a systemic perspective (see also Frantzeskaki et al. 2019). Along these lines, the adaptation of the pathways concept in climate science manifests the shift towards actionable and/or decision-making relevant knowledge (Beck and Mahony 2017). A development pathway, as we use the term, then describes the development of a niche innovation from the initial idea until the current state as a dynamic succession of key moments along the activities of involved actors. The framework consists of a series of - parallel and iterative - steps (Figure 1). Taken together, the steps of the framework provide a complementary and comprehensive understanding about where a niche innovation is currently at, which moments have brought it to that state and what factors, actors and activities have influenced the moments.

Taking such a process perspective as an overall frame allows combining frameworks and concepts developed by sustainability transition scholarship that provide different knowledge about how niche innovations develop (Table 1). As a "middle-range theory that conceptualizes overall dynamic patterns in socio-technical transitions" (Geels 2011), the MLP, for instance, it has been argued, needs to be enriched with other theories to understand the types of agency underlying such patterns (Levidow and Upham 2017). It is the complexity of the phenomenon under study that calls for making use of and combining a plurality of co-existing transition-related frameworks and concepts (cf. Caniglia et al. 2020; Mitchell 2002). Doing so, allows to mobilise their respective strengths (see 'Insights' in Fig. 1).

The proposed analytical framework combines frameworks and concepts within three analytical dimensions (Table 1): 1) The *pathways dimension* covers important moments in the development of a niche innovation, including timing and effects of the niche innovation development on sustainability transitions. 2) The *system dimension* pays attention to the systemic context within which the niche innovation takes place and helps identifying key drivers and barriers. 3) The *agency dimension* zooms in on the different types of actors taking up roles in the development pathways as well as their activities to respond to system influencing factors.

For each of the dimensions, there are different frameworks and concepts we could have built upon, and we have made certain choices here. Largely, these choices resulted from both analytical and conceptual considerations (e.g., taking up established frameworks and adding more recent explicitly complementary ones), and pragmatic considerations in the applied research context (e.g., the use of concepts and frameworks which have received less scholarly attention but are relevant for making actionable choices). We outline each step in detail below including more specific details on the choices made. Supplementary Material A contains the operational questions per analysis step.

2.1. Step 0: System definition and description

A preparatory step includes the definition and description of the socio-technical system within which the niche innovation is developed (Findeisen and Quade 1985). This serves to position the niche innovation within its context, such as describing its guiding

Table 1
Frameworks and concepts for understanding the development pathways of niche innovations.

Analytical dimensions	Frameworks and concepts	Results
Pathways	Critical turning points (Pel and Bauler 2015; Pel et al. 2017)	Identification of key development moments in development pathway of niche innovation
	Sustainability impact (Olfert et al. 2020; 2021a)	Assessment of sustainability impact
	Transformative impact (Avelino et al. 2019; Loorbach et al. 2020)	Assessment of changes in regime
System	Socio-technical system model (Rotmans and Loorbach 2009; van Raak 2016)	Definition of system boundaries and key system elements
	Multi-level Perspective (MLP) (Rip and Kemp 1998; Geels and Schot 2007; Geels et al. 2018)	Description of innovation (niche), dominant structures, cultures, and practices (regime) and societal meta-trends (landscape)
Agency	Multi-actor Perspective (MAP) (Avelino and Wittmayer 2016) and Multi-level Governance (MLG) (Hooghe and Marks 2003)	Identification of actors and associated roles within different societal sectors (community, market, government, third sector) at multiple governance levels (e.g., supranational, national, regional, local)
	Agency capacities (Hölscher 2019; 2020)	Analysis of actors' activities and identification of action opportunities

idea and the relation to dominant technologies, institutions, behaviours etc., and to provide a baseline for the further analytical steps in terms of how the niche innovation both influences and is influenced by the system.

To describe the system, firstly the geographical, functional, and temporal system boundaries are defined (van Raak 2016). Geographical system boundaries concern the geographic unit in which the niche innovation is taking place (e.g., a city, region). Functional system boundaries relate to the (sub-)sectors that the innovation addresses (e.g., water, mobility, energy). The temporal system boundaries span from the formulation of the idea for the niche innovation to its current state. We suggest conducting a system analysis for the idea-stage of the niche innovation to detail the then status-quo of the socio-technical system, and to contrast the sought for with the achieved changes in relation to the then existing regime. System boundaries remain dependent on the observer (ibid.) - they should be chosen to make for a meaningful analysis and such choice should be reflected upon.

Then, the system elements are described based on the MLP, because it allows to easily identify factors and their interactions at different levels influencing transition dynamics starting from the concept of the niche. The MLP views transitions as non-linear processes that result from the interplay of developments at three levels - niche, regime, and landscape - influencing change or resistance (Rip and Kemp 1998; Geels and Schot 2007). In this way, the MLP allows one to apprehend multiple factors and processes that link up with, reinforce and challenge each other over the course of transitions. Niches are 'protected spaces' where radical innovations (e.g., new technologies, lifestyles, business models) emerge and mature. Niche innovations articulate new guiding expectations or visions that deviate from and aim to change or even replace existing regimes. The socio-technical regime refers to generally accepted and applied structures (e.g., market structures, infrastructures, institutions), cultures (e.g., values, expectations) and practices (e.g., production routines, individual behaviour). The regime accounts for the dynamic stability of an existing socio-technical system. The exogeneous landscape describes broader societal trends, environmental influences, discourses, and institutional conditions outside the system (e.g., climate change, new social movements, demographic transition), which influence regime and niche.

2.2. Step 1: Identifying key development moments

After the baseline (in form of a system description) at the idea-stage of the niche innovation is set, the development of a niche innovation is reconstructed over time.

Turning to insights from process theory and process tracing (Pentland 1999, Langley 1999), we suggest to reconstruct a development pathway of a niche innovation by identifying and describing its key moments of development - e.g., key events, phases and steps - as well as their effects. This approach has been described by Pel et al. (2017) to develop an understanding of the emergence and development of comparable innovation phenomena (i.e., transformative socio-material innovation). Along these development moments, the analyst develops a narrative on the past, present and future of niche innovation development (cf. Garud and Gehman 2012) from the guiding idea to the present state.

True to the underlying process character of the pathways concept, reconstructing the development pathway provides a dynamic perspective on sequence, timing, and conjunctures of event chains, how and by whom these are shaped. Such a process perspective considers innovation as evolving phenomenon, adds a sense of time, timing, continuing effects of past influences and the longevity of change to the analysis of the system at specific points in time (cf. Kristof 2010) and the role of agency therein (Hölscher et al., 2020a). It allows one to discern mechanisms or specific phases of innovation development and puts attention onto origins and changes in the innovation processes.

2.3. Step 2: Identifying system factors influencing the development moments

For each development moment, the system factors that influence the moment are identified, including how and why they do so. System factors refer to conditions, dynamics and processes resonating the three MLP levels, which were defined in step 0. We distinguish between the following - together with policy and practice partners pragmatically conceived - categories of factors that can support or hinder the development of niche innovations:

- *Socio-cultural factors (e.g., user behaviours, expectations, political goals):* create or resist new demands (Frantzeskaki and de Haan 2009; Geels et al. 2018; Wilson et al. 2012).
- *Local technological factors (e.g., energy grids, open space, retrofitted buildings):* foster path-dependencies or lead to internal regime stress that open opportunities for change (Frantzeskaki and de Haan 2009; Geels 2002).
- *Institutional factors (e.g., organisational or market structures, networks):* standardise, align, or fragmentise strategic planning processes, collaboration, and funding streams (Geels 2002; Truffer et al. 2010; Markard 2011).
- *Incentives and regulations (e.g., laws, funding programmes, subsidies):* support or limit/prohibit niche innovations or regime practices (Markard 2011; Geels et al. 2018; Kern et al. 2017).
- *Societal meta-factors (e.g., climate change, discourses, technological development):* can only to a limited extent be influenced by the actors within the system but that influence change processes within the system (Frantzeskaki and de Haan 2009; Geels and Schot 2007; Markard 2011).

2.4. Step 3: Identifying actors and activities to mobilise or react to system factors

In a following step, for each development moment the activities by which actors mobilise or react to the system factors are identified. In this way, the agency underlying each development moment is scrutinised. To this end, we approach agency as the culturally and historically contingent capacity of actors “to interpret and morally evaluate their situation and to formulate projects and try to enact them” (Ortner 1995: 185) - both individually and collectively. Since we are specifically interested in how such embedded agency influences the development pathway of a niche innovation, we use the concept of roles as a vehicle for such agency (Callero 1994; Wittmayer et al. 2017). This allows us to operationalise agency through understanding which types of actors make use of which roles in developing, supporting or hindering niche innovations and which types of activities they engage in in doing so.

Firstly, the different types of actors and their roles in the development moments are identified by drawing on the multi-actor perspective (MAP) (Avelino and Wittmayer 2016) and the multi-level governance (MLG) framework (Hooghe and Marks 2003). The MAP has been developed to distinguish between individual (e.g., political decision-makers, citizens, entrepreneurs) and organisational actors (e.g., public offices, NGOs) from different societal sectors, namely government, market, community and third sector. It has been chosen because it explicitly was conceived to address the lacking precision of existing frameworks such as the MLP for “analysing the complex diversity of roles of different actors at different levels of aggregation” (Avelino and Wittmayer 2016: 644). In addition, the MLG discerns actors at different governance levels (e.g., national, supranational, regional), thus allowing to acknowledge the embedding and nestedness of actors within institutional structures across scales (Raven et al. 2012). This yields an overview of key actors at different scales of governance and the roles they take up in the development pathway.

In a next step, the type of activities by which these actors mobilise, respond to, and change the system factors within each development moment are analysed. We differentiate between transformative activities to experiment with and embed innovation and orchestrating activities to align and mediate between actors for innovation and embedding (Hölscher 2019; 2020a). This approach zooms in on those activities that have been identified by transition scholars as fostering niche innovation emergence and maturing (e.g., Berkhout et al. 2010, Bos & Brown 2012; Bulkeley et al. 2014; Felipe et al. 2016) and further informs understanding how agency is, and can be enacted for actionable knowledge:

- *Transformative activities* create innovations and diffuse and embed them in relation to dominant structures, cultures, and practices. They include activities for enabling novelty creation (e.g., experimenting with new practices, processes, providing protected and informal space, network creation); increasing the visibility of the novelty (e.g., mobilising support for change, creating forging alliances); and anchoring the novelty in the context (e.g., aligning institutional processes and short-term actions to long-term visions).
- *Orchestrating activities* serve to coordinate multi-actor processes across scales, sectors, and time to foster coherence and create synergies between strategies, activities, and resources. They include activities for strategic alignment (e.g.,defining a shared and integrative strategic direction); mediating across scales and sectors (e.g., brokering and integrating resources, creating formal and informal spaces for knowledge exchange); and creating opportunity contexts (e.g.,providing financial incentives, determining normative action mandates).

2.5. Step 4: Assessing the contribution to sustainability transitions

This step serves to critically reflect on the innovation as a potentially desirable solution that challenges the dominant regime: To what extent does the innovation (have the potential to) contribute to regime change and sustainability? What are the risks, uncertainties, and challenges, including higher technological and organisational costs and controversial social and economic consequences that the innovation bares (Raven et al. 2016a; Bulkeley et al. 2014)?

Firstly, the extent to which the niche innovation contributes to sustainability is assessed. Sustainability as the normative endpoint of desired transitions refers to a socially negotiated set of goals encompassing environmental integrity, social equity, human well-being, and economic feasibility now and in the future (O’Riordan 2009; Leach et al. 2010). Indicators or matrixes to assess sustainability should be chosen in relation to the focus of the research. Since our applied research focused on infrastructure development, we chose infrastructure-oriented sustainability criteria addressing issues of performance, resilience, resource efficiency as well as social and economic viability (Olfert et al. 2020; 2021a).

Secondly, the transformative impact of the niche innovation is assessed. Because transitions are defined as shifts from one regime to another (Geels 2011), transformative impact refers to the extent to which a niche innovation challenges, alters, or replaces (elements of) the dominant regime, including existing institutions, technologies, and behaviours (Loorbach et al. 2020; Avelino et al. 2019). Since transformative impact will only be visible over the long-term, reflections might rather focus on the potential for such impact (McFarland and Wittmayer 2018).

It is important to critically reflect on possible (reasons for) limitations of sustainability impacts and transformative impacts resulting from change dynamics in the development pathway. For example, adaptations of the guiding vision in the planning and implementation process can lead to an increased or a reduced sustainability contribution.

3. Method

In this section, we outline our applied research context and approach (Section 3.1), our case studies to illustrate the use and insights of the analytical framework (Section 3.2) and how we have collected and analysed data for doing so (Section 3.3).

3.1. Research context and approach

The analytical framework presented and illustrated here was developed and used in an applied research context on innovative coupled infrastructures - the TRAFIS project[1]. Running from 2016 to 2019, TRAFIS was funded by the German Environment Agency (UBA) with the aim to generate actionable knowledge for national policy-making, in particular for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)[2], and for infrastructure planning practice more locally in order to mobilise innovative coupled infrastructure solutions for achieving sustainability transitions. Coupled infrastructures have been put forth in policy-oriented debates to increase resource efficiency, resilience, and 'smart' development. By combining service provision across multiple sectors (e.g., between water and energy supply, transport, and energy storage), coupled infrastructures can leverage synergies of resource flows, technologies, institutions, and financing between different infrastructure domains that have traditionally been managed separately (Monstadt and Coutard 2019). We define infrastructures as coupled when an exchange relationship is established between any infrastructure sector or their sub-sectors: e.g., when excess wind power is being used to produce synthetic hydrogen, when a waste water treatment plant provides energy in Demand-Side Management to help stabilising power grids, or when digital solutions enable inter-modality between different transport means (Olfert et al. 2020).

The TRAFIS project was organised along four sub-objectives, each with a dedicated set of (research) approaches, concepts, and methods. This included a) defining and clustering coupled infrastructures to describe potentials and risks for sustainability (Olfert et al. 2020), b) identifying influencing factors and intervention opportunities in the development pathways of innovative coupled infrastructures (Hölscher and Wittmayer 2018; Hölscher et al., 2020a), c) applying action research methods to support on-going innovation processes on local and regional levels (Hirschnitz-Garbers et al. 2020a) and d) integrating and transferring results for research, policy, practice and education (Olfert et al. 2021b, Hirschnitz-Garbers et al. 2020b). Elsewhere, we present a more comprehensive overview of the project objectives, approach, and results (Hölscher et al., 2021).

The analytical framework presented here was developed as part of sub-objective b), but includes the sustainability assessment matrix developed under a) and was also used in action-oriented research under c). As thus, our primary research approach was a knowledge-first approach with researchers generating knowledge subsequently discussed with policy and practice actors (see Section 3.3). The application of the framework in action-oriented research processes under sub-objective c) included using the framework to structure discussions with local actors in the on-going development of innovative coupled infrastructures to allow for their understanding of transition dynamics and options for actions to emerge (Hirschnitz-Garbers et al. 2020a).

3.2. Case selection

In the context of this overall research project, nine cases were selected to study the development pathways of innovative coupled infrastructure solutions. These were selected for their potential to contribute to sustainability, and for harbouring a technological or organisational innovation, for either being largely completed or discontinued, and for relating to the sectors energy, mobility, water, and ICT. For this article, we have chosen three of these cases of innovative coupled infrastructure solutions at local and regional levels in Germany: a wastewater heat utilisation, a solar village, and a Virtual Power System (VPS) (see Table 2 for details). These cases serve to illustrate the application of the framework and have been chosen for being diverse in terms of sectors covered, their status of implementation and the kind of actors involved.

3.3. Data collection and analysis

Data collection and analysis took place between November 2016 and June 2017 and relied on two types of data: grey literature and interviews. In a first step, publicly available grey literature on the cases were compiled including newspaper articles, press releases and policy documents. This literature was reviewed and coded using the operationalised questions of our analytical framework (see Supplementary Material A) as guidance. After the coding a first sketch of the development pathway of the coupled infrastructure innovation was drawn up. This allowed both, to identify knowledge gaps, and possible interviewees to address those gaps.

Subsequently, we conducted semi-structured interviews with actors involved in the development and implementation of the coupled infrastructure solutions. The interviews were done via phone and included questions concerning a) the coupled infrastructure, b) the development pathway and key development moments; c) the contribution of the coupled infrastructure and d) the future of the coupled infrastructure. Each interview was recorded and an interview summary including relevant direct quotes was prepared. A total of six interviews involving seven interviewees were conducted for the three cases. This interview data was also systematically analysed using the operationalised questions of our analytical framework (see Supplementary Material A). Using this data, the development pathways for the coupled infrastructure innovations were complemented, and a more extensive case report prepared using the same template which allowed for better comparability of the results.

In addition, the analytical framework and preliminary case analysis results were presented, discussed and validated through regular meetings of the research consortium and representatives from UBA and BMU as well as an external advisory board of researchers from different disciplines (e.g., spatial planning, engineering, transformation research) and practitioners from specialist associations. Over the course of three years, five of such meetings took place. These meetings, as moments of knowledge co-production, served shared sense making and a validation of the emerging analytical framework as well as the analysis of the cases - including those

[1] The acronym 'TRAFIS' stands for "Transformations towards resource-conserving and climate-resilient coupled infrastructures".

[2] At the time of the TRAFIS project, the responsible Ministry was called Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), at the time of writing, it is referred to as Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).

Table 2
Case studies of innovative coupled infrastructure solutions.

Case study	Guiding idea	What is coupled	Location	Time	Status of implementation	Key actors
Sewage heat Waiblingen: Sewage water heat utilisation through district heating grid	Alternative heat generation through sewage heat	Sewage treatment (+gas generation) + heat generation/ distribution	City of Waiblingen (Baden-Württemberg)	Project concept and installation: 1983 (since 1984 under operation) Modernisation: 2004-2006	Under operation since 1984, today modernisation need	Public utilities (Stadtwerke Waiblingen); city council
Solar village Norderstedt: Renewable energy production and electric mobility in city district	Alternative energy generation (PV and wind) and energy storage (electric mobility)	Energy generation + energy storage + mobility	District in city of Norderstedt (Schleswig-Holstein)	Stepwise implementation since 2012, partially implemented by late 2017	At the end of the research (2017): residents moved into houses that mostly have PV and storage, but the smart-grid was not implemented, only one e-car	Estate company (Schilling Immobilien); buildings department; homeowners
VPS Allgäu: Virtual power system	Energy storage and distribution via smart grids	Energy generation + energy storage + ICT	Kempten and Allgäu region	Research programme 2008-2012: pilot study from autumn 2009 to end 2011, then evaluation	The virtual power system was deactivated after the pilot study on January 1 2012	Energy company (Allgäuer Überlandwerk GmbH), consulting (B. A.U.M. Consulting Group GmbH); tourism organisation (Allgäu GmbH)

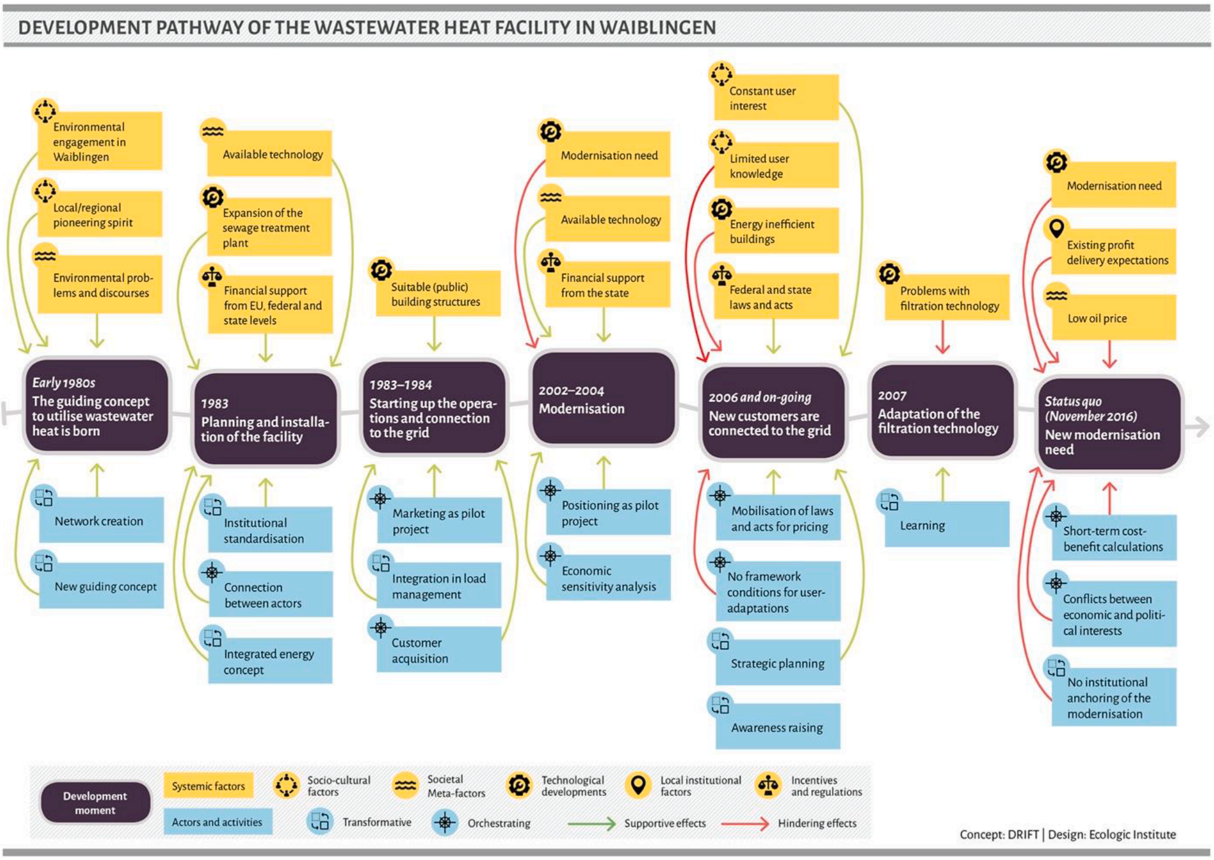

Fig. 2. Development pathway of the sewage heat utilisation facility in Waiblingen.

presented here.

4. Results: understanding development pathways of innovative coupled infrastructure solutions

By applying the framework to understand the development pathways of innovative coupled infrastructure solutions, we obtained four types of insights based on the different analytical steps: (1) key development moments and the present state of the innovative coupled infrastructure solution, (2) system factors that support or hinder each development moment, (3) activities by different actors who aim to overcome hindering or mobilise supporting factors, and (4) the contribution to sustainability transitions. Figs. 2-4 visualise the three development pathways, Supplementary Material B includes the full overview tables of the development pathways for each case, Supplementary Material C includes a comparison across cases.

4.1. Key development moments

As shown in Figs. 2-4, the development pathways of our case studies span different timeframes. The development pathway of the sewage water heat facility in Waiblingen provides a long-term perspective on the facility's operation (since 1983), including a development moment to address the need for modernisations. In contrast, the VPS in Allgäu has been implemented as a pilot study within a European research programme and spans the years from 2009-2011. After the study was concluded, the VPS was shut down and the last development moment concerns evaluation and knowledge transfer. The development pathway of the solar village in Norderstedt shows how an innovative project can become 'stuck' and requires going back to previous development moments. Due to conflicts and financing challenges, the initial guiding idea and concept had to be revised. The revised concept of a 'goodnest solar village' also faced conflicts between the leading real estate developers, homeowners and the building department of the city of Norderstedt, prolonging the implementation.

Despite this diversity, the development pathways show similar development moments. All pathways start with the *development of a guiding idea* that defines the goals for the innovation and gives an important impulse for its development. Subsequently, all development pathways include the *development of an implementation concept*, including feasibility analyses, mobilising resources, obtaining permissions (e.g., building permits) and establishing actor networks. As shown in Norderstedt, this phase can become challenging if there are conflicts of interests and technological, financial, and regulatory hurdles. All case studies include an *installation and start-up* moment for the building of the physical structures, including the mobilisation and connection of users. In Waiblingen, it also included laying ground for the longer-term operation of the facility by institutionally embedding the interfaces between wastewater treatment and heat generation within the public energy utility and the drainage agency - the latter operates the sewage treatment plant.

Other development moments were specific to a case, especially those concerning installation and start-up. *Technical adaptations* in form of modernisation were undertaken in Waiblingen, resonating the long lifetime of the sewage treatment plant. At present, the facility faces an uncertain future: it has become out-dated and, while still in use, the heat pump does not work efficiently anymore,

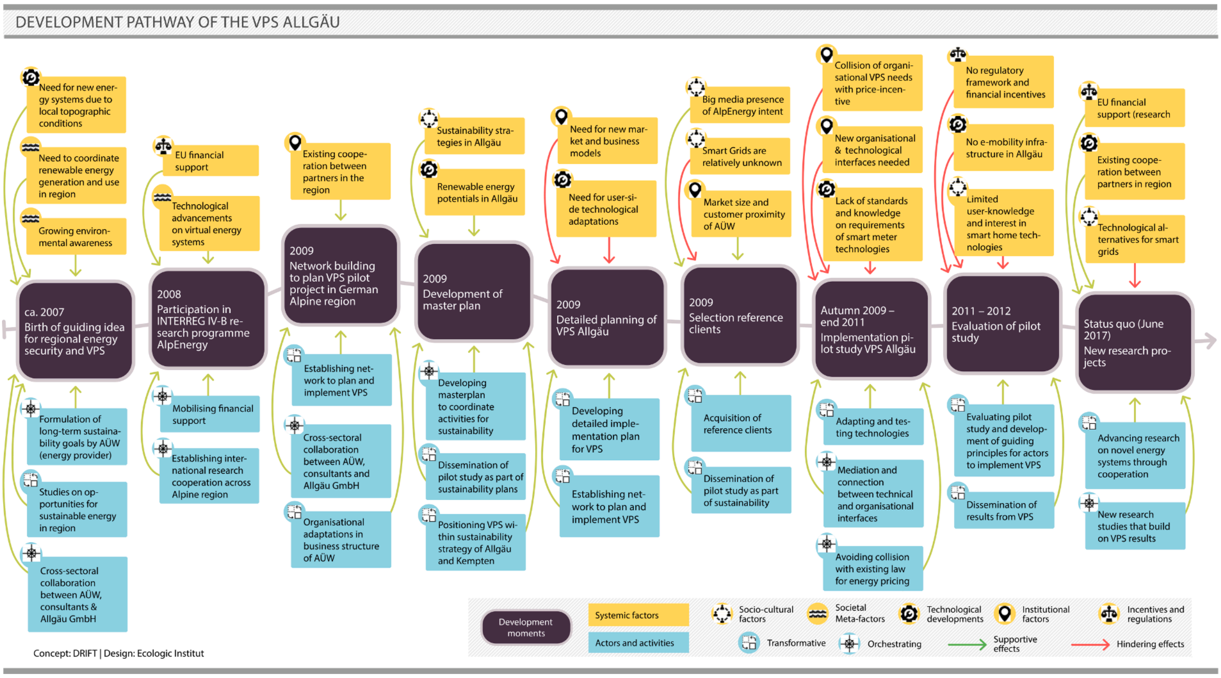

Fig. 3. Development pathway of the solar village in Norderstedt.

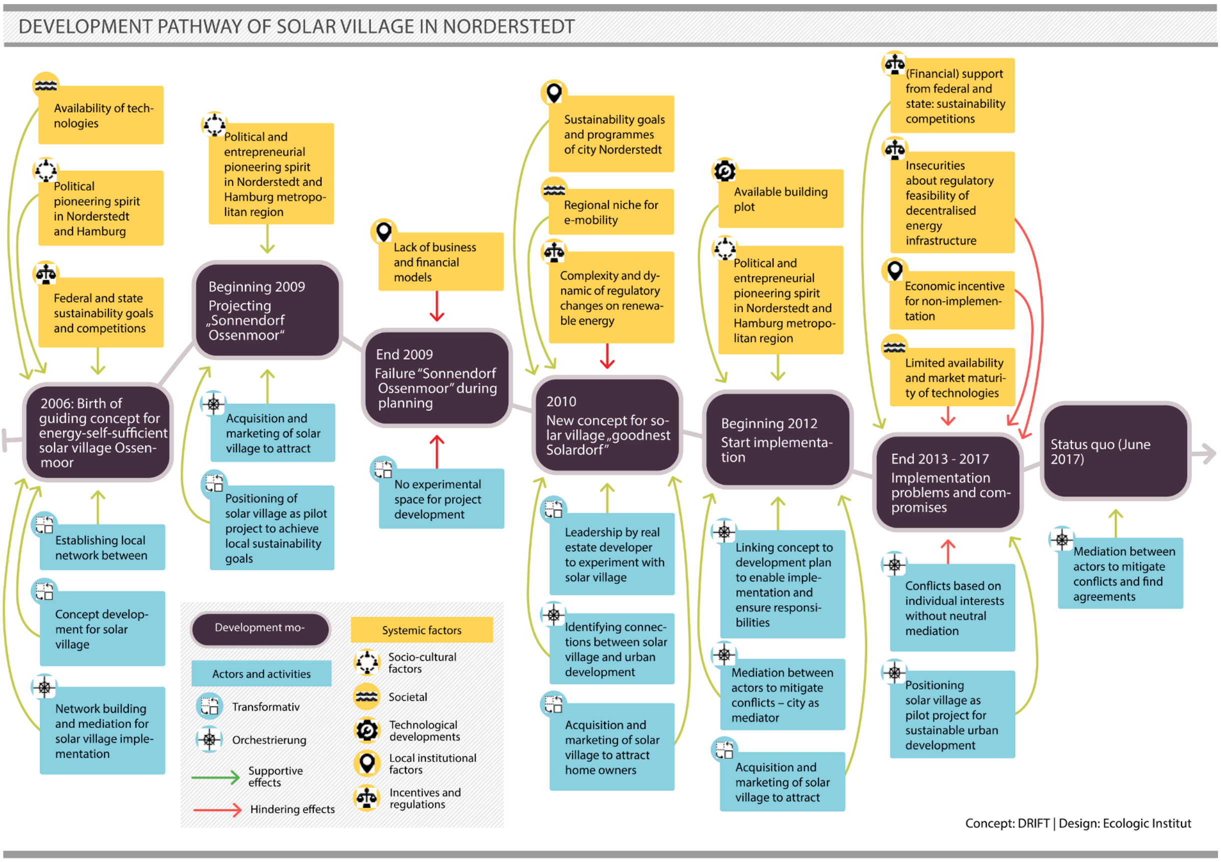

Fig. 4. Development pathway of the VPS Allgäu.

resulting in a comparatively low reduction of CO_2-emissions. Moments for *scaling and replicating* include the implementation of the coupled infrastructure solution in other contexts or increasing the number of users. Over the development pathway of the facility in Waiblingen, an increasing amount of - largely public - customers were connected to the district heating grid. Even though the VPS Allgäu is not operating anymore, the development pathway includes moments for *knowledge transfer* to the process and disseminate knowledge from the experience with the pilot study.

4.2. System factors that support or hinder development moments

For each development moment, we identified and described the supporting and hindering factors. This revealed opportunities and challenges at specific moments in time and how they influence the development pathway and its contribution to sustainability transitions in the long-term.

Socio-cultural factors and *societal meta-factors* were particularly relevant at the beginning of all development pathways. They created opportunity contexts for the guiding concepts to emerge and for mobilising political and societal support and financial resources. Across cases, new political and societal discourses on environmental and sustainability problems, and the connection of the innovations to local political leadership and sustainability strategies supported the search for alternative infrastructures. The results of the pilot study on the VPS Allgäu show that the high complexity for using smart home technologies limited their applicability and caused operating errors. In addition, customers reacted to price signals (energy is cheaper when abundant) rather than information (better use energy when abundant). Broader technological developments on wastewater heat utilisation, virtual grids, e-mobility and decentral energy provision enabled the actors involved in the respective cases in the drafting of the implementation concept.

Local technological factors influenced the technical feasibility of installing, operating, and modernising the coupled infrastructure solutions. Local physical and technical potentials can enable the piggybacking of innovation to local developments, but can also exclude options and reduce efficiency of service provision. In Waiblingen, the availability of technically suited buildings (e.g., closeness to the sewage treatment plant) and the district heating grid ensured that the facility could provide heat efficiently. Conversely, the lack of required infrastructure did not allow to connect the VPS Allgäu to e-mobility as initially planned.

Incentives and regulations from European, federal, and state levels influenced the economic and institutional feasibility of the coupled infrastructure innovations. Funding programmes for investments or research contributed subsidies and loans. They also supported the modernisation in Waiblingen and knowledge transfer of the VPS Allgäu. Regulations set investment incentives and enabled profitable marketing. Since the 2000s, several federal and state regulations support wastewater heat and renewable energies (e.g., federal and state renewable heat laws, building laws, energy saving regulations) by improving their economic profitability for both users and operators over the long-term. However, the uncertain future of the German renewable energy law caused planning and financial insecurities for investing in and marketing decentral renewable energy in Norderstedt and Allgäu.

Institutional factors influenced the opportunities for collaboration between multiple actors. Organisational interfaces facilitate knowledge and resource exchange and the mediation of interests. In Waiblingen, the disintegration between the public energy utility and the drainage agency required institutional embedding of interfaces for combined wastewater treatment and heat generation. In Norderstedt, interest conflicts between homeowners, the real estate company (project developer) and the local building department hindered further development. One key outcome of the VPS Allgäu is the long-term cooperation between partners in the region on new renewable energy projects.

Table 3
Actors and roles in the development pathways of innovative coupled infrastructure solutions.

Roles	Actors (Sector)	Sewage heat facility Waiblingen	Solar village Norderstedt	VPS Allgäu
Planning, installation, and operation	*Government*	***Public utility Waiblingen (local):*** installing and operating of facility ***Public drainage agency Waiblingen (local):*** owning and operating the sewage treatment plant ***Sewage treatment plant Waiblingen (local):*** providing location of the implementation and operating the solution	***Building department Norderstedt (local):*** supporting local sustainability strategies and solar village as pilot project ***Public utility Norderstedt (local):*** operating thermal power station, neighbourhood management for electricity and heat	***Regional advisory board (regional):*** advising and supporting VPS
	Market	***EnBW Energy Solutions Stuttgart (regional-global):*** planning, construction management ***Technical companies (e.g., Combitherm GmbH Fellbach, national):*** supplying technology (e.g., Combitherm: heat pump)	***Real estate developer Schilling Immobilien (local-national):*** leading and developing project ***Engineering office EST Volker Stracker (local-national):*** technical planning - but relieved later	***Regional energy utility Allgäuer Überlandwerk GmbH (AÜW) (regional):*** initiating, developing, and managing of VPS ***B.A.U.M. Consulting Group GmbH (national):*** initiating, financial and organisational management, documentation of VPS ***Allgäu GmbH (regional):*** support of VPS
	Community		***Homeowners (local):*** consuming and installing PV and storage units in individual houses	
Financial support	*Government*	***State Ministry of Economics Baden-Württemberg (regional/state):*** financing programmes, regulation ***Federal Ministry for Research and Technology (national):*** financing programmes ***European Union (European):*** financing programmes, sustainability strategies		***INTERREG NEW (European):*** financing programme, coordination of project partners ***European Fond for regional development (European):*** financing programme Alpine Spaces
Regulating and strategic agenda setting	*Government*	***City council Waiblingen (local):*** (positioning of facility within) local sustainability strategies	***State Ministry for energy transition, agriculture, environment, nature, and digitalisation (regional/state):*** ensuring legitimacy of innovation (private grids) ***Federal Network Agency (national):*** ensuring legitimacy of innovation (private grids)	***Federal Ministry for Environment, Nature Conservation and Nuclear Safety (national):*** regulating (e.g., renewable energy law)
Research and knowledge transfer	*Market*			***Energy4U (national); EVB Energy Solutions (national); Joonior (national); Siemens (national); Lackmann (national):*** supplying technical knowledge
	Third sector			***RWTH Aachen (national); Fachhochschule Osnabrück (national); Hochschule Kempten (national):*** supplying technical knowledge
Using services	*Government*	***Customers (e.g.,hospital, city hall, art gallery) (local):*** consuming heat		
	Community		***Homeowners (local):*** consuming energy	***Reference clients (local):*** testing VPS

4.3. Actors and activities to address influencing factors

The framework allowed us to identify the different actors involved in the development pathways of innovative coupled infrastructure solutions, including their role(s) (Table 3), as well as the activities by which actors address the influencing factors per development moment (Figs. 2-4).

Different types of actors were responsible for and involved in the planning, installation, and operation of the coupled infrastructure solutions. The analysis shows that governmental actors clearly take up key roles in all case studies, including the planning, installation, and operation, as well as setting legal and financial framework conditions. The public utility Waiblingen planned and implemented the wastewater heat facility and until now manages its operations including maintenance and acquisition. Market actors can also take leading roles in the planning and operation, and they support particularly research and knowledge transfer. Market actors initiated and implemented the solar village in Norderstedt and the VPS Allgäu - a real estate developer (Schilling Immobilien) and regional energy utility (Regional energy utility Allgäuer Überlandwerk GmbH (AÜW)), respectively. Being implemented as part of a European research project, the VPS Allgäu included the extensive involvement of research institutes in developing the technologies and conducting and evaluating the pilot study. Community actors used limited roles in all case studies, apart from being users of the services. Only in Norderstedt, community actors were involved as homeowners in the development of the solar village, installing the PV and energy storage units in their houses and using the energy.

The analysis of activities shows *how* actors have shaped each development moment and addressed the influencing factors. *Transformative activities* included the development of the guiding idea and planning concept of the innovations. In all case studies, the initiating actors created space for an innovative solution to emerge by mobilising political and social interest, networks, expertise, and financial resources. In Waiblingen, the city council formulated the guiding concept for the utilisation of wastewater heat and created a network with key actors (e.g., sewage treatment plant operators) and with the public utility as central actor for its further elaboration. The VPS Allgäu was driven by the interest of the regional energy utility AÜW in decentral and regional solutions for renewable energy generation and the pro-active engagement in research projects. The wastewater heat facility in Waiblingen and the VPS Allgäu were also more widely marketed as innovative pilot projects to increase political and societal support, acquire new users and facilitate replication. The VPS Allgäu pilot study was comprehensively evaluated and guiding principles were formulated to support future implementations of similar systems. The public utility Waiblingen informed about the benefits of wastewater heat utilisation to mobilise user interest. Additionally, the facility's long-term operation was embedded in institutional and organisational interfaces between the public energy utility and the drainage agency (e.g., selling sewage gas to the public utility), the integration of wastewater heat in the city's load management and informal monitoring and learning processes to ensure the cooperation of key actors and facility the daily operations.

Orchestrating activities aligned the innovative coupled infrastructure solutions to long-term sustainability strategies and visions and facilitated collaboration and knowledge, interest, and resource mediation. The positioning of the infrastructure solutions as pilot projects within local, regional, and national sustainability strategies spurred the search for synergies between different goals and resources and generated political support. In Waiblingen, the positioning of the wastewater heat facility within the city's energy and climate goals and strategies and the participation in the European Energy Awards ensured long-term political support and interest in (financing) the modernisation of the facility. The VPS Allgäu is positioned within AÜW's long-term sustainability goals. The goals created strategic space for innovation, facilitated connections between innovations and supported knowledge feedback from innovation experiences. EU, federal and state governments are critical actors in the creation of opportunity contexts for innovation and collaboration by providing financial resources (e.g., funding programmes), regulations and mediating between actors. In Waiblingen, the city council brought the public utilities and the drainage agency together for the further elaboration of the guiding concept, which did not have interfaces before. However, in all case studies mismatches of regulations hamper innovation. In Norderstedt and Allgäu, the institutional embedding was hindered because of unclear regulations on renewable energy generation, storage, and distribution on national levels - impeding for example viable business models.

4.4. Contribution to sustainability transitions

A fourth type of insight concerns the contribution of the innovative coupled infrastructure solutions to sustainability transitions.

Since the innovative coupled infrastructure solutions were chosen in relation to their potential to support sustainability transitions, it was to be expected that they perform well along the *sustainability* criteria. All cases contribute to resource efficiency and climate mitigation through sustainable energy generation and strengthening decentral energy generation and security of supply. Therefore, their performance in terms of social viability and equity is relevant to highlight. Here, the solar village in Norderstedt required high investment capitals of the homeowners while long-term cost-covering energy provision might not be given due to feed-in to local energy grid. The VPS Allgäu has proven to be financially unviable because the price guarantee of the renewable energy law did not allow for a flexible pricing model to offer cheaper energy during peaks.

The *transformative impact* of all solutions lies in the alternative modes of energy generation, shifting from fossil fuel-based energy to renewables and challenging existing user behaviours and market structures. The innovations contributed to changing technologies (e.g., district heating grid, smart home/PV installations), organisational structures (e.g., connection between sewage treatment and energy provision in Waiblingen), partnerships and collaborations (e.g., between energy and tourism in Allgäu), knowledge (e.g., about technical options, institutional opportunities and barriers) and user behaviours (e.g., not using energy in peak hours in virtual grid). Waiblingen and Norderstedt embody primarily technical innovations, and users do not have to extensively change existing behaviours. The long-term view on the wastewater heat facility in Waiblingen reveals how the facility perpetuated existing and created new path-dependencies by adding new technological structures without fundamentally questioning existing ones (such as of the sewage treatment plant itself). The VPS Allgäu sought to strengthen already existing alternative sustainable energy generation by improving security of sustainable energy supply, including changing energy use (at peaks). The transformative impact is limited because many technical components (e.g., smart meters) were not sufficiently mature and the business model to provide price signals to users at peaks was unviable.

5. Discussion

We presented and illustrated an analytical framework to support the generation of actionable knowledge about how to intervene in complex systems, namely by developing and embedding niche innovations. There are different ways in which this framework can be used in actual research processes: in 'knowledge-first' and 'process-oriented' approaches (cf. Mach et al. 2020). We have worked with both approaches, involving policy and practice actors to different degrees.

We firstly discuss the kind of actionable knowledge developed by applying the framework in the knowledge-first approach that was presented in this paper (Section 5.1), and, secondly, how the framework can be applied to generate actionable knowledge through process-oriented approaches (Section 5.2).

5.1. *Actionable knowledge through knowledge-first research*

We initially developed and applied the framework largely separate from action, with the aim to support policy actors and practitioners in acting upon sustainability transitions dynamics through providing recommendations (cf. Mach et al. 2020). Our premise was that the presented framework was to offer an understanding of the complex dynamics of niche innovations by combining system-centred and agency-centred perspectives, and in this way support the formulation of action recommendations to help the innovations emerge and mature.

Our application to cases of innovative coupled infrastructures shows that, *taken together*, the steps of the framework provide a complementary and comprehensive understanding about the co-construction of niche innovations as dynamic, context-dependent, and historically contingent processes, including its trajectory to date, different (e.g., social, institutional, technical, economic) influencing factors, relevant actors and activities, and impacts in terms of contribution to sustainability transitions. First, tracing a development pathway until the status quo unveils the different steps and phases as well as multiple temporalities of innovation processes, including, for instance, the longer-term influence of factors such as path-dependent changes in practice and technologies or short-term factors of political decisions (Monstadt 2022). Second, the system-centred perspective shed light on the context in which innovative solutions developed including their driving forces and barriers and how the system is impacted (or not). Third, the agency-centred perspective added depth to the socio-political dimension of how innovations are developed and supported (e.g., Raven et al. 2016b; Ampe et al. 2021; Geels and Raven 2006), such as who takes up - or failed to and should take up - which roles in development pathways, and how actors have navigated their contexts, mobilised opportunities and struggled with challenges. Finally, the reflection on the contribution to sustainability transitions provided a critical lens to the analysis of niche innovations, a relatively understudied aspect (Geels et al. 2018; Luederitz et al. 2017). This analysis was crucial to unveal risks, trade-offs, uncertainties, and challenges, including higher technological and organisational costs and controversial social and economic consequences (Barton and Campion 2020; Larkin et al. 2019; Raven et al. 2016a), as well as what factors and decisions throughout the development pathways influenced this contribution.

In the TRAFIS project, we have translated these insights into action recommendations that detailed how specific actors (e.g. planners, regional regulators or political leaders) can intervene in and support development pathways (Hölscher et al. 2020a; Olfert et al. 2021b). Thus, the actionable knowledge is based on a comparative analysis of the development pathways of niche innovations and can help actors anticipate and act towards comparable developments, such as barriers to deal with, opportunities to seek out, or actors to collaborate with (cf. Mach et al. 2020). For example, combining the insights into archetypical development moments with insights into potential influencing factors and actors' activities allows to anticipate opportunities and challenges for specific development moments, anticipating changes to the contribution to sustainability transitions and necessary activities to address the influencing factors at specific moments in time.

While the insights and recommendations provided answers to questions that the involved stakeholders considered as intricate, the extent to which the recommendations are taken up remains unclear. Despite valuing the insights, the involved representatives of the UBA and BMU considered the recommendations as too complex and not specific or instrumental enough to inform their policy processes. The question of whether recommendations have a life beyond a report is a recurring one when aiming to generate actionable knowledge at the science-policy interface (cf. Kovacic and Benini 2022). Based on our experiences, we ascribe this to several challenges. Firstly, the case studies covered a whole range of different coupled infrastructure solutions (rather than zooming in on one type of solution in depth) with the aim to gain insights into the diversity of coupled infrastructures. That, however meant that the comparison necessarily led to more abstract and general recommendations. Secondly, the formulation of actionable recommendations that still reflect the complexity of sustainability transitions is a balancing act. In their work with the European Environment Agency (EEA), Turnheim et al. (2020) similarly noted that facilitating the uptake of sustainability transitions thinking in policy requires more synthetic research findings, which might affect conceptual rigour and nuance. This challenge, thirdly, hints at institutional hurdles faced within governmental departments when aiming to integrate and take up novel, and complex knowledge. In the TRAFIS project, there had been an opportunity to feed policy relevant findings into a cross-departmental government commission, yet this faded due to internal restructuring processes and loss of continuity in the project's BMU expert group. In general, the uptake of the recommendations could have benefitted from more 'communicative interaction' between the researchers and policy actors to facilitate shared sensemaking and social learning for joint commitment and understanding about the problems at hand and possible solutions (Fazey et al. 2018; van Poeck et al. 2018). In our case, the task for developing action recommendations was completed by the research team. Our workshops with representatives from UBA and BMU as well as the external advisory board of researchers and practitioners were rather used to validate and - to a more limited extent - translate or transfer our results.

5.2. Actionable knowledge through process-oriented research

In a later stage of the research project, we have also used the framework to support the ongoing development of specific innovative coupled infrastructure solutions through action-oriented research that considers action and knowledge as being co-constituted (cf. Mach et al. 2020; Caniglia et al. 2020). Here, the framework application sought to generate actionable knowledge by structuring discussions and reflections with local actors about the current state of their coupled infrastructure and pinpointing relevant developments (Hirschnitz-Garbers et al. 2020a; Hölscher et al. 2021).

In this application, the framework facilitated sketching out - both in hindsight and in foresight - factors that have affected or could affect positively or negatively the implementation of the coupled infrastructure solution. Furthermore, the local actors were able to identify relevant actors that have been instrumental in the past or could become so in the future. For example, actors involved in the development of a flexible powerhouse in Steinfurth were enabled to anticipate and prepare for key future milestones by identifying necessary actions such as applying to new emerging funding opportunities.

Meetings and workshops with local partners responsible for the coupled infrastructure in question (i.e. infrastructure planners from utilities, regional authority, municipality-owned building company) underpinned the co-design approach in the elaboration of support mechanisms and provided space for exchange and joint learning. Specifically, the framework facilitated intra-institutional discussions and learning. This bridged positions and visions of different actors and fostered joint understanding and reflexivity about potential effects of and options to advance the infrastructure solution. However, while the framework was suitable to stimulate reflection in the course of action-oriented research, it was still perceived as complex by the local actors and especially highly comprehensive. Most of the application has been through 'back office' analytical work by the researchers.

Collaborative research processes at the science-policy-society interface - like transdisciplinary and action research - pose various challenges to both researchers and research partners. High amounts of time as well as new skills, roles and ways of relating between actors are needed for facilitating and engaging in meaningful interaction that induces reflexivity and trust-building (Fazey et al. 2018; Bartels and Wittmayer 2018; Jahn et al. 2012). Our TRAFIS experiences show that everybody, including policy and local actors, needs to see clear (if different) benefits from participating in the research. The process of supporting local infrastructural developments was met with uncertainty by most research partners, our funders and local partners. This meant that we needed to invest a high amount of time in communicating and trust-building as well as adapting our research design to accommodate the interests of local partners (Hölscher et al., 2021). Similar to the generation of actionable knowledge through knowledge-first approaches, a final issue concerns the uptake of the knowledge. While co-production is said to enhance uptake by empowering and enhancing capabilities of actors (Jagannathan et al. 2020; Caniglia et al. 2020), the local actors we worked with faced institutional and financial hurldes that limited their abilities to step back and adapt their planned solution in view of new insights. One limitation resulted from our research design adaptation: since we foregrounded sound working relationships with practice partners to a more critical stance. This limited the extent to which the framework's application in the local cases gauged a more critical evaluation of the coupled infrastructure solution in terms of its normativity and desirability within a broader transformation context - which, in principle, is a key characteristic of transition research. Nonetheless, bringing diverse actors within an institution together in a space to reflect about past, present and future developments provided valuable input.

6. Conclusions

The framework is not a silver bullet to generate actionable knowledge that contributes to real-world changes towards sustainability transitions. While it offers many insights, the crux lies in the framework's application at the science-policy interface, which requires a balancing between 'opening up' and 'closing down' problem definitions and possible solutions (Stirling 2008). The intention of our framework was to first facilitate an 'opening up' appraisal true to the sustainability transitions research lens that embraces complexity, uncertainty and contested definitions and solutions that maintain a counter-hegemonic stance aiming for radical societal change (Hölscher et al. 2021). The insights generated by the framework's application - through different research approaches - were indeed able to expand and enrich the dialogue space around coupled infrastructures as niche innovations. However, the aim to provide actionable knowledge also requires 'closing down', which evokes a tension between, on the one hand, maintaining the view on complexity and, on the other, simplifying complexity to arrive at recommendations and insights upon which one can act. The latter risks loosing the transformative power of sustainability transitions thinking (Kovacic and Benini 2022).

We identify two central issues for the generation and uptake of actionable knowledge for sustainability transitions. Firstly, attention needs to be paid to the (long-term) relations between researchers and other actors in the science-policy interface to facilitate co-production and social learning based on trust (Bartels and Wittmayer 2018). In TRAFIS, trusting relations between the research team and involved policy and practice actors were essential to make our respective concepts, knowledge and needs understandable to each other. Also Turnheim et al. (2020) emphasise the need to sustain interactions between policy audiences and transition research communities over a longer period of time. However, the complexity of sustainability transitions conflicts with the tendency of policy institutions to seek certainty and deterministic solutions (Kovacic and Benini 2022). This, secondly, points to the underlying issue that taking up actionable knowledge for sustainability transitions would require policy institutions to acknowledge the limits of governability of the future and shift towards 'governance *in* complexity' that embraces reflexivity and pluralism (ibid.). In this context, we find that the value of our framework and its applications lies not necessarily in the real-world changes, but, more modestly, in opening up new questions and narratives about the complexity of niche innovaton processes.

It is only in actual research practice at the science-policy interface, that these two issues materialise and can be navigated. Their navigation in ways that allow relation-building, critical thinking and a systems perspective with and between actors is absolutely crucial when sustainability transitions research is to live up to its aims of both, understanding and supporting sustainability transitions.

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Declaration of Competing Interest

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

Data Availability

The data that has been used is confidential.

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Supplementary materials

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