Infrastructures and Transformation: Between Path Dependency and Opening-Up for Experimental Change

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Abstract Infrastructure development faces multiple challenges in the present. These are generated by digitalization, ecological orientation, transformation, and the emergence of a multipolar de-colonial world order. Under these conditions, infrastructure development faces the problem that, although designed for stability and continuity, it requires a new flexibility. To address these issues more precisely, this article first proposes a heuristic for studying infrastructures in times of transformation and tests it with two examples. In it, it is shown that the qualification of future infrastructure development lies in the characteristics of scalability, inclusivity, and updateability.

Keywords Transformation · Infrastructure · Socio-technical change · Energy transition · Structural change

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1 Infrastructures: New Challenges with Regard to Their Design

Infrastructures form the backbone of societies. Typically, specified functions such as mobility, nutrition, health, or even electricity supply are ensured in this way. Infrastructures are characterized by their normality, by their working in the background, as it were. In industrial modernity, with its expansion of positions of entitlement and thus the demands for the realization of the common good, the significance of infrastructures has taken on a completely different dimension. This is also reflected in a current definition of infrastructures, which are described as "networked plants and facilities that are geared to the provision, storage, and transformation of products for collective use (common good) and, as social inputs, determine the social, economic, and ecological conditions of life in a spatially specific manner" (Kropp and Sonnberger 2021: 189; translation the authors). Infrastructures are characterized by their stability, but at the same time, they are changed more or less imperceptibly. If, however, infrastructures are fundamentally technically rearmed and realigned, then a transformation space emerges in the process, in which it is quite obviously no longer only a matter of technical, but also of social and cultural changes. In the present, infrastructure development is receiving new attention due to developments that have brought the "vulnerability" or "criticality" of infrastructures into the spotlight.

To describe it with a short example, the flood disaster in North Rhine-Westphalia in the summer of 2021 clearly showed how dramatic the need for adaptation to climate change is, even in Central Europe. At the same time, it has highlighted the particular sensitivity of critical infrastructures (water and wastewater, transport, rescue and telecommunications, power supply, and telecommunications). The reconstruction of these infrastructures is of particular urgency. At the same time, however, this reconstruction also opens up the opportunity to create new, more flexible and adaptable infrastructures for the future and to turn away from old ones and systems. This catastrophe thus also offers an opportunity for renewal. As another example, following Russia's war in Ukraine, wholesale gas as well as electricity prices in Germany rose rapidly due to restrictions on Russian gas supplies. This affected many industrial companies as well as households and has put pressure on policymakers to find an immediate solution. One result was that Germany built terminals to use liquefied natural gas (LNG) to at least partially replace Russian gas. In addition, these terminals are planned to be adaptable and to supply liquid hydrogen in the future, which the German government calls "green readiness" (Bundesregierung 2023). However, for several reasons, retrofitting these existing terminals may be quite difficult, which is why these potential switches are best addressed in the context of their design and processes of being established (Schreiner et al. 2022).

These are only the first hints that the question of adaptability of infrastructures has to be seen as highly challenging. In any case, it cannot be a matter of reconstruction alone. The real task is to make infrastructures adaptable to future development demands at the time of their (re-)construction. This is also evident, albeit in a different way, with regard to transformation processes such as the one in the Rheinish mining area. Old infrastructures must be ex-novated, new ones built, and at the same time future development options must be anticipated and taken into account now, i.e., it has to be materially anchored in the infrastructure. This presents itself as a multi-layered problem. Infrastructures are typically a haven of stability and longevity. This is why they are typically constructed to provide services of general interest continuously and safely over a longer period of time. Moreover, infrastructures are associated with socio-technical path dependencies. The maintenance and stability of legacy infrastructures are largely due to generic principles of path dependency (David 2007) in different domains. Infrastructures are stabilized by "increasing returns" (Pierson 2000), which create incentives for policymakers, investors and planners, among others, to deepen a particular path and to make it even more costly to switch to another one. These developments are often supported by institutional designs that place advocates of a particular path in a privileged position, creating political resistance to any substantial change and making incremental change much more likely (Mahoney and Thelen 2010). Paths can also be understood as an artifact of (aggregated) behavioral patterns, such as daily routines or personal habits of using infrastructure in a certain way (Seto et al. 2016). These patterns are not reinforced by conscious rational choices, but by routines and institutionalization, which makes them difficult to change. These path dependencies can create very strong configurations that lead to technological, economic, political, and behavioral lock-ins, such as the carbon lock-in described by Seto et al. (2016), making it unlikely to switch to alternatives. Theoretically, the MLP approach describes such processes of innovation diffusion—and its difficulties. Technical developments are protected in a niche environment (e.g., subsidies) and enter the socio-technical regime when an window of opportunity emerges. The specific socio-technical regime and the overarching landscape are influencing, often blocking, the diffusion of new options. However, there might be changes by the transition of the innovative technology (Geels 2002; Geels and Schot 2007).

Research on infrastructures has experienced a renaissance in recent years (e.g., Larkin 2013; Howe et al. 2016; Pinzur 2021; Kropp 2023). While research in the 1980s focused mainly on the emergence and control of large technical systems (for many: Hughes 1993), the concept of infrastructure is now being further differentiated in very different subfields of social science research in order to investigate the specific dependencies and particular patterns of collective order formation (Barlösius 2019). Looking at infrastructures that way offers an insight in their multi-layered working unfolding not only the named function (e.g., mobility), but at the same time inscribing and stabilizing social injustice as well as developmental narratives, beside others (Larkin 2013). Through the classifications and determinations embedded in infrastructures (Bowker and Star 1999) and their independent dynamics, there are specific forms of infrastructural power performed. Bowker and Star (1999: 321) stated: "We need to recognize that all information systems are necessarily suffused with ethical and political values, modulated by local administrative procedures. These systems are active creators of categories in the world as well as simulators of existing categories." Infrastructures are not simply passive networks of artifacts, to the contrary, they are in action (Pinzur 2021). In this sense "(…) infrastructures were not only momentary subjects of contestation, but also ongoing means of exerting power through discretion over indispensable, everyday labor" (ebd.: 647; emphasis in Orig.) Notwithstanding this, the aspect of the dynamic change of infrastructures and their form typically remain in the background, even if this aspect is described by Paul Edwards with his idea of infrastructures as "posing a linked series of socio-technical problems (…)" (Edwards 2004: 209). Infrastructures are examined from the perspective of the articulation and solution of socio-technical problems. Following Edwards' considerations, the concept of socio-technical problems has been further specified (cf. Büscher et al. 2020). Important here are theoretical connections that allow to capture the diversity of processes of defining and dealing with socio-technical problems. In the abstract, socio-technical problems can be examined according to the aspects of "control despite complexity," "change despite stability," and "agency despite opacity" (Büscher et al. 2020: 13). It is these fundamental tensions that have always determined infrastructurization, and which can be examined very precisely in their form determining everyday practice from a practice-theoretical perspective (Shove and Trentmann 2019).

Currently, there are various overarching developments that challenge the maintenance and further development of infrastructures. These include the technological development of smartification (cf. Lösch and Schneider 2016), ecological integration (cf. Kropp 2023), transformation (cf. Cass et al. 2018) and, finally, the emergence of a multipolar de-colonial world order (cf. Larkin 2013). If one takes these developments together, then these changes reveal, on the one hand, an expansion of control possibilities through new socio-technical arrangements of infrastructures. On the other hand, entirely new forms of vulnerability are emerging. For example, the digitalization of infrastructures creates both new opportunities, such as the instant availability of information and data, and new risks, such as cybersecurity issues. Infrastructure development in such a present, which can be described as transformative, should continue to enable the stable provision of services for the common good, but the definition of the common good becomes more open, but even more and especially the previous conditions under which the operation and further development of infrastructures were assumed, change along with it and cannot simply continue to be assumed. This is shown, for example, by the many challenges for the design of future infrastructures in a "non-stationary age" (Chester and Allenby 2019), meaning that previous conditions of infrastructure design are no longer applicable to the status quo and beyond. For example, in civil engineering or urban planning, conventional weather data can no longer be used in the context of climate change, as weather extremes have already changed and are likely to become more severe in the future. Similarly, in the social sphere, the conditions for designing infrastructure have become more participatory and less hierarchical over time, creating space for different modes such as collaboration, negotiation, persuasion, compensation, etc. Finally, in the economic domain, massive productivity gains in the construction of infrastructure need to be gauged against the often highly increased complexity, and lifetime changes of systems and system components, affecting profitability of investments, adequately taken into account. In sum, these processes introduce new vulnerabilities, as they can slow down urgently needed steps to mitigate climate change, such as the construction of wind turbines or new transmission lines.

Therefore, it seems to be a reasonable claim to have a correspondingly adapted conceptually theoretically motivated investigation heuristic available against the background of the aforementioned development dynamics and the associated confusion of relations and ties in infrastructurization. In order to embark on this path, a greater sensitivity regarding different socio-technical forms of infrastructure development and their explanation appears relevant. To achieve this goal, two elements seem to us to be of particular importance. First, it is essential to identify the different elements that characterize such mentioned forms. For this purpose, we propose a search heuristic based on social-theoretical dimensions, but without understanding them as theory dimensions. Rather, they serve us as an exploration procedure. Second, we make a theoretical proposal that serves to disentangle the web of relevant references in each case. Therefore, for example, the observation of economy, which is of great importance for such processes of infrastructural change, does not appear on the level of the heuristic dimensions, but rather on this level of relevant factors for the formation of socio-technical ensembles. In doing so, the argumentation is enfolded in three steps. In the first step, such a heuristic is outlined, whereby we will as first sketch highlight especially five heuristical dimensions: factual dimension, social dimension, time dimension, spatial dimension, and environmental dimension. In doing so, we would like to emphasize that we do not reify these dimensions as a priori major categories but recognize here solely their heuristic value for sorting a confusing situation. The fruitfulness of such a heuristic, however, can then only become apparent in the concrete analysis, in which precisely the moments of hybridity and mutual constitution are of central importance. In addition, the innovation theory of Rammert (2010) will be used to point out that it is the individual or linked references to social fields (such as the economy, politics, civil society, art, etc.) that help to describe an innovation event and the specific valuations taking place (Sect. 2). Following this, two concise vignettes will be used to make the heuristic useful. On the one hand, the two vignettes deal with infrastructures in structural change; on the other hand, the energy transition through renewable energies and the accompanying requirements for the development of flexible infrastructures are discussed (Sect. 3). Finally, the following chapter will focus attention on the design of future infrastructure developments. Thus, the question is of how to rethink infrastructures for making them at the same time stable as well as flexible for the respective challenges. More focused: Can infrastructures, although being the epitome of societal stability through materiality, be reshaped in a way to be agile, inclusive and updateable—and, if so, how? (Sect. 4).

2 Development of a Heuristic

If one takes the dynamics of socio-technical problems and their processing as the central perspective in the maintenance and further development of infrastructures, then this is a decision in favor of a fundamentally experimental understanding of infrastructures. This is because the articulation of socio-technical problems and an innovative action triggered by them opens up scope for groping, testing, and stabilizing solutions. It is a perspective in which the ongoing balancing of technical and social innovations keeps infrastructures stable. Typically, technical and social innovations are treated as opposites. However, this is a problematic positing. This fact has recently been brought into focus, particularly through a social innovation perspective (see Howaldt et al. 2018). Based on a practice-theoretical reading of social innovations, these can be understood as "creative and purposeful changes in social practices, i.e., changes in the way we live, work, and consume, how we organize, and how we shape our political processes." (Howaldt and Schwarz 2010: 6; translation the authors). This has the advantage of actually capturing those innovations whose focus is very much on the establishment of new social practices. At the same time, however, it can equally be used to study the reconstruction of socio-technical practices, namely as the imitation of functionally specific patterns of action promising improvements and possessing technical qualities (e.g., Howaldt et al. 2018).

In the context of infrastructures, this interweaving of social and technical innovations takes on yet another significance. In fact, it can be argued that the special quality of infrastructures is precisely that they require a synchronicity of technical and social innovations. Otherwise, socio-technical problems cannot be transformed into socio-technical innovations. In order to further specify these considerations in the following, two argumentative steps will be taken. First, for the investigation heuristics of infrastructural development barriers, a sorting of relevant aspects according to the social-theoretical dimensions of factual, social, temporal, spatial, and ecological will be carried out (Sect. 2.1). Second, it is crucial not only to show such relations, but ultimately to be able to decipher the patterns of configuration. To this end, we argue on the basis of Rammert's (2010) theory of innovation, which presents a model of relations and references, that the specification of references (meaning always references to selected fields of society, such as economy, science or law) can make visible in which intricate relations infrastructure maintenance and development sometimes takes place (Sect. 2.2). Taken together, the confusing challenges of infrastructural change can be made visible in this way.

2.1 Relations of Infrastructural Change

When we speak here of relations of infrastructural change, we are referring, on the one hand, to the relations within the individual dimensions, which contain selected aspects of the socio-technical construction of infrastructures. The respective weighting of these aspects creates relations and thus makes specific qualities of infrastructures visible. On the other hand, this also refers to the relations between the dimensions, which are configured differently depending on the respective socio-technical development situations of the infrastructures studied.

Factual Dimension: Materiality, Functionality, Interconnectedness. Materiality is an anchor of stability (Latour 1991). Materiality points to a fundamental quality of sociality, even though sociality was for a long time designed precisely without the aspect of materiality (Appadurai 1986; Bennett 2010; Coole and Frost 2010). Once arrived at, however, multi-layered questions of relationality then arose. Does material agency represent itself as resistance alone? Can material agency be for itself? Pickering (1993) made this concept of material agency prominent as the "mangle of practice". Such material agency does not exist by itself, but only in its entanglement with human agency. His example of scientific experiments in particle physics traces a long historical process of mutually adapting scientific instruments and theories. A dynamic linkage of these forms of agency can be seen in the concept of "imbrication" (Leonardi 2011) or "interaction scenarios" (Schulz-Schaefer and Meister 2017), whereby prototype scenarios, in which designs of technical objects are brought into an interaction context with people, emphasize precisely the relevance of the material (cf. also: Ryghaug et al. 2018). Importantly, technology is not to be understood simply as an artifact, but rather as a product of social processes (Bijker and Law 1992) in which it is framed for specific functions. For a long time, it was assumed that technology had its own logic, which would lead to the fact that the formation of social order could also be explained by the formation of technology. Such a technological determinism has repeatedly imposed itself against the background of the insight into the overwhelming impact of technical artifacts and ensembles of the technical. At the same time, however, it falls short and is empirically and theoretically of little use. Rather, the development of technology already shows how strongly social conditions are not only inscribed as functions in technology, but also contribute to the stabilization of social conditions. This becomes particularly obvious when we look at socio-technical systems (e.g., Mayntz and Hughes 1988; Büscher et al. 2019). Here, too, it is true at first that due to the networked, complex, and large-scale technical configuration (interconnectedness), the moment of the factual appears on the front stage, but at the same time, a closer look reveals how strongly the formation of technology is directly interwoven with processes of collective order formation. This is also evident with regard to networking as another quality that is essential here. Networking refers to the character of the ensemble, which makes it clear that it is not the individual technologies, but rather their interplay in which infrastructures unfold. This applies in particular to the design of infrastructures as networked or smart infrastructures (e.g. Marcovich and Shinn 2020; Marres and Stark 2020; Lösch and Schneider 2016).

Social Dimension: Identity, Cooperation, Participation. Infrastructures have an institutional character. The functions of services of general interest relate to areas of action that are of outstanding importance for societies: Health, nutrition, mobility, and energy, as it were as basic infrastructure. Practices of everyday life take place in relation to infrastructures and influence them (Shove and Trentmann 2019). Three aspects seem to be of particular importance for a closer characterization. The aspect of identity allows us to break down the interconnected and mutually stabilized relations of actors, institutions, cultural classifications, and political economies (cf. Bernstein 2005). The concept of identity derives its importance and explosiveness from the fact that it is fundamentally positioned at the intersection of individual agency and politics (Hall 2000: 16). It is, as it were, a two-way process that establishes, on the one hand, what is considered a "we" and, on the other, positions this against a "you" (for an overview, see Wetherell 2010). The aspect of cooperation, on the other hand, emphasizes the interplay of actors in infrastructuring and thus in articulating as well as solving socio-technical problems. Infrastructuring in the present is much more dependent on cooperation than in the past; protests against infrastructure projects illustrate this: NIMBYism is the refusal of certain forms of cooperation (Schwenkenbacher 2017). At the same time, infrastructures open up new opportunities for cooperation, if one thinks of the very different digital platforms, for example (using the example of Citizen Science: Dickel and Franzen 2016). Finally, the aspect of participation refers to the legitimacy bases of projects of collective order formation (Lezaun et al. 2017). Participation plays a central role in many processes of infrastructurization (using the example of the energy transition: Chilvers et al. 2018). In the course of this, issues of knowledge, interests, and values are negotiated, and basic understandings for the collective development of infrastructures as the backbone of common good are formed. This is reflected, for example, in VDI Guideline 7001 "Communication and Public Participation in Planning and Construction of Infrastructure Projects," which identifies early participation as an essential element of successful infrastructure development.

Time Dimension: Past, Present, Future. The temporal dimension opens a triple view of past, present, and future. The dimension of the past is very present in infrastructures through the materiality of the built structure as well as the whole ensemble that is at stake here. It is the complex arrangement of various elements that as path dependency and legacy shapes and limits the space of future possibilities in the further development of infrastructures. It should not be forgotten that limitation is always necessary for the opening of experimental space. At the same time, however, in light of sustainable development, exnovation, the leaving behind of old paths, is a crucial prerequisite (cf. Kropp 2015; David and Gross 2019). However, there are a lot of examples showing, of how difficult such exnovations are. Thus, the aspect of permanence plays a decisive role. The dimension of the present is marked in particular by the aspect of urgency under which the maintenance and further development of infrastructures is negotiated. Quite different developments can build up such urgency here, be it in the form of external shocks (in the form of environmental disasters or wars), but also in the form of accidents and thus inherent development limits of infrastructures. Admittedly, the aspect of the future plays the biggest role. In the articulation and solution of socio-technical problems, visions, drafts, and scenarios play an essential role. In these, the future is visualized. With which "socio-technical visions" (Lösch et al. 2019) or "socio-technical imaginaries" (Jasanoff 2015) can and will the collective open up the future anew? Such images allow us to coordinate innovation processes of collective order despite their socio-technical complexity. Which futures are designed and which are marked as desirable? It is striking that many current practices aim at producing a multiplicity of designs, be it as scenarios in which very different futures are designed in contrasting ways in order to then pave ways into the future based on them. Or in the form of prototypes: While for a long time people were rather sparing with the formation of prototypes, i.e., the materialized design of futures, the present shows a development toward the multiplication of prototypes (Dickel 2019). With multiplicity, the space of possibilities is illuminated, but at the same time, through materiality, it is already more firmly foreshadowed than if it were just a thought, an idea (Schulz-Schaeffer and Meister 2017). This connection between cognitive and material formation is taken as a starting point in the concept of the "promise requirement cycle," according to which, in the expectation match between technological promises and social requirements, both are increasingly related to one another, materialized and stabilized (van Lente and Rip 1998).

Space Dimension: Density, Connectivity, Distance. In many cases, urban space acts as a catalyst for a system transition toward sustainability and can thus be seen as an exemplary case of spatial density. More important than the steadily growing proportion of an urban population is the role of cities as incubators and catalysts for changes in the socio-economic system (c.f. Jacobs 1970). It is primarily urban space that provides blueprints for new forms of production as well as social and cultural interaction, driving exchange between people, products, and information (Vojnovic 2014). At the same time, urban space provides "protected places" where different approaches to socio-technical change can be formulated and implemented, basically giving a space to diversity (Fincher and Iveson 2008). Incidentally, this density can also emerge in regional contexts (Späth and Rohracher 2010). Another aspect of infrastructural development can be seen with regard to connectivity. Regional developments are often intertwined with other spaces or regions of the world. And here, overlooking such interconnections qua connectivity can easily lead to false assessments with regard to the respective local socio-technical development situation. It is the teleconnections that significantly shape the spatial order, even if they are easily ignored (Seto et al. 2012). The aspect of distance has long been corresponded with the quality of the global because spatial distance meant a negligible development horizon. Exactly this circumstance is undermined by the talk of the Anthropocene, because here the earth is set level as the relevant development horizon. Already Giddens (1990) pointed out that modernity is characterized by space–time bridging, so this project seems to come to its conclusion in the present, which seems to be characterized, as it were, by an omission of distance.

Environmental Dimension: Co-Existence, Availability, Extinction. The notion of social relations of nature expresses a fundamentally relational perspective in understanding the ecological integration of society and the co-constitutive character of nature and society (current review: Hummel et al. 2023). Going further still, approaches from a post-humanist or neo-materialist perspective formulate an ontology in which non-human nature is ascribed agency (see, e.g., Haraway 2008; Latour 2017). Here, the insight into the co-existence of human and non-human living beings as well as nature as a whole resonates. This can be seen as the quasi-fundamental aspect in the environmental dimension, and deviations from it as a potentially serious problem of collectives. The decline of human collectives can often be seen in a destruction of the ecological niche on which they depended (Diamond 2005; Grober 2010). The reason for this is both complex and simple. Society cannot be thought of without the use of resources: materialization gives stability to social processes. To this end, societies establish functions that require the ongoing mobilization of resources. Infrastructures are the medium for this. Without the continuous utilization of resources, there is no provision of services. In the course of industrial modernity, the aspect of co-existence receded into the background due to the increasing and diverse functionalization of nature. The metabolism of society with nature was mechanized to the point where the limits of growth (Meadows et al. 1972) became visible. Crucial for the maintenance of infrastructures is the availability of resources necessary for this. The aspect of availability describes all those practices that raise, transform, and then purposefully use nature-environment in the form of resources for specific purposes. Renewability or non-renewability, renewable or non-renewable give here important classifications for the characterization of availability. In concepts of scarcity and criticality, moreover, the particular dependence of resources becomes thematic (e.g., MIT 2010). Finally, the aspect of extinction thematizes the extreme form of human intervention in the natural environment, in which other life is eradicated (see, e.g., Jetzkowitz 2023). In the Anthropocene, therefore, biodiversity is assigned an essential role, because the age determined by humans may be the age in which planetary boundaries become existential boundaries for the human species.

2.2 References Within Infrastructural Change

The topos of references may seem somewhat strange at first. Basically, however, the idea associated with it is not difficult to grasp. Rammert (2010) argues that, for a theory of innovation, its strong ties to an understanding of economic innovations must be severed. After all, innovations also take place in other social fields. However, these innovations take on a different character according to the structuring logic of the respective fields. Political innovations are different from innovations in the field of science or in the field of economics. The latter are characterized by market success; in the field of politics, the focus is on power and control. Therefore, innovations in this field take a different form. However, Rammert goes further. His crucial difference is the distinction between relation and reference. The category of relation addresses the question of how the quality of the new can actually be captured. To this end, he uses a differentiation formed along the three social-theoretical dimensions of factual, social and temporal, and therefore distinguishes between old and new (temporal), like and new (factual), and normal and deviant (social). The category of reference, on the other hand, focuses the reference on selected social fields in which the innovation takes place. This is because the respective fields—Rammert takes a particular look at the economy, politics, and art in his analysis, but his theory is not limited to these—shape their own structural characteristics of the production, evaluation, and selection of innovations. Thus, the field of economics is characterized by the features of profit promise and market success, the field of politics by the features of increasing power and gaining control. It becomes particularly exciting when innovations are not considered in an "exclusive" reference to a selected social field, but when the multireferential dynamics are appreciated. The nonlinearity of socio-technical change owes itself in many cases to the hardly synchronized (or even only limitedly synchronizable) interlockings between fields in the course of innovations. In this sense, this theory of innovation broadens the view of complex collective processes of structure formation, in which and through which innovations are formed, but also selected and normalized.

However theoretically speaking, this does not mean that mechanisms of diffusion by imitation would not continue to happen. However, it is the specific formation and selection conditions that are set by the field references. According to this, innovations can basically spread further and further through multiplication and imitation until they finally establish themselves in a more or less large social field. The institutionalization of new social practices plays an essential role. These practices depend on the social field (e.g., with regard to sustainable consumption: Jaeger-Erben et al. 2015). The question of the relationship between (social) innovation and transformative change has now become a core topic of social innovation research (Nicholls et al. 2015). This question is relevant because change is often blocked by established social practices (Shove and Walker 2010) and the diffusion of innovations is therefore subject to complex and fractured dynamics (cf. Shove et al. 2012). The form and dynamics of change vary not only with the degree of institutionalization (cf. Fuenfschilling and Truffer 2014) but also with the emerging tension between macro- and micro-change (or top-down versus bottom-up).

With regard to the maintenance and further development of infrastructures, these considerations come together in the sense that basic references may be clear at first. But this does not necessarily have to be the case. The next stage in the development of infrastructures can be seen precisely in the fact that they are reconfigured in their central reference. In the late twentieth century, the enthusiasm for privatization also hit infrastructure development. The initial result was that cash-strapped municipalities sold off infrastructure. Water and energy were then provided by private companies in a large number of municipalities. In the meantime, these developments have also revealed their unintended side effects. This is because the quality of service provision deteriorated in a couple of cases. In Paris, for example, the quality of the water dropped considerably and at the same time the price of the service more than doubled. The city eventually re-municipalized the water supply and also offered drinking water at a lower price than the companies. This shows that infrastructures, due to their special importance, can—or should—only be exposed to a change of references to a limited extent. But in the end, it all depends on the specific case. In the following, two selected cases will be sketchily examined in order to subject the investigation heuristics to an initial proof of concept.

3 Exemplary Cases of Infrastructural Change

Explicit transformation, which is sought through laws and measures, differs from a transformation dynamic that is always already taking place. To mark this specificity, transformation researchers speak of transition (Köhler et al. 2019). Transformation can ultimately be understood as a specific variant of innovation process. A form of networked innovation in which the framework conditions of innovation are changed at the same time. It is no coincidence that the Multi-Level Perspective (MLP) (cf. Geels 2004; Geels and Schot 2007) places a significant focus on the structural dimensions of change. It was specifically developed for the analysis of transformation processes and heuristically puts three levels—landscape, socio-technical regime, and niches—and their interconnection at the center of the analysis. Innovations are developed in niches and diffuse more or less rapidly when a favorable window of opportunity arises through situational de-stabilization at the level of socio-technical regimes.

In the following, two selected developments are reported as vignettes in order to illuminate infrastructural change in light of the heuristics and thus to make special features as well as demands on infrastructural change visible. These are the structural change in the Rhenish mining area (Sect. 3.1) and the problem of flexibilization of power grids in the course of the energy transition (Sect. 3.2). In particular, it will be asked whether and, if so, in what way forms of experimental practices can be observed in the five dimensions mentioned, which characterize the network of socio-technical problems in each case. What are the particular challenges that go hand in hand with this and can be marked as relevant?

3.1 Transformation and Structural Change

"Structural change" marks yet another form of large-scale change processes; in short, this means leaving a situation of seemingly irreversible path dependency due to an established, one-sided form of value creation and at the same time opening up new innovation opportunities (cf. Herberg et al. 2021). If we view structural change as networked innovations, we can distinguish three important dynamics that can be systematically differentiated but are at the same time interrelated. First, targeted exnovation (David and Gross 2019): How does one get out of the fixations of previous innovation activity in a planned way? Second, targeted innovation: How does one unleash suitable new settlements for innovation, i.e., which companies should and can be settled? Third, the accompanying transformation: What impulses for the transformation are made possible and what new determinations are made at the same time? This is obviously a multi-layered task in which, in addition to discursive design, the task of targeted infrastructure development in particular is of great importance. It is in the infrastructures that the new paths are defined—which then also have an effect as a self-commitment on the future development possibilities of regions. Let us look at what is happening along the various dimensions mentioned earlier:

Factual Dimension: There is a multi-layered and often not easily disentangled configuration of (technical) objects in space. This meshwork as a "stable structure without a future" stabilizes in its materiality a condition that is nevertheless supposed to be overcome precisely through transformation. With exnovation, these established ensembles of technologies and infrastructures should be rearranged. Ultimately, the previous materialization becomes more or less worthless and at the same time stands as a legacy in the way of innovations. At the same time, previous functions lose relevance or are even completely dissolved. The phase-out of lignite-fired power generation puts an end to this form of energy production. At the same time, however, it is conceivable that with the use of renewable energies, the coalfield will continue to function as an energy district, i.e., this function will be retained, but then on the basis of a different material foundation. At the same time, innovations will be spurred on. In the Rhenish mining area, there seems to be an oversupply here (cf. Böschen et al. 2021). The coalfield is thought of as an energy district, a bioeconomy district, a hydrogen district, an Innovation Valley with a variety of different material foundations (ZRR 2021). In terms of tapping into an uncertain future, this seems plausible, but with each of these options comes a different material determination. Which one seems reasonable? Which avoids too rigid a determination, like the one from which one is about to be released? At the same time, this raises the question of how to shape infrastructural conditions with particular sharpness. It is not just about a selected infrastructure, but rather about the ensemble of infrastructures. This is why the aspect of networking is particularly prominent in structural change and is perceived as a critical boundary condition for development. To mention just one aspect: the network of previous interconnections must be maintained until the phase-out is completed, but at the same time, it is necessary to build new interconnections that contain the opportunity for the targeted development of a new innovation base that is also diverse enough to avoid the former one-sidedness.

Social Dimension: Structural change situations are characterized by the fact that they take place in a ruptured manner, mobilizing hopes and fears—especially those of social decline. Identity is in danger, previous forms of collaboration are being reformatted, and participation is therefore the order of the day. Structural change represents a bundle of change processes in which the previous distribution of welfare and influence is subject to transformation. Such a rupture raises special problems of identity politics. What is reinterpreted as path dependency in the presence of structural change has in the past fueled a development in which specific local cultures have emerged, with their very own forms of identity construction. This can be observed, for example, in places characterized by mining cultures. Structural change initially entailed the establishment of a new organization: the Zukunftsagentur Rheinisches Revier (ZRR), founded as a central institution. This initially had to undergo a learning process with a view to the requirements in the social dimension. In 2020, the self-description on the homepage read: "The Agency is the strategic partner of the federal and state governments in the region. It performs the regional coordination function in order to manage structural change in the Rhenish lignite mining region together with the state, municipal and regional stakeholders." Currently, it says: "The Agency for the Rhenish Lignite Region develops mission statements, innovation strategies and action plans and supports structural change by initiating and implementing projects. The agency works closely with its partners from science, business, politics, and associations both inside and outside the region. Energy transition and climate change pose a challenge to the region. However, foreseeable changes should not be suffered here as structural breaks but should be shaped early and together by bundling all existing potentials. The agency will describe and prepare the way by which the Rhenish Lignite mining region can continue to be a modern, prosperous and innovative energy and industrial region in the twenty-first century." At least in its self-description, the three aspects of identity, collaboration, and participation are now being given greater prominence.

Time Dimension: The past plays an exposed role in the context of structural change. Structural change means leaving behind a past, and even more: a break with the past. It is multi-layered ties to the past that make it an essential aspect in structural change as a socio-technical problem of exnovation. The present in structural change is characterized by the difficult coupling of urgency and uncertainty. Finally, it is certainly not accidental that the design of futures in structural change shows considerable diversity and density. In addition, attempts are often made to valorize the structural break in the future as a positive goal to be striven for by designating regions in structural change as "model regions." These are then seen as model regions for selected innovation processes and their infrastructures. However, this raises the question of who designed this future and whether it can take on a structuring role as an inspiring model—or not.

Space Dimension: In the further development of the ensemble of infrastructures in the Rhenish coalfield, the question of the fundamental use of space plays an essential role. In opencast lignite mining, the use of space was geared to precisely its requirements. Now the task is to evaluate space differently and reorganize infrastructures accordingly. The current spatial strategy of the ZRR proposes a strategy of limited density. Density locations are to be made possible without at the same time using space unnecessarily. Settlement development, which is based on the assumption of an increasing population (ZRR 2023: 172), is to be designed according to the spatial strategy in such a way that precisely the valuable soil in the precinct is protected. This also includes a system of developed connectivity between regionally placed places with different qualities (from local points to metro areas, such as Cologne or Düsseldorf).

Environmental Dimension: The economy is essentially determined by two sectors based on natural resources and their utilization: lignite mining and agriculture. The Rhenish mining area represents the largest lignite mining area in Europe, with up to 100 million tons of lignite mined annually (2019 = 65 million tons). As of 2019, this corresponds to almost 70% of the primary energy consumption in North Rhine-Westphalia (data according to: Herberg et al. 2020: 12). Agriculture in the district is favored by good or very good soils and a diverse food industry has developed. One can simply state: It was the particular situation of availability that created the path dependency. Interestingly, however, with the soils being very fertile, there was also a distinct agricultural use of nature. This double availability has thus shaped the region in a tense way since the use of lignite. And it is no coincidence that both options, energy district and bioeconomy district, are being considered in many ways in the current transformation. Both make different demands with regard to the availability of environmental resources for the associated infrastructure developments. While the bioeconomy model entails a reassessment of regional availability, the model of the energy district de-localizes the question of availability under the guiding star of renewables. Overall, however, the focus is more on co-existence, as formulated in the spatial strategy (ZRR 2023).

Field of References: The transformation region of the Rhenish lignite mining area has been and still is characterized by monopoly structures. It is the large energy supplier RWE that essentially dominates the situation. However, the transformation of this company also illustrates the dynamics of the transformation as a whole. The transformation of RWE into an energy company for renewable energies has both begun and already gained contour. Precisely because the situation in such regions appears fixed or even blocked, transformation processes are taking place in a groping, searching manner that also allows the social order to be shifted along with it. The transformation problem to be solved is that the innovations do not immediately lead to new major path dependencies. Path dependencies are expressed in structural monopolies that give the regional economic structure a one-sided character. However, if we look at the economic and structural program (WSP 1.1; ZRR 2021) for the Rhenish mining region, it is striking how much emphasis is placed on the circumstantial effect of innovation and how little attention is paid to the corresponding development of institutional framework conditions for such innovation. This does not seem to be a coincidence. For it is precisely in moments of great uncertainty about future developments that it seems particularly attractive to use innovation programs to maintain control over future developments, at least discursively. If we consider the participation expectations of citizens, this perspective can only cover one aspect. Rather, it is to be expected that structural change will have taken place successfully when civil society has established itself as a stable reference. This is the litmus test, so to speak. Structural change represents only one, albeit exposed, form of regional transformation. At the same time, it must be surprising how much the question of structural change is negotiated in technocratic patterns. Yet the very openness of these processes should encourage people to recognize the potential they contain for the further development of democracy.

3.2 Flexibilization of Infrastructures in the Context of the Energy Transition

The energy transition toward sustainable forms of energy production, distribution, and use represents one of the major societal challenges of the present day. The scale of this challenge is determined by the shift from centralized to decentralized energy production, the diversification and multimodality of storage, and the increasing sector coupling through electrification and digitization. This can only succeed if flexibly designed distribution grids are available as a backbone. At the same time, the infrastructures are subject to socio-technical stabilization requirements from the outset and even more so in the event of a system change. The system transformation in the energy transition from a centralized to a system characterized by decentralized structural patterns brings into focus the socio-technical stabilization of technology options in niches and a diffusion dynamic based on this. Direct current technologies have a high potential for the energy transition. The fact that it has not been sufficiently exploited so far can be explained by looking at the different heuristic dimensions.

Factual Dimension: The development of infrastructures in the present can be seen as a phenomenon in which the materialization of historically grown and culturally embedded large socio-economic-technological systems are (supposed to be) subjected to a targeted change. The decisive factor for a change is, in sum, the systemic benefit, when system effects such as security of supply or system stability are achieved despite volatility, which results from the interaction of primary energy use, generation and storage park, transmission grid and flexibility of consumers nationally, taking into account imports and exports. The tension between decentralized and centralized functionalization of the energy system is demonstrated by the volatility of renewables, which produce regionally and then produce a supra-regional system problem. For the design task thus addressed, direct current (DC) technology has relevant advantages, especially supporting decentralized grid structures, minimizing grid complexity, and simplifying load flow control. However, the field of DC technologies differs strongly related to the technology maturity level (TRL) of DC technologies and thus their market readiness. Technical standards (e.g., rules and regulations for the connection of plants to the power grid) ensure a minimum level of system-compatible behavior. However, such standards are often not yet available with regard to DC technologies.

Social Dimension: The tension between centrality and decentralization is impressively reflected in all aspects of the social dimension. Although the established players, i.e., the huge companies, are playing further a decisive role, they have the re-invent their economic positioning. Moreover, it is no coincidence that forms of community play a growing role in shaping an "energy transition from below." In this context, it is precisely the interplay of identity formation, collaboration and participation that plays an essential role in shaping local energy transition situations (Holstenkamp and Radtke 2018). At the same time, there are different forms of such "citizen energy." In principle, the relevance of these organizational forms of energy production for the energy transition has been demonstrated (see Gui and MacGill 2017; Gui et al. 2017). But here, too, the question of infrastructural organization arises: the conflict between decentralized and centralized organization of the energy supply system is also reflected in variants of citizen energy production (e.g., citizen wind farms, community biomass cogeneration plants). In general, it can be shown that the interest in citizen energy cooperatives is much higher than the number of those who are already involved. Equally, it can be seen that winning over citizens is facilitated by communication, personal contacts, and the opportunity to actively participate, as well as by disclosing advantages and disadvantages. After all, the motives for getting involved vary. Citizens want to make well-informed decisions and be involved in the design of measures (Jakobs 2019).

Time Dimension: In contrast to structural change, the three aspects of time play a different role here. Although the past also plays a role in this transformation, it does so more strongly in the sense of specific constraints that, materialized as alternating current infrastructure, make it difficult to make energy networks more flexible. Therefore, a complicated design task arises in the present, because the past must be taken into account in the transition to a possibly different future. Thus, there cannot be an either-or in the design of distribution grids, but rather the question of how to keep the infrastructure change to another basic technology manageable with a phase of targeted simultaneity of both forms. At the same time, the exploration of futures also plays an essential role here. In the energy transition, it is generally striking how diverse scenario techniques have been used to create a picture of the future. Multifaceted visioneering plays an exposed role in the energy transition (Lösch et al. 2017). This may be precisely related to the fact that this production of the future is done under very strict requirements of maintaining the present.

Space Dimension: An energy transition of decentralization and flexibilization goes hand in hand with the creation of a new structure of density, connectivity, and distance. On the one hand, the aspect of distance is intensified, because different regions are developing in their own way, and on the other hand, the regional structure that was previously able to form dense structures around power plants is being broken up. The wind farm electricity of the north has to go to the south. Power plants and consumer locations have new distances. On the other hand, new local niches are emerging around renewables. How measures and formats of the energy transition are accepted and evaluated seems to depend, among other things, on the location (Hellmut and Jakobs 2019). The design of niches, and thus new density situations, acquires a particularly high relevance here. Connectivity is reflected in systemic benefits from a techno-economic perspective, e.g., in relation to transmission networks (van Leeuwen, 2018), distribution networks (Geschermann, 2017), and generation as well as storage systems (van Bracht, 2018). As a rough orientation, a benefit can be considered systemic if it is not the local balance but the national, European or global balance that is decisive for achieving a goal, e.g., costs and CO_2 reductions of the energy transition.

Environmental Dimension: The restructuring of the energy system is taking place under the conditions of a shift in environmental impact. On the one hand, renewables are expected to significantly improve the climate footprint of current energy production and consumption. On the other hand, the expansion of renewables is accompanied by other problems. For example, the expansion of renewable energies often underestimates the aspect of resource utilization. This means that availability in a new form is put to the test here. After all, the resource requirements for a corresponding form of energy transition are immense (cf. Michaels 2021), even for classic metals such as copper. Therefore, the reduction of resource consumption for copper, as offered by DC technologies, appears to be quite desirable. On the other hand, this conversion will take many decades. But questions also arise with regard to co-existence. In this respect, wind power in particular has side effects that can severely disrupt biodiversity (cf. Galparsoro et al. 2022).

Field of References: The energy transition toward a post-fossil production and consumption structure also poses a structural challenge, especially in view of the simultaneously required transformation from a centralized to a decentralized system architecture, which is marked by a shift in references. With the first steps into a breakup of the monopoly structure since the 1990s, which is in fact a highly fragile and open process, the network of actors might be shifting not only in the economic field, but also in the areas of science, civil society, and politics. Triggered by the change of cultural-institutional patterns on the landscape level (especially: Renewable Energy Act), but equally bottom-up from individual niches, the emergence and diffusion of socio-technical innovations in the context of the energy transition can be very well demonstrated (Geels et al. 2016). One important dynamic is the emergence and shaping of niche situations. Forms of community formation, such as energy cooperatives, show high potential as transformative actors in the energy transition, which was formulated as goal by German but also European legislation. However, these ambitions and their outcomes are fragile; e.g., after a rapid increase in start-ups, the 2017 reform of the Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG 2017) in particular slowed down the spread of civic energy production. Also relevant for CEC types seems to be their degree of interconnectedness. German energy cooperatives, for example, are better networked than other citizen energy companies (Kahla et al. 2017). Obviously, in this case, too, it can be assumed that the litmus test for a successful transformation can be demonstrated when the reference is shifted to the space of civil society. Efforts to do so can already be identified in the form of energy citizenship (Hamann et al. 2023). With regard to the case discussed here, the possible use of DC technologies, this circumstance is likely to be even more significant because these technologies, except for high-voltage transmission lining, are still at a prototypical stage. So far, their use varies not only in terms of technological maturity, but also depending on the socio-technical conditions of their embedding—for example, use and implementation differ strongly depending on the country. So far, it is largely unclear what socio-economic conditions must be in place not only to increase their maturity, but also to support and accelerate their market diffusion. This is where the density of niches plays a decisive role.

4 Scalability, Inclusiveness, Updateability: Ambitions and Restrictions Within Infrastructural Change

From the point of view of transformation, obviously, new demands are placed on infrastructure development. Transformation implies a requirement for continuous re-organization, which in detail means adaptability to environmental change as well as synchronization of potentially divergent infrastructure developments in the midst of transformative change. In order to be able to do justice to these special qualities, the study of infrastructure development must be expanded to enhance its flexibility. To put it succinctly, infrastructures are needed that are agile, participative and capable of being updated. An intimidating task. How can this be achieved? How do we have to think and design infrastructures so that they can meet such demands? This can be addressed in the aspects of scalability, openness to participation and updateability.

Scalability: Typically, scalability refers to the question of diffusion by an increase in volume and/or transfer of an innovation and is thereby expressed by easily measurable indicators (e.g., Seyfang and Longhurst 2016). This form of scalability is only one, nevertheless important form. However, in many, if not most, cases of socio-technical innovations, scalability is highly related to forms and dynamics of translation and has to be analyzed and designed accordingly (Raven et al. 2011). The question of scalability as an infrastructure development challenge was evident in both vignettes. This is because this problem does not owe itself solely to the question of whether the solution found in one niche will also work in other places. Rather, behind it lies a whole set of questions that, according to the proposed heuristic, relate to the different dimensions and their interactions. Typically, the social dimension, for example, contains a wealth of preconditions that cannot be transferred from one place to another without difficulty. The questions of identity and cooperation can be answered very differently and have therefore led to different local cultures. Or also the environmental dimension: the scalability of a new infrastructure solution, if one takes sustainability as a yardstick, depends essentially on whether the designed pattern of the problem solution also maintains the availability situation despite scaling and, moreover, is not accompanied by negative teleconnections. This dimension requires a completely different knowledge base than before, which could be called a set and strategy of transformation indicators. To illustrate this limited scalability/translation of niche applications with a concrete example, one could take a look at the diversified structures of wind turbines operated by citizen energy cooperatives in Germany (Klagge and Schmole 2018). Social acceptance of these technologies is high where both environmental conditions and socio-economic factors such as economic wealth allow citizen cooperatives to successfully operate wind turbines (Ohlhorst 2018). This is the case, for example, in northwestern Germany, where certain environmental and social conditions are given at the same time. However, in areas with even higher wind potential (Mecklenburg-Vorpommern) or economic wealth (Bavaria), fewer wind turbines are operated by cooperatives (MV) or installed at all (BV) (Kahla et al. 2017). The five heuristical dimensions presented in this paper allow us to describe these different infrastructural outcomes in more detail and to investigate why a particular niche solution does not work in a different but comparable context.

Inclusivity: Social formation of inclusive infrastructures. The essential value is the binding in social practices, which allows to increase the legitimacy and functionality of socio-technical problems and their solutions. Infrastructures are expressions of the social as well as technological formation of societies. If the logic of the development of infrastructures changes, then patterns of social order in societies also change. Against this background, the question arises what effects the maintenance and further development of infrastructures have on the different user groups (be they professional users who operate the infrastructures, but also everyday users who manage their daily lives on the basis of infrastructures)? The notion of "infrastructural inversion" introduced by Bowker (Bowker and Star 1999) could also be helpful in highlighting the everyday work of maintaining infrastructures in order to enable new forms of participatory access for affected user groups as well as professionals. This means focusing more analytically and empirically on the "grind challenges" (Madhavan 2022) associated with infrastructural work in order to better understand the social conditions of infrastructural reproduction. As it seems to be essential to synchronize the development of infrastructures and the corresponding changes in social practices already in the design of infrastructures, there is a high demand for participatory accessibility. Fortunately, tools have also been proposed in the meantime, which can be applied in this context, such as the "Societal Readiness Thinking Tool" (Bernstein et al. 2022) or the concept of "Niche Readiness Levels" (Schöpper et al. 2023).

Updateability: How can updateability be built into infrastructures? To give just one example, can experimental elements be built into infrastructures—and if so, how should they be designed? In which areas could it be implemented particularly well? Wouldn't various such developments also have to be specifically interlocked, i.e., synchronized? Infrastructures that are updateable permit the prototyping of socio-technical problems and the corresponding opening of experimental spaces already in operation. If we look at this in terms of the smartification of infrastructures, then the armoring of infrastructures with new digital technologies inscribes their own temporal logic into the further development of infrastructures. In particular, this means that other dynamics of prototyping as well as ongoing updating will shape the development of infrastructures. Furthermore, smartification requires new qualities of infrastructure that allow for continuous updateability, such as compatibility, connectivity, and modularization (cf. Chester and Allenby 2019). Other examples can be found in urban planning, where infrastructure designs in some places have already addressed higher levels of uncertain weather conditions due to climate change by shifting from large, centralized, fail-safe designs (that can no longer be guaranteed) to small, decentralized, safe-to-fail designs (Kim 2018). Failure is thus calculated as a realistic option. That represents an attempt to absorb and incorporate higher levels of uncertainty, making it an adaptive type of design (Chester and Allenby 2022).

In a nutshell, taking the different lines of the argumentation unfolded here together, it is first important to emphasize that the considerations presented here owe to a perspective that, in the context of socio-technical change, specifically focuses on the permanence as well as the more or less targeted reconstruction of infrastructures. The presented offers for a heuristic refer exactly to this form of shaping reality. Which socio-technical problems of infrastructural development are articulated and solved, and what are the social and material forces at work in the process? The primary purpose of the proposed heuristic is to identify such forces and thus facilitate an analysis of the mostly hybrid situations. In this context, the aforementioned three design claims of future infrastructure development (scalability, inclusivity, updateability) can be understood as guiding values that link the socio-technical analysis of infrastructure developments with the question of a possible better design. This is why that they aim at enabling an agile development of infrastructures, but on the other hand, it poses new challenges for cooperation between very different knowledge actors: developers, architects, engineers, and construction industry, just to name a few. In this sense, one could and should investigate patterns of prototyping and updating of infrastructures, focusing on issues of stability and instability of such processes. Moreover, one can examine how the representatives of participating knowledge cultures work together to solve socio-technical problems—and what challenges need to be overcome in the process.

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