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Research Article

The system building perspective for building sustainable system configurations using the German energy transition as an example

Sarah Olbrich [1,*] and Dierk Bauknecht [1,2]

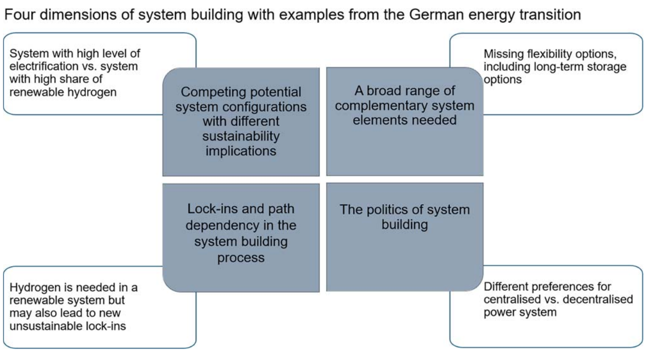
[1]Chair of Sustainability and Transitions Research, University of Freiburg, Freiburg 79085, Germany
[2]Department of Energy and Climate, Oeko-Institut, Freiburg 9017, Germany

*Corresponding author. E-mail: sarah.olbrich@sustainability-transitions.uni-freiburg.de

Abstract

An increasing number of countries employ net-zero decarbonization targets in their climate policies, which requires decarbonizing socio-technical systems like the energy system by mid-century. While there is a high level of agreement about net-zero targets, there remains great uncertainty as to how to meet them. At the same time, the challenges of building a new system that fulfils systemic targets such as net-zero are insufficiently reflected on in the sustainability transitions literature. With the help of a literature review building on theories of socio-technical transitions, this paper introduces system building dimensions that account for the difficulties of net-zero transitions. We identify four such dimensions: (1) competing potential system configurations with different sustainability implications; (2) a broad range of complementary system elements needed; (3) lock-ins and path dependencies in the system building process; and (4) the politics of system building. We offer the German energy transition as an empirical case study to illustrate the relevance of these system building dimensions.

Graphical Abstract



Lay summary

Like other countries, Germany agreed in reaching net-zero greenhouse gas emissions by mid-century, which requires decarbonizing the energy system. Despite the agreement of net-zero goals, it is uncertain of how to achieve net-zero. We propose four system building challenges that account for the difficulties of achieving net-zero: (i) competing potential system configurations with different sustainability implications; (ii) a broad range of complementary system elements needed; (iii) lock-ins and path dependencies in the system building process; and (iv) the politics of system building. We use examples from the German energy transition to illustrate the relevance of these system building dimensions.

Key words: sustainability transitions; net-zero transitions; transition challenges; system building; energy transitions

Introduction

Reducing greenhouse gas emissions to net-zero by mid-century has become a central target in climate policy, linked to the goal of limiting global warming set out in the Paris Agreement [1, 2]. Despite agreement on the net-zero target itself, there is a lack of clarity and consensus about how to best meet it [3]. Reducing greenhouse gas emissions requires to transition from fossil fuels to renewable alternatives in multiple socio-technical systems such as energy, mobility and heating.

Transitions in socio-technical systems are addressed by sustainability transitions research which deals with 'radical shifts

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to new kinds of socio-technical systems, shifts which are called "sustainability transitions"' [4]. The development of new systems is a complex process that can be described as having three phases [5–8]: (i) the emergence of innovations; (ii) the acceleration of innovations and the decline of unsustainable system elements; (iii) the stabilization of a new system.

Sustainability transitions can be considered successful if new socio-technical systems replace current unsustainable systems and fulfil societal functions in a sustainable way. The above net-zero transitions are a prominent example. However, sustainable transitions research has only started to address the implications of ambitious sustainability targets such as net-zero transitions [5]. Key frameworks such as the Multi-Level-Perspective (MLP) or Technological Innovation Systems use an open-ended approach to transitions, which disregards both the urgency of and the set timeframe for achieving net-zero transitions. Thus, the research community identified a need to examine the acceleration of socio-technical system change [9, 10] and strategies for increasing the speed, breadth and depth of sustainability transitions [11] and made first suggestions for negotiating and closing this research gap [5].

A further area for reflection is the implications of clearly defined sustainability targets for our understanding and steering of sustainability transitions. Scholars of sustainability transitions often assume that a new system that results from a transition is more sustainable than its predecessor [12], without critically questioning whether it actually is so [13]. The new system may still not meet sustainability requirements like the net-zero targets described above, which entail very ambitious requirements for the new socio-technical systems.

Moreover, current research mainly focuses on the acceleration of innovations and the decline of unsustainable system elements. These processes provide alternatives and room for new solutions respectively, but they do not ensure that these alternatives can fulfil societal functions on a system level in a sustainable way. The actual development of a *sustainable* system such as a system in line with net-zero targets is a challenge for transitions that has not received sufficient attention to date. Therefore, we consider it helpful to explore the development of sustainable systems, which we refer to as 'system building'.

The development of a new system can be viewed from two perspectives:

1) The development of a new system requires aligning actors and core and complementing innovative technologies with old system elements in a new system configuration, and adjusting the formal and informal rules [14, 15]. This perspective puts the focus on the stability of the new system and how it emerges. However, alignment and stabilization as such do not ensure that the emerging system fulfils societal functions in a sustainable way, e.g. whether it fulfils sustainability requirements like net-zero targets. The processes of alignment and stabilization also need further research, but analysing these processes is not the focus of this paper.

2) In contrast to the above perspective, our system building perspective places the focus on the challenges that stem from the need to develop a system that fulfils societal functions and fulfils sustainability requirements. For that, stabilization of the new system is necessary but not a sufficient condition in itself.

Based on a literature review, we propose four system building dimensions. These are:

1) Competing potential system configurations with different sustainability implications,
2) A broad range of complementary system elements needed,
3) Lock-ins and path dependency in the system building process, and
4) The politics of system building.

The system building perspective considers that, on the one hand, transitions are complex, long-term processes with many uncertainties: transitions are emergent, affect multiple system elements and are enacted by multiple actors; on the other hand, they should lead to a sustainable system [4]. System building is one way of negotiating and tackling this complexity by addressing the specific challenges of building systems that fulfil systemic sustainability targets such as net-zero. System building moves center stage once core alternatives to the incumbent system have been developed and are upscaled to replace the incumbent system which is on the decline. The energy transition in Germany is a case in point and is used to provide examples for the system building dimensions that we have identified.

The aim of this paper is exploring the perspective of building sustainable systems, such as net-zero systems, and its dimensions.

Methodology

System building is about building a sustainable system around diffusing core innovations, as in the example of net-zero transitions. This is not yet sufficiently considered in the existing literature [5, 11]. This system building perspective needs to reflect that (i) the objective of sustainability transitions is not just the transition to any kind of new socio-technical system, but to a sustainable one; and that (ii) socio-technical transitions are characterized by complexity and uncertainty [4, 16].

To explore the system building perspective, we take the following steps:

In the next section, Section 3, we establish the need for the system building perspective by discussing how systems change and by reflecting on the role of normativity in and sustainability requirements for sustainability transitions.

Section 4 offers more details on the design and content of such a system building perspective based on a literature review and complemented by examples from the German energy transition.

Firstly, we conducted a narrative literature review [17] based on the results of Section 3 and the existing literature on sustainability transitions. The narrative literature review does not aim to cover all articles published on this topic. Rather, it encompasses the literature that allows initial conceptualizations to be developed by combining different perspectives and insights and synthesizing literature in a way that enables new theoretical perspectives to emerge [17–19].

Based on this literature review, we developed the system building perspective by synthesizing the literature into four system building dimensions. Our key guiding question for this purpose was: What does the existing literature has to offer when the objective is not just to achieve socio-technical transitions but building new systems that meet sustainability targets such as net-zero?

Secondly, we drew on examples from the German energy transition to illustrate and support the dimensions identified in the literature review. The German energy transition is an example of an advanced transition in which system building can be expected to become relevant, as explained below. As the German energy transition is well documented, we rely on existing studies in and beyond transition studies that have analysed specific system

Table 1. System building dimensions and examples from the German energy transition

System building dimensions	*Description*	*Examples from the German energy transition*
1) Competing potential system configurations	• There are several potential future system configurations based on the same core innovation. • It can still be unclear how a future *sustainable* system built around the core innovation can or should be designed. • They differ in their level of sustainability.	• Centralized vs decentralized renewable system. • System with high level of electrification vs. high share of renewable hydrogen. • Yes, in terms of environmental, social and economic repercussions.
2) A broad range of complementary system elements needed	• Besides the core innovation, complementary innovations need to be in place and aligned to make the new sustainable system work. • This also depends on the specific system configuration (see dimension 1). • These could not or have not been developed in the niche phase, especially given the uncertainty about the system configuration. The development may only start once the core innovation is no longer in the niche phase.	• Market design for systems with high renewable shares • Flexibility options, including long-term storage options. • Incumbent technologies also need to be developed further (transmission grid) or solutions that were considered necessary may need to be phased out (combined heat and power). • For both market design and flexibility, there are different requirements in a centralized vs. a decentralized power system. • There are different phases of renewables growth, and systemic implications have been addressed only at higher renewables shares.
3) Lock-ins and path dependency in the system building process	• There are potential new path dependencies and lock-ins that do not result from the incumbent system, but can emerge in the transition process and that can prevent the development of the most sustainable system (see dimension 1).	• Hydrogen is needed in a renewable system, but may also lead to new unsustainable lock-ins.
4) The politics of system building	• Even if there is consensus on the core innovation, in the face of competing potential system configurations (dimension 1) and different complementary innovations (dimension 2), different actors have different interests and preferences. • System building also implies that some options and related actors will lose out.	• Strong heterogeneity in preferences even among actors that agree on renewables. • Different preferences for centralized vs. decentralized power system, for the role of hydrogen and for grid expansion vs. alternative flexibility options.

Source: Authors' own

building dimensions or can show the relevance of them. Our examples relate both to the power sector transition and to energy sector integration, i.e. the increasing use of power from renewable sources in the mobility, heating and industry sectors. A summary of the detailed description of the system building dimensions and related examples from the German energy transition is offered in Table 1 further below.

We consider Germany's energy transition a useful example for an ongoing net-zero transition that has moved beyond the first phase of developing renewable generation technologies as core innovations in niches. Germany has set net-zero targets for 2045 and renewable power generation has increased significantly over the past two decades (see Fig. 1). Renewables are no longer niche technologies and it is expected that their share in the power mix will continue to grow, while fossil fuels and nuclear energy have been on the decline.

The generation mix indicates that a successful transition is taking place in the sense that the German power system is in the process of becoming a system dominated by renewables, while fossil technologies are being phased out. As net-zero affects all sectors, renewable power is also becoming the core generation technology for many sectors (sector integration). Thus, the question of what is needed to complement this core innovation

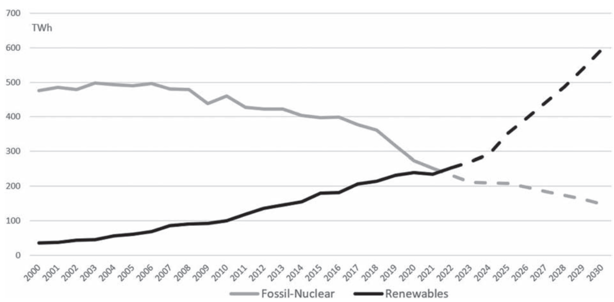

Figure 1. Power generation mix in Germany. Source: Up to 2022: [20]; 2023 and later: [21], Linear interpolation.

to ensure a functioning and reliable renewable energy system becomes even more relevant across different sectors [22]. All this implies that a renewable system now needs to be built in a functioning and sustainable way.

Contextualizing system building

In this section, we elaborate on the need for the system building perspective. To do so, we firstly explain how systems change using the MLP and the whole system perspective and, secondly, we reflect on the role of normativity in sustainability transitions research.

Understanding system change

One of the most prominent concepts for system change is the Multi-Level Perspective [15, 23, 24]. The MLP analyses transition dynamics across three analytical levels [23]: *niches* are protected spaces in which radical innovations can develop and mature; the *landscape* contains developments that are exogenous to regimes and niches; *regimes* form the institutional structuring of a system and link system elements together with formal and informal rules that are highly institutionalized.

From this perspective, transitions are understood as a shift from one regime to another that results from interactions between processes on the three analytical levels [25, 26]: (i) Niche innovations build internal momentum through learning processes, cost/performance improvements, and support from powerful groups; (ii) changes at the landscape level put pressure on the regime; and (iii) the destabilization of the regime creates a window of opportunity for new socio-technical configurations. The alignment of these processes enables the breakthrough of novelties and eventually the stabilization of a new system configuration.

Although the MLP was designed to explain system change, it has been criticized for a bottom-up bias: transitions are often portrayed as the result of the breakthrough and diffusion of innovations, neglecting transformation processes at the regime level [24, 27–29]. When breaking through, the new niche configuration is rather loosely-structured [26] and through institutionalization processes and anchoring needs to reach a point of high structuration [30]. This happens via a stepwise process of reconfiguration as new regimes grow out of old ones after a series of adaptations and changes over time [23] that alter the way regime elements interact and social actors perform. However, research has not yet analysed reconfiguration processes thoroughly [4] and has focused primarily on gradual changes rather than on radical changes in the system configuration [31] that may be necessary for an emerging system configuration to work.

As a reaction to the criticism of a bottom-up bias, the whole-system perspective was developed. This perspective understands system reconfigurations as the result of multiple change mechanisms at multiple regime and niche levels [32]. This adds to the understanding of transitions in two ways [33]: Firstly, it no longer uses the vertical understanding of transitions as a single niche innovation that challenges the incumbent regime. Rather, the multiplicity, co-existence and interdependencies of change processes are analysed by understanding transitions as a series of techno-economic and socio-institutional changes. Secondly, the whole-system perspective argues that innovations can influence the operational logic of whole-system linkages, thus altering the system configuration.

While sustainability transitions research initially focused on niche innovations, it is increasingly examining whole systems. For the system building perspective, it can be argued that in the course of a transition, the system perspective becomes important, in contrast to the early stages of a transition in which the focus is on niche innovations. However, the MLP was developed on the basis of historical case studies which were driven by the commercial motivation of entrepreneurs [34]. Normative orientations and sustainability requirements for the emerging system were not relevant for concept development. Therefore, we consider it useful to reflect on normativity in more detail.

Normativity in sustainability transitions

Sustainability transitions need orientation through normative statements about what transitions seek to achieve [4]. Normative statements in the sustainability transitions literature are usually used to legitimize transitions and for resource attraction for niche innovations [35]. The former focuses on problem framing as discursive changes are needed at the societal level, through which persistent problems are recognized and translated into new future directions [36]. Such a perspective is at the heart of the sustainability transitions research as societal problems such as climate change, loss of biodiversity and resource depletion are the underlying motivation in this research field [4].

Regarding the latter, normative statements are used to justify niches to a wider audience, to change institutions in a niche-friendly manner, and to challenge the incumbent system to open up opportunities for niche innovations [37]. Visions are also an important driver for innovation and experimentation as visions of alternative futures can motivate, coordinate and empower actors to work strategically on transitions [36]. To date, the role of normativity and visions have mostly been analysed for transitions in early stages. Few contributions broaden the scope by discussing normative orientations within transitions [34], by showing how directionality depends upon developments at the niche, regime and landscape levels [38], or by analysing the extent to which incumbent and new actors try to shape the direction of change [39]. However, the sustainability of the emerging system is often limited to references to more sustainable modes of production and consumption [12].

Examples of such normative statements providing direction are the United Nations 2030 Agenda with its 17 Sustainable Development Goals or the global emission reduction targets formulated in the Paris Agreement and translated to the national level in the form of national net-zero targets. Alongside giving direction, these examples of normative statements also formulate sustainability requirements for the new system and set a timeframe by which these targets need to be achieved.

The field of sustainability transitions research has recently started to engage with net-zero transitions [5, 11]. In particular, the literature highlights that the timeframe set in net-zero targets requires a transition of unprecedented speed. Specific challenges to accelerating transitions have been identified [9, 40] and much research has been conducted on how to increase the speed of transitions [41, 42]. However, these studies are typically process-oriented and follow a bottom-up perspective without reflecting on the sustainability requirements and the actual sustainability of the emerging system configuration.

System building dimensions

There are several strands of research in the transitions literature that are relevant for the system building perspective. In this section, we present our literature review and use the results to propose four system building dimensions. While the system building dimensions have been discussed in the literature in principle, they have not yet been geared towards the question of how a functioning and sustainable system can develop and have not yet been connected to each other in a holistic perspective. Table 1 summarizes the system building dimensions and provides examples from the German energy transition.

As for the German examples, the issues summarized in Table 1 have emerged only with increasing shares of renewables and when a renewable energy *system* came into view. They were therefore difficult to address in earlier transition phases when the focus was on developing renewable technologies and complementary innovations needed for individual renewable projects.

Competing potential system configurations

Conceptual foundations

The system building perspective moves away from the focus on how to initiate transitions via niches and towards a focus on the system configuration that emerges from the transition and its sustainability. Engaging with the emerging system configuration is important as the 'race-track' [43] bias resulting from a too strong focus on the cultivation of innovation [44] can lead to a 'harmony fallacy' [45]: the innovation focus is not able to account for broader transition dynamics and obscures diverse and competing socio-technical pathways and future visions as well as underlying goals, values and interests, as discussed in more detail in Section 3.4. This is relevant in the context of advanced transitions as different targets in technical, social and spatial dimensions lead to competing system configurations [12] that can all be built around the same core innovation. However, the different possible system configurations are not necessarily sustainable [38]. Dealing with the question of directionality and related uncertainties is also necessary due to the need to speed up sustainability transitions with the aim of decarbonizing systems [46].

A need to account more explicitly for the directionality of transitions and the diversity of possible socio-technical development paths has therefore been identified [4, 43]. This interest in the directionality of innovation has a dual nature: some directions of change can be perceived as more desirable from a sustainability perspective (*normative directionality*); others are more plausible due to the evolutionary character of transitions (*positive directionality*) [12]. System building is mainly concerned with normative directionality, as in the example of net-zero transitions, but needs to consider positive directionality.

The question of directionality and how directionality can be analysed is relevant for system building as delineating directionality helps to make sense of the competing possible system configurations and their underlying goals, visions and interests, as well as evaluating their respective sustainability. Thus, this dimension is also linked to the question of politics, which we discuss in Section 4.4.

While the debate on directionality highlights that a transformation based on a core innovation can lead to different directions of the transition process, system building is not only concerned with the direction, but with the 'final' system configuration and its sustainability. Moreover, while directionality also emphasizes the uncertainty regarding these directions and how they will play out, system building places the focus on the normative requirements that result from sustainability targets.

Example

In the German case, the breakthrough of renewables has led to questions of what direction the transition will take and what the future energy *system* can look like since a range of different system configurations are possible, all of which are in line with Fig. 1. Thus, the focus shifts from 'renewables vs. fossil/nuclear' to 'which renewable system?'. While there are certain areas of agreement among all future scenarios (e.g. hydrogen will be needed in a renewable system), there are also significant differences [47].

A prominent example is the debate about whether the power system will be centralized or decentralized. This has significant implications for the overall system configurations, including infrastructures and the role of consumers. Given that these terms can also mean different things (e.g. referring to power networks or market models), many different power system configurations are possible [48, 49] and this diversity is also reflected in the options for the German energy transition [50].

While the share of renewables was still relatively small, the introduction of these comparatively small-scale technologies suggested a power system decentralization at the plant level. Yet with larger shares it becomes apparent that decentralization also refers to broader systemic questions. These are not relevant at lower renewable shares; however, they need to be considered at higher shares. Therefore, this debate has only emerged in an advanced transition stage [51].

With sector integration, even more potential system configurations become available [52, 53]. For example, to what extent should electricity be used directly, or should it be converted to hydrogen and other secondary products?

Importantly, these different configurations also have different sustainability implications [52, 54, 55]. From the perspective of developing alternatives and destabilizing the incumbent system, the focus is not on the sustainability of the new system nor net-zero since renewables are considered to be more sustainable than fossils. Therefore, the main challenge at earlier stages is to develop renewable technologies. However, with system building, the focus shifts to the sustainability implications of transition pathways towards different renewable systems, in terms of environmental, social and economic repercussions, as well as in terms of security of supply and system stability [56–58].

The German case illustrates that building a sustainable energy system is not only about upscaling renewables but also about uncertainty as to what a sustainable renewable system could and should look like and how to bring about such a system.

A broad range of complementary system elements needed

Conceptual foundations

The focus of system building on functioning, sustainable systems raises the question of what is needed for this system to work beyond the core niche innovation.

To ensure the functioning of the system, complementary interactions are needed between multiple innovations on the one hand and between multiple systems on the other hand [9]. Complementarities, understood as a positive interaction of at least two system elements, are central for the development of technologies and for the transition of systems [59]. They can accelerate innovations or hamper them if they are missing or lag behind. Especially the diffusion of innovations that do not fit into the incumbent system logic causes struggles in several system dimensions [30]. To solve these struggles, configuration processes are needed that result in a re-structured new system [31, 37]. These configuration processes are not internal to the niche; rather, they rely upon processes of change within the system and the broader society and economy [37].

If these configuration processes do not happen, it can lead to a mismatch between a system element and its wider sectoral environment [60]. This mismatch can lead to systemic problems, which are also referred to as 'bottlenecks' [59], 'reverse salients' [61] or 'structural tensions' [62]. Systemic problems can occur across related technologies and sectors that in turn generate pressure on other parts of the system [63] if system components fall behind or do not work harmoniously [61]. A failure in solving systemic problems might decelerate a transition or inhibit the stabilization of a new system [60], resulting in system breakdown, backlash or lock-in [64]. Such 'transition failures' [65] can also occur in advanced transitions [66].

If radical innovations fail to trigger or align with wider changes in the system, their diffusion stalls [31]. Therefore, the success of an innovation not only depends on its maturity and a window of opportunity, but on its ability to mobilize institutional change and altering the underlying system logics. However, sustainability transition research has not yet thoroughly reflected on these transition failures [65] and their causes [64].

In addition, the system building perspective stresses that transition failures are not just about whether a new system stabilizes and the complementary elements needed for stabilization. With its focus on reaching concrete targets like net-zero, system building emphasis that *specific* elements are needed for the envisioned system to stabilize *and* be sustainable. The uncertainty about this system configuration addressed in the first dimension also leads to uncertainties regarding the required complementary elements.

Example

Power systems do not just consist of generation technologies; the power system transition in Germany is, therefore, not limited to the developments shown in Fig. 1. The energy transition goes beyond replacing one set of generation technologies with another, but has repercussions for the energy *system*, from generation to consumption and including both technical and institutional elements [51]. It is often uncertain what these will look like, either because several options are available, or because no option has yet arisen.

Some of these elements could be developed while renewables are still niche technologies and have small shares, such as network integration technologies or new actor roles like energy communities. Others become relevant only with larger market shares. Various phases of renewables development and their system implications are presented by Matthes [67]. This shows that while upscaling renewables and complementary solutions are important, the energy transition is also about constantly solving new challenges and finding new solutions as the share of renewable increases.

In the German case, the market design for systems with high renewable shares is exemplary for a complementary element that needs to be developed: How can financing mechanisms work for renewables that no longer benefit from a support scheme for a niche technology [67, 68]? Moreover, with sector integration, the power market also needs to be linked to additional power consuming sectors. As renewables grow, there are increasing tensions between their characteristics and conventional market design.

Another example in this context is power system flexibility that in early phases can be provided by fossil generation technologies [69]. Later, new options such as batteries or demand-side management need to fulfil this role. At renewable shares of more than 80%, these need to be complemented by long-term storage options that are still to be developed, like hydrogen [70], and coordinated with sector integration. These questions were not relevant as long as renewables had a small share, and it was difficult to address them in the niche phase.

Both market design and flexibility demand depend on the future system configuration, e.g. centralization vs. decentralization [54, 55], see Section 3.1.2.

Besides innovations, some elements of the old system also play a role in the new system. The transmission grid is a case in point: It is a core element of both the old fossil system and the new renewable system but needs to be adapted. In the case of Germany, the need for transmission grid expansion and innovation plays a prominent role, even in decentralized scenarios [71].

Finally, niche innovations that were considered an important element of the future system might become less relevant or even counterproductive as the transition evolves. For example, combined heat and power plants used to be an important energy transition technology in the German case, but now only play a minor role in long-term scenarios [52]. Phasing out such technologies and respective institutions can also be part of system building.

Lock-ins and path dependency in the system building process

Conceptual foundations

A third element of the system building process is combining the various elements into a new sustainable system, which includes configuring the new system with the help of the complementary elements described in 3.2.

As described in section 4.1, multiple possible system configurations can be built around core innovations. Thus, the question remains as to how to achieve these configurations. The concept of transition pathways is one way to describe the change processes that lead to possible future system configurations [72]. Comparable to the plurality of possible future system configurations (system building dimension 1), multiple transition pathways emerge that lead towards possible futures [4].

As transition pathways unfold, new lock-ins and path-dependencies may emerge. These can prevent the transition from moving towards the required sustainability level, such as net-zero targets. This can be particularly problematic given the first system building dimension. Thus, system building includes managing path dependencies and the related uncertainties, i.e. build the system and in this process avoid getting stuck in unsustainable configurations.

Path dependencies have played a key role in sustainability transitions research. Path dependency refers to the inflexibility, inertia, stickiness, or rigidities of a system, explaining institutional, regional, technological or organizational persistence to change [73, 74]. Path dependency can be defined as a 'process triggered by a [series of] contingent events, then moved along through positive feedback mechanisms until it results in rigidity or lock-in' [74], creating trajectories that can foster or hinder innovations [75].

The focus in research has mainly been on path-dependencies and lock-ins in the incumbent system that need to be overcome for sustainability transitions to take off. Path dependencies and lock-ins that can emerge in the course of a transition have been identified as an issue [76], but have received less attention up to now. The need to establish a pathway towards a sustainable configuration thus highlights the need to avoid new undesired lock-ins and path dependencies. System building needs to deal with these emerging path dependencies to make sure that they do not prevent the development of a sustainable system configuration.

Example

While the early German energy transition focused on renewables and then phasing out fossil fuels, it is now about developing the new system, which includes navigating between potential system configurations and developing all the elements needed for the system to work as described in the previous sections. In previous phases, a main challenge was to overcome lock-ins of the incumbent system (carbon lock-in) [77]. Now, as the incumbent system is on the decline, a new challenge is to avoid new lock-ins and path dependencies that can put at risk the development of a new sustainable energy system or can entail sustainability issues in the transition process.

With sector integration, these issues become particularly prominent and the development of renewable hydrogen is a case in point [78, 79]. Hydrogen is one way to use renewable power in other sectors and this technology will most likely be needed for the energy transition. However, there are different pitfalls and path dependencies regarding the production and use of hydrogen. These can lead to unsustainable configurations and might limit possibilities in the future, e.g. hydrogen can be produced both using renewable and non-renewable energy.

Another example of a potential lock-in is the development of the gas infrastructure. On the one hand, this infrastructure will need to be adapted to hydrogen. On the other hand, a system which has the current volumes of natural gas and is replaced with hydrogen is likely to be unsustainable since it will scarcely be possible to generate that amount of sustainable hydrogen. The further development of the gas infrastructure can thus represent a relevant lock-in risk [80].

As a result, even though Germany has clearly embarked on a renewable energy system, the question of future system configuration (see Section 3.1) and how to bring it about in a sustainable way while avoiding new unsustainable lock-ins is still unresolved.

The politics of system building

Conceptual foundations

The system building dimensions described above lead to issues of politics as different future system configurations, even if built around one core innovation, can have different implications for different actors [40]. Different actors are likely to have different interests and preferences for the future system configuration (dimension 1) and the elements that do or do not play a role in it (dimension 2), as well as the transition pathway taken (dimension 3).

Although sustainability transitions engage with socio-technical change, the research field has been criticized for putting too strong a focus on technological innovations and thereby neglecting agency in transitions [29, 81]. Considering agency is important because socio-technical change depends on the interplay between technological innovation, regime particularities and actor strategies [82]. Actors try to shape the directionality of transitions by using different types of actions that aim at creating a new system, maintaining it, or disrupting it [82, 83].

While in the first phase of transitions, incumbent actors are likely to take a hostile stance towards new, radical innovations [84], they can also take a proactive role [28], especially in later transition phases. Recently, scholars have thus criticized the often-portrayed dichotomy between incumbents as defenders of the old system and newcomers as drivers of change, and called for pluralizing incumbencies [28]. Indeed, actor roles in transitions are likely to change over time [85, 86] and incumbents can proactively contribute to system change rather than combating it if considered necessary to keep pace with change [87]. Thus, both incumbent and new actors with divergent interests are involved in system building.

Consequently, system building is also about political struggles about the directionality of transitions, which add to the complexity and uncertainty of system building. Competing actors use their resources to frame problems and influence solutions [88], thereby influencing the direction of change. The direction of transitions is thus not only influenced by technological possibilities but also results from political contestation and choices [88]. This is also true for advanced transitions as the new system configuration is highly contested [40].

While contestation and disagreement are central characteristics of sustainability transitions [4], the argument here is that new and different actor struggles emerge in the course of system building. System building is no longer about niches and experiments whereby alternative options can be tested alongside each other. Rather, it deals with the 'final' system configuration, which is likely to increase the stakes for the actors involved.

Example

The case of the German energy transition also shows that the shift towards renewables does not mean the end of political struggles. Rather, new political struggles emerge with regard to how the renewable system should be designed, including struggles around the issues presented in the previous sections. Even though there is a broad consensus about moving towards a renewable system, the range of potential renewable system configurations and the technologies, institutions and actors that do or do not play a prominent role in these configurations affect various actors in very different ways. Again, the example of the various potential power system configurations in terms of decentralization can support this argument [89]. There is a strong heterogeneity in preferences for the energy transition [90], rather than convergence towards a specific renewable system. This heterogeneity can also be observed with regard to hydrogen [91].

The German energy transition shows that the dichotomy between incumbents favoring the old system and new entrants favoring the new one can become more diverse. With system building, incumbents try to shape the new system and find a position within it, while for new entrants it is no longer sufficient to simply promote the alternative. This is exemplified by the case of power transmission grid expansion and alternative flexibility options in Germany. Both new actors and incumbent actors consider transmission grid expansion as an important flexibility option but have different preferences for how to complement transmission grid expansion with central and decentral flexibility options [92].

Conclusion

As transitions like the energy transition proceed, the focus shifts from developing alternatives, diffusing them and disrupting the incumbent system to building new functioning and sustainable systems that meet concrete targets such as net-zero emissions. We argue that this system building perspective has not received sufficient attention in transition research and needs to be analysed in more detail. This can also contribute to the debate on policy mixes for the governance of sustainability transitions, which has also focused up to now on stimulating different innovations, diffusing them and destabilizing the incumbent system [93, 94].

We used insights from the transition literature to explore system building in more detail. We propose four system building dimensions: Competing potential system configurations with different sustainability implications; the broad range of complementary system elements needed; lock-ins and path dependency in the system building process; the politics of system building.

System building goes along with uncertainties about directionality, the complementary innovations that are needed to form a sustainable system, and how to deal with competing interests and visions about future system configurations and possible pathways towards them. Moreover, new lock-ins that may lead to unsustainable system configurations need to be avoided. These strands of research are not explicitly connected with each other and are not geared towards achieving sustainability targets such as net-zero targets.

Shifting the perspective from developing alternatives and destabilization to system building and thus to 'thinking about transitions from the end,' i.e. the 'final' system configuration that is to be achieved and its sustainability, makes it necessary to analyse these dimensions explicitly from that perspective.

In addition to the literature review, the paper provides empirical examples from the German energy transition to demonstrate the relevance of the system building perspective and its four dimensions. The rise of renewables in Germany is accompanied by new questions, options, uncertainties, and interests. The system building dimensions are relevant in this case and differ from earlier transition phases, in which the focus was on the development of renewable energy technologies rather than a renewable energy system.

We do not consider the list of system building dimensions as final. Further dimensions may be identified in future work. Also, not all four dimensions may be relevant in all cases. With these considerations in mind, we conclude that it is worthwhile to further investigate the system building perspective and its dimensions.

We see the following ways forward: Firstly, the system building dimensions that we have discussed can be tested in different sectors and country contexts to develop a more detailed understanding of these dimensions and to complement the list of dimensions.

Secondly, system building should also be included in studies on the governance of transitions. Policy mixes are essential for the governance of transitions to both develop alternatives and to overcome system inertia [95]. For advanced transitions, additional policies are needed that reflect system building. Gaining a better understanding of the system building dimensions is therefore essential to being able to design better policy mixes, and to gather insights into how to govern later phases of transitions, which has not yet been sufficiently carried out [4].

In the coming decade, as sustainability transitions advance, system building will become more relevant across different sectors. The system building perspective can contribute to understanding the challenges of advanced transitions and of developing systems that meet sustainability objectives, to developing strategies that can tackle those challenges, and to formulating policies that facilitate system building, in different contexts and in a political process. This can be based on a repository of case studies of system building and a systematic cross-sectoral analysis. By addressing these issues, researchers can help to close the knowledge gap and contribute to the governance of transitions.

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Authors contributions

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