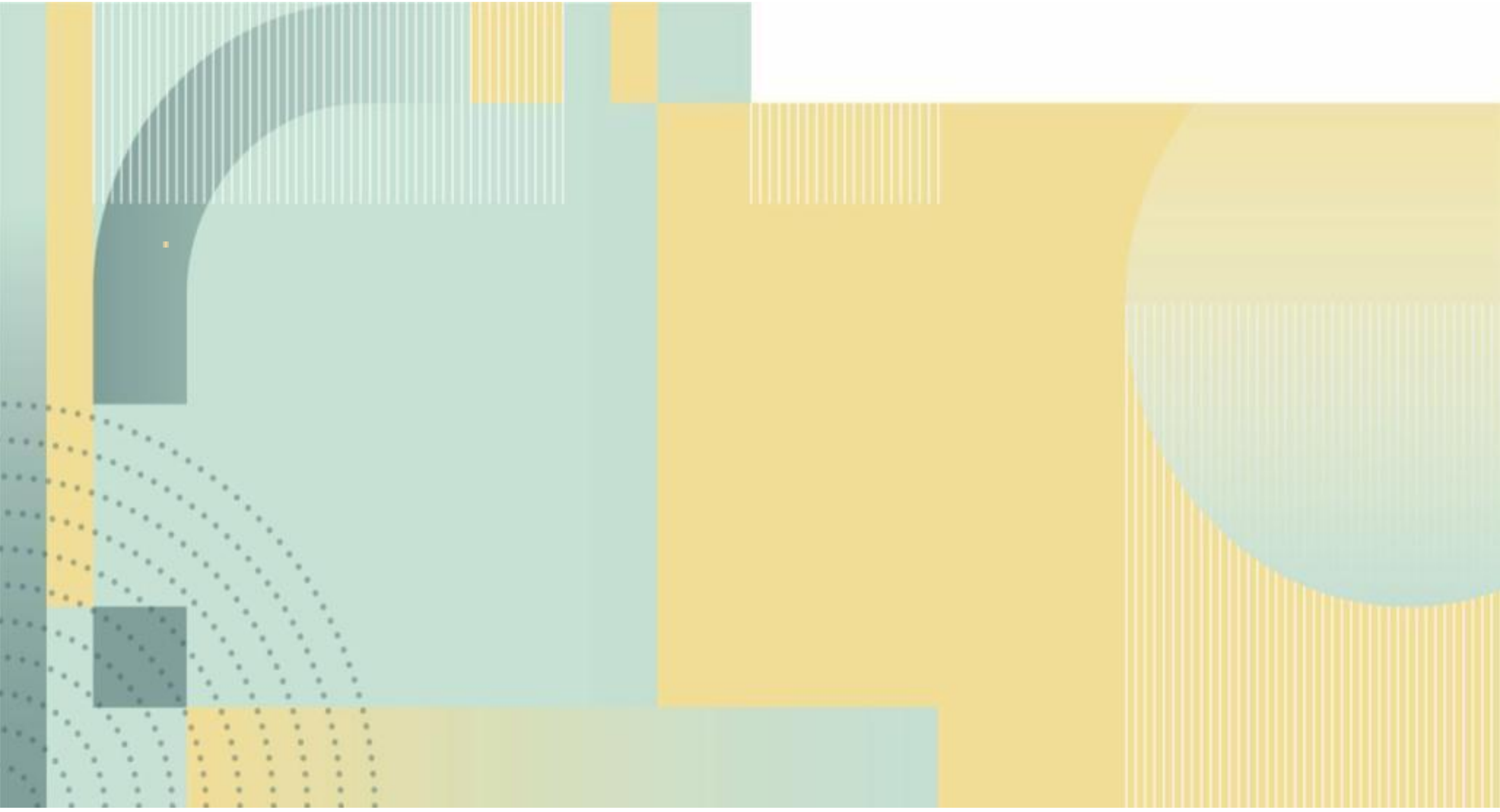
RESEARCH REPORT
Mission-oriented innovation policies
October 23



Mission-Oriented Innovation Policies for the Twin Transition

A CO:DINA research report

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In a nutshell

We explore how mission-oriented innovation policies might help directing digital innovation towards sustainable development. Our report with two separate papers shows the major systemic issues in the twin transition as well as how policy makers might choose suitable transformative policies to address them.

Wuppertal Institut

Fraunhofer ISI

Summary

Challenge: While digital technologies hold significant transformational potential, current policy making might not be directing digital innovation towards sustainable development sufficiently

Approach: We analyze - in an exploratory empirical study and a conceptual discussion paper - how mission-oriented innovation policies might help disentangling the complex twin transition and design policy interventions to facilitate transformative change in Germany.

Exploratory study: "*Pursuing a Mission-Oriented Twin Transition: Directionality for Systemic Digital Innovation*" focuses on tentative empirical insights on the state of current problems and solutions in terms of the degree of actor consensus, role clarity and knowledge availability in the two case studies Energy Transition and Circular Economy.

Discussion paper: "*Selecting transformative policies: Acknowledging situational differences for policy design*" depicts - based on the example of the twin transition - a structured step-by-step approach for the design of mission-oriented policies including policy instruments and opportunities for policy learning.

Results: Mission-oriented innovation policies can direct digital innovation towards sustainable development. In order to do that, a variety of technological, economic, socio-cultural as well as political problems and solutions must be addressed. Across the analyzed case studies these issues vary significantly in terms of actor consensus, role clarity and scientific as well as practical knowledge. Therefore, policy makers need to be able to utilize a variety of policies to run successful missions. However, there is no "one-fits-all" approach to policy making in the twin transition. The situational differences for each case (e.g. circular economy, energy transition, etc.) must be taken into account in order to politically ensure the necessary alignment of actors and the rollout of systemic solutions - by choosing suitable instruments and ensuring synergetic management and policy learning in the twin transition.

Recommended Key Measures

Based on the findings from our project, we would like to recommend the following concrete key measures to drive transformative policy-making for the twin transition in Germany:

Implementation concept "mission-oriented policies for digitalization and sustainability" in Germany
The concept for mission-oriented policies for the twin transition must be detailed to prepare the application of such policy approaches in Germany. For this, an initiative is needed in which actors from science, civil society and politics are brought together with experts in mission-oriented policy across transformation areas and ministries. Through the exchange of information on current missions (incl. international practical examples) and the transfer to the concrete issues of digitalisation and sustainability, it should be worked out when and how mission-oriented policies should be used - but also in which contexts other (transformative) policy approaches should be applied. The current topics of "Digitalization for the Circular Economy" and "Sustainable AI" may be first use cases for this. The project could be organized by policy units in various ministries ("Grundsatzreferate Digitalisierung und Nachhaltigkeit") as well as by central actors in sustainability governance such as the Federal Chancellery ("Bundeskanzleramt") or specialized institutions such as the Federal Environment Agency ("Umweltbundesamt" (UBA)).

Policy learning on (international) governance best practices
Many countries have gained experience with the political and social shaping of the digital-ecological transformation. These insights into success factors, but also obstacles and risks, should be systematically tapped and used, e.g. by establishing a format for cooperation and networking between European and international policy actors and civil society with a focus on exchange of experience and policy learning. This offers the basis for know-how transfer, for instance, via selected projects that contribute to making change tangible and initiating it in political action. This initiative could be started, for example, by the Federal Environment Agency ("Umweltbundesamt" (UBA)) , which has already taken the first steps to explore the international governance landscape at the interface of digitalization and sustainability through the "CODES" project.

Synergies between transformation areas of digitalization

In all transformation areas (energy transition, mobility transition, industrial transition, etc.), diverse technological, economic, socio-cultural and political challenges must be overcome to effectively use digital technologies for sustainability. In part, they are similar and can be addressed through cross-cutting measures. At the same time, there are opportunities for synergies through learning and exchange of experience between the fields of application (e.g. what can a digital product passport rollout learn from a smart meter rollout?). We propose an initiative that links the digitization measures in different transformation areas and accompanies them across the board. The results can contribute to the avoidance of already known undesirable developments, the reduction of obstacles and the acceleration of the sustainability transformation via digital technologies. The project could also be organized by the above-mentioned policy units in various ministries ("Grundsatzreferate Digitalisierung und Nachhaltigkeit") as well as by central actors in sustainability governance such as the Federal Chancellery ("Bundeskanzleramt") or specialized institutions such as the Federal Environment Agency ("Umweltbundesamt" (UBA)).

Overview of the contributions

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Pursuing a Mission-Oriented Twin Transition: Directionality for Systemic Digital Innovation

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In a nutshell

In this study, we explore the problem-solution space of the twin transition. Based on the tentative results of two case studies, we are able to suggest several starting points for designing mission-oriented innovation policies at the interface of the green and digital transitions.

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Abstract

While digital technologies hold significant transformational potential, anecdotal evidence suggests that the digital transformation might not be directed towards sustainable development sufficiently. Drawing on a modified and extended version of the framework proposed by Wanzenböck et al. (2020), we explore the cases of the circular economy and the transition towards a sustainable energy system in the twin transition. Making use of insights from 20 expert interviews and two in-depth interviews, we aim to gain a first careful indication of the convergence/divergence in societal views on key problems and solutions across different dimensions (technological, economic, socio-cultural, regulatory) and derive insights for integrated policy-making. Thereby the study contributes to bridging the existing gap between mission-oriented policies and the twin transition. Overall, our first insights indicate that while showing high similarities in the structure of problems and solutions across cases, the variety in wickedness (contestation, complexity, uncertainty) calls for differentiated policy-making: Significant parts of the relatively young twin transition might be in a state of disorientation where societal views on problems and solutions diverge. This would require policy-makers to follow a "discovery-mode" (basic research, experiments and monitoring) with only selected diffusion-focused strategies. Further, we show that missions in the twin transition require highly flexible policy-making as different approaches need to be applied simultaneously. Finally, there are several options for exploiting synergies in policy-making due to some overlapping characteristics as well as learning opportunities between cases. We believe that particularly our holistic perspective on the twin transition can yield substantial guidance for researchers and policy-makers in the field.

1. Introduction

1.1. The CO:DINA project

As part of the "CO:DINA – Transformation Roadmap Digitalization and Sustainability" project, innovative approaches to promoting sustainable development of digital transformation are being researched. The researchers analyze the complex interactions between technology, society and the environment and look for ways to make digitization more sustainable. In terms of content and concept, CO:DINA contributes to enriching the scientific, social and political discussions surrounding sustainable digitalization.

The researchers are investigating which factors and framework conditions are crucial for making digitization sustainable and how these findings can be used for political measures. The main objective is to present the current state of research in the field of the interaction between digitization and sustainability by means of a research map.

1.2.Relevance and research questions

In the face of the sustainability challenges ahead, increasing evidence suggests that the low hanging fruits in the societal transformation towards a greener future are picked - in the years ahead a significantly higher pace of transition is required. Concurrently, the rise of digital technologies has led to substantial and fast systemic changes. The so-called "twin transition" relates to a political concept that calls for harnessing these transitional forces for sustainable development. It encompasses a systemic societal shift towards a more sustainable future that is driven by digital technologies. It assumes that the digital as well as green transition need an integrated management in order to exploit potential synergies. Additionally, this shift needs to account for fair social conditions and uphold economic competitiveness. At the heart of the concept is innovation in the technological, socio-economic, behavioral, cultural and regulatory domains of digitalization to enable sustainability transitions (like energy, agriculture, industry,...) (Muench et al. 2022).

Research on digitalization for sustainability is recently experiencing a significant uptake (Guandalini 2022). Studies suggest that digitalization may - beyond the risks it carries - indeed drive sustainable development (Ahmadova et al. 2022; George et al. 2021; Guo et al. 2022; Del Río Castro et al. 2021; Ren et al. 2021). Positive effects are ascribed to, for instance, rising technologies such as artificial intelligence (Vinuesa et al. 2020), blockchain (Parmentola et al. 2021) or big data (Beier et al. 2020), new digitally-enabled business models (Broccardo et al. 2023) and digital ecosystems (Addo 2022; Hellemanns et al. 2021) that enable a better and faster provision of information and operation. However, these positive implications will depend on how digital innovation is shaped (and how well the negative externalities of digital technologies can be kept at bay). This shaping depends on a strong political framework that helps maximizing the positive externalities of digital innovation (Ahmadova et al. 2022; Guo et al. 2022).

Such political framework could be needed in order to account for “transformational system failures”. From the perspective of Weber & Rohracher (2012), such instances complement the traditional view on rationales for political intervention for supporting innovation. These are on the one hand “market failures” that mostly relate to underinvestment into research. On the other hand, there are “structural system failures” that concern systemic issues producing feeble performance of the more broader innovation system (like missing infrastructure or institutions). However, in broad scope and long-term horizon system transformation “transformational system failures” need to be taken into consideration. They refer to failures in steering innovation towards desired long-term transformative change and pertain to issues of directionality, demand articulation, policy coordination and reflexivity (Weber & Rohracher 2012).

Insights from policy practice indicate that the twin transition might face such “transformational system failures”. For instance, the German project “Digitalization for sustainability” points out that “the European Union has set itself a Green Deal while at the same time it has tabled landmark legislations that address digital markets, digital services, data governance, or artificial intelligence. While all important and needed, none of them are systematically integrating the digitalisation and sustainability areas” and calls for clear and legitimate goals (Digitalization for sustainability 2022). Additionally, the twin transition is often discussed in terms of collections of potential use cases as opposed to holistically designed and targeted futures. For instance, Del Río Castro et al. (2021) points out that the interface of digitalization and sustainability is “still nascent, showing a fragmented and immature landscape, based on standalone pilots, unable to scale and mainstream as a solution to global challenges” (Del Río Castro et al. 2021).

Based on these insights, we suggest that the twin transition might suffer, in particular, from a directionality failure. It refers to a failure in defining a societal challenge, shared vision or other normative framework for guiding innovation processes. Thus, directionality originates from setting collective priorities that guide transformation processes (Weber & Rohracher 2012). It thereby represents a normative statement that pinpoints what issues are to be achieved or approached (Köhler et al. 2019) and might require amongst others detailed goals and a certain degree of agreement as well as support by the respective stakeholders (Wiek & Iwaniec 2013).

Directing systemic digital innovation towards sustainable ends would require a new type of innovation policies. As opposed to the more traditional focus of science and technology policies as well as innovation system policies on economic performance, this type would target innovation to tackle societal challenges (Diercks et al. 2019). From this point of view, setting direction means shaping actors' expectations of the future. Governance innovation in capacities, processes and organizational structures is required in order to mobilize talent, knowledge and other resources towards a societal issue (Fagerberg 2018).

Mission-oriented innovation policies (MOIP) have been suggested for setting direction (Mazzucato 2018; Janssen et al. 2021; Wittmann et al. 2021). Scholars from this stream have recently proposed that a closer look at problems, solutions as well as consens mechanisms should be at the heart of designing missions in order to provide directionality (Wanzenböck et al. 2020). This is in line with Weber & Rohracher (2012) which describe that directionality failures can be solved if societal requirements that are external to an innovation system are negotiated between actors and connected to finding the appropriate solutions (Weber & Rohracher 2012). We will therefore draw on MOIP literature to answer the following research question: a. What are currently the most relevant problems and solutions in the twin transition? b. What are the societal views on problems and solutions? c. How should potential missions in the twin transition be prioritized and designed based on these views?

1.3. Structure of the report

This paper is structured as follows: Reviewing relevant literature from the twin transition and mission-oriented innovation policy we will extend the framework proposed by Wanzenböck et al. (2021) making it applicable for the empirical study of selected cases of the twin transition. The subsequent section provides further details on the approach to the empirical analysis and discusses the rationale for the selection of circular economy and the sustainable energy system as diverse cases. The empirical section first presents detailed results on the two case studies that are later discussed against the background of its implication for MOIP and the twin transition in general, as well as potential ways for policy design.

2. Background

2.1. The twin transition

The notion of twin transition - being originally used in contexts such as transitions towards democracy, material sciences, and informatics - has been increasingly used to describe the interplay of digitalization and sustainability. In this regard the twin transition may be looked at from different angles: as a political concept aiming to connect digital change with sustainability transition or as an analytical perspective of (un)connected systemic change processes. However, this implies quite different perspectives and assumptions being rooted in different theoretical backgrounds.

The term of twin transition has particularly been coined by the European Union, using it as a political concept aimed at managing these on-going change processes in order to facilitate a change towards a more sustainable future aiming "to benefit from synergies and manage the risks" (Muench et al. 2022). This understanding of the twin transition as an approach linking different political agendas has also received uptake at the national and international level (e.g. BMZ 2022; WEF 2022).

However, the idea of a twin transition might also be approached from an analytical perspective. Even when departing from the idea of the EU twin transition, Fouquet & Hippe (2022) take a historical perspective to analyze the coinciding structural transformation processes in the field of ICT and sustainability and their possible interactions in Europe. From this perspective, the analytical lense focuses on on-going change and innovation processes affecting established modes of production and economic activity as well as the interplay between digitalization and sustainability (e.g. Bohnsack et al. 2021; Geels et al. 2021).

While speaking of a twin transition it is important to note that processes of digitalization and sustainability are not to be considered at the similar level. While transition towards sustainability can be understood as a policy-driven process that is actively shaped by deliberate decisions at the political level, digitalization is an on-going change process that is driven bottom-up by economy and private enterprises (Muench et al. 2022). Moreover, as Fouqet & Hippe (2022) highlight the two strands may run at different pace, with digitalization and ICT running ahead of sectoral transformation in energy systems.

At the same time, digitalization and sustainability may interact in different ways, emphasizing different kinds of prioritization and relationship: while digitalization may be a key driver for sustainability by providing new digital solutions, also sustainability thinking may have an effect on digitalization making ICT solutions more sustainable (Gensch et al. 2017; Sacco et al. 2021). In the context of the twin transition, some authors argue that digitalization and sustainability "are not equal twins, as the former is a means and the latter is an end" (Digitalisation for Sustainability 2022). At the same time, complexity may even increase as sustainability transitions are linked with additional goals. For example, the case of the EU twin transition is also linked to its growth agenda (Muench et al. 2022) making the twin transition both a vehicle for sustainability transition and economic considerations of the EU. This has been criticized for creating potential tensions between different goals (Digitalization for Sustainability 2022)

Closely related to the previous point, the twin transition may be understood differently because it facilitates transformation processes in different areas. The EU approach of the twin transition emphasizes the need for an integrated approach in order to mitigate risks and use potential synergies between the two fields (Muench et al. 2022) aiming to mobilize those for sustainability. However, as a recent report (Digitalization for Sustainability 2022) argues, a twin transition approach might not only require a mobilization of digital solutions for sustainability, thus rely on technological innovation alone, but also require a comprehensive transformation of consumption and production patterns. In consequence, integration may range from mobilizing digitalization for sustainability to a systemic transformation that encompasses the field of ICT, its structures and practices itself.

Table 1 summarizes these two possible (ideal type) lenses, pinpointing different perspectives on the nature of the twin transition. While acknowledging these different access points, our main focus in the following follows the rather narrow understanding of the twin transition as a political concept.

Perspectives	TT as analytical frame	TT as a political concept
Main driver	Combination of top-down and bottom-up dynamics	Policy-driven sustainability agenda (in combination with other goals like growth)
Relationship between digitalization and sustainability	Parallel co-existence of dynamics that interact at different points and develop with different speed	Digitalization as a mean to support sustainable development
View on unintended effects	Part of analysis	Mitigation/anticipation of risks to faciliate sustainability outcomes
Scope of changes	Both in ICT and the relevant sector	Primarily in the relevant target sector (e.g. energy)

Table 1 . Different lenses of the twin transition;
note: TT = Twin transition, ICT = Information and Communication Technology.

Finally, we suggest that the twin twin transition may be understood from a horizontal and vertical perspective. On the one hand, from a vertical perspective the twin transition might be relevant for different fields of transition, like agriculture, cities, industry, etc. On the other hand, the twin transition might be perceived as horizontally cross-cutting different sectors and fields. For example, the twin transition might be analyzed from the perspective of services and infrastructure that might be relevant for different fields of transition.

2.2. Mission-oriented innovation policies

Mission-oriented innovation policies represent a departure from former policy paradigms. Schot & Steinmüller (2018) describe that innovation policies evolved in three steps:

1. After World War II, innovation was more and more understood as a source of economic growth. Public policies were seen as instruments for amending the fact that private actors might not provide socially desirable amounts of investments into scientific research. Thus, the state's task was to fix such public good related market failure via funding of basic research and business

research and development (R&D). The role of science was to produce knowledge without alignment with the usage of their developments. And private actors turned scientific inventions into commercializable products that drive economic growth.

2. After the war, competitiveness of domestic firms was brought into focus. A deeper understanding of innovation shifted attention towards industrial structures and the interaction between actors along with a stronger emphasis on the use-side of scientific knowledge. Innovation policies supported learning between private actors as well as the formation of entrepreneurship, thus, complementing funding for invention with driving diffusion. In both described paradigms (mostly technological) innovation leads to welfare and the state fixes the remaining negative externalities to achieve optimal social results

3. Recently, social and ecological development were prioritized on the innovation agenda. The underlaying assumption is that technological innovation alone will not lead to sufficient societal sustainability outcomes. A broad pool of inter- and transdisciplinary stakeholders are to be involved in wide-spread activities to produce socio-technical innovation encompassing technological, economic, cultural, behavioral and regulatory dimensions (Schot & Steinmüller 2018).

MOIP evolved as an approach for particular endeavors, often for achieving prestigious or ideological goals (e.g. during Cold War). As such, well defined missions with a technological focus e.g. in aerospace (like landing a man on the moon) or defense were set up. These missions focused on technological achievements and were developed by a smaller group of actors. They were not meant to diffuse outside this circle and control was centrally held by governmental actors. In the past years, a different notion of mission-orientation has increasingly gained popularity that aimed to link missions to addressing societal challenges. Accordingly, they involve a broader set of actors and push for diffusion of systemic solutions (Mazzucato 2018; Fisher et al. 2019). Current typologies of MOIP therefore distinguish between accelerator (technology-focus & relying on more traditional science and technology funding instruments) and transformer missions (system-focus & involving a wider set of policies) (Fisher et al. 2019; Wittmann et al. 2021). In the following paragraph we will outline key building blocks of MOIP.

First, MOIP seek to create *directionality*. However, a closer look at the relevant literature reveals that it is yet to be determined by what mechanism. There seems to be relative clarity on ambitious, well defined and measurable goals as a way of guiding smaller scope technology-focused missions (e.g. Diercks et al. 2019; Schot & Steinmüller 2018; Robinson & Mazzucato 2019). At the same time, whether such goals can guide larger societal missions remains unclear. Some authors endorse the setting of concrete targets that allows actors to direct their activities towards them (e.g. Mazzucato 2018; Hekkert et al. 2020; Wittmann et al. 2021). This point of view corresponds, for instance, with the current EU missions as part of the Horizon Europe programme (e.g. 100 Climate-Neutral and Smart Cities by 2030) (EU 2023). Others relate to transformer missions as open-ended challenges in which setting goals might lead to choosing the wrong path. In this case, a strong focus is set on bottom-up initiatives (Kuhlmann & Rip 2018; Schot & Steinmüller 2018). Critics of the latter perspective argue that urgency needs to be taken into account when deciding whether setting concrete goals is required. For instance, Reale (2021) argues that "these propositions suppose that the time and pace that these modes of governance require overlap with the time and pace that the challenge which they are tackling allows" (Reale 2021).

Second, MOIP rely on organizational structures and processes that enable *policy coordination and implementation*. Kattel & Mazzucato (2018) describe three essential dynamic capabilities that missions rely upon: 1. They require the engagement of a wide variety of actors in decentralized bottom up activities that still contribute to the overarching goals as well as adaptability to changing conditions. 2. They are in need of coherent policy instrument mixes and experimentation particularly focusing on the demand-side 3. They have to bring together knowledge from formerly unrelated areas in the management of missions (Kattel & Mazzucato 2018). Larrue (2021) analyzed various MOIP initiatives and shows that organizational and procedural set ups vary significantly between cases. These set ups depend on the overall nature of the initiatives like more overarching mission frameworks or more focused missions. He finds that in all cases are coordinated via multi-level steering mechanisms like cross-ministerial or cross-agency approaches. Furthermore, the cases implemented portfolio management to give room for exploring alternative options. Moreover, the initiatives are not started from scratch but built on existing policy landscapes (Larrue 2021).

2.3. Contextualizing Missions: The problem-solution-space

In this study, we follow the underlying assumption that the twin transition might miss directionality. Recently, Wanzenböck et al. (2020) conceptualized a framework which allows to understand whether a societal challenge faces a directionality failure. The authors call for a process-based perspective, arguing that challenges might face different constellations of converging/diverging perspectives and therefore require different policy approaches. This section first outlines the main foundations of the framework and discusses multiple adjustments to the framework that are necessary for a detailed empirical analysis. Figure 1 shows the framework.

The framework proposes that missions should be contextualized by taking into account the problems as well as solutions at the heart of a respective societal challenge. Arguing that "societal challenges may fundamentally differ in nature" (Wanzenböck et al. 2020) as the convergence or divergence of views on problems and possible solutions depends on the respective degree of wickedness. The degree of wickedness of a problem or solution relates to a. whether it is agreed upon or contested by actor groups (*Contestation*) b. whether the problem or solution faces limited or substantial systemic situational or institutional complexity (*Complexity*) c. whether knowledge on the problems and solutions is sufficient or insufficient and solutions are available or not available (*Uncertainty*).

This differentiation allows to open up a two-dimensional space with the degree of wickedness of problems on the horizontal axes and the degree of wickedness of the solutions on the vertical axes. In addition, by differentiating between a high degree of wickedness (Convergence of societal views) and a low degree of wickedness (divergence of societal views) the problem-solution-space can be divided into four quadrants, representing different constellations of problems/solutions: a. disorientation (problem and solution wickedness high) b. problem in search of a solution (problem wickedness low, solution wickedness high) c. solution in search of a problem (problem wickedness high, solution wickedness low) d. alignment (problem and solution wickedness low). Different societal challenges may be localized at different positions in the problem-solution space providing distinct implications for policy design.

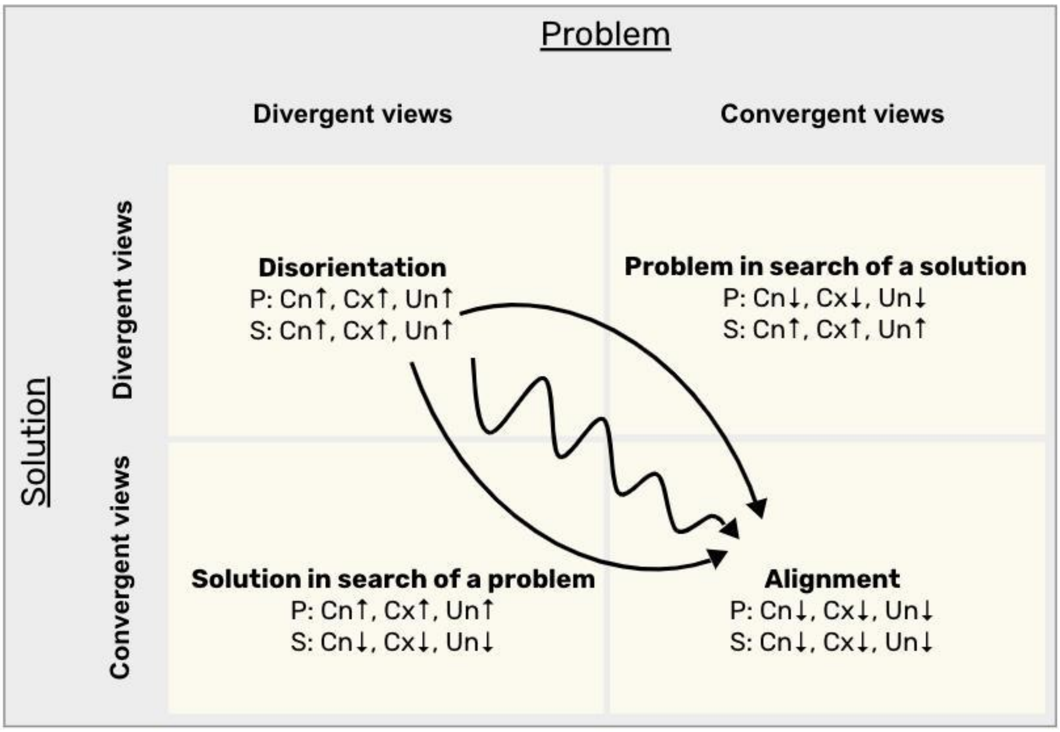

Figure 1. Problem-Solution-Space including wickedness;
note: The diagram shows three pathways how societal challenges can develop from the stage of disorientation to the stage of alignment. Within the quadrant, the wickedness of each stage is depicted. The wickedness is shown on the basis of the three criteria contestation, complexity and uncertainty as well as their degree of expression (high/low).; P = problem, S = solution, Cn = Contestation, Cx =Complexity, Un = Uncertainty, ↑ = high, ↓ = low.
Source: Own diagram based on Wanzenböck et al. (2020), p. 484

Calling for a process-oriented perspective, Wanzenböck et al. (2020) describe three stylized pathways how societal challenges may evolve from the stage of disorientation towards alignment. a. A problem-led pathway that moves from a convergence of views on problems towards alignment b. A solution-led pathway that indicates an increase in convergence of societal views on solutions before convergence on problems c. a hybrid pathway following a co-evolutionary logic aimed at increasing consensus on problem and solutions simultaneously. Finally, the framework suggests that in case of alignment, diffusion of the agreed solutions for solving the agreed problems should be the goal of policies.

Considering the presented framework, we propose several clarifications and extensions to the framework, to further enhance its potential for empirical analysis:

a. *Connection between problems and solutions:* Wanzenböck et al. (2020) suggest to locate societal challenges in the problem solution space which might then - with the help of MOIP - take different pathways. However, their examples imply a disconnection between problems and solutions. For instance, they describe autonomous vehicles as agreed upon solution while the problems it was suggested to solve varied over time (comfort and safety, increased labor productivity, higher capacity of highways, etc.) so that they are not related to a specific societal challenge. In consequence, it may be difficult to locate a societal challenge in the problem-solution space and trace their development over time, as solutions in search of a problem may emerge independently from the underlying challenge. For example, how can "sustainable agriculture (as suggested by Wanzenböck et al. 2020) be located in disorientation, if problems as well as solutions are not clear. And how could it then move in the space if it might become an entirely different challenge in case problems and solutions change? We therefore suggest to limit the focus on problems and solutions to aspects that are related to the underlying societal challenges (like problems with regard to agriculture and solutions for sustainable agriculture).

b. *Different sources and constellations of wickedness:* Locating a societal challenge in the four quadrants might not be sufficient in order to contextualize MOIP. First, currently the quadrants as well as policy implications do not regard detailed wickedness scenarios for the overall challenges like combinations of low contestation and low complexity but high uncertainty. This has profound implications for policy-making as a high level of contestations (e.g. driven by different sectoral interests/path dependencies) might require a different approach than a situation that suffers from a lack of scientific knowledge. For instance,Is a mission with well-defined goals still feasible if there is little scientific knowledge on problems? We therefore propose to account for the different origins of wickedness, aiming to analyze different possible constellations. In consequence, this also implies that societal challenges might not only be positioned in different quadrants, but also may exhibit different locations within these quadrants.

c. *Multidimensionality of problems and solutions:* Moreover, while taking a broader perspective to system change beyond technological developments, wickedness is only assessed for problems and solutions in general. However, such aggregated perspectives may overlook the fact that potential developments may occur at different levels, entailing the risk of overly focusing e.g. on a single problem or group of actors. Hence, we propose a more detailed view on wickedness by analyzing technological, economic, socio-cultural and regulatory problems and solutions.

d. *Accounting for varying starting points for policy-making*: While the proposed stylized pathways are of great analytical value to trace development over time, they provide little guidance for policy-making for constellations of disorientation. Therefore, we propose to take the location in the problem-solution as the starting point to clarify four potential policy approaches: a) In case of disorientation we consider a co-evolutionary approach, as proposed by Wanzenböck et al. (2020) as most appropriate, given the high urgency of the underlying challenge and the need to maintain openness in the face of uncertainty. Both a purely solution- or problem-oriented approach in this context would be at risk of blocking potential avenues of development. In contrast, for problem in search of a solution or solution in search of a problem potential policy approaches might be problem- and solution oriented transformer missions (Wittmann et al. 2021) respectively. A problem-driven approach would imply the definition of a goal to be achieved, aiming to mobilize different approaches and experimentation to develop appropriate solutions and ensure market creation for an uptake of the to-be-developed solutions, by creating a favorable environment e.g. by appropriate regulation, standardization, public procurement etc. In contrast, a solution-driven approach would instead depart from a promising solution, trying to bring this solution into application, potentially in different areas. Therefore, the focus is less on new developments, but rather the integration and accelerated uptake into different areas, to explore in which way the solution can contribute to overcoming the key problems. In case of alignment, we side with Wanzenböck et al. (2020) that diffusion-oriented policies might be sufficient to further facilitate the necessary changes. A brief preliminary overview of potential policy approaches is given in the appendix (see Table A.1 in the appendix).[1]

[1] However, it is important to note that constellations within different dimensions (economic, political, technological, socio-cultural) may vary, so that different combinations of elements might be necessary for an integrated policy approach. Moreover it is obvious that all suggested approaches require flexibility and reflexivity, allowing to react to changing external (e.g. economic shocks) and challenge-specific (e.g. novel developments, setbacks with promising solutions etc.) context conditions.

3. Methodology

We follow a two-step approach in the current study. In two case studies, we are going to, first, identify key problems and solutions and, second, evaluate their wickedness in order to construct a problem-solution space for the twin transition. Overall, as there is rather little research on the twin transition as a systemic concept (technological, economic, etc.) we will conduct a qualitative approach to gain a first understanding on the relevant elements and potential relationships. In the following section, we will detail our approach.

3.1. Case studies

We decided to select contrasting or diverse cases in order to capture the twin transition more holistically and allow for analytic generalization (Yin 2014; Seawright & Gerring 2008). Thereby, we take a perspective of the twin transition as a concept that might strive for change in different transition areas (vertical perspective on twin transition). We chose "digitalization for the circular economy" and "digitalization for a sustainable energy system" in Germany for the following reasons: a. *Sustainability focus:* The circular economy has a strong resource focus while the energy system emphasizes energy flows b. *State of development:* The circular economy is a rather young phenomenon while the energy debate prevails for quite some time c. *Public awareness*: The debate on circular economy is not as public as the energy debate (e.g. on the German "Energiewende" in general or, for instance, spatial requirements of wind turbines). Accordingly, we expect variation across problems and solutions as well as wickedness elements that will allow to make assumptions on the twin transition as a whole.

3.2. Identifying problems and solutions

After considering potential analytical approaches and data sources, we believe that expert interviews with an inductive coding approach might serve best to assess the problems and solutions in our case. That is because a. For some dimensions (e.g. regulatory) there might not be sufficient data available in other sources (e.g. due to a traditional focus of research in these areas on technological issues) b. some potential data sources (like websites) often don't allow a detailed analysis c. data sources might only exist for one but not the other case (e.g. as circular economy is a rather young phenomenon) d. a deductive approach would require established frameworks which is not the case for all systemic dimensions e. the multifaceted nature of the object of research in this study could in other scenarios restrict realizability due to cost-efficiency issues.

We conducted 20 Interviews (10 for each case) have been conducted and processed. The participants were selected via purposeful sampling (Palinkas et al. 2015). The selection process focused on, on the one hand, their assumed knowledge on the respective cases and systemic dimensions. Suitability was assumed if publications (scientific or otherwise), position descriptions or project contributions were topic specific. On the other hand, we consider their background. We balance actors from science, technology users, technology providers, civil society actors and politics. Additionally, we try to take into account case specific supply chains. We focus on a balanced sample on the case-level, not the level of systemic dimensions. The participants self-selected the systemic dimension in which they assumed to possess most expertise. Table 2 shows the backgrounds of the interviewees.

	Circular Economy	**Energy**
1	Association (waste management)	Research (Digitalization for Energy Systems)
2	Technology Provider (Digitalization for Circular Economy, small-medium)	Technology Provider (Digitalization for Energy Systems, small-medium)
3	Research (Digitalization & Circular Economy)	Consultancy (Energy Systems)
4	Technology Provider (IT-Services, large)	Research (Digitalization for Energy Systems)
5	Research (Business Administration & Circular Economy)	Research (Digitalization for Energy Systems)
6	Research (Sustainability & Circular Economy)	Research (Sustainable Energy Systems)
7	Technology Provider (Digitalization for Circular Economy, small-medium)	Research (Sustainable Energy Systems)
8	Research (Recycling)	Research (Digitalization for Energy Systems)
9	Technology Provider (Digitalization for Circular Economy, small-medium)	Association (Energy)
10	Technology Provider (Digitalization for Circular Economy, small-medium)	Research (Digitalization for Energy Systems)

Table 2. Background of the interviewees.

The interview guideline was based on the process proposed by Kallio et al. (2016) including internal testing and expert assessment (Kallio et al. 2016). Interviewees answered questions on the core problems as well as solutions (see questions on interview slide in Table A.2 in the appendix). In line with established coding procedures (e.g. Corbin & Strauss 2015), we suggest that problems and solutions should be detailed as diagrams with dependent elements to fully understand the underlying relationships. Based on Kim & Andersen (2012), we visualized every interview in the whiteboard tool Miro (four diagrams per interview; 80 in sum) and then built consolidated path dependent diagrams for each problem-dimension combination (8 diagrams in sum for the current state) following several steps: *Per Interview:* 1. Conducting interviews with two interviewers (incl. audio recording & taking detailed notes) 2. After the interviews, collaboratively building first level elements 3. Sketching interdependencies with ("leads to" arrows). *Consolidation:* 1. Merging all problem diagrams and all solution diagrams per systemic dimension 2. Building clusters 3. Ascribing titles to the newly established diagrams.

3.3. Evaluating the wickedness

Due to the exploratory character of this study we consider our results as first indications that need to be double-checked with a more robust empirical setting. At this point, we conducted an in-depth interview per case with experts that have generalist knowledge in the respective cases and had not been part of the original interviews. We operationalized the wickedness dimensions via level of consensus (Contestation), clarity of actor responsibilities (Complexity) and sufficiency of (scientific) knowledge and evidence. The experts evaluated each wickedness dimension for each of the 8 diagrams with rather high/rather low and gave a short explanation for each answer (see questions in Table A.3).

4. Results

4.1. The case of the circular economy

The circular economy concept refers to "an economic system the linear supply-chains that replaces replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes" (Kirchherr et al. 2017). Compared to current linear economies, it encompasses changes at several societal levels from consumers and companies to cities or nations and beyond). The concept targets all dimensions of sustainability, thus the social, ecological and economic dimensions (Kirchherr et al. 2017). The most relevant drivers of the circular economy are the so called "R-strategies" by that seek to improve manufacturing processes and product use (Refuse, Rethink, Reduce), extend the lifetime of products (Reuse, Repair, Refurbish, Remanufacture, Repurpose) and push for a better application of materials (Recycle, Recovery) (Morseletto 2017). These new strategies particularly require new configurations of supply chains and actor interaction (Govindan & Hasanagic 2018). There is growing recognition that digital technologies might provide substantial contributions for a path towards a circular economy (e.g. Awan et al. 2022; Rejeb et al. 2022; Van Schalkwyk et al. 2018). In this case, we analyze the underlying problems as well as solutions of applying digital technologies to increase circularity. The expert interviews yielded several key problems and solutions along the predefined systemic dimensions (see Table 3 for a summary).

4.1.1. Problems and solutions

Technological: From a technological perspective, the circular economy mostly seems face issues regarding the availability of information. Particularly, product-related information gaps hinder the application of the R-strategies. Actors can often do not have the required information on products, components or materials. Products can not be identified, and insights on how they were affected in production or use as well as their composition often remains unknown. What hinders sufficient data sharing is related to data (varying formats, common data vocabulary and data infrastructures), access (missing interfaces, difficulty in finding information in databases, missing access rights) and development-processes (uncertain development context). A central issue emerged around waste streams. Often there is little transparency on small quantities are decentrally stored and don't reach a "critical mass" for being fetched and processed. For more complex products, processes and product use cases these issues seem to be amplified. Concerning solutions, a "digital product passport" is recommended. Based on standardized data sets, data vocabulary and unique identifiers actors may feed product-related data into the passport and retrieve data in a user-defined manner which will allow R-strategy implementation and thereby resource efficiency. Low bureaucratic burden and opportunities through rising technologies are relevant context factors. Another important solution might be found in artificial intelligence which could unify data and correct data-related errors which often come about due to varying data handling of respective actors. Additionally, digital automization might help companies to comply with bureaucratic demands and real-time insights on waste composition and amount could improve waste management.

Economic: One core economic issue appears to be a false allocation of environmental costs. The costs of issues that are brought about by resource extraction, processing and its end of life are not allocated to the respective phases of the product life cycle (e.g. producers don't need to take waste management into their calculations). Furthermore, there is a lack of circular business models as linear business models are still profitable, there are difficulties in promoting (green washing assumption) or assessing the value (more complex business models) of circular products, actors miss courage to try new things or fear the consequences and protect even currently untouched data due to potential future competitive advantages. As for solutions, digital platforms should be built that allow efficient, secure and traceable collaboration and data sharing. They require an ecosystem with supporting services (like insurance models), researchers support, customer trust and readiness and digitally-driven learning environments for circular business models. These platforms might facilitate subscription business models (e.g. pay per use or outcome) and trigger new ways of selling bundles of goods and data. As a result, the respective actors are incentivized to push for the implementation of R-strategies.

Socio-cultural: Many consumers don't have a detailed understanding of the waste they produce or what it causes. Additionally, missing transparency on waste streams (like filling levels of bins) means uniform billing, thereby some pay for others. Thus, they don't proactively engage in reducing their waste and waste amount increases and waste separation is unfavorable from an environmental point of view. Furthermore, missing transparency results in large waste trucks causing visual and olfactory annoyances. Another issue concerns a fear of the future that some actors experience. As for instance, if residual waste is reduced those actors responsible for managing it become obsolete. Finally, a missing vision for a circular economy and thereby for the roles of individual actors further increases the fear. As a solution, particularly for the first point, digitalization of waste bins, trucks and processes is suggested. It might allow monitoring waste amount and composition in real-time. This might give consumers the information they need to adjust their behavior in line with more sustainable patterns.

Regulatory: Several issues pertain to the regulatory system dimension. For one, poor communication between Germany and the EU in terms of stating clear requirements towards EU decision makers seems to be an issue. Moreover, clear indicators in EU regulation are often missing. Another cause of insufficient policies lies in the relatively strong lobby activities of manufacturing companies compared to end-of-life operators as well as too little stakeholder involvement in policy-making. Additional problems are, on the one hand, slow regulation leading to uncertainty on the side of business actors which inhibits investments into digital solutions for the circular economy. On the other hand, more regulation causes bureaucratic burdens for companies which might overwhelm them. As for solutions, supply- and demand-side policies should be applied. These should be combined carefully from a policy mix perspective. Their goal should be to support the disclosure of data while maintaining profitability of the respective companies.

Dimension	Problem	Solutions
Technological	Weak circularity due to missing product-related information; Hindered data sharing between actors along supply chains due to data-, data access- and development process-related issues; Decentralized waste streams hindering implementation of R-strategies	Standardized product passports as enabler of product-related transparency and circular R-strategies; Architecture for artificial intelligence enabling error-free data sharing; Digital automation for efficient compliance with regulatory demands; Digitally-enabled waste transparency leading to more efficient waste management processes
Economic	Limited sustainable actions due to false allocation of environmental costs; Profitable linear business models, firm- & consumption-side perceptions and problematic value evaluation leading to a lack of circular business models	Digital platforms and ecosystems enabling subscription business models and implementation of R-strategies

Table 3. Circular economy case: problems and solutions (part I).

Dimension	Problem	Solutions
Socio-cultural	Digital optimization and missing circular visions leading to actors fearing the future; Lack of waste transparency causing environmental and social flaws due to insufficient consumer responses and annoyances	Transparency of waste streams as starting point for process improvements that enable consumers to adjust behaviors
Regulative/ political	Weak policy support for digitalized circular economy due to multi-level issues and unfavorable stakeholder involvement; Slow regulation causing uncertainty for companies that in turn hinders investment; Increasing bureaucratic burdens for companies due to regulation	Supply- and demand-side policies preserving environmental and economic balance for increased circularity

Table 3. Circular economy case: problems and solutions (part II).

4.1.2. Problem-solution-space of the circular economy case

By discussing these results in the expert workshop, we elaborated a first prototypical problem-solution-space for the circular economy case. We will locate and describe each dimension in the space. We will detail the reason for the location for each dimension (see Figure 2) by showing the degree con-/divergence (Contestation (Cn↑↓), Complexity (Cx↑↓), Uncertainty (Un↑↓). A detailed overview can be found in Table A.3 in the appendix.

In the technological dimension, societal views on the missing data and weak data sharing as problems might diverge as some actors could rather see issues with other data related tasks (like gathering or integration), roles behind data-related tasks might be unclear and empirical evidence is lacking (P: Cn↑, Cx↑, Un↑). For digital product passports, AI-supported data sharing and other solutions, unclear roles related to data and the relatively young field of AI as well as insufficient scientific knowledge due to mostly ongoing initiatives lead to divergence. Albeit, there is consensus particularly on the digital product passport (S: Cn↓, Cx↑, Un↑).

In regards to the economic dimension, we could assume a potential convergence on the false allocation of environmental costs in the linear economy as well as barriers to circular business models. However, there is limited scientific evidence on the interface of digital business models and circular economy (P: Cn↓, Cx↓, Un↑). For the solutions, namely digital platforms enabling subscription models, societal views might diverge, particularly due to various actors trying to establish a dominant role and insufficient research (S: Cn↓, Cx↑, Un↑).

From a socio-cultural perspective, especially fear of the future as an issue might be contested as many might rather see opportunities. Also, who is responsible for potentially unsettled actors remains uncertain. Still, looking at waste management there is relevant scientific work on the matter (P: Cn↑, Cx↑, Un↓). Societal views on increasing the transparency of waste streams might diverge. That is because sorting could be prioritized over consumer-oriented solutions and knowledge on behavioral adjustments in the context of the circular economy is rather insufficient. However, in waste management due to regulation and state-ownership roles are quite clear (S: Cn↑, Cx↓, Un↑).

Finally, on the regulatory side, responsibilities behind multi-level issues, slow regulation and bureaucratic burdens might often be unclear on the German side as cross-departmental and -ministerial collaboration is often missing in Germany. Additionally, research on governance of digitalization and circular economy is barely available. Still, the issues are often debated in workshops or other meetings (P: Cn↓, Cx↑, Un↑). Supply- and demand-side policies that preserve business opportunities are agreed upon and responsibilities between EU and GER are rather clear (S: Cn↓, Cx↓, Un↑).

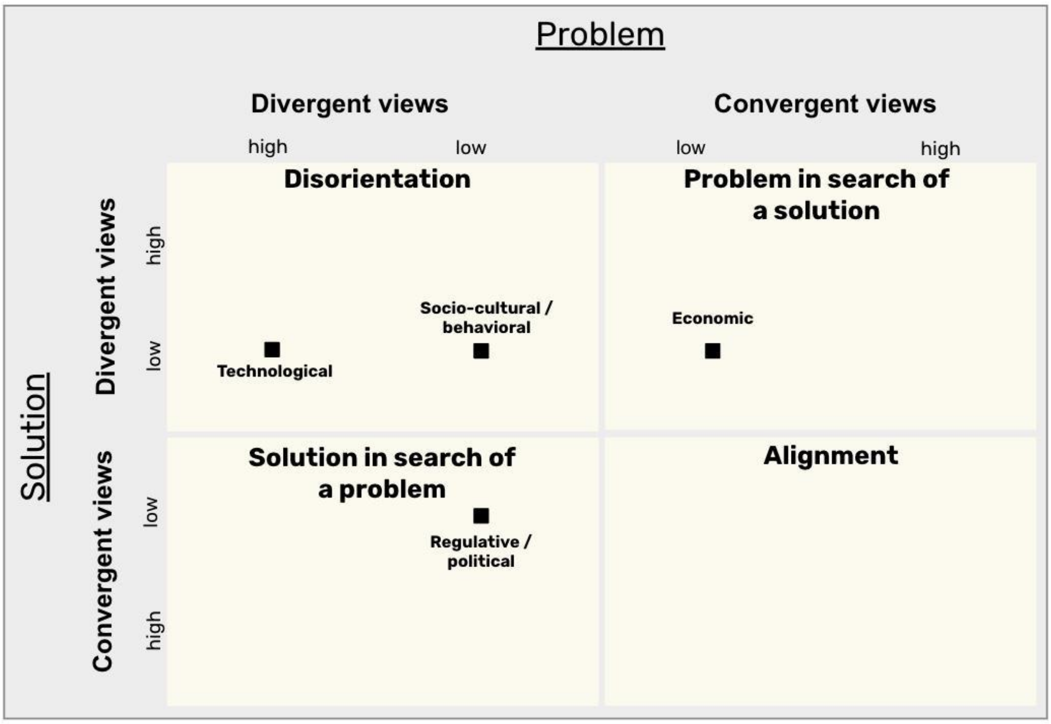

Figure 2. The problem-solution-space of the circular economy case;
note: The four dimensions (regulative/political, technological, socio-cultural/behavioral, economical) are located within the quadrants of the two-dimensional problem-solution-space. The classification into category high or low refers to the amount of high/low evaluations of the wickedness dimensions (e.g. two times high -> low in the figure; three times -> high). Two or three times high/low means an allocation in di-/convergent views (see Table A.4. in the appendix).
Source: Own diagram based on Wanzenböck et al. (2020)

4.2. The case of the sustainable energy system

The "Energiewende" is the key leitmotif for the transition of the German energy system towards sustainability (Strunz 2014; Rogge & Johnstone 2017). Comprising the gradual phase-out of nuclear energy and support mechanisms for renewable energy since the 2000s, it recently has been complemented by a planned phase-out of coal until 2038 to meet climate goals. While these phase-out processes are to be driven by technological change (shift towards different sources of renewable energy production), such change processes challenge established actors roles and constellations, business models, and behavioral patterns of consumers (e.g. Markard 2018). At the same time, there is globally a growing attention to the role digital technologies may play for the transition towards a more sustainable system of energy production (e.g. Kangas et al. 2021; Nižetić et al. 2023). This second case study explores the problems and solutions of applying digital technologies to facilitate the transition towards a sustainable energy system. Drawing on expert interviews with focus on the four key dimensions, the main issues with and solutions by digitalization were the following (see Table 4 for a summary).

4.2.1. Problems and solutions

Technological: The major technological issue with regard to energy transition was identified in the incompatibility of the existing energy grid with the newly emerging requirements that arise from an increasingly decentralized energy production on the one hand and new patterns of energy consumption, e.g. by heat pumps, on the other hand. Lacking the means for a more flexible load management due to insufficient monitoring/steering options and the increased but volatile energy flows in distribution grids that were not designed for this purpose, will increasingly put the energy grid in its current form under pressure. Digitalization in this regard is considered as a means to improve grid management by an improved flow of information between the different actors that also allows to incorporate and automatically handle the large number of new, decentralized energy producers. Thereby, it could alleviate the problem of providing costly overcapacities due to peaks in a system with volatile energy production. Besides these major aspects, the impact of decentralization was judged differently by some of the interviewees. Whereas some interviewees pointed to the potential increase of resilience of energy systems emerging through digital interconnectivity of a decentralized system, other interviewees argued that the increased numbers of actors in the energy sectors increases the risk for cyber attacks, particularly if these small energy producers are not considered and regulated as critical infrastructure.

Economic: Among the major obstacles from an economic point of view the interviews pointed to two major aspects. Firstly, insecurity whether investments will financially pay-off, as necessary overcapacities might not be sufficiently rewarded by high prices in peak times. Secondly, the limited market integration of different stakeholders, including small energy producers (e.g. from PV) as well as actors being active in the field of local energy storage systems. At the same time, it was assumed that digitalization in the energy sector could help to better integrate different stakeholders in the market system by automatically handling market preferences of different actors, a flexibilization of energy consumption through dynamic pricing, and the emergence of new business models, e.g. by local marketing of produced energy. These advantages leading to an improved handling of volatility might also increase overall efficiency resulting in economic savings, as it might reduce the need for expanding the energy infrastructure.

Dimension	Problem	Solutions
Technological	Increased volatility in decentralized energy production incompatible with existing grid (management) structure; Increased vulnerability through decentralized systems with low levels of protections	Improved grid management by accelerated information exchange and involvement of small producers/actors; More resilient energy system through digital interconnectivity
Economic	Insecure pay-off for the provision of overcapacities of renewables due to uncertainty about recompensation for prices in high-demand situations Limited market integration of stakeholders (producers, energy storage)	Improved information sharing as a mean to create new business models and generate economic savings
Socio-cultural	Lacking incentives, information and narratives to limit energy consumption; Limited incentives for flexibilization of energy consumption	Digitalization/automatization to reduce human error and strengthen user involvement; Information provision to change consumer behavior
Regulative/ political	Insufficient administrative, political and regulatory processes and priority setting	Accelerating digitalization of energy system by improved regulation, data-trustees, experimental approaches, improved processes and smart meter roll-out; Re-orientation of priorities towards robustness of energy systems instead of cost efficiency

Table 4. Energy case: problems and solutions.

Socio-cultural: A first problem identified in the dimension of socio-cultural aspects are general concerns about energy consumption in general. Relating e.g. to "rebounce" effects and unfavorable narratives, as well as lacking information, households may put additional pressure on the energy system. An increased demand for energy consumption may put additional pressure on the energy system. This problem may be reinforced by the limited roll-out of smart meters in Germany that might be a prerequisite for the provision of detailed information. A second consumer-related aspect might be the limited flexibilization of energy consumption that suffers from a lack of incentives, like flexible pricing schemes and the fact that individual optimization of energy consumption might not necessarily be in line with systemic goals (e.g. loading electric vehicles simultaneously by different consumers). From this perspective, a digitalization of household devices and their automated control might help to overcome human-related errors in use and limited capacity to implement adjustments manually, while optimizing device setting and identifying defective devices. Moreover, digital solutions may help to visualize and provide relevant consumption information and therefore contribute to changing consumption patterns.

Regulatory: At the political level, the interviews identified multiple factors inhibiting a faster digitalization of energy systems. Potential problems include a low political awareness and prioritization and a primarily on security issue focused regulation (particularly in context of smart meters). In combination with change-averse actors (in politics and beyond) this did not create a favorable environment for the introduction of basic digitalization solutions that in the longer run might have led to positive feedback effects through new business models, improved data exchange etc. This problem was reinforced by the fact that the strong silo structure of ministries and the established working routines made it difficult to reach a problem-oriented consensus in a situation that involves a large variety of different sectors and stakeholders. Tackling these issues to facilitate favorable conditions for a more digitalized energy system that may then also lead to new solutions and business models is linked to different requirements. Among the aspects mentioned by interviewees were clear public support, a problem-oriented regulation, possible solutions to collective action problems (data trustees) and an approach relying more on experimentation to identify new solutions. Moreover, it was pointed out by some interviewees that the shift towards an decentralized energy system may make it necessary to challenge existing paradigms shifting from (economic) optimization towards a greater system stability/resilience.

4.2.2. Problem-solution-space of the sustainable energy system case

The following paragraphs details the wickedness of problems and solutions problem-solution-space for the energy case. Figure 3 shows the location of each systemic dimension.

First, the technological dimension seems to be clearly running ahead of other analytical dimensions regarding converging views. Sharing high degrees of convergence both on the problem (increased volatility in grids) (P: Cn↓, Cx↓, Un↓) and the potential contributions of digitalization to improved grid management and tackling peaks in energy production (S: Cn↑, Cx↓, Un↓), places technology in the quadrant of alignment. The main issue of contestation remains the balance between upgrading the existing network vs. an increased digitalization. Based on these results, it might be argued that from a technological perspective the way forward is already rather clear, whereas the main bottleneck at the moment appears to be the remaining dimensions where convergence is less pronounced.

For the economic dimension, that was found to be located in the upper right quadrant (problem in search of a solution). While on the problem side the question of integration of different actors are still contested despite limited levels of complexity and uncertainty (P: Cn↑, Cx↓, Un↓), the main issue remains a limited convergence on the solution side (S: Cn↑, Cx↓, Un↑). Above all, the main issue for contestation and uncertainty remain the costs associated with digitalization in comparison to the option of infrastructure upgrading.

In a similar vein, the dimension of socio-cultural aspects is affected by rather low convergence. On the problem side (P: Cn↑, Cx↓, Un↑) the key issue remains to what extent households should be taken into consideration, exhibiting only limited knowledge about possible consumer behavior in a new setting. This represents the clash of two fundamental paradigms, representing behavioral change vs. technological adjustments. These problems also translate to the solution side suggesting that there is little convergence due to high contestation and high uncertainty about the implications of digitalization (S: Cn↑, Cx↓, Un↑).

Finally, similar to the socio-cultural aspects, also the area of political/ regulatory aspects can be found in the quadrant of disorientation, showing low degrees of convergence in all dimensions on both the problem (P: Cn↑, Cx↑, Un↑) and solution (S: Cn↑, Cx↑, Un↑) side. Main reasons for this assessment were the perceived little consensus on goals and the role of different means and ways to tackle these challenges in combination with unclear responsibilities among public actors. This resonates well with the insights from the interviews pointing to the delayed smart meter roll-out as a key bottleneck that also affects potential means for behavioral adjustment (flexible pricing) and the creation of new business models and more efficient management of peaks and volatility.

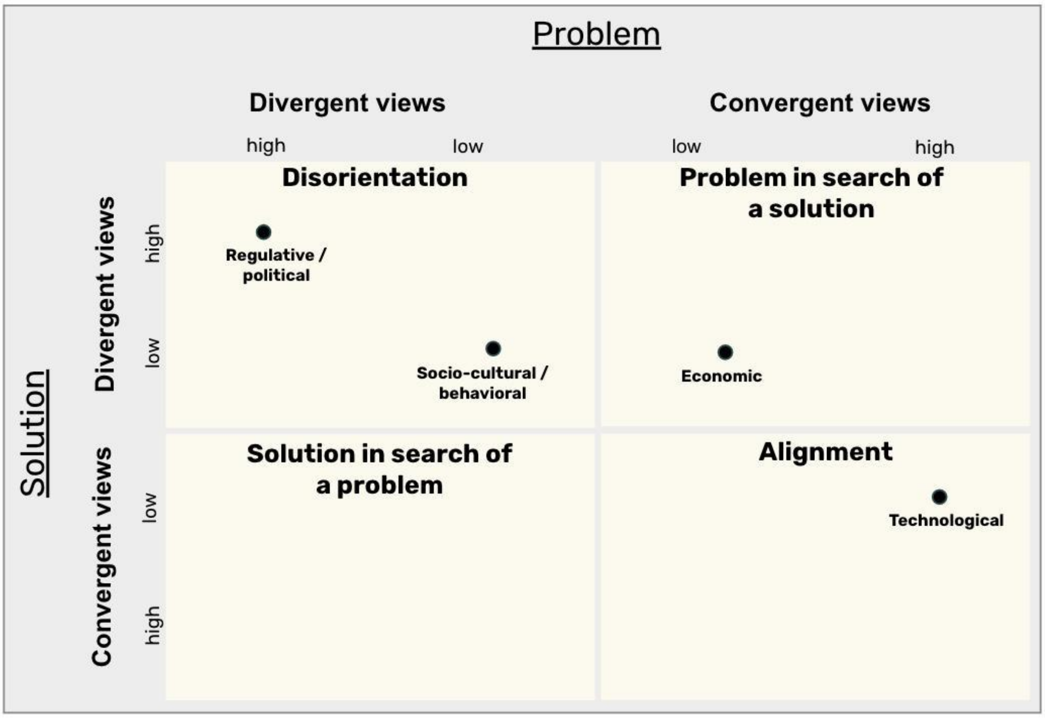

Figure 3. The problem-solution-space of the energy case;
note: The four dimensions (regulative/political, technological, socio-cultural/behavioral, economical) are located within the quadrants of the two-dimensional problem-solution-space. The classification into category high or low refers to the amount of high/low evaluations of the wickedness dimensions (e.g. two times high -> low in the figure; three times -> high). Two or three times high/low means an allocation in di-/convergent views (see Table A.5. in the appendix).
Source: Own diagram based on Wanzenböck et al. (2020)

4.3. Implications

The current study is still in a prototypical state with about half of the planned interviews conducted to understand problems and solutions and the wickedness measurement relying on only two expert workshops instead of a survey. Yet, in the following sections we will - based on the cases analyzed - tentatively make suggestions for the twin transition as a whole. We thereby follow the line of argumentation of Wanzenböck et al. (2020), first describing insights on the underlying problems and solutions of the twin transitions, then summarizing insights from the different wickedness dimensions locating the cases in the problems-solution-space, and finally discuss potential policy implications.

4.3.1. Problems and solutions in the twin transition

In both cases, we experience a situation in which linear modes of conduct are replaced by non-linear logics. In the circular economy, used products are supposed to find their way back into production which requires new and non-linear actor arrangements. In the energy transition, new actors function as energy producers and challenge the traditional linear energy flows. Across the four analytical dimensions we identify the following key problems:

In line with this, the missing access to information in new actor constellations is a core issue, as it impedes actors from implementing core sustainability levers (like R-Strategies or load management to tackle volatile energy flow). Also, decentralized steering mechanisms based on this information are currently hindered. Furthermore, the profitability of linear business models or more general modes of conduct as well as the insecurity of substantial and long-term change (e.g. into new circular business models or towards renewable energies) prevents actors from investing. Additionally, a lack of incentives functions as a barrier to change individual behavior (either due to fear or comfort). And in the political sphere, lobbyism of established actors of the more traditional logics, the insufficient involvement of actors, slow regulation processes as several horizontal and vertical structures and processes between regulatory actors are perceived as core issues in policy-making.

Solutions focus mostly on providing technologies that enable better exchange of information on needs and offers as well as automatizing such exchange. Additionally, they are supposed to enable new actor interactions and open up new revenue streams and cost saving options. Consumers are to better reflect on their consumption behavior, adjust it intentionally or let machines automatically adjust for them. Politically, more holistic policy-making is suggested (e.g. through supply- and demand-side policies or a new understanding of the relevance of experimentation and new process design). While this is not to neglect existing differences between the cases, the identified problems and solutions when being decontextualized appear to show profound similarities.

4.3.2. The wickedness of the twin transition

Drawing on the empirical analysis, the assessment of the wickedness provides several implications for understanding the twin transition (see Figure 4 for the consolidated problem-solution-space):

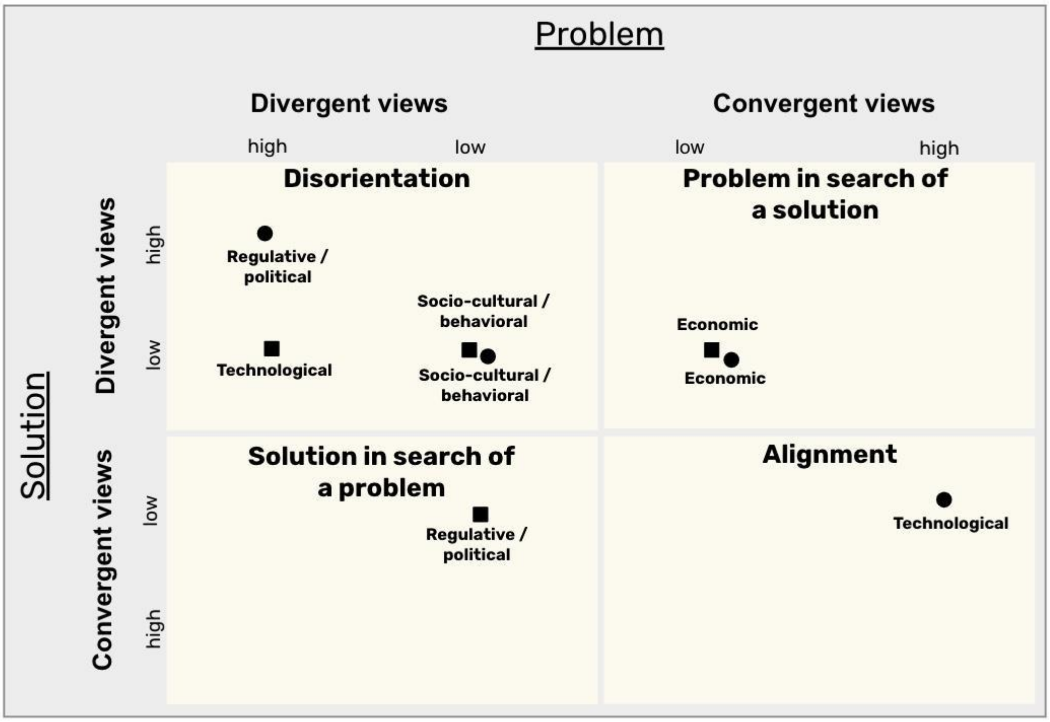

Figure 4. The problem-solution-space of the twin transition;
note: The four dimensions (regulative/political, technological, socio-cultural/behavioral, economical) are located within the quadrants of the two-dimensional Problem-Solution-Space. The results of the CE case have a square and those of the energy case have a circle as a symbol. The classification into category high or low refers to the amount of high/low evaluations of the wickedness dimensions (e.g. two times high -> low in the figure; three times -> high). Two or three times high/low means an allocation in di-/convergent views (see Table A.4. & A.5 in the appendix).
Source: Own diagram based on Wanzenböck et al. (2020)

First, the wickedness along many systemic dimensions seems to be quite high. Many of the analyzed dimensions are located in the disorientation quadrant or close to it while little are in a state of alignment. This result is in line with the argument that the idea of thinking sustainability and digitalization jointly has only emerged recently, implying there is little integration of these fields so far.

Second, the results imply that there exists considerable diversity among the cases studied in this paper. While these variations - at least partly - reflect differences in cases, they illustrate the diverse character of the twin transitions. While the twin transition may be considered as an umbrella term or concept bundling different application areas, the results point to the importance of a more differentiated perspective on different sectoral or transition area configurations of the twin transition.

Third, despite the emphasis on digitalization as a key driver of different twin transition the results underline that these are not a purely technological endeavor. As indicated by the analysis, the most complex issues in facilitating a development towards sustainability goals are not merely located in technology as such but rather in aspects at the intersection of technology with different fields (e.g. regulatory aspects as in the case of sustainable energy transition). In the end, the success of the twin transition might be less a matter of digitalization itself but above all an issue of sound governance structures that manage to facilitate an alignment across different dimensions.

Fourth, the analysis indicates that within a specific twin transition the different dimensions (economic, technological, regulatory, socio-cultural) may not necessarily be closely related to each other. Based on preliminary assessments, it appears that individual dimensions in the energy case are much less congruent than it is the case for circular economy. The key question emerging from this result is whether such highly dispersed problem-solution constellations might require a prioritization of activities in some of the areas.

Fifth, when comparing the results of the analysis across different cases, there might be similarities with regard to the location of specific dimensions in the problem-solution space. Whereas further validation and a more detailed analysis against the background of the different wickedness dimensions is necessary, this might be indications for similar developmental states across different cases of the twin transition.

Sixth, results might be indicative of substantial knowledge gaps as well as an overall need to address contestation rather than focusing on complexity. Depending on the case under consideration, these tendencies might intensify or fade out (see also table A.6 in the appendix).

4.3.3. Policy implications for the twin transition

In this final summary section, we will describe assumptions on policy implications that are based on the prototypical insights on problems and solutions as well as their wickedness.

Specific policy approaches

While sharing considerable similarities in the overarching structure of problems and solutions, the divergent positioning in the problem-solution-space indicates that there might not be a need for a twin transition strategy, but rather for a bundle of twin transition strategies as different sectors may face different problems and evolve at different pace. For instance, the technological dimension of the circular economy case calls for a more exploratory approach (basic research and experiments) while in the energy case the diffusion of several technologies could be pushed via political initiatives. Additionally, in the circular economy case, it is predominantly uncertainty that needs to be addressed whereas in the energy case consensus building appears to be more promising. Thus, while maintaining the idea of the twin transition as an overarching strategy, a case specific strategy is necessary.

Flexibility in policy-making

policy-makers should take into account the relatively young state of the twin transition. In such a phase of disorientation, a hybrid strategy should be applied for many systemic dimensions: a. the focus of policy-making should be on bringing actors together and pushing for consensus building as well as role clarification b. basic research should be funded in order to clarify potential problems as well as solutions b. experimentation must be enabled in order to test various potential solutions c. the levels of contestation, complexity as well as uncertainty should be monitored closely to identify whether the twin transition begins to move within the problem-solution-space opening the door for strategic adjustments.

Additionally, our results indicate that in situations (e.g. energy transition) in which societal views on problems and solutions in different systemic dimensions differ substantially (wide-spread locations in the problem-solution-space) policy-makers need to be able to respond with a diversified portfolio of initiatives - e.g. from a strong "discovery-mode" towards more of a "diffusion-mode" or a solution- vs. a problem-driven (goal setting) approach. Further, it might be advisable to address first dimensions that are lagging behind, in order to prevent a bottleneck hindering an overall convergence process.

Exploiting synergies

In some situations (e.g. technological and socio-cultural dimension in circular economy), societal views in the respective systemic dimensions within cases might be located closer to each other in the problem-solution-space. Here, the focus should be on exploiting synergies in policy-making as, for instance, problems and solutions in two different dimensions within a case might require similar policy approaches.

Furthermore, even between cases some dimensions might be located in a similar state (like in the case of the economic as well as socio-cultural dimension). As a result, also here, synergies in policy-making across cases might be leveraged. Surely, the underlying specifics of wickedness need to be considered.

Finally, policy learning could be recommended if in some cases (e.g. technological dimension in the energy case) there is already alignment on problems and solutions while others (e.g. technological in the circular economy case) are still in a state of disorientation. As described above, core problems and solutions represent - at least on an abstract level - similar issues. Therefore, policy-makers in one case should strive to understand how these issues have been solved and trigger respective “ways forward” in other fields.

5. Summary of the empirical results

In this first of two papers, we explored diverse cases of the twin transition - the energy transition and circular economy. Relying on an extended version of the framework of Wanzenböck et al. (2020) and conducting expert and in-depth interviews, the paper sought to locate problem-solution constellations in the problem-solution space as the foundation for a better understanding of potential ways forward in the twin transition.

Even though the study currently relies on a limited methodology, the results indicate the analytical value of the framework and allow to derive first insights for a better understanding of the twin transition. While even such diverse cases of the twin transition share a similar structure of underlying problems and solutions they differ substantially in the degree of wickedness. Therefore, we argue that the twin transition does not require one but a case-specific strategy that tailors responses to the case-specific constellations. The refined framework in this regard may provide a valuable heuristic for policy design, pinpointing potential avenues. At the same time, the results show new challenges for analysis, e.g. the question how different wickedness constellations may play out and how/under which circumstances synergies between and within cases can best be mobilized.

Selecting transformative policies: Acknowledging situational differences for policy design

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In a nutshell

In this discussion paper, we suggest a step-by-step approach for designing transformative policies. Based on a detailed understanding of the problem-solution space of a societal challenge, we show how policy makers can identify suitable policy instruments and ensure synergetic management as well as learning to direct innovation processes towards sustainable development. We illustrate our ideas with the example of the twin transition.

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1. A framework for designing transformative policies

Societal challenges such as mitigating climate change or fighting cancer require new approaches that challenge established modes of policy-making. These new policies need to effectively trigger widespread systemic innovation to shift societies towards better outcomes. They rely on aligning policy strategies, organizational structures, processes, and instruments across different sectors and stakeholder groups. While various concepts of transformative policies promise a coordinated approach that cuts across disciplinary, sectoral, and ministerial boundaries, their implementation still constitutes a challenge for policy-makers. In this discussion paper, we propose a context-specific and process-oriented framework to support policy-makers developing policies to tackle societal challenges in different circumstances.

By building upon a refined and extended version of the framework by Wanzenöck et al (2020), we hope to contribute to the debate on transformation processes and provide an easy to use hands-on tool for selecting and prioritizing policies. We give direction for choosing suitable policy strategies and an appropriate instrument mix. Above all, we propose a way for disentangling the complexity of transformation processes, by focusing on specific problem-solution constellations and the interaction between different strands of activities.

2. The clarity of problems and solutions can guide policy design

The challenges we face today are difficult to handle due to missing clarity, often referred to highly wicked situations: Issues are difficult to define, different opinions may contradict each other, determining roles and responsibilities is challenging, causes and consequences are opaque, and their constellations change over time.

It has been suggested that in order to address societal challenges policy-makers need to understand the specifics of a wicked challenge. More specifically, situations in which problems and solutions of a societal challenge are clear require a different policy approach, compared to unclear problem-solution constellations. Therefore, policy-making needs to take a process-oriented perspective reflecting the current degree of clarity of problems and solutions as a means to overcoming the transformational failures. From this perspective, policy measures seek to align actors and activities on certain problem-solution constellations as the foundation for successful solution rollouts (see Figure 1).

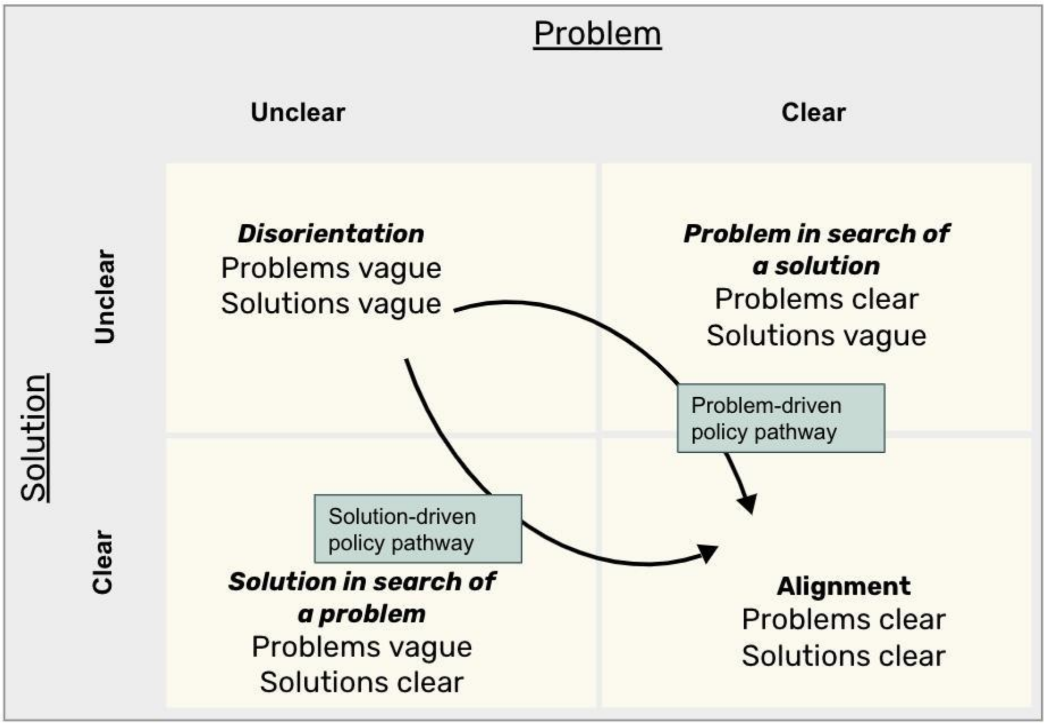

Figure 1: Policy-pathways through the problem-solution space
Source: Own diagram based on Wanzenböck et al. 2020

We choose the digital and green twin transition as an exemplary case for illustrating the framework. policy-makers seek to leverage digital technologies to tackle sustainability issues. The twin transition allows us to not only focus on a highly relevant endeavor of current policy-making but also a field that lacks orientation from a policy point of view. For instance, digital and sustainability policy strategies are often unconnected in European policy-making (Digitalization for Sustainability 2022). Additionally, as digitalization is pushed in various transitions (e.g. agricultural, industrial etc.) simultaneously, we can take a cross-case perspective in reviewing policies for problems and solutions. Applying cross-case policy learning, we focus on a digitally-enabled energy transition and a digitalized circular economy.

3. Step-by-Step towards a transformative policy package

Step 1: Understand potential problem-solution constellations

The first step is to understand potential problems and solutions. From our perspective, policies need to effectively bring together these two sides in order to tackle the overall societal challenge. Therefore, the first step is to break down a respective societal challenge into specific sub-problems/solutions, which may comprise a combination of technological, economic, socio-cultural, and political aspects (see Figure 2).

Then problems and solutions are bundled to form problem-solution constellations representing the central units of analysis in our framework. We consider problems and solutions as interlinked if solutions can (substantially) contribute to solving/overcoming a problem. Expert interviews can help with the identification of the problems and solutions.

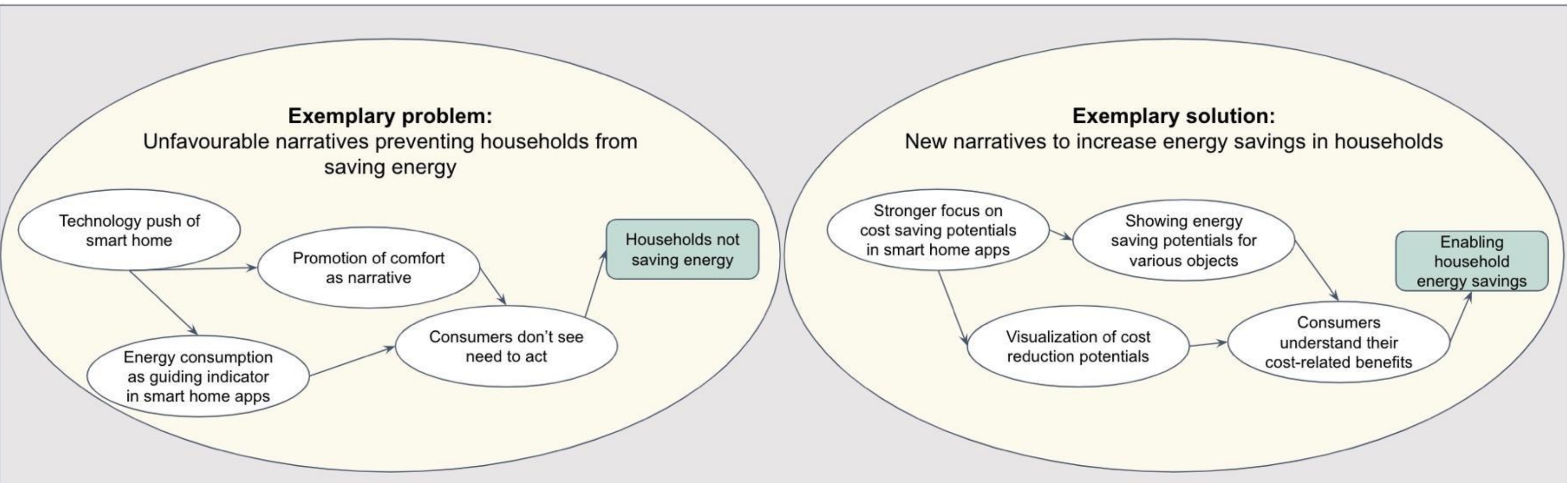

Figure 2: Example for problem-solution constellation
Source: Own representation

Step 2: Assess the clarity of selected problem-solution constellations in order to locate them in the problem-solution space

In this step, problems and solutions are assessed separately in terms of clarity. Information on consensus between relevant actors, role clarity as well as the availability of scientific and practical knowledge needs to be gathered for both the problem and the solution part. This way, the di-/convergence of perspectives can be analyzed and a particular problem-solution-constellation can be located in the problem-solution space (see Figure 3).

Accordingly, problem-solution constellations for a societal challenge can be located in four distinct quadrants to obtain a more systemic perspective on the different facets of the addressed challenge:

- ***Disorientation***: In this state, problems as well as solutions lack consensus, role clarity, and knowledge. Oftentimes, in this state, constellations are vaguely described and limited specific information on their building blocks is available. This complicates the process of clarification.
- **Problem in search of a solution**: Here, the problem part of a constellation becomes clear, meaning that actors agree on a particular issue that needs solving, responsibilities behind the issue are set and (scientific) knowledge gives detailed insights on the problem components). Solutions for the problem on the other hand remain blurry.
- **Solution in search of a problem:** In these situations, actors commonly believe in a particular solution, roles in a solutions implementation are clear and sufficient knowledge on the efficacy of the solution and application is available. But it still needs to be defined what exactly to tackle and direct the solution capacities towards.
- **Alignment**: If a solution for a problem is found and all the aforementioned aspects are clarified we can assume alignment with rather detailed problems and solutions.

Please note that since the assessment is based on variables (Degree of consensus, role clarity and knowledge availability) problems and solutions will often not be purely clear or unclear. There are several ways of ensuring the right allocation to the four quadrants. We suggest to characterize a problem/solution as clear/unclear if at least two of the three variables are clear/unclear. In the later selection of suitable policies these facets need to be taken into account.

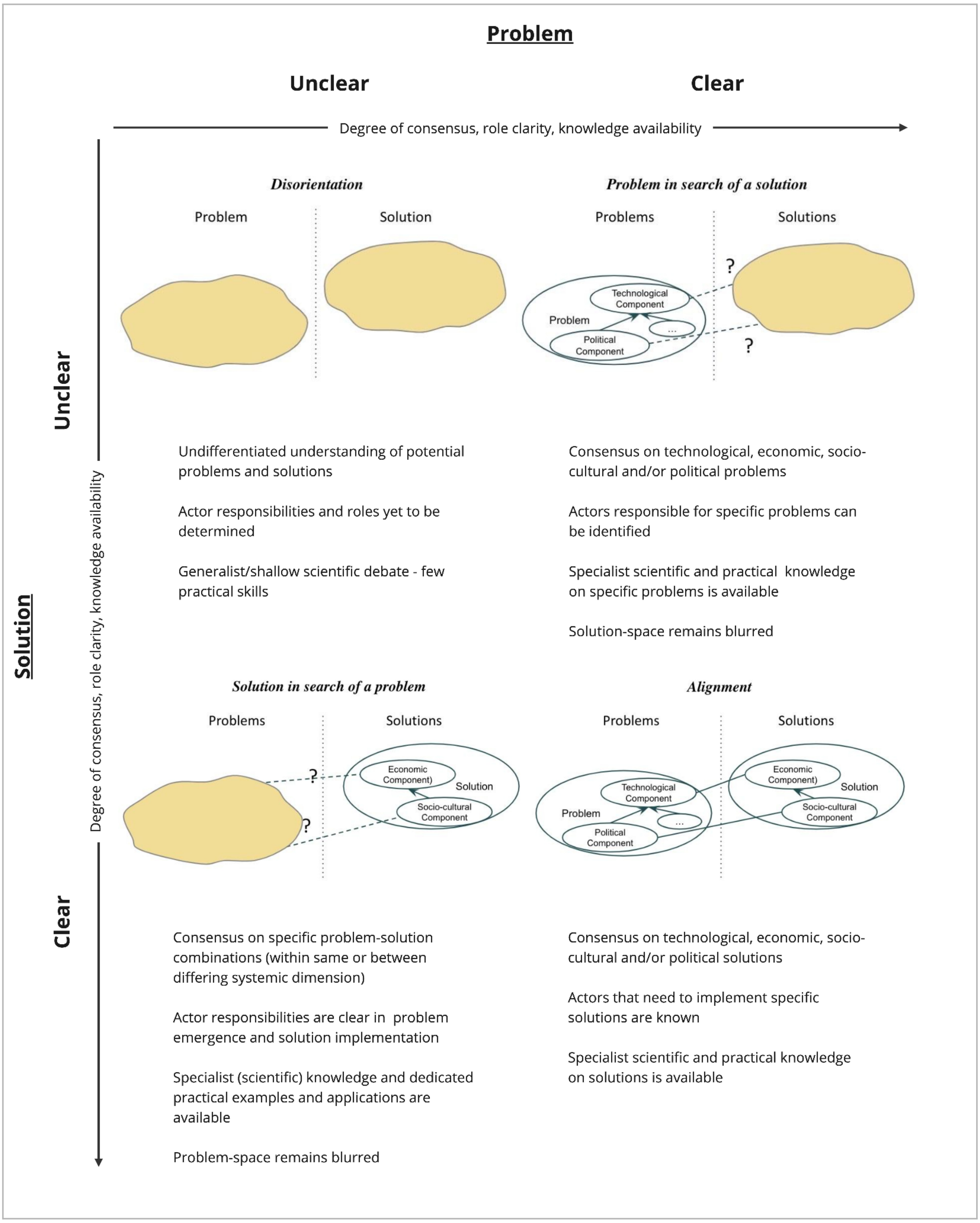

Figure 3: The problem-solution space of societal challenges
Source: Own diagram based on Wanzenböck et al. 2020

Figure 4 shows a simplified illustration of examples from the twin transition based on the empirical results of this project. It shows how problem-solution constellations can be scattered across several quadrants of the problem-solution space i.e. within a societal challenge problem-solution constellations will be found in different states. Thus, different policies need to be implemented, as the next section details.

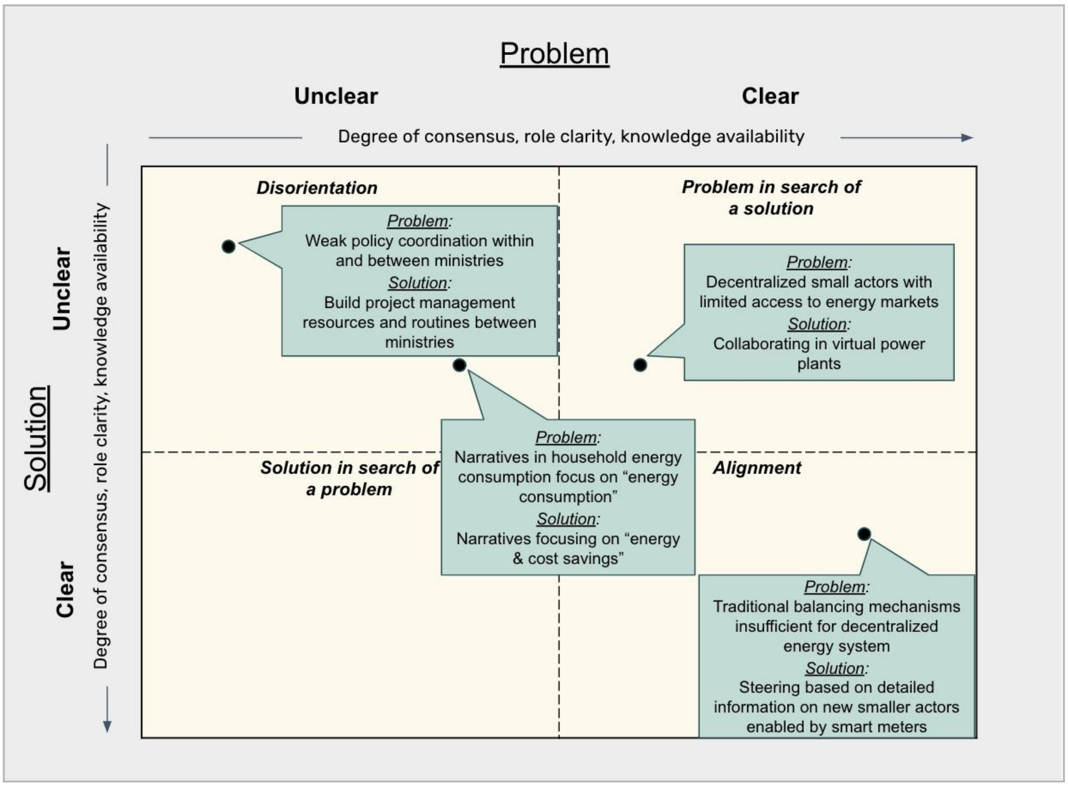

Figure 4: Examples of problem-solution constellations in the problem-solution space of the twin transition (energy transition)
Source: Own diagram based on Wanzenböck et al. 2020

Step 3: Define policy instruments to reach alignment and diffuse solutions

A policy approach's major goal is to reach alignment on specific problem-solution constellations and diffuse the respective solutions. Therefore, the design of policy instruments in such an approach depends on the location of a specific problem-solution constellation in the problem-solution space. Taking the specific constellations outlined in Figure 3 as a starting point, we propose the following priorities for policy-makers to facilitate change towards greater alignment (see Figure 5):

- **Start the debate**: The key focus of policy-making in the *disorientation* state is to establish an environment that can contribute to the societal clarification process for problems or solutions. Creating a knowledge base and spurring debates on certain problems and solutions, or areas in which problems and solutions need to be specified, should be at the heart of policy-making in this state. Thus, funding for basic research, the creation of new institutions and forums for discussion are the most relevant policy instruments.
- **Connect to solve:** In cases in which problems are taking shape but solutions remain blurred (*problem in search of a solution*) a wide-spectrum of stakeholders must be brought together to explore and develop suitable solutions. Policies should focus on signaling direction, incentivizing the development of impactful solutions, and pushing for networking and collaboration.
- **Apply to pinpoint:** If solutions may help with various problems that remain underspecified (*solution in search of a problem*) such solutions should be applied in order to identify the problems they best match with. Policies should focus on testing the efficacy of solutions in various contexts and circulate ideas, technologies, skills etc. between communities.
- **Establish markets:** If there is consensus, role clarity, and sufficient knowledge available regarding a certain problem-solution constellation, policy-makers should prioritize the rollout of a solution in markets. This involves the planning and execution of market diffusion, ensuring diffusion-friendly conditions, and promoting the solution to trigger widespread systemic change.

Disorientation

Start the debate

Increase knowledge base
(e.g. funding basic research in topic area (inter-) disciplinary research, new research groups)

Create or strengthen new institutions to spur debate and exchange between stakeholders and/or public
(e.g. think tanks, research institutes, thematic networks etc.)

Establish fora for exchange and discussion
(e.g. visioning and scenario building, stakeholder and public dialogues)

Problem in search of solution

Connect to solve

Increase awareness of key problems and signal for long-term direction
(e.g. information campaigns, long-term strategies, new directions of study etc.)

Incentivice development of novel solutions and evaluate efficacy
(e.g. public/pre-commercial procurement solutions, innovation prices, regulatory sandboxes, living labs, foresight, assessment of upscaling potential, etc.)

Support inter-/transdisciplinary activities and collaboration
(e.g. research networks, innovation network policies, cluster policy, technology scouting)

Solution in search of a problem

Apply to pinpoint

Create opportunities for exploring application of solutions in different contexts
(e.g. assessment of efficacy, technical services and advice, access to innovation facilities or laboratories, public procurement)

Ensure circulation of solution components (ideas, people, blueprints, technologies) between diverse communities
(e.g. networking and information instruments, collaborative platforms, etc.)

Alignment

Roll out solutions

Incentivice diffusion in markets
(e.g. roadmapping, investment facilitation, crowding in investment by traditional actors, standardization)

Shape favorable uptake conditions to ensure further alignment
(e.g. subsidies, regulation, standardization)

Push promotion
(e.g. information campaigns)

Figure 5: Policy strategies for developmental states of problem-solution constellations
Source: Own representation

Based on the twin transition, Figure 6 illustrates that policy-makers need to be able to develop and implement several policy instruments at the same time in order to direct innovation capacities towards solving a particular societal challenge.

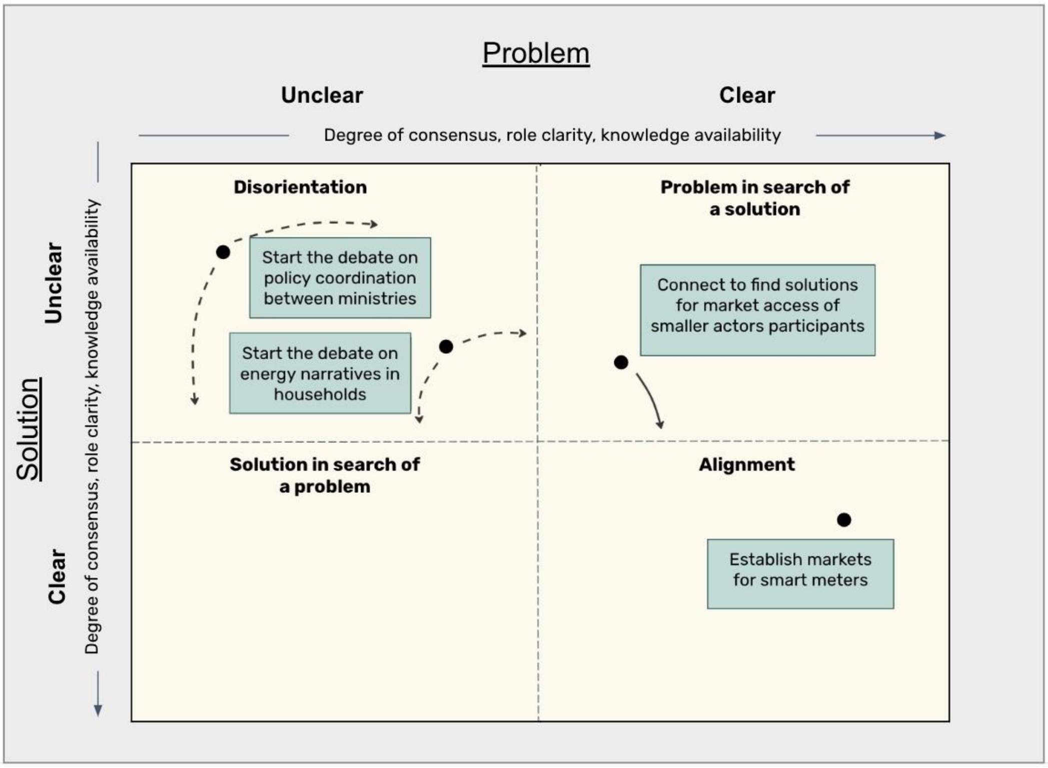

Figure 6: Examples of policy strategies for the the twin transition (energy transition)
Source: Own diagram based on Wanzenböck et al. 2020

Step 4: Ensure policy coordination within and between policy programmes

So far, we have described how policy instruments as part of larger transformative policy-making need to be selected based on the respective problem-solution constellation under consideration. At the same time, policy-making needs to address the interplay of problem-solution constellations within and between closely related policy programmes (and therefore societal challenges). In policy practice, often transitions and policy processes need to be handled in parallel. Such interaction concerns either common learning or implementation processes. This framework allows to systematically address the described interfaces and design them in a synergetic fashion.

Depending on the similarity of the problems and solutions to be addressed (e.g. similar technology is used or a similar actor arrangement is considered) and the similarity of the location in the problem-solution space (e.g. if considering two cases both located in the alignment state) different coordination approaches might an be recommended (see Figure 7):

- **Synergetic Capacities:** In case of two problem-solution constellations with different problems and solutions but comparable positions in the problem-solution space, policy-makers might seek to exploit synergies in the resources and capacities used. As comparable policy instruments (like discussion platforms, funding mechanisms for basic research, etc.) might be applied in these situations, it is recommended to commonly develop or share tools, processes, etc. necessary for implementation.
- **Deep Collaboration:** If two cases contain similar problems and solutions and can be found in the same quadrant, we propose deep collaboration. In addition to collaborating in resource usage, policy-makers might also collaborate in common problem-solving (e.g. exchanging insights on similar technological solutions during development).
- **Creative Pool:** Here, both problems and solutions as well as the location in the problem-solution space of two cases are highly disparate. As the compared problem-solution constellations are still part of the same underlying societal challenge or of related challenges, policy learning in these situations might still be relevant. Common learning might leverage "out of the box" thinking and inspire solutions to gridlocked situations.
- **Lesson Drawing:** In these instances, the problems and solutions considered are highly similar but in different quadrants of the problem-solution space. An example might be a case in which a political issue was solved in one ministry and another ministry might draw lessons from that particular case for solving a similar issue.

Finally, it must be noted that in practice decision makers must also take into account the specific circumstances of the cases considered. In particular, the degree of consensus or contestation, actor role clarity as well as availability of practical and scientific knowledge behind certain problems and solutions affect the policy strategies to be chosen as well as the coordination mechanisms described here.

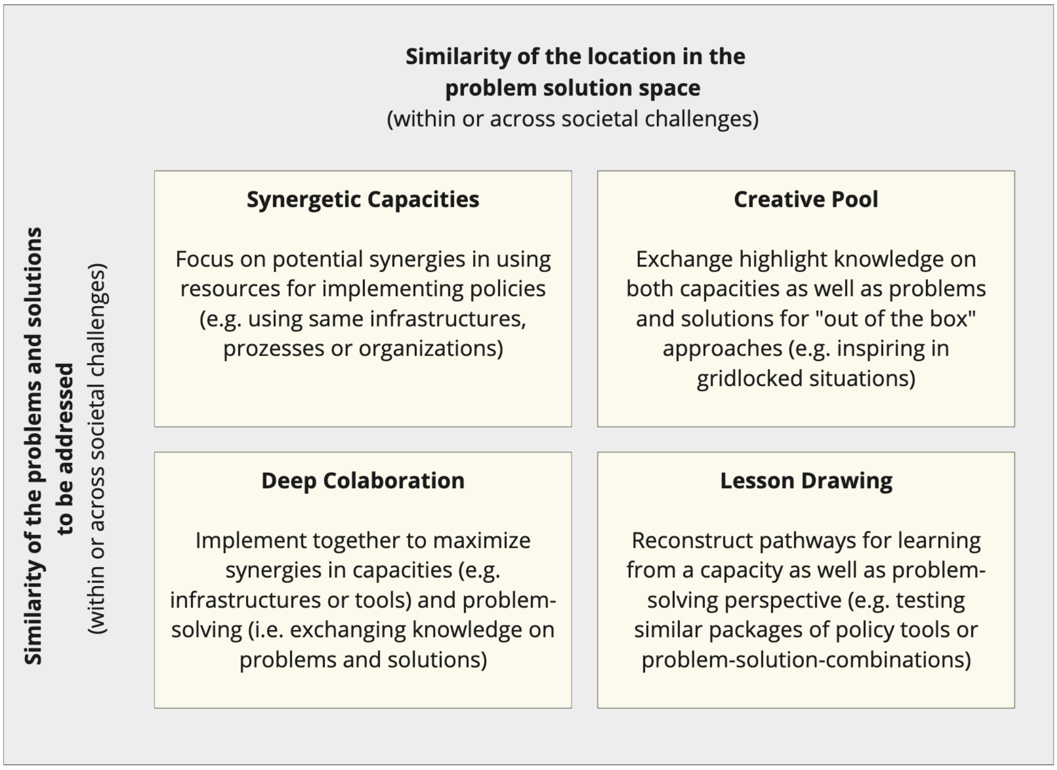

Figure 7: Policy coordination between problem-solution constellations
Source: Own representation

Figure 8 shows two exemplary cases of coordination based on the empirical results of this project. We can see that collaborating and exploiting synergies within and between policy programmes might lead to improved overall transformative outcomes in terms of reaching alignment. Also coordination will require policy-makers to implement several different measures at the same time to gain effective results.

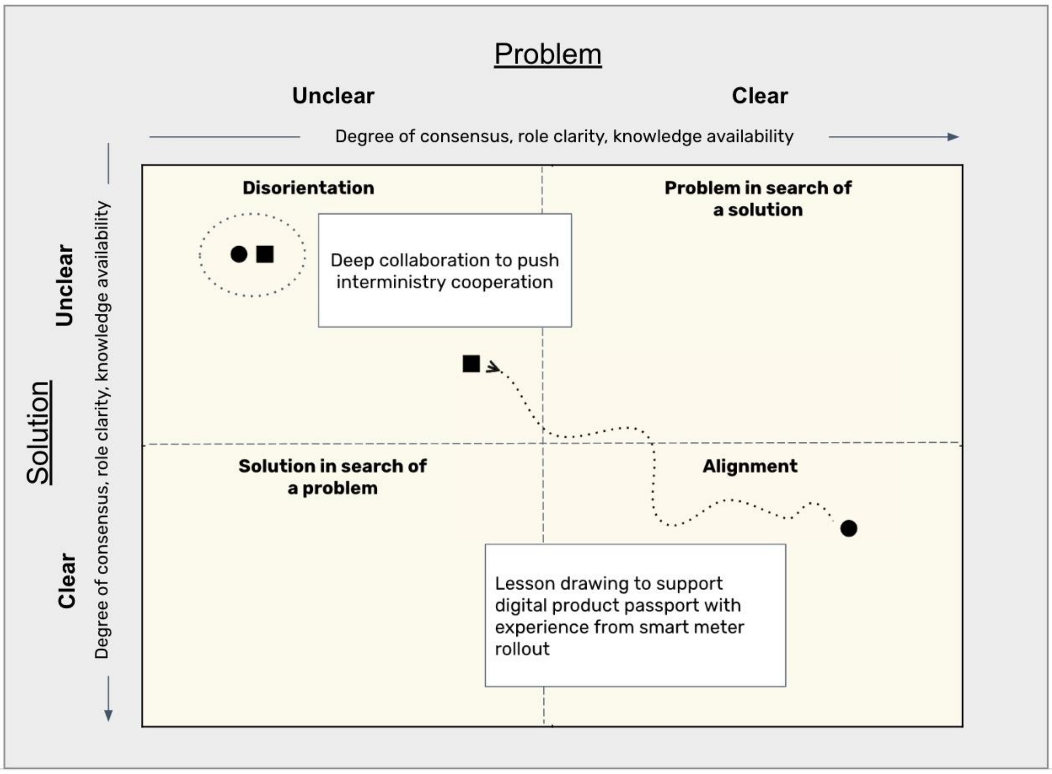

Figure 8: Examples for policy coordination for the twin transition (energy transition and circular economy)
Source: Own diagram based on Wanzenböck et al. 2020

Step 5: Monitoring progress

We suggest that monitoring is necessary to implement our approach and contribute to transformative change. Two perspectives are important:

- *Monitoring of the societal challenge:* In order to decide upon the most effective policies for certain situations, it is essential to monitor the problem-solution space constantly. Certain problems or solutions could go back to more blurry states creating new opportunities and threats. Additionally, as several instruments are applied, these must be monitored to ensure that the portfolio of policies is balanced and adjusted (e.g. from a coherence and consistency point of view).
- *Monitoring of adjacent societal challenges:* Considering systemic transformations in isolation is impossible. New policies are part of an existing landscape and interact with other initiatives and other societal challenges. Moreover, developments in other areas may change the context, affecting the perceptions of problems and solutions. Thus, monitoring the context of transformative policy-making thoroughly to ensure swift adjustments is necessary.

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Appendix

Starting point	**Disorientation**	**Problem in search of solution**	**Solution in search of a problem**	**Alignment**
Policy approach	Gradual learning/ experimentation for knowledge generation and exploration	Problem-oriented transformer mission	Solution-oriented transformer mission	Targeted development and diffusion-oriented policies
Goal	Facilitation of convergence of views on both dimensions as a prerequisite for more specified policy approaches	Develop promising solutions for a problem and bring them into implementation	Improve understanding about link between solution and problem	Facilitating deployment of identified solutions
Key means/ instruments	Problem-oriented research, experimental approaches dialogue processes, Foresight	Experimentation with different solutions, creating markets for new solutions, technology scouting, incentive setting via support and/or regulation	Technology assessment, Diffusion of solution to different application areas, standardization to facilitate spill-over	Regulation, demand-side policies
Mode of consensus building	Generate knowledge to improve understanding of the underlying problem Linking different spheres and perspectives	Dealing with potential losers of change processes Increase convergence on consensus for possible solution(s)	Explore which key problems within a challenge can be solved by the solution Communication/Show-casing of potential benefits & problems of solutions	

Table A.1. Pathways for the quadrants of the problem-solution-space

	Problems
Definitions	Focus: Opportunities of digitization for the Circular Economy in Germany. Energy system: especially energy supply, i.e. all processes through which energy is supplied to the consuming sectors (including people or organizations that consume and produce energy in parallel). Digitalization: Systemic change from an analog to a digital society
Dimensions of problems and solutions	Please focus on one of the following dimensions: technological economic socio-cultural regulatory
Questions	1. What is currently the central *technological* problem in the achievement of a sustainable energy system that if solved enables digitalization to have an effect for the sustainable energy system or that could be resolved through digitalization? Please focus on describing the problem, not the contribution of digitization. Please describe causes, consequences as well as possible contextual conditions of the problem. 2. What was the central *technological* problem in achieving a sustainable energy system approx. 5-10 years ago, that if solved would have enabled digitalization to have an effect for the sustainable energy system or that could have been resolved through digitalization? You are welcome to focus on describing the problem, not the contribution of digitization. Please describe causes, consequences as well as possible contextual conditions of the problem. 3. What is currently the key potential *technological* solution to overcoming problems of a sustainable energy system that could be enabled by digital technologies or could enable the use of digital technologies for a sustainable energy system? In doing so, you do not have to relate your solution to the problem you have just outlined. Please focus on the solution, not the problem, and describe the prerequisites, mode of action, and possible contextual conditions of the solution. 4. About 5-10 years ago, what was the key potential *technological* solution to overcoming problems of a sustainable energy system that could have been enabled by digital technologies or could have enabled the use of digital technologies for a sustainable energy system? In doing so, you do not have to relate your solution to the problem you have just outlined. Please focus on the solution, not the problem, and describe the prerequisites, mode of action, and possible contextual conditions of the solution.

Table A.2: Interview slide incl. questions (example: energy transition case; technological dimension)

	Problems	Solutions
Contestation	Please evaluate the degree of consensus on these problem chains across actor groups (business/technology providers, politics, civil society, science): rather high degree of consensus vs. rather low degree of consensus Please explain your decision briefly.	Please evaluate the degree of consensus on these solution chains across actor groups (business/technology providers, politics, civil society, science): rather high degree of consensus vs. rather low degree of consensus Please explain your decision briefly.
Complexity	Please evaluate whether actor responsibilities behind the individual steps of the problem chains are clear: rather clear responsibilities vs. rather unclear responsibilities Please explain your decision briefly.	Please evaluate whether actor responsibilities behind the individual steps of the solution chains are clear: rather clear responsibilities vs. rather unclear responsibilities Please explain your decision briefly.
Uncertainty	Please evaluate whether there is sufficient knowledge/evidence on the problems? Related to… -the risks or damages of action and non-action -the specific relationship between causes and consequences -clarity on the (side-) effects of not tackling a problem rather sufficient scientific knowledge/evidence vs. rather insufficient scientific knowledge/evidence Please explain your decision briefly.	Please evaluate whether there is sufficient scientific knowledge/evidence on the solutions? Related to… -availability & feasibility of potential solutions -lack of clarity about effects and side effects rather sufficient scientific knowledge/evidence vs. rather insufficient scientific knowledge/evidence Please explain your decision briefly.

Table A.3. Questionnaire for wickedness expert workshop

System Dimension	Problems/ Solutions	Wickedness Dimension	Rather high/ rather low	Explanation
Technological	Problem	Contestation	low	Some actors might rather focus on data processing incl. storage, gathering, collection, integration and analysis
		Complexity	low	Unclear who is supposed to gather and manage data
		Uncertainty	low	Mostly conceptual, not empirical (little degree of CE-related digitalization in practice); In regards to certain sectors and products little insights
	Solution	Contestation	low	Strong focus on product passport in debate; (counterarguments: focus on product passport a bit too strong - particularly as it doesnt exist so far AI young field in regards to CE, no specified opinions)
		Complexity	high	Unclear roles in regards to data collection, integration, analysis along certain steps of product life cycles; AI young field in regards to CE, no specified responsibilities
		Uncertainty	high	Young research field; Initiatives ongoing; Mostly gravy literature; Interdisciplinary research as new approach (Mix: digitalization, business models, CE); Few experts available
Economic	Problem	Contestation	low	*No explanation* (Counterarguments: image: in recycling possible to build image complex value: selective examples exist as proof-of-concept (e.g. Schwarz Gruppe) data as property: Some are already selling their data as business model (e.g. Michelin))

		Complexity	low	Rather clear (® producing companies) but many dependencies, danger of lockins, and competitive issues that prevent action (Counterarguments: in politics unclear who is responsible for supportive policies)
		Uncertainty	high	Few high quality publications at the interface of dig, CE, business models
	Solution	Contestation	low	(Counterarguments: Decentralized dataspaces could be prioritized vs. centralized platforms)
		Complexity	high	Challenged responsibilities (e.g. various standardization organizations, tech. providers want lockins,…)
		Uncertainty	high	Mostly ongoing research, but not yet sufficient results
Socio-cultural / behavioral	Problem	Contestation	high	Fear of future: many see opportunities as opposed to fearing the future; Opposing views on waste management: Focus should not be on consumer-near waste processes but on later sorting processes Consumers not improving behavior with more insights Incentives don't work
		Complexity	high	Ongoing market-based exploration (finding responsibilities "on the fly")
		Uncertainty	low	Much (international research) on waste management; Research institutions established in GER; Relevant research questions known
	Solution	Contestation	high	Others might focus more on sorting than on consumer-oriented solutions (consumers can not optimize their behavior; incentives don't work)
		Complexity	low	In waste management responsibilities are clear due to wide-spread regulation and state ownership
		Uncertainty	high	Little research on behavioral adjustments in context of digitalization and circular economy
Regulative/ political	Problem	Contestation	low	Often discussed in focus groups and workshops
		Complexity	high	No cross-departmental and cross-ministerial responsibilities and collaboration in Germany; (On EU-level: directorates-general env, grow and connect collaborate closely

				and are often together in meetings with experts)
		Uncertainty	high	Very little research(ers) for governance of digitalization and circular economy; Merely selected examples
	Solution	Contestation	low	Particularly high if business opportunities are not affected negatively; Additionally: Demand-side policies become relevant when digital product passport is available
		Complexity	low	Responsibilities are informally known (supply-side by EU; demand-side by GER); On EU-level: directorates-general env, grow and connect collaborate closely and are often together in meetings with experts
		Uncertainty	high	Little existing, only ongoing research; Demand-side policies: too little exploration

Table A.4. Wickedness overview for the circular economy case

System Dimension	Problems/ Solutions	Wickedness Dimension	Rather high/ rather low	Explanation
Technological	Problem	Contestation	low	Generally broad consensus as overarching problem, variation between role decentralization (part of solution or problem), more clear for grid management/coordination
		Complexity	low	Rather clearly defined
		Uncertainty	low	Sufficient knowledge available
	Solution	Contestation	high	Infrastructure vs. digitalization still contested, unclear role of small providers
		Complexity	low	Clear who has to act, rather question of "make or buy" as key aspect
		Uncertainty	low	Systemic perspective established and supported by research
Economic	Problem	Contestation	high	Unclear importance of integration consumers, established players focus on existing technologies and large-scale technology

		Complexity	low	Clear role definition, some new players try to get access to new chains of value creation (e.g. telecommunication providers)
		Uncertainty	low	Established models with clear predictions (assumption based)
	Solution	Contestatio n	high	Cost-benefit ratio yet unclear, different perspectives available on costs of digitalization (e.g. smart meter roll-out)
		Complexity	low	Mainly new start ups with new solution, existing players rather existent, in sum rather clear picture
		Uncertainty	high	High importance of assumptions, uncertainty about economies of scale
Socio-cultur al/ behavioral	Problem	Contestatio n	high	Different opinions on importance of involving household consumption, discourse is shaped by technology vs. behaviorally-based approaches, predominant paradigm of the past was technology focus of policy-making
		Complexity	low	Responsability to set incentives for politics, however so far politics and economy are waiting for signals from each other
		Uncertainty	high	While framework conditions are rather clear, approaches for socio-cultural/behavioral so far lack clear evidence
	Solution	Contestatio n	high	Linked to high contestation at the problem level, provided contestation there solution is even less clear
		Complexity	low	Mainly responsibility of technology providers but problem with lacking incentives, politics need to create favorable framework conditions for the development and deployment of technological solutions
		Uncertainty	high	So far only abstract concepts are available
Regulative/ political	Problem	Contestatio n	high	Unclear defined goals with varying prioritization (data protection), risk perspective
		Complexity	high	Changing role e.g. of distribution net providers, diffusion of responsibility
		Uncertainty	high	No comment

	Solution	Contestation	high	Ideas lack so far empirical support
		Complexity	high	Unclear responsibilities e.g. for data trustees
		Uncertainty	high	Insufficient scientific research yet

Table A.5. Wickedness overview for the energy case

	Contestation		**Complexity**		**Uncertainty**	
	H	**L**	**H**	**L**	**H**	**L**
CE	**3**	**5**	**5**	**3**	**7**	**1**
Energy	**7**	**1**	**2**	**6**	**5**	**3**
Total	**10**	**6**	**7**	**9**	**12**	**4**

Table A.6. Wickedness comparison in both cases;
note: Contestation, complexity and uncertainty as three wickedness dimensions; P = problem, S = solution, H = high, L = low

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About CO:DINA

The project CO:DINA - Transformation Roadmap Digitalization and Sustainability connects actors from science, politics, civil society and business to identify new strategic directions for sustainable digitalization. Diversity in ways of thinking, perspectives and experience are the prerequisite for better understanding the complexity of digitalization and for addressing fundamental issues, particularly those relating to artificial intelligence, with viable solutions. In the process, networks are created between groups of actors that were previously insufficiently connected. In this way, the political and social capacity to act for a social, ecological and digital transformation is strengthened.

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