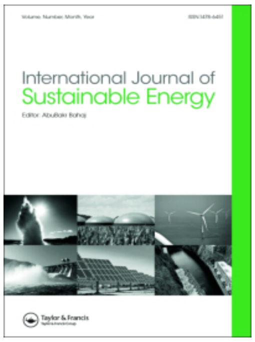

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Wicked facets of the German energy transition – examples from the electricity, heating, transport, and industry sectors

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ABSTRACT
We shed light on wicked problems in the German energy transition. Our methods consist of a multiple-case study and multi-criteria analysis, utilising the wicked problems theoretical framework introduced by Horst Rittel and Melvin Webber [1973. "Dilemmas in a General Theory of Planning." *Policy Sciences* 4 (2): 155–169. Accessed August 20, 2019. https://doi.org/10.1007/BF01405730]. Results from the energy supply, heating/cooling, transport, and industry sectors illustrate where and how the 10-point frame of wicked problems manifests in the German energy transition. The four cases exhibit more wicked tendencies in the governance domain than the technical domain and differ in their degrees of technology maturity, policy regulation, and knowledge states. We do not find that the German energy transition is inherently wicked. However, wickedness unfolds through the social setting into which technical solutions of the energy transition are embedded. We aim to highlight these intricacies and encourage scrutinising these wicked facets early on.

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energy transition; wicked problems analysis; onshore wind power; shallow geothermal energy systems; decarbonising the chemical industry; decarbonising the transport sector

1. Introduction

Many complex and challenging global issues, such as climate change, world hunger and poverty, share commonalities: They are multi-faceted and resist simple and final solutions. They are classic examples[1] of 'wicked problems' since they avoid straightforward problem definitions, are often based on heterogeneous values, and defy simple solutions. Horst Rittel and Melvin Webber coined the term 'wicked problems' in the 1970s in the public policy-planning domain (Rittel and Webber 1973). Over five decades, the literature on wicked problems has grown considerably. The wickedness concept was linked to complex systems research (Akamani, Holzmueller, and Groninger 2016; Alford and Head 2017; Andersson and Törnberg 2018; Head 2019; Innes and Booher 2016; Peters 2017; Zellner and Campbell 2015) and the socio-ecological system's framework (Craig 2020;

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Guimarães et al. 2018; Norris et al. 2016). Although rooted in the public policy domain, wicked facets can occur in technical, economic, environmental, and socio-political domains. More recently, climate change (Conradie 2020; FitzGibbon and Mensah 2012; Kelley 2018; Larrabee 2018; Levin et al. 2012) and other social-environmental issues (Duckett et al. 2016; Kirschke, Borchardt, and Newig 2017), the Covid19 pandemic (Angeli, Camporesi, and Dal Fabbro 2021; Auld et al. 2021; Head 2022b; Klasche 2021; Lawrence 2020), and energy supply and efficiency (Brunnengräber et al. 2014; Everingham et al. 2016; Thollander, Palm, and Hedbrant 2019) have been associated with the 'wickedness' theory. Wicked problems affect pluralistic societies since they involve conflicts of interests and value trade-offs, and are 'dilemma-laden social choice problems' (Glasser 1998, 230). Head (2022b, 29–30) states that the wickedness concept, as a reflective tool, 'has provided a way to […] make sense of rapid changes, disruptive conditions and divergent perspectives'.

The German energy transition is characterised by rapid changes (Markard 2018), disruption (Fuchs 2019; Johnstone and Kivimaa 2018) and highly divergent perspectives (Juerges, Leahy, and Newig 2020; Köppel and Biehl 2023; Sovacool et al. 2022). While Germany's energy transition started with transforming the energy supply sector from fossil to renewable energy sources (Morris and Jungjohann 2016; Renn and Marshall 2020), the term 'energy transition' now also comprises the end-use sectors of heating/cooling, transport and industry. Although it is technically feasible to build a 100% renewable energy system (Hansen, Breyer, and Lund 2019; Kendziorski et al. 2021; Prognos AG, Öko-Institut e.V., and Wuppertal Institut 2020; Traber, Fell, and Hegner 2021), the German case illustrates persistent barriers and bottlenecks. The socio-political implementation of the energy transition is contested, and a multitude of stakeholders with different interests (cf. Kühne et al. 2022; Reusswig, Komendantova, and Battaglini 2018), trade-offs and unmitigated conflicts can inhibit the transition process.

Schmid, Knopf, and Pechan (2016, 272) argue that the German energy transition is a 'power struggle between a large variety of actors that differ profoundly as with respect to their motives and underlying worldviews', hinting at a great stakeholder divergence, one of the defining characteristics of wicked problems. Steinbacher and Pahle (2016, 70) argue that the German energy transition 'stands out globally as one of the most prominent and widely discussed plans to transform an energy system'. Germany faces a 'double exit strategy', phasing out coal (by 2038) and nuclear energy (by mid-April 2023) while basing the evolving carbon-neutral energy system on renewable energy sources. Therefore, the wickedness concept provides a promising framework for analysing the German energy transition to gain insights into the existing challenges and their interconnections as a basis to address them.

The German energy transition has been analysed from various perspectives, and the term 'wicked problem' has been used as rhetoric (cf. Blohm 2021; Komendantova 2021; Roggema 2020; Stremke and Schöbel 2019). A bibliometric analysis[2] of all articles mentioning the search query 'wicked problem*' in the title, abstract, or author keywords shows that academic interest in wicked problems has increased (absolute number of publications by 2023: 1.962). Based on the bibliometric analysis, we deduce that energy topics are still only scarcely (n = 33) examined compared to ecological and environmental topics. The studies in the energy domain either pick a specialised subfield [energy efficiency: Thollander, Palm, and Hedbrant (2019) or heat decarbonisation: Cowell and Webb (2021)] or assume wickedness (Moallemi and Malekpour 2018). Jakimowicz (2022) describes the energy transition as part of prosumer capitalism and describes some, yet not all, elements of a wicked problem with reference to Rittel & Webber, but without further elaboration or critique (Jakimowicz 2022).

The literature lacks a systematic analysis of the wicked tendencies of the German energy transition – a country paradigmatic for challenges of low-carbon energy transitions in industrialised economies. Our analysis contributes to filling this research gap by applying the wickedness concept to the German energy transition. The challenges of Germany's energy transition discussed in this article may also occur in energy transitions elsewhere. Although different case applications may show different facets, this contribution raises awareness of the problems posed by complex challenges in energy transitions and the applicability of the wickedness concept.

We describe wicked problems across four core sectors of the German energy transition. However, we do not conceptualise the German energy transition as an inherently wicked problem. Instead, we use the wickedness approach to identify energy transition challenges, which can serve as a basis for further debate. The paper contributes to the wickedness literature by exploring bottlenecks and wickedness of sustainability transitions (specifically the German energy transition). We distinguish between technological (*techno-centric*) and governance (*socio-centric*) aspects of wickedness. Therefore, we use the ten wickedness criteria (cf. Rittel and Webber 1973) as an analytical framework to tease out wicked facets in four case studies:

- Energy supply sector: Case 1 – Decarbonising the electricity sector by installing onshore wind farms
- Heating/cooling sector: Case 2 – Decarbonising the space heating/cooling sector by installing shallow geothermal energy systems
- Transport sector: Case 3 – Decarbonising the transport sector by transforming road mobility
- Industry sector: Case 4 – Decarbonising the industry sector by transforming the chemical industry.

The four cases are in different transition stages as of 2021 (Luderer, Kost, and Sörgel 2021; BMWK and UBA 2022), which is reflected in the results of our analysis. This contribution aims to contextualise the German energy transition in its wicked facets, on the one hand, to show why progress is not achieved faster and easier. On the other hand, we aim to utilise the wicked problems approach to gain a broader overview and understanding of the four cases and their challenges. The following section 2 introduces the theoretical framework ‘wicked problems’. Section 3 presents the materials and methods of our analysis: We present our study design in section 3.1, while section 3.2 introduces the four case studies, outlining the sector’s progress towards the energy transition and the barriers ahead. Cross-case results and highlights are presented in Section 4. Section 5 discusses and critically reflects findings, while Section 6 concludes.

2. Theoretical framework: wicked problems

We revisit Horst Rittel and Webber’s 1973 seminal work on wicked problems. Rittel and Webber presented ten characteristics of wicked (policy) problems (Table 1) as an answer to normal science and rational planning in the 1970s United States of America (Lönngren and van Poeck 2020). With all or a certain combination of these characteristics, problems do not need to meet all ten characteristics to show wicked tendencies (Alford and Head 2017; Head 2019; Lönngren and van Poeck 2020; Newman and Head 2017). Ruhl and Salzman (2020) distil a dominant theme in Rittel’s and Webber’s work – the open system’s property, which they attribute as the core characteristic and challenge of wicked problems. The open system’s property links closely with social-ecological systems[3] and complex systems (cf. Chan and Xiang 2022), frameworks applicable to the German energy transition.

Over the last 50 years, scholars have contributed to a substantial body of literature expanding, revising, criticising or applying Rittel’s and Webber’s concept (Crowley and Head 2017; Hou, Li, and Song 2022; Termeer, Dewulf, and Biesbroek 2019). The wickedness framework features a varying subset of characteristics that aim to categorise the ten original attributes into clusters (Table 2), thus, illustrating various conceptualisations of the wicked problems framework.

Contrary to the reduction attempts collated in Table 2, Ritchey (2011, 26) advocates maintaining the 10-point frame, arguing that Rittel’s and Webber’s properties may serve as *heuristic perspectives* rather than as analytical concepts. The original 10-point frame is not intended as a checklist or a set of absolute criteria but rather as ‘insight which may aid the decision maker in judging whether their particular problem has some degree of wickedness associated with it.’ (Camilus 2008). Similarly to

Table 1. List of properties for wicked problems (based on Rittel and Webber 1973).

Properties of wicked problems	Description
(1) No clear definition	The **formulation of the wicked problem** as such is the problem. The classic approach of (A) identifying the problem and (B) finding solutions is not applicable here. Wicked problems would require problem-solvers to know all viable solutions before describing the issue in detail.
(2) No boundary lines	Wicked problems have **no boundary lines**, i.e. problem-solvers never know whether they are finished. Therefore, decision-makers stop problem-solving at their discretion if they run out of 'time, money or patience' (Rittel and Webber, 162).
(3) Better-or-worse answers	Solutions to wicked problems are not 'true-or-false', but '**better-or-worse' solutions**. Formal decision-making rules do not exist, but personal bias, values and ideological or cultural constraints play a significant role in finding solutions.
(4) No test for solutions	There is neither an ultimate nor an immediate test for solving a wicked problem. The full consequences of **solutions can neither be tested** nor predicted, i.e. they unfold once solutions are implemented.
(5) One-shot approach	Actions, decisions and solutions are irreversible, and the consequences are usually far-reaching. Every answer to a wicked problem is, therefore**, a one-shot operation**. There is no carte blanche for trial-and-error solutions with unforeseen consequences, as every attempt counts.
(6) Infinite set of potential solutions	Wicked problems have **no enumerable solutions** (including those not even thought of). No criteria enable decision-makers to prove that all solutions to a wicked problem have been considered. Therefore, the scope of solutions and the selection of solutions is a matter of judgement.
(7) Uniqueness	'Every wicked problem is essentially **unique**' (Rittel and Webber 1973, 164). Even if situations seem similar, solutions for one problem cannot be transferred to another problem, as a characteristic, a property, or a framework condition might differ from the previous problem (Rittel 1972, 393).
(8) Causal Webs	When solving one wicked problem, a **new problem** may arise. Therefore, every wicked problem 'can be viewed as a nested system of another problem' (Brinkerhoff 2014, 333).
(9) Numerous explanations	The way a wicked problem is explained determines how the problem is solved. As views and beliefs of stakeholders involved often contrast, **explanations are not given objectively, and bias prevails**. 'The analyst's 'world view' is the strongest determining factor in explaining a wicked problem' (Rittel and Webber 1973, 166).
(10) Normative framing (no right to be wrong)	'Wicked problems demand acting while displaying great resistance to change. This […] can generate […] individual risks for would-be problem solvers who may be held to have no right to be wrong yet may be morally obliged to act' (Duckett et al. 2016, 46). Therefore, contesting the decisions and outcomes, pursuing adaptive strategies, and revising unintended faulty conclusions are always necessary.

the different conceptualisations of wicked problems, understanding how to apply the framework varies (Table 3).

Scholarly work also focused on management approaches and coping strategies for wicked problems (i.a., Daviter 2017; 2019; Levin et al. 2012; Roberts 2000). Roberts (2000), for instance, identifies authoritative, collaborative, or competitive coping strategies – depending on whether conflicts over problem definition and coping strategies are low or high. Further scholarly work highlights governance responses, such as adaptive management (i.a., DeFries and Nagendra 2017; Head 2014), resilience thinking (Craig 2020), collaborative networks (i.a. Brick, Snow, and van de Wetering 2001; Weber and Khademian 2008), incrementalism (DeFries and Nagendra 2017; Termeer et al. 2015; Termeer and Dewulf 2019), reflexive governance, or strategies ranging from high-, mid- to low risk-taking and commitment [realignment of governance systems and high-profile leadership – modest policy reform – tokenism or placebos, cf. McConnell (2017)]. Breitkreuz (2022) calls for 'epistemologically, ecologically informed research' to cope with and manage wickedness in complex social systems. Although this list of coping strategies is neither exhaustive nor complete, the spectrum of management responses is broad and difficult to generalise.

As there is no coordinated and concerted concept of wicked problems (McCall and Burge 2016; Ruhl and Salzman 2020), Lönngren and van Poeck (2020) further stress the need for researchers to describe how they use the concept, if utilising it as a descriptive/analytical tool. We position ourselves and our research in the following. We combine a constructivist approach with elements of

Table 2. Overview of wickedness frameworks.

Framework	Characteristics	Primary source(s)
2-point-frame	Clusters the 10 characteristics into social capriciousness (dynamism and contestation of social goals and norms) and ecological panarchy (embeddedness and interaction of multiple systems)	Craig (2020)
	Wickedness spectrum: Degree of complexity of problem and stakeholder propensity	Alford and Head (2017),
3-point-frame	Categorising the 10 attributes into ontological claims, epistemological claims and methodological claims	Catron (1981)
	Defining characteristics: uncertainty-complexity-divergence	Head (2008), Newman and Head (2017)
	Categorising the 10 attributes into non-resolvability, multi-actor environments, and problem definition	Danken, Dribbisch, and Lange (2016)
5-point-frame	Attributes: goals, uncertainty, variables, connections, dynamics (congruent with five-dimensional operationalisations of complex problems in psychology)	Kirschke et al. (2019)
6-point-frame	Aggregation of attributes: You will not understand the problem until you have developed a solution. Wicked problems have no stopping rule. Solutions to WP are not right or wrong. Every WP is essentially unique and novel. Every solution to a WP is a 'one-shot operation'. WP have no given alternative solutions	Tatham and Houghton (2011)
7-point-frame	Attributes: complexity, contingency, ambiguity, temporality, politicisation, and normativity (congruent with policy models and literature)	Grundmann (2017)
10-plus-4-point frame	Super-wicked problems: 10 attributes plus: time is running out; those who cause the problem also seek to provide a solution; the central authority needed to address them is weak or non-existent; irrational discounting occurs that pushes responses to the future	Lazarus (2009), Levin et al. (2012)

pragmatism, as we see the wickedness concept as a flexible framework that can assist in understanding a problem or phenomenon [the German energy transition]. Nevertheless, we do not view wicked problems as ontologically distinct from 'tame' science or engineering problems. Instead, we argue that wickedness facets can be multi-faceted and thus occur in parts of a problem – whether a technical or a social one. We believe that the ongoing discourse about problem definition [Why are energy transition attempts in the four analysed cases not moving ahead faster? What is/are the reasons(s)?] and which management approaches to utilise can ultimately lead to energy transition bottlenecks and delays in target attainment. We understand the wicked problems concept and the ten dimensions as a means to explain these energy transition hurdles or bottlenecks, as the wicked attributes can become 'more informative about how to think about and manage social problems' (Ruhl and Salzman 2020, 1577).

3. Materials & methods

3.1. Study design

We apply the original wicked problems framework (cf. Rittel and Webber 1973) to the German energy transition. Our methods include multiple-case studies and multi-criteria analysis, utilising the original 10-point frame of the wicked problems.

3.1.1. Multiple-case study analysis

We conduct a multi-case study analysis of the German energy transition with four cases, following the case study design proposed by Yin (2018). Case study research, according to Creswell (2009, 73), 'involves the study of an issue' [here: wicked problems] 'explored through one or more cases' [here: four] 'within a bounded system' [here: German energy transition context in 2022].

The four cases provide insights into different (sub)sectors of the German energy transition (electricity supply, heating/cooling, transport, industry) that face different challenges and are at different transition stages (Luderer, Kost, and Sörgel 2021). We introduce the four case studies

Table 3. Overview of selected operationalisation approaches for the wickedness concept.

Source	Application	Methods	Wickedness framework
FitzGibbon and Mensah (2012)	Climate change in Ghana	using primary data from expert interviews; ‘diagnostic and prescriptive with a qualitative analytical slant’	10-point-frame
Thollander, Palm, and Hedbrant (2019)	Energy efficiency – energy-related empirical phenomena	literature review of 19 energy-related articles mentioning the terms ‘wicked problem’	10-point-frame
Brunnengräber et al. (2014) and Brunnengräber (2019)	Nuclear waste governance	argumentative reasoning	6-point-frame and 10-point-frame
May, Jochim, and Pump (2013)	Limits of policy processing – financial crisis, climate change, health care, K-12 education, drug abuse, food safety, critical infrastructure, obesity epidemic, ocean health, terrorism, extreme events	desktop-approach	No direct link to wickedness literature, yet similar categories to Alford and Head (2017) – nature of the problem and evidence for linkages among relevant policymaking institutions
Peters (2018)	—	surveys with experts in the field of policy studies to identify wicked problems	10-point-frame
Peters and Tarpey (2019)	Policy issues: climate change, food policy, health care policy, income inequality, obesity, or poverty	expert surveys with academic public policy researchers to analyse six public policy problems	10-point-frame and super-wicked problems framework
Kirschke, Borchardt, and Newig (2017)	German water management	gradual-numerical and qualitative approach to complex problems; semi-structured expert interviews	5-point-frame
Kirschke, Zhang, and Meyer (2018)	Wicked problems in the water-soil-nexus in China	questionnaire for focus-group discussions within the author team	5-point-frame
Levin et al. (2012)	Climate change as a super-wicked problem	reasoning approach	Super-wicked problems framework
Conradie (2020)	Climate change	logical reasoning	

in section 3.2. According to Sovacool, Axsen, and Sorrell (2018, 30), typical case studies investigate ‘common, frequently observed, representative and/or illustrative cases’, which holds true for the German energy transition as a ‘prominent and widely discussed’ transition plan (Steinbacher and Pahle 2016, 70).

According to van Graaf and Sovacool (2020, 12–16), the energy system ‘cuts across other systems such as electricity, transport, buildings, and agriculture […] [which can be broken down] into three layers: the supply infrastructure, the demand infrastructure, and the social infrastructure.’ Two of our four analysed cases – onshore wind power (case 1) and shallow geothermal energy systems (case 2) – are part of the supply infrastructure, as they are both energy conversion systems. The remaining two cases – road mobility (case 3) and chemical industry (case 4) pertain to the demand infrastructure, including energy consumption patterns, use or practice.

Conradie (2020, 231) states that, initially, wickedness literature focused on systems design at a micro-level or intermediate level, when later the concept was applied to a broader – meso- or macro-level, e.g. to social and economic public policy problems. In line with calls from socio-technical-systems methodologies to ‘avoid hollow-arch and snapshot biases’ (Hyysalo 2021), we aim to encompass multiple loci, i.e. levels and units of analysis. With this article, we aim to address both the intermediate level of analysis (frog’s perspective) and the macro level (bird’s eye). Therefore, we analysed two sets of cases at two different analytical levels:

- Cases 1 and 2 apply a 'frog's eye', i.e. scrutinising one way to decarbonise or transform a subsector. Focusing on one subsystem for the electricity and heating/cooling subsectors allows more in-depth insight and examples.
- Cases 3 and 4 assume a 'bird's eye' in that they are analysed at subsector level. The cases from the road transport and chemical industry subsectors are analysed on this slightly more general analytical level to illustrate more complex interconnections within the sub-cases, e.g. the interaction between technological pathways and policy options.

Although there are differences in the scope of analysis, we aim to show that the wickedness concept is applicable at both a meso- and macro-analytical level. Table 4 briefly collates the differences and similarities between the four cases.

We conducted this research within the PhD graduate college 'Socio-environmental questions of energy transitions' of the German Federal Environmental Foundation (DBU). The co-authors of this work have diverse backgrounds in energy economics, sustainability sciences, geosciences, wind energy research, and environmental resource management and planning. We selected the cases based on the core expertise of the co-authors.

Additionally, we selected the cases to gain insights into different transition stages and particularities in the sectors: While historically the energy transition has mainly been achieved in the electricity sector (Morris and Jungjohann 2016; Renn and Marshall 2020), recently, attention has been given to transforming the end-use sectors (heating/cooling, transport, and industry). We therefore hope to gain complementary insights from a sector with nearly 40 years of transition (electricity sector) and sectors that recently started the transformation process (heating/cooling, transport, industry sectors). We use several data sources to explore the multifaceted dimensions of the German energy transition. Our material includes qualitative data (journal articles, academic literature, press releases, newspaper articles, white papers, and legislative documents). We conducted configurative literature research (Gough and Thomas 2017) to synthesise data on wicked facets in the four case studies.

3.1.2. Multicriteria analysis to apply the 'wicked problems' concept

We acknowledge the multitude of approaches to conceptualise (Table 2) and operationalise (Table 3) wicked problems but find that there is no one-size-fits-all formula to be applied in all exploratory case studies. In this contribution, we are adapting Rittel's and Webber's original 10-point frame (Table 1) as a perceptual lens. We contribute to the wickedness literature by exploring bottlenecks and wickedness of sustainability transitions (specifically the German energy transition). We do not aim to assess whether the cases are wicked or not, nor do we assess how wicked they are, nor do we conduct a comparative assessment of wickedness. We therefore, approach our research question in an explorative way by conceptualising wicked facets of the energy transition in four qualitative case studies. We limit our analysis to unpacking practical challenges in the German energy transition. Proposing potential coping mechanisms or governance responses was beyond the feasible scope of our analysis but could be explored in further research. We offer our approach and findings for further debate.

We apply an argumentative-discursive approach based on literature analysis and the authors' expertise. We use explanations from different levels (from individual project level to national policy-making and governance) and (sub)sectors to illustrate the characteristics of wicked problems. We assume a techno-centric and socio-centric perspective in this article to prevent 'biases and blind spots resulting from an overly technical perspective' (cf. Fournis and Fortin 2017, 3 in the social acceptability literature). We therefore seek to represent examples for wickedness facets from a *technical perspective* (i.e. the technological possibility of a transition) and a *governance perspective* (i.e. the socio-political implementation of the transition). We base the differentiation into societal and technical dimensions on prior work (cf. Craig 2020; Stahl 2014; Wanzenböck et al. 2020). With a strong focus on stakeholder divergence on problem statements and potential solutions, Wanzenböck et al. (2020, 476) argue that '[c]onceptually disentangling societal challenges

Table 4. Generic differences (and similarities) between the four analysed case studies.

Criteria	Case 1	Case 2	Case 3	Case 4
Case study description	Decarbonising the electricity sector by installing onshore wind farms	Decarbonising the space heating and cooling sector by installing shallow geothermal energy systems	Decarbonising the transport mobility sector by transforming road mobility	Decarbonising the industry sector by transforming the German chemical sector
Problem definition	Stagnating installation of onshore wind farms, un-harmonised policy mix for wind development, highly politicised issue (heterogeneous and fragmented actors)	Little progress in increasing the share of RES in space heating and cooling	Insufficient emission reduction in the (sub)sector	No coherent and feasible decarbonisation pathway identified (decarbonisation targets are not coordinated centrally, heterogeneity of actors)
Case boundaries	German onshore wind power development	German building stock, only space heating and cooling (not industrial process heat/cold)	German transport sector with a focus on road mobility, excluding shipping, aviation, and biking	German chemical industry
Energy transition sector	Electricity	Heating/cooling	Transport	Industry
Transition phase/stage: pre-development, take-off, breakthrough, stabilisation (cf. Rotmans et al. 2001; Laes et al. 2014)	Breakthrough, on the verge of acceleration (Markard 2018; Markard, Geels, and Raven 2020)	Take-off	Take-off (early)	Take-Off (early)
Technological readiness	Technological solutions exist and are market-ready but need to be upscaled.	Proven technological solutions exist and are already used/applied.	Low-emission technologies such as electric vehicles are available and have been starting to diffuse. Decarbonising the transport sector requires changes in other technological systems (such as grids, electricity production, possibly e-fuels etc.), where upscaling is still necessary.	Some technological solutions exist but are not market-ready / up-scaleable (green hydrogen), and others are still in the R&D phase (methane pyrolysis). Few technologies are market-ready and upscaled (power-to-heat)
Spatial dimension & affected sectors of transition solutions	Public sector (federal, state, regional and municipal) Industry sector (wind energy industry) Private sector (land-owners, individuals etc.)	Building sector	Public sector, private sector, industry sector, individual level	Industry sector, company-level
Energy systems' perspective – supply or demand or social infrastructure (cf. van Graaf and Sovacool 2020)	Energy supply infrastructure (systems of energy conversion)	Energy supply infrastructure (systems of energy conversion)	Demand infrastructure	Demand infrastructure
Analytical level: macro-, meso-, micro-level; sector, subsector, subsystem	Meso-level & subsystem (one energy transition solution within a sector)	Meso-level & subsystem (one energy transition solution within a sector)	Macro-level & entire subsector	Macro-level & entire subsector

by their problem and solution structures may prove particularly useful if we assume that technological innovations may indeed be key but not necessarily sufficient in tackling current challenges.' Similarly, Stahl (2014) distinguishes between decision-making processes (i.e. the governance perspective) and technical implementation (i.e. technical perspective). Although Craig (2020) does not differentiate between social and technical, the author offers two sources of wickedness, focusing on the one hand on social and on the other hand on ecological characteristics – *social* capriciousness and *ecological* panarchy.

We presented, discussed, and revised the individual case study analyses in a working group workshop in June 2022. Annexes A–D contain the individual case study portfolios (i.e. the within-case analyses) as supplementary material for additional documentation. Section 4 presents the results and highlights from the four cases, thus illustrating wicked facets in the German energy transition.

3.2. Introduction of case studies

With a global energy politics view, van Graaf and Sovacool (2020, 47) argue that most of the growth in renewables is 'confined to the power sector but, thanks to the ongoing electrification […], they will find their way to other end-use sectors', indicating different transition stages for the different sectors. For Germany, the energy transition has mainly been achieved in the electricity sector (Morris and Jungjohann 2016; Renn and Marshall 2020), given its long evolution since the 1970s. More recently, attention has been given to transforming the end-use sectors, heating and cooling[4], transport, and industry. With the adoption of the Climate Action Act (KSG) in 2019 and its amendment in 2021, the German Federal government set greenhouse gas (GHG) emissions reduction targets (Figure 1). The sectors face different challenges and bottlenecks, which we introduce in the following. Table 5 contains a summary of information on the four cases. We analyse one case each in the electricity supply, heating/cooling, transport, and chemical industry subsector.

3.2.1. Electricity supply: case 1 – Decarbonising the electricity sector by installing onshore wind farms

Transforming the German energy supply sector is a prime concern in achieving net-zero emissions (Luderer, Kost, and Sörgel 2021). In 2021, the energy supply sector accounted for the largest share of 32.4% of German GHG emissions (UBA and BMWK 2022). van Graaf and Sovacool (2020) describe three main ways to decarbonise the electricity sector: expansion of renewables, nuclear

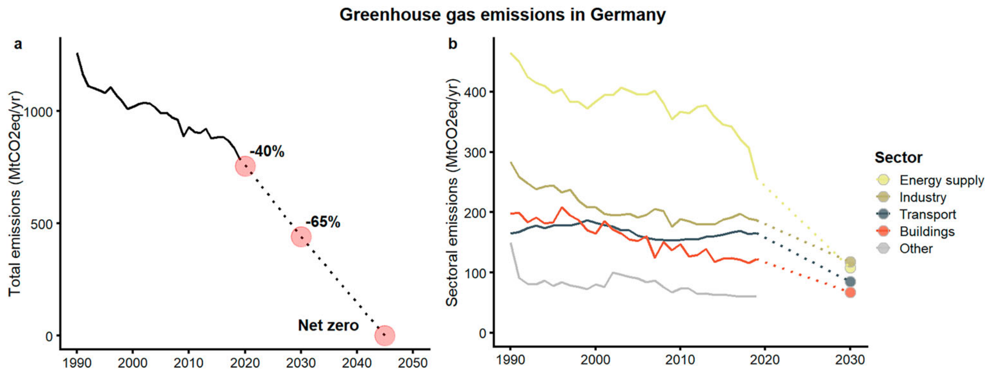

Figure 1. Historical greenhouse gas (GHG) emissions and reduction targets in CO_2 equivalents in Germany, in total until 2050 (a) and disaggregated by sector until 2030 (b). Overall GHG reduction targets are relative to 1990 levels. Emissions from space heating and cooling are predominantly accounted for in the buildings sector (fuel combustion in residential and commercial buildings) but also occur in the energy supply sector (e.g. district heating, electrified heating and cooling). Source Bundes-Klimaschutzgesetz (KSG 2021).

power, and carbon capture and storage (CCS). As the German transition strategy for the power supply sector does not foresee a revival of nuclear power use and the use of CCS technologies is not unanimously agreed upon, we focus our analysis on developing onshore wind power, currently the powerhouse of renewable energy sources in Germany.

In 2022, wind power was contributing considerably to the renewable electricity share (23.1%[5], cf. Fraunhofer ISE 2022), with accelerated development goals underway. By 2030, 115 GW cumulative installed capacity should be reached (Windenergie-an-Land-Gesetz 2022), with 58.1 GW installed in 2022 (Deutsche WindGuard GmbH 2023). However, wind power infrastructure is not evenly distributed across the country, causing a North-South divide.[6] The installation of wind power infrastructure has stagnated since 2018 (Deutsche WindGuard GmbH 2022) and faces (local) opposition (Fritsch 2020). The main barriers are land availability, nature conservation concerns and other land-use conflicts[7], litigation, switching to a tendering funding system, limited repowering and lengthy permitting (Biehl, Köppel, and Grimm 2021). A legislation package was passed in 2022 to address bottlenecks and relax restrictions on development.[8]

Nevertheless, hurdles remain that can show complex if not wicked facets: Firstly, the potential time-lag of policy measures for acceleration (Hanke 2022; Lehmann et al. 2022). Secondly, the provision of raw materials, logistics and personnel to permit, develop and maintain the facilities, despite worldwide supply bottlenecks (Taylor 2022). Thirdly, potential grid congestion, as utilisation loads of the transmission grid have reached a maximum with ca. 2.5 million[9] renewable energy producers connected to the grid by 2022. Persisting challenges and the trade-offs between competing interests and stakeholders in the onshore wind power field provide a compelling case for applying the ‘wicked problems’ framework in this article.

3.2.2. Heating and cooling: case 2 – Decarbonising the space heating and cooling sector by installing shallow geothermal energy systems

Although the building sector reduced GHG emissions to around 115 $MtCO_2$ in 2021, this sector still exceeds the permitted annual emissions volumes, thus illustrating the great importance of decarbonising the sector, e.g. by switching to renewable heating/cooling. The low share of renewable energy sources, 16.5% in 2021 (UBA 2022), in the German heating/cooling sector further stresses the need to transform the heating and cooling sector. In order to increase this share, the coalition agreement of the German Federal government states the target of 50% renewables in the heat supply by the year 2030 (SPD, BÜNDNIS 90/DIE GRÜNEN & FDP 2021). For the building sector, the German Climate Action Act targets a reduction of greenhouse gas emissions of 68% by 2030 compared to 1990 (KSG 2021).

A sustainable and environmentally friendly heating and cooling supply in the building sector is thus an integral element of an effective heat transition as part of the overarching energy transition. Shallow geothermal systems represent one possible technological solution[10] to foster this transition. These systems include ground source heat pumps, groundwater heat pumps and shallow aquifer thermal energy storage systems, which are feasible technologies for significantly reducing GHG emissions compared to conventional heating/cooling technologies (Born et al. 2022).

While air conditioning via heat pumps was implemented in around 50% of the newly built residential buildings in 2020, most systems are air source heat pumps (Born et al. 2022). This type of heat pump usually has lower efficiencies than ground source or groundwater heat pump systems, indicating a great potential for even higher GHG emission reductions in the future (Born et al. 2022). Nevertheless, several barriers could potentially prevent an accelerated development of shallow geothermal energy systems for space heating and cooling. These include thermal overexploitation in densely populated areas, detrimental changes due to an even slight increase in temperature negatively affecting groundwater ecosystems and conflicts of use of shallow groundwater and the subsurface in general (Blum et al. 2021; Bonte 2013; Bonte et al. 2011; García-Gil et al. 2020). Finding an optimal trade-off between these aspects exhibits wicked facets, which we discuss in this article.

Table 5. Summary of case study introductions.

Energy Transition Sector	Energy supply (electricity)	Heating/cooling	Transport	Industry
Case study	Installing onshore wind power (short: onshore wind power)	Installing shallow geothermal energy systems (short: shallow geothermal energy systems)	Transforming road mobility (short: road mobility)	Transforming the German chemical industry (short: chemical industry)
Transition targets	• GHG emissions reduction of 65% compared to the 1990 baseline (466 $MtCO_2$) • Min. 80% of gross electricity from renewable energy sources by 2030 • Capacity targets for onshore wind: 115 GW by 2030, 160 GW by 2040	• GHG emissions reduction target of 68% in the building sector compared to the 1990 baseline (210 $MtCO_2$) • 50% renewable energy sources in the heat supply by 2030 • 52.8% of new residential buildings to be equipped with heat pumps in 2020 (20% ground source heat pumps)	• GHG emissions reduction target of 48% compared to the 1990 baseline (164 $MtCO_2$) • GHG-neutrality until 2045	• GHG emissions reduction target of 58% for industry sector compared to the 1990 baseline (284 $MtCO_2$)
Transition status in 2021 (considering available information as of mid-2022)	• GHG emissions: 247 $MtCO_2$ • 23.1% share of the electricity mix (*on-and offshore) • 56.1 GW cumulative installed capacity (28,230 onshore wind turbines)	• GHG emissions in the building sector: 115 $MtCO_2$ • 16,2%* (199,5 TWh) share of RES in the energy consumption in the sector (* space & process heating/cooling) • 9% share of RES supplied by shallow geothermal energy & environmental heat	• GHG emissions: 148 $MtCO_2$ • Marginal reduction of emissions levels compared to 1990 • Technological progress is counteracted by increase in demand	• GHG emissions: 181 $MtCO_2$ • Alternative production processes and technologies are known; first pilot projects are being tested/upscaled • Regulatory framework does not favour low-carbon technologies; conventional technologies are mostly more economically feasible
Exemplary barriers	• Polycentric governance increases complexity and value divergence • Limited land availability & land use conflicts (military, DVOR stations) • Species & nature conservation • Lengthy permitting processes (bureaucracy, long communication times, litigation at all levels) • Acceptance & participation (hurdles for community wind projects, no mandated procedural or financial participation) • Undersubscribed volumes in tender rounds • Limited repowering (only ca. 50% within designated areas) • Raw materials and skills shortage • Inadequately equipped administration (lack of personnel, lack of know-how)	• Costly retrofitting • Skills shortage • Competing use of shallow underground resources (groundwater abstraction, subsurface infrastructure etc.) • Groundwater ecosystem protection • Adverse thermal interferences are possible in densely populated areas (thermal overexploitation) • Insufficient regulatory framework • Inefficient permissions of too large capacities • Negative public perception	• Multi-level governance (EU-level, country-level, local level) increases complexity and requires ‘second-best’ solutions • A multitude of conceivable instruments (performance standards, command and control, emissions pricing, fuel taxation, subsidies) • Dynamic demand for transport services • A multitude of actors, information asymmetry • High degree of path dependencies • Public acceptance is critical for successful policy implementation. Public acceptance might hinge on unequal distribution of policy impacts (e.g. urban/rural gap)	• Limited availability of renewable electricity and hydrogen • Insufficient industry regulation: no mandatory decarbonisation targets, no incentives for low-carbon technologies • Low technology readiness of key technologies (e.g. electrification of steam crackers, alternative production routes) • High costs of alternative technologies and production processes, lacking competitiveness with current fossil-fuel-based technologies) • Lack of capacities (personnel, financial, organisational) in companies • Decarbonisation is not a prime concern for the companies (short-term competitiveness)

3.2.3. Transport: case 3 – Decarbonising the transport sector by transforming road mobility

In 2021, transport services accounted for 19.4% of GHG emissions in Germany (148 $MtCO_2$) (UBA and BMWK 2022). The German government aims to curb transport sector GHG emissions by 48% by 2030 compared to levels of 1990 (KSG 2021). The transition targets in the transport sector constitute a challenge since the sector's emission levels have remained virtually unchanged for decades. Technological advances enabling the diffusion of more fuel-efficient and less polluting transport vehicles were insufficient to lower emission levels since aggregated demand for mobility increased simultaneously with growing consumer demand for larger and heavier vehicles (rebound effect, cf. Dimitropoulos, Oueslati, and Sintek 2018). Consequently, the question of *how* to meet sectoral emission reduction targets is subject to vital public debate.

Research suggests that the electrification of aviation and shipping subsectors is more challenging (Becattini, Gabrielli, and Mazzotti 2021) and will instead require hydrogen and e-fuel technologies (Ueckerdt et al. 2021). Given high production costs, hydrogen and e-fuel technologies are unlikely to play a substantial role in decarbonising road mobility (Luderer, Kost, and Sörgel 2021; Ueckerdt et al. 2021). Therefore, direct electrification in the road transport subsector is crucial. This work will analyse road mobility transition approaches from a wickedness perspective with a strong focus on electrification of private transport.

The road mobility subsector entails various features which render it susceptible to an inherently complex transition process: Firstly, individual transportation links strongly to personal sentiments (Javaid, Creutzig, and Bamberg 2020), embodies various path dependencies (Berkhout 2002) and spans across a multitude of scattered actors in a highly dynamic setting. Secondly, policy interventions in this sector entail distributional consequences, i.e. differing economic consequences for different parts of society (Guo and Kontou 2021, and Annex D; Douenne 2020; Sterner 2012). Any policy's perceived (un)fairness could affect political support and inhibit effective implementation, which became apparent during the Yellow Vests[11] movement in France (Douenne and Fabre 2022). Similarly, the discussion on speed limits in 2022 (Jakob and Klöckner 2021; Kluth 2022) and the reduction of gasoline taxes in Germany exemplify of the highly complex and value-laden policy environment, which we discuss in this article.

3.2.4. Industry: case 4 – Decarbonising the German chemical industry

The chemical subsector is one of the largest and most energy-intensive German industries, accounting for 5–6% of Germany's GHG emissions in 2018 (BMWK 2022; Gniffke and Günther 2022a; 2022b). The subsector is vital to Germany's economy, as it employs ca. 460.000 people and accounts for 10% of industry revenue. Therefore, many stakeholders argue that maintaining the subsectors' competitiveness is crucial. Decarbonising the chemical industry implies three technical and economic challenges: Firstly, it is a grown system with complex and intertwined production processes, which are complicated to decarbonise step-by-step (Ausfelder 2015; Joas et al. 2019). Secondly, ca. 70% of the products remain within the industry for further processing, thus, limiting visibility for end customers who otherwise might demand low-carbon products (BMWK 2022). Thirdly, investment cycles and technology lifetimes are long, as an average steam cracker can be operated for about 50 years (Joas et al. 2019). Investments in conventional technology could lead to a technological lock-in for the next 50 years.

Alternatives for conventional processes exist or are in development. The most widely applied technology is the electrification of steam and heat (power-to-heat) (Joas et al. 2019; Madeddu et al. 2020; Wesseling et al. 2017). Other key technologies will likely be available within the next decade, including olefins and aromatics produced from green methanol and chemical recycling (Wesseling et al. 2017; Luderer, Kost, and Sörgel 2021). End-use applicability of green hydrogen in this subsector remains uncertain, given the short-term scarcity (until 2030) and long-term uncertainty of electrolysis capacity (Odenweller et al. 2022). Carbon capture at combined heat and power plants and electrified steam crackers is expected to reach technological readiness between 2035 and 2045 (Joas et al. 2019).

The main implementation barriers for low-carbon technologies include a lack of incentives to adopt them and comparatively higher costs than conventional technologies (Chiappinelli et al. 2021). Current carbon abatement costs for low-carbon technologies are much higher than carbon prices in the European Union Emissions Trading Scheme (EU ETS). For example, abating one ton of carbon by the methanol-to-olefins method costs 160 €, while emitting one ton of CO_2 under the ETS currently costs about 90 € (Boerse.de 2022; Joas et al. 2019). The high electricity demand of a fully decarbonised chemical industry (expected to be 11 times higher than today[12]) is another main caveat (Geres et al. 2019). Decarbonisation in the chemical subsector depends on various technical, economic, and political factors. Assessing its potential wickedness can illuminate the main challenges and their solutions.

Table 5 contains a summary of information on the four cases.

4. Results: wicked facets of the German energy transition

4.1. No clear definition

'*The information needed to understand the problem depends upon one's idea for solving it.*' (Rittel and Webber 1973, 161)

All four case studies show that the *technical definition of the problem* (*techno-centric*) is relatively straightforward. At the same time, the question of *how* to achieve transition targets in the individual subsectors (*socio-centric*) is often subject to diverging viewpoints (Table 6).

We will utilise an example from the transport sector (case 3) to illustrate this wicked tendency:

Technically, decarbonising road mobility in the transport sector requires meeting individuals′ demand for transport services at lower levels of aggregate GHG emissions. Several channels exist to accomplish sectoral targets, including lowering the emission intensity of transport fuels, lowering the energy intensity of transport services (such as modal shifts towards public transport) or demand-side measures. Reducing emissions in the road transport subsector is technologically feasible, and various corresponding policies are conceivable or even in practice. Insecurity prevails on which policies to introduce, i.e. *how* to reach sectoral targets, including trade-offs. Since many people will likely demand mobility services, the feasible solution space will need to deal with persisting (high) demand levels. Without affordable and widely available technological solutions, decarbonising the transport sector will entail distributional consequences, i.e. creating winners and losers. How to address those consequences is inherently normative but also limited by institutional capacities. Therefore, defining the problem of *efficient and equitable* decarbonisation of the transport sector within existing governance structures is wicked while reducing emissions in the transport sector is technically feasible, i.e. a tame problem.

4.2. No boundary lines (no-stopping rule)

'*… because there are no criteria for sufficient understanding and because there is no end to the causal chains that link interacting open systems, the would-be planner can always try to do better.*' (Rittel and Webber 1973, 162)

All cases show similar results in our analysis for the *no-stopping rule* (Table 7), where target attainment in the transition is possible to assess; therefore, decision-makers, policy-makers, or actors would know when the transition goals are reached. However, the governance domain (*socio-centric*) shows various examples of wicked facets.

We will further explore the *no-stopping rule* criterion with the electricity subsector case.

On the one hand, installation targets for installing onshore wind facilities exist (EEG 2023; WaLG 2022), and wind developers know when they have installed sufficient capacities. On the

Table 6. Summary of case study analysis – examples for wickedness dimension #1 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #1 – no clear definition
Case 1: Installing onshore wind energy	**TD:** Technical definition is clear: more wind turbines must be installed to advance transition in the electricity sector. **GD:** Socio-political problem definition is less straightforward given myriad explanatory approaches, and no consensus on if, where and how many wind turbines should be installed. Defining a suitable transition pathway & policy mix is highly contested, as, e.g. explanatory approaches for stagnating development vary, incl.: • policy drift & governance mismatches: Juerges, Leahy, and Newig (2018); Biehl, Köppel, and Grimm (2021); Reitz, Goshen, and Ohlhorst (2022) • conflicts with conservation objectives: Wiehe et al. (2021), Weber, Biehl, and Köppel (2019) • vocal opposition & citizen's discontent: Reusswig et al. (2016), Reusswig, Komendantova, and Battaglini (2018), Hübner et al. (2019), Fachagentur Windenergie an Land (2021), Köppel et al. (2019).
Case 2: Installing shallow geothermal energy systems	**TD:** Technical definition is clear: more buildings have to be heated and cooled in a renewable and sustainable way to advance transition in the heating/cooling sector. **GD:** Problem definition is far less straightforward since political, social, ecological and economic aspects have to be considered, and a variety of stakeholders need to be involved, e.g. municipalities, regional supply companies & citizens, which all have differing interests (Brielmann et al. 2011; Hähnlein, Bayer, and Blum 2010). Defining which problem(s) to address and designing a regulatory framework to account for all aspects, e.g. cost-effectiveness and feasibility for proprietors and tenants (cf. Popovski et al. 2019) and availability of resources, is not a straightforward task.
Case 3: Transforming road mobility	**TD:** Technical definition is clear, and it is technologically feasible to reduce emissions in the transport sector: Various policies are conceivable or in practice, and several channels exist to accomplish sectoral targets. **GD:** Insecurity prevails on which policies to introduce, i.e. *how* to reach sectoral targets, including trade-offs and potentially distributional consequences (creating winners and losers).
Case 4: Transforming the chemical industry	**TD:** The problem definition is clear from a technical perspective: the chemical industry needs to be decarbonised (Geres et al. 2019; Joas et al. 2019). **GD:** The transformation is far more complex from a social, economic and political perspective, cf. (Bang, Rosendahl, and Böhringer 2022; Díaz et al. 2019; European Commission 2019): • maintain competitiveness on a national and international level • align decarbonisation pathways with other sustainability goals (like preserving biodiversity), • just and inclusive transformation.

other hand, these targets have been adjusted continuously in the past. Technical adjustments and repowering of installed wind facilities will still be necessary from 2040 onwards, but a clear goal exists. The question remains if future exogenous shocks (such as the war on Ukraine in 2022) will require additional system changes and more ambitious targets. Moreover, uncertainties about the future electricity demand (for direct electrification in other sectors, production of green hydrogen, increasing energy consumption) and supply (energy emergency, decommissioning and end-of-life of first- and second-generation wind turbines) could lead to a *de-facto no-stopping-rule*. Policy uncertainty and time lag can also lead to a *no-stopping rule*. Attempts to accelerate onshore wind development and create a link between transition targets in the electricity sector and state designation of sites to develop wind farms still exhibit signs of wickedness: The Onshore Wind Demand Act will free up potential land for installations after five to ten years (Lehmann et al. 2022), making it challenging to monitor the success of policy measures in the meantime. Therefore, decision-makers cannot quickly check if the measures are sufficient and might be tempted to continue addressing the problem or wait too long to intervene.

Table 7. Summary of case study analysis – examples for wickedness dimension #2 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #2 – no-stopping rule
Case 1: Installing onshore wind energy	**TD:** Target attainment is easy to assess (measured in cumulative installed capacity), a federal registry for wind turbines exists, and the Federal States need to report new land allocations and cumulative installation annually. **GD:** De-facto no-stopping rule applies: • Given uncertainties about future gross electricity supply (land availability, decommissioning, repowering): Biehl, Köppel, and Grimm (2021) and future electricity demand (direct electrification in other sectors, green hydrogen, increasing/decreasing energy consumption, additional capacities due to exogenous shocks): cf. Löffler et al. (2022) • Time lag of policy packages, cf. Lehmann et al. (2022), Römling (2023) and therefore uncertainty if further policy measures are required.
Case 2: Installing shallow geothermal energy systems	**TD:** Target attainment is easy to assess for individual buildings. **GD:** Deciding on a stopping rule for the overall decarbonisation pathway is far more complex: • interaction between heating networks, geothermal energy, and other renewable energy sources (e.g. solar thermal) subjected to conflicts of interest • continued subsidies for fossil-fuelled combined heat and cooling supply • regulatory and policy uncertainties, e.g. nature conservation • no specification for individual technological contributions to decarbonisation goal in the heating/cooling sector (SPD, BÜNDNIS 90/DIE GRÜNEN & FDP 2021)
Case 3: Transforming road mobility	**TD/GD:** Lowering transport sector emissions will require operation in a highly dynamic environment: • consumer preferences are persistent (i.e. ‘sticky’) & influenced by non-monetary factors (comfort, security, habits) • high degree of path dependency in the transport sector (large-scale infrastructure) • transport sector transition is highly non-linear, requiring different policy instruments at different transition stages, which respond to sector-specific dynamics in the supply and demand of transport services
Case 4: Transforming the chemical industry	**TD:** Technical dimension seems clearly defined, stopping when the chemical industry operates carbon neutral. • goal is to achieve climate neutrality through electrification and the use of biomass (Joas et al. 2019) • remaining complexities: definitions of carbon neutrality, greenhouse gas neutrality, climate neutrality, and the systems’ boundaries. **GD:** Conflicts of interest arise, e.g. whether biomass should be used as an energy source or a feedstock for the chemical industry – both uses imply trade-offs for biodiversity conservation or food security (Bataille et al. 2018).

4.3. Better-or-worse answers

‘*Solutions to wicked problems are not true-or-false but […] good, bad, better, worse, satisfying, good enough.*’ (Rittel and Webber 1973, 162–63)

We identify different examples for Rittel’s and Webber’s *better-or-worse answers* category from the technical and governance perspectives (Table 8). An outlier in this dimension is case 2 (heating/cooling), which could be attributed to the relatively low installation density of heat pumps as of 2022 and the sparse knowledge basis of technical and environmental impacts (Table 8 and Annex C).

Examples from the electricity supply subsector (case 1) – from both the technical and governance perspectives can illustrate the wicked facets of energy transition solutions.

From a technical viewpoint, there are no right or wrong answers, only *better or worse*. An algorithm for determining the best wind farm layout, for example, usually will not be able to

Table 8. Summary of case study analysis – examples for wickedness dimension #3 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #3 – Better-or-worse answers
Case 1: Installing onshore wind energy	**TD:** Technical choice of turbine or wind farm layout is highly complex, with only 'better' solutions: 'optimal' solutions for the technical layout and site selection cannot be identified; e.g. algorithm for determining the best wind farm layout will only achieve a locally optimum not global maximum power yield, cf. Feng and Shen (2015) **GD:** Diversity of values, priorities and interests from a plethora of stakeholders – preventing a 'right' or 'optimal' decision: Reitz, Goshen, and Ohlhorst (2022), Juerges, Leahy, and Newig (2020), Reusswig et al. (2016)
Case 2: Installing shallow geothermal energy systems	**TD:** Feasibility of shallow geothermal utilisation is easy to asses & proof of concepts for various geothermal systems exist (Pratiwi and Trutnevyte 2021; Sanner et al. 2003; Tissen et al. 2021; Todorov et al. 2020). **GD:** The shallow subsurface is affected by many stakeholders with different interests and perspectives (Brielmann et al. 2011; Hähnlein, Bayer, and Blum 2010) & identification, justification and prioritisation among multiple distinct subsurface aspects are complex tasks (García-Gil et al. 2020).
Case 3: Transforming road mobility	**TD/GD:** Technological solutions need to meet diverse requirements and user preferences from many actors: • formulation of 'optimal' solutions depends on concepts of fairness and justice; subjected to normative assumptions, political preferences & public acceptance (Creutzig et al. 2020) • any successful transformation towards low-emission mobility will create losers (and possibly winners) • efficient solutions (e.g. emissions pricing) are likely to affect poorer households adversely (see additional simulation analysis in Appendix C). Policy-makers, therefore, face a difficult efficiency-equity trade-off, which might result in the enactment of less effective (and potentially unequal) policies.
Case 4: Transforming the chemical industry	**TD:** Uncertainty about which technology to implement for decarbonising a specific process, like hydrogen production (Wietschel et al. 2021). **GD:** No consensus exists about what a future chemical industry sector should look like: • whether: to decrease production and implement sufficiency strategies or to count on green growth and decoupling of economic growth and carbon emissions (Eckert and Kovalevska 2021; Wachsmuth and Duscha 2019) • different scenarios & transformation pathways in the scientific debate (Brandes et al. 2021; Burchardt et al. 2021; Joas et al. 2019; Luderer, Kost, and Sörgel 2021)

find the global maximum of power yield but a local one, which is only close to the global maximum (Feng and Shen 2015) and, therefore, a '*better solution*'. Moreover, the onshore wind power development affects many stakeholders at various levels of governance, which pursue a multitude of interests. Decision-makers can only make *better-or-worse* rather than right-or-wrong decisions and could 'always try to do better' (Rittel 1972, 392).

4.4. No test for solutions

'*[A]ny solution, after being implemented, will generate waves of consequences over an extended – virtually an unbounded – period of time.*' (Rittel and Webber 1973, 163)

Although all cases found that testing ultimately for solutions is hardly possible (Table 9), examples from the road transport (case 3) and chemical industry (case 4) subsectors stand out, which we highlight in the following.

Results from the road transport subsector (case 3) show that, on the one hand, ex-post evaluation of policies aiming to decarbonise the transport sector can help design effective instruments tailored to context-specific circumstances. Nevertheless, the prevalence of path dependencies and the long-term effects of current policies impede just and effective transformation processes. For instance, the widespread use of battery-fuelled electric vehicles requires an accompanying roll-out of charging infrastructure (Schroeder and Traber 2012). Shifting transport from road to rail calls for long-

Table 9. Summary of case study analysis – examples for wickedness dimension #4 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #4 – No test for solutions
Case 1: Installing onshore wind energy	**TD/GD:** Onshore wind power and its impacts are not easily verifiable and testable (absence of ultimate tests, likelihood of unintended impacts), e.g. • unintended socio-environmental and ecological impacts of onshore wind farms (Köppel et al. 2019; Wiehe et al. 2021), which are still difficult to anticipate, predict and manage • unintended technical impacts and disturbance effects, e.g. on radio navigation devices (Schrader et al. 2022), which require retrofitting of devices (DFS 2023) • impact mitigation requires financial investments, illustrating required trade-offs • outcome, effectiveness, and acceptance of, e.g. policy and governance responses, are not verifiable
Case 2: Installing shallow geothermal energy systems	**TD:** Uncertainty over long-term sustainability in a priori assessments: • systems reach steady state after few operational years (Pophillat et al. 2020; Vanhoudt et al. 2011), • adverse thermal interferences between systems in densely populated areas can reduce efficiency of installations (Attard et al. 2020; Bloemendal, Jaxa-Rozen, and Olsthoorn 2018) **GD:** Long-term regulatory planning should ensure optimal and sustainable operation, yet has to deal with uncertainties: • few studies on long-term environmental consequences, thus insufficient knowledge on groundwater ecosystem effects (Blum et al. 2021; Hähnlein et al. 2013) • information deficit is reflected in legislation: nature and water protection laws do not consider groundwater protection at an ecosystem-level perspective (Hahn, Schweer, and Griebler 2018; Koch et al. 2021)
Case 3: Transforming road mobility	**TD:** Prevalence of path dependencies & long-term effects of current policies impede just/effective transformation processes, e.g.: • widespread use of battery-fuelled electric vehicles requires roll-out of charging infrastructure (Schroeder and Traber 2012) • shifting transport from road to rail calls for long-term planning of complex railway infrastructure • achieving net-zero emissions might require different solutions than meeting intermediate sectoral goals • instruments facilitating the diffusion of 'niche' products might prove inefficient in stages of market saturation or in times of low prices for transport fuels (Cats, Susilo, and Reimal 2017; Caulfield et al. 2022) **GD:** Aforementioned inefficiency implies constant evaluation of the effectiveness and efficiency of any policy mix. Each solution is highly context-specific and might create additional frictions, requiring additional measures. Testing ultimately for solutions is hardly possible.
Case 4: Transforming the chemical industry	**TD/GD:** This dimension carries a high level of complexity or even wickedness from both technical and governance perspectives: • technologies are tested in real-life laboratories and pilot studies, uncertainties regarding their large-scale implementation remain (Joas et al. 2019); financial profitability of new technologies can only be assumed, not tested (Chiappinelli et al. 2021) • the same holds for implementing economic and political measures to switch to low- or no-carbon technologies

term planning of complex railway infrastructure. Moreover, achieving net-zero emissions might require different (technological and institutional) solutions than meeting intermediate sectoral goals. Instruments, which facilitate the diffusion of 'niche' products (such as subsidies), might prove inefficient in stages of market saturation or in times of low prices for transport fuels (Cats, Susilo, and Reimal 2017; Caulfield et al. 2022). From a technical and governance perspective, each probable solution is highly context-specific and might create additional frictions, requiring additional measures.

Furthermore, results from the chemical industry subsector (case 4) pinpoint that uncertainties regarding large-scale implementation remain while technologies are tested in real-life laboratories and pilot studies (Joas et al. 2019). Actors rely on assumptions about the financial profitability of new technologies, but testing proves difficult (Chiappinelli et al. 2021). The same holds for implementing economic and political measures to switch to low- or no-carbon technologies. Therefore, *no test for solutions* is a wicked facet of the chemical industry sector from both a *technical* and *governance* perspective.

4.5. One-shot approach

'[E]very implemented solution is consequential. It leaves 'traces' that cannot be undone. […] And every attempt to reverse a decision or correct for the undesired consequences poses yet another set of wicked problems […].' (Rittel and Webber 1973, 163)

Table 10. Summary of case study analysis – examples for wickedness dimension #5 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #5 – One-shot approach
Case 1: Installing onshore wind energy	**TD:** Dismantling of turbines & restoration of landscapes/habitats is possible. From a technical viewpoint, wind power development is reversible, although wind turbines reflect a long investment cycle (two decades), which could lead to sunk costs. • largest parts (85–90%) can be recycled (WindEurope 2020), limiting the overall footprint • installation of wind farms & technical mitigation measures for impact reduction are linked to investment risks, thus errors or faulty siting decisions reduce revenues **GD:** Planning and permitting are one-shot decisions, as permits can be revoked or wind farms curtailed if unforeseen impacts occur, cf. Köppel et al. (2019). Wind power development has become a publicly discussed topic (Dehler-Holland, Okoh, and Keles 2022), with broad media coverage and little room for errors.
Case 2: Installing shallow geothermal energy systems	**TD:** Geothermal installations for space heating and cooling are designed for more than two decades, reflecting long investment cycles in the building sector (Bloemendal, Olsthoorn, and Boons 2014; Saner et al. 2010), which leaves no room for technical planning errors. **GD:** Regulatory framework would have to address qualitative and quantitative changes in groundwater and ensure long-term planning certainty over several decades.
Case 3: Transforming road mobility	**TD:** Product lifecycles span over a decade, slowing down ambitions and constraining future opportunities to correct prior decisions if stranded assets should be avoided. **GD:** Infrastructure investment creates path-dependencies that create 'lock-in' situations (Unruh 2000), likely to inhibit any form of transformation: • time-intensive planning cycles in transport sector • reducing the use of a 'hegemonial technology' (fuel-combusting vehicles) will likely face resistance from actors who benefit from the status quo (cf. Falck, Czernich, and Koenen 2021)
Case 4: Transforming the chemical industry	**TD:** Narrow window of opportunity to decarbonise chemical sector with little to no margin for errors: • long lifespans of technologies (e.g. steam crackers) can result in sunk costs for the next decades and prevent a low-carbon transformation of the sector (Janipour et al. 2020; Joas et al. 2019) • decarbonising the complex and intertwined value chains requires addressing all aspects of the production process (Geres et al. 2019; Janipour et al. 2020; Kümmerer, Clark, and Zuin 2020) **GD:** The governance of industrial decarbonisation is characterised by a lot of trial-and-error-processes, e.g. ongoing reform process EU ETS (Dorsch, Flachsland, and Kornek 2020; European Commission 2021b; Joltreau and Sommerfeld 2019; Lilliestam, Patt, and Bersalli 2021) or the German EEG (Luderer, Kost, and Sörgel 2021; BMWK 2022). However, we there is no time left for more attempts at stringent policies as climate change is advancing ever faster.

All cases exhibit the wickedness characteristic *one-shot approach* (no-trial-and-error rule), given long-term investments in energy transition technologies and likely negative externalities and consequences (Table 10).

Examples from the subsectors of road transport (case 3) and the chemical industry (case 4) will further illustrate this 'wicked problems' property.

Current emission levels in the transport sector reflect, to some extent, decisions on infrastructure investments from past decades. Constructing roads, rails and airports create path dependencies, influencing consumers′ demand for transport services. Those path-dependencies create 'lock-in' situations (Unruh 2000), likely to inhibit any form of transformation. In the transport sector, this does not only imply that society has to consider time-intensive planning cycles (e.g. to invest in public transport infrastructure) but also that past decisions narrow the currently feasible solution space. In addition, reducing the use of a 'hegemonial technology' (such as fuel-combusting vehicles) will likely face resistance from actors who benefit from the status quo (cf. Falck, Czernich, and Koenen 2021). Ineffective attempts to decarbonise the transport sector might leave limited leeway for alternative approaches since this transformation will likely require considerable investments in infrastructure and up-scaling of novel technologies. In addition, ineffective policies might be detrimental to sustaining public acceptance. Similarly, from a technical perspective, product lifecycles span over a decade, slowing down today's ambitions and constraining future opportunities to correct prior decisions if stranded assets should be avoided. Nevertheless, it appears as if decarbonising the road mobility subsector will require a set of (technological) solutions, including bridging technologies, such as battery-fuelled electric vehicles.

For the chemical industry subsector (case 4), we find a narrow window of opportunity to decarbonise. Because technologies like steam crackers, i.e. petrochemical plants that break the long hydrocarbon chains of Naphtha into shorter molecules, have long lifetimes, an investment in them today would result in sunk costs (i.e. already incurred and unrecoverable money) for the next decades and prevent a low-carbon transformation of the sector (Janipour et al. 2020; Joas et al. 2019). Since value chains are complex and intertwined, decarbonising them requires addressing all aspects of production (Geres et al. 2019; Janipour et al. 2020; Kümmerer, Clark, and Zuin 2020). Many trial-and-error-processes have characterised the governance of industrial decarbonisation, such as the ongoing reform process of instruments like the EU ETS (Dorsch, Flachsland, and Kornek 2020; European Commission 2021; Joltreau and Sommerfeld 2019; Lilliestam, Patt, and Bersalli 2021) or the Renewable Energy Sources Act (Luderer, Kost, and Sörgel 2021; BMWK 2022). However, we argue that there is no time left for more trial-and-error attempts as climate change advances ever faster. Therefore, the *one-shot approach* applies to the *technical* and *governance* perspectives.

4.6. Infinite set of potential solutions

'*There are no criteria which enable one to prove that all the solutions to a wicked problem have been identified and considered.*' (Rittel and Webber 1973, 164)

Rittel's and Webber's *infinite set of potential solutions* characteristic (Table 11) is best illustrated by examples from the road transport and chemical industry subsectors (cases 3 & 4).

Many technical options are available to curb GHG emissions in the road transport subsector (case 3). Current demand levels for transport services will likely require individual transportation modes resting on energy conversion technologies. Given the time horizon to drastically reduce German climate targets, it is unlikely that non-mature technologies (such as hydrogen-fuelled road transport) will be part of the solution space (cf. Ueckerdt et al. 2021). On the contrary, the question of *how* to align the preferences and perspectives of many fragmented actors (citizens, corporates, authorities) is ambiguous. There are interdependencies between regulatory and institutional frameworks at multiple levels of governance (local, regional, national, international), which enforce

Table 11. Summary of case study analysis – examples for wickedness dimension #6 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #6 – Infinite set of potential solutions
Case 1: Installing onshore wind energy	**TD/GD:** There are many technical solutions for transforming the electricity sector, as research continuously identifies innovative solutions, e.g. new wind turbine types or designs, mitigation measures, etc. However, in practice, new approaches are extremely limited: • a domination of horizontal axis turbine design, thus limiting applicability of vertical axis or airborne wind farms • by actors' preferences, economic cost pressure and investment risks, and the current regulatory and policy framework (Raschke 2015; Schwarzenberg and Ruß 2016) • current policy framework does not enable 'energy law engineering' (allowing innovative approaches to be tested and adapted if framework conditions change); although, in theory policies can mandate, incentivise, encourage, and could be set up in myriad ways.
Case 2: Installing shallow geothermal energy systems	**TD/GD:** Any technical realisation of thermal utilisation of the shallow subsurface is linked to a change in the underground thermal regime. Finding new technical solutions is thus not the key issue of the transition process, rather setting a regulatory framework to establish an acceptable middle way between a multitude of distinct interests.
Case 3: Transforming road mobility	**TD:** Many technical options are available to curb GHG emissions in the road transport sector. **GD:** How to align the preferences and perspectives of many fragmented actors (citizens, corporates, authorities) is ambiguous: • interdependencies between regulatory and institutional frameworks at multiple levels of governance (local, regional, national, international), • tailored, context-specific regulations owing to contemporary developments (such as fluctuations in transport fuel prices or large economic shocks).
Case 4: Transforming the chemical industry	**TD:** Indefinite number of solutions to decarbonise the (chemical) industry: • various low- or no-carbon technologies are already available or will become available in the following years • different strategies for decarbonising the operations exist; solutions range from electrifying processes, alternative feedstocks and carbon capture, utilisation and storage to the flexibilisation of energy usage (Ausfelder, Seitz, and von Roen 2018; Geres et al. 2019; Joas et al. 2019) **GD:** There are many solutions, although their implementation may face challenges on different levels, e.g. lacking public acceptance for carbon capture and utilisation (CCU) (Lee 2019).

tailored, context-specific regulations owing to contemporary developments, such as fluctuations in transport fuel prices or large economic shocks.

In the chemical industry subsector (case 4), there is already an indefinite number of solutions to the decarbonisation challenge. Technically, various low- or no-carbon technologies are already available or will become available in the following years. Different strategies exist for decarbonising operations. Potential solutions range from electrifying processes, alternative raw materials and carbon capture, utilisation and storage to the flexibilisation of energy usage (Ausfelder, Seitz, and von Roen 2018; Geres et al. 2019; Joas et al. 2019). On a governance level, there are many solutions. However, their implementation may rely on different approaches: the dominant implementation discourse focuses on green growth (Geres et al. 2019), but several scholars stress the need to consider sufficiency approaches (Luderer, Kost, and Sörgel 2021; Niessen and Bocken 2021; Zell-Ziegler et al. 2021).

4.7. Uniqueness

'*[D]espite long lists of similarities between a current problem and a previous one, there always might be an additional distinguishing property that is of overriding importance. […] In the more complex world of social policy planning, every situation is likely to be one-of-a-kind.*' (Rittel and Webber 1973, 164–65)

Scholarly work that utilises the wickedness concept often claims that every problem is essentially *unique*. However, our analysis found differences among the analysed cases (Table 12) – with case 1 (onshore wind energy) and case 3 (road mobility) deemed technically not unique.

The chemical industry subsector (case 4) is *unique* on both a technical and a governance level, as it has never before faced a similarly significant transition. Because fully decarbonised chemical industries do not exist anywhere in the world yet, Germany will be a pioneer if it succeeds in transforming its industry (The European Chemical Industry Council 2022). The chemical industry is characterised by a high degree of uniqueness, given its complex value chains, diverse company structures, which lead to very company-specific challenges, and its dependency on fossil-based substances like Naphtha for many production processes (Joas et al. 2019; Wesseling et al. 2017). On a governance level, no other sector in Germany – except steel production – has a higher risk of carbon leakage (European Commission 2021), further highlighting the uniqueness. Therefore, policies have to precisely address this challenge while simultaneously being tailored towards the different kinds of companies and production chains.

Table 12. Summary of case study analysis – examples for wickedness dimension #7 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #7 – Uniqueness
Case 1: Installing onshore wind energy	**TD:** Technically, wind power installation cannot be considered unique, as technical solutions were adapted from aviation and shipping (Bruns et al. 2011). **GD:** Governing the electricity transition and onshore wind installations is unique, given the setting, policy mix, polycentric planning system, governance framework, transition pathway – double-exit strategy, and ambitious transition targets), (cf. Fuchs 2019; Goldthau and Sovacool 2012).
Case 2: Installing shallow geothermal energy systems	**TD:** Installations and solutions are highly space- and site-dependent, incl.: • (hydro-)geological characteristics determine intensity of thermal anomaly propagation & suitable system design (Hähnlein et al. 2013), • risks of pre-existing local contaminations (García-Gil et al. 2020; Possemiers, Huysmans, and Batelaan 2014) • thermal interferences & anthropogenic structures (basements, underground car parks, urban surface sealing etc.) can alter thermal subsurface regime (Blum et al. 2021; Menberg et al. 2013; Tissen et al. 2019) • high installation density affects systems' performance (interference). **GD:** Above mentioned factors impede a simple & universal regulatory framework. Large-scale heat transition is a unique and unprecedented transformation process.
Case 3: Transforming road mobility	**TD/GD:** Transport sector transition hinges on complex socio-technical systems integrating dynamics in technology, social norms and subsequent demand for transportation services. • highly space- and time-specific solution set: each city or municipality will likely require unique solutions; demand for transport services is likely to be more elastic (Labandeira, Labeaga, and López-Otero 2017), giving greater weight to exogenous shocks (e.g. fluctuations in fuel prices).
Case 4: Transforming the chemical industry	**TD:** The chemical sector has never before faced a similarly significant transition; it is unique on both a technical and a governance level. • potential pioneer role, as fully decarbonised chemical industries do not exist anywhere yet (The European Chemical Industry Council 2022) • chemical industry is characterised by a high degree of uniqueness, complex value chains, diverse company structures which lead to company-specific challenges, dependency on fossil-based substances like Naphtha for many production processes (Joas et al. 2019; Wesseling et al. 2017). **GD:** No other sector in Germany – except steel production – has a higher risk of carbon leakage (European Commission 2021). Policies have to address this challenge while still being tailored towards different companies and production chains.

Likewise, the case from the heating/cooling subsector (case 2) shows *uniqueness* in technical and governance settings. The optimal realisation of space heating and cooling via shallow geothermal energy is highly space-dependent due to several factors. For example, geological and hydrogeological subsurface characteristics determine the intensity of thermal anomaly propagation underground and the suitable system design (Hähnlein et al. 2013). Especially open shallow geothermal systems using groundwater bear the risk of mobilising pre-existing local contaminations (García-Gil et al. 2020; Possemiers, Huysmans, and Batelaan 2014). A large number of systems in a small area can detrimentally affect the systems' performance due to thermal interferences. Additionally, other anthropogenic influences such as basements, underground car parks and urban surface sealing can significantly alter the thermal regime in the subsurface (Blum et al. 2021; Menberg et al. 2013; Tissen et al. 2019). These factors also impede a simple and universal regulatory framework. The successful transformation to a renewable heating/cooling sector not only requires new technologies but also depends on efficiency measures for reducing thermal energy demand (Grossmann 2019). For these reasons, the large-scale heat transition as a part of the greater energy transition can be identified as a unique and unprecedented transformation process, which also reflects in the variety of motivations, such as reducing greenhouse gas emissions and a decreased dependence on fossil energy imports.

4.8. Causal webs

'*Problems can be described as discrepancies between the state of affairs as it is and the state as it ought to be. The process of resolving the problem starts with the search for causal explanation of the discrepancy. Removal of that cause poses another problem of which the original problem is a 'symptom'.'* (Rittel and Webber 1973, 165)

All four cases show signs of *causality* and interconnectedness of problems (Table 13), which we highlight in the following with results from the cases in the electricity and heating/cooling subsectors (cases 1 & 2).

Installing onshore wind farms (case 1) requires vast resources, especially raw materials (e.g. raw earth elements, concrete, steel, copper), logistics, and transportation. Another technical – likely wicked – challenge is the recycling of rotor blades' composite materials – described by Jani et al. (2022) and Majewski et al. (2022) as a 'waste legacy problem'. Procuring resources and waste management can negatively affect both resource-exporting and waste-importing countries. The requirements for transport and logistics can lead to complex bottlenecks and dependencies on volatile global supply chains (Fichtner 2022; Landwehr 2022), which is emblematic of the *causal webs*' wickedness dimension.

In the heating and cooling subsector, the extensive thermal use of the shallow subsurface (case 2) can lead to detrimental thermal interference between individual systems in the case of a high density of installed systems. Lower system efficiencies are associated with higher operating costs and possibly the need for fossil auxiliary technologies such as gas boilers or compression chillers (Miglani, Orehounig, and Carmeliet 2018; Tissen et al. 2019). Besides technical drawbacks, shallow geothermal utilisation may entail other trade-offs, including environmental aspects such as detrimental changes to the groundwater ecosystem and loss of the respective ecosystem services (Blum et al. 2021; Griebler and Avramov 2015; Koch et al. 2021). Conflicts of use of shallow groundwater and decreasing profitability of regional supply companies, which often base their business model on the profitable gas supply, might also arise from an increasing spread of this technology.

4.9. Numerous explanations

'*There is no rule or procedure to determine the 'correct' explanation or combination of them. […] The analyst's 'world view' is the strongest determining factor in explaining a discrepancy and, therefore, in resolving a wicked problem.'* (Rittel and Webber 1973, 166)

Table 13. Summary of case study analysis – examples for wickedness dimension #8 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #8 – Causal webs
Case 1: Installing onshore wind energy	**TD/GD:** Accelerated wind power installation is symptomatic of the increased need for low-carbon energy. Wind power installations may lead to new technical and socio-political challenges, e.g.: • wildlife impacts (Gartman et al. 2014; Voigt, Straka, and Fritze 2019; Warren et al. 2005) • interference with radio navigation stations(Schrader et al. 2022b) • social and distributional (in)justice (Köppel et al. 2019; Reitz, Goshen, and Ohlhorst 2022) • land use conflicts (Biehl, Köppel, and Grimm 2021) • provision of materials, personnel and logistics despite worldwide supply bottlenecks (Taylor 2022) • future 'waste legacy problem' (Jani et al. 2022; Majewski et al. 2022): recycling rotor blades' composite materials (Karatairi and Bischler 2020)
Case 2: Installing shallow geothermal energy systems	**TD:** Extensive thermal use of the shallow subsurface (i.e. high density of installed systems) can lead to detrimental thermal interference between individual systems. Lower system efficiencies are associated with higher operating costs and possibly the need for fossil auxiliary technologies (e.g. gas boilers or compression chillers), cf. Miglani, Orehounig, and Carmeliet (2018), Tissen et al. (2019). **GD:** Shallow geothermal utilisation may entail other trade-offs, incl.: • environmental aspects (detrimental changes to groundwater ecosystem, loss of ecosystem services), cf. Blum et al. (2021), Griebler and Avramov (2015), Koch et al. (2021) • conflicts of use of shallow groundwater & decreasing profitability of regional supply companies might arise when upscaling the technology
Case 3: Transforming road mobility	**TD/GD:** Transport systems are embedded in many other socio-economic systems, with ripple-effects from one system to another, which are difficult to predict or evaluate, e.g.: • electrifying individual transport requires various scarce natural resources (lithium, cobalt or rare earth metals); resource extraction establishes links to environmental degradation and human health (Banza Lubaba Nkulu et al. 2018) but also creates local resource booms • effective recycling of energy storage technologies is subject to extensive research (Harper et al. 2019) • transport sector transition may affect competitiveness of industries, primarily if value-chains rely on comparatively cheap and reliable transport facilities
Case 4: Transforming the chemical industry	**TD/GD:** Chemical industry transition may lead to new technical and socio-political challenges, creating causal webs: • increased use of biomass might entail trade-offs in other areas, e.g. biodiversity loss/food security (Bataille et al. 2018; Joas et al. 2019) • potential for regional deindustrialisation & loss of competitiveness (European Commission 2021; Evans et al. 2021; Fahl et al. 2021; Johansen et al. 2021) • use of intermediary technology (e.g. blue hydrogen) is readily discussed (Bataille et al. 2018; Joas et al. 2019), but could reinforce resource dependency & can be criticised in light of gas shortage • socio-technical challenges (food security, deindustrialisation and resource dependency) would imply significant socio-economical risks.

Although we find that the wickedness characteristics *numerous explanations* applies more to the governance than the technical perspective (Table 14), examples from the road transport subsector (case 3) will further explore the wickedness dimension.

Decarbonising the road transport subsector affects multiple fragmented actors with diverse objectives. The ample solution space and various intersections with other socio-economic domains manifest many explanations, exacerbated by multiple externalities. For instance, shifting individual

Table 14. Summary of case study analysis – examples for wickedness dimension #9 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #9 – Numerous explanations
Case 1: Installing onshore wind energy	**TD:** The motivation for technically installing wind farms is explained with the goal to transform the energy production sector from fossil and fissile energy sources to renewables. **GD:** The problem of governing, planning and developing onshore wind power can be explained in numerous ways, as shown above.
Case 2: Installing shallow geothermal energy systems	**TD/GD:** The motivation for geothermal space heating and cooling is mainly rooted in reducing greenhouse gas emissions in the building sector (e.g. Self, Reddy, and Rosen 2013). Recently, the pressing issues of supply reliability and reduced dependence on imported natural gas and heating oil have come into focus.
Case 3: Transforming road mobility	**TD/GD:** Transport sector transition affects multiple fragmented actors with diverse objectives. • The large solution-space and various intersections with other socio-economic domains manifest a large variety of explanations, which is exacerbated by multiple externalities. Describing socially optimal demand and supply levels for transport services is difficult, which adds substantial uncertainty to determining desirable and feasible transformation pathways.
Case 4: Transforming the chemical industry	**TD:** Different pathways towards net-zero GHG emissions exist, yet all are explained in a similar way (assuming a green growth perspective, arguing that decoupling economic growth and GHG emissions is possible). Different transition scenarios focus on different technologies: • Burchardt et al. (2021): enhanced usage of CCS and biomass • Joas et al. (2019): prioritisation of green hydrogen and electrification. **GD:** Various explanations about the goal of decarbonisation exist [green growth narrative or sufficiency strategies, e.g. lowering consumption (Eckert and Kovalevska 2021)]

transport to public transport services would likely reduce congestion and create incentives for transport system changes that are more socially inclusive and equitable. Contrarily, frequent calls to subsidise purchasing electric vehicles or lowering fuel taxes often implicitly link to the pivotal role of (individual) transport for economic activity and welfare. Describing socially optimal demand and supply levels for transport services is difficult, which adds substantial uncertainty to determining desirable and feasible transformation pathways.

4.10. Normative framing (no right to be wrong)

Decision-makers and 'planners are liable for the consequences of the actions they generate; the effects can matter a great deal to those people that are touched by those actions.' (Rittel and Webber 1973, 167)

We illustrate Rittel's and Webber's *no right to be wrong* characteristic using results from the electricity (case 1) and road transport (case 3) subsectors (Table 15).

In governing the spatial development of onshore wind power (case 1), regional planners have *no right to be wrong*, as they are responsible for their actions and can be held accountable. Given the high population density and installed cumulative capacity of onshore wind power in Germany, conflicts with other land uses[13] and goals have increased (Biehl, Köppel, and Grimm 2021), which will intensify with further increasing exploitation yields (Dehler-Holland, Okoh, and Keles 2022). An example from Northern Germany (Schleswig-Holstein) shows that actors are liable for the consequences of their actions and might be challenged by the administrative courts. At the beginning of 2015, the Higher Administrative Court of Schleswig declared all regional plans in Schleswig-Holstein invalid due to legal errors (Hassink et al. 2021). It thus overturned the spatial governance of onshore wind power for an entire state in one court ruling, which led to a moratorium for new wind installations until the end of 2021 and the re-initiation of spatial planning processes.

Table 15. Summary of case study analysis – examples for wickedness dimension #10 in the four cases, incl. supporting arguments (TD: technical domain; GD: governance domain).

Case study	Examples for wickedness dimension #10 – No right to be wrong.
Case 1: Installing onshore wind energy	**TD/GD:** Actors are responsible for their actions and can be held accountable. Planning and permitting decisions can be challenged before (administrative) courts.
Case 2: Installing shallow geothermal energy systems	**TD/GD:** Both, a successful heat transition & security of supply in the building sector, and ecosystem concerns & economic profitability are highly relevant for the future. It is crucial to reconcile all aspects through coherent and comprehensive planning, thus planners and decision-makers have 'no right to be wrong'.
Case 3: Transforming road mobility	**TD/GD:** Decarbonising the transport sector is a politically delicate task since it entails tremendous distributional consequences and would likely affect poorer households more heavily than wealthier households (see Annex C). Transition instruments in this sector affect many actors, which negates a 'right to be wrong' for political decision-makers, which might delay stringent and effective action.
Case 4: Transforming the chemical industry	**TD/GD:** Framing of decarbonising the chemical sector is not normative (Joas et al. 2019), as decarbonisation is only ever described as technically feasible. The current dominant discourse also displays the need for green growth on a governance level. There are other argumentative lines like sufficiency or the call for a just transition (Eckert and Kovalevska 2021).

Decarbonising the road transport subsector (case 3) is politically delicate since it involves political decisions that entail tremendous distributional consequences. An effective policy will create winners and losers in domains as different as street space allocation, employment or capital rents. Instruments, which are economically efficient (such as carbon pricing), would have unequal cost effects for consumers (see additional simulation analysis in Annex D). In Germany, pricing transport fuels according to their carbon content would likely be regressive, i.e. affect poorer households more heavily than wealthier households. If unaddressed, unintended distributional consequences could affect public acceptance and thus inhibit policy implementation. Instruments aiming at lowering emissions in the transport sector affect many actors, which negates a *right to be wrong* for political decision-makers, thereby delaying stringent and effective action.

5. Discussion

5.1. Technological and governance aspects of wickedness

We illustrate in the results section how the original dimensions of wicked problems manifest in the German energy transition. The perspective of wicked problems contributes to an enhanced understanding of challenges in energy transition efforts in the four analysed cases. The separate analysis of *technical* and *governance* dimensions allows us to distinguish between issues that require additional research (e.g. given uncertainty due to knowledge gaps or ambiguous knowledge base of the technology or its impacts) and issues that stem from stakeholder divergence and pluralism (socio-centric perspective).

We find fewer examples of wickedness if perceived and analysed as merely technological or engineering problems. However, a sound technological basis might not reduce all wicked facets due to embedded financial, economic, social, environmental, or policy aspects. As described by Head (2022a, 155), the value of the wickedness concept is that Rittel and Webber were concerned 'about the weaknesses of policy design derived from technocratic analysis of scientific data, and of policy derived from simplistic ideology'. In the governance dimension, the cases highlight questions of justice and affordability, environmental concerns, and land use, which need to be considered when proposing, discussing or implementing energy transition strategies. Craig (2020, 1755) states that although it was not their primary focus, Rittel's and Webber's work was the first to 'acknowledge the governance issues that arise in a world of complex systems' and that the core insight of their work was its 'continual attempts to grapple with the then relatively new perception of social *change*' (Craig 2020, 1736). The four cases highlighted a diverse stakeholder set and pluralism of interest, which in twenty-first-century Germany, is an essential nature of the social realm. Based on our analysis, we argue that it is technically possible to achieve the energy transition, as the technical implementation of the energy transition shows fewer examples of wickedness. Nevertheless, the energy transition's socio-political governance exhibits more wickedness in all analysed cases, given complex values and goal trade-offs and a plurality and divergence of interests and stakeholders.

Our analysis aims to represent the particularities of the different cases and sectors. Especially the wickedness criteria 'uniqueness' (#7) and 'infinite set of potential solutions' (#6) yield differing results in the four cases, which stem from the different analytical levels. Uniqueness can be assessed from diverse perspectives (uniqueness at the sectoral level, the technology level, or the site/implementation/geographic level). Although we refrained from assessing uniqueness at the same analytical level, which might yield some inconsistency in analysis, we aimed to highlight what makes the case special/unique. The analytical levels differ, as discussed in Section 3.1.1. Cases 1 and 2 analyse one renewable energy source within the electricity supply or heating subsectors. In contrast, cases 3 and 4 analyse a subsector (road transport with a strong focus on direct electrification or chemical industry) where transformation strategies are broader and diverse. These different analytical levels allow us to tease out particularities and avoid myopia and hollow-arch bias (cf. Hyysalo 2021); they also show that the wickedness concept is applicable at different levels.

Moreover, the illustrated uncertainties in, e.g. rollout of policies, effectiveness in measures, or the uncertainty of impacts of new technologies or heavy industry, differ greatly. For instance, Bond et al. (2015) distinguish between broader categories of ambiguity, uncertainty, and ignorance, while Marshall et al. (2019) and Diwekar et al. (2021) differ between 'known-knowns' (that are known to exist and information available), 'known-unknowns' (that are known to exist, but the information is not available), 'unknown-knowns' (that are not included in the analysis but the information would be available), and 'unknown-unknowns' (neither known to exist nor is information available). Differentiating between these different types of uncertainty was beyond the feasible scope of our analysis. It would have increased the complexity of the analysis but could be explored by future research. Furthermore, the broader concepts of green growth, degrowth, and sufficiency apply to all cases, but were found to stand out specifically in the chemical industry subsector (case 4).

5.2. Bottlenecks and wickedness of sustainability transitions

Our results reflect that the four cases are at different stages in transition (see sections 3.1.1 and 3.2), are subject to different barriers and strengths, and unfold different intricate facets. In other words, the wicked problems concept as a theoretical framework enables us to gain 'interpretative and/or explanatory insights into phenomena and the relations among them' (Rule and John 2015, 2). In the following, we discuss our results along these underlying sustainability transition characteristics and differences in the cases, e.g. transition stages (technology maturity, states of knowledge, degree of policy regulation), affected stakeholders, and other sectoral particularities. This section concludes with implications and impulses for further research.

In linking wicked problems with socio-ecological systems literature, Craig (2020, 1747) argues that problems 'can be classified as wicked because social ecological problems partake of complex systems, where the whole is not only *greater* than the sum of its parts but also different from the sum of its parts and where complex adaptive systems interject with elements of unpredictability and surprise.' The author later argues that 'if society, governance, and law can better internalize this new model of reality, we might be able to better conceptualize and resolve certain kinds of wicked problems' (Craig 2020, 1753).

5.2.1. Transition stages

In analysing different energy transition (sub)sectors or subsystems in different transition stages (from early take-off to breakthrough and acceleration), we analyse a changing system where technological maturity and diffusion vary across the sectors. Some differences in our results on the wicked facets in the different (sub)sectors can be traced back to their different transition stages.

While onshore wind power installations have reached technological maturity and are applied large-scale (see section 3.2.1), shallow geothermal energy sources are to be upscaled (see section 3.2.2). New technological solutions can have higher uncertainties and risks, as research on the technology is sparse, as shown in case 2, with potentially detrimental impacts on groundwater ecosystems and thermal interferences and comparatively fewer studies (case 2, Annex C). Contrarily, the impacts of wind power use have been researched extensively since late 1990[14] with tailored mitigation measures for adverse impacts. In contrast, our cases from the transport and industry subsectors (cases 3 & 4) are in the early take-off stages in the energy transition process. This is reflected in the diversity of potential energy transition solutions, which are not (yet) politically decided. It is equally reflected in the technological maturity of low-carbon technologies in the chemical industry sector, which are still niche innovations with limited competitiveness to conventional processes (see section 3.2.4).

Three sectors (electricity supply, heating/cooling, and transport) are under more political control and public governance. However, policy output in the more regulated sectors differs – with various policy documents, reforms and exhaustive policies and legislation for onshore wind power in the electricity sector, and less regulation density in the heating/cooling and transport sectors (cf. cases 1 & 2). We argue that technological maturity and large-scale application, as seen in the onshore wind power case, can increase wickedness by layering or stacking policy measures[15], causing a lack of coherence and coordination (cf. Biehl, Köppel, and Grimm 2021). On the contrary, our case from the heating/cooling sector identified policy gaps and found that some aspects currently lack regulation (e.g. regarding the density of shallow geothermal applications to counteract potential detrimental groundwater changes). We argue that wicked facets can occur given a time lag of strategies to address a policy problem. This finding is in line with scholarly work on 'pacing problems', which occur when the pace of technological diffusion 'far outstrips the capability of regulatory systems to keep up' (Marchant 2020, 1863). According to Marchant (2020, 1862), the wicked problems framework can assist in identifying a 'mix in substandard' governance for emerging technologies, i.e. 'a mix of substandard solutions that must "satisfice"'. The case from the transport sector illustrates myriad pathways to transform road mobility with political regulation, yet, the process of finding and agreeing on a feasible and coherent pathway is found to be rather difficult, contested or 'wicked'. The sectors mentioned above (electricity, heating/cooling, transport) are not as company-driven as the chemical industry subsector, which demonstrated a lack of incentives to adopt low-carbon technologies, given their comparatively higher costs to conventional technologies and the predominant goal of maintaining short-term competitiveness in the sector.

The transition stage of the energy supply sector highly affects the transformation in the demand sectors, i.e. transport and industry sectors (cf. Kanger and Schot 2019; Kern, Sharp, and Hachmann 2020; Luderer, Kost, and Sörgel 2021), as the current energy transition road map foresees direct electrification in these sectors. However, direct electrification of vehicles, the industry, or operating heat pumps in the heating/cooling sector will require higher capacities for renewable energy sources, which could further stress wickedness in the electricity sector. Wicked facets on the supply side (electricity sector) can inhibit target attainment in all other sectors, exemplified by the current stagnation of onshore wind installations (section 3.2.1 and results case 1).

Our findings on the differing degrees of technology maturity, policy regulation, and knowledge states align with research on niche-innovation trajectories (Verbong, Geels, and Raven 2008) and hype-disappointment cycles (Bakker and Budde 2012; Kriechbaum, Posch, and Hauswiesner 2021). Hype cycle research stresses the potential disappointment and disillusionment associated with too high expectations on (any) technological innovation if either negative impacts or consequences occur or expectations cannot be met (Bakker and Budde 2012). While hypes can attract investors and a favourable regulating framework, they can cause a standstill once the hype is over and disappointment prevails.[16] In 2022, newly hyped technologies, such as shallow geothermal energy sources (heat pumps, case 2) or hydrogen and e-fuels (as discussed strategies in the transport and industry sectors), face similar pathways if overly ambitious expectations cannot be met or controlled. We argue that in considering energy transition issues in their (more or less) wicked facets early on, decision-makers and other stakeholders could address criticism proactively (Lönngren and van Poeck 2020) and identify adequate coping strategies. We propose that exploring how far wicked problems can affect hype cycles, and vice versa would be worthwhile.

5.2.2. Stakeholders, pluralism of interests & socio-political contestation

Stakeholder diversity and value conflicts were important factors in all cases. Though, our case studies show different levels of affectedness (Table 4): While the transformation of the transport sector affects specifically the individual citizens and end-users, transformation in the electricity sector is rather affecting the public provision of energy services, thus the public sector (at various levels of government), but also neighbouring communities, citizens, and the wind power industry. The example from the chemical sector hardly affects the individual consumer but affects individual companies in the German chemical industry. In installing shallow geothermal energy systems, homeowners, proprietors, and the building sector are affected. Our analysis highlights myriad actors in all cases and multi- if not polycentric governance systems in two of the four cases (cases 1 & 3). We argue that complex interactions between international, European, national or federal, and state-level policies can trigger wickedness if policy measures are not coherent and harmonised. Pluralism can be both – a strength (e.g. energy democracy, checks and balances) and a contributing factor to wickedness.

Moreover, we were able to show that various aspects in all cases are contested. As early as 1972, Horst Rittel argued that most planning and social problems are *not* found 'in the context of a strong autocratic decision structure' (Rittel 1972, 391). Hence 'the knowledge needed in a […] wicked problem is […] usually distributed over many people' (Rittel 1972, 394), which makes dealing with wicked problems political and a matter of moral judgement. Head (2022b) argues that stakeholder divergence is why contested (social) problems are 'wicked problems'. Ritchey (2011, 22) points to a 'common-sense approach' to the wickedness concept, as ultimately 'WP are about people and politics; they are subjective problems. […] Above all, WP are about people as stakeholders […] competing, vying for position, and willing to re-think and change their positions when it suits them'. As Head (2014, 665) states, 'the wicked problem perspective in public policy is a call for governments to embrace scientific uncertainty and stakeholder divergence'; in other words, decision-makers should acknowledge the underlying pluralism, social change and uncertainties as facets of reality.

Furthermore, our findings indicate that the question of *how* to design the energy transition in the four sectors represents a 'wicked problem'. The design and solution space for the energy transition is socially and politically contested. Fuchs (2019, 2) argues that the energy transition is not just a technical task but a radical innovation that is ultimately about 'how actors coordinate […] and how they legitimize their coordination efforts'. Our findings are in line with wickedness literature: Head (2022b, 24) argues that Rittel's and Webber's seminal paper highlighted the '[…] fundamental contradiction between the achievements of technological systems and the evident social complexities […]'. In focusing on the moral implications of wicked problems, Wexler (2009, 539) stresses that 'wicked problems are viewed as imbedded in the moral dimension of a relatively unregulated and 'hype' oriented knowledge market'. Given 'concurring challenges of systemic complexity, contested knowledge, competing problem frames and unclear evaluative standards', Daviter (2019, 77–78) argues that 'wicked problems need to be understood as essentially contested', thus calling into question evidence-based policy or best-available-science-approaches.

In applying the wickedness lens, we acknowledge that there is no panacea to energy transition challenges. Wicked problems are ultimately decision problems embedded in rich social, organisational and political contexts, which do not necessarily have one finite solution (Ritchey 2011). Although R&D continuously identifies new technical approaches and innovations for the energy transition, existing governance frameworks, social acceptance, or divergent stakeholders can limit their application in practice. Thus, in understanding the energy transition in its wicked facets, we acknowledge the need to rethink its perception and management and reshape what once began as ‘simple problem solving’.

5.2.3. Implications for further research

We argue that the wickedness lens assists in managing expectations and unravelling potential pitfalls and unintended consequences. It could be valuable to analyse how far wicked facets of energy transitions are socially constructed, i.e. how actors or actor groups frame or perceive and/or communicate about the energy transition and its challenges.

It would be valuable to analyse how the debates about energy security, energy independence, and acceleration affect the illustrated wickedness facets of the German energy transition. Our results, e.g. from the heating/cooling, transport and industry sector cases, address the challenge of looming new carbon lock-ins or path dependencies, which can pose another set of potentially wicked problems (cf. Brunnengräber 2019 for nuclear power; Kemfert et al. 2022; Seto et al. 2016 for carbon lock-ins). Likewise, they could serve as an impulse to accelerate the energy transition, e.g. by intensifying energy efficiency measures and sufficiency efforts. We argue that the German energy transition acceleration and streamlining debate could benefit from a thorough wickedness analysis to avoid pitfalls (on pitfalls of streamlining low carbon energy transitions, cf. Cotton 2020; Geißler and Jiricka-Pürrer 2023) and manage expectations. Although the wickedness lens can offer only a snapshot picture, a longitudinal study over various energy transition stages could be valuable to compare results. Moreover, extending the analysis to the agricultural sector would be worthwhile.

Additionally, further research could identify points of action to address the wicked facets illustrated in this research. The cases exhibit wickedness facets in the governance domain, stressing the need to invest more in coping strategies on the governance side and further research on a societal level. We argue that the wicked facets dimensions can decrease or increase over time, advocating for a more fluid wickedness concept.

5.3. Methodological and theoretical reflections

This section critically reflects benefits and shortcomings of the study and the theoretical concept.

5.3.1. Benefits of the wickedness concept in analysing energy transitions

Noordegraaf et al. (2019) summarise the advantages and value of the wickedness theory. It enables scholars to (1) ‘tie scholarly debates to contemporary societal issues’, such as the energy transition in our analysis, (2) ‘revitalize age-old insights into contestation, related to notions such as multiple actors, interests, values, mutual dependencies, networks, and uncertainty’, and (3) ‘to bring together academic *and* organizational *and* societal concern.’ (Noordegraaf et al. 2019, 279–80). Moreover, Lönngren and van Poeck (2020) argue that the concept of wicked problems is a multi-faceted and evocative approach beneficial in exploratory research stages. We find the values of the wickedness concept to be true for our application of the wickedness concept to the German energy transition.

The concept of the wicked problems assists us in understanding the multifaceted background of contemporary policy problems, such as the German energy transition. We were able to show how and where the ten original dimensions of wicked problems still manifest today in energy transition issues. As a theoretical framework, the wickedness concept is flexible and allows us to analyse a (policy) problem (here: German energy transition) from various angles. Contemporary societal and environmental problems are becoming increasingly intertwined and difficult to manage. The ‘wicked problem’ concept provides a practical analytical framework to address these challenges. It forces the analyst to gain a broader overview of the entire problem, thus preventing a ‘micro-analysis’ of individual aspects of a problem. It is an analytical approach that allows the analyst to understand socially strongly contested (or politicised) problems and conflicts.

The wickedness concept can help to identify access points for coping strategies to manage wickedness. Likewise, it can stop decision-makers from opting for a ‘worse’ solution, which would lead to unintended consequences. For example, we identify potential adverse effects and likely complex, if not wicked, problems from large applications of geothermal energy sources (case 2) that require adequate policy measures. It can also assist in raising awareness of transition stages or (wicked) policy blockages that require policy action (applicable for case 1). Ideally, it can assist in managing expectations in early research or transition stages, as applicable to the transport and industry sector cases (3 & 4). In researching and acknowledging the wicked facets, we argue that new energy transition technologies or policies should be thoroughly and realistically scrutinised to counter tendencies to leap from one energy transition hype cycle to the next. Therefore, we found the concept of wicked problems a valuable approach for conceptualising a complex and highly politicised problem, such as the German energy transition.

5.3.2. Methodological and theoretical shortcomings of the analysis

Our methodological and theoretical approaches have some shortcomings, i.e. (i) threat of discouragement, totalising, paralysis and stretching of the concept, (ii) dichotomy and binary approach, and (iii) methodological delimitations and bias.

Firstly, the potential for discouragement, totalising and paralysis has been discussed in the literature (Alford and Head 2017; Termeer, Dewulf, and Biesbroek 2019). Totalising poses challenges of paralysis, i.e. analysts and problem solvers think that as a particular problem is inherently complex, it defies problem resolution, thus justifying non-action. We acknowledge the potential pitfall of discussing the German energy transition as a wicked problem. However, we do not argue that the energy transition is inherently wicked; instead, we stress the need to consider potentially wicked facets, which call for tailored management approaches.

Secondly, methodological limitations include the absence of clear coding rules for the ten wickedness properties (Peters 2017). In Rittel (1972) and Rittel and Webber (1973), the wickedness concept was not further operationalised; it is also unclear whether the authors intended this. The lack of clearly operationalised coding rules and operationalisation limited our analysis. The dichotomy of the wicked problems concept (wicked/tame) has been criticised by Alford and Head (2017), Termeer, Dewulf, and Biesbroek (2019), and Noordegraaf et al. (2019), among others. We use the original 10-point frame for applicability and to limit complexity in our analysis. We are aware of potentially unprecise attribute allotment or differing normative biases of the analysts. Nevertheless, we do not understand the original ten characteristics of wicked problems as a set of necessary or sufficient conditions for a particular policy dynamic, i.e. a mathematical or rational test for wickedness. We followed Peters's (2017, 390) argument to understand the ten dimensions of wicked problems as individually free-standing attributes of a social or policy problem, which is 'useful in understanding a policy problem by itself.'

Thirdly, the methodological limitations of our research include the researchers' biases. Although conducting expert interviews, surveys, or focus groups was beyond the feasible scope of our analysis, we increased scientific rigour by conducting an internal Delphi round within the interdisciplinary PhD college to scrutinise, discuss, defend and adjust the categorisation of the four cases. Additionally, various internal circulations and a review round with principal investigators in the PhD college assisted in validating our categorisations. Co-authors have diverse disciplinary backgrounds, which further increases the scientific rigour of our analysis. Our perspectives on the German energy transition are drawn from personal and mutual research interests. We all come from different disciplinary backgrounds and focus on subdisciplines and subsystems in the German energy transition. We acknowledge that no individual lens or framework illuminates all issues or is perfect. Future studies on wicked facets of energy transitions could explore other operationalisations of the wickedness concept (see section 2) and thus validate, corroborate or build upon our analysis. Additionally, further research could increase scientific rigour by triangulation, e.g. conducting interviews or a Delphi round with experts in the energy transition field.

Lastly, a potential for oversimplification of energy transition issues remains. Differentiation into a technical/or engineering perspective and a governance perspective, and therefore differing between aspects of the environment, society, science or technology/engineering, is only possible on an analytical and conceptual level. In reality, these categories are entwined and show complex interconnections. Conversely, the split into technical and governance perspectives enables us to avoid totalising and work out subtleties.

6. Conclusion

We utilise the framework of the wicked problems to map persistent bottlenecks or problems in the German energy transition. Cases from the electricity, heating/cooling, transport and industry sectors illustrate where and how the original dimensions of wicked problems manifest in the German energy transition. We were able to show some wicked tendencies in the technical aspects, as we show that energy transition issues can cause further wicked technical problems, such as sourcing materials for the transition and waste management. Moreover, our results indicate that the socio-political implementation and governance of the energy transition exhibit wickedness, given high stakeholder diversity, value divergence, and complex governance structures. However, we do not imply that the energy transition is inherently wicked.

This article explores wicked facets of the German energy transition in an interdisciplinary approach. Although we, as researchers, stem from different disciplines and have different normative framings and epistemologies, the wicked problems framework allowed us to analyse the phenomena of the German energy transition in a cross-disciplinary way by applying a common theoretical approach. We argue that Rittel's and Webber's original criteria hold utility. They enabled us to highlight explicit examples of wicked facets in the four case studies without labelling them as absolutely tame or wicked.

In understanding the energy transition in its (partially more, partially less) wicked facets, we argue that there is no panacea to energy transition issues. Our study underpins the need to consider the potentially wicked facets of the German energy transition. We show that current energy transition solutions can cause ripple effects or negative consequences. We discuss and interpret our results along aspects such as technology maturity and transition stage (incl. state of knowledge, degree of regulation, and hype-disappointment cycles), stakeholder pluralism, and socio-political contestation.

Although our research does not focus on coping strategies for the identified wicked facets, we argue that it requires leadership, collaboration and harmonisation efforts among actors and institutions to overcome wickedness in the German energy transition. Communication between stakeholders and sensitising the public about the topic and potential negative impacts can be vital in managing expectations and wickedness. Technological or engineering solutions should be scrutinised regarding their economic, social, and environmental impacts, as there is no silver bullet, panacea or 'quick fix' to energy transition challenges and problems in the four analysed cases and sectors.

We find the wickedness lens to be a flexible analytical concept that allows us to analyse a (policy) problem, i.e. the German energy transition, from various angles. As an interdisciplinary research team, this approach allowed us to analyse different case studies of the energy transition. In illustrating wicked facets as a first step, this work can initiate a debate to match coping strategies, which can be relevant for both policymakers and analysts. We argue that wickedness is not static, as it can decrease or increase over time.

Notes

1. For climate change: among others Levin et al. (2012), FitzGibbon and Mensah (2012), Head (2014), Peters (2018), Gilligan and Vandenbergh (2020), Conradie (2020); for terrorism: Fischbacher-Smith (2016); for world hunger and poverty: Durant and Legge (2006).
2. The bibliometric analysis was conducted using the Web of Science database and the *bibliometrix* package in the programming language R.
3. In their guest editorial, Chan and Xiang (2022, 2) argue that 50 years after Rittel's and Webber's paper, 'it is now widely recognised that wickedness […] is the norm in social systems of all kinds, including socio-

ecological systems where human-human […] relations and human-nature […] relations are intertwined with each other […]'.

4. Emissions from space heating/cooling are predominantly accounted for in the buildings sector (fuel combustion in residential and commercial buildings) but also occur in the energy supply sector (e.g. district heating, electrified heating and cooling). The further analysis focuses on space heating and cooling using geothermal energy systems.
5. On- and offshore contributions.
6. Saxony, Baden-Württemberg, Bavaria and Berlin contribute less than 100 kW/m² to the cumulative installed capacity, albeit their 35% share of the federal territory. The Northern federal states; Schleswig-Holstein, Lower Saxony, Brandenburg, and Saxony-Anhalt, each contribute between 200–400 kW/m² to the cumulative installed capacity, see Deutsche WindGuard GmbH 2022
7. E.g. governance gaps, military use and aviation safety, local opposition, forest and landscape conservation, and heritage protection.
8. The legislation package aims at raising development targets, lifting caps to installations, abolishing blanket distances to military and civil radar stations, introducing an Onshore Wind Demand Act with tangible contribution targets for the 16 States, and adapting planning regulations, such as the Federal Nature Conservation Act, the Federal Building Code and the Spatial Planning Act.
9. The number of renewable power generation plants was generated via the central registry Marktstammdatenregister on 25 May 2022: https://www.marktstammdatenregister.de/MaStR/Einheit/Einheiten/OeffentlicheEinheitenuebersicht Filter: 'Energieträger entspricht nicht andere Gase und Braunkohle und Druck aus Gasleitungen und Wasserleitungen und Grubengas und Kernenergie und Klärschlamm und Mineralölprodukte und nicht biogener Abfall und Speicher und Steinkohle und Wärme'.
10. According to van Graaf and Sovacool (2020), the potential set of transformation approaches in the heating sector includes passive building design, electric pumps, and district heating.
11. The Yellow Vests Movement surged after the government's announcement to increase the carbon tax levied on transport fuels in 2018
12. With projected demand rising from 54 terawatt-hours (TWh) in 2020 to 685 TWh in 2050 (Geres et al. 2019).
13. Conflicts of interest include but are not limited to nature and species protection, citizens' preferences and health concerns, and perceptions of landscape scenery.
14. For a detailed knowledge base: https://tethys.pnnl.gov/knowledge-base-wind-energy.
15. Howlett and Rayner (2007, 1) state that 'most existing policy […] regimes have been developed incrementally […] These regimes sometimes contain a unifying overall logic, but more often' lead to policy drift.
16. For wind power use in Germany, Kriechbaum, Posch, and Hauswiesner (2021, 9) found a 'hype phase with an unprecedented increase in […] media attention and expectations […] (2006–2011), a phase of disillusionment (2012–2014), and a phase of 'recovery' (2015–2017)'. Still, onshore wind power installations are stagnating from 2017 – 2022, which calls into question if the enlightenment phase has been reached, i.e. a phase where the technology reveals its value and diffuses widely or whether the trough of disappointment continues.
17. The green-on-green-dilemma is a prioritisation conflict among „environmentally conscious groups' (cf. Warren et al. 2005), which has at the heart the question if climate action goals should be prioritised over species conservation goals.
18. 40 VHF Doppler omnidirectional radio range equipment (D-VOR).
19. Deutsche Flugsicherung GmbH.
20. This renders policy design more difficult, since counteracting policies, which would be progressive on average would still leave some poor households adversely affected.
21. Blue hydrogen is produced via steam reformation with carbon capture and storage, CCS.
22. The production of green hydrogen requires vast amounts of electricity from renewable sources.

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Annex

Annex A. Case 1 – Developing onshore wind power

Property 1: No clear definition

From a technical perspective, expanding onshore wind energy is initially a very clearly defined task for which numerous solutions (both turbine designs and manufacturers) are available.

From a governance perspective, however, onshore wind development can be problematised, as there might be multiple reasons for the stagnating development. Explanatory approaches range from mismatches in the polycentric governance system (Biehl, Köppel, and Grimm 2021; Juerges, Leahy, and Newig 2018) to conflicts with conservation objectives (Wiehe et al. 2021). Additionally, there is vocal local opposition to onshore wind farms, albeit high national acceptance levels (Reusswig et al. 2016; Reusswig, Komendantova, and Battaglini 2018) and a strong vocal minority and silent majority (Fachagentur Windenergie an Land 2021; Hübner et al. 2019). However, there is no consensus on the reasons for citizens' discontent (Köppel and Biehl 2018), which illustrates intractability

Property 2: No boundary lines (no-stopping rule)

Installation targets for developing onshore wind facilities exist, and wind developers know when they have installed sufficient capacities. Minor technical adjustments and repowering will still be necessary from 2040 onwards, but a clear goal exists.

However, the question remains if future exogenous shocks (such as the war on Ukraine in 2022) will require additional system changes. Moreover, uncertainties about the future electricity demand (for direct electrification in other sectors, green hydrogen, increasing energy consumption) and supply (energy emergencies, decommissioning and end-of-life of first- and second-generation wind turbines) could lead to a *de-facto* no-stopping-rule. Policy uncertainty and time lag can also lead to a no-stopping rule. For example, the onshore wind demand act will free up potential land for installations after five to ten years (Lehmann et al. 2022), making it challenging to monitor success. Decision-makers often cannot quickly check if the measures were sufficient and might be tempted to continue addressing the problem or wait too long to intervene.

Property 3: Better-or-worse answers

From a technical viewpoint, there are no right or wrong answers, only better or worse. The choice of the turbine make (horizontal, vertical, airborne wind energy cf. Schmehl 2018) as well as the number of turbines in the wind farm is such a complex task that – in practice – optimal solutions for the technical layout and site selection cannot be identified. An algorithm for determining the best wind farm layout, for example, usually will not be able to find the global maximum of power yield but a local one, which is only close to the global maximum (Feng and Shen 2015) and therefore a '*better solution*'.

The onshore wind power development affects many stakeholders at various levels of governance, which pursue a multitude of interests. The diversity of views, values and interests ranges from economic interests, job creation and preservation, prevention of change and maintenance of existing energy supply structures, and nature conservation to tourism/recreational use. Decision-makers can only make better or worse rather than right-or-wrong decisions and could 'always try to do better' (Rittel 1972, 392).

Property 4: No test for solutions

Clean energy solutions, such as onshore wind energy, and their impacts are not reasonably verifiable and testable. The absence of ultimate tests and the likelihood of unintended side effects have become most apparent for the socio-environmental and ecological impacts of onshore wind farms (Köppel et al. 2019; Wiehe et al. 2021). For instance, the green-on-green[17] dilemma (wind-wildlife conflict) was not foreseeable. It arose after high fatalities for avifauna on onshore wind turbines were recorded at the US-American Altamont Pass Wind Farm in the early 1990s (National Renewable Energy Laboratory and Defenders of Wildlife 2020). Still, some impacts pertaining to onshore wind farms and their mitigation are difficult to anticipate and manage, i.e. uncertainties remain. Similarly, the exact results and effectiveness of, e.g. policy and governance responses, are not testable.

Equally, unintended technical impacts and disturbance effects of onshore wind turbines, e.g. on radio navigation devices, could not have been foreseen. Two targeted research projects (WERAN & WERAN plus) evaluated the disturbance effects of wind turbines on rotating radio devices[18] (Schrader et al. 2022), which caused vetoes from the German air navigation service provider[19] for many wind projects until 2022 (Fachagentur Windenergie an Land 2019). In 2022, an agreement was reached on the better compatibility of radio navigation and onshore wind turbines. By retrofitting radio navigation stations restrictions on land are lifted for an estimated 5 GW, i.e. approx. 1,000 wind turbines (Bundesministerium für Wirtschaft und Klimaschutz and Bundesministerium für Digitales und Verkehr 2022). However, retrofitting requires large financial investments, illustrating the required trade-offs.

Property 5: One-shot approach

Planning culture and litigation have forced onshore wind governance into a tight corset, which leaves little to no tolerance for trial-and-error solutions (Biehl, Köppel, and Grimm 2021). Therefore, each solution is considered a one-shot decision – if planners do not get it right, permits can be revoked or wind farms curtailed. Due to the strong corset of jurisdiction and limited valuation of climate action concerns compared to other public interests (Wegner 2021), planners may even lack leeway or political back-up to favour wind development over other concerns. Moreover, the energy transition in general and the expansion of wind energy, in particular, have become publicly discussed topics (Dehler-Holland, Okoh, and Keles 2022). Every mistake or unexpected effect is savaged (by the media), which shows that the public does not allow trial-and-error situations.

On the contrary, from a technical viewpoint, onshore wind power development is reversible. Turbines can be dismantled, thus restoring landscapes and habitats to baseline settings. The largest parts (85-90%) of the wind turbine can be recycled (WindEurope 2020), limiting the overall footprint considerably compared to other energy carriers, such as nuclear power, coal, or biomass. However, the selection and application of technologies, e.g. a particular turbine make, technical design conditions, or technical mitigation measures for impact reduction on wildlife or human receptors are linked to investment risks. The reliability of the wind turbine system is a critical factor, as operations and maintenance costs account for ca. 20-25% of the levelised cost of electricity (Costa et al. 2021). Faulty technical parts or settings and errors in site selection could therefore reduce the operators' revenues, thus exhibiting some wicked facets.

Property 6: Infinite set of potential solutions

Potential technical solutions to wind energy problems are not finite, as new research continuously identifies innovative solutions.

From a governance perspective, tolerance for and applicability of new approaches is often limited by actors' preferences, economic cost pressures, judgements and the regulatory framework (Raschke 2015; Schwarzenberg and Ruß 2016). The current legal framework does not enable 'energy law engineering', i.e. allowing innovative approaches to be tested and adapted if framework conditions change.

Property 7: Uniqueness
From a technical perspective, research and development of wind power cannot be considered unique, as technical solutions from both aviation and shipping industries were adapted (Bruns et al. 2011). Likewise, technical learning and adaptation from other countries can be possible, although copy-paste approaches are rarely satisfactory, given the different regulatory settings.

The governance of onshore wind and the accelerated development are unique problems: Unique to Germany, as other countries have selected other pathways to decarbonise their electricity systems (utilising, e.g. nuclear or hydropower). Goldthau and Sovacool (2012) argue that energy stands out compared to other policy fields, given its greater complexity, higher costs, and stronger path dependency. On a case study level, the German onshore wind power development stands out given its unique polycentric planning and governance framework (Biehl, Köppel, and Grimm 2021; Juerges, Leahy, and Newig 2020) with ambitious targets of installing up to 115 GW onshore wind capacity by 2030 in a densely populated country.

Property 8: Causal webs
The problem is a symptom of another: The accelerated development of onshore wind power is symptomatic of an increased need for low-carbon energy, which in turn is symptomatic of the combat against climate change. The increased use of onshore wind power caused socio-environmental problems, illustrating that problems are interrelated and symptomatic of another. Problems associated with onshore wind energy use include the green-on-green dilemma (Gartman et al. 2014; Voigt, Straka, and Fritze 2019; Warren et al. 2005), social, procedural and distributional (in)justice (Köppel et al. 2019), and land use conflicts (Biehl, Köppel, and Grimm 2021).

Developing onshore wind power requires personnel, financial and materials resources, which are finite. The German wind industry struggles with increased transportation, energy, and raw materials prices. Major manufacturers, such as Vestas or Nordex, are closing down production sites in Germany (Frese, Mumme, and Metzner 2021; Nordex SE 2022). Closing production sites can lead to a higher dependency on volatile global supply chains (Taylor 2022) and locational disadvantages for the German wind industry (Löhr and Mattes 2022). Additional problems arise, e.g. the provision of materials (Taylor 2022) and the recycling of the rotor blades' composite materials (Karatairi and Bischler 2020), creating a 'waste legacy problem' in the future (Jani et al. 2022; Majewski et al. 2022), further illustrating interconnectedness and complexity.

Property 9: Numerous explanations
The problem of governing, planning, developing and technically installing onshore wind power can be explained in numerous ways, as shown in the characteristics above. The increasing need for onshore wind energy facilities could be explained by (A) the adoption of the Paris Agreement and the Sustainable Development Goals, which aim at a sustainable development pathway and 'clean and affordable energy' (SDG 7); (B) by the phase-out of fossil and fissile power plants; (C) an increase in energy consumption, which needs to be covered by renewable electricity generation, or (D) a commitment to reduce energy dependency from other states and a pending energy security emergency (European Commission 2022).

Property 10: Normative framing (no right to be wrong)
Given a high population density and installed cumulative capacity of onshore wind power in Germany, conflicts with other land uses and values have increased (Biehl, Köppel, and Grimm 2021), which will intensify with further increasing exploitation yields (Dehler-Holland, Okoh, and Keles 2022). Conflicts of interest include but are not limited to environmental protection, citizens' preferences and health concerns, and perceptions of landscape. When trading the public interests and values, planners must follow a coherent planning system (Bundesverwaltungsgericht 2002, 2012). All spatial development plans and planning decisions might be challenged by the (administrative) courts, showing that actors are liable for the consequences of their actions and decisions. Like other public policy problems, regional planners, which govern the spatial development of onshore wind power, have 'no right to be wrong', as they are responsible for their actions and can be held accountable.

Annex B. Case 2 – Space heating and cooling using shallow geothermal energy systems

Property 1: No clear definition
The technical definition of the problem is clear. In order to advance decarbonisation in the heating and cooling sector, more buildings have to be heated and cooled in a renewable and sustainable way. Shallow geothermal systems such as ground source heat pumps, groundwater heat pumps and aquifer thermal energy storage systems have proven to be feasibly when the subsurface conditions are suitable (Hähnlein, Bayer, and Blum 2010; Sanner et al. 2003; Stemmle et al. 2021).

From a governance perspective, the problem definition is far less straightforward since political, social, ecological and economic aspects have to be considered. The transformation process needs to integrate a variety of stakeholders, such as municipalities, regional supply companies and citizens. Protecting the groundwater ecosystem and its ecosystem services is also highly relevant (Griebler et al. 2016).

Property 2: No boundary lines (no stopping rule)

From a technical perspective, achieving the objectives is relatively easy to assess for individual buildings potentially supplied by shallow geothermal energy resources.

From the governance perspective, however, deciding on a stopping rule regarding the overall decarbonisation pathway is far more complex. While the German government's coalition agreement sets an interim target of 50% renewables in the heat supply by 2030, it does not specify how individual technologies should contribute to this target (SPD, BÜNDNIS 90/DIE GRÜNEN & FDP 2021). The interaction between heating networks, geothermal energy, and other renewable energies such as solar thermal energy is subject to conflicts of interest. In this context, continuing subsidies for fossil-fuelled combined heat and power plants or the question of the economic viability of renewable heating and cooling supply are worth mentioning. Ultimately, the definition of decarbonisation pathways and the formulation of clear targets themselves are influenced by regulatory uncertainties and trade-offs, for example, concerning nature conservation.

Property 3: Better-or-worse answers

From a technical point of view, the feasibility of shallow geothermal utilisation for renewable space heating and cooling is relatively easy to assess. Provided the basic geological and hydrogeological subsurface properties are suitable, geothermal systems can be designed and deployed sustainably. Various types of geothermal systems, such as heating networks with centralised or decentralised heat pumps and the individual supply of single buildings, have proven effective (Pratiwi and Trutnevyte 2021; Sanner et al. 2003; Tissen et al. 2021; Todorov et al. 2020).

The shallow subsurface is affected by many stakeholders with different interests and perspectives (Brielmann et al. 2011; Hähnlein, Bayer, and Blum 2010), which have to be accounted for from a governance perspective. Finding ways to identify and justify prioritisation among multiple distinct aspects regarding the subsurface is a fundamental requirement when dealing with conflicts of interest (García-Gil et al. 2020). Conflicts of interest include but are not limited to groundwater ecosystem protection, thermal use for heating and cooling, groundwater use for drinking water supply, irrigation, and industrial use. At the same time, it is essential to consider other renewable energy sources such as solar thermal energy or biomass.

Property 4: No ultimate test for solutions

Shallow geothermal installations using groundwater for energy supply or storage often only reach a steady state after a few years of operation (Pophillat et al. 2020; Vanhoudt et al. 2011). With an increasing spread of the technology and consequently an increasing system density, long-term sustainability can thus prove problematic, especially in urban areas with multiple systems in close vicinity. Adverse thermal interferences between systems in densely populated areas can significantly reduce the efficiency of individual installations (Attard et al. 2020; Bloemendal, Jaxa-Rozen, and Olsthoorn 2018). The technical operation, therefore, does not always allow a conclusive *a priori* assessment.

Long-term regulatory planning of geothermal installations, which allows for additional systems to be placed in the future, is thus required from a governance perspective to ensure optimal and sustainable operation of a large number of installations. On the one hand, holistic and adaptive underground planning and management can prevent thermal overexploitation of the subsurface. During the permission process, it can also prevent excluding subsurface space from future thermal utilisation due to inefficient permissions of vast capacities, which are often not fully used (Bloemendal, Olsthoorn, and Boons 2014; García-Gil et al. 2020; Perego et al. 2022). A comprehensive legislative framework should also factor in the counteractive effects of groundwater ecosystem protection and the thermal use of groundwater as a renewable energy source. Until now, there is only a small number of studies on the long-term environmental consequences revealing an insufficient knowledge base on how groundwater ecosystems are affected by shallow geothermal systems (Blum et al. 2021; Hähnlein et al. 2013). This information deficit is also reflected in legislation. While there is a variety of individual laws and regulations in Germany regarding the protection of groundwater as a resource, the legislation (including the Federal Water Act, Federal Groundwater Regulation and the Federal Nature Conservation Act,) does not consider groundwater protection at an ecosystem-level perspective (Hahn, Schweer, and Griebler 2018; Koch et al. 2021).

Property 5: One-shot approach

Geothermal installations for space heating and cooling are typically designed for more than two decades, reflecting long investment cycles in the building sector (Bloemendal, Olsthoorn, and Boons 2014; Saner et al. 2010). The long lifespan of geothermal installations leaves no room for technical planning errors. Additionally, securing the public water supply should have an absolute priority.

Thus, it is necessary to establish a clear regulatory framework regarding qualitative and quantitative changes in groundwater. At the same time, a too restrictive legislative framework could prevent a more widespread thermal utilisation of shallow geothermal resources. From the governance side, it is also vital to ensure long-term planning certainty over several decades by setting clear target paths and defining overarching strategies.

Property 6: Infinite set of potential solutions

Any technical realisation of thermal utilisation of the shallow subsurface as an energy source or storage medium is fundamentally linked to a change in the underground thermal regime. Finding new technical solutions is thus not the key issue of the transformation process but instead setting a regulatory framework to establish an acceptable middle way between a multitude of distinct interests.

Property 7: Uniqueness

The optimal realisation of space heating and cooling via shallow geothermal energy is highly space-dependent due to several factors. For example, geological and hydrogeological subsurface characteristics determine the intensity of thermal anomaly propagation underground and the suitable system design (Hähnlein et al. 2013). Especially open shallow geothermal systems using groundwater bear the risk of mobilising pre-existing local contaminations (García-Gil et al. 2020; Possemiers, Huysmans, and Batelaan 2014). Additionally, a large number of systems in a small area can detrimentally affect the systems' performance due to thermal interferences. Moreover, other anthropogenic influences such as basements, underground car parks and urban surface sealing can significantly alter the thermal regime in the subsurface (Blum et al. 2021; Menberg et al. 2013; Tissen et al. 2019).

These factors also impede a simple and universal regulatory framework. Instead, each city should best tackle the targets set at a national level by adapting to local conditions regarding subsurface characteristics and urban structure. These aspects significantly impact the local conflict potential arising from shallow geothermics. In socioeconomic terms, the creation of citizen energy cooperatives could also make municipalities play a central role in the realisation of geothermal systems and heat networks if they are not otherwise financially viable. This way, municipalities could effectively contribute to the heat transition. Ultimately, the large-scale heat transition as a part of the greater energy transition can also be identified as a unique and unprecedented transformation process.

Property 8: Causal webs

Extensive thermal use of the shallow subsurface can lead to detrimental thermal interference between individual systems in the case of a high density of installed systems. Lower system efficiencies are associated with higher operating costs and possibly the need for fossil auxiliary technologies such as gas boilers or compression chillers (Miglani, Orehounig, and Carmeliet 2018; Tissen et al. 2019).

Besides technical drawbacks, shallow geothermal utilisation may entail other trade-offs, including environmental aspects such as detrimental changes to the groundwater ecosystem and loss of the respective ecosystem services (Blum et al. 2021; Griebler and Avramov 2015; Koch et al. 2021). Conflicts of use of shallow groundwater and decreasing profitability of regional supply companies, which often base their business model on the profitable gas supply, might also arise from an increasing spread of this technology.

Property 9: Numerous explanations

The motivation for geothermal space heating and cooling and the utilisation of environmental heat, in general, is mainly rooted in reducing greenhouse gas emissions in the building sector (e.g. Self, Reddy, and Rosen 2013). More recently, the pressing issues of supply reliability and reduced dependence on imported natural gas and heating oil have also come into focus.

Property 10: Normative framing (no right to be wrong)

On the one hand, a successful heat transition and security of supply in the building sector, and on the other hand, conflicting aspects such as ecosystem concerns and economic profitability, are all highly relevant for the future. Therefore, it is crucial to reconcile all these aspects through coherent and comprehensive planning. The planners and decision-makers have 'no right to be wrong'.

Annex C. Case 3 – Decarbonising the transport sector

Property 1: No clear definition

Technically, decarbonising the transport sector requires meeting individuals´ demand for transport services at lower levels of aggregate GHG emissions. Several channels exist to accomplish sectoral targets, including lowering the emission intensity of transport fuels, lowering the energy intensity of transport services (such as modal shifts towards public transport) or demand-side measures. It is technologically feasible to reduce emissions in the transport sector, and various corresponding policies are conceivable or even in practice.

Insecurity prevails on which policies to introduce, i.e. *how* to reach sectoral targets, including trade-offs. Since many people will likely demand mobility services, the feasible solution space will need to deal with persisting (high) demand levels. Without affordable and widely available technological solutions, decarbonising the transport sector will entail distributional consequences, i.e. creating winners and losers. How to address those consequences is inherently normative but also limited by institutional capacities. Therefore, defining the problem of *efficient and equitable* decarbonisation of the transport sector within existing governance structures is wicked.

Property 2: No boundary lines (no stopping rule)

Ambitious efforts to increase the share of renewable energy sources in electricity generation hand in hand with coupling sectors and electrifying individual mobility could help to cut emissions caused by road transport (Jaramillo et al. 2022). Decarbonising aviation and shipping will require the use of hydrogen or eco-fuels.

From a governmental perspective, lowering transport sector emissions will require operation in a highly dynamic environment. For example, market-based interventions, e.g. fuel taxes, could help to lower emissions since research suggests that consumers are relatively sensitive to fuel prices (Frondel and Vance 2018; Zimmer and Koch 2017). Nevertheless, lower fuel demand (following efficiency gains or consumers switching to electric vehicles) might lead to lower fuel prices, which might cause further delay. In addition, consumer preferences are sometimes persistent (, i.e. 'sticky') and influenced by non-monetary factors (comfort, security, habits). Resting on large-scale infrastructure suggests a high degree of path dependency. Overcoming this path dependency is time-consuming and requires extensive planning of transport systems. Transforming the transport sector is highly non-linear, requiring different policy instruments at different transition stages, which respond to sector-specific dynamics in the supply and demand of transport services.

Property 3: Better-or-worse answers

Optimal transport systems would have to meet the requirements of many actors, obeying local, regional and transregional infrastructure. Various low-emission transport systems are conceivable that could, among other things, depend on decreased demand for transport services (sufficiency), on public transport and shared mobility concepts or on low-emission technologies for individual mobility. Therefore, the formulation of optimal solutions strongly depends on concepts of fairness and justice and is subject to normative assumptions, political preferences and public acceptance (Creutzig et al. 2020). Any successful transformation towards low-emission mobility will create losers (and possibly winners), emblematic of a '*better-or-worse*' solution.

To further illustrate the wicked tendency for *better-or-worse answers* in this case, we combine multi-regional input-output data and household-level microdata to simulate the cost burden on German households of a 35€ carbon tax on transport fuels, such as diesel or gasoline, which will be levied in 2023 (BEHG 2020). Our results indicate that a carbon tax in the transport sector, which would provide an economic incentive for consumers to cut emissions, would disproportionately affect poorer households (Panel a) in Figure 2). This observation also holds in France (Douenne 2020) (where the Yellow Vest movement has been successful in influencing policy (Douenne and Fabre 2022)) and is consistent in many other high-income countries (Sterner 2012). Specifically, it expresses larger expenditure shares spent on energy services (such as transport) among households with lower incomes (Panel b) in Figure 2). Moreover, within-quintile differences exceed between-quintile differences, i.e. substantial heterogeneity of additional cost burden among poorer households.[20] We depict substantial differences between urban and rural households, with households living in rural, less densely populated households being more heavily affected by carbon pricing than urban households are (Panel b) in Figure 2).

This brief analysis shows that policy-makers face a difficult efficiency-equity trade-off, which might result in the enactment of less effective (and potentially unequal) policies aiming at decarbonising the transport sector. For example, electric vehicle subsidies will likely benefit wealthier households proportionally (Guo and Kontou 2021). In contrast, direct regulation (e.g. fleet standards and bans) usually proves economically inefficient and potentially more regressive (Levinson 2019; see Baldenius et al. 2021 for a comprehensive assessment for Germany).

Property 4: No ultimate test for solutions

Ex-post evaluation of policies aiming to decarbonise the transport sector can help design effective instruments tailored to context-specific circumstances. Nevertheless, the prevalence of path dependencies and long-term effects of current policies impede just and effective transformation processes. For instance, the widespread use of battery-fuelled electric vehicles requires an accompanying roll-out of charging infrastructure (Schroeder and Traber 2012). Shifting transport from road to rail calls for long-term planning of complex railway infrastructure. Moreover, achieving net-zero emissions might require different (technological and institutional) solutions than meeting intermediate sectoral goals. Instruments, which facilitate the diffusion of 'niche' products (such as subsidies), might prove inefficient in stages of market saturation or in times of low prices for transport fuels (Cats, Susilo, and Reimal 2017; Caulfield et al. 2022). This inefficiency implies a requirement for constant evaluation of the effectiveness and efficiency of any mix of multiple policy instruments, which exacerbate or alleviate each other. From a technical and a governance perspective, each probable solution is highly context-specific and might create additional frictions, requiring additional measures. Testing ultimately for solutions is hardly possible.

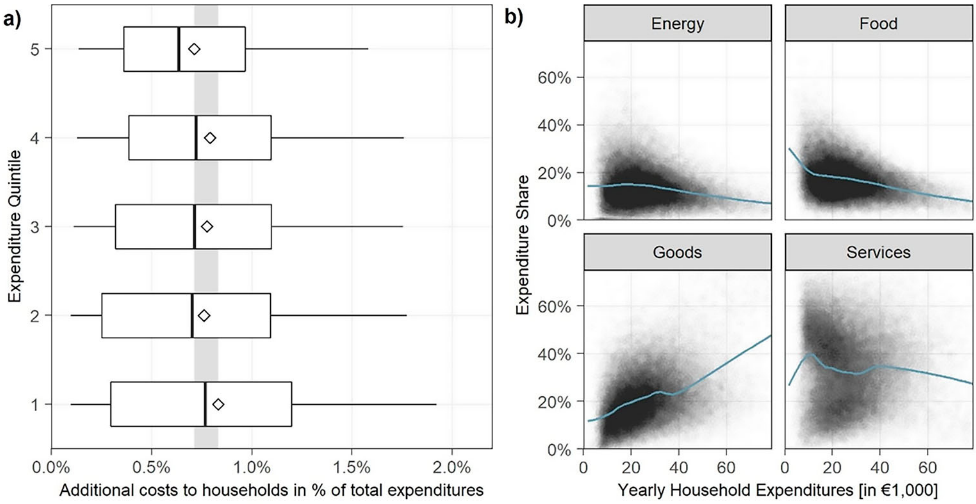

Figure 2. Panel a) shows first-order additional costs of transport fuel carbon pricing (35 EUR/tCO_2) among German households. Y-axis shows expenditure quintiles. Expenditure quintile 1 comprises the 20% of German households with the lowest per capita expenditures. Expenditure quintile 5 comprises the 20% of German households with the highest per capita expenditures. The X-axis displays additional costs in per cent of total consumption expenditures. Whiskers represent within-quintile 5th to 95th percentiles. The rhombi represent the mean. The Grey vertical bar represents the difference between first and fifth quintiles' average additional costs. Panel c) shows household-level expenditure shares for energy, food, goods and services over total household expenditures in Germany. The blue line indicates a polynomially fitted regression line.

Property 5: One-shot approach

Current emission levels in the transport sector reflect, to some extent, decisions on infrastructure investments from past decades. Constructing roads, rails and airports create path dependencies, influencing consumers´ demand for transport services. Those path-dependencies create 'lock-in' situations (Unruh 2000), likely to inhibit any form of transformation. In the transport sector, this does not only imply that society has to consider time-intensive planning cycles (e.g. to invest in public transport infrastructure) but also that past decisions narrow the currently feasible solution space. In addition, reducing the use of a 'hegemonial technology' (such as fuel-combusting vehicles) will likely face resistance from actors who benefit from the status quo (cf. Falck, Czernich, and Koenen 2021). Ineffective attempts to decarbonise the transport sector might leave limited leeway for alternative approaches since this transformation will likely require considerable investments in infrastructure and up-scaling of novel technologies. In addition, ineffective policies might be detrimental to sustaining public acceptance.

From a technical perspective, product lifecycles span over a decade, slowing down today's ambitions and constraining future opportunities to correct prior decisions if stranded assets should be avoided. Nevertheless, it appears as if decarbonising the transport sector will require a set of (technological) solutions, including bridging technologies, such as battery-fuelled electric vehicles.

Property 6: Infinite set of potential solutions

Many technical options are available to curb GHG emissions in the road transport sector. Current demand levels for transport services will likely require individual transportation modes resting on energy conversion technologies. Given the time horizon to drastically reduce German climate targets, it is unlikely that non-mature technologies (such as hydrogen-fuelled road transport) will be part of the solution space.

On the contrary, how to align the preferences and perspectives of many fragmented actors (citizens, corporates, authorities) is ambiguous. There are interdependencies between regulatory and institutional frameworks at multiple levels of governance (local, regional, national, international), which enforce tailored, context-specific regulations owing to contemporary developments, such as fluctuations in transport fuel prices or large economic shocks.

Property 7: Uniqueness

Decarbonising the transport sector hinges on complex socio-technical systems integrating dynamics in technology, social norms and subsequent demand for transportation services. Moreover, transformation challenges will likely obey region- and time-specific circumstances. Each city or municipality will likely require unique solutions.

Like the heating and cooling sector, actors are fragmented, restricting the applicability of several effective policy instruments (such as cap-and-trade schemes and command-and-control approaches). On the contrary, the demand for transport services is likely to be more elastic (Labandeira, Labeaga, and López-Otero 2017), which gives greater weight to exogenous shocks, such as fluctuations in fuel prices. The sheer amount of users, routines and potentially influencing factors, as well as complex interactions between supply and demand for transport technology, restrict the applicability of instruments, which could help decarbonise other sectors, such as industry or electricity.

Property 8: Causal webs

Transport systems are embedded in many other socio-economic systems, and transition attempts will cause fundamental shifts in those systems, which are difficult to predict or evaluate. For instance, electrifying individual transport requires various scarce natural resources, such as lithium, cobalt or rare earth metals. Extracting such resources establishes links to environmental degradation and human health (Banza Lubaba Nkulu et al. 2018) but also creates local resource booms. How to effectively recycle energy storage technologies is subject to extensive research (Harper et al. 2019). Moreover, transforming the transport sector may affect the competitiveness of industries, primarily if value-chains rely on comparatively cheap and reliable transport facilities. Adjusting road and rail infrastructure causes changes in cities and rural areas with benefits and losses to different societal groups. Many conceivable pathways to decarbonising the transport sector are likely to cause changes in individual well-being, i.e. through positive effects of particulate matter reduction on health (Klauber et al. 2021).

Property 9: Numerous explanations

Decarbonising the transport sector affects multiple fragmented actors with diverse objectives. The large solution-space and various intersections with other socio-economic domains manifest a large variety of explanations, which is exacerbated by multiple externalities. For instance, shifting individual transport to public transport services would likely reduce congestion and create incentives for transport system changes that are more socially inclusive and equitable. Contrarily, frequent calls to subsidise purchasing electric vehicles or lowering fuel taxes often implicitly link to the pivotal role of (individual) transport for economic activity and welfare. Describing socially optimal demand and supply levels for transport services is difficult, which adds substantial uncertainty to determining desirable and feasible transformation pathways.

Property 10: Normative framing (no right to be wrong)

Decarbonising the transport sector is a politically delicate task since it involves political decisions, which entail tremendous distributional consequences. An effective policy will create winners and losers in domains as different as street space allocation, employment or capital rents. Instruments, which are economically efficient (such as carbon pricing), would have unequal cost effects for consumers. In Germany, pricing transport fuels according to their carbon content would likely be regressive, i.e. affect poorer households more heavily than wealthier households. If unaddressed, unintended distributional consequences could affect public acceptance and thus inhibit policy implementation. Instruments aiming at lowering emissions in the transport sector affect many actors, which negates a ‘right to be wrong’ for political decision-makers, which might delay stringent and effective action.

Annex D. Case 4 – Decarbonising the German chemical industry

Property 1: No clear definition

The problem definition is clear from a technical perspective: the chemical industry needs to be decarbonised (Geres et al. 2019; Joas et al. 2019). The problem definition from a social, economic and political perspective is far more complex. Competitiveness has to be maintained on a national and international level, decarbonisation pathways have to be in line with other sustainability goals like preserving biodiversity, and the transition should be just and inclusive (Bang, Rosendahl, and Böhringer 2022; Díaz et al. 2019; European Commission 2019).

Property 2: No boundary lines (no-stopping rule)

Again, the technical dimension seems rather clearly defined. One can stop when the chemical industry is operating carbon neutral. The goal is to decarbonise the industry and achieve climate neutrality through electrification and the use of biomass (Joas et al. 2019). Of course, some complexities exist regarding the definitions of carbon neutrality, greenhouse gas neutrality or even climate neutrality, and the definition of system boundaries.

However, from a governance perspective, conflicts of interest arise, for example, regarding whether biomass should be used as an energy source or a feedstock for the chemical industry. Furthermore, both uses imply trade-offs for biodiversity conservation or food security (Bataille et al. 2018).

Property 3: Better-or-worse answers

Both from a technical and a governance perspective, there is no clarity on exactly what the best solution would be. On a technological level, this manifests in uncertainty about which technology to implement for decarbonising a specific process, like hydrogen production (Wietschel et al. 2021).

From a governance perspective, no consensus exists about what a future chemical industry sector should look like – whether the solution is to decrease production and implement sufficiency strategies or to count on green growth and the decoupling of economic growth and carbon emissions (Eckert and Kovalevska 2021; Wachsmuth and Duscha 2019). Moreover, different scenarios and transformation pathways exist in the scientific debate (Brandes et al. 2021; Burchardt et al. 2021; Joas et al. 2019; Luderer, Kost, and Sörgel 2021).

Property 4: No ultimate test for solutions

While technologies are tested in real-life laboratories and pilot studies, uncertainties regarding their large-scale implementation remain (Joas et al. 2019). The financial profitability of new technologies can only be assumed, not tested (Chiappinelli et al. 2021). The same holds for implementing economic and political measures to switch to low- or no-carbon technologies. Therefore, this dimension carries a high level of complexity or even wickedness from both technical and governance perspectives.

Property 5: One-shot approach

There is a narrow window of opportunity for decarbonisation in the chemical sector. Because technologies like steam crackers have long lifetimes, an investment in them today would result in sunk costs for the next decades and prevent a low-carbon transformation of the sector (Janipour et al. 2020; Joas et al. 2019). Because value chains are complex and intertwined, decarbonising them requires addressing all aspects of the production (Geres et al. 2019; Janipour et al. 2020; Kümmerer, Clark, and Zuin 2020); there is little to no margin for error in this complex process.

The governance of industrial decarbonisation has been characterised by a lot of trial-and-error-processes, such as the ongoing reform process of instruments like the EU ETS (Dorsch, Flachsland, and Kornek 2020; European Commission 2021b; Joltreau and Sommerfeld 2019; Lilliestam, Patt, and Bersalli 2021) or the German EEG (Luderer, Kost, and Sörgel 2021). However, we argue that there is no time left for more attempts at stringent policies as climate change is advancing ever faster. Therefore, both technical and governance perspectives can be defined as wicked.

Property 6: Infinite set of potential solutions

There is an indefinite number of solutions to the decarbonisation challenge in the (chemical) industry. On a technical level, various low- or no-carbon technologies are already available or will become available in the following years. Different strategies for decarbonising the operations exist. Potential solutions range from electrifying processes, alternative feedstocks and carbon capture, utilisation and storage to the flexibilisation of energy usage (Ausfelder, Seitz, and von Roen 2018; Geres et al. 2019; Joas et al. 2019).

On a governance level, there are many solutions, although their implementation may face challenges on different levels, like lacking public acceptance for new technologies such as carbon capture and utilisation (CCU) (Lee 2019).

Property 7: Uniqueness

The chemical sector has never before faced a similarly significant transition. It is unique on both a technical and a governance level. Because fully decarbonised chemical industries do not exist anywhere in the world yet, Germany could be a pioneer if it succeeds in transforming its industry (The European Chemical Industry Council 2022). The chemical industry is characterised by a high degree of uniqueness, given its complex value chains, diverse company structures which lead to very company-specific challenges, and its dependency on fossil-based substances like Naphtha for many production processes (Joas et al. 2019; Wesseling et al. 2017). On a governance level, no other sector in Germany – except steel production – has a higher risk of carbon leakage (European Commission 2021). Therefore, policies have to precisely address this challenge while at the same time being tailored towards the different kinds of companies and production chains.

Property 8: Causal webs

Decarbonising the chemical industry may lead to new technical and socio-political challenges, creating causal webs. The increased use of technologies like biomass might entail trade-offs in other areas, e.g. biodiversity loss or food security (Bataille et al. 2018; Joas et al. 2019). Furthermore, a transition of the chemical sector could cause regional deindustrialisation because of lower costs elsewhere and, consequently, the loss of competitiveness (European Commission 2021; Evans et al. 2021; Fahl et al. 2021; Johansen et al. 2021). Using blue hydrogen[21] as an intermediate technology until green hydrogen[22] is largely available has been discussed readily (Bataille et al. 2018; Joas et al. 2019). However, the reliance on blue hydrogen could reinforce resource dependency and can be criticised in light of the current gas shortage.

Food security, deindustrialisation and resource dependency are inherently socio-technical challenges and, therefore, would also imply significant socio-economical risks.

Property 9: Numerous explanations

While on a technical level, different pathways towards net-zero GHG emissions in the chemical sector exist, they are explained in a similar way. Different transition scenarios imply a focus on different technologies for decarbonising the chemical sector – for example, Burchardt et al. (2021) call for enhanced usage of CCS and biomass, whereas Joas et al. (2019) favour the prioritisation of green hydrogen and electrification. However, these studies assume that decarbonisation can be achieved while upholding the current status quo. The studies explain the transformation from a green growth perspective and argue that decoupling economic growth and GHG emissions is possible.

From a governance perspective, various explanations about the goal of decarbonisation exist. While many actors follow a similar green growth narrative, there are proponents of alternative strategies such as lowering consumption in line with the paradigm of sufficiency (Eckert and Kovalevska 2021).

Property 10: Normative framing (no right to be wrong)

The framing of decarbonising the chemical sector is not normative from a technical point of view (Joas et al. 2019). Of course, framings inherently are normative; however, decarbonisation is only ever described as technically feasible. As mentioned above, the green growth narrative is very present in these descriptions.

The current dominant discourse also displays the need for green growth on a governance level. There are other argumentative lines like sufficiency or the call for a just transition (Eckert and Kovalevska 2021).