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

Juliane Biehl (✉ juliane.biehl@tu-berlin.de)
https://orcid.org/0000-0002-3613-0670
Leonard Missbach
https://orcid.org/0000-0002-8389-3208
Franziska Riedel
https://orcid.org/0000-0001-5823-1619
Ruben Stemmle
https://orcid.org/0000-0003-4290-1694
Julian Jüchter
Jessica Weber
https://orcid.org/0000-0002-9071-5805
Johanna Kucknat
Adrian Odenweller
https://orcid.org/0000-0002-1123-8124
Christian Nauck
Laura Lukassen
Matthias Zech
Marie Grimm
https://orcid.org/0000-0001-5812-5162

Research Article

Keywords: Energy transition, wicked problems analysis, onshore wind power, shallow geothermal energy systems, decarbonising the chemical industry, decarbonising the transport sector

Posted Date: October 5th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2134870/v1

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

Juliane Biehl[1*], Leonard Missbach[2, 3], Franziska Riedel[4], Ruben Stemmle[5], Julian Jüchter[6], Jessica Weber[1], Johanna Kucknat[4], Adrian Odenweller[7], Christian Nauck[7], Laura Lukassen[6], Matthias Zech[8], Marie Grimm[1]

[1] Environmental Assessment and Planning Research Group, Technische Universität Berlin, Berlin, Germany

[2] Working group Climate and Development, Mercator Research Institute on Global Commons and Climate Change (MCC), Berlin, Germany

[3] Department Economics of Climate Change, Technische Universität Berlin, Berlin, Germany

[4]Team Energy Systems and Markets – Energy System Analysis, Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, Germany

[5] Institut für Angewandte Geowissenschaften – Abteilung Ingenieurgeologie, Karlsruhe Institut für Technologie (KIT), Karlsruhe, Germany

[6] Computational Fluid Dynamics for Wind Physics & ForWind – Center for Wind Energy Research, Carl von Ossietzky Universität Oldenburg, Oldenburg, Germany

[7] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

[8] Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institute of Networked Energy Systems Energy Systems Analysis, Oldenburg, Germany

*** Correspondence:**
Corresponding Author
juliane.biehl@tu-berlin.de

Keywords: Energy transition, wicked problems analysis, onshore wind power, shallow geothermal energy systems, decarbonising the chemical industry, decarbonising the transport sector.

Abstract

Wicked problems occur when decision-makers face constant change or unprecedented challenges and when uncertainty, complexity, and stakeholder divergence are high. We shed light on wicked problems in the German energy transition. Our methods consist of a multiple-case study and comparative multi-criteria analysis, utilising the wicked problems theoretical framework introduced by Horst Rittel and Melvin Webber (1973). Based on four exemplary cases, our research covers four core energy transition sectors: energy supply (developing onshore wind power), heating/cooling (using shallow geothermal energy systems), transport (decarbonising the transport sector), and industry (decarbonising the chemical industry sector). Cross-case results illustrate where and how the 10-point frame of wicked problems manifests in the German energy transition. We do not argue that the German energy transition is inherently wicked, yet we stress the need to consider potentially wicked facets of energy transition challenges. Our results show that the four cases exhibit more wicked tendencies in the governance domain than in the technical dimension. All cases exhibit wicked facets in the governance dimension, given strong normative assumptions, value divergence, and complex governance structures with a plurality of actors. From a technical perspective, the four cases still exhibit some wicked tendencies, e.g. raw material provision, skilled workforce, and waste management. The cases differ in technology maturity, state of knowledge, and degree of policy output and regulations. In applying the wickedness lens, we acknowledge that energy transition problems cannot be solved merely by technical measures but need to be tamed. Our work reflects which challenges and main barriers pertain to the four cases of the German energy transition. Understanding the elements of wickedness in a specific problem in the first step offers insights for addressing and managing these challenges in the next step.

Unstructured abstract

We shed light on wicked problems in the German energy transition. Our methods consist of a multiple-case study and comparative multi-criteria analysis, utilising the wicked problems theoretical framework introduced by Horst Rittel and Melvin Webber (1973). Cross-case 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 in the technical dimension and differ in their degrees of technology maturity, policy regulation, and knowledge states. We do not argue that the German energy transition is inherently wicked, yet we stress the need to consider potentially wicked facets of energy transition challenges. In applying the wickedness lens, we acknowledge that energy transition problems require more than just smart proposals and technologies or financial resources; they need to be tamed.

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 definition, 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 almost five decades, the literature on wicked problems has grown considerably. The wickedness concept was linked to complex systems research (Zellner and Campbell 2015; Innes and Booher 2016; Head 2019; Alford and Head 2017; Peters 2017; Akamani, Holzmueller, and Groninger 2016; Andersson and Törnberg 2018) and the socio-ecological system's framework (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 (Larrabee 2018; Levin et al. 2012; Kelley 2018) and other social-environmental issues (Duckett et al. 2016), the Covid19 pandemic (Klasche 2021; Lawrence 2020; Auld et al. 2021; Head 2022; Angeli, Camporesi, and Dal Fabbro 2021), and energy supply and efficiency (Thollander, Palm, and Hedbrant 2019; Brunnengräber et al. 2014; Everingham et al. 2016) have been associated with the 'wickedness' theory. Wicked problems affect pluralistic societies since they involve conflicts of interests, value trade-offs, and are "dilemma-laden social choice problems" (Glasser 1998, 230). Head (2022, p. 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".

[1] (Levin et al. 2012 for climate change); (Fischbacher-Smith 2016 for terrorism); (Durant and Legge 2006 for world hunger and poverty).

The German energy transition is characterised by rapid changes (Markard 2018), disruption (Johnstone and Kivimaa 2018; Fuchs 2019) and highly divergent perspectives (Juerges, Leahy, and Newig 2020; Köppel and Biehl in preparation; Sovacool et al. 2022). While Germany's energy transition started with transforming the energy supply sector from fossil to renewable energy sources (Renn and Marshall 2020; Morris and Jungjohann 2016), 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 (Prognos AG, Öko-Institut e.V., and Wuppertal Institut 2020; Kendziorski et al. 2021; Traber, Fell, and Hegner 2021; Hansen, Breyer, and Lund 2019), 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. Reusswig, Komendantova, and Battaglini 2018; Kühne et al. 2022), 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 the end of 2022) 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.

A bibliometric analysis[2] of all articles mentioning 'wicked problems' in the title, abstract, or author keywords shows that academic interest in wicked problems has increased (Annex A, absolute number of publications by 2022: 1.757). Based on the bibliometric analysis, we deduce that energy topics are still only scarcely (n = 27) 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). The German energy transition has been analysed from various perspectives, and the term 'wicked problem' has been used as rhetoric (Blohm 2021; Rechsteiner 2020; Roggema 2020; Stremke and Schöbel 2019; Komendantova 2021). Nevertheless, 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 the nature of wicked problems across four core sectors of the German energy transition as the first step towards their resolution. However, we do not conceptualise the German energy transition as an inherently wicked problem. Instead, we use the wickedness approach to identify emerging energy transition challenges that are not sufficiently addressed

---

2 The bibliometric analysis was conducted using the Web of Science database and the *bibliometrix* package in the programming language R. For details, see Annex A.

currently, which can serve as a basis for debate. We conduct a comparative multicriteria analysis to illustrate wicked tendencies in the four case studies:

- Energy supply sector: Case 1 – Developing onshore wind power
- Heating and cooling sector: Case 2 – Space heating and cooling using shallow geothermal energy systems
- Transport sector: Case 3 – Decarbonising the transport sector
- Industry sector: Case 4 – Decarbonising the German 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 presents the materials and methods of our analysis. Section 2.1 introduces the theoretical framework 'wicked problems'. We present our study design in section 2.2, while section 2.3 introduces the four case studies, outlining the sector's progress towards the energy transition and the barriers and problems ahead. Cross-case results and highlights are presented in Section 3. Section 4 discusses and critically reflects findings, while Section 5 concludes.

2 Materials & methods

2.1 Theoretical framework: Wicked problems

We revisit Horst Rittel's & Melvin 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). Problems do not need to meet all ten characteristics to show wicked tendencies (Lönngren and van Poeck 2020; Alford and Head 2017; Newman and Head 2017; Head 2019).

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, p. 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, p. 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.

Over the last 50 years, scholars have contributed to a substantial body of literature critiquing, expanding, revising, and applying Rittel's and Webber's concept (Hou, Li, and Song 2022; Termeer, Dewulf, and Biesbroek 2019; Crowley and Head 2017). In an attempt to address theoretical and methodological shortcomings of the original set of wickedness criteria (see section 4.2), e.g. Alford and Head (2017) advocate for understanding wickedness as a matter of degree, as "complex problems vary in the extent of their wickedness" (Alford and Head 2017, 397). Scholars proposed three broader dimensions of wicked problems: complexity, uncertainty and value divergence (Head 2008; Alford and Head 2017; Newman and Head 2017), which could be utilised to "map issues in terms of low-medium-high levels of complexity, uncertainty and divergence" (Head 2022, 33). Lönngren and van Poeck (2020) argue that there is no coordinated and concerted concept of wicked problems; thus if utilising the concept as a descriptive/analytical tool, researchers need to describe how they use the concept.

In our contribution, we are adapting Rittel's and Webber's 10-point frame as a perceptual lens to analyse the four cases and to identify the wicked facets of energy transition issues. Although the trichotomy approach (complexity, uncertainty, value divergence) is closely linked with Rittel's and Webber's initial 10-point frame, the dimensions 'complexity', 'uncertainty', and 'value divergence' are less concrete and more generic than the original properties. We argue that Rittel's and Webber's original criteria hold utility, as they enabled us to highlight more explicit examples and wicked facets in the four case studies without labelling them as absolutely tame/wicked. We use the broader categories of complexity, uncertainty and value divergence in the discussion to summarise and reflect our results at a higher level.

2.2 Study design

We apply the original wicked problems framework (cf. Rittel and Webber 1973) to the German energy transition. Our methods consist of multiple-case studies and comparative multi-criteria analysis, utilising the theoretical framework of the wicked problems (Figure 1).

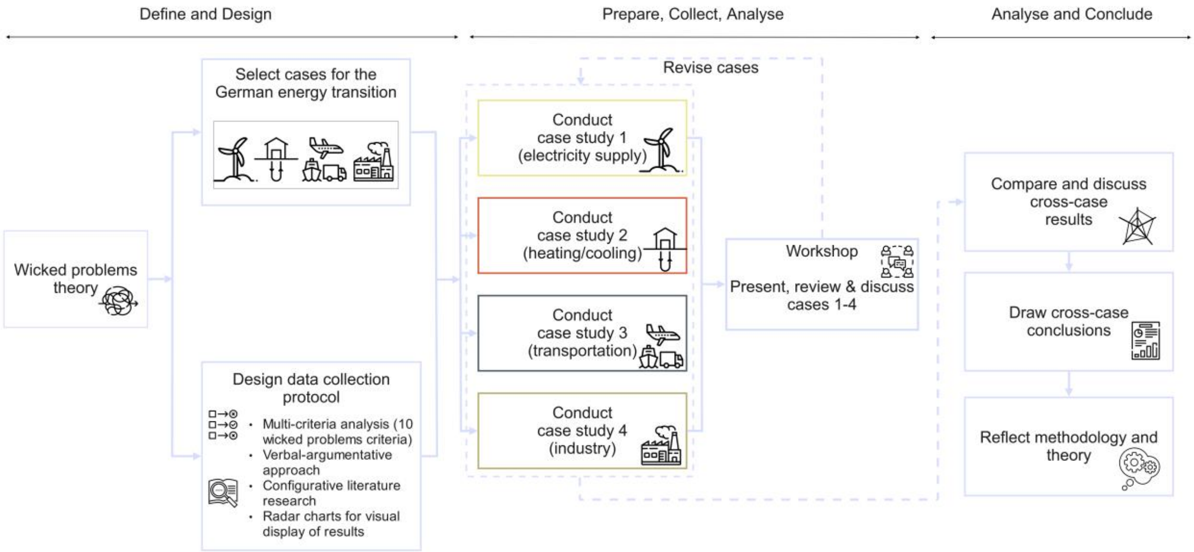

Figure 1: The research methodology design depicting the process of conceptualisation, sampling and analysis (left to right) to apply the wickedness concept to the German energy transition in the four cases. (Sources: Case study procedure adapted from Yin 2018, p. 58, icons: CC from www.flaticon.com, icons by Freepik, Smashicons and Kiranshastry).

2.2.1 Multiple-case study analysis

We conduct a comparative case study analysis of the German energy transition with four embedded sub-cases, following the case study design proposed by Yin (2018) (Figure 1. The four cases provide insights into different sectors (energy supply, heating/cooling, transport, industry) of the German energy transition that face different challenges and are at different transition stages (Luderer, Kost, and Sörgel 2021). We introduce the four case studies in section 2.3. 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).

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. 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 focusing on wicked facets in the four case studies.

2.2.2 Multicriteria analysis to apply the ‘wicked problems’ concept

To analyse the wicked tendencies, we conduct a multi-criteria analysis of the four cases by applying the ten properties of wicked problems (Table 1). We use the ten dimensions to help judge whether a problem exhibits wicked tendencies.

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 use a binary scale (Yes/No) to represent if a case exerts tendencies for wickedness 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 presented, discussed, and revised the individual case study analyses in a working group workshop in June 2022. Annexes B–E contain the individual case study analyses. We compare, structure and discuss the multiple-case results in Section 3.

2.3 Introduction of case studies

While the German energy supply sector looks back at almost 50 years of the transition process (Morris and Jungjohann 2016; Renn and Marshall 2020), in more recent times, attention has been given to transforming the end-use sectors, heating and cooling[3], 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 2). The sectors face different challenges and bottlenecks, which we introduce in the following. Table 2 contains a summary of information on the four cases. We analyse one case each in electricity supply, heating/cooling (both energy supply sector), transport sector, and chemical industry subsector (industry sector).

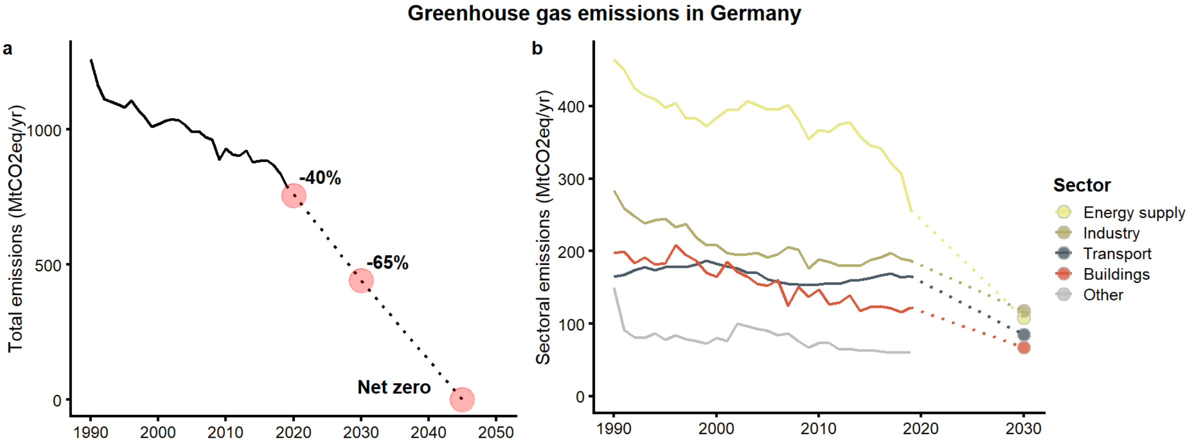

Figure 2: Historical greenhouse gas (GHG) emissions and reduction targets in CO_2 equivalents in Germany, in total until 2050 (a) and disaggregated by sector until 2030 (b). Overall GHG reduction targets are relative to 1990 levels. Emissions from space heating and cooling are predominantly accounted 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).

2.3.1 Electricity supply: Case 1 – Developing onshore wind power

Transforming and decarbonising the German energy supply sector by developing renewable energy sources 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 [27 million tons of carbon dioxide ($MtCO_2$)] (UBA and BMWK 2022). With a 50.5% share of the electricity mix in 2020 (Fraunhofer ISE 2021) and a 45.7% share in 2021 (Fraunhofer ISE 2022), renewable energy sources constitute the backbone of Germany's electricity supply.

[3] 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). The further analysis focuses on space heating and cooling using geothermal energy systems.

In 2021, on- and offshore wind energy accounted for the largest share of the electricity mix, i.e. 23.1% (Fraunhofer ISE 2022). By 2022, 28,230 onshore wind turbines were installed, totalling 56.1 gigawatts (GW) capacity (Deutsche WindGuard GmbH 2022). Although the Renewable Energy Sources Act (EEG) offers site-specific funding for electricity from onshore wind power, the wind facilities are not evenly distributed across the country, causing a North-South divide[4]. Even though onshore wind power plays an important part in the German electricity transition, the installation of onshore wind turbines has stagnated since 2018 (Biehl *et al.* 2021, Deutsche WindGuard GmbH 2021, Fachagentur Windenergie an Land 2021). The main barriers are land availability, nature conservation concerns (green-vs-green dilemma) and other land-use conflicts[5], litigation, the switch to a tendering funding system, limited repowering of turbines and lengthy permitting processes (Biehl, Köppel, and Grimm 2021). From 2025 until 2035, 10 GW capacity will have to be installed annually to reach the German electricity transition targets, yielding a planned cumulative installed capacity of 115 GW by 2030 and 160 GW by 2040 (BT Drucksache 20/1630).

In the summer of 2022, the German Federal Parliament passed legislation to relax restrictions for onshore wind power[6]. Nevertheless, hurdles remain that can show complex if not wicked facets: Firstly, the new Onshore Wind Demand Act will show delayed results, as planning laws and spatial plans at the state, regional, and municipal levels will have to be adjusted, requiring five to ten years (Hanke 2022; MultiplEE 2022). Secondly, the accelerated onshore wind power development will require raw materials, logistics and personnel to permit, develop and maintain the facilities, despite worldwide supply bottlenecks (Taylor 2022), increasing material and transport prices, and a workforce shortage. Thirdly, utilisation loads of the transmission grid have reached a maximum with ca. 2.5 million[7] small, medium and large renewable energy producers connected to the grid by 2022. Grid congestion has caused redispatch measures (e.g. curtailment of renewable and cogenerated electricity) and a temporary cap for wind installations in the Northern States from 2017-2020 (Bundesnetzagentur 2021). Persisting challenges and the trade-offs between competing interests and stakeholder divergence in the onshore wind energy field provide a compelling case for applying the ‘wicked problems’ framework.

2.3.2 Heating and cooling: Case 2 – Space heating and cooling using shallow geothermal energy systems

More than 50% of Germany’s final energy consumption in 2020 accrues to the heating and cooling sector[8] (Agentur für Erneuerbare Energien 2021). Space heating (including domestic hot water) and cooling account for a share of ca. 30% of the final energy consumption in 2018 (Arbeitsgemeinschaft Energiebilanzen e.V. 2020), thus illustrating the great importance of

---

[4] 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

[5] E.g. governance gaps, military use and aviation safety, local opposition, forest and landscape conservation, heritage protection.

[6] 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.

[7] 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".

[8] Including industrial process heat.

decarbonising the space heating and cooling sector. The low share of renewable energy sources, 16.5% in 2021 (UBA 2022), in the German heating and cooling sector in 2021 further stresses the need to transform the heating and cooling sector. In order to increase this share, the coalition agreement of the current German 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 law 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 possibility to foster the transition. These systems include ground source heat pumps, groundwater heat pumps and shallow aquifer thermal energy storage systems. These are feasible technologies for significantly reducing GHG emissions compared to conventional heating and 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 greenhouse gas 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 et al. 2011; Bonte 2013; García-Gil et al. 2020). Finding an optimal trade-off between these aspects exhibits wicked facets, which we discuss in this article.

2.3.3 Transport: Case 3 – Decarbonising the transport sector

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 emission levels in the German transport sector 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. Theoretically, many instruments are conceivable (Parry, Walls, and Harrington 2007), such as performance standards for vehicle fleets or bans on inefficient cars or combustion engines in general, as proposed by the European Parliament (European Commission 2021a; Ainger 2022). Market-based interventions include transport fuel taxes or subsidy removal (Sterner 2007), carbon pricing on transport fuels, congestion charges (such as city taxes (Anas and Lindsey 2011)), and subsidies for low-emission vehicles (such as battery-fuelled electric vehicles) or cash-for-clunkers programs (Mian and Sufi 2012). Many stress the relevance of an accessible public transport sector (Hodges 2010), which might help to lower the demand for individual transportation (Gillingham and Munk-Nielsen 2019).

During the last decade, low-emission transport technologies became increasingly available and affordable following reductions in production costs for energy storage technologies, such as lithium-ion batteries (Ziegler and Trancik 2021). In 2021, the share of electric vehicles in German car sales accounted for 13.6% (Kraftfahrt-Bundesamt 2022). Nevertheless, research suggests that the electrification of other transport sectors, such as aviation or shipping, is more challenging (Becattini, Gabrielli, and Mazzotti 2021). Assuming the absence of short-term technological breakthroughs, decarbonising those ‚hard-to-abate‘ sectors will likely require deploying hydrogen and e-fuel technologies (Ueckerdt et al. 2021). Given current 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, it is necessary to decarbonise road transportation rapidly, where low-emission technologies are available.

Prominently, policy interventions in the transport sector entail distributional consequences, i.e. differing economic consequences for different parts of society (Guo and Kontou 2021, and Annex D; Sterner 2012; Douenne 2020). Any policy‘s perceived (un)fairness could affect political support and inhibit effective implementation, which became apparent during the French Yellow Vests movement after the government‘s announcement to increase the carbon tax levied on transport fuels in 2018 (Douenne and Fabre 2022). The transport sector entails various features which render it susceptible to an inherently complex transition process. 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. The discussion on speed limits in 2022 (Kluth 2022; Jakob and Klöckner 2021) and the reduction of gasoline taxes serve as an example of the highly complex and value-laden policy environment. In addition, the transport sector comprises many externalities, such as congestion, traffic accidents, roadway noise and local air pollution (Santos et al. 2010), which might require tailored policies.

2.3.4 Industry: Case 4 – Decarbonisation of the chemical industry sector

The chemical sector is one of the largest and most energy-intensive German industries, employing roughly 460.000 people and accounting for 10% of Germany’s industry revenue and 5–6% of Germany’s GHG emissions in 2018 (Gniffke and Günther 2022b, 2022a; BMWK 2022). The sector is vital to Germany’s economy; therefore, many stakeholders argue that maintaining its competitiveness is crucial. However, decarbonising the chemical industry implies three technical and economic challenges. Firstly, the industry is a grown system with complex and intertwined production processes, which are complicated to decarbonise step-by-step (Joas et al. 2019; Ausfelder 2015). Secondly, most of the products – about 70% – remain within the industry for further processes, leading to little visibility for end customers who might otherwise demand low-carbon products (BMWK 2022). Thirdly, investment cycles and technology lifetimes are long. An average steam cracker can be operated for about 50 years (Joas et al. 2019). Therefore, investing in conventional technology today 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), which is already deployed on a large scale (Joas et al. 2019; Wesseling et al. 2017). Other key technologies, which will be available as soon as 2025-30, include green hydrogen from electrolysis, producing olefins and aromatics using green methanol, and chemical recycling (Wesseling et al. 2017; Luderer, Kost, and Sörgel 2021). Carbon capture at combined heat and power plants and electrified steam crackers are expected to reach technological readiness between 2035 and 2045 (Joas et al. 2019). The main caveat of these technologies is their high electricity demand. The electricity demand of a fully decarbonised chemical industry is expected to be 11 times higher than today, with projected demand rising from 54 terawatt-hours (TWh) in 2020 to 685 TWh in 2050 (Geres et al. 2019).

The most significant barriers to implementing decarbonised technologies include a lack of incentives to adopt them and currently high costs compared to 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 € (Joas et al. 2019; Boerse.de 2022). Four main policy instruments to tame this challenge are proposed. Firstly, a reform of the EU ETS is planned, introducing a lower emissions cap and a benchmarking system, where free certificates are only allocated to the best available technologies (European Commission 2021c). Secondly, a carbon border adjustment mechanism for specific sectors (like fertilisers) is planned. It will impose a border tax on carbon-intensive products to ensure the competitiveness of low-carbon products manufactured in the EU (European Commission 2021b). Thirdly, Carbon Contracts for Difference could incentivise individual low-carbon projects by funding the cost difference between conventional and low-carbon technologies (Gläser and Caspar 2021; Neuhoff et al. 2021; Hauser et al. 2022). Fourthly, green public procurement could ensure that public entities consider climate-related indicators when procuring goods and services (not only from the chemical industry) (Chiappinelli et al. 2020). These aspects show that a discussion of the wickedness of the decarbonisation of the chemical industry sector is worthwhile to identify possible bottlenecks.

Table 2 contains a summary of information on the four cases.

Table 2: Summary of case study introductions (sources are cited in the text segments that introduce the case studies, Sections 2.4.1-2.4.4)

Energy Transition Sector	**Energy supply (electricity)**	**Heating/cooling**	**Transport**	**Industry**
Case study	Developing onshore wind power	Space heating and cooling using shallow geothermal energy systems	Decarbonising the transport sector	Decarbonising the German 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 • Cumulative installed capacity onshore wind: 115 GW by 2035, 157 by 2035	• 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	• 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 2021 (considering available information as of mid-2022)	• GHG emissions in 2021: 247 $MtCO_2$ • 23.1% share of the electricity mix (*on-and offshore) • 56.1 GW cumulative installed capacity (28,230 onshore wind turbines)	• 16.5%* (199,4 TWh) share of RES in the energy consumption in the sector (* space & process heating/cooling) • 9% share of renewable energy sources supplied by shallow geothermal energy & environmental heat in 2021 • 52.8% of new residential buildings to be equipped with heat pumps in 2020 (20% ground source heat pumps)	• GHG emissions in 2021: 148 $MtCO_2$ • Marginal reduction of emissions levels compared to 1990 • Technological progress is counteracted by increase in demand	• GHG emissions in 2021: 181 $MtCO_2$ • Renewable electricity becomes more widely available • 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)	• Slow progress in the existing building stock • Costly retrofitting • Groundwater ecosystem protection • Adverse thermal interferences are possible in densely populated areas (thermal overexploitation)	• 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,	• 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

	• 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)	• Inefficient permissions of too large capacities	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)	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 (short-term competitiveness)

3 Results

3.1 Cross-case analysis

The following section briefly summarises cross-case and individual case study results. Section 3.2 presents highlights from the multiple-case study analysis that illustrates how Rittel's and Webber's 10-point frame manifests in the German energy transition. Annexes B – E contain the detailed and individual case study analysis portfolios.

3.1.1 Cross-case results

When viewed from a technical or engineering perspective, the four cases exhibit some, yet not all, of the wicked tendencies originally proposed by Rittel and Webber 1973. The characteristics of *no test for solutions* and *causal webs* were found to apply to all four case studies (Table 3). The cases from the electricity supply, transport and industry sectors (cases 1, 3 & 4) further share similarities in the category of the *better-or-worse answer*. The case from the industry sector (case 4) shows the most wicked facets in the technical dimension, which could be attributed to the relative novelty of the transition pathway (less technology maturity) and the sector's *uniqueness*.

The governance dimension of the four case studies is more wicked than the technical dimension. Our case study analysis documents that two cases (cases 3 & 4) show all ten original characteristics of a wicked problem. The two remaining case studies (cases 1 & 2) exhibit wicked tendencies in all but one characteristic, with the *infinite set of potential solutions* characteristic not applicable to the electricity and heating/cooling sectors. The difference in applicability of the characteristic of *infinite set of potential solutions* links to the differing levels of analysis, as cases 1 and 2 analyse one renewable energy source within the electricity supply or heating sectors, while cases 3 and 4 analyse an entire sector (transport) and a subsector (chemical industry).

3.1.2 Case 1: Developing onshore wind power

Our analysis (Table 3) shows that the technical problem of developing onshore wind power is – for the most part – a relatively tame problem. However, technically developing onshore wind power still exhibits some wicked tendencies (*better or worse answers*, *no test for solutions*, *infinite set of potential solutions* and *casual webs*). We argue that the technical task of developing onshore wind is clearly defined, and solutions exist. However, target attainment and ever more ambitious development targets can lead to a *de facto no-stopping rule,* as further elaborated in Annex B. Moreover, the provision, logistics of transport, and waste management of raw material for the required additional 100 GW can be considered wicked problems.

From a governance perspective, more wicked facets (*no definition*, *no boundary lines*, *better or worse answers*, *no test for solutions*, *one-shot approach*, *uniqueness*, *causal webs*, *numerous explanations* and *normative framing*) arise, which often stem from the fact that onshore wind development is highly contested, values and interests diverge, and myriad stakeholders interact in the complex German polycentric governance system for onshore wind power. Most wicked facets occurred in our analysis where judgements and normative values were mal-aligned (Annex B).

3.1.3 Case 2: Space heating and cooling using shallow geothermal energy systems

We find four of the ten wickedness dimensions from a technical perspective applicable to case 2 (*no test for solutions*, *one-shot approach, uniqueness* and *casual webs*). In contrast to the electricity sector case 1, fewer studies exist that could highlight potential negative impacts from shallow geothermal systems on the environment and other protected assets, e.g. soil, groundwater, biodiversity, and human health (Annex C). Similarly, the regulatory framework for the electricity case is far more exhaustive than for utilising shallow geothermal energy sources; thus, complexity is lower in case 2.

On the contrary, the governance perspective analysis results are similar to the first case since all dimensions apply but one (not applicable: *infinite set of potential solutions*). Our findings show the need for long-term, holistic and adaptive underground planning and management of geothermal installations to prevent thermal overexploitation of the subsurface, thermal interferences of individual geothermal energy systems, and trade-off conflicts of (public) interests (Annex C).

3.1.4 Case 3: Decarbonising the transport sector

We argue that decarbonising the German (road) transport sector (case 3) is technically feasible and urgent, yet complex and politically delicate for policymakers. We are able to depict some wickedness dimensions to the technical perspective of decarbonising the transport sector (*better or worse answers*, *no test for solutions*, *causal webs*).

Nevertheless, *how* to steer this transition process is ambiguous. It rests on a set of strong normative assumptions or political will to support the interests of specific societal actors (e.g. poor households, households with high demand for mobility, car manufacturing industries, and fossil fuel companies; see Annex D). As we show in an additional simulation analysis in Annex D, efficient solutions (such as emissions pricing) are likely to affect poorer households adversely. Without complementing and compensating policies, this would inhibit a fair and sustainable transition. This example is paradigmatic for the complexity and wickedness of decarbonising the German transport sector. From a governance perspective in case 3, we demonstrate the applicability of all of the ten wickedness dimensions (*no clear definition*, *no boundary lines*, *better or worse answers*, *no test for solutions*, *one-shot approach*, *infinite set of potential solutions, uniqueness, casual webs, numerous explanations, normative framing*).

3.1.5 Case 4: Decarbonising the chemical industry

We reason that, from a technical perspective, decarbonising the chemical sector (case 4) is a relatively tame problem. Rising electricity demand seems the most significant challenge, while switching from fossil-based to decarbonised technologies seems feasible within the next 15 years (Annex E). Nevertheless, our analysis still pinpoints some wicked tendencies (*better or worse answers*, *no test for solutions*, *one-shot approach*, *infinite set of potential solutions, uniqueness* and *casual webs*).

Similar to the transport sector case, the socio-political and economical implementation of decarbonising the chemical industry shows all wicked dimensions (*no clear definition*, *no boundary lines*, *better or worse answers*, *no test for solutions*, *one-shot approach*, *infinite set of potential solutions, uniqueness, casual webs, numerous explanations, normative framing*). This case shows that accomplishing large-scale changes in a mature system with technical and financial lock-ins while maintaining competitiveness requires coordinated efforts from political and economic actors.

Table 3 offers an overview of the analysis of wicked tendencies in the individual case studies.

Table 3: A checkbox approach – wicked tendencies of the German energy transition (○ = wicked property not applicable; ● = wicked property applicable)

	Characteristics of wicked problems (cf. Rittel & Webber 1973)	Case 1: Developing onshore wind power		Case 2: Space heating and cooling using shallow geothermal energy systems		Case 3: Decarbonising the transport sector		Case 4: Decarbonising the German chemical industry	
		Technical perspective	Governance perspective	Technical perspective	Governance perspective	Technical perspective	Governance perspective	Technical perspective	Governance perspective
1	No clear definition (intractable and often ill-defined)	○	●	○	●	○	●	○	●
2	No boundary lines (no stopping rule)	○	●	○	●	○	●	○	●
3	Better-or-worse answers	●	●	○	●	●	●	●	●
4	No test for solutions	●	●	●	●	●	●	●	●
5	One-shot approach (no trial-and-error)	○	●	●	●	○	●	●	●
6	Infinite set of potential solutions	●	○	○	○	○	●	●	●
7	Uniqueness (essentially unique problem)	○	●	●	●	○	●	●	●
8	Causal webs (unintended consequences)	●	●	●	●	●	●	●	●
9	Numerous explanations	○	●	○	●	○	●	○	●
10	Normative framing (no right to be wrong)	○	●	○	●	○	●	○	●

3.2 Highlights: Wicked facets of the German energy transition

3.2.1 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 is relatively straightforward. At the same time, the question of *how* to achieve transition targets in the individual sectors is often subject to diverging viewpoints. The case from the transport sector (case 3) can illustrate this wicked tendency:

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, while reducing emissions in the transport sector is technically feasible, i.e. a tame problem.

3.2.2 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)

The *no-stopping rule* criterion becomes most apparent in the electricity sector case (1).

On the one hand, installation targets for developing onshore wind facilities exist (EEG 2021 & BT Drucksache 20/1630), and wind developers know when they have installed sufficient capacities. On the other hand, these targets have been adjusted continuously in the past. Minor 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*. For example, the German polycentric governance system for onshore wind power had a blindspot, given the missing link between federal expansion targets and the provision of land for installations in the states (Rodi 2017; Biehl, Köppel, and Grimm 2021). In 2022, attempts to solve this governance gap with policy measures (see section 2.3.1) still exhibit signs of wickedness. The Onshore Wind Demand Act (BT Drucksache 20/2355) will free up potential land for installations after five to ten years (MultiplEE 2022), making it challenging to monitor the success of policy measures. 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.

3.2.3 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)

Examples from the electricity supply sector (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*. 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 farm 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'*. Moreover, the onshore wind power development affects many stakeholders at various levels of governance, which pursue a multitude of interests. The diversity of 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).

An outlier concerning this aspect of wickedness in our analysis 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 (Annex C).

3.2.4 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, examples from the transport (case 3) and industry (case 4) sectors stand out, which we highlight in the following.

Results from the transport sector (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 long-term effects of current policies impedes 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 (Caulfield et al. 2022; Cats, Susilo, and Reimal 2017). 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 governance perspective, each probable solution is highly context-specific and might create additional frictions, requiring additional measures.

Furthermore, results from the industry sector (case 4) pinpoint that, while technologies are tested in real-life laboratories and pilot studies, uncertainties regarding their large-scale implementation remain (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 dimension of the industry sector from both a technical and governance perspective.

3.2.5 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)

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. Examples from the heating/cooling (case 2) and the industry (case 4) sectors will further illustrate this 'wicked problems' property.

Geothermal installations for space heating and cooling (case 2) are typically designed for more than two decades, reflecting long investment cycles in the building sector (Bloemendal, Olsthoorn, and Boons 2014a; Saner et al. 2010). The long lifespan of geothermal installations leaves no room for technical planning errors. Additionally, securing the public water supply is of high priority to policy practitioners and civil society. 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 utilisation of shallow geothermal resources. From the governance side, ensuring long-term planning certainty over several decades is vital by setting clear target paths and defining overarching strategies, illustrating that every attempt at problem solution counts.

For the industry sector (case 4), we find a narrow window of opportunity for decarbonisation in the chemical sector. 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 (Joas et al. 2019; Janipour et al. 2020). Since 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). The governance of industrial decarbonisation has been characterised by many trial-and-error-processes, such as the ongoing reform process of instruments like the EU ETS (Lilliestam, Patt, and Bersalli 2021; Dorsch, Flachsland, and Kornek 2020; Joltreau and Sommerfeld 2019; European Commission 2021c) 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.

3.2.6 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 applies to all cases from a technical perspective but is best illustrated by examples from the transport and industry sectors (cases 3 & 4).

Many technical options are available to curb GHG emissions in the road transport sector (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 tailored, context-specific regulations owing to contemporary developments, such as fluctuations in transport fuel prices or large economic shocks.

In the (chemical) industry sector (case 4), there is already an indefinite number of solutions to the decarbonisation challenge. On a technical level, 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 (Geres et al. 2019; Joas et al. 2019; Ausfelder, Seitz, and Roen 2018). 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 (Lee 2019).

3.2.7 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. For example, the electricity sector case (case 1) highlights that technical solutions from both aviation and shipping industries were adapted to wind energy applications (Bruns et al. 2011). Therefore, we found the electricity sector case a less unique technical problem than, for instance, the industry sector case.

The chemical sector (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 (Wesseling et al. 2017; Joas et al. 2019). On a governance level, no other sector in Germany – except steel production – has a higher risk of carbon leakage (European Commission 2021b), further highlighting the uniqueness. Therefore, policies have to precisely address this challenge while at the same time being tailored towards the different kinds of companies and production chains.

Likewise, the case from the heating and cooling sector (case 2) shows *uniqueness* in both 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. 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.

3.2.8 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, which we highlight with results from the cases in the electricity and heating and cooling sector (cases 1 & 2).

The installation of 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 lead to negative consequences in 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 (Landwehr 2022; Fichtner 2022), which is emblematic of the *causal webs'* wickedness dimension.

Moreover, 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.

3.2.9 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)

Although we find that the wickedness characteristics *numerous explanations* and *normative framing* apply more to the governance than the technical perspectives, examples from the transport sector (case 3) will further pinpoint the wicked facet of *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.

3.2.10 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 transport (case 3) sectors.

Regional planners, which govern the spatial development of onshore wind power (case 1), have *no right to be wrong*, as they are responsible for their actions and can be held accountable. Given a high population density and installed cumulative capacity of onshore wind power in Germany, conflicts with other land uses[9] and values 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.

Decarbonising the transport sector (case 3) 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 (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.

4 Discussion

[9] Conflicts of interest include but are not limited to nature and species protection, citizens' preferences and health concerns, and perceptions of landscape scenery.

4.1 Discussion of results

The four cases comprise (more or less) wicked tendencies (section 3.2), and our results illustrate how the original dimensions of wicked problems manifest in the German energy transition. Section 3.1 provides a relative comparison between the four cases. The comparative analysis reflects that the four cases are at different stages in transition, are subject to different barriers and strengths, and unfold different intricate facets. 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 signs of wickedness. Nevertheless, the energy transition's socio-political governance exhibits more wicked facets across all analysed cases, given complex trade-offs between values and goals, different land uses, a plurality of interests, and diverging stakeholders.

The perspective of wicked problems contributes to an enhanced understanding of current energy transition challenges in the four analysed cases. The wickedness concept cf. Rittel and Webber (1973) enabled us to identify and compare these complex, uncertain or highly contested energy transition issues in the four case studies (Table 4), which is in line with contemporary wickedness literature (Alford and Head 2017; Head 2022, 2019). Although the cases exhibit less wicked tendencies if perceived and analysed as merely technological or engineering problems, financial, economic, social, environmental, or policy aspects can show that a sound technological basis might not reduce all wicked tendencies in these problems. 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 solutions. In the following, we discuss our results in light of the wickedness trichotomy – complexity – uncertainty – value divergence, as proposed by more recent literature on wicked problems analysis. The broader features of wickedness allow summarising and clustering the identified challenges on another level (Table 4), still reflecting the 10-point frame of Rittel and Webber.

Table 4: Wicked facets (uncertainty, complexity and value divergence) in exemplary cases of the German energy transition (for a detailed analysis, see Annexes B – E)

Case study	Complexity	Uncertainty	Value divergence
Case 1 – onshore wind	• Choice of turbine or wind farm layout is highly complex • Complex polycentric governance system for onshore wind • Complex regulatory framework and policy drift • Interrelated problems, e.g. wind-wildlife conflict, interference with radio navigation stations	• Future demand for renewable electricity (transition targets in other sectors, need for direct electrification, production of green hydrogen, overall energy consumption) • Impacts on social and environmental receptors • Future supply of renewable electricity from onshore wind (land availability, accelerated or curbed development, repowering) • Availability of resources (personnel, financial, material, transportation) • Effectiveness of legislation package to debottleneck onshore wind power	• No consensus on reasons for stagnation (multiple explanations) • Plethora of stakeholders with different values and interests (European-level, federal-level, State-level, regional planning level, municipal level, private parties, developers, operators, lobby groups, citizens, NGOs) • Politicised issue
Case 2 – shallow geothermal energy	• Groundwater as a highly complex resource • Detrimental impacts from large-scale use of geothermal energy are possible • Detrimental thermal interferences between individual geothermal systems are possible	• No clearly defined legislative /regulatory framework • Thermal interferences and adverse impacts on groundwater (very few studies on effects and impacts available) • Insufficient knowledge on groundwater effects and ecosystem services	• Variety of stakeholders (municipalities, regional supply companies, citizens, home-owners) • Very different stakeholder interests and perspectives
Case 3 – transport	• Prevalence of path dependencies and potential for carbon lock-ins • Hinges on socio-economic-systems • Complex interactions between supply and demand • Interconnectedness with other sectors (electricity and industry)	• Policy mix (how to reach targets?) • Effectiveness of policy measures and policy mix • Likely to cause changes in individual well-being	• Plethora of actors and a multitude of consumers with very differing preferences • Local, regional, and trans-regional infrastructure levels • Fragmented ideas over how to align user preferences
Case 4 – industry	• Complex value chains and production processes • Potential path dependencies and carbon lock-ins • Interconnectedness with other sectors (electricity and transport)	• Definition of "GHG neutrality / climate neutrality / carbon neutrality"	• Diversity of company structures in the chemical industry • No consensus about the future vision for the chemical industry

Firstly, our results show that sectors are telecoupled; they affect each other, which can lead to high *complexity*. For example, the transition stage of the energy supply sector highly affects the transport and industry sectors (cf. Luderer, Kost, and Dominika 2021). We further illustrate this interconnectedness and causality with the electricity sector case. The transition status shows two outstanding points: the probability of target attainment (by successfully installing wind farms) and the frequency of re-adjustments (which lead to ever more ambitious targets that need to be attained). Our results suggest that wicked facets can inhibit target attainment, highlighted by the current stagnation of onshore wind installations (section 2.3.1 and highlights case 1). We show that the problem definition, i.e. *why* the development is stagnating, has not been defined unanimously by all actors, which limits taming approaches. Wicked facets in one sector might inhibit the target attainment in other sectors (cases 3 & 4). Direct electrification in the transport or industry sectors or heat pumps in the heating/cooling sector will eventually require higher installation capacities for renewable energy sources. Continuous adjustment and increasing climate action targets in the other sectors can lead to further wicked challenges in developing onshore wind power. We document some of these challenges in section 3.1.2 and Highlights from case 1.

Secondly, our results indicate that dealing with *risks, uncertainties, and externalities* of energy transition solutions constitutes a 'wicked problem' itself, i.e. a social problem that is difficult to solve and requires continuous taming approaches and constant attention from different actors. R&D continuously identifies new technical approaches and innovations. However, existing governance frameworks, social acceptance or divergent stakeholders can limit the application of these R&D solutions in practice. Furthermore, wickedness can occur given a time lag and uncertainty of answers to a policy problem and the required involvement of stakeholders.

Thirdly, *stakeholder diversity and value conflicts* were the influencing factors in all cases. 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 always political and a matter of moral judgement. Head (2022) argues that stakeholder divergence is why contested (social) problems are 'wicked problems'. Our findings for the German energy transition concur, highlighting 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. The pluralism can be both – a chance (e.g. checks and balances, energy democracy, energy justice) and a contributing factor to the wickedness. 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 far the problem itself is wicked or whether actor and case constellations contribute to the standstill and gridlock situations.

Additionally, we observe that the cases differ in their states of (a) technology maturity, (b) knowledge and research, and (c) regulation (science-policy gap & complexity). We will use the cases from the electricity supply and heating/cooling sectors (cases 1 & 2) for further elaboration. Onshore wind power installations have reached technological maturity and are applied large scale (see section 2.3.1). In contrast, shallow geothermal energy sources are yet to be upscaled (see section 2.3.2). New technological solutions can have higher uncertainties, 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, impacts of wind power use have been researched extensively since late 1990[10] with tailored mitigation measures for adverse impacts. Similarly, onshore wind power legislation is exhaustive (case 1, Annex B), whereas the regulatory framework for shallow geothermal energy sources is not as comprehensive (case 2, Annex C). Technological maturity and large-scale application can increase complexity, e.g. the policy mix is stacked or layered[11], causing a lack of coherence and coordination, which can be observed

---

[10] For a detailed knowledge base: https://tethys.pnnl.gov/knowledge-base-wind-energy.

[11] 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.

in case 1. We argue that the wicked dimensions can decrease or increase over time, advocating for a more fluid and less static wickedness concept. For example, uncertainty can decrease over time with increasing knowledge from research & development (R&D) projects. The complexity of a problem can increase with increasing regulations, policy drift and stakeholder divergence but could also decrease if a suitable policy mix exists and stakeholder interests align.

Furthermore, our findings indicate that the socio-political contestation, i.e. the question of *how* to design the energy transition, represents a ‘wicked problem’. This finding is in line with wickedness literature: Head (2022, 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 […]”. Moreover, 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". In applying the wickedness lens, we acknowledge that energy transition problems cannot be solved merely by technical measures but need to be tamed (Grint 2008; cf. Rittel and Webber 1973; Head and Xiang 2016; Head 2019) while needing to “recognise plural perspectives and to work with this pluralism rather than to suppress it.” (Head 2022, p. 27). Our analysis illustrates the potential challenges of energy transition solutions, which shows that there is no panacea for energy transition problems. 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’.

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 (Kriechbaum, Posch, and Hauswiesner 2021; Bakker and Budde 2012). Hype cycle research further stressed 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. For wind power use in Germany, Kriechbaum, Posch, and Hauswiesner (2021) found a “hype phase with an unprecedented increase in both 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. In 2022, newly hyped technologies, such as shallow geothermal energy sources (heat pumps, case 2) or hydrogen and e-fuels, are facing 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, problem-solvers and decision-makers could address criticism proactively (Lönngren and van Poeck 2020) and identify adequate taming measures. Our results show the need for sensitisation for and communication of wicked facets and making transparent values, beliefs and normative judgements to tame stakeholder divergence. We propose that it would be worthwhile to assess how far wicked problems can affect hype cycles and vice versa.

Lastly, we propose that it would be valuable to analyse how the current debates about energy security and energy independence, i.e. exogenous shocks, can affect the highlighted wicked 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 could be a limiting factor for the energy transition. The energy independence and security debate can lead to new carbon or nuclear lock-ins, which pose another set of potentially wicked problems (cf. Brunnengräber 2019 for nuclear; Kemfert et al. 2022; Seto et al. 2016 for carbon lock-ins). Likewise, the exogenous shock 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 debate could benefit from a thorough wickedness analysis to avoid pitfalls, manage expectations, and identify better solutions, i.e. to avoid further wicked problems. Identifying these tendencies can help decision-makers target points for future research and actions. Additionally, our results indicate that further research should aim to identify points of action to tame the wicked facets identified in this research. The cases exhibit more wicked facets in the governance domain, stressing the need to invest more in solution attempts on the governance side and further research on a societal level.

4.2 Methodological reflections

This section critically reflects on our approaches' benefits and shortcomings.

4.2.1 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 are able to show how and where the ten original dimensions of wicked problems still manifest today in energy transition issues. We document wicked tendencies that can be subsumed under three broader categories – uncertainty, complexity and stakeholder divergence.

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 towards taming approaches. Likewise, it can stop decision-makers from opting for a 'worse' solution, leading 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 would require policy action (applicable for case 1). Ideally, it can assist in changing the perception of people, i.e. public awareness, by managing expectations in early research or transition stages, as applicable to the transport and industry sector cases (3 & 4). 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.

4.2.2 Methodological and theoretical shortcomings of the analysis

Our methodological and theoretical approaches have some shortcomings, i.e. (a) threat of discouragement, totalising, and paralysis and stretching of the concept, (b) dichotomy and binary approach, and (c) methodological limitations 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 solutions.

Secondly, methodological limitations include the absence of clear coding rules for the ten wickedness properties (Peters 2017). We found the lack of clearly operationalised coding rules limiting 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 binary scale 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 type of policy dynamic, i.e. as a mathematical or rational test for wickedness. We followed Peters (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, methodological limitations of our research include the researchers’ bias and an oversimplification. 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, showing more or less wicked facets in our analysis. We increase 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. Co-authors have diverse disciplinary backgrounds, which further increases the scientific rigour of our analysis. Future studies on wicked facets of energy transitions could explore the differing degrees of wicked problems (Head 2008; Alford and Head 2017) or apply the small wins framework to recognise marginal steps towards problem re-solution (Termeer and Dewulf 2019). Additionally, further research could increase scientific rigour by conducting interviews or a Delphi-round with experts in the energy transition field.

5 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. Our results show that the four cases exhibit more wicked tendencies in the governance domain than in the technical dimension. However, we were able to show some wicked tendencies in the technical aspects, which link to uncertainties and causal webs. We show that energy transition issues can cause further wicked technical problems, such as sourcing materials for the transition and waste management. Our results indicate that the socio-political implementation and governance of the energy transition can be considered a ‘wicked problem’, given high stakeholder diversity and value divergence and complex governance structures. However, we do not imply that the energy transition is unsolvable or inherently wicked.

Further, the analysis highlights the four cases' uncertain, complex or socially contested issues. 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 findings underpin the need to consider the potentially wicked facets of governing the German energy transition, as 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, state of knowledge and research, degree of regulation, multi-level or polycentric governance, and hype-disappointment cycles. This article shows that in researching and acknowledging the wicked facets, analysts and policy-makers could counter more thoroughly and realistically the tendency to leap from one energy transition hype cycle to the next.

We argue that it requires leadership, collaboration and harmonisation efforts among actors and intuitions to overcome wicked facets of the German energy transition. The communication between stakeholders and sensitising the public about the topic and potential negative impacts can be vital elements in taming the wicked facets. We show that R&D projects and technological or engineering solutions could provide a thorough base for evidence-based policy. However, they should be scrutinised as to their economic, social, and environmental impacts.

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. The wickedness approach is a concept which can assist in identifying emerging challenges that may not be sufficiently addressed currently. In illustrating wicked tendencies as a first step, this work can initiate a debate to identify adequate taming solutions, which can be relevant for policymakers and analysts. Our analysis of wicked facets can be used to map strategies to tackle wicked problems onto the identified critical points. We argue that wickedness is not a static concept, as it can decrease or increase over time, depending on the scales of uncertainty, complexity, and stakeholder divergence.

Conflict of Interest

The authors report that there are no competing interests to declare. The article was written in the context of a PhD scholarship program funded by the German Federal Environmental Foundation.

Author Contributions

Juliane Biehl: Conceptualisation; Methodology; Analysis Case 1; Resources; Writing – original draft; Writing – review & editing; Visualisation
Leonard Missbach: Analysis – Case 3; Writing – original draft; Writing – review & editing; Visualisation
Franziska Riedel: Analysis – Case 4; Writing – original draft; Writing – review & editing
Ruben Stemmle: Analysis – Case 2; Writing – original draft; Writing – review & editing
Julian Jüchter: Writing – review & editing; Analysis Case 1 – review and editing

Jessica Weber: Writing – review & editing; Analysis Case 1; Conceptualisation – Discussion & conclusions
Adrian Odenweller: Writing – review & editing; Visualisation
Christian Nauck: Analysis Case 3; Writing – review and editing
Johanna Kucknat: Analysis Case 4; Writing – original draft
Laura Lukassen: Conceptualisation; Writing – review & editing
Matthias Zech: Methodology – bibliometric analysis; Writing – original draft
Marie Grimm: Conceptualisation; Writing – review & editing

Acknowledgements

This work was supported by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt, DBU). We are particularly grateful for helpful suggestions on earlier drafts of this work from Prof. Dr Doris Fuchs at WWU Münster, Prof. Dr Johann Köppel at TU Berlin, and Dr Volker Wachendörfer at DBU. We also acknowledge students from TU Berlin, who contributed to this work through discussion and reflection rounds on the concept of the wicked problems in the study project “WICKED? – Transitioning to low-carbon energy sources”.

Annex A: Results of bibliometric analysis

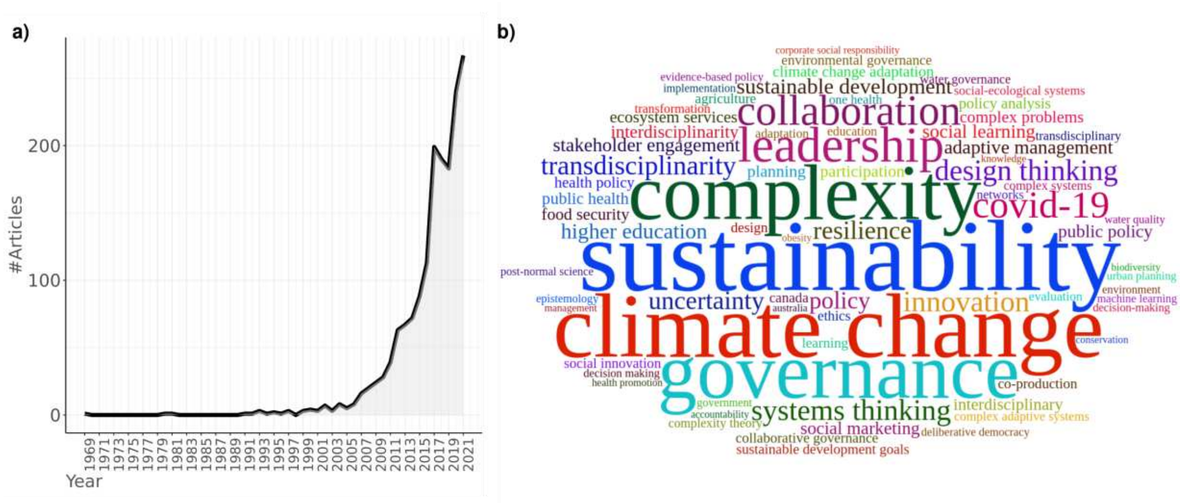

Figure 3: Yearly number of published articles (a) and a word cloud of the 75 most frequently named author keywords (b).

Annex B: 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, there might be multiple reasons for the current stagnation of onshore wind power development. Explanatory approaches range from mismatches in the polycentric governance system (Juerges, Leahy, and Newig 2018; Biehl, Köppel, and Grimm 2021) 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 (Hübner et al. 2019; Fachagentur Windenergie an Land 2021). However, there is no consensus on the reasons for citizens’ discontent (Köppel and Biehl 2018), which illustrates that the social problem is intractable or ill-defined.

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

Installation targets for developing onshore wind facilities exist (cf. RES Act 2021 and BT Drucksache 20/1630), 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 (MultiplEE 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[12] 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.

[12] The green-on-green-dilemma is a prioritisation conflict among „environmentally conscious groups" (cf. Warren 2005), which has at the heart the question if climate action goals should be prioritised over species conservation goals.

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[13] (Schrader et al. 2022), which caused vetoes from the German air navigation service provider[14] 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

[13] 40 VHF Doppler omnidirectional radio range equipment (D-VOR).
[14] Deutsche Flugsicherung GmbH.

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 (BT Drucksache 20/1630) onshore wind capacity 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 (Voigt, Straka, and Fritze 2019; Warren et al. 2005; Gartman et al. 2014), 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 (Nordex SE 2022; Frese, Mumme, and Metzner 2021). 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 (Majewski et al. 2022; Jani 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 (*Kohleausstiegsgesetz: Gesetz zur Reguzierung und zur Beendigung der Kohleverstromung und zur Änderung weiterer Gesetze* 2019; *AtomG: Dreizehntes Gesetz zur Änderung des Atomgesetzes* 2011); (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 C: 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 (Hähnlein, Bayer, and Blum 2010; Brielmann et al. 2011), 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 (García-Gil et al. 2020; Bloemendal, Olsthoorn, and Boons 2014b; 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 and Federal groundwater regulation as well as 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 2014a; 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 realization 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 D: 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 trans-regional 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 4). 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 4). Moreover, within-quintile differences exceed between-quintile differences, i.e., substantial heterogeneity of additional cost burden among poorer households[15]. 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 4).

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).

[15] This renders policy design more difficult, since counteracting policies, which would be progressive on average would still leave some poor households adversely affected.

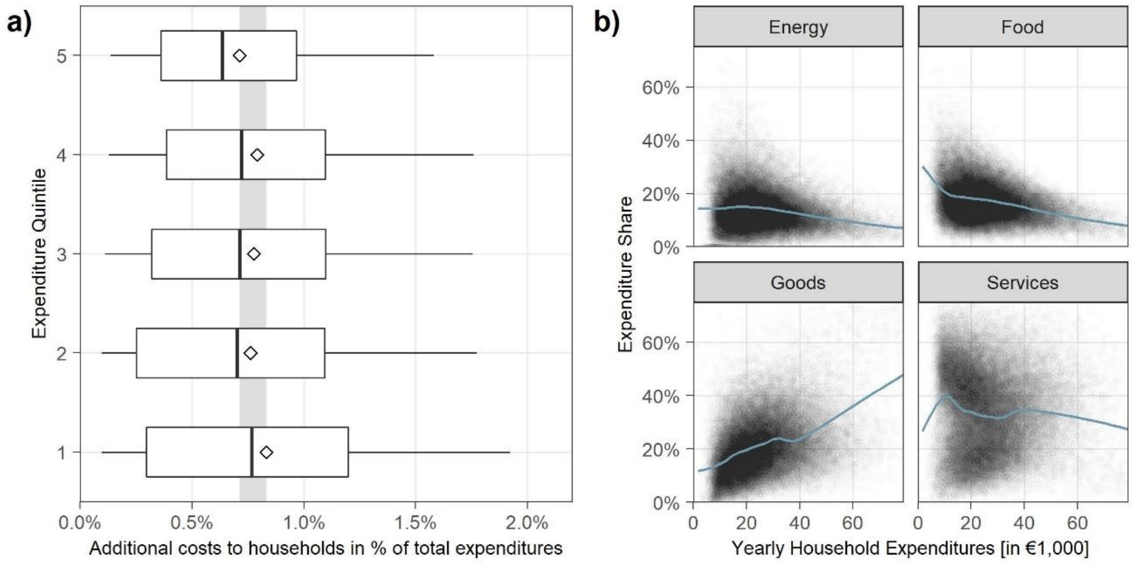

Figure 4: Panel a) shows first-order additional costs of transport fuel carbon pricing (35 EUR/tCO_2) among German households. Y-axis shows expenditure quintiles. Expenditure quintile 1 comprises the 20% of German households with the lowest per capita expenditures. Expenditure quintile 5 comprises the 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 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 (Caulfield et al. 2022; Cats, Susilo, and Reimal 2017). 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.

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 E: 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 (European Commission 2019; Díaz et al. 2019; Bang, Rosendahl, and Böhringer 2022).

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 (Joas et al. 2019; Luderer, Kost, and Sörgel 2021; Brandes et al. 2021; Burchardt et al. 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 (Joas et al. 2019; Janipour et al. 2020). 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 (Lilliestam, Patt, and Bersalli 2021; Dorsch, Flachsland, and Kornek 2020; Joltreau and Sommerfeld 2019; European Commission 2021c) or the German EEG (Luderer, Kost, and Sörgel 2021; BMWK 2022). 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 (Geres et al. 2019; Joas et al. 2019; Ausfelder, Seitz, and Roen 2018).

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 (Wesseling et al. 2017; Joas et al. 2019). On a governance level, no other sector in Germany – except steel production – has a higher risk of carbon leakage (European Commission 2021b). 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 (Evans et al. 2021; European Commission 2021b; Johansen et al. 2021; Fahl et al. 2021). Using blue hydrogen[16] as an intermediate technology until green hydrogen[17] 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

---

16 Blue hydrogen is produced via steam reformation with carbon capture and storage, CCS.
17 The production of green hydrogen requires vast amounts of electricity from renewable sources.

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).

Sources of Law

Abbreviation	Source of Law	English Translation
BT-Drucksache 20/1630 (EEG 2022)	Erneuerbare-Energien-Gesetz 2022	Renewable Energy Sources Act
KSG 2021	Klimaschutzgesetz 2021	Climate Action Act
BT-Drucksache 20/2355 (WindBG 2022)	Windenergiebedarfsgesetz 2022	Onshore Wind Demand Act
BEHG 2020	Brennstoffemissionshandelsgesetz 2020	Fuel Emissions Trading Act
BNatSchG 2017	Bundesnaturschutzgesetz 2017	Federal Nature Conservation Act

6 References

Agentur für Erneuerbare Energien. 2021. "Endenergieverbrauch nach Strom, Wärme und Verkehr." Accessed June 22, 2022. https://www.unendlich-viel-energie.de/mediathek/grafiken/endenergieverbrauch-strom-waerme-verkehr.

Ainger, John. 2022. "EU Lawmakers Uphold Ban on New Combustion Engine Cars by 2035." *Bloomberg*, June 8. Accessed July 13, 2022. https://www.bloomberg.com/news/articles/2022-06-08/eu-lawmakers-uphold-ban-on-new-combustion-engine-cars-by-2035.

Akamani, Kofi, Eric J. Holzmueller, and John W. Groninger. 2016. "Managing Wicked Environmental Problems as Complex Social-Ecological Systems: The Promise of Adaptive Governance." In *Landscape Dynamics, Soils and Hydrological Processes in Varied Climates*, edited by Assefa M. Melesse and Wossenu Abtew, 741–62. Cham: Springer International Publishing.

Alford, John, and Brian W. Head. 2017. "Wicked and less wicked problems: a typology and a contingency framework." *Policy and Society* 36 (3): 397–413. doi:10.1080/14494035.2017.1361634.

Anas, Alex, and Robin Lindsey. 2011. "Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice." *Review of Environmental Economics and Policy* 5 (1): 66–88. doi:10.1093/reep/req019.

Andersson, Claes, and Petter Törnberg. 2018. "Wickedness and the anatomy of complexity." *Futures* 95: 118–38. doi:10.1016/j.futures.2017.11.001.

Angeli, Federica, Silvia Camporesi, and Giorgia Dal Fabbro. 2021. "The COVID-19 Wicked Problem in Public Health Ethics: Conflicting Evidence, or Incommensurable Values?" *Humanit Soc Sci Commun* 8 (1): 1–8. doi:10.1057/s41599-021-00839-1.

Arbeitsgemeinschaft Energiebilanzen e.V. 2020. "Private Haushalte sparen bei Raumwärme und Beleuchtung." News release. January 27. Accessed June 22, 2022. https://ag-energiebilanzen.de/private-haushalte-sparen-bei-raumwaerme-und-beleuchtung/.

AtomG. Dreizehntes Gesetz zur Änderung des Atomgesetzes. July 31.

Attard, Guillaume, Peter Bayer, Yvan Rossier, Philipp Blum, and Laurent Eisenlohr. 2020. "A novel concept for managing thermal interference between geothermal systems in cities." *Renewable Energy* 145: 914–24. doi:10.1016/j.renene.2019.06.095.

Auld, Graeme, Steven Bernstein, Benjamin Cashore, and Kelly Levin. 2021. "Managing Pandemics as Super Wicked Problems: Lessons From, and For, COVID-19 and the Climate Crisis." *Policy Sci* 54 (4): 707–28. doi:10.1007/s11077-021-09442-2.

Ausfelder, Florian. 2015. "Diskussionspapier Elektrifizierung chemischer Prozesse.".

Ausfelder, Florian, Antje Seitz, and Serafin von Roen. 2018. "Flexibilitätsoptionen in der Grundstoffindustrie: Methodik, Potenziale, Hemmnisse." http://www.diw.de/documents/dokumentenarchiv/17/diw_01.c.579556.de/buch_flexibili taetsoptionen_web.pdf?utm_campaign=Background&utm_medium=Email&utm_source=Tagess piegel_Newsletter.

Bakker, Sjoerd, and Björn Budde. 2012. "Technological hype and disappointment: lessons from the hydrogen and fuel cell case." *Technology Analysis & Strategic Management* 24 (6): 549–63. doi:10.1080/09537325.2012.693662.

Baldenius, Till, Tobias Bernstein, Matthias Kalkuhl, Maximilian von Kleist-Retzow, and Nicolas Koch. 2021. “Ordnungsrecht oder Preisinstrumente? Zur Verteilungswirkung von Klimaschutzmaßnahmen im Verkehr.” *ifo Schnelldienst* 74 (6): 6–10.

Bang, Guri, Knut E. Rosendahl, and Christoph Böhringer. 2022. “Balancing cost and justice concerns in the energy transition: comparing coal phase-out policies in Germany and the UK.” *Climate Policy*, 1–16. doi:10.1080/14693062.2022.2052788.

Banza Lubaba Nkulu, Célestin, Lidia Casas, Vincent Haufroid, Thierry de Putter, Nelly D. Saenen, Tony Kayembe-Kitenge, Paul Musa Obadia et al. 2018. “Sustainability of Artisanal Mining of Cobalt in DR Congo.” *Nat Sustain* 1 (9): 495–504. doi:10.1038/s41893-018-0139-4.

Bataille, Chris, Max Åhman, Karsten Neuhoff, Lars J. Nilsson, Manfred Fischedick, Stefan Lechtenböhmer, Baltazar Solano-Rodriquez et al. 2018. “A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement.” *Journal of Cleaner Production* 187: 960–73. doi:10.1016/j.jclepro.2018.03.107.

Becattini, Viola, Paolo Gabrielli, and Marco Mazzotti. 2021. “Role of Carbon Capture, Storage, and Utilization to Enable a Net-Zero-CO 2 -Emissions Aviation Sector.” *Ind. Eng. Chem. Res.* 60 (18): 6848–62. doi:10.1021/acs.iecr.0c05392.

Berkhout, Frans. 2002. “Technological regimes, path dependency and the environment.” *Global Environmental Change* 12 (1): 1–4. doi:10.1016/S0959-3780(01)00025-5.

Biehl, Juliane, Johann Köppel, and M. Grimm. 2021. “Creating space for wind energy in a polycentric governance setting.” *Renewable and Sustainable Energy Reviews* 152: 111672. doi:10.1016/j.rser.2021.111672.

Bloemendal, Martin, Marc Jaxa-Rozen, and Theo Olsthoorn. 2018. “Methods for planning of ATES systems.” *Applied Energy* 216: 534–57. doi:10.1016/j.apenergy.2018.02.068.

Bloemendal, Martin, Theo Olsthoorn, and Frank Boons. 2014a. “How to achieve optimal and sustainable use of the subsurface for Aquifer Thermal Energy Storage.” *Energy Policy* 66: 104–14. doi:10.1016/j.enpol.2013.11.034.

Bloemendal, Martin, Theo Olsthoorn, and Frank Boons. 2014b. “How to achieve optimal and sustainable use of the subsurface for Aquifer Thermal Energy Storage.” *Energy Policy* 66: 104–14. doi:10.1016/j.enpol.2013.11.034.

Blohm, Marina. 2021. “An Enabling Framework to Support the Sustainable Energy Transition at the National Level.” *Sustainability* 13 (7): 3834. doi:10.3390/su13073834.

Blum, Philipp, Kathrin Menberg, Fabien Koch, Susanne A. Benz, Carolin Tissen, Hannes Hemmerle, and Peter Bayer. 2021. “Is Thermal Use of Groundwater a Pollution?” *Journal of Contaminant Hydrology* 239: 103791. doi:10.1016/j.jconhyd.2021.103791.

Boerse.de. 2022. *CO2-Emissionsrechte*. Accessed July 01, 2022. https://www.boerse.de/rohstoffe/Co2-Emissionsrechtepreis/XC000A0C4KJ2.

Bonte, M. 2013. *Impacts of shallow geothermal energy on groundwater quality: A hydrochemical and geomicrobial study of the effects of ground source heat pumps and aquifer thermal energy storage.* Amsterdam: Vrije University Amsterdam.

Bonte, M., P. J. Stuyfzand, G. A. van den Berg, and W. A. M. Hijnen. 2011. “Effects of Aquifer Thermal Energy Storage on Groundwater Quality and the Consequences for Drinking Water Production: a Case Study from the Netherlands.” *Water science and technology : a journal of the International Association on Water Pollution Research* 63 (9): 1922–31. doi:10.2166/wst.2011.189.

Born, Holger, Rolf Bracke, Timm Eicker, and Michael Rath. 2022. “Roadmap Oberflächennahe Geothermie: Erdwärmepumpen für die Energiewende - Potenziale, Hemmnisse und Handlungsempfehlungen.”.

Brandes, Julian, Markus Haun, Daniel Wrede, Patrick Jürgens, Christoph Kost, and Hans-Martin Henning. 2021. “Wege zu einem klimaneutralen Energiesystem – Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen: Update November 2021: Klimaneutralität 2045.” Accessed July 02, 2022. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Fraunhofer-ISE-Studie-Wege-zu-einem-klimaneutralen-Energiesystem-Update-Klimaneutralitaet-2045.pdf.

Brennstoffemissionshandelsgesetz (BEHG). vom 3. November 2020 (BGBl. I S. 2291) geändert worden ist Brennstoffemissionshandelsgesetz vom 12. Dezember 2019 (BGBl. I S. 2728), das durch Artikel 1 des Gesetzes vom 3. November 2020 (BGBl. I S. 2291) geändert worden ist. November 3.

Brielmann, Heike, Tillmann Lueders, Kathrin Schreglmann, Francesco Ferraro, Maria Avramov, Verena Hammerl, Philipp Blum, Peter Bayer, and Christian Griebler. 2011. “Oberflächennahe Geothermie und ihre potenziellen Auswirkungen auf Grundwasserökosysteme.” *Grundwasser - Zeitschrift der Fachsektion Hydrogeologie* 16 (2): 77–91. doi:10.1007/s00767-011-0166-9.

Brinkerhoff, Derick W. 2014. “State fragility and failure as wicked problems: beyond naming and taming.” *Third World Quarterly* 35 (2): 333–44. doi:10.1080/01436597.2014.878495.

Brunnengräber, Achim. 2019. “The Wicked Problem of Long Term Radioactive Waste Governance.” In *Conflicts, Participation and Acceptability in Nuclear Waste Governance: An International Comparison Volume III*, edited by Achim Brunnengräber and Maria R. Di Nucci, 335–55. Wiesbaden: Springer Fachmedien Wiesbaden.

Brunnengräber, Achim, Maria R. Di Nucci, Daniel Häfner, and Ana M. Isidora Losada. 2014. “Nuclear Waste Governance – ein wicked problem der Energiewende.” In *Im Hürdenlauf zur Energiewende*, edited by Achim Brunnengräber and Maria R. Di Nucci, 389–400. Wiesbaden: Springer Fachmedien Wiesbaden.

Bruns, Elke, Dörte Ohlhorst, Bernd Wenzel, and Johann Köppel. 2011. *Renewable Energies in Germany’s Electricity Market.* Dordrecht: Springer Netherlands.

Bundes-Klimaschutzgesetz (KSG). Bundes-Klimaschutzgesetz vom 12. Dezember 2019 (BGBl. I S. 2513), das durch Artikel 1 des Gesetzes vom 18. August 2021 (BGBl. I S. 3905) geändert worden ist 10. August 18.

Bundesministerium für Wirtschaft und Klimaschutz. 2022. “Chemie und Pharmazie: Wirtschaftsbranchen.” Accessed July 02, 2022. https://www.bmwk.de/Redaktion/DE/Artikel/Branchenfokus/Industrie/branchenfokus-chemie-pharmazie.html.

Burchardt, Jens, Katharina Franke, Patrick Herhold, Maria Hohaus, Henri Humpert, Joonas Päivärinta, Elisabeth Richenhagen et al. 2021. “Klimapfade 2.0: Ein Wirtschaftsprogramm für Klima und Zukunft.” Accessed July 02, 2022. https://issuu.com/bdi-berlin/docs/211021_bdi_klimapfade_2.0_-_gesamtstudie_-_vorabve.

Cats, Oded, Yusak O. Susilo, and Triin Reimal. 2017. “The prospects of fare-free public transport: evidence from Tallinn.” *Transportation* 44 (5): 1083–1104. doi:10.1007/s11116-016-9695-5.

Caulfield, Brian, Dylan Furszyfer, Agnieszka Stefaniec, and Aoife Foley. 2022. “Measuring the equity impacts of government subsidies for electric vehicles.” *Energy* 248: 123588. doi:10.1016/j.energy.2022.123588.

Chiappinelli, Olga, Katharina Erdmann, Timo Gerres, Manuel Haussner, Ingmar Juerges, Karsten Neuhoff, Alice Pirlot, Jörn Richstein, and Yeen Chan. 2020. “Industrial Innovation: Pathways to deep decarbonisation of Industry: Part 3: Policy Implications.” Accessed July 02, 2022. https://ec.europa.eu/clima/system/files/2020-07/industrial_innovation_part_3_en.pdf.

Chiappinelli, Olga, Timo Gerres, Karsten Neuhoff, Frederik Lettow, Heleen de Coninck, Balázs Felsmann, Eugénie Joltreau et al. 2021. “A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions.” *Climate Policy* 21 (10): 1328–46. doi:10.1080/14693062.2021.1922340.

Costa, Ángel M., José A. Orosa, Diego Vergara, and Pablo Fernández-Arias. 2021. “New Tendencies in Wind Energy Operation and Maintenance.” *Applied Sciences* 11 (4): 1386. doi:10.3390/app11041386.

Cowell, Richard, and Jan Webb. 2021. “Making useful knowledge for heat decarbonisation: Lessons from local energy planning in the United Kingdom.” *Energy Research & Social Science* 75: 102010. doi:10.1016/j.erss.2021.102010.

Creutzig, Felix, Aneeque Javaid, Zakia Soomauroo, Steffen Lohrey, Nikola Milojevic-Dupont, Anjali Ramakrishnan, Mahendra Sethi et al. 2020. “Fair street space allocation: ethical principles and empirical insights.” *Transport Reviews* 40 (6): 711–33. doi:10.1080/01441647.2020.1762795.

Crowley, Kate, and Brian W. Head. 2017. “The enduring challenge of ‘wicked problems’: revisiting Rittel and Webber.” *Policy Sci* 50 (4): 539–47. doi:10.1007/s11077-017-9302-4.

Dehler-Holland, Joris, Marvin Okoh, and Dogan Keles. 2022. “Assessing technology legitimacy with topic models and sentiment analysis – The case of wind power in Germany.” *Technological Forecasting and Social Change* 175: 121354. doi:10.1016/j.techfore.2021.121354.

“Der Windenergie an Land ausreichend Flächen bereitstellen: Policy Brief.” 2022.

“Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich, (Ariadne-Report).” 2021.

Díaz, Sandra, Josef Settele, Eduardo Brondízio, Hien Ngo, Maximilien Guèze, Almut Arneth, Patricia Balvanera, Kate Brauman, and Stuart H. M. Butchart. 2019. “Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.” Accessed July 02, 2022. https://ipbes.net/sites/default/files/downloads/spm_unedited_advance_for_posting_htn.pdf.

Dimitropoulos, Alexandros, Walid Oueslati, and Christina Sintek. 2018. “The rebound effect in road transport: A meta-analysis of empirical studies.” *Energy Economics* 75: 163–79. doi:10.1016/j.eneco.2018.07.021.

Dorsch, Marcel J., Christian Flachsland, and Ulrike Kornek. 2020. “Building and enhancing climate policy ambition with transfers: allowance allocation and revenue spending in the EU ETS.” *Environmental Politics* 29 (5): 781–803. doi:10.1080/09644016.2019.1659576.

Douenne, Thomas. 2020. “The Vertical and Horizontal Distributive Effects of Energy Taxes: A Case Study of a French Policy.” *EJ* 41 (3). doi:10.5547/01956574.41.3.tdou.

Douenne, Thomas, and Adrien Fabre. 2022. “Yellow Vests, Pessimistic Beliefs, and Carbon Tax Aversion.” *American Economic Journal: Economic Policy* 14 (1): 81–110. doi:10.1257/pol.20200092.

Duckett, D., D. Feliciano, J. Martin-Ortega, and J. Munoz-Rojas. 2016. “Tackling wicked environmental problems: The discourse and its influence on praxis in Scotland.” *Landscape and Urban Planning* 154: 44–56. doi:10.1016/j.landurbplan.2016.03.015.

Durant, Robert F., and Jerome S. Legge. 2006. ""Wicked Problems," Public Policy, and Administrative Theory." *Administration & Society* 38 (3): 309–34. doi:10.1177/0095399706289713.

Eckert, Eva, and Oleksandra Kovalevska. 2021. "Sustainability in the European Union: Analyzing the Discourse of the European Green Deal." *JRFM* 14 (2): 80. doi:10.3390/jrfm14020080.

European Commission. 2019. "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee of the Regions: The European Green Deal." Accessed July 02, 2022. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX%3A52019DC0640.

European Commission. 2021a. "Proposal for a Regulation of the European Parliament and of the Coucil amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition: COM(2021) 556 final." Accessed July 13, 2022. https://www.europarl.europa.eu/RegData/docs_autres_institutions/commission_europeenne/com/2021/0556/COM_COM(2021)0556_EN.pdf.

European Commission. 2021b. "Proposal for a Regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism." Accessed July 02, 2022. https://ec.europa.eu/info/sites/default/files/carbon_border_adjustment_mechanism_0.pdf.

European Commission. 2022. "Joint Statement between the European Commission and the United States on European Energy Security." News release. March 25. Accessed June 24, 2022. https://ec.europa.eu/commission/presscorner/detail/it/statement_22_2041.

Evans, Stuart, Michael A. Mehling, Robert A. Ritz, and Paul Sammon. 2021. "Border carbon adjustments and industrial competitiveness in a European Green Deal." *Climate Policy* 21 (3): 307–17. doi:10.1080/14693062.2020.1856637.

Everingham, Jo-Anne, Nina Collins, Jim Cavaye, Will Rifkin, Sue Vink, Thomas Baumgartl, and Daniel Rodriguez. 2016. "Energy from the foodbowl: Associated land-use conflicts, risks and wicked problems." *Landscape and Urban Planning* 154: 68–80. doi:10.1016/j.landurbplan.2016.01.011.

Fahl, U., K. Hufendiek, L. Kittel, J. Siegle, M. Pahle, N. aus dem Moore, H. Gruhl et al. 2021. "Industriewende: Wettbewerbseffekte und Carbon Leakage. Neue Politikmaßnahmen im Zuge des Europäischen Green Deal: Ariadne-Kurzdossier.".

Falck, Oliver, Nina Czernich, and Johannes Koenen. 2021. "Auswirkungen der vermehrten Produktion von elekrtisch betriebenen Pkw auf die Beschäftigung in Deutschland: Studie im Auftrag des Verbands der Automobilindustrie." Accessed July 20, 2022. https://www.ifo.de/en/publikationen/2021/monograph-authorship/effects-increased-production-electric-vehicles-employment.

Feng, Ju, and Wen Z. Shen. 2015. "Solving the wind farm layout optimization problem using random search algorithm." *Renewable Energy* 78: 182–92. doi:10.1016/j.renene.2015.01.005.

Fichtner, Sophie. 2022. "Ausbau der Windenergie: Mit Flügeln über die Autobahn." *taz*, June 25. Accessed July 22, 2022. https://taz.de/Ausbau-der-Windenergie/!5860734/.

Fischbacher-Smith, Denis. 2016. "Framing the UK's counter-terrorism policy within the context of a wicked problem." *Public Money & Management* 36 (6): 399–408. doi:10.1080/09540962.2016.1200801.

Fraunhofer-Institut für Solare Energiesysteme ISE. 2021. "Nettostromerzeugung in Deutschland 2020: erneuerbare Energien erstmals über 50 Prozent - Fraunhofer ISE." Accessed February 08, 2021. https://www.ise.fraunhofer.de/de/presse-und-medien/news/2020/nettostromerzeugung-in-deutschland-2021-erneuerbare-energien-erstmals-ueber-50-prozent.html.

Fraunhofer-Institut für Solare Energiesysteme ISE. 2022. "Nettostromerzeugung in Deutschland 2021: Erneuerbare Energien witterungsbedingt schwächer - Fraunhofer ISE." Accessed February 04, 2022. https://www.ise.fraunhofer.de/de/presse-und-medien/news/2022/nettostromerzeugung-in-deutschland-2021-erneuerbare-energien-witterungsbedingt-schwaecher.html.

Frese, Alfons, Thorsten Mumme, and Thorsten Metzner. 2021. "„Mehr als ein Schock": Windanlagenbauer Vestas schließt Werk in der Lausitz." *Potsdamer Neuste Nachrichten (PNN)*, September 21. Accessed September 23, 2021. https://www.pnn.de/ueberregionales/inland/mehr-als-ein-schock-windanlagenbauer-vestas-schliesst-werk-in-der-lausitz/27633996.html.

Frondel, Manuel, and Colin Vance. 2018. "Drivers' Response to Fuel Taxes and Efficiency Standards: Evidence from Germany." *Transportation* 45 (3): 989–1001. doi:10.1007/s11116-017-9759-1.

Fuchs, Gerhard. 2019. "Die Transformation des deutschen Systems der Stromversorgung." In *Handbuch Innovationsforschung*, edited by Birgit Blättel-Mink, Ingo Schulz-Schaeffer, and Arnold Windeler, 1–19. Wiesbaden: Springer Fachmedien Wiesbaden.

García-Gil, Alejandro, Gregor Goetzl, Maciej R. Kłonowski, Staša Borovic, David P. Boon, Corinna Abesser, Mitja Janza et al. 2020. "Governance of shallow geothermal energy resources." *Energy Policy* 138: 111283. doi:10.1016/j.enpol.2020.111283.

Gartman, Victoria, Kathrin Wichmann, Lea Bulling, María Elena Huesca-Pérez, and Johann Köppel. 2014. "Wind of Change or Wind of Challenges: Implementation factors regarding wind energy development, an international perspective." *AIMS Energy* 2 (4): 485–504. doi:10.3934/energy.2014.4.485.

"Gemeinsam für die Energiewende: Wie Windenergie an Land und Belange von Funknavigationsanlagen und Wetterradaren miteinander vereinbart werden." 2022. Accessed May 25, 2022. https://www.bmvi.de/SharedDocs/DE/Pressemitteilungen/2022/013-windenergie-an-land.html.

Geres, Roland, Andreas Kohn, Sebastian C. Lenz, Florian Ausfelder, Alexis Bazzanella, and Alexander Möller. 2019. "Roadmap Chemie 2050: Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland: eine Studie von DECHEMA und FutureCamp für den VCI." Accessed July 02, 2022. https://edocs.tib.eu/files/e01fn19/1682254917.pdf.

Gillingham, Kenneth, and Anders Munk-Nielsen. 2019. "A tale of two tails: Commuting and the fuel price response in driving." *Journal of Urban Economics* 109: 27–40. doi:10.1016/j.jue.2018.09.007.

Gläser, Anne, and Oldag Caspar. 2021. "Less confrontation, more cooperation: Increasing the acceptability of the EU Carbon Border Adjustment in key trading partner countries." https://www.germanwatch.org/en/20355. Policy Brief.

Glasser, H. 1998. "On the evaluation of "wicked problems": Guidelines for Integrating Qualitative and Quantitative Factors in Environmental Policy Analysis." In *Evaluation in Planning: Facing the Challenge of Complexity*, edited by Nathaniel Lichfield, Angela Barbanente, Dino Borri, Abdul Khakee, and Anna Prat, 229–49: Spinger-Science + Business Media, B.V.

Gniffke, Patrick, and Dirk Günther. 2022a. "Berechnung der Treibhausgasemissionsdaten für das Jahr 2021 gemäß Bundesklimaschutzgesetz: Begleitender Bericht." Kurzfassung.

Gniffke, Patrick, and Dirk Günther. 2022b. "Nationale Trendtabellen in der Abgrenzung der Sektoren des Klimaschutzgesetzes: 1990-2020." Accessed July 02, 2022. https://www.umweltbundesamt.de/themen/klima-energie/treibhausgas-emissionen.

Goldthau, Andreas, and Benjamin K. Sovacool. 2012. "The uniqueness of the energy security, justice, and governance problem." *Energy Policy* 41: 232–40. doi:10.1016/j.enpol.2011.10.042.

Gough, David, and James Thomas. 2017. "Commonality and Diversity in Reviews." In *An Introduction to Systematic Reviews*, edited by David Gough, Sandy Oliver, and James Thomas. 2nd edition, 43–70. Los Angeles: SAGE.

Griebler, Christian, and Maria Avramov. 2015. "Groundwater ecosystem services: a review." *Freshwater Science* 34 (1): 355–67. doi:10.1086/679903.

Griebler, Christian, Heike Brielmann, Christina M. Haberer, Sigrid Kaschuba, Claudia Kellermann, Christine Stumpp, Florian Hegler, David Kuntz, Simone Walker-Hertkorn, and Tillmann Lueders. 2016. "Potential impacts of geothermal energy use and storage of heat on groundwater quality, biodiversity, and ecosystem processes." *Environ Earth Sci* 75 (20). doi:10.1007/s12665-016-6207-z.

Grint, Keith. 2008. "Wicked Problems and Clumsy Solutions: the Role of Leadership." Clinical Leader I (II).

Guimarães, Maria H., Nuno Guiomar, Diana Surová, Sérgio Godinho, Teresa Pinto Correia, Audun Sandberg, Federica Ravera, and Marta Varanda. 2018. "Structuring wicked problems in transdisciplinary research using the Social–Ecological systems framework: An application to the montado system, Alentejo, Portugal." *Journal of Cleaner Production* 191: 417–28. doi:10.1016/j.jclepro.2018.04.200.

Guo, Shuocheng, and Eleftheria Kontou. 2021. "Disparities and equity issues in electric vehicles rebate allocation." *Energy Policy* 154: 112291. doi:10.1016/j.enpol.2021.112291.

Hahn, Hans J., Christian Schweer, and Christian Griebler. 2018. "Grundwasserökosysteme im Recht?" *Grundwasser - Zeitschrift der Fachsektion Hydrogeologie* 23 (3): 209–18. doi:10.1007/s00767-018-0394-3.

Hähnlein, Stefanie, Peter Bayer, and Philipp Blum. 2010. "International legal status of the use of shallow geothermal energy." *Renewable and Sustainable Energy Reviews* 14 (9): 2611–25. doi:10.1016/j.rser.2010.07.069.

Hähnlein, Stefanie, Peter Bayer, Grant Ferguson, and Philipp Blum. 2013. "Sustainability and policy for the thermal use of shallow geothermal energy." *Energy Policy* 59: 914–25. doi:10.1016/j.enpol.2013.04.040.

Hanke, Steven. 2022. "Windkraft-Gesetz nimmt Konturen an." *Tagesspiegel Background Energie & Klima*, May 4. 6.

Hansen, Kenneth, Christian Breyer, and Henrik Lund. 2019. "Status and perspectives on 100% renewable energy systems." *Energy* 175: 471–80. doi:10.1016/j.energy.2019.03.092.

Harper, Gavin, Roberto Sommerville, Emma Kendrick, Laura Driscoll, Peter Slater, Rustam Stolkin, Allan Walton et al. 2019. "Recycling Lithium-Ion Batteries from Electric Vehicles." *Nature* 575 (7781): 75–86. doi:10.1038/s41586-019-1682-5.

Hassink, Robert, Huiwen Gong, Klaas Fröhlich, and Arne Herr. 2021. "Exploring the scope of regions in challenge-oriented innovation policy: the case of Schleswig-Holstein, Germany." *European Planning Studies*, 1–19. doi:10.1080/09654313.2021.2017857.

Hauser, Philipp, Paul Münnich, Helen Burmeister, Andreas Kohn, and Benjamin Görlach. 2022. "Klimaschutzverträge für die Industrietransformation: Kurzfristige Schritte auf dem Pfad zur Klimaneutralität der deutschen Grundstoffindustrie." Accessed July 02, 2022. https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_10_DE_KIT/A-EW_249_Klimaschutzvertraege-Industrietransformation-Studie_WEB.pdf.

Head, Brian W. 2008. "Wicked problems in public policy." *Public policy* 3 (2): 101–18.

Head, Brian W. 2019. “Forty years of wicked problems literature: forging closer links to policy studies.” *Policy and Society* 38 (2): 180–97. doi:10.1080/14494035.2018.1488797.

Head, Brian W. 2022. *Wicked Problems in Public Policy: Understanding and Responding to Complex Challenges.* 1st ed. 2022. Springer eBook Collection. Cham: Springer International Publishing; Imprint Palgrave Macmillan.

Head, Brian W., and Wei-Ning Xiang. 2016. “Working with wicked problems in socio-ecological systems: More awareness, greater acceptance, and better adaptation.” *Landscape and Urban Planning* 154: 1–3. doi:10.1016/j.landurbplan.2016.07.011.

“Hemmnisse beim Ausbau der Windenergie in Deutschland: Ergebnisse einer Branchenumfrage zu Klagen gegen Windenergieanlagen sowie zu Genehmigungshemmnissen durch Drehfunkfeuer und militärische Belange der Luftraumnutzung.” 2019. Accessed December 06, 2019. https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/Analysen/FA_Wind_Branchenumfrage_beklagte_WEA_Hemmnisse_DVOR_und_Militaer_07-2019.pdf. Umfrage.

Hodges, Tina. 2010. “Public Transportation's Role in Reducing Greenhouse Gas Emissions.” https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/PublicTransportationsRoleInRespondingToClimateChange2010.pdf.

Hou, Xiaojing, Ruichang Li, and Zhiping Song. 2022. “A Bibliometric Analysis of Wicked Problems: from Single Discipline to Transdisciplinarity.” *Fudan J. Hum. Soc. Sci.* 15 (3): 299–329. doi:10.1007/s40647-022-00346-w.

Howlett, Michael, and Jeremy Rayner. 2007. “Design Principles for Policy Mixes: Cohesion and Coherence in ‘New Governance Arrangements’.” *Policy and Society* 26 (4): 1–18. doi:10.1016/S1449-4035(07)70118-2.

Hübner, Gundula, Johannes Pohl, Jan Warode, Boris Gotchev, P. Nanz, Dörte Ohlhorst, Michael Krug, Steven Salecki, and Wolfgang Peters. 2019. “Naturverträgliche Energiewende: Akzeptanz und Erfahrungen vor Ort.” Accessed June 24, 2022. https://www.bfn.de/sites/default/files/2021-05/BfN-Broschuere_Akzeptanz_bf.pdf.

Innes, Judith E., and David E. Booher. 2016. “Collaborative rationality as a strategy for working with wicked problems.” *Landscape and Urban Planning* 154: 8–10. doi:10.1016/j.landurbplan.2016.03.016.

Jakob, Michael, and Philipp Klöckner. 2021. “Klimaschutzinstrumente im Verkehr: Tempolimit auf Autobahnen.” Für Mensch und Umwelt. Accessed July 13, 2022. https://www.umweltbundesamt.de/sites/default/files/medien/366/dokumente/uba-kurzpapier_tempolimit_autobahnen_kliv_0.pdf.

Jani, Hardik K., Surendra Singh Kachhwaha, Garlapati Nagababu, and Alok Das. 2022. “A brief review on recycling and reuse of wind turbine blade materials.” *Materials Today: Proceedings* 62: 7124–30. doi:10.1016/j.matpr.2022.02.049.

Janipour, Zahra, Reinier de Nooij, Peter Scholten, Mark A. Huijbregts, and Heleen de Coninck. 2020. “What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production.” *Energy Research & Social Science* 60: 101320. doi:10.1016/j.erss.2019.101320.

Jaramillo, P., S. Kahn Ribeiro, P. Newman, S. Dhar, O. E. Diemuodeke, T. Kajino, D. S. Lee et al. 2022. “Chapter 10: Transport.” In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by IPCC. Cambridge, UK: Cambridge University Press.

Javaid, Aneeque, Felix Creutzig, and Sebastian Bamberg. 2020. “Determinants of Low-Carbon Transport Mode Adoption: Systematic Review of Reviews.” *Environ. Res. Lett.* 15 (10): 103002. doi:10.1088/1748-9326/aba032.

Joas, Fabian, Wido Witecka, Thorsten Lenck, Fiona Seiler, Sascha Samadi, Clemens Schneider, and Georg Holtz. 2019. “Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement: Studie.” Accessed July 02, 2022. https://static.agora-energiewende.de/fileadmin/Projekte/2018/Dekarbonisierung_Industrie/164_A-EW_Klimaneutrale-Industrie_Studie_WEB.pdf.

Johansen, B., B. Louro, I. Kukla, G. Pattle, J. Denmark, H. Chris, and D. J. Roque. 2021. “Economic Analysis of the Impacts of the Chemicals Strategy for Sustainability - Phase 1 Report: Report for the European Chemicals Industry Council (cefic).” Accessed July 02, 2022. https://cefic.org/app/uploads/2021/12/Economic-Analysis-of-the-Impacts-of-the-Chemicals-Strategy-for-Sustainability-Phase-1.pdf.

Johnstone, Phil, and Paula Kivimaa. 2018. “Multiple dimensions of disruption, energy transitions and industrial policy.” *Energy Research & Social Science* 37: 260–65. doi:10.1016/j.erss.2017.10.027.

Joltreau, Eugénie, and Katrin Sommerfeld. 2019. “Why does emissions trading under the EU Emissions Trading System (ETS) not affect firms’ competitiveness? Empirical findings from the literature.” *Climate Policy* 19 (4): 453–71. doi:10.1080/14693062.2018.1502145.

Juerges, Nataly, Jessica Leahy, and Jens Newig. 2018. “Actor perceptions of polycentricity in wind power governance.” *Env Pol Gov* 28 (6): 383–94. doi:10.1002/eet.1830.

Juerges, Nataly, Jessica Leahy, and Jens Newig. 2020. “A typology of actors and their strategies in multi-scale governance of wind turbine conflict within forests.” *Land Use Policy* 96: 104691. doi:10.1016/j.landusepol.2020.104691.

Karatairi, Eva, and Ruben Bischler. 2020. “Gone with the Wind: the Life and Death of a Wind Turbine Rotor Blade.” *MRS Bulletin* 45 (3): 178–79. doi:10.1557/mrs.2020.71.

Kelley, Peter L. 2018. “Crossing the divide: Lessons from developing wind energy in post-fact America.” *Zygon* 53 (2): 642–662.

Kemfert, Claudia, Fabian Präger, Isabell Braunger, Franziska M. Hoffart, and Hanna Brauers. 2022. “The Expansion of Natural Gas Infrastructure Puts Energy Transitions at Risk.” *Nat Energy* 7 (7): 582–87. doi:10.1038/s41560-022-01060-3.

Kendziorski, Mario, Leonard Göke, Claudia Kemfert, Christian von Hirschhausen, and Elmar Zozmann. 2021. “100% erneuerbare Energie für Deutschland unter besonderer Berücksichtung von Dezentralität und räumlicher Verbrauchsnähe - Potenziale, Szenarien und Auswirkungen auf Netzinfrastrukturen.” http://www.diw.de/documents/publikationen/73/diw_01.c.816979.de/diwkompakt_2021-167.pdf.

Klasche, Benjamin. 2021. “After COVID-19: What can we learn about wicked problem governance?” *Social Sciences & Humanities Open* 4 (1): 100173. doi:10.1016/j.ssaho.2021.100173.

Klauber, Hannah, Felix Holub, Nicolas Koch, Nico Pestel, Nolan Ritter, and Alexander Rohlf. 2021. *Killing Prescriptions Softly: Low Emission Zones and Child Health from Birth to School*.

Kluth, Andreas. 2022. “To Save Ukraine, Slow Down on the Autobahn.” *Bloomberg*, July 3. Accessed July 13, 2022. https://www.bloomberg.com/opinion/articles/2022-07-03/germany-s-cult-of-autobahn-speed-comes-up-against-the-need-to-fight-putin.

“Koalitionsvertrag 2021 – 2025 zwischen der Sozialdemokratischen Partei Deutschlands (SPD), BÜNDNIS 90 / DIE GRÜNEN und den Freien Demokraten (FDP): Mehr Fortschritt wagen - Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit.” 2021. https://www.spd.de/koalitionsvertrag2021/.

Koch, Fabien, Kathrin Menberg, Svenja Schweikert, Cornelia Spengler, Hans J. Hahn, and Philipp Blum. 2021. “Groundwater Fauna in an Urban Area – Natural or Affected?” *Hydrol. Earth Syst. Sci.* 25 (6): 3053–70. doi:10.5194/hess-25-3053-2021.

Kohleausstiegsgesetz. Gesetz zur Reguzierung und zur Beendigung der Kohleverstromung und zur Änderung weiterer Gesetze. 2019. Accessed December 05, 2019.

Komendantova, Nadejda. 2021. “Transferring awareness into action: A meta-analysis of the behavioral drivers of energy transitions in Germany, Austria, Finland, Morocco, Jordan and Iran.” *Energy Research & Social Science* 71: 101826. doi:10.1016/j.erss.2020.101826.

Köppel, Johann, and Juliane Biehl. in preparation. *Wie heterogene Akteure das verzwickte Feld der Energiewende bestellen: Buchbeitrag zum Sammelband "Innovationsgesellschaft: Befunde und Ausblicke"*.

Köppel, Johann, Juliane Biehl, Volker Wachendörfer, and Alexander Bittner. 2019. “A Pioneer in Transition: Horizon Scanning of Emerging Issues in Germany's Sustainable Wind Energy Development.” In *Wind Energy and Wildlife Impacts: Balancing Energy Sustainability with Wildlife Conservation*, edited by Regina Bispo, Joana Bernardino, Helena Coelho, and José Lino Costa, 67–91: Springer Nature Switzerland AG.

Kraftfahrt-Bundesamt. 2022. “Fahrzeugzulassungen im Dezember 2021 - Jahresbilanz: Pressemitteilung 01/2022.” News release. January 5. Accessed July 13, 2022. https://www.kba.de/DE/Presse/Pressemitteilungen/Fahrzeugzulassungen/2022/pm01_2022_n_12_21_pm_komplett.html?snn=3662144.

Kriechbaum, Michael, Alfred Posch, and Angelika Hauswiesner. 2021. “Hype cycles during socio-technical transitions: The dynamics of collective expectations about renewable energy in Germany.” *Research Policy* 50 (9): 104262. doi:10.1016/j.respol.2021.104262.

Kühne, Olaf, Debi Parush, Deborah Shmueli, and Corinna Jenal. 2022. “Conflicted Energy Transition—Conception of a Theoretical Framework for Its Investigation.” *Land* 11 (1): 116. doi:10.3390/land11010116.

Kümmerer, Klaus, James H. Clark, and Vânia G. Zuin. 2020. “Rethinking Chemistry for a Circular Economy.” *Science (New York, N.Y.)* 367 (6476): 369–70. doi:10.1126/science.aba4979.

Labandeira, Xavier, José M. Labeaga, and Xiral López-Otero. 2017. “A meta-analysis on the price elasticity of energy demand.” *Energy Policy* 102: 549–68. doi:10.1016/j.enpol.2017.01.002.

Landwehr, Susanne. 2022. “BSK warnt: Windenergieausbau in Gefahr.” *Deutsche Verkehrs-Zeitung (DVZ)*, April 5. Accessed July 22, 2022. https://www.dvz.de/rubriken/land/strasse/detail/news/windenergieausbau-in-gefahr.html.

Larrabee, David A. 2018. “Climate change and conflicting future visions.” *Zygon* 53 (2): 515–44. Accessed August 20, 2019.

Lawrence, Mark. 2020. “Das "Wicked Problem" der Covid-19-Pandemie.” Accessed March 01, 2021. https://www.iass-potsdam.de/de/blog/2020/04/das-wicked-problem-der-covid-19-pandemie.

Lee, Roh P. 2019. “Alternative carbon feedstock for the chemical industry? - Assessing the challenges posed by the human dimension in the carbon transition.” *Journal of Cleaner Production* 219: 786–96. doi:10.1016/j.jclepro.2019.01.316.

Levin, Kelly, Benjamin Cashore, Steven Bernstein, and Graeme Auld. 2012. “Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change.” *Policy Sci* 45 (2): 123–52. doi:10.1007/s11077-012-9151-0.

Levinson, Arik. 2019. “Energy Efficiency Standards Are More Regressive Than Energy Taxes: Theory and Evidence.” *Journal of the Association of Environmental and Resource Economists* 6 (S1): S7-S36. doi:10.1086/701186.

Lilliestam, Johan, Anthony Patt, and Germán Bersalli. 2021. “The effect of carbon pricing on technological change for full energy decarbonization: A review of empirical ex-post evidence.” *WIREs Clim Change* 12 (1). doi:10.1002/wcc.681.

Löhr, Meike, and Jannika Mattes. 2022. “Facing transition phase two: Analysing actor strategies in a stagnating acceleration phase.” *Technological Forecasting and Social Change* 174: 121221. doi:10.1016/j.techfore.2021.121221.

Lönngren, Johanna, and Katrien van Poeck. 2020. “Wicked problems: a mapping review of the literature.” *International Journal of Sustainable Development & World Ecology*, 1–22. doi:10.1080/13504509.2020.1859415.

Luderer, Gunnar, Christoph Kost, and Dominika. 2021. *Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich:* Potsdam Institute for Climate Impact Research.

Majewski, Peter, Nick Florin, Joytishna Jit, and Rodney A. Stewart. 2022. “End-of-life policy considerations for wind turbine blades.” *Renewable and Sustainable Energy Reviews* 164: 112538. doi:10.1016/j.rser.2022.112538.

Markard, Jochen. 2018. “The next phase of the energy transition and its implications for research and policy.” *Nat Energy* 3 (8): 628–33. doi:10.1038/s41560-018-0171-7.

Menberg, Kathrin, Peter Bayer, Kai Zosseder, Sven Rumohr, and Philipp Blum. 2013. “Subsurface Urban Heat Islands in German Cities.” *The Science of the total environment* 442: 123–33. doi:10.1016/j.scitotenv.2012.10.043.

Mian, Atif, and Amir Sufi. 2012. “The Effects of Fiscal Stimulus: Evidence from the 2009 Cash for Clunkers Program*.” *The Quarterly Journal of Economics* 127 (3): 1107–42. doi:10.1093/qje/qjs024.

Miglani, Somil, Kristina Orehounig, and Jan Carmeliet. 2018. “A Methodology to Calculate Long-Term Shallow Geothermal Energy Potential for an Urban Neighbourhood.” doi:10.3929/ETHZ-B-000217121.

Moallemi, Enayat A., and Shirin Malekpour. 2018. “A participatory exploratory modelling approach for long-term planning in energy transitions.” *Energy Research & Social Science* 35: 205–16. doi:10.1016/j.erss.2017.10.022.

Morris, Craig, and Arne Jungjohann. 2016. *Energy Democracy: Germany’s Energiewende to Renewables.* Cham: Palgrave MacMillan.

Neuhoff, Karsten, Olga Chiappinelli, Jörn Richstein, Heleen de Connick, Pedro Linares, Timo Gerres, Gauri Khandekar et al. 2021. “Closing the Green Deal for Industry: What design of the carbon border adjustment mechanism ensures an inclusive transition to climate neutrality?” Accessed July 02, 2022. https://climatestrategies.org/wp-content/uploads/2021/06/Closing-the-Green-Deal-for-Industry_FINAL.pdf. Position Paper.

Newman, Joshua, and Brian W. Head. 2017. “Wicked tendencies in policy problems: rethinking the distinction between social and technical problems.” *Policy and Society* 36 (3): 414–29. doi:10.1080/14494035.2017.1361635.

Noordegraaf, Mirko, Scott Douglas, Karin Geuijen, and Martijn van der Steen. 2019. “Weaknesses of wickedness: a critical perspective on wickedness theory.” *Policy and Society* 38 (2): 278–97. doi:10.1080/14494035.2019.1617970.

Nordex SE. 2022. “Nordex SE: Nordex Group plant Beendigung der Rotorblattfertigung am Standort Rostock.” News release. February 28. Accessed June 01, 2022. https://www.nordex-online.com/de/2022/02/nordex-se-nordex-group-plant-beendigung-der-rotorblattfertigung-am-standort-rostock/.

Norris, Patricia E., Michael O'Rourke, Alex S. Mayer, and Kathleen E. Halvorsen. 2016. “Managing the wicked problem of transdisciplinary team formation in socio-ecological systems.” *Landscape and Urban Planning* 154: 115–22. doi:10.1016/j.landurbplan.2016.01.008.

Parry, Ian W. H., Margaret Walls, and Winston Harrington. 2007. “Automobile Externalities and Policies.” *Journal of Economic Literature* 45 (2): 373–99. doi:10.1257/jel.45.2.373.

Perego, Rodolfo, Giorgia Dalla Santa, Antonio Galgaro, and Sebastian Pera. 2022. “Intensive thermal exploitation from closed and open shallow geothermal systems at urban scale: unmanaged conflicts and potential synergies.” *Geothermics* 103: 102417. doi:10.1016/j.geothermics.2022.102417.

Peters, B. G. 2017. “What is so wicked about wicked problems? A conceptual analysis and a research program.” *Policy and Society* 36 (3): 385–96. doi:10.1080/14494035.2017.1361633.

Pophillat, William, Guillaume Attard, Peter Bayer, Jozsef Hecht-Méndez, and Philipp Blum. 2020. “Analytical solutions for predicting thermal plumes of groundwater heat pump systems.” *Renewable Energy* 147: 2696–2707. doi:10.1016/j.renene.2018.07.148.

Possemiers, Mathias, Marijke Huysmans, and Okke Batelaan. 2014. “Influence of Aquifer Thermal Energy Storage on groundwater quality: A review illustrated by seven case studies from Belgium.” *Journal of Hydrology: Regional Studies* 2: 20–34. doi:10.1016/j.ejrh.2014.08.001.

Pratiwi, Astu S., and Evelina Trutnevyte. 2021. “Life cycle assessment of shallow to medium-depth geothermal heating and cooling networks in the State of Geneva.” *Geothermics* 90: 101988. doi:10.1016/j.geothermics.2020.101988.

Prognos AG, Öko-Institut e.V., and Wuppertal Institut. 2020. “Klimaneutrales Deutschland: In drei Schritten zu null Treibhausgasen bis 2050 über ein Zwischenziel von -65 % im Jahr 2030 als Teil des EU-Green-Deals: Studie erstellt im Auftrag von Agora Energiewende, Agora Verkehrswende und Stiftung Klimaneutralität.” https://www.stiftung-klima.de/app/uploads/2020/11/2020_KNDE_Langfassung_WEB.pdf.

Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757. European Commission. July 14c. Accessed July 01, 2022. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0551.

“Quartalsbericht Netz- und Systemsicherheit: Viertes Quartal 2020.” 2021.

Raschke, Marcel. 2015. “Die Windenergieerlasse der Länder.” In *Energiewende im Föderalismus*, edited by Thorsten Müller and Hartmut Kahl, 261–89. Schriften zum Umweltenergierecht 18: NOMOS.

Rechsteiner, Rudolf. 2020. “German Energy Transition (Energiewende) and What Politicians Can Learn for Environmental and Climate Policy.” *Clean technologies and environmental policy*, 1–38. doi:10.1007/s10098-020-01939-3.

“Referentenentwurf: Entwurf eines Gesetzes zu Sofortmaßnahmen für einen beschleunigten Ausbau der erneuerbaren Energien und weiteren Maßnahmen im Stromsektor.” 2022. Accessed July 02, 2022. https://www.bmwk.de/Redaktion/DE/Downloads/E/referentenentwurf-erneuerbaren-energien-und-weiteren-massnahmen-im-stromsektor.pdf?__blob=publicationFile&v=6.

Renn, Ortwin, and Jonathan P. Marshall. 2020. “History of the Energy Transition in Germany: from the 1950s to 2019.” In *The Role of Public Participation in Energy Transitions*, edited by Ortwin Renn, Frank-Jörg Ulmer, and Anna Deckert, 9–38. London: Academic Press.

Reusswig, Fritz, Florian Braun, Ines Heger, Thomas Ludewig, Eva Eichenauer, and Wiebke Lass. 2016. “Against the wind: Local opposition to the German Energiewende.” *Utilities Policy* 41: 214–27. doi:10.1016/j.jup.2016.02.006.

Reusswig, Fritz, Nadejda Komendantova, and Antonella Battaglini. 2018. “New Governance Challenges and Conflicts of the Energy Transition: Renewable Electricity Generation and Transmission as Contested Socio-technical Options.” In *The Geopolitics of Renewables*. Vol. 61, edited by Daniel Scholten, 231–56. Lecture Notes in Energy. Cham: Springer International Publishing.

Rittel, Horst W. 1972. “On the Planning Crisis: Systems Analysis of the "First and Second Generations".” *Bedriftsøkonomen* (8): 390–96.

Rittel, Horst W., and Melvin M. Webber. 1973. “Dilemmas in a general theory of planning.” *Policy Sciences* (4): 155–69. Accessed August 20, 2019.

Rodi, Michael. 2017. “Das Recht der Windkraftnutzung zu Lande unter Reformdruck.” *Zeitschrift für Umweltrecht (ZUR)* (12): 658-666. Accessed June 16, 2020.

Roggema, Rob. 2020. “Planning for the Energy Transition and How to Overcome the Misfits of the Current Paradigm.” *World* 1 (3): 264–82. doi:10.3390/world1030019.

Saner, Dominik, Ronnie Juraske, Markus Kübert, Philipp Blum, Stefanie Hellweg, and Peter Bayer. 2010. “Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems.” *Renewable and Sustainable Energy Reviews* 14 (7): 1798–1813. doi:10.1016/j.rser.2010.04.002.

Sanner, Burkhard, Constantine Karytsas, Dimitrios Mendrinos, and Ladislaus Rybach. 2003. “Current status of ground source heat pumps and underground thermal energy storage in Europe.” *Geothermics* 32 (4-6): 579–88. doi:10.1016/S0375-6505(03)00060-9.

Santos, Georgina, Hannah Behrendt, Laura Maconi, Tara Shirvani, and Alexander Teytelboym. 2010. “Part I: Externalities and economic policies in road transport.” *Research in Transportation Economics* 28 (1): 2–45. doi:10.1016/j.retrec.2009.11.002.

Schmehl, Roland, ed. 2018. *Airborne Wind Energy: Advances in Technology Development and Research.* Green Energy and Technology. Singapore: Springer.

Schmid, Eva, Brigitte Knopf, and Anna Pechan. 2016. “Putting an energy system transformation into practice: The case of the German Energiewende.” *Energy Research & Social Science* 11: 263–75. doi:10.1016/j.erss.2015.11.002.

Schrader, Thorsten, Thomas Kleine-Ostmann, Heyno Garbe, Jens Werner, Karsten Schubert, Jens Wellhausen, and Harald Löwe. 2022. “Bericht zur Wechselwirkung von Windenergieanlagen mit terrestrischer Navigation/Drehfunkfeuern.”.

Schroeder, Andreas, and Thure Traber. 2012. “The economics of fast charging infrastructure for electric vehicles.” *Energy Policy* 43: 136–44. doi:10.1016/j.enpol.2011.12.041.

Schwarzenberg, Lars, and Sylvia Ruß. 2016. “Die Windenergieerlasse der Länder – Überblick und neue Entwicklungen.” *Zeitschrift für Umweltrecht (ZUR)* (5): 278–86.

Self, Stuart J., Bale V. Reddy, and Marc A. Rosen. 2013. “Geothermal heat pump systems: Status review and comparison with other heating options.” *Applied Energy* 101: 341–48. doi:10.1016/j.apenergy.2012.01.048.

Seto, Karen C., Steven J. Davis, Ronald B. Mitchell, Eleanor C. Stokes, Gregory Unruh, and Diana Ürge-Vorsatz. 2016. “Carbon Lock-In: Types, Causes, and Policy Implications.” *Annu. Rev. Environ. Resour.* 41 (1): 425–52. doi:10.1146/annurev-environ-110615-085934.

Sovacool, Benjamin K., Jonn Axsen, and Steve Sorrell. 2018. “Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design.” *Energy Research & Social Science* 45: 12–42. doi:10.1016/j.erss.2018.07.007.

Sovacool, Benjamin K., David J. Hess, Roberto Cantoni, Dasom Lee, Marie Claire Brisbois, Hans Jakob Walnum, Ragnhild Freng Dale et al. 2022. “Conflicted transitions: Exploring the actors, tactics, and outcomes of social opposition against energy infrastructure.” *Global Environmental Change* 73: 102473. doi:10.1016/j.gloenvcha.2022.102473.

“Status des Windenergieausbaus an Land in Deutschland Jahr 2021.” 2022. https://www.windguard.de/veroeffentlichungen.html?file=files/cto_layout/img/unternehmen/veroeffentlichungen/2022/Status%20des%20Windenergieausbaus%20an%20Land_Jahr%202021.pdf.

Steinbacher, Karoline, and Michael Pahle. 2016. “Leadership and the Energiewende: German Leadership by Diffusion.” *Global Environmental Politics* 16 (4): 70–89. doi:10.1162/GLEP_a_00377.

Stemmle, Ruben, Philipp Blum, Simon Schüppler, Paul Fleuchaus, Melissa Limoges, Peter Bayer, and Kathrin Menberg. 2021. “Environmental impacts of aquifer thermal energy storage (ATES).” *Renewable and Sustainable Energy Reviews* 151: 111560. doi:10.1016/j.rser.2021.111560.

Sterner, Thomas. 2007. “Fuel taxes: An important instrument for climate policy.” *Energy Policy* 35 (6): 3194–3202. doi:10.1016/j.enpol.2006.10.025.

Sterner, Thomas. 2012. “Distributional effects of taxing transport fuel.” *Energy Policy* 41: 75–83. doi:10.1016/j.enpol.2010.03.012.

Stremke, Sven, and Sören Schöbel. 2019. “Research through design for energy transition: two case studies in Germany and The Netherlands.” *SASBE* 8 (1): 16–33. doi:10.1108/SASBE-02-2018-0010.

Taylor, Kira. 2022. “Securing its supply of raw materials: the wind industry’s next challenge.” *EURACTIV*, April 12. Accessed July 02, 2022. https://www.euractiv.com/section/energy/news/securing-its-supply-of-raw-materials-the-wind-industrys-next-challenge/.

Termeer, Catrien J., and Art Dewulf. 2019. “A small wins framework to overcome the evaluation paradox of governing wicked problems.” *Policy and Society* 38 (2): 298–314. doi:10.1080/14494035.2018.1497933.

Termeer, Catrien J., Art Dewulf, and Robbert Biesbroek. 2019. “A critical assessment of the wicked problem concept: relevance and usefulness for policy science and practice.” *Policy and Society* 38 (2): 167–79. doi:10.1080/14494035.2019.1617971.

The European Chemical Industry Council. 2022. “Landscape of the European Chemical Industry: Germany.” Accessed July 02, 2022. https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/germany/.

Thollander, Patrik, Jenny Palm, and Johan Hedbrant. 2019. “Energy Efficiency as a Wicked Problem.” *Sustainability* 11 (6): 1569. doi:10.3390/su11061569.

Tissen, Carolin, Kathrin Menberg, Peter Bayer, and Philipp Blum. 2019. “Meeting the Demand: Geothermal Heat Supply Rates for an Urban Quarter in Germany.” *Geotherm Energy* 7 (1): 1–21. doi:10.1186/s40517-019-0125-8.

Tissen, Carolin, Kathrin Menberg, Susanne A. Benz, Peter Bayer, Cornelia Steiner, Gregor Götzl, and Philipp Blum. 2021. “Identifying key locations for shallow geothermal use in Vienna.” *Renewable Energy* 167: 1–19. doi:10.1016/j.renene.2020.11.024.

Todorov, Oleg, Kari Alanne, Markku Virtanen, and Risto Kosonen. 2020. “A method and analysis of aquifer thermal energy storage (ATES) system for district heating and cooling: A case study in Finland.” *Sustainable Cities and Society* 53: 101977. doi:10.1016/j.scs.2019.101977.

Traber, Thure, Hans-Josef Fell, and Franziska S. Hegner. 2021. “100 % Erneuerbare Energien für Deutschland bis 2030: Klimaschutz - Versorgungssicherheit - Wirtschaftlichkeit.” Accessed February 11, 2022. https://www.energywatchgroup.org/wp-content/uploads/EWG_Studie_2021_100EE-fuer-Deutschland-bis-2030.pdf.

Ueckerdt, Falko, Christian Bauer, Alois Dirnaichner, Jordan Everall, Romain Sacchi, and Gunnar Luderer. 2021. “Potential and Risks of Hydrogen-Based E-Fuels in Climate Change Mitigation.” *Nat. Clim. Chang.* 11 (5): 384–93. doi:10.1038/s41558-021-01032-7.

“Umfrage zur Akzeptanz der Windenergie an Land Herbst 2021: Ergebnisse einer repräsentativen Umfrage zur Akzeptanz der Nutzung und des Ausbaus der Windenergie an Land in Deutschland.” 2021. Accessed May 25, 2022. https://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA_Wind_Umfrageergebnisse-2021.pdf.

Umweltbundesamt. 2022. “Erneuerbare Energien in Zahlen.” Accessed June 22, 2022. https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#uberblick.

Umweltbundesamt, and Bundesministerium für Wirtschaft und Klimaschutz. 2022. “Gemeinsame Pressemitteilung: Treibhausgasemissionen stiegen 2021 um 4,5 Prozent.” https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2022/03/20220315-treibhausgasemissionen-stiegen-2021-um-45-prozent.html.

Unruh, Gregory C. 2000. “Understanding carbon lock-in.” *Energy Policy* 28 (12): 817–30. doi:10.1016/S0301-4215(00)00070-7.

Vanhoudt, D., J. Desmedt, J. van Bael, N. Robeyn, and H. Hoes. 2011. “An aquifer thermal storage system in a Belgian hospital: Long-term experimental evaluation of energy and cost savings.” *Energy and Buildings* 43 (12): 3657–65. doi:10.1016/j.enbuild.2011.09.040.

Verbong, Geert, Frank W. Geels, and Rob Raven. 2008. “Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970–2006): hype-cycles, closed networks and technology-focused learning.” *Technology Analysis & Strategic Management* 20 (5): 555–73. doi:10.1080/09537320802292719.

Voigt, Christian, Tanja M. Straka, and Marcus Fritze. 2019. “Producing wind energy at the cost of biodiversity: A stakeholder view on a green-green dilemma.” *Journal of Renewable and Sustainable Energy* 11 (6): 63303. doi:10.1063/1.5118784.

Wachsmuth, Jakob, and Vicki Duscha. 2019. “Achievability of the Paris Targets in the EU—the Role of Demand-Side-Driven Mitigation in Different Types of Scenarios.” *Energy Efficiency* 12 (2): 403–21. doi:10.1007/s12053-018-9670-4.

Warren, Charles R., Carolyn Lumsden, Simone O'Dowd, and Richard V. Birnie. 2005. “‘Green On Green’: Public perceptions of wind power in Scotland and Ireland.” *Journal of Environmental Planning and Management* 48 (6): 853–75. doi:10.1080/09640560500294376.

Wegner, Nils. 2021. “Ansätze zur Begrenzung der Fehleranfälligkeit und des Aufwands von Konzentrationszonenplanungen.” Würzburger Studien zum Umweltenergierecht. Accessed June 24, 2022. https://stiftung-umweltenergierecht.de/wp-content/uploads/2021/08/Stiftung_Umweltenergierecht_WueStudien_22_Fehlervermeidung.pdf.

Wesseling, J. H., S. Lechtenböhmer, M. Åhman, L. J. Nilsson, E. Worrell, and L. Coenen. 2017. “The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research.” *Renewable and Sustainable Energy Reviews* 79: 1303–13. doi:10.1016/j.rser.2017.05.156.

Wiehe, Julia, Julia Thiele, Anna Walter, Ali Hashemifarzad, Jens Hingst, and Christina Haaren. 2021. “Nothing to regret: Reconciling renewable energies with human wellbeing and nature in the German Energy Transition.” *Int J Energy Res* 45 (1): 745–58. doi:10.1002/er.5870.

Wietschel, M., L. Zheng, M. Arens, C. Hebling, O. Ranzmeyer, A. Schaadt, C. Hank et al. 2021. “Metastudie Wasserstoff – Auswertung von Energiesystemstudien: Studie im Auftrag des Nationalen Wasserstoffrats.”.

“Wildlife & Wind Energy Webinar Series: History of wind energy and wildlife interactions and overview of the webinar series.” 2020. Webinar Series 1. https://tethys.pnnl.gov/events/wildlife-wind-energy-webinar-series-history-wind-energy-wildlife-interactions-overview.

WindEurope. 2020. “Circular Economy: Blade recycling is a top priority for the wind industry.” Accessed July 02, 2022. https://windeurope.org/newsroom/news/blade-recycling-a-top-priority-for-the-wind-industry/.

Zellner, Moira, and Scott D. Campbell. 2015. “Planning for deep-rooted problems: What can we learn from aligning complex systems and wicked problems?” *Planning Theory & Practice* 16 (4): 457–78.

Ziegler, Micah S., and Jessika E. Trancik. 2021. “Re-examining rates of lithium-ion battery technology improvement and cost decline.” *Energy Environ. Sci.* 14 (4): 1635–51. doi:10.1039/D0EE02681F.

Zimmer, Anne, and Nicolas Koch. 2017. “Fuel consumption dynamics in Europe: Tax reform implications for air pollution and carbon emissions.” *Transportation Research Part A: Policy and Practice* 106: 22–50. doi:10.1016/j.tra.2017.08.006.